Hydrogeology of the Dry Zone — Central Myanmar

Dr Leonard Warren Drury
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Acknowledgements
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Cover Photo: Groundwater flow from a recently completed artesian village tubewell, Ayadaw Artesian Zone, Mu River Valley, Sagaing Region. Source: *U Ngwe*

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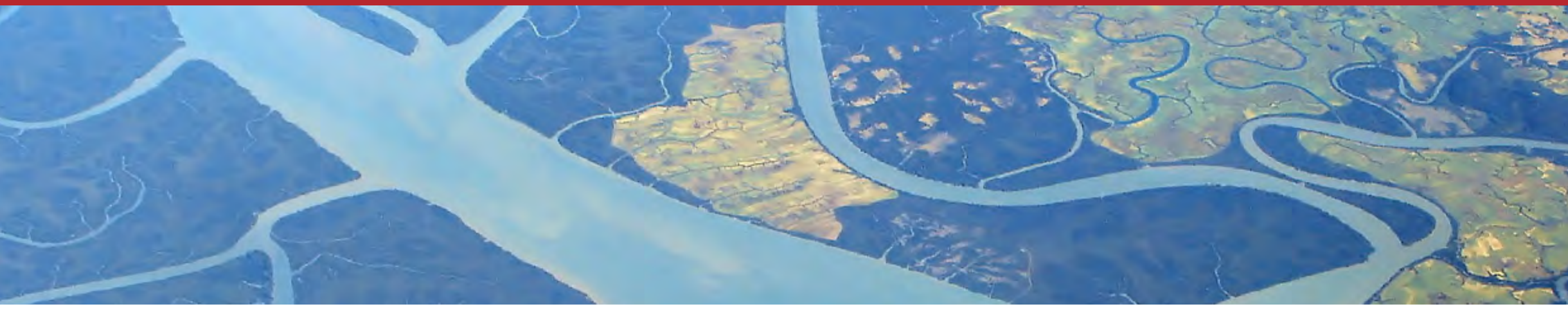


Foreword

Approximately 15.4 million people, just under 30 percent of the population of Myanmar, live in the Dry Zone, Central Myanmar. Most villages, towns and cities rely on groundwater for potable water supplies- some partially, most fully. Seventy five percent of residents rely on groundwater for drinking and domestic purposes (2014 Census)[1].

Although the Dry Zone is endowed with abundant surface water from the Ayeyarwady River and its major tributaries, these sources are unevenly distributed. Most of the flow occurs in the Wet Season, with 71 percent of annual discharge occurring during the July to October monsoon period. For the remainder of the year river flow is maintained by groundwater discharge and, more recently, from hydropower and irrigation dams.

Away from the Ayeyarwady River and tributaries the Dry Zone is extremely short of water especially during the latter part of the Dry Season. Villagers without tubewells travel great distances to collect small quantities of water from shallow dugwells and polluted earth ponds. The water shortage causes the people to suffer from water-borne and related diseases.

Photo 1: Village Water Collection from Earth Pond

Photo 2: Village Water Collection from Algae Covered Pond

Photo 3: Village Water from Shallow Dugwell. Source: *DRD*

Photo 4: Village Water Collection from Artesian Tubewell. Source: *U Ngwe*

[1] Myanmar Academy of Agriculture, Forestry, Livestock and Fishery et. al. (2003) indicate 69 percent groundwater use

The lack of access to a reliable water source and the variability in yield and quality constrains livelihood and agricultural development, contributing to the prevailing rural poverty and food insecurity. The provision of low salinity, potable groundwater to Central Myanmar is of extreme importance to the development of the nation and socio-economic welfare of its people. The Myanmar Government as a matter of national policy, ranks improved drinking water supply and sanitation, farming strategies and socio-economic development as major priorities.

In consequence of low rainfall and a steadily increasing population, water supply projects in Central Myanmar should depend on professional advice based on reliable hydrogeological, hydrological, meteorological and geological information. There are hundreds of thousands of tubewells and dugwells located within the Dry Zone however no hydrogeological database is centrally located or readily accessible. Many archived, hand-written databases have been destroyed during civil unrest and multiple relocations of government departments. Currently rigorous assessment of the hydrogeological regime within the Dry Zone is not always possible.

There is no groundwater legislation or regulation to mandate monitoring and management of the regional groundwater resource[2]. Unrestricted use of groundwater has resulted in over-exploitation of the resource, excessive water level drawdown, reduced long-term availability to the community and water quality deterioration.

Although groundwater is widespread across the Dry Zone in both unconsolidated and sedimentary rocks, there is a high variability in depth, yield, water quality (salinity, hardness, arsenic) and hydraulic condition (artesian, non-artesian, confined, unconfined). Once the geological structure is understood and documented, the magnitude of groundwater yield and variability in quality can be reasonably predicted.

In 2017, a regional assessment of the Ayeyarwady River Basin is being undertaken under the World Bank funded Ayeyarwady Integrated River Basin Management (AIRBM) Project. Part of this study includes the State of the Basin Assessment (SOBA) Package 2 *'Groundwater and Data Management'* carried out by IWMI with Aqua Rock Konsultants (ARK) as sub-consultant. As part of this study, Australian Aid (AusAID) financially supported ARK for the hydrogeological assessment of the Dry Zone, including the updating and publishing of this text *'Hydrogeology of the Dry Zone – Central Myanmar'.* The book is an update of the unpublished text (Drury 1986).

This publication is not a definitive treatise on the hydrogeology of the Dry Zone. It should be considered as a summary of the current understanding of the significance and role of groundwater in the context of overall basin water resources. This book includes an assessment of groundwater occurrence; availability; utilisation; recharge and discharge dynamics; quality; aquifer characteristics; connectivity and interaction with surface resources; current and potential use patterns; constraints to use; and threats. As more data becomes available the maps, text and tables should be regularly updated by an indigenous groundwater authority and disseminated to hydrogeological practitioners. This technical book has been prepared in an endeavour to:

- overcome the lack of easily accessible groundwater information;
- improve the knowledge of the hydrogeological regime;
- assist the investigation, development, monitoring and management of groundwater resources;
- address database gaps;
- guide in the successful siting of tubewells with a decrease in drilling costs;
- train hydrogeologists in groundwater investigation techniques and management;
- contribute in the planning of regional water development schemes;

[2] There are groundwater laws relating to urban water utilisation. A regional groundwater management act is still being considered

- suggest areas of academic research; and
- assess long-term groundwater availability for the beneficial use of the people in this complex geological and hydrogeological environment.

This report includes a detailed 1:500,000 geological map of Central Myanmar as well as local hydrogeological and hydrogeochemical drawings. These maps have been prepared by compiling available geological and hydrogeological reports, field observations, water sampling and tubewell data inventories. The detail of this report is governed by data availability which is still largely qualitative. Generalisations have been necessary in preparing the maps and notes. More detailed site-specific information may be obtained from sources listed in the bibliography and visiting relevant government authorities.

Glossary of groundwater terms and metric to imperial conversions are given in **Appendix I** and **Appendix II** respectively.

Dr Len Drury
Aqua Rock Konsultants

Representation of Groundwater Specialists 1986 and 2017

1986: RWSD Meiktila Hydrogeological Training Centre, Central Myanmar

Back Row L to R: Saya San Howe, U Thu Ra, Chit Htwe, Tin Win, Hlaing Hun Oo, Kyaw Myint Htun, Aung Naing Tun, Wai Zim, Win Zaw, Nyunt Lwin, Zaw Htay, Saya Myint Htwe
Front Row L to R: ? (military), Nyunt Lwin, Myint Thwin, Dr Len Drury, Kyaw Win, Tun Ag Kyaw, ? (military)

2017: Attendees at Hydrogeological Draft Text Workshop, Nay Pyi Taw

Back Row L to R: U Ngwe, Aung Khine Moe, Soe Maung, Ye Thu Aung, Dr Saw Aung Zaw Aye, U Thura, Myo Zaw Win, Tin Linn, Tun Win, Toe Aung, Aung Kyaw Moe, Thet Naing, Thein Soe, Tin Win, Htein Win, Chit Htwe, Tin Win, Geoff Adams, Dr Win Naing, Khin Zaw, Han Tint, Nicolas Foster, Myo Nyein, Aung Htin, Zaw Htay, Aung Myint, Mathieu Voissanges, Dr Pwint Thwe Win, Myint Aung, Zaw Oo, Kyaw Nyunt, Than Zaw, Ana Zavuovic, Hlaing Tun, Daw Phyu Thinzar Kyaw, Khin Mg Htwe
Front Row L to R: Kyaw Win, Dr Win Tint, Dr Ye Myint Swe, Hla Myint Mg, Tin Mg Aye Htoo, Dr Robyn Johnston, Dr Len Drury, Myint Soe, Soe Myint, Htay Lwin

Contents

Summary of Figures

Summary of Tables

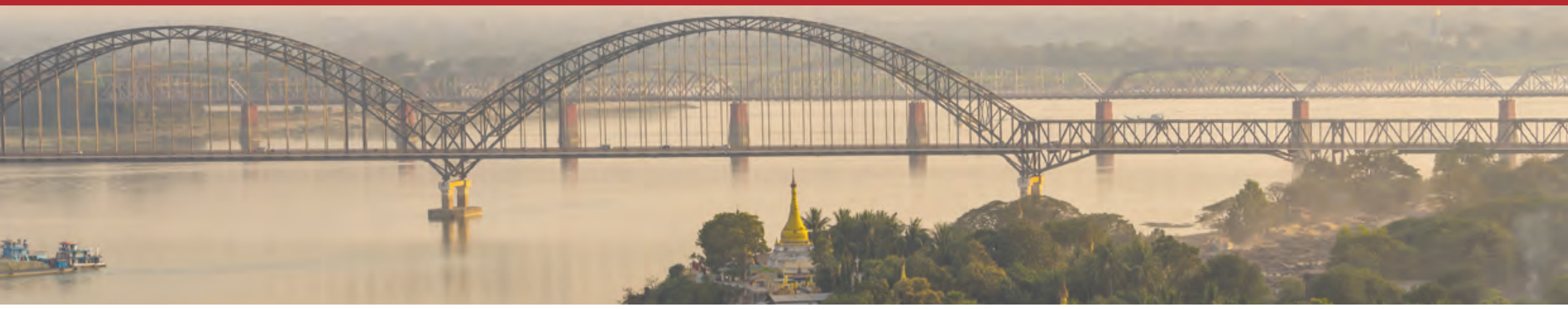
Summary of Photos

Chapter Heading Photos

Abbreviations

A	Stage 2 new ponds- 99 Pond Project
AAEC	Australian Atomic Energy Commission
AAZ	Ayadaw Artesian Zone
ADAB	Australian Development Assistant Bureau
AIRBM	Ayeyarwady Integrated River Basin Management
Al	Aluminum
All.	Alluvium
am	Ante meridiem: midnight to noon (12:00)
AMD	Agricultural Mechanisation Department
AMSL	Above mean sea level
ANSTO	Australian Nuclear Scientific Technology Organisation
Aq.	Aquifer
ARC	Ayeyarwady River Corridor
ARD	Acid rock drainage
ARK	Aqua Rock Konsultants
As^{-} As^{3-}	Arsenic
AusAID	Australian Aid
av.	Average
B	Boron
Ba^{2+}	Barium
Be^{2+}	Beryllium
Bgl	Below ground level
BMSL	Below means sea level
Bpd	Barrels per day
Br^{-}	Bromium
BVWSP	Burma Village Water Supply Project
C	Centre
Ca^{2+}	Calcium
$CaCO_3^{2-}$	Calcium carbonate
Cd^{2+}	Cadmium
Ch.	Chapter
Cl^{-}	Chloride
cm/year	Centimetre per year
CN^{-}	Cyanide
CO_3^{2-}	Carbonate
C-14	Radiocarbon (carbon-14) dating
Cr^{-}	Chromium
Cu^{+} Cu^{2+}	Copper
cusec	Cubic feet/second
DD	Drawdown level
DDL	Drawdown water level
dia.	Diameter
DRD	Department of Rural Development
DTW	Deep tubewell
DW	Dugwell
E	East
EC	Electrical Conductivity
e.g.	For example
et. al.	And other authors
etc.	Etcetera (and so on)
F^{-}	Fluoride
FAO	Food and Agriculture Organisation
Fe^{2+} Fe^{3+}	Iron
$ft.d^{-1}$	Feet per day
GAB	Great Artesian Basin
$gal.d^{-1}.ft^{-1}$	Gallons per day per foot
Govt.	Government
Gr.	Group
F-coli.	Faecal Coliforms
Fm. fm.	Formation formation
$ft.d^{-1}$	Feet per day
GABSI	GAB Sustainability Initiative
GAD	General Affairs Department
$gal.d^{-1}.ft^{2}$	Gallons per day per square feet
GDC	Groundwater Development Consultants (Int.) Ltd
Ha	Hectare
HCO_3^{-}	Bicarbonate
Hg^{2+}	Mercury
H_2S	Hydrogen Sulphide
IBRD	International Bank for Reconstruction and Deve.
ICEM	International Centre Environmental Management
ID	Irrigation Department
IDA	International Development Association
INGO	International Non-government Organisation
Irr. Fm.	Irrawaddy Formation
Irrig.	Irrigation
IWMI	International Water Management Institute
IWUMD	Irrigation Water Utilization Management Department
JICA	Japan International Co-operation Agency
k	Hydraulic Conductivity (permeability)
K^{+}	Potassium
Km	Kilometre
km^2	Square kilometres
km^3	Cubic kilometres
km^3/year	Cubic kilometre/year
KOICA	Korean International Cooperation Agency
L	Ponds on left of Yinmabin Road
L/d/p	Litres/day/person
L/sec	Litres/second
L/sec/m	Litres/second/metre
L/d/p	Litres/day/person
L/sec	Litres/second
L/sec/m	Litres/second/metre
m	Metre
MAF	Ministry of Agriculture and Forests
m AMSL	Metres above mean sea level

max.	Maximum
m BMSL	Metres below mean sea level
MCDC	Mandalay City Development Committee
$Mm^3.yr^1$	Million cubic metres per year
MCM	Million cubic metres
$m.d^{-1}$	Metres per day
m/d	Metres per day
meq/L	milliequivalents/litre
Mg^{2+}	Magnesium
MGD	million gallons per day
MGIP	Monywa Groundwater Irrigation Project
mg/L	milligrams/litre
min.	minimum
ML/day	million litres per day
ML/year	million litres per year
Mm	millimetres
mm/day	millimetres per day
$Mm^3.yr^{-1}$	million cubic metres per year
Mn^{2+} Mn^{4+}	Manganese
MOALI	Ministry of Agriculture, Livestock and Irrigation
MPN	Most Probable Number
MSc.	Master of Science
Mt.	Mount
MTGIP	Meiktila Thazi Groundwater Irrigation Project
m^2/day	square metres per day
m^3/day	cubic metres per day
N	North
Na^+	Sodium
NDWQS	National Drinking Water Quality Standards
NGO	Non-government Organisation
NH_4^+	Ammonium
Ni^{2+} Ni^{3+}	Nickel
NNW	North North West
NO_2^-	Nitrite
NO_3^-	Nitrate
NPWSS	Nanmyingtaung Piped Water Supply Scheme
NSDS	National Sustainable Development Strategy
NTU	Nephelometric Turbidity Units
NW	Northwest
NWQS	National Water Quality Standard
NWRC	National Water Resources Committee
O^{2-}	Oxygen
Pb^{2+} Pb^{4+}	Lead
pers comm	Personal communication
pH	Negative logarithm of hydrogen ion
PhD	Doctor of Philosophy
Pm	Post meridiem: noon to midnight
PO_4^{3-}	Phosphate
PPGIP	Pwaybwe-Payangazu Groundwater Irrig. Project
Pv	Private
Q_{in}	Groundwater inflow
Q_{out}	Groundwater outflow
Pv	Private
Q_{in}	Groundwater inflow
Q_{out}	Groundwater outflow
$Q_{out\ add}$	Additional groundwater outflow
R	Ponds right of Yinmabin Road
RDD	Rural Development Department
RL +	Reduced Level (surface)
RSWSB	Rural Sanitation and Water Supply Board
RWSD	Rural Water Supply Division
RWSSB	Rural Water Supply and Sanitation Board
S	South
SAC	Superficial Alluvium cover
SAR	Sodium Absorption Ratio
Sb^{3+}	Antimony
SC	Storage co-efficient
Se	Selenium
SiO_2^-	Silica
SO_4^{2-}	Sulphate
SOBA	State of Basin Assessment
St. Dev.	Standard deviation
STW	Shallow tubewell
Sub Mu	Subsurface flow to Mu River
SWL	Static water level (Potentiometric surface)
T	Transmissivity
T-Coli	Total Coliforms
TCU	True Colour Unit
TDS	Total dissolved solids
TGIP	Tatkon Groundwater Irrigation Project
TW	Tubewell
TWS	Town Water Supply
TU	Tritium Units
TZPWSS	Taung Zin Piped Water Supply Scheme
U^{4+} U^{6+}	Uranium
UNDP	United Nations Development Program
UNICEF	United Nations Children's Fund
V	Vanadium
VGPWSP	Village Group Piped Water Supply Scheme
VWS	Village water supply
W	West
WHO	World Health Organisation
WRUD	Water Resources Utilization Department
WS	Water supply
Y/A	Ywatha/Aungban Aquifer
Zn^{2+}	Zinc
Ω.cm	Ohms centimetre
^3H	Tritium
°C	Degrees Celsius
°F	Degrees Fahrenheit
Φ	Porosity
%	Percent
µg/L	Microgram/Litre
$\mu S.cm^{-1}$	Micro Siemens/centimetre at 25°C
<	Less than
>	Greater than
+	Above ground level
≈	Approximately
ΔS	Change in aquifer storage



1 Introduction

The Republic of Myanmar is situated in the northwest of the Indochina Peninsula, bordering Bangladesh, India, Thailand, China and Laos. It covers 680,000 square kilometres (km^2). There is one administrative capital, seven administrative regions (taing-myar) and seven states (pyi ne-myar):

- Union Territory: Nay Pyi Taw;
- Regions: Ayeyarwady, Bago, Magway, Mandalay, Sagaing, Tanintharyi, Yangon; and
- States: Chin, Kachin, Kayah, Kayin, Mon, Rakhine and Shan.

The major ethnic groups are: Burman 68%, Shan 9%, Karen 7%, Rakhine 4%, Chinese 3%, Indian 2%, Mon 2%, other 5%. The life expectancy in Myanmar is: male 64.6 years; female 68.5 years [3], which places Myanmar at a World Life Expectancy ranking of 126.

1.1 The Dry Zone

Figure 1 and **Figure 2** show the location of the Dry Zone. It is sited in an elongated sedimentological basin, between latitudes 19° to 23° North and longitudes 94° to 96° 30' East. It has a maximum length of 560 kilometres, width of 270 kilometres and a total area over 75,700 km^2. It is located within Sagaing Region (Sagaing, Shwebo and Monywa districts); Mandalay Region (Kyauske, Myingyan, Meiktila, Yamethin and Nyaung Oo districts) and Magway Region (Pakokku, Magway, Minbu and Theyet districts). The Ayeyarwady River and major tributaries (Chindwin and Mu rivers) traverse roughly north-south through this region. The Dry Zone encapsulates 53 townships.

The Dry Zone is ringed by steep, rugged highlands (Naga Hills, Chin Hills and Rakhine Yoma (west); the Bago Yoma (southern central) and Shan Plateau (east)). All mountain ranges are orientated roughly north to south.

The Dry Zone is a climatic geographical location not an administrative boundary. It is defined as the area where rainfall is less than 1,000 millimetres (mm) per year. It is located within a rain shadow of the Rakhine Yoma.

Fertile alluvial soil is found along the Ayeyarwady River plains. Sagaing Region has the largest area of alluvial soil, Magway the smallest. Less fertile sandy land is located over sandstone outcrops and poor soil of 'badlands' topography exists over marine shales.

Table 1 gives population, health and poverty information for the three Regions that are partly occupied by the Dry Zone. The average country poverty level is 22.9 percent[4].

[3] WHO (2015)

[4] Asian Development Bank (2017)

Figure 1 Location of the Dry Zone, Central Myanmar

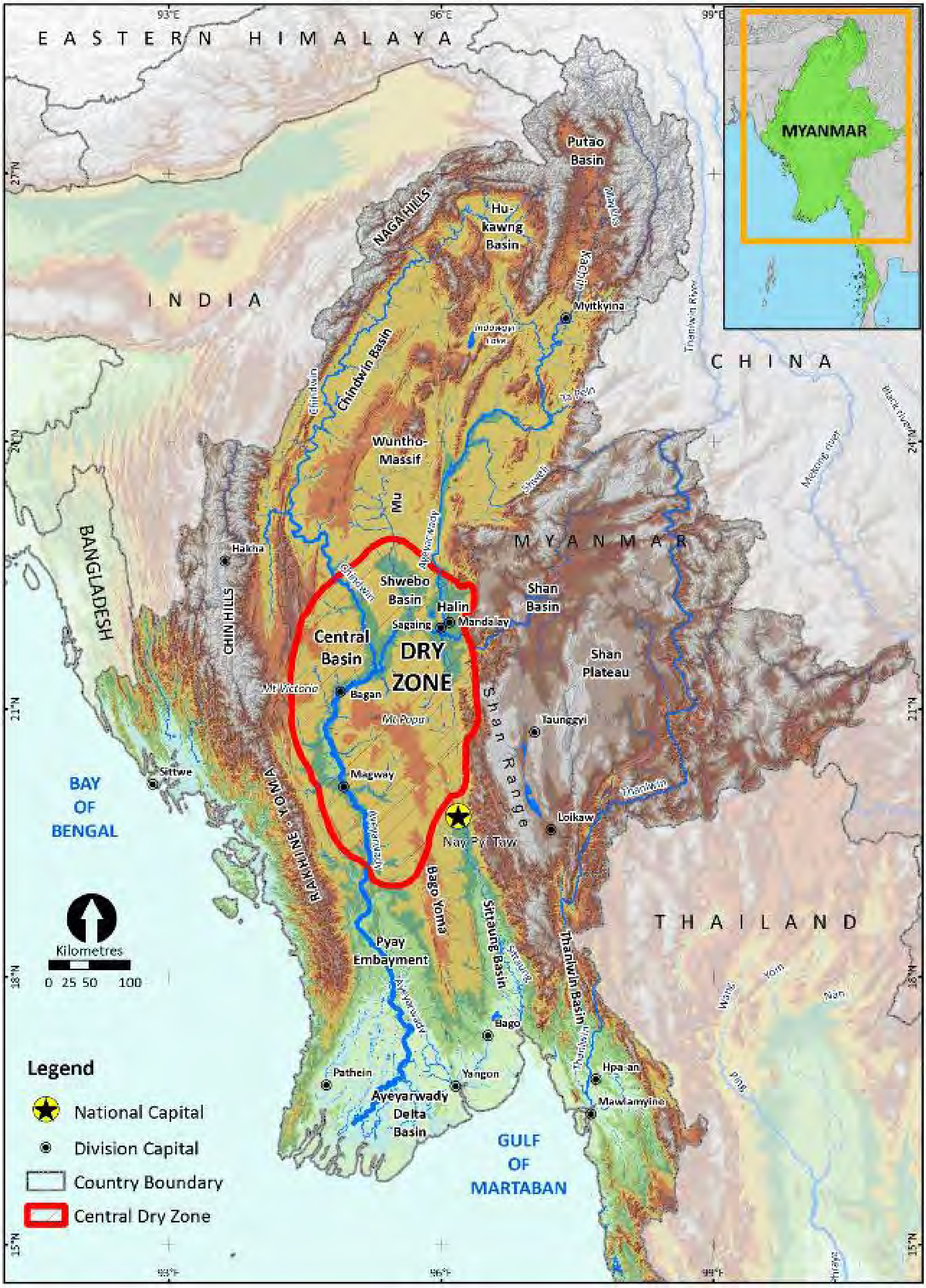


Figure 2 Satellite Image of the Dry Zone

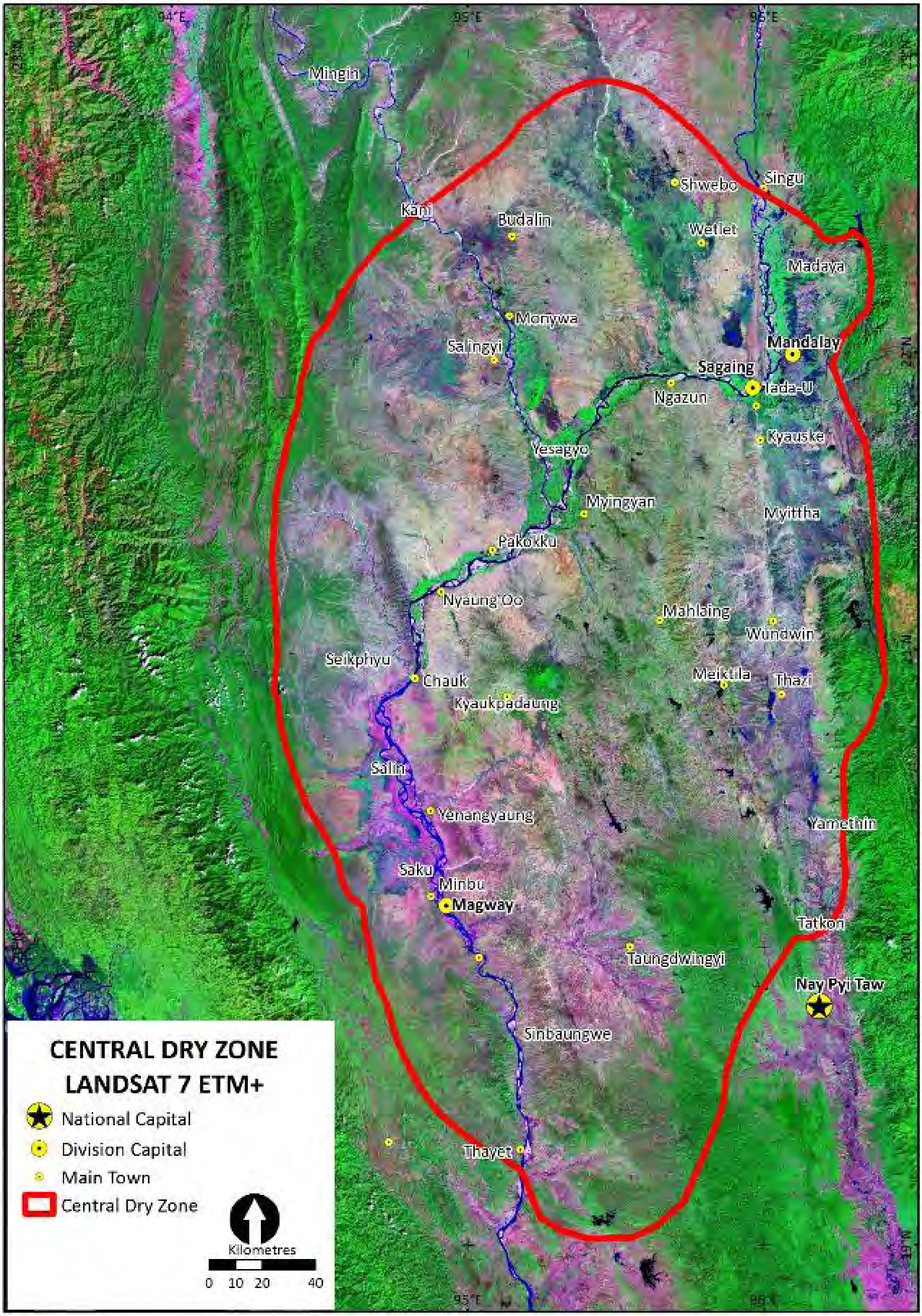


Table 1 Population, Health and Poverty Statistics for Dry Zone, Myanmar

Region	Total Population	Child Population (Under 18)	Poverty Rate (%)	Comment on Health and Poverty
Mandalay	6,165,723	1,935,378	26.6	Has the third largest population in Myanmar. Mandalay City is the second-biggest urban centre after Yangon. Being a relatively developed area, the population has better health and education services but poverty is still high.
Sagaing	5,325,347	1,819,046	15.1	Covers the second-largest region in Myanmar. Towns near the India border (Nagaland State) are remote and difficult to reach in Myanmar.
Magway	3,917,055	1,249,172	27	Is in the centre of the Dry Zone. Families frequently face water scarcity and a regular supply of clean water. It is a region of high infant mortality rate.

Source: UNICEF (2014) https://www.unicef.org/myanmar/overview_25057.html.

1.2 Groundwater Authorities

Established under the constitution of Myanmar and directly answerable to the Parliamentary Cabinet, the National Water Resources Committee (NWRC) is the highest National statutory governing body to formulate groundwater and surface water law, policy, administration and development. They receive advice from a panel of key technical counsellors from the Advisory Group.

The Government authorities responsible for water development and management are listed in **Table 2.** They formulate short-term and long-term water activities; carry out drilling, pump installation, maintenance, rehabilitation and water analyse; construct piped water schemes; and attract aid donors within the scope of the authority they have been given.

Historically, there has been a proliferation of government authorities responsible for village water supply:

- 1952 Rural Water Supply and Sanitation Board (RWSSB), Ministry of Social Welfare;
- 1953 Rural Sanitation and Water Supply Board (RSWSB), Ministry of Social Welfare;
- 1959 Agriculture and Rural Development Corporation, Ministry of Agriculture;
- 1962 Rural Water Supply Project, Ministry of Agriculture;
- 1972 Rural Water Supply Division (RWSD), Ministry of Agriculture and Forests;
- 1995 Water Resources Utilization Department (WRUD), Ministry of Agriculture and Irrigation; and
- 2015 Rural Development Department (RDD) and Irrigation and Water Utilization Management Department (IWUMD), Ministry of Agricuture Livestock and Irrigation.

1.3 Groundwater Utilisation in Myanmar

There is little published information on the regional assessment of groundwater resources in Central Myanmar. There are a few exceptions[5], along with some short reports and university theses[6] describing the occurrence of groundwater in localised areas. Other technical papers are often unpublished departmental reports.

[5] Ivanitsin (1962a,b), Tahal (Water Planning) Ltd (1963), Maung Thin (1971), Aung Ba (1972), Coffey and Partners et. al. (1977) and UNICEF (1980)

[6] Tin Maung Nyunt (1976, 1980), Maung Maung Lwin (1981), Maung Tun Lwin (1981), Than Tun (1981), Maung Kyaw Aung (1984), Cho U (1986), Than Zaw (2010, 2016), Kyi Kyi Thwin (2011), Nyi Nyi Tun (2013), Su Mon Win (2013), Tin Ni Nyi Win (2013), Aye Aye Min (2016), Hein Thu (2016), Khin Nilar Tin (2016), Tun Aung (2016), Wai Wai Phyo (2016)

Table 2 Government and Private Organisations Involved in Water Development

Agencies	Ministry	Functions
Irrigation and Water Utilization Management Department	Agriculture, Livestock and Irrigation	Irrigation/groundwater exploration
Rural Development		Rural water supply and sanitation
Myanmar Fishery Enterprise		Fishery works
Directorate of Water Resources and Improvement of River Systems	Transport	River training and navigation
Meteorology and Hydrology		Assessment of major rivers
Department of Hydropower Implementation	Electricity and Energy	Hydropower generation
Factories	Industry	Industrial use
Forest Department	Environmental Conservation and Forest	Conservation of forest
Public Works	Construction	Industrial water supply/sanitation
Human Settlement and Housing Development		Domestic water supply
Health	Health and Sport	Health, water quality assessment
Central Health Education Bureau		Mobilisaton health promotion
Yangon Technology University	Education	Training and research
City Development Committee	Yangon/ Mandalay/Nay Pyi Taw	City water supply and sanitation
Township Development Committee	Regional Government	Town water supply and sanitation
Private Organisation, Non-government Organisations (NGOs) and International Non-government Organisations (iNGO), UN	Independent Local and International donors	Domestic water supply, navigation and fisheries

1.3.1 History of Groundwater Development

Little is known about the history of groundwater development in Central Myanmar. The hot mineral springs at Halin, near Shwebo were used for bathing in the eighth century, when the city was the capital of Upper Myanmar. Historians believe that during the Pagan Period (eleventh to thirteenth centuries), dugwells were used in the city of Bagan for domestic purposes. Water sellers distributed the groundwater to the residences. From that time dugwells were used throughout Central Myanmar in increasing numbers. This was especially so when new administrative capitals were established at Sagaing, Ava, Shwebo, Amarapura and Mandalay[7].

Photo 5: Sithaw Village, Nyaung Oo. Source: *DRD*

The first reported hydrogeological investigation in Myanmar was undertaken by the Geological Survey of India[8]. The oldest known tubewell was drilled in 1889 in Dalla Township, Yangon by E. Solomon and Sons, using a water jet rig for the Bombay Burma Trading Company Ltd. This 75-millimetre diameter tubewell was sunk to 53 metres but abandoned due to saline water being encountered[9]. The location and year of construction of the first tubewell in the Dry Zone are unknown. The RWSSB recorded 22 tubewells sunk in 1952.

[7] All ancient capitals are close to Mandalay
[8] Oldham (1893)
[9] Leicester (1932)

Before the establishment of the Union of Burma in 1948, groundwater legislation and regulations[10] were well advanced and equalled or surpassed most other countries. The Burma Underground Water Act of 1930 was an attempt to obtain relevant groundwater information to manage underground water supplies and prevent aquifer contamination. One step was that all tubewells within a 40 kilometres (km) radius of the Shwedagon Pagoda, Yangon had to be registered and tubewell completion details submitted for recording. In 1941 under the Public Health Branch of the Health and Public Works Department, the Underground Water Rules were introduced. All tubewells sunk in Myanmar had to be licenced (fee of 50 Rupees). Specific rules of such a licence included retention of cutting samples, full detailed tubewell completion data, a lithological log, compulsory full chemical and bacteriological water analyses, water level, groundwater yield and pumping test results. Severe penalties were imposed on drillers and owners who did not conform to the conditions of the licence. Under this Act there were also guidelines and procedures for groundwater litigation problems.

Unfortunately, all databases have been lost and acts and regulations abandoned.

1.3.2 Village Groundwater Supplies

By 1952, with limited budget the Burmese Government commenced drilling for village groundwater supplies. The initial areas were mainly outside of the Central Myanmar (Bago, Yangon and Ayeyarwady regions). More intense groundwater drilling activity in the Dry Zone commenced in 1963. By 1977 the government, using its own resources completed 3,760 tubewells equipped with hand pumps.

A major development in village water supply occurred in 1976 when the World Health Organisation (WHO), United Nations Children's Fund (UNICEF) and the Australian Development Assistance Bureau (ADAB), planned and funded the Burma Village Water Supply Project (BVWSP)[11] and the Taung Zin Piped Water Supply Scheme (TZPWSS)[12], both in the Dry Zone. Between 1978 to 1986 the US$100 million project constructed groundwater supplies in 3,100 villages in the Dry Zone. The RWSD carried out the works in association with Australian groundwater and drilling expertise. A further four-year tubewell programme proposal (1987-1991) including the Nanmyinttaung Piped Water Supply Scheme (NPWSS)[13] was proposed but never happened due to the period of internal civil unrest. The Netherlands supported the RWSD in undertaking a piped reticulation scheme (Village Group Piped Water Supply Project (VGPWSP) using BVWSP tubewells.

Since 2008 the Japan International Co-operation Agency (JICA) and the Department of Rural Development (DRD) have undertaken village water supplies in the Dry Zone under the '22', '87' and '110 tubewell programs'.

Over the last half century rural water supply development has dominated groundwater development activities. There are hundreds of private drillers that operate in the Dry Zone. With limited resources, many NGOs and INGOs may each construct or rehabilitate five to ten tubewells per year. The KBZ Future Bank Lights Myanmar Foundation has recently purchased a new drilling rig crewed by experienced drillers as part of their charitable works. **Figure 3** shows the location of the village tubewells that have had GIS coordinates assigned (about 30 percent of IWUMD holes in the Dry Zone). Water supplies from other government authorities, private owners and NGOs are not included.

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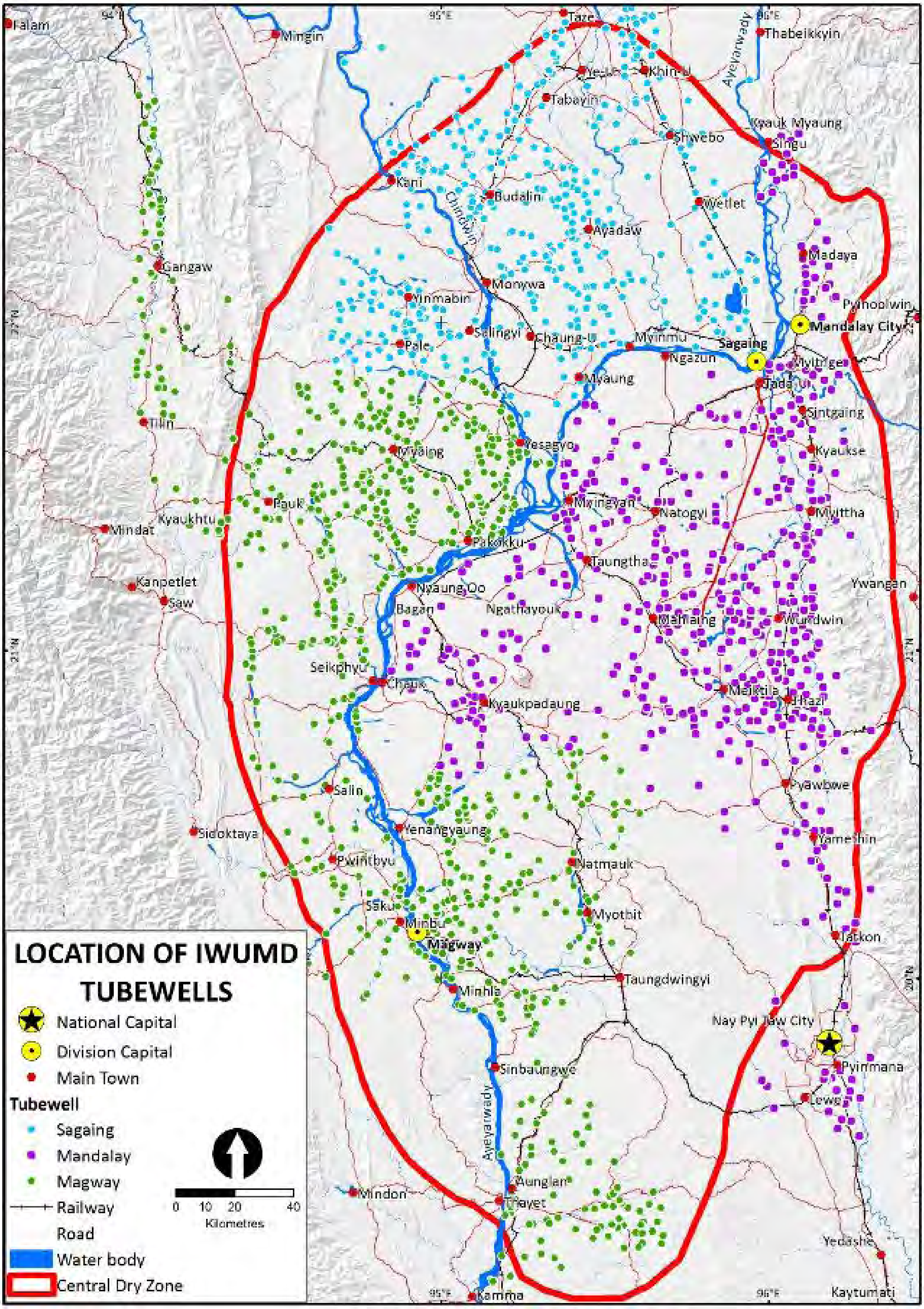
[10] Rangoon Water Works Act (1885), Burma Municipal Act (1898), Canal Act 1905 (amended 1914, 1924, 1928 and 1934), Embankment Act, 1909 (amended 1923 and 1931), City of Rangoon Municipal Act (1922), Underground Water Act (1930), Water Power Rules (1932)

[11] Coffey and Partners et. al. (1977, 1979, 1980, 1981a,b, 1982, 1984a,b,c, 1986), Coffey and Partners (1981, 1983a,b, 1984a-e, 1985a-f), ADAB (1982, 1986), Thein Maung Myint (1983, 1984, 1985, 1986), UNICEF (1980, 1983a,b, 1984, 1985), Nyi Win Hman (1984) and AMD (1985)

[12] World Health Organisation (1980), Coffey and Partners Pty Ltd (1981, 1983b), Coffey and Partners Pty Ltd and Sinclair Knight & Partners Pty Ltd (1982, 1984)

[13] Soe Win et. al. (1983, 1985), Soe Win & Shwe Ko (1983), Soe Win (1984a, b), Coffey and Partners (1984f, 1985a)

Figure 3 IWUMD Digitised Tubewells in Dry Zone



In most cases village water committees select the drilling site without professional advice (even in the same proximity to previously abandoned holes). Consequently, in hydrogeologically challenging environments tubewell abandonment still regularly occurs. With no technical construction advice, drilling by the cheapest contractor and poor-quality materials, many 'successful' tubewells quickly become dysfunctional. In contrast, the RWSD tubewells and helical-rotor Mono pumps have been successfully operated for almost 40 years. With the increased availability of electric power, the original diesel driven pump engines are been replaced with electric motors.

A total of 13,355 domestic village tubewells have been constructed by IWUMD and predecessors throughout the Dry Zone (**Table 3**). Completion records were hand written in large voluminous books—village names were their only coordinate reference. The table omits the hundreds of thousands of private domestic tubewells and dugwells.

Table 3 Government Constructed Drinking Water Tubewells in Dry Zone (1952-March 2017)

Region	Groundwater				Spring Gravity Flow		Total Beneficiaries
	DTW	STW	Total	Population	System	Population	
Sagaing	2,845	1,830	4,675	2,184,105	8	28,248	2,212.353
Magway	2,686	1,877	4,563	2,069,818	13	23,860	2,093,678
Mandalay	3,199	918	4,117	2,161,815	7	9,798	2,171,613
Total	8,730	4,625	13,355	6,415,738	28	61,906	6,477,644

Source: IWUMD data (2017).

1.3.3 Urban Groundwater Supplies

Mandalay City and the various Township Development Committees develop and operate urban water supply and sanitation schemes for their respective locations. **Table 4** and **Figure 4** indicate the source of domestic water for the major towns in the Dry Zone.

Table 4 Water Supply Sources to Main Towns in Magway, Mandalay and Sagaing Regions

Region	Cities/Towns		
	Groundwater	Groundwater/Surface Water	Surface Water
Magway	Minbu, Myothit, Salin, Taungdwingyi, Yenangyaung	Magway, Natmauk, Thayet, Minhla, Pauk	Chauk, Sinbaungwe, Siekphyu
Mandalay	Kyaukpadaung, Natogyi, Mahlaing, Pwaybwe, Wundwin, Yamethin, Takton	Mandalay, Myingyan, Taungtha, Thazi, Myittha, Sintaing	Bagan, Kyauske, Meiktila, Nyaung Oo
Sagaing	Ayadaw, Budalin, Myaing, Pakokku, Pale, Salingyi, Yinmabin, Wetlet, Khin-U, Ye-U, Tabayin	Sagaing, Monywa, Shwebo	

Source: IWUMD data (2017).

Most towns utilise groundwater as their primary source for domestic water. Towns with surface water as their primary supply, still have large numbers of privately owned and operated tubewells and dugwells.

Since 1981, the Government with assistance from the Japanese Government (JICA), has carried out urban water development schemes throughout the Dry Zone[14].

Construction of the Mandalay City Water Supply[15] wellfield commenced in 1986. Currently, groundwater supplies 90 percent of the city's reticulated water supply of 136,364 cubic metres per day (m^3/day) and close to 100 percent of non-piped urban demand.

[14] Japan International Co-Operation Agency (1985, 2003, 2007, 2010, 2015, 2016)

[15] Department of Applied Geology (1983), Coffey and Partners, Sinclair Knight & Scott and Furphy Engineers (1984, 1985), JICA (2003, 2015), Mandalay City Development Committee (1989), Ministry of Home and Religious Affairs (1984), San Lwin et. al. (1988), Tin Win (2016)

1.3.4 Industrial Supplies

The industrial sector consumes large volumes of water. Throughout Myanmar groundwater supplies around 30 percent of industrial water needs[16]. Sugar mills, paper production and cement factories usually use surface water, whilst the remainder heavily rely on groundwater. The industrial areas within Mandalay City totally rely on groundwater supplies through 1,522 tubewells.

1.3.5 Irrigation Supplies

Surface Water

The earliest known irrigation works in the Mandalay area were constructed in the first century and greatly improved during the eleventh century. The maintenance of irrigation works lapsed somewhat after the fall of the monarchy in the late nineteenth century. British authorities repaired and extended parts of these ancient systems during the early twentieth century. Since 1988 the government has made considerable effort to increase the area of irrigation. Nationally 233 dams and weirs and more than 350 river pumping stations have been constructed (FAO 2011) for irrigation purposes.

In the Dry Zone a large number of surface water irrigation projects have been developed on the Ayeyarwady, Chindwin and Mu rivers. The Dry Zone contains large areas suitable for irrigation— the majority is irrigated by gravity diversion and pumped surface water schemes.

Table 5 gives an estimate of surface water irrigation command areas for IWUMD diesel and electric pumping stations in the Dry Zone, Central Myanmar.

Photo 6: Irrigation Pumping Station on Mu River, Ayadaw

Photo 7: Irrigation Channel from Myitynge River, Mandalay.

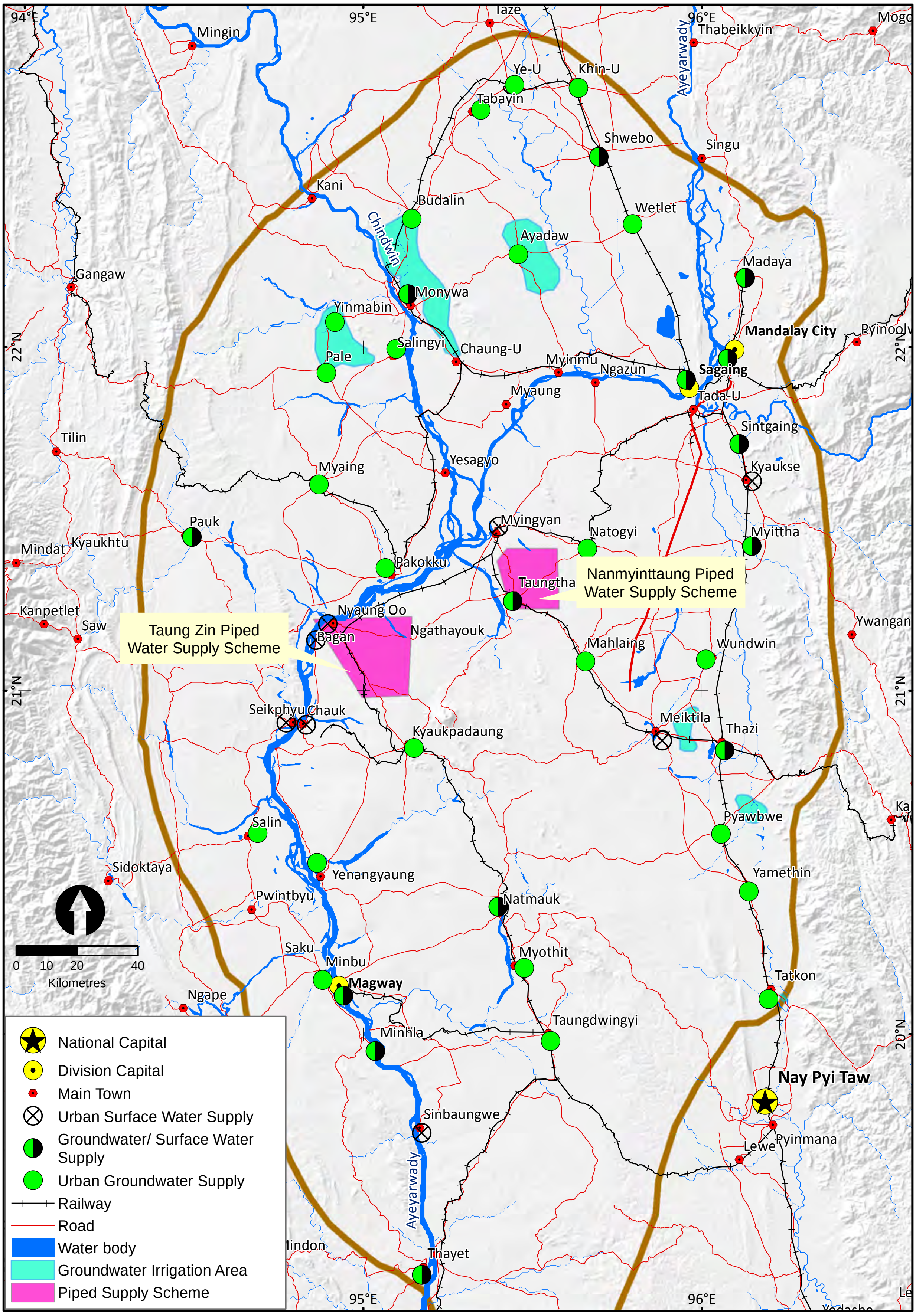
Table 5 Surface Water Irrigation Activities in the Dry Zone

Region	IWUMD				TOTAL	
	Electric		Diesel			
	No. of sites	Command area (ha)	No. of sites	Command area (ha)	No. of sites	Command area (ha)*
Sagaing	19	47,289	1	162	20	47,451
Magway	28	33,710	-	-	28	33,710
Mandalay	33	38,318	3	761	36	39,079

Source: IWUMD data (2017). * 'command area' is planned, rarely actual.

[16] McCartney et. al (2013)

Figure 4 Town Water Supply and Groundwater Irrigation Projects



Groundwater

In 1977, the Burma Agricultural Sector Review by the World Bank and the Irrigation Department (ID) recommended groundwater exploration and development. A pilot tubewell project, the 'Umbrella Project'[17], was instigated to increase cropping intensities. Financed by the United Nations Development Program (UNDP) and the International Development Association (IDA) of the World Bank through the ID, the 1978 to 1984 study involved the procurement of drilling rigs, the construction of 137 tubewells (of which 63 proved successful for irrigation purposes), soil reconnaissance studies, pilot irrigation systems and training. Of the five areas investigated, four (Yinmabin, Monywa, Yamethin and Ye U) are within the Dry Zone.

The location of government developed groundwater irrigation projects in the Dry Zone are shown on **Figure 4** and summarised on **Table 6.**

Along the alluvial flats of the Ayeyarwady River and tributaries there are tens of thousands of private farmer-owned and operated irrigation systems extracting groundwater from 50 to 100 millimetres diameter shallow tubewells.

Table 6 Groundwater Irrigation Areas, Dry Zone

Irrigation Project	Region	Established	Tubewell No. and 2017 Total Yield	Command Areas* (ha)
Monywa	Sagaing	1982- 1992	141 (105@ 50 L/sec and 36 @ 25 L/sec). Irrigation season pumping yield of 53.3 million cubic metres per year ($Mm^3.yr^{-1}$)	6,360
99 Pond Artesian Zone, Yinmabin	Sagaing	1994- 1995 (Stage 1) / 2000 (Stage 2)	449 flowing holes in 107 ponds. Average flow 3 L/sec. Annual flow of 44.7 $Mm^3.yr^{-1}$	3,300
Ayadaw Artesian Zone	Sagaing	Commenced before 1982 and continuing	> 60 artesian tubewells flowing 62.2 m^3/day, 5.5 $Mm^3.yr^{-1}$	664
Pyawbwe – Payangazu	Mandalay	2009- 2011	100, (75 initially artesian). Yield 3 $Mm^3.yr^{-1}$	485
Meiktila – Thazi	Mandalay	2008	486. Yield 5.6 $Mm^3.yr^{-1}$	2,590
Tatkon	Mandalay	2014- 2015	10. Yield 3 $Mm^3.yr^{-1}$	191

Source: IWUMD data (2017). * 'command area' is planned, not necessarily actual.

1.4 Water and Environment Related Laws and Regulations

Laws and Regulations directly or indirectly related to water resource development are listed in **Table 7.** There is no holistic Groundwater Law or associated Regulations or specific laws governing water quality or pollution.

[17] Groundwater Development Consultants (1979, 1980a-c, 1981a-g, 1982a-c, 1983a,b, 1984a-c), Euroconsult (1983), IBRD (1977)

Table 7 Myanmar Laws and Regulations Related to Water

Specialist Area	Name of Legislation	Year
Constitution	Constitution of the Republic of the Union of Myanmar	2008
Guideline	Myanmar Agenda 21	2009
Development Strategy	National Sustainable Development Strategy (NSDS)	1997
Organisation Act	Development Committee Law	1993
Environmental Administration	Gazette Notification No. 26/94 dated 5 December 1994	1994
	Environmental Conservation Law	2012
	Environmental Conservation Rules	2014
	Prevention of Hazard from Chemical and Related Substances Law	2013
	Protection of Wild Life and Wild Plants and Conservation of Natural Areas Law	1994
Agriculture	Farm Land Law	2012
	Fallow and Virgin Management Rules	2013
Dangerous Chemicals	Chemical Safety Law	2013
Forest Administration	Forest Law	1992
	Forest Rules	1995
	National Forest Policy	1995
Natural Protection	Wildlife and Wild Plants and Conservation of Natural Areas Law	1994
Mineral Resources Development	Mines Law	1994
	Mining Rules	1996
Oil/Gas Resources Development	Petroleum Act	1934
	Petroleum Rules	1937
Water Resources	Conservation of Water Resources and Rivers Law	2006
	Conservation of Water Resources and Improvement of the River Systems Rule	2013
	Water Power Act	1927
Fisheries	Fresh Water Fisheries Law	1991
Science and Technology	Science and Technology Law	1993
	Engineering Council Law	2013
Cultural Inheritance	Protection and Preservation of Cultural Heritage Regions Law	1998
Public Health	National Drug Law	1992
	Public Health Law	1972
	Prevention and Control of Communicable Diseases Law	1995
City Development Corporations	City of Yangon Development Law	1999
	City of Mandalay Development Law	1992
Foreign Investment	Foreign Investment Law	2012
	Foreign Investment Rules	2013

2 Physiological and Climatological Environment

2.1 Physiographical Features

The geography of Myanmar can be divided into five physiographic regions: the northern mountains; the western ranges; the eastern plateau; the central basin and lowlands of the coastal plains. The international border mountains connecting to the Tibetan Plateau of the eastern Himalayan Syntaxis, divide Myanmar into three main river systems: the Ayeyarwady – Chindwin rivers, the Thanlwin River and the Sittaung River **(Table 8)**. Together these river systems drain 81 percent of surface flow in Myanmar and contain 82 percent of the assumed groundwater resources. Minor drainage systems include the Mekong River Basin, Rakhine Coastal Plain and Tenasserim Coastal Basin.

Table 8 Major Surface Water Systems, Myanmar

River Systems		Length (km)	% Country Drained	Catchment Area (km^2)	Average Inflow (km^3/year)
Ayeyarwady	Ayeyarwady	2,000 +	58	288,900	313.72
	Chindwin	1,100		115,300	141.29
Thanlwin		420	18.4	34,395	41.95
Sittaung		2,410	5.4	158,000	257.92
TOTAL		5,930 +	81.8	586,595	754.88

Source: Zaw Win (2014), Sein Aung Min (2014).

Most of the Dry Zone is located within the Ayeyarwady River Basin. Upstream of Nyaung Oo the Ayeyarwady River catchment is 309 x 10^3 km^2. Recent hydrological studies[18] show that over the last 100 years water discharge in the Ayeyarwady River has progressively decreased.

The Dry Zone is surrounded on three sides by large mountain ranges **(Figure 2)**. To the west and north are the mountains of the Indo-Burman Range (Western ranges)- the Rakhine Yoma rises to elevations over 2,000 metres, whilst Mount Victoria in the Chin Hills attains a height of 3,110 metres. The highlands of the Shan Plateau rise abruptly to an average height of 600 metres, forming the eastern boundary. The lower elevated Bago Yoma Anticlinorium rises in the central part of the Dry Zone and extends from Nay Pyi Taw for 480 kilometres to Sagaing. This anticlinorium divides the basin into two almost equal meridional valley systems.

Mount Popa is an extinct volcano which rises to 1,518 m AMSL to form a prominent local topographic feature.

The Ayeyarwady River flows south along the north-south Sagaing Fault line to Mandalay where it turns west and then south to occupy the western valley. There are many tributaries which have confluence with the Ayeyarwady River within the Dry Zone. These include the Sindewa, Thinbon, Mondaing, Yin, Kadaung, Pin, Pyinma and Chaungmagyi chaungs and associated drainage systems. Fertile alluvial soils are found along the extensive alluvial flats of the major rivers, but it is less productive on the sandy soil of the Bago Yoma[19].

[18] Robinson et. al. (2007), Furuichi et. al. (2009)

[19] McKerral (1910, 1911), Charlton (1932), Richards (1954), Rozanov (1961, 1965, 1974), Rovanov & Rozanova (1961), Obukhov (1968a,b), FAO (1973)

The Sittaung River catchment occupies the lower part of the eastern drainage system.

The alluvial flats of the Ayeyarwady River gently slope to the south, with surface elevation varying from 70 m AMSL at Mandalay to 45 m AMSL at Magway. The overall flat morphology of the central area is interrupted by a series of tectonically-induced, NNW-SSE orientated elongated anticlinal ridges. They sharply rise over the surrounding plains and significantly impede the continuity of wide alluvial deposits.

2.2 Climatological Features

Central Myanmar has two distinct seasons- a Dry Season from mid-November to mid-May and a Wet Season for the remainder of the year. Over 90 percent of the annual rainfall occurs during the May to October monsoon period. Within the monsoonal period the rainfall is generally bimodal with July being drier than the other monsoonal months **(Table 9)**.

An isohyet map of Central Myanmar is given on **Figure 5**. Rainfall usually comes from the south-westerly monsoons which move in from the Bay of Bengal. Moisture is precipitated over the western slopes of the Rakhine Yoma and Chin Hills and the northern mountain ranges bordering India. In these areas, annual precipitation ranges from 2,000 to more than 5,000 mm. In the lee of the Chin Hills and Rakhine Yoma, a rain shadow is developed over Central Myanmar. Here rainfall is much less and irregular, ranging from 380 to 1,500 mm per year.

The area within the '1,000 millimetres' isohyet is known as the Dry Zone. An increase in precipitation radiates from the centre of this area. The average number of rainy days in the Dry Zone varies from 30 to 52 days per year. Rainfall occurs primarily as light showers with occasional heavy downpours. **Table 9** indicates annual rainfall in Mandalay over a twenty-year period. The annual averages were 837 mm (1991-2000) and 962 mm (2001 to 2011).

Table 9 Average Monthly Rainfall in Mandalay (1991-2000 and 2001-2011)

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1991-2000	0.3	7.5	11.1	53.3	128.7	95.8	73.1	142.5	186.3	99.2	36.4	3.1	837.3
2001-2011	1.6	0.4	7.4	39.8	186.4	103.8	71.5	168.4	178.3	162.7	31.0	10.5	962.0

The amount of annual rainfall in the Dry Zone by itself does not warrant the name given. Other factors such as high potential evaporation, low humidity, consistently high temperature, sandy soil, thin soil cover, erosional landscape, saline base flow, sparse vegetation, scarcity of shallow groundwater (in some areas) and tectonically complex geological features all combine to give the appearance of a semi-arid, barren region.

The potential evaporation in Central Myanmar exceeds the average rainfall in almost every month of the year, except the very wet August to September period. At Nyaung Oo, rainfall never exceeds the potential evaporation. Most of the light showers quickly evaporate after falling. Around the periphery of the Dry Zone, rainfall exceeds evaporation during most of the heavier rainfall months of the monsoon period.

Throughout Central Myanmar, temperatures vary seasonally and geographically. The mean minimum and maximum temperatures do not fall below 18.8 degrees Celsius (° C) and 28.5° C respectively. After February, temperatures rise and peak at an average maximum around 38° C in April **(Table 10)**. During April, temperatures up to 43° C are not unusual, especially around Mandalay and Magway.

Figure 5 Isohyet Map of Myanmar and Location of the Dry Zone

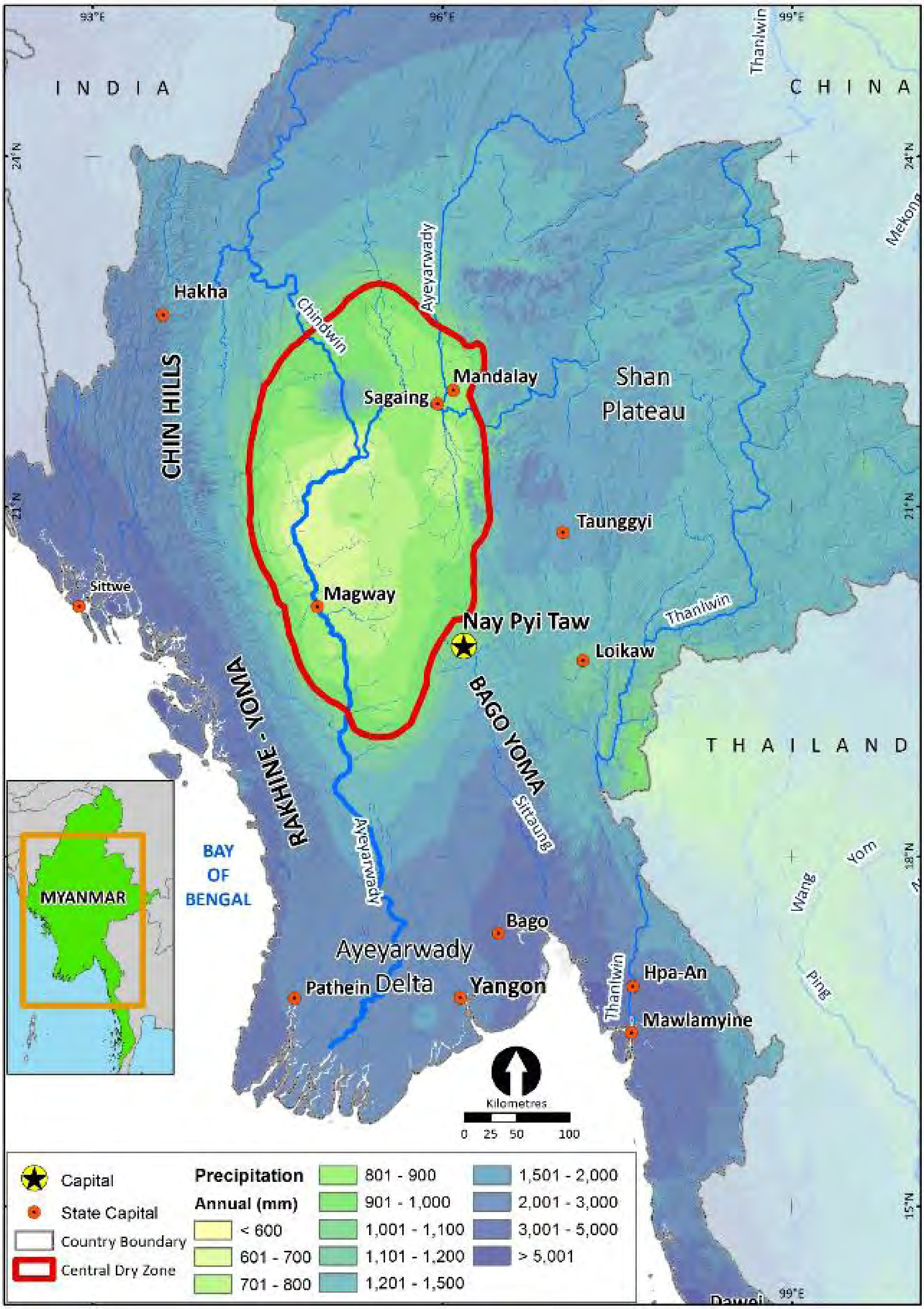


Table 10 Average Maximum/Minimum Temperature (° C), Mandalay (1991-2000 and 2001-2011)

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1991-2000	29.8/ 13.5	32.4/ 15,8	36.0/ 20.1	38.0/ 24.3	37.0/ 25.8	35.4/ 25.9	35.2/ 26.1	34.0/ 25.9	33.7/ 25.1	33.4/ 24.0	31.2/ 20.2	29.1/ 15.0	33.7/ 21.8
2001-2011	30.0/ 14.2	33.5/ 16.3	37.2/ 21.2	39.3/ 25.4	36.3/ 26.0	35.3/ 26.4	35.3/ 26.4	34.4/ 25.8	34.1/ 25.6	33.5/ 24.3	31.7/ 20.0	28.5/ 16.3	34.1/ 22.3

Mandalay has some of the largest daily temperature ranges, varying about 12° C. The average relative humidity is over 65 percent from June through to December, peaking around 75 to 85 percent in the wet August to October period. The humidity falls to 40 to 55 percent during the dry months of March and April.

Winds are generally light, occur spasmodically and are less than 16 kilometres per hour, except during strong gales which often occur during April and May.

Central Myanmar has the lowest rainfall and highest potential evaporation and temperature within the country. These climatological factors result in a considerable soil moisture deficiency and a lack of significant surface water availability.

2.3 Natural Vegetation and Agriculture

Tree felling to provide fuel for cooking, heating and brick-making over the centuries has resulted in much of the Dry Zone being denuded of vegetation. Serious soil erosion has occurred over large areas. Erosion is particularly dominant in areas of thin, sandy soil cover. Where soil erosion is intense, 'badland' topography has developed. Re-forestation of denuded areas under 'Greening of the Dry Zone' policy using eucalypt (Eucalyptus Camaldulensis) and native trees has been successful in remedial work on soil erosion in many parts of the Dry Zone.

In the watercourse areas, the topsoil is very sandy. Surface runoff appears small, recharge by percolating to the subsurface is high and very little moisture is retained in the upper layers of soil to support plant growth. Saline groundwater base flow commonly occurs in watercourses during the Dry Season. Native vegetation is restricted to scrub typical of semi-arid areas, such as thorn bushes. In areas where low salinity groundwater is near the surface, toddy palms (Palmyra) are widespread, the degree of growth is strongly controlled by soil type and availability of moisture. Toddy palms are grown for tapping of juices, alcoholic drinks, sweets, shade and construction material.

Large native trees such as Tamar, Tamarind, Kokko, Tanaung, Mango and Plum are sparsely spread throughout the area. In the more isolated, elevated, higher rainfall areas, the natural vegetation becomes denser and tropical monsoon forests are present. In these areas, valuable timbers such as Neam, Pyingado, In, Ingyin, Padauk, Ngu and Panga may occur.

The main agricultural crops are rice, millet, bean, pulse, chilli, cotton, groundnut, maize, onion, pea, plum, sesame, sorghum, sugarcane, watermelon (high demand from China), allspice and sunflower. Grazing of cattle, sheep and goats occurs in most villages.

The economic basis of the Dry Zone is agriculture which is in the hands of the small village farmers. From 1953 to 2011 all land was owned by the government (Land Nationalization Act of 1953 and Constitution 2008), but the villagers had hereditary land rights which were controlled by the Village Land Rights Committee. The Farmland Bill (2011) allows a person with 'land use rights' to transfer, exchange, or lease their land.

3 Geology of Central Myanmar

3.1 History of Geological Research

The descriptions of shallow hand dug oil wells at Yenangyaung and those on fossils and minerals at Ava appear to be amongst the earliest geological reports on Central Myanmar[20].

Before Myanmar became annexed into British India in 1886, European geologists, particularly from the Geological Survey of India reported on various geological features including structures near Amarapura (Amarapoora), the Ayeyarwady (Irrawadi) River Alluvium and petroleum deposits[21].

Once Myanmar was incorporated into British India a period of extensive and well-organised scientific research followed with a wealth of geological knowledge being published. Before the end of the nineteenth century, accurate and detailed geological reports by geologists[22] began to appear in respected British scientific publications such as:

- Memoirs of the Geological Survey of India;
- Records of the Geological Survey of India;
- Transactions of the Mining, Geological and Metallurgical Institute of India;
- British Burma Gazette; and
- Nature (London).

Detailed geological research, particularly on oil and economic mineral deposits, continued almost unabated from 1900 until the Japanese occupation in 1942. During this period, significant contributions to the understanding of the geology came from many authors[23].

The first regional geological synthesis of Myanmar appeared just after the turn of the twentieth century. Other reports reviewed the status of geological knowledge of Central Myanmar[24].

After World War 2 and the establishment of the Union of Burma in 1948, geological publications[25] became less frequent. Detailed geological exploration concentrated on economic mineral deposits and oil/gas fields near known deposits. Over this time geological research, mapping and reports in the form of unpublished papers were dispersed within various government departments and not publicly available.

Significant regional geological reports[26] have been published. Pascoe published a Manual of the Geology of India and Burma (three volumes- 1950, 1959, 1964).

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20 Cox (1799), Bedford (1831), Prinsep (1831, 1832, 1835), Brewster (1834), Pemberton & Hannay (1837)

21 Oldham (1858, 1872), Theobald (1870a,b, 1873), Romanis (1884, 1885)

22 Oldham (1883, 1893, 1906), Noetling (1890a,b, 1892a,b, 1894a,b, 1895a,b, 1896, 1897, 1899, 1900, 1901), Theobald (1895), Grimes (1898)

23 Pascoe (1906a-c, 1907, 1908a-c, 1909), Cotter (1908a-c, 1909, 1910, 1912a-c, 1914, 1922, 1923), Pascoe & Cotter (1908), Boin (1913), Aubert (1914), Porro (1915), Cotter et. al. (1916), Hallowes (1920), Penzer (1922), Stamp (1922a-c, 1925, 1927a-d, 1928, 1929), Kelterborn (1925), Chhibber (1927a-j), Stamp & Chhibber (1927), Das Gupta (1930), Clegg (1933, 1936, 1938), Barber (1935, 1936), Cotter & Clegg (1938), Dutt (1942)

24 Dalton (1908), Pascoe (1912, 1930), La Touche (1913a,b), Cotter (1918, 1924, 1933), Brown (1924), Stamp (1925, 1929), Burri & Huber (1932), Chhibber (1933, 1934a,b), Barber (1935), Clegg (1941)

25 Iyer (1953), Aung Khin (1966), Ba Than Haq (1966), Bentham (1966), Aung Khin & Kyaw Win (1969), Maung Maung Khin et. al. (1970), Bateson et. al. (1972), Krisl (1975)

26 Krishnan (1949), Pascoe (1950, 1959, 1964), Holland et. al. (1956), Gorshkov (1959), Brunnschweiler (1966a-c, 1974, 1974), Maung Thein (1971, 1972, 1973, 1984, 1985a), Adams (1977), Earth Science Research Division (1977), Goossens (1978a,b), Bender (1983), Stokes (1988), Hadden (2008), Subagyo Pramumijoyo et. al. (2010), Kyi Khin and Sakai (2012), Kyaw Linn Oo et. al. (2014)

3.2 Regional Plate Tectonic Setting

Central Myanmar is located within a tectonically active area. The location of different rock types, structural features and geological evolution can be understood by considering the regional geological setting and the relationship to crustal plate movements.

Many studies of tectonic activity in Myanmar and associated areas have been published[27].

Figure 6 indicates the principal regional geotectonic features of Myanmar and associated areas. The predominantly northeast-southwest suture lineation through the Shillong Plateau of the Eastern Himalayas continues southwards[28], west of the Western Fold Belt into the Bay of Bengal and joins the Indonesian-Andaman Trench. This suture is an active Zone of Subduction (Andaman Megathrust Zone) due to the northward movement of the Indian Plate over the South East Asian Plate (average rate of four to six centimetres per year (cm/year)) and the smaller Burma Plate (average 2.5 to three cm/year). The subduction zone is marked by severe underthrust movements giving rise to violent earthquakes.

In between the mountain ranges, the Inner Burman Tertiary Basin (Inner Burman Geosyncline) developed as a subsidiary trough, the axis of which gradually shifted west during the Cenozoic[29]. It extends from the Gulf of Martaban 1,300 kilometres northwards to the Eastern Himalayas. Offshore the basin can be traced for 3,200 kilometres under the Andaman Sea.

Figures 6 and **7** show principal geotectonic features east of the Zone of Subduction. These are:

Western Fold Belt		Western edge of Dry Zone
Central Lowlands	Western Trough (Inter Arc Trough)	Within Dry Zone
	Central Volcanic Line (Inner Volcanic Arc)	
	Eastern Trough (Back Arc Basin)	
Eastern Highlands		Eastern edge of Dry Zone

The orogenetically deformed Western Fold Belt comprises the Rakhine Yoma, Chin Hills, and Naga Hills (north, outside map). These ranges consist of pre-orogenic Triassic, Cretaceous and Lower Tertiary flysch deposits[30] which are tightly folded along the range, the intensity increasing to the north. They are associated with basic to ultra-basic intrusive igneous rocks along the structural contact with the Inner Burman Tertiary Basin.

The Western Trough is located east of the Western Fold Belt and consists of Upper Cretaceous to Middle Tertiary marine and non-marine deposits overlain by Upper Miocene to Recent continental clastic sediments. The Minbu (Central) and Chindwin basins are located within this Inter Arc Trough System.

The Central Volcanic Line is characterised by a series of NNW-SSE orientated igneous rocks in Thayetmyo, Mount Popa[31], Shinmataung Range, Salingyi and volcanoes at Monywa. The igneous rocks can be intermittently traced along this volcanic arc extending for more than 400 kilometres. Where present, this belt separates the Western Trough from the Eastern Trough.

The Eastern Trough can be divided into several sedimentary basins including the Sittaung Basin, Bago Yoma Anticlinorium and the Shwebo-Monywa Basin. All basins are filled with Tertiary marine sediment with an increase in continental sediments to the north.

[27] Gansser (1964, 1966, 1973, 1976), Brunnschweiler (1966b), Ba Than Haq (1967, 1972), Burton & Bignell (1969), Fitch (1970, 1972), Curray & Moore (1971, 1974a,b), Win Swe (1972), Carey (1975), Mitchell & McKerrow (1975), Verma et. al. (1976a,b), Mitchell (1977, 1981), Curray et. al. (1979), Bender (1983), Le Dain et. al. (1984), Curray (2005)

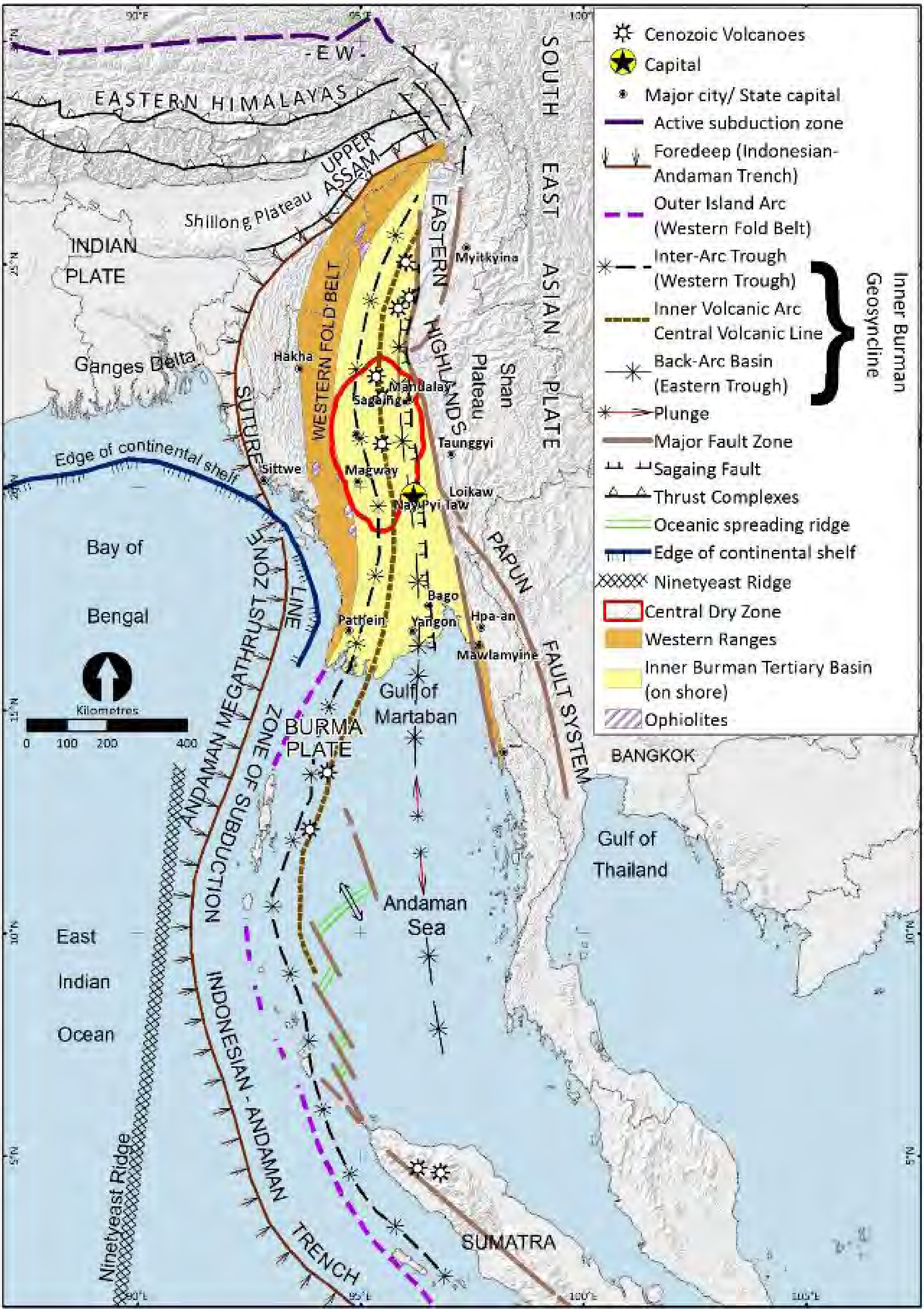
[28] Stoneley (1974)

[29] also known as the Central Lowlands or Central Cenozoic Belt (Maung Thein 1985a)

[30] Brunnschweiler (1966), Mitchell (1981)

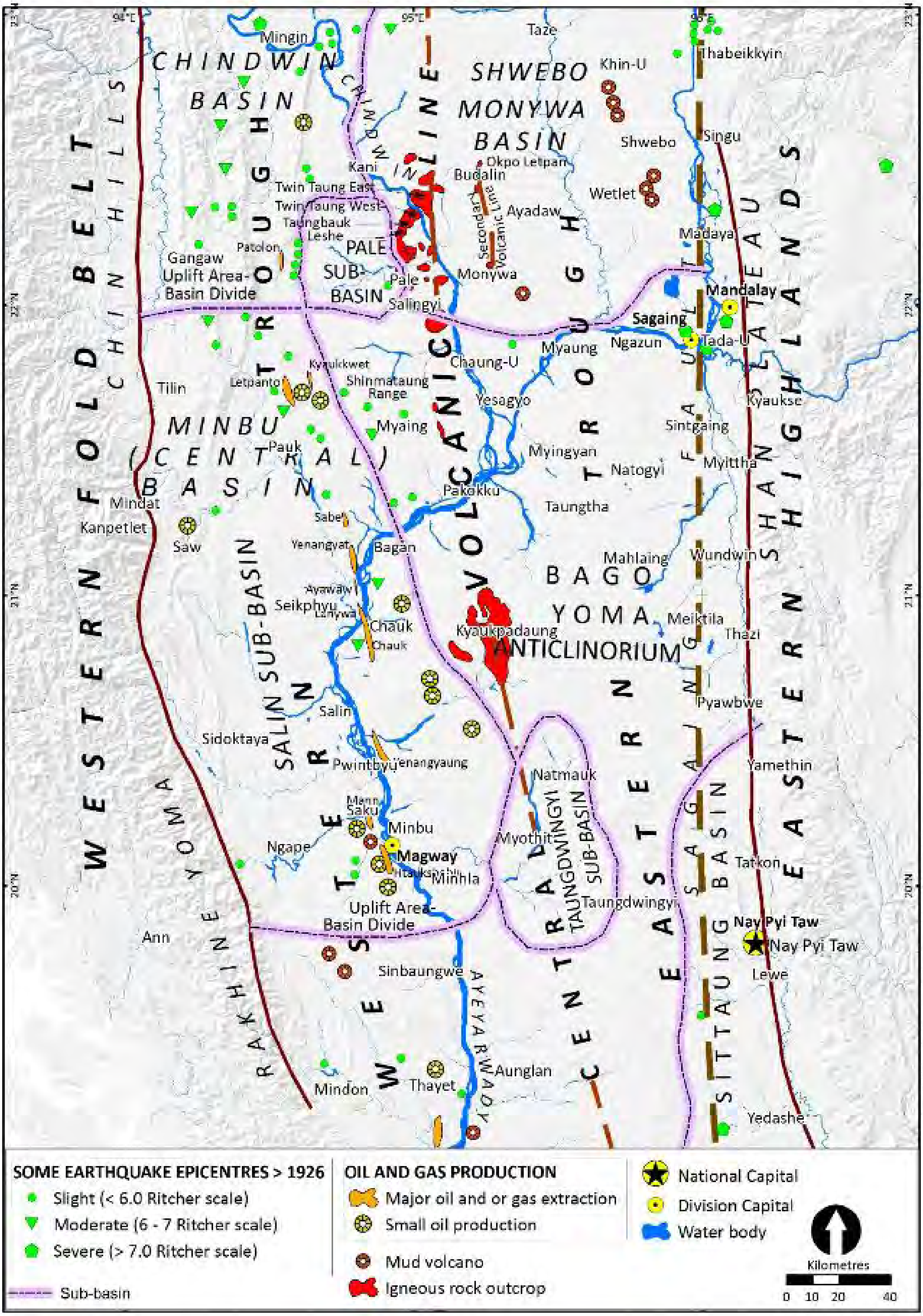
[31] Stephenson and Marshall (1984)

Figure 6 Principal Regional Geotectonic Features of Myanmar and Neighbouring Countries



Source: Modified from Bender (1983), Ridd and Racey (2016).

Figure 7 Principal Tectonic Features of Central Myanmar



Source: Modified from Bender (1983), Ridd and Racey (2016).

The semi-consolidated sediments of the Inner Burman Tertiary Basin are separated from the tectonically consolidated rocks of the Eastern Highlands by the Sagaing Fault and a zone of faults known collectively as the Shan Boundary Fault Complex. The right lateral strike-slip Sagaing Fault runs along a remarkably straight north-south orientation for over 1,000 kilometres from the Gulf of Martaban to around 24° N, where it splits into SE-NW striking offset fault lineaments[32].

The Shan Plateau consists of Lower Precambrian to Cretaceous sediments, metamorphic rocks and intrusive and extrusive igneous rocks of various ages. It is traversed by a myriad of major and minor fault systems.

3.3 Structural Geological Setting of the Inner Burman Tertiary Basin

The geology of Central Myanmar and major structural features are shown on **Plate 1** and cross sections and legend on **Plate 2** [inserted at end of the text]. Shan Plateau rocks have not been mapped during this study, thus should be considered as indicative only. The vertical scale of the geological cross sections is exaggerated. Lithological and structural details beyond depths of 600 metres are only available from petroleum exploration. Only the upper 500 metres is here considered important for groundwater consideration.

3.3.1 Major Geological Structures

The regional geological structures have major impacts on the hydrogeology of the Dry Zone. They affect groundwater occurrence, direction of flow, depth to the potentiometric surface, presence of artesian flow and water quality.

North of the '20° N Uplift Area', the axis of the Salin Syncline plunges northwards. To the west, many tightly folded structures are present (for example, Setsetyo, Ngahlaing-Dwin and Pondaung anticlines). They are accompanied by steep normal faults and associated with broad synclines (for example, the Handauk Syncline). The boundary of the Minbu Basin with the Western Ranges is not clearly defined and various opinions exist on the presence of a rift valley[33].

Near the eastern edge of the Salin Syncline a series of narrow, elongated, highly faulted anticlines associated with major oil fields are present. These include:

- Changtha Anticline;
- Mann-Minbu Anticline;
- Yenangyaung Anticline;
- Chauk Anticline;
- Yenangyat Anticline; and
- Letpanto Anticline.

Further east another belt of sharply asymmetrically folded anticlines and westerly dipping, highly faulted Oligocene and Miocene rocks of lesser petroleum significance are exposed. From south to north these are:

- Ondwe Anticline;
- Yedwet Anticline;
- Gwegyo-Ngashandaung Hills;

[32] Noetling (1900), La Touche (1913), Chhibber (1934a), Dey (1968), Win Swe (1970, 1980), Myint Thein et. al. (1981, 1982, 1983), Khin Maung Latt (1991), Vigny et. al. (2003), Soe Thura Tun (2005), Win Swe and Soe Thura Tun (2007), Tsutsumi and Sato (2009), Maurin et. al. (2010), Hurukawa and Maung Maung (2011), Myint Thein (2011)

[33] Stamp (1925), Maung Thein (1973), Bender (1983)

- Pagan Hills; and
- Myaing Anticline.

The Bago Yoma Anticlinorium is composed of Miocene to Pliocene sediments. Many tectonic structural features are present (for example, Kabet-Shinmataung, Taungtha, Indaw and Legyi anticlines). The anticlines are tight, ripple-like structures, generally north plunging, with narrow elongated anticlinal folds. They are highly faulted by diagonal and peripheral normal and high angle thrust faults. Major basinal structures associated with the Bago Yoma include the Yonzingyi and Thangedaw synclines. Around 22° N the Bago Yoma plunges beneath unconsolidated sediment of the Shwebo-Monywa Basin. The age of the tectonic structures is Upper Pliocene to Lower Pleistocene[34].

Regional faults comprise the north-south orientated Mahlaing Fault and NW-SE Sameikkon and Shinmataung faults. Salt springs are common along these lineaments.

Regionally extensive tectonic features include the Bahin-Pagan and Myaing-Kyaukpadaung structural lines. These systems trend NNW-SSE with numerous offset NE-SW transverse faults.

A large synclinal basin known as the Taungdwingyi Sub-basin is located between the Ondwe and Yedwet anticlines and the Bago Yoma.

The '22° N Uplift Area' consists of north-south trending synclines and anticlines with rocks of Eocene to Oligocene age in their axial cores. It separates the Salin Sub-basin from the Chindwin Basin.

Anticlines, synclines and associated faults occur within the Pale Sub-basin (Kabaing Syncline, Lengauk Anticline and Medin Fault), east of the 22° N Uplift Area and west of the Monywa volcanic complex.

To the east of Monywa, the Chaung-U Syncline and Kyaukka Fault are located on the northernmost spur of the Bago Yoma.

Photo 8: Mount Popa Complex. Source: Wikipedia.org

Photo 9: Ayeyarwady River Cuts Pegu Group Rocks in 20° N Uplift

The northern boundary of the Shwebo-Monywa Basin occurs along the Wuntho Massif (outside the Dry Zone). The western flank of the Kyaukka Range dips gently east underneath the southern part of the basin. Here the NNW-SSE orientated Ayadaw and Shwebo synclines are located and are infilled with semi-consolidated Upper Miocene to Quaternary sediments. The 220-kilometre eastern boundary strikes north along the Sagaing Fault.

Entering the Dry Zone, the Ayeyarwady River flows north to south along the Sagaing Fault, only altering its course around volcanic outcrops at Letha Taung, and exits the fault lineament near Mandalay. It has been postulated on physiographical grounds that during the Early Pleistocene Period the Ayeyarwady River flowed south of Mandalay, through Thazi and Yamethin and into the Sittaung River Valley. Earth movements

[34] Aung Khin & Kyaw Win (1968)

caused the river to change course and be captured by the Chindwin River system[35]. Other researchers[36] reject the concept of a proto-Ayeyarwady River south of Mandalay along the eastern edge of the Inner Burman Tertiary Basin.

3.3.2 Basins and Sub-basins

The Western and Eastern troughs can be subdivided into north-south orientated sedimentary basins (Minbu (Central), Chindwin and Shwebo-Monywa basins) infilled with Cretaceous to Recent sediments.

Some basins can be further divided into smaller depositional Sub-basins along the axis of regional north-south trending synclines with eastern and western uplifted margins (Pale, Salin[37] and Taungdwingyi Sub-basins). The Salin Sub-basin forms the largest regional structural feature (300 x 130 kilometres) of the Minbu Basin. It stretches north-south along the base of the Western Ranges. Depending on the basin dimensions and geographic location, the sediments have been deformed by tangential compression folding over several geological periods. This is particularly evident in the sedimentary rocks of the Salin Sub-basin where elongated folds along the eastern basin margin lie above reverse faults. Localised overthrusts in the range of 900 metres can be observed.

3.3.3 Central Volcanic Line

The NNW-SSE striking Central Volcanic Line of extinct volcanoes with small crater lakes and eroded cones is traced through Central Myanmar by a discontinuous chain of Cretaceous to Quaternary basic, intermediate and acid igneous rocks. Volcanic activity began as intermittent bursts and peaked in the Pliocene Period[38]. The southern-most igneous outcrop is near Thayetmyo. The volcanic plug of Mount Popa containing its eruption vent and associated stocks occupies an area near Kyaukpadaung. Volcanic activity at Mount Popa occurred during the Upper Miocene to Quaternary period[39]. Further north igneous rocks of the Central Volcanic Line are in the Lower Chindwin (Shinmataung Range and Monywa areas), the latter containing remnant explosive craters at Twin Taung East, Twin Taung West, Taungbauk and Leshe[40]. The age of these volcanics is from Mid Miocene to Lower Pleistocene[41]. A secondary line of volcanics running parallel to the first but east of Monywa, is located on the Kyaukka Range to Okpo Letpan. Volcanic tuff and ash are intercalated with the sediment- thus are contemporaneous.

3.3.4 Earthquakes

The earliest recorded earthquake in the Inner Burman Tertiary Basin was at Bago (south of the study area) in 297 BC[42]. Being before the Pyu Period the stated year of occurrence may not be exact. Since that time many disastrous earthquakes have been recorded with the destruction of buildings (particularly pagodas) and a large loss of human life. A notable earthquake (8 July 1975) of 6.8 Richter Scale severely damaged 90 percent of Bagan's ancient pagodas and temples. Many major earthquakes have occurred along the Sagaing Fault[43]. In the 20th century, many severe earthquakes (> 7.0 Richter Scale) and moderate earthquakes (6-7 Richter Scale), have occurred in Sagaing and Magway regions. **Figure 7** and **Plate 2** show the location of some of the epicentres of earthquakes since 1926. Most occur within the Western Trough and along the Sagaing Fault. Overall the Bago Yoma Anticlinorium appears tectonically stable.

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[35] Chhibber (1934a)
[36] Aung Ba (1972), GDC (1984c)
[37] Trevena et. al. (1991), Naing Maw Than (2012), Pivnik et. al. (1998)
[38] Rodolfo (1969)
[39] Chhibber (1934a)
[40] Pinfold et. al. (1927), Stamp & Chhibber (1927), Chhibber (1934a), Barber (1936), Aye Ko (1985)
[41] Union of Burma (1973)
[42] Shwe Win (1984), Brown (1917, 1929), Brown et. al. (1931, 1933)
[43] March 23, 1839, 300 to 400 people were killed at Ava and Sagaing; May 5, 1930 the death toll was 500 at Pegu; and July 16, 1956, 50 deaths were recorded at Sagaing (Santo 1969; Maung Thein 1985b)

3.4 Stratigraphy of the Dry Zone – Inner Burman Tertiary Basin

The stratigraphy of rocks of the Minbu Basin within the Inner Burman Tertiary Basin is given in **Table 11** and legend of the regional geology map **(Plate 2)**.

Table 11 Stratigraphy and Lithology - Minbu (Central) Basin, Inner Burman Tertiary Basin

	STAGE		AGE*	TYPE	FORMATION[44]		LITHOLOGICAL DESCRIPTION	VOLCANICS
QUATERNARY	Holocene		0.01	Unconfined Semi-confined Auifer Aquitard Clay	Unconsolidated Sediment <75m thick		Fluviatile clay, silt, sand, gravel, wood, cobble deposited on alluvial flats, river terraces and piedmont plains	Thayetmyo
	Pleistocene	Upper	2.5					
		Middle		Semi-confined to confined aquifer. Confined clay aquitard zones	Maw Gravel 15m		Sand and gravel, wood, lignite, clay and silt, fluviatile and alluvial	Mt. Popa; Kabwet
		Lower			Upper Irrawaddy <1,500m thick	Irrawaddy Fm		Lower Chindwin; Wuntho Massif
	Pliocene							
TERTIARY	Miocene	Upper	5.5		Lower Irrawaddy	Irrawaddy Fm	Medium to coarse grained, yellow-brown to blue-grey sand and gravel loosely cemented, current bedded, abundant fossil wood and calcareous nodules, clay beds, minor red bed, fluviatile	
		Middle						
		Lower		Aquitard	Obogon 900m	Upper Pegu Gp	Alternating blue-grey shale, fine to medium sandstone, minor gypsum	
			23	Poor Aquifer	Kyaukkok 1500m	Upper Pegu Gp	Sandstone, fine-medium grained, minor shale, rich molluscan fauna, marine	
				Aquitard	Pyawbwe 900m	Upper Pegu Gp	Shale, bluish black/grey, minor fine to medium grained sandstone	
	Oligocene	Upper	34	Poor Aquifer	Okhmintaung 1,500m thick	Lower Pegu Gp	Sandy sequence between shale beds, lepidocyclina limestone, gypsum, marine	
		Middle		Aquitard	Padaung 750m	Lower Pegu Gp	Shale, dark bluish grey, minor sandstone, coral, gypsum, foraminifera and mollusc rich, marine	
		Lower		Poor Aquifer	Shwezetaw 600-1200m	Lower Pegu Gp	Sandstone, fine grained, sandy shale, coal, gypsum, calcareous at base	
TERTIARY	Eocene	Upper	56	Aquitard	Yaw 2,000m thick		Shale, grey, minor sandstone, limestone, marine	Wuntho Massif
				Poor Aquifer	Pondaung 6,000m thick		Sandstone, minor conglomerate, fossil wood, marl, carbonaceous shale, molluscs, marine	
		Middle		Aquitard	Tabyin 1,200m thick		Shale, bluish black, minor brown sandstone, limestone, lignite, coal, conglomerate, marine	
		Lower		Poor Aquifer	Tilin ?		Sandstone, fine to medium grained, blue grey, minor silicified wood, red bed, gravel, marine	
				Aquitard	Laungshe 3,000m thick		Shale, bluish black, minor sandstone, conglomerate, limestone, marine	
	Oligocene	Upper	66	Poor Aquifer	Paunggyi 1,800m thick		Conglomerate, gritty sandstone	
		Middle		KABAW GROUP			Shale, clay, mudstone, calcareous sandstone, dark grey, soft, laminated, occasional limestone lenses	
		Lower						
	Cretaceous		145					

Modified from Bender (1983).

[44] Chhibber (1934), Aung Ba (1972)

Alternative terminology is presented by some researchers[45] in specific areas. For simplicity, the 'traditional' stratigraphic subdivision is only used here. Description of lithological units is given in **Chapters 6 to 16**.

3.5 Alluvial Sedimentation in the Dry Zone

The Shan Plateau and Upper Ayeyarwady River Valley consists of resilient rocks. Upstream of Mandalay the Ayeyarwady River occupies the Sagaing Fault in which alluvial flats are narrow and discontinuous. Between Mandalay to the confluence with the Chindwin River the alluvial flats are only a few kilometres wide. The sediment-rich Chindwin River and the watercourses draining the Salin Sub-basin and the Mount Popa Complex cut through less resistant rocks, developing broad Alluvium deposits and braided streams. The alluvial flats become progressively wider downstream of Pakokku and the Ayeyarwady River becomes prone to rapid lateral sand migration during the Wet Season.

Sand budget studies show that most of the unconsolidated sediment within the Dry Zone is derived from the Chindwin River and downstream watercourses. Only a small percentage of sediment comes upstream of Mandalay[46]. The Alluvium at Mandalay has different mineralogy and grain size than that further downstream.

To the south of Magway, the extensive alluvial flats of the Dry Zone terminate adjacent to the 20° N Uplift Area.

3.6 Oil and Gas Fields

Much of Myanmar's on-shore hydrocarbon production **(Table 12)** is from Middle Eocene to Middle Miocene rocks (especially sandstones of the Shwezetaw, Pyawbwe and Kyaukkok formations) in the Dry Zone.

Table 12 Summary of Major Oil and Gas Fields in the Dry Zone

Oilfield / Location	Discovery / Dimensions	Peak / Cumulative Production	Resources / Reserves
Kanni-Peppi Minbu-Saku Township Magway	1985 5 km long and 1.5 km wide	Peak – 1992 at 3535 bpd. To October 2015, 13.5 million barrels	Total oil-in-state is 55.6 million barrels
Htaukshabin Minbu Township, Magway Region	1978 15 km long and 1.5 km wide	Peak – 1986 at 10,359 bpd. To Oct. 2015, 22 million barrels extracted	Total oil-in-state is 157.3 million barrels
Mann Magway Region	1970 16 km long and 1.5 km wide	Peak – 1979 at 24,711 bpd. Oct. 2015, 114 million barrels extracted	Total oil-in-state 433 million barrels
Yenangyaung Yenangyaung, Magway Region	Before 1887 32 km long and 3 km wide	Peak – 1918 at 16,000 bpd. To Oct. 2015, 229 million barrels extracted	Total oil-in-state is 540 million barrels. With > 251 million recoverable
Chauk-Lanywar Chauk, Magway Region	1901 17 km long and 1.5 km wide	Peak – 1941 at 12,805 bpd. To Oct. 2015, 149 million barrels extracted	Total oil-in-place > 400 million barrels, 169 million recoverable
Yenangyat-Sabei Pauk Township, Magway Region	2000 25 km long and 5 km wide	Peak – 2004 at 2057 bpd. To Oct. 2015, 1.6 million barrels extracted	Total oil-in-state is 137.8 million barrels
Letpanto Pauk, Magway Region	1997 28 km long and 2.5 km wide	Peak – 1998 at 1155 barrels. To Dec. 2015, 2.3 million barrels extracted	Total oil-in-state 76.7 million barrels. Recoverable 20 million

[45] Aung Khin and Kyaw Win (1968), Myint Zaw Han et. al. (1993), Myo San Oo (1993), Ko Ko Gyi (2012), Myo Kyaw Tun (2015)
[46] Gordon (1885), Robinson et. al. (2007), Furuichi et. al (2009), Swe (2011), Garzanti (2016), ICEM and Myanmar Institute of Integrated Development (2017)

The oilfields occur within structural and stratigraphic traps of the Mann-Minbu, Yenangyaung, Chauk, Yenangyat, Letpanto and Myaing anticlines along the eastern edge of the Salin Sub-basin.[47] These anticlines are offset 'en echelon' to the east with overturned bedding and some major overthrusting along the eastern flanks.[48]

Less significant petroleum discoveries have occurred along the Gwegyo-Ngashandaung Hills and Yedwet and Ondwe anticlines. Analogous structures occur along the western margin associated with numerous hydrocarbon seeps.

Mud volcanoes[49] produced by natural gas seepage occur along fault zones **(Figure 7)**. This includes those at Minbu (locally known as 'Naga Bwet Taung'- Dragons breath). On 24th August 2016, a 6.8 Richter earthquake (epicentre 20 kilometres west of Chauk), temporarily altered the flow characteristics of the mud volcanoes — ceasing to flow for a few days, then eventually recovering.

3.7 Mineral Deposits

Myanmar has a vast and diverse mix of mineral resources, including jade, copper, gold, lead, zinc, coal, tin, tungsten, nickel and limestone. Many small to large scale mines exist in the upper catchment areas of the Chindwin and Ayeyarwady river valleys and the western and eastern mountains.

Within the Dry Zone the only significant mine is at the Monywa copper porphyry deposit. This mining operation is located west of Monywa and the Chindwin River along the Central Volcanic Line. The open cut mines are operated by Wambao Mining and Burmese partners[50].

Typical mine related environmental concerns would include:

- mercury from small scale gold operations into rivers and shallow aquifers;
- inappropriate disposal or leakage of dirty water and mineral process waste;
- soil and sediment loss from jade and other precious minerals;
- forest removal for mining operations, especially coal; and
- failing of tailings dam and waste rock dumps.

In most mining operations in Myanmar, Occupational Health and Safety issues are not usually a priority.

Although there are many small to medium scale mines in the upper catchment of the Upper Chindwin and Ayeyarwady rivers any subsequent contamination will have little effect on the groundwater within the Dry Zone. This is due to the restricted width of alluvium upstream in both valleys and groundwater predominantly discharging to the river systems, except in flood conditions. Little data is available on the environmental impact of the Monywa Copper Project **(Chapter 11.5)**.

[47] Pivnic et. al. (1998), Wandrey (2006), Harun (2014), Racey and Ridd (2015), Ridd and Racey (2015, 2016a-k)
[48] Kyaw Nyein (1969)
[49] Brown (1909)
[50] http://www.wbmining.cn/mainbusiness/resourcedevelopment/index.htm

Photo 10: Small Mud Volcanoes, Minbu. Htaukshabin Oil Field to the South

Photo 11: Mud and Gas Eruption, near Minbu Oilfield

Photo 12: Donkey Pump,Minbu-Mann Oilfield, Minbu. Source: *resourcegovernance.org*

Photo 13: Letpadaung Taung Copper Project.

Photo 14: Small Scale Gold Mining Source: *Wordpress.com*

Photo 15: Mining for Jade, Myanmar. Source: *ibtimes.co.uk*

4 Theory of Hydrogeology and Hydrochemistry

4.1 Principles of Groundwater

Hydrogeology (Groundwater Hydrology) is the study of the occurrence, distribution and movement of water below the surface of the earth. It is a complex science, largely unseen at the surface and a mystery to many. It is interdisciplinary in scope, involving the application of physical, chemical, biological, mathematical and environmental sciences, economics and law. The glossary of groundwater technical terms is given in **Appendix I**.

Detailed treatises on groundwater occurrence and hydraulics are available[51].

4.1.1 Occurrence

Groundwater refers to water completely occupying all voids (saturated zone) within a geological stratum. The unsaturated zone (vadose zone) has voids which are filled with air and water. The vadose zone is found above the saturated zone and extends upwards to the ground surface.

Groundwater is the earth's major reservoir of potable water. There is more water stored beneath the ground than that collectively in streams, lakes, dams and the atmosphere. The ratio of groundwater to surface water is likely to be considerably higher in the Dry Zone which does not support large areas of surface water or permanent snow. Slow moving groundwater is generally free of pollution and contamination and is relatively unaffected by droughts. However, groundwater systems need to be thoroughly understood and extraction needs to be effectively managed so that significant water level declines and deleterious chemical changes do not occur.

Groundwater in the Dry Zone forms part of the hydrological cycle in Myanmar (**Figure 8**). All water on the earth is in a state of continual movement through this cycle, although it may be held in some stages of the cycle for thousands of years:

- energy derived from the sun's radiation evaporates water as vapour from the surface water bodies, land and vegetative surfaces into the atmosphere;
- the sun's energy, together with the earth's rotation, continuously moves this water vapour until it condenses to form clouds and ultimately precipitation;
- some of this rainfall evaporates immediately, some runs off into streams, lakes and eventually oceans whilst some penetrates the ground;
- the water that infiltrates the ground but is not taken up by plants in the unsaturated zone moves downwards under gravity to the zone of saturation. Here it fills interconnected spaces in the unconsolidated sediment or fractures in the hard rock;
- water enters the groundwater systems in recharge areas and moves downgradient to discharge areas. Unless water is intercepted by tubewells or dugwells, groundwater is naturally discharged back to the surface by evapotranspiration or to springs, rivers and oceans; and
- when natural groundwater movement is artificially modified by pumping, a cone of depression is produced around the withdrawal facility, the water table or potentiometric surface is steepened and groundwater velocity increases towards the production tubewell for withdrawal.

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[51] Davis & De Weist (1966), Lohman (1972), Hazel (1975), Bouwer (1978), Freeze & Cherry (1979), Todd (1980), Mandel & Shiftan (1981), Heath (1983), Drury (1985a,b, 1986), Driscoll (1986), Price (1986)

Rocks or unconsolidated sediment within the saturated zone that are sufficiently permeable to store and transmit quantities of water are called aquifers. **Table 13** gives some hydraulic properties of important aquifer types. **Figure 9** indicates typical hydraulic conductivity values for selected rocks.

Figure 8 Typical Hydrologic Cycle for Myanmar

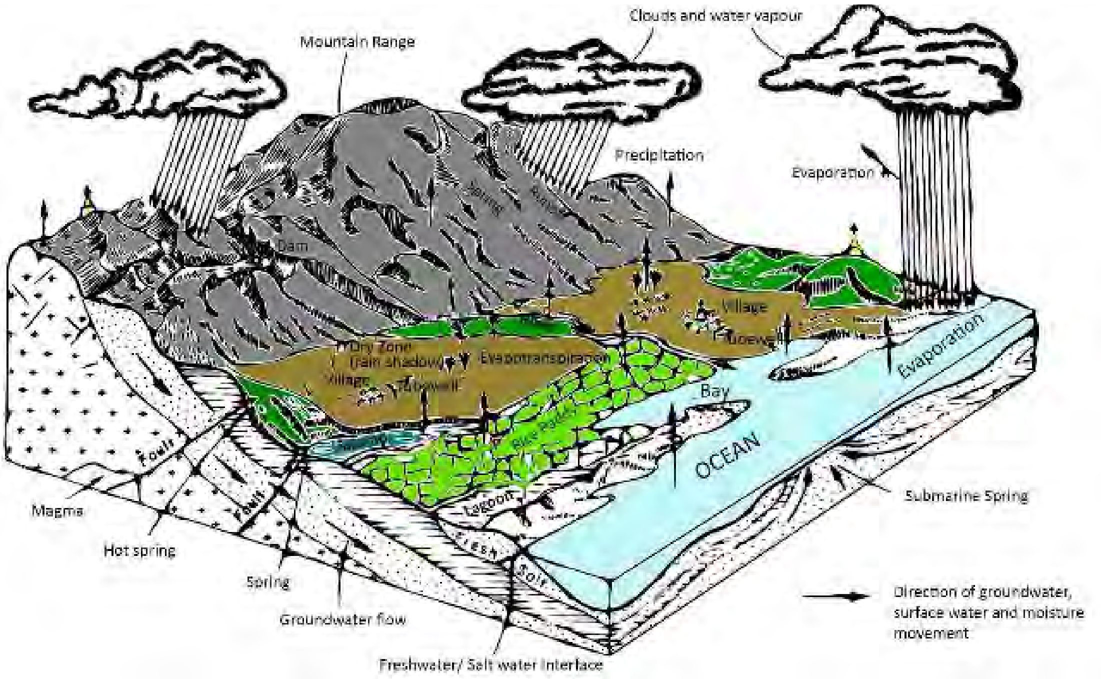
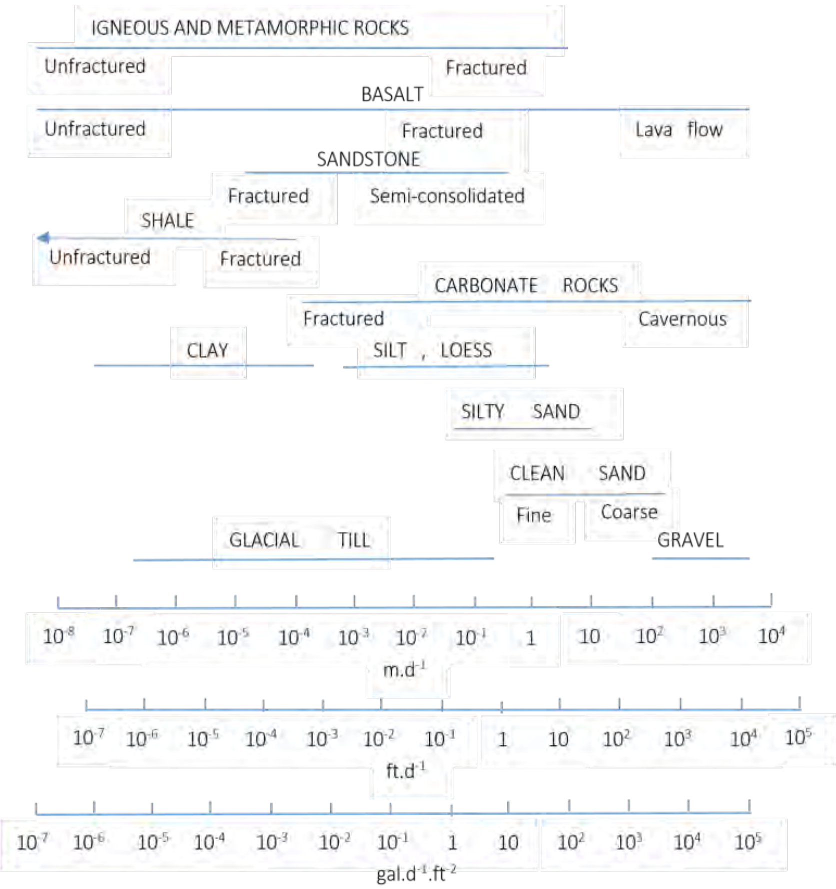


Figure 9 Hydraulic Conductivity of Selected Rocks



Source: Heath (1983).

Table 13 General Hydrogeological Properties of Important Aquifer Types

	Aquifer Type	General Nature of Porosity	Typical Porosity (%)	Hydraulic Conductivity (m/d)	Typical Specific Yield (%)	Remarks
Unconsolidated Sediment	Silt and clay	Intergranular	45 – 50	5 x10 $^{-7}$ to 5 x10 $^{-3}$	5 – 15	High porosity but poor transmitting properties
	Fine medium sand	Intergranular	35 – 50	0.5 to 50	15 – 25	High porosity, moderate yielding capacity
	Coarse sand	Intergranular	25 – 35	50 to 500	20 – 30	Good porosity and yielding potential, high aquifer yield
	Gravel	Intergranular	25 – 35	100 to 5,000	> 30	Good porosity and yielding potential, high aquifer yield
Sedimentary Rocks	Sandstone	Intergranular to joints	5 – 30	5 x10 $^{-4}$ to 50	5 – 15	Poorly cemented- high yield. Highly cemented and fine-grained rock are relatively impermeable
	Shale	Intergranular to joints	1 – 10	5 x10 $^{-8}$ to 5 x10 $^{-3}$	0.5 – 5	Water usually in fractured zones. Generally poor aquifers
	Limestone	Joints and solution channels	1 – 20	Low if poorly fractured. High in porous rock	0.5 – 90	High yielding aquifers in joints and solution channels. Poor aquifers in massive rock
Igneous and Metamorphic Rocks	Basalt	Fracture joints	1 – 10	0.5 to 50	0.5 – 5	Good aquifers in fractures, poor aquifers where massive
	Basalt	Vesicular	10 – 30	50 to 1,000	5 – 20	Good aquifers in vesicular zones
	Granite	Joints and weathered zones	1 – 10 in joints 35 weathered	Low if poorly fractured. higher if weathered	20 in highly weathered zones	Good aquifers where highly weathered joints are interconnected. Massive rock impermeable
	Schist	Joints	1 – 10	Low in fractured rock	0.5 – 5	Generally poor aquifer. Joints quickly weather to a clayey matrix

Source: Modified from Meinzer (1923a,b), Freeze and Cherry (1979), Todd (1980)

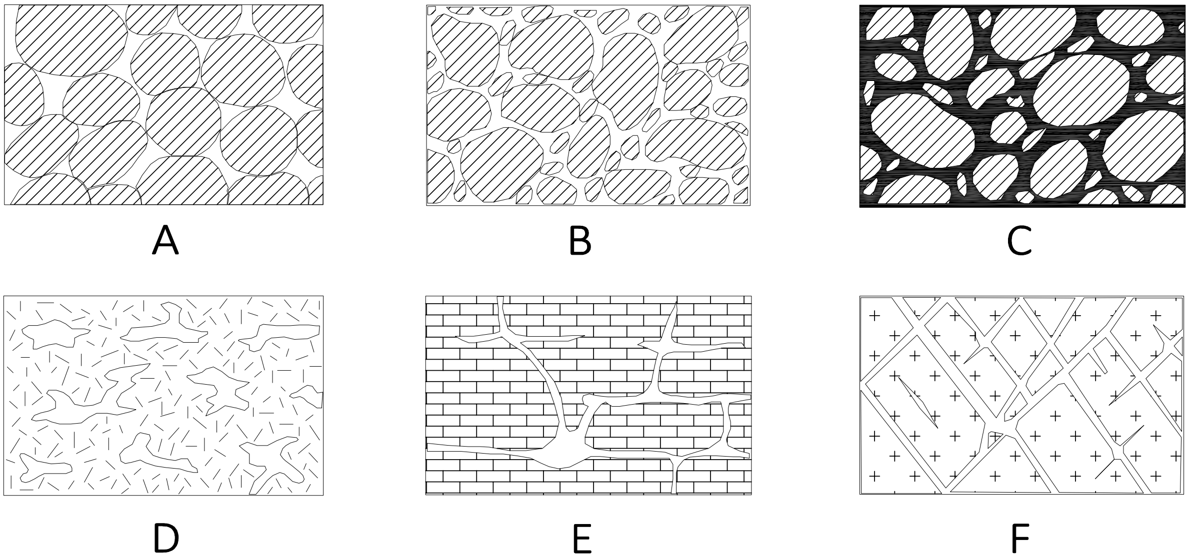
Figure 10 shows several ways in which porosity and permeability occur. Porosity depends on the shape, arrangement, compaction and size of the grain particles and fractures, as well as the concentration of cementing material. Permeability (hydraulic conductivity)[52] depends on the size of the voids and fractures, and degree of hydraulic interconnection.

Movement of water from one point to another in the aquifer takes place whenever a difference in pressure (or head) occurs between the two points. The rate of groundwater progress is proportional to the hydraulic gradient and permeability. Low hydraulic gradients and low permeability result in slow groundwater movement (10 metres per year); whereas steep gradients and high permeability give higher rates of advancement (> 1,000 metres per year).

Groundwater flow direction can be assessed by plotting water levels from several tubewells to determine hydraulic gradients, hence groundwater direction and velocity.

[52] In this text permeability and hydraulic conductivity are interchangeable. This is a close approximation. However, in strict groundwater theory, the latter depends on the intrinsic permeability of the material, the degree of saturation and on the density and viscosity of the fluid.

Figure 10 Types of Rock Porosity and Permeability



(A) Well-sorted sedimentary deposit with high primary porosity and good permeability, (e.g. clean gravel, clean sand).
(B) Poorly sorted sedimentary deposit having low primary porosity and low permeability, (e.g. clayey sand, silty gravel).
(C) Well-sorted sedimentary deposit with porosity and permeability diminished by the deposition of mineral matter in the interstices, e.g. during consolidation, (e.g. tightly cemented sandstone).
(D) Basalt honeycombed by vesicles (small gas cavities) which, if interconnected, provide high permeability and porosity.
(E) Secondary porosity, solution channels and good permeability, (e.g. limestone).
(F) Secondary porosity by fracturing, (e.g. tectonically active areas).

Source: Modified from Meinzer (1923a, b) and Freeze and Cherry (1979)

4.1.2 Aquifer Types

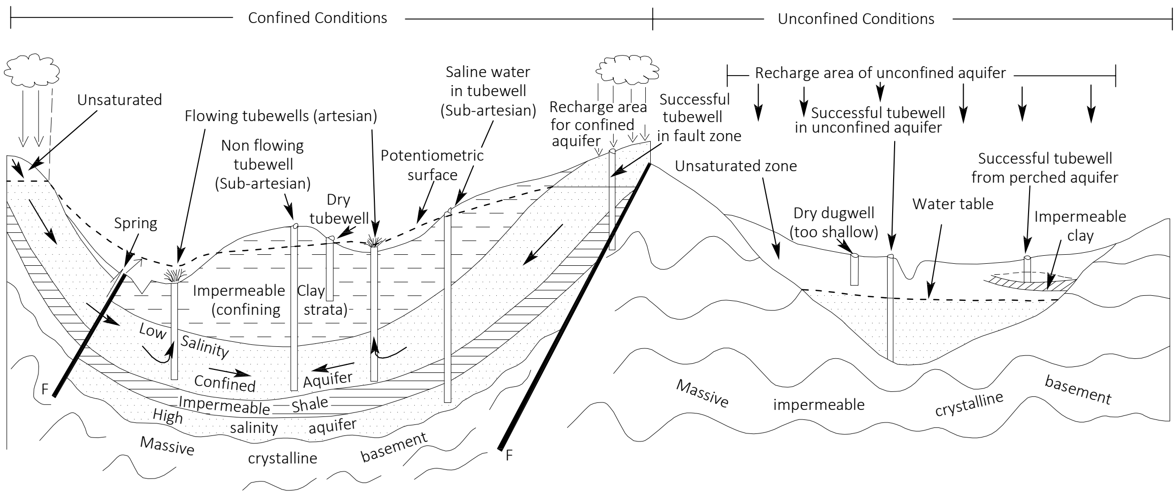
Aquifers behave differently depending on their relationship to atmospheric pressure. Aquifers can be defined as:

- unconfined[53]- an aquifer that does not have an overlying impermeable layer. Groundwater at the top of the aquifer is in direct connection with the atmosphere through pore or joint spaces. Groundwater does not rise in the hole when intersected by a dugwell or tubewell. Most unconfined aquifers are shallow;
- confined[54]- an aquifer where groundwater is held under pressure greater than atmospheric. This occurs when the aquifer underlies a confining bed (e.g. clay or shale). When a tubewell intercepts a confined aquifer, groundwater will rise in the hole in response to the water pressure. If this potentiometric surface is above ground level, groundwater will flow freely out of the hole (artesian flow). Under sub-artesian conditions the potentiometric surface is below ground level and pumping is required[55]; and
- semi-confined and semi-unconfined[56]- intermediatory aquifer conditions.

A typical example of groundwater occurrence in confined and unconfined aquifer conditions is given on **Figure 11**.

[53] Storage Co-efficient of 0.1 to 0.5
[54] Storage Coefficient typically = x 10^{-4}
[55] 'Artesian' applies to both 'artesian' and 'sub-artesian' confined aquifers in United States of America groundwater nomenclature
[56] Storage Co-efficient of 10^{-2} to 10^{-3}

Figure 11 Examples of Groundwater Occurrence in Confined and Unconfined Aquifers



Depending on the rock type, degree of weathering and deformation, some rocks form better aquifers than others:

- extrusive igneous rocks and limestones are good aquifers if highly fractured or vesicular;
- alluvial sand and gravel and coarse sandstone form excellent aquifers;
- massive, metamorphic and intrusive igneous rocks are generally poor aquifers unless they have been tectonically fractured or highly weathered;
- massive sandstones are usually poor aquifers; and
- clay, shale and mudstone are normally aquitards, unless fractured.

4.1.3 Water Level Fluctuation

The water table fluctuates because climatic factors affect groundwater recharge and discharge rates. Under natural conditions the potentiometric surface cyclically fluctuates, rising in the Wet Season and declining during the Dry. Short-term fluctuations occur due to atmospheric pressure variations. Artificial changes in water levels are caused by groundwater withdrawals (pumping or artesian flow), surface water irrigation and changes to the natural vegetation cover. Groundwater levels should be continuously measured by observation tubewells to monitor these effects.

4.1.4 Transmissivity and Hydraulic Conductivity

For quantitative studies, the hydrogeological parameters of transmissivity and hydraulic conductivity need to be assessed. Hydraulic conductivity is a measure of the ease that water can be transmitted through an aquifer. It is measured as the flow per unit cross-sectional area under a unit hydraulic gradient. Typical values for hydraulic conductivity are given on **Table 13**.

Transmissivity is equal to the hydraulic conductivity multiplied by the saturated aquifer thickness. Transmissivity for clean sand and gravel aquifers generally exceed 200 square metres per day (m^2/day), whereas for a sandstone a lower value is recorded. These hydrogeological parameters are generally determined from measuring the water level response to groundwater discharge during controlled pump-out tests.

4.1.5 Groundwater Temperature

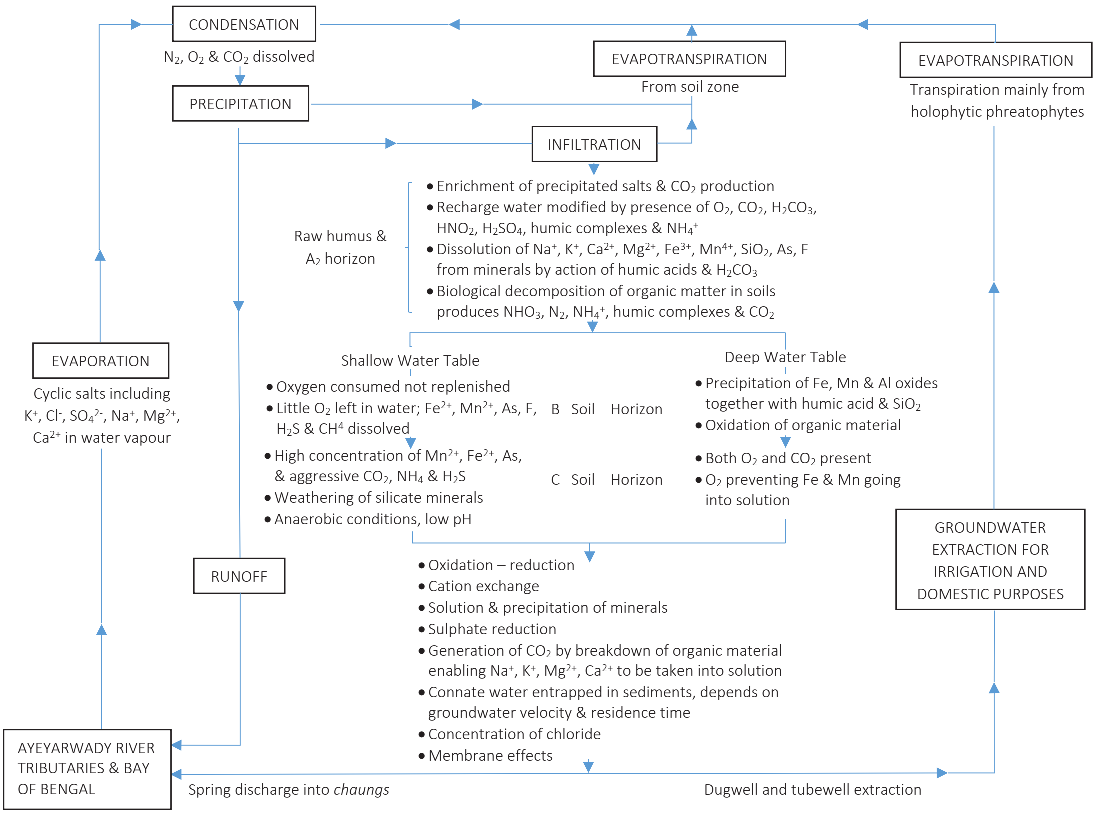
The temperature of groundwater generally increases with depth in accordance with the geothermal gradient, at rates varying from 0.4 to 1° C per 100 metres in areas underlain by thick sections of sedimentary rock to 0.8 to 2° C per 100 metres in areas adjacent to volcanic activity. The groundwater temperature near the surface is usually 25 to 27° C.

4.2 Groundwater Quality

4.2.1 Changes in Chemical Composition

A typical hydrochemical flow model is given on **Figure 12**. Elevated arsenic, fluoride and iron, especially in shallow groundwater, are major concerns for domestic water supplies.

Figure 12 A Hydrochemical Flow Model for Central Myanmar



A Hydrochemical Flow Model for Central Myanmar

(modified after Davis et. al. 1959, Eriksson & Khurakasen 1968, Lawrence 1975 and Drury 1982).

Modified after Davis et. al. (1959), Erikkson and Khurakasen (1968), Lawrence (1975), Drury (1982), Erikkson (1986)

Rainfall usually contains small concentrations of minerals and dissolved gases (such as carbon dioxide, oxygen and nitrogen). The pH in rainfall is usually less than 7 (slightly acid) and the water is slightly corrosive. Rainfall which infiltrates into the soil horizon incorporates organic acids from decaying vegetable matter and carbon dioxide from the root zone, both of which increase the corrosive characteristics of the water. The acidic water attacks minerals which it dissolves.

The quantity of dissolved salts in groundwater depends on:

- nature and chemical composition of minerals in the host rock;
- residence time for the water to be in contact with the rock;
- rainfall chemistry;
- soil type and thickness;
- evapotranspiration;
- topography;
- temperature; and
- pressure (depth).

The constituents going into solution will not necessarily be in the same proportion as those in the rock, but depend on the solubility of the minerals present. Depending on whether the water level is shallow or deep, oxidation or reduction chemical reactions may occur.

The most commonly encountered naturally occurring inorganic constituents are:

Cations	Anions
Calcium (Ca^{2+})	Carbonate (CO_3^{2-})
Magnesium (Mg^{2+})	Bicarbonate (HCO_3^-)
Sodium (Na^+)	Sulphate (SO_4^{2-})
Potassium (K^+)	Chloride (Cl^-)
Iron (Fe^{2+})	Nitrate (NO_3^-)
	Fluoride (F^-)
	Silica (SiO_2^-)

Most elements may be present in groundwater and the mineral content may vary from aquifer to aquifer as well as within one hydrogeological system. Reactions such as cation exchange or sulphate reduction may take place along a flowline. The chemistry of groundwater is complex[57].

Appendix III indicates the effect that these inorganic ions and other physical parameters have on water use, if present in excessive concentrations. In general, likely chemical components in various aquifers can be qualitatively predicted:

- groundwater passing through basalts frequently has a high concentration of Ca^{2+}, Mg^{2+} and SiO_2^- due to the decomposition of ferromagnesium;
- water traversing limestone or calcareous sandstone usually dissolves appreciable quantities of Ca^{2+} and Mg^{2+}. Both these aquifer types may contain water with high 'hardness' values;
- clean quartzose sand, gravel and quartzite commonly contain low salinity, 'soft' water as silica is relatively insoluble. There is generally an absence of soluble constituents in quartzose aquifers; and
- trace minerals present in the host rock may also cause deterioration of water quality associated with iron, manganese, arsenic, fluoride and heavy minerals. Iron and manganese are widely present in most rocks which create aesthetic concerns. Dissolved arsenic is known to occur within the Ayeyarwady River Alluvium

4.2.2 Water Quality Standards

There is no official water quality standard for Myanmar. The proposed National Drinking Water Quality Standards (NDWQS)[58] is pending ministerial approval. These parameters are listed in **Table 14** along with WHO guidelines and those used by Mandalay City Development Committee (MCDC).

[57] Erikkson & Khunakasen (1968), Hem (1970), National Academy of Science (1972), Freeze & Cherry (1979), Eriksson (1986)
[58] Ministry of Health (2014)

Table 14 Proposed National Drinking Water (NDWQS), WHO and MCDC Quality Standards

Bacteriological Quality Type: Water Sources	NDWQS (2014)		WHO Guidelines (2011)		Units
	F-coli	T-coli	F-coli	T-coli	
Treated pipe water	0	0	0	0	MPN/ 100 ml
Untreated pipe water	0	0	0	0	
Water in distribution system	0	0	0	0	
Unpiped water	0	3	0	0	
Bottled water	0	0	0	0	
Emergency water	3	10	0	0	

Physical Quality	NDWQS (2014)	MCDC Maximum Desirable Value	MCDC Maximum Allowable Value
True Color Unit (TCU)	15	5	50
Taste and Odour	(Not offence)		
Turbidity Nephelometric Turbidity (NTC)	5	5	25

Inorganic Chemical Quality of Health Significance	NDWQS (2014)	WHO (2011)	MCDC Maximum Desirable Value	MCDC Maximum Allowable Value
	(mg/L)			
Arsenic (As^-)	0.05	0.01		
Cadmium (Cd^{2+})	0.003	0.003		
Chromium (Cr^-)	0.05	0.05		
Copper (Cu^+)	2.0	2.0		
Cyanide (CN^-)	0.07	-		
Fluoride (F^-)	1.5	1.5		
Lead (Pb^{2+})	0.01	0.01		
Manganese (Mn^{2+})	0.4	0.3	0.05	0.5
Mercury (Hg^{2+})	0.001	0.006		
Nitrate (as NO_3^-)	50	50		
Selenium (Se)	0.04	0.04		

Inorganic Chemical Quality of No Health Significance	NDWQS (2014)	MCDC Maximum Desirable Value	MCDC Maximum Allowable Value
	(mg/L)		
Aluminum (Al)	0.2		
Chloride (Cl^-)	250	200	600
Hardness (as $CaCO_3^{2-}$)	500	100	500
Iron (Fe^{2+})	1.0	0.1	1.0
pH	6.5-8.5	7.0 – 8.5	6.5 – 9.2
Sodium (Na^+)	200		
Sulphate (SO_4^{2-})	250	200	400
Zinc (Zn^{2+})	3	200	400
Calcium (Ca^{2+})	200	75	200
Magnesium (Mg^{2+})	150	30	150
Total Dissolved Solid	1,000		1,000
Electrical Conductivity (EC)	1,500		1,500 $\mu S.cm^{-1}$

Source: World Health Organisation (1971), Ministry of Health (2014) and MCDC (pers. comm.).

5 Regional View: Hydrogeology

5.1 Regional Aquifers

For convenience of discussion, most of Central Myanmar has been divided into 11 areas **(Figure 13)**. The subdivision is based on groundwater catchment/drainage areas or into 'manageable units' of the Ayeyarwady River Valley. The areas discussed are not in order of hydrogeological importance, but are based on government administration divisions- Magway (first four sections), followed by Sagaing and Mandalay regions.

Table 15 indicates the main aquifers in the Dry Zone. The depth and their hydrogeological and hydrochemical characteristics are largely controlled by topographic location, mode of geological deposition and associated geological structure.

Table 15 Major Aquifers in the Dry Zone

Formation	Area (%)	Lithology	Location	Mode of Deposition	Quality/Yield
Alluvium	29	Sand, silty sand	Major watercourses, intermountain Sub-basins	Fresh water fluviatile	Usually low salinity, high yield
Piedmont	5	Sand, gravel, cobble	Eastern and western foothills	Fresh water colluvial	Low salinity, moderate yield
Irrawaddy Formation	38	Sand, sandstone, gravel, clay	Regional aquifer throughout Dry Zone	Fresh water fluviatile, deltaic	Low salinity to brackish, moderate to high yield
Pegu Group	20	Sandstone, fractured shale	Central and west	Marine, fluviatile and deltaic	Brackish to saline, low yield
Eocene	7	Sandstone, shale	Western foothills	Marine	Brackish, low yield
Volcanics	1	Intrusive and extrusive	Central Volcanic Line / Secondary	Volcanic eruption or emplacement	High yield, low salinity, hard

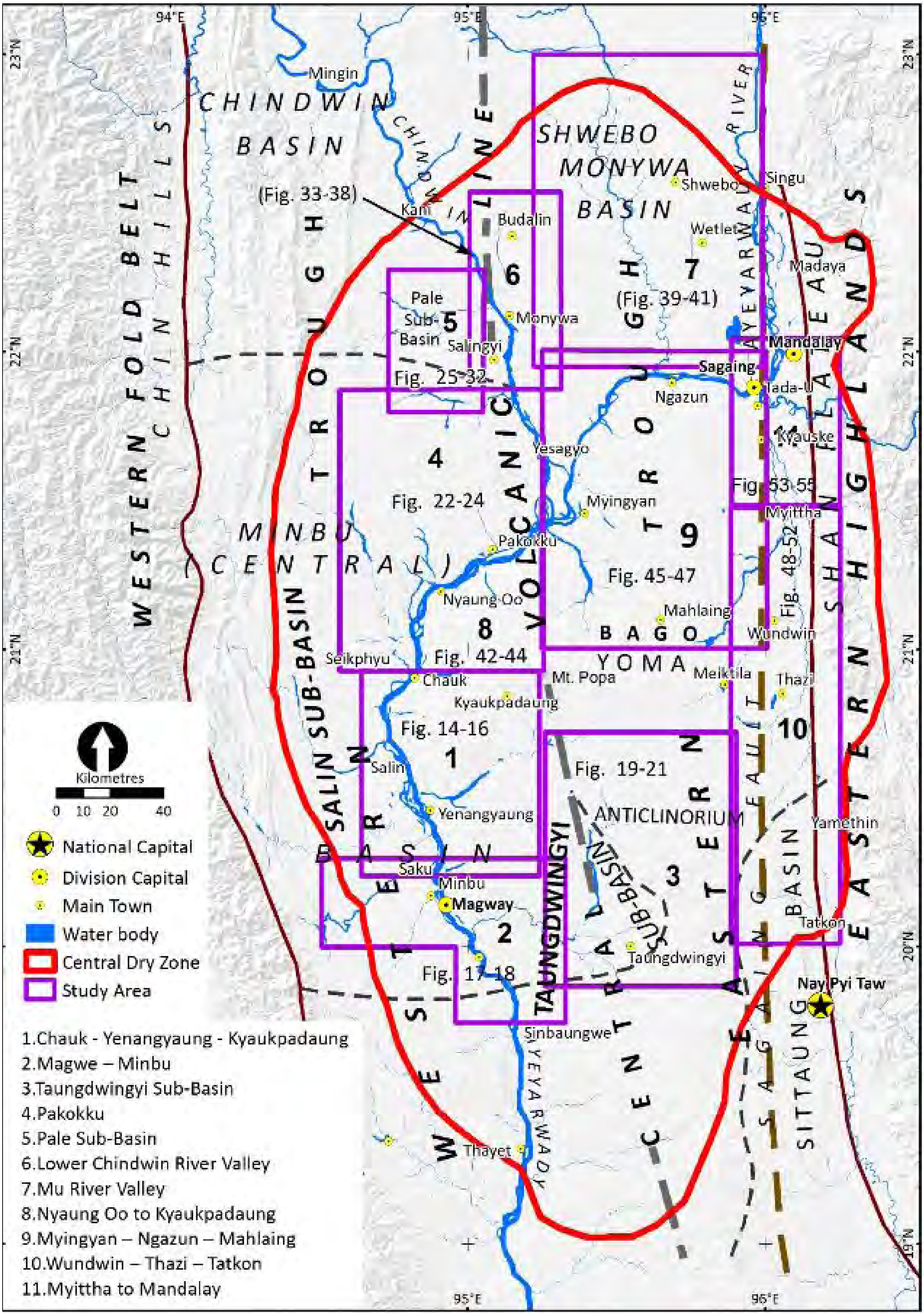
5.2 Regional Hydrogeological and Hydrochemical Map

The regional hydrogeological and hydrochemical maps are given in **Plates 1**, **2** and **3**.

There was difficulty in representing minor lateral and vertical variation in aquifer hydraulic and chemistry characteristics. In this publication generalisation is applied when required. The maps mostly ignore localised variations in preference of regional trends.

Groundwater exists throughout most of Central Myanmar but useful supplies are not encountered everywhere, particularly in areas underlain by the Pegu Group. Where no data is available, the likely salinity and yield potential have been based on experience in similar rock types in other parts of the Dry Zone. Hydrogeological and hydrochemical boundaries are approximate and should not be taken as definitive- their accuracy is based on available data and assessment of reliability. The application of these maps requires professional interpretation and reference to the accompanying text. As more data becomes available, modification to these maps may be required.

Figure 13 Chapter Subdivision of Central Dry Zone



The hydrochemistry map **(Plate 3)** is based on what would be reasonably expected in aquifers within the region. It is subdivided into five salinity ranges based on the general usefulness of water. Although the suitability of groundwater for various purposes is here expressed as specific conductance (analogous to Electrical Conductivity (EC)), its use is also governed by the presence and concentration of individual salts and gases.

Variations in groundwater quality sometimes occur with depth. Specific conductance ranges and corresponding uses are:

- 0 to 1,500 $\mu S.cm^{-1}$ — Good quality – usually suitable for drinking, stock, irrigation, town water supply and industry
- 1,500 to 3,000 $\mu S.cm^{-1}$ — Fair quality – can be used for village water supply if necessary and all stock. Salt tolerant crops under favourable conditions
- 3,000 to 6,000 $\mu S.cm^{-1}$ — Inferior quality – suitable mainly for stock and washing. Avoid consumption by villagers if possible
- 6,000 to 10,000 $\mu S.cm^{-1}$ — Poor quality – suitable only for goats and sheep. Cattle will not tolerate > 8,000 $\mu S.cm^{-1}$
- Greater than 10,000 $\mu S.cm^{-1}$ — Bad quality – unsuitable for any purpose except salt harvesting

The locations where aquifers of high yields (greater than 6 L/sec) and low salinity (< 1,500 $\mu S.cm^{-1}$) are likely to be intersected are shown on **Plate 3**. Due to lateral and horizontal variations in hydrogeology not all tubewells within these areas may be successful for the intended purpose.

The hydrogeological interpretation in the following chapters is mainly based on village water supply data supplied by the IWUMD and through personal experience. Due to the construction of small diameter village tubewells, the IWUMD information lacks hydraulic characteristics from pump-out tests. Data from the Umbrella Project, JICA, MCDC, DRD and university Master of Science (MSc.) theses supplement information gaps. The number of tubewells considered is small compared to the hundreds of thousands of private tubewells and dugwells. However, quality of information, not quantity is critical to hydrogeological interpretation.

The regional hydrogeological and hydrochemical maps are intended as a broad guide to the groundwater resources of Central Myanmar. When future groundwater development is planned, more detailed information may be found in the following text, from appropriate government departments and by additional field studies of appropriate magnitude.

5.3 Regional Hydrochemical Trends

5.3.1 Aquifer Contamination

Underlying towns and villages, localised microbial pathogens may occur in some shallow aquifers (< 10 metres) due to the pollution from vertical seepage of contaminated surface water, septic tanks, markets, abattoirs, industrial areas (tanneries, vegetable and petroleum oils processing). Contamination of shallow aquifers underlying industrial, petroleum and mining areas may also occur in the Dry Zone.

Evidence of aquifer pollution from mining (for example, Monywa Copper) or oilfield (for example, Htankai Oilfield) activities are sensitive issues and data hard to access. Several NGO's express opinion of unmitigated groundwater contamination from these activities but lack actual validatory data. There is no doubt that some pollution occurs, just like any industrial activity- the degree of such contamination to shallow aquifers is currently unknown to the author. There is no legislation for prevention of pollution to groundwater systems or remediation activity to be undertaken.

5.3.2 Tritium Analysis

Groundwater from Dry Zone tubewells was tested by the Australian Atomic Energy Commission (AAEC) laboratory for tritium analysis[59]. The results are reported by Drury (1986) and shown on **Table 16**.

Most samples assayed (84 percent) had a tritium activity under two tritium units (TU). This indicates that the samples have been in the groundwater system for more than 30 years, that is, before atmospheric nuclear testing. Samples greater than 12 TU represent 'Modern' water which suggests proximity to recharge areas. These are usually located in unconfined alluvial aquifers close to chaungs. Results between three to six TU are most likely a mixture of both Modern recharge and older groundwater.

5.3.3 Arsenic in Groundwater

Arsenic in groundwater is geogenically derived primarily from Quaternary organic rich, fluviatile alluvial and deltaic sediments. In high concentrations, it can be a threat to public health.

Groundwater samples were collected from 17 of the 53 townships in the Dry Zone for analysis of naturally occurring arsenic[60]. **Table 17** indicates the townships and arsenic levels above 10 micrograms/L (µg/L), the upper limit for WHO Drinking Water Guideline and 50 µg/L (NDWQS). Around 80 percent had arsenic less than 10 µg/L.

5.3.4 Radiocarbon (C-14) Analysis

In May 2017 ten samples were collected for radiocarbon dating (C-14)[61] to obtain preliminary estimates of groundwater age from different hydrogeological regimes. Analyses were undertaken by the Australian Nuclear Science and Technology Organisation (ANSTO)[62], Lucas Heights, Sydney (formerly AAEC). Groundwater ages from artesian and deep aquifer systems range from 1,355 ± 30 to 26,120 ± 120 years.

The C-14 analysis provides empirical evidence of aquifer system dynamics. It is important to understand the age of groundwater for water management purposes so that:

- aquifer recharge and discharge areas can be located;
- the duration of residence time, chemical reactions and flow direction within major regional aquifer systems can be understood; and
- practitioners and community can better conceptualise groundwater movement and appreciate the need for monitoring and implementation of management plans.

Further hydrochemical details for the Dry Zone are discussed in detail in various parts of **Chapters 6** to **16**.

[59] Tritium (3H) is the radioactive isotope of hydrogen, emitting beta radiation. It has a half-life of 12.26 years. It is naturally produced in the atmosphere at a low rate through cosmic high energy radiation. Tritium enters the hydrological cycle in precipitation and begins radioactive decay when it enters the groundwater system. In 1952 the natural level of tritium concentration in the atmosphere was drastically increased due to the detonation of thermonuclear devices. International agreements to curb this testing has significantly reduced atmospheric tritium levels.

[60] WRUD and UNICEF (2005), Bacquart et. al. (2015)

[61] Naturally occurring C-14 in the water is detected, in association with its half-life (5,730 years), to estimate the age of groundwater. Dating up to 40,000 years is sometimes achieved

[62] ANSTO Code Number OZV690 to OZV699 (Fink et. al. 2004)

Table 16 Tritium Analysis of Groundwater in the Dry Zone

Area	Village	Township	TW No (RWSD)	Aquifer Depth (m)	Aquifer Type	AAEC No.	Tritium Activity (TU)
Chauk	Thalugan	Yenangyaung	5456	207-227	Irra Fm	6981	1.0 ± 0.4
	Gwebinlay	Chauk	1903	244-253	Irra Fm	6982	1.2 ± 0.4
Yenangyaung	Thonzin	Chauk	3227	107-120	Irra Fm	6983	0.7 ± 0.4
	Thwenet	Chauk	3235	175-181	Irra Fm	6984	0.6 ± 0.4
Kyaukpadaung	Wathesan	Chauk	5009	377-390	Irra Fm	6985	1.3 ± 0.4
	Gwegyo	Chauk	5422	76-79	Pegu Group	6986	0.4 ± 0.4
	Ywama	Chauk	3232	211228	Irra Fm	6987	0.3 ± 0.4
	Thayetok	Pwintpyu	2806	21-24	Alluvium	6992	17.6 ± 1.5
	Indaing	Kyaukpadaung	3074	224-232	Irra Fm	7030	0.1 ± 0.4
	Indaw	Kyaukpadaung	3080	91-101	Irra Fm	7031	0.7 ± 0.4
	Pwegyi	Kyaukpadaung	3201	113-120	Irra Fm	7032	0.4 ± 0.4
Minbu	Thabyeyin	Magway	3003	185-198	Irra Fm	6988	0.6 ± 0.4
Magway	Drilling Station	Magway	3222	65-83	Irra Fm	6990	0.2 ± 0.4
	Kyakyaunggon	Myothit	4406	24-31	Irra Fm	6991	1.6 ± 0.4
Taungdwingyi	Kwetthit	Natmauk	0757	64-67	Irra Fm	6993	1.0 ± 0.4
	Hingayaw	Taungdwingyi	0764	118-147	Irra Fm	6994	0.4 ± 0.4
	Satthwa	Taungdwingyi	5451	59-70	Irra Fm	6996	1.8 ± 0.4
	Ngamin	Taungdwingyi	3993	77-83	Irra Fm	6997	1.3 ± 0.3
Pakokku	Aungtha	Pakokku	2532	21-24	Alluvium	6967	0.5 ± 0.4
	Paunglaunggan	Pakokku	1099	76-79	Irra Fm	6968	3.3 ± 0.4
	Aletaik	Pakokku	5094	21-26	Alluvium	6969	1.6 ± 0.4
	Kudok	Yesagyo	1668	17-21	Alluvium	6970	16.9 ± 1.4
	Myebyu	Yesagyo	4164	73-110	Irra Fm	6971	0.9 ± 0.4
	Satthwa	Yesagyo	0597	46-52	Pegu Group	6972	0.5 ± 0.4
	Kundok	Myaing	0536	101-110	Irra Fm	6973	0.1 ± 0.4
	Wetthonnaing	Myaing	1061	137-143	Irra Fm	6974	0.3 ± 0.4
	Sinsein	Myaing	5409	57-66	Irra Fm	6975	0.3 ± 0.4
	Ywadanshe	Myaing	3465	208-213	Irra Fm	6976	0.2 ± 0.4
	O-Yin	Myaing	3467	156-165	Irra Fm	6977	0.8 ± 0.4
	Magyisin	Pauk	3644	97-101	Irra Fm	6978	0.2 ± 0.4
	Kanthit	Pauk	4193	110-134	Irra Fm	6979	0.5 ± 0.4
	Myingyawgone	Pauk	5754	9-15	Alluvium	6980	13.1 ± 1.1
Pale Sub-basin	Ywadaung	Yinmabin	2906	143-183	Ywatha/Aungban	7006	0.8 ± 0.4
	Thabyeaye	Yinmabin	3419	55-60	Ywatha/Aungban	7007	3.8 ± 0.4
	Ywathaleingon	Pale	3511	232-250	Kokkogon	7016	0.3 ± 0.4
	Chitpyit	Pale	5005	53-61	Kokkogon	7017	0.1 ± 0.4
Chindwin River Valley	Kyaukka South	Monywa	4008	167-171	Irra Fm	7000	3.4 ± 0.4
	AMD	Monywa	4479	12-32	Alluvium	7001	2.0 ± 0.4
	Kyaukkyit	Monywa	2907	17-29	Alluvium	7003	13.4 ± 1.2
Mu River Valley	Moeza Quarter	Sagaing	1775	27-43	Alluvium	6998	1.8 ± 0.4
	Test well No. 1	Sagaing	4475	136-146	Irra Fm	6999	0.8 ± 0.4
	Ngakin	Myinmu	3533	78-83	Irra Fm	7002	0.7 ± 0.4
	Saingbyingyi	Dabayin	2613	156-165	Irra Fm	7004	0.6 ± 0.4
	Inkokku	Taze	2963	33-40	Alluvium	7005	0.3 ± 0.4
	Tactile	Ayadaw	2616	121-149	Irra Fm	7008	1.6 ± 0.4
	Kyauksayitkan	Ayadaw	3817	122-130	Irra Fm	7009	0.6 ± 0.4
	Kebaywathit	Ayadaw	4919	34-37	Alluvium	7010	0.3 ± 0.4
	Halin	Wetlet	-		Irra Fm	7018	0.9 ± 0.4
Myingyan-Ngazun-Mahlaing area	Chaungzone	Taungtha	3185	104-143	Irra Fm	7027	0.3 ± 0.4
	Phettaw	Taungtha	2935		Alluvium	7028	0.4 ± 0.4
	Phettaw	Taungtha	6140		Alluvium	7029	0.9 ± 0.4
	Htadawma	Natogyi	3256	87-95	Pegu Group	7033	1.7 ± 0.4
	Khuywa	Myingyan	2775	43-61	Pegu Group	7034	0.9 ± 0.4
	Kanzin (N)	Myingyan	6112	24-31	Irra Fm	7035	0.4 ± 0.4
Wundwin-Thazi-Tatkon area	Paukmyaing	Myittha	6106	21-27	Alluvium	7020	0.7 ± 0.4
	Ywashe	Wundwin	3252	217-299	Irra Fm	7021	1.1 ± 0.4
	RWSD (2)	Meiktila	1330	183-195	Pegu Group	7022	0.6 ± 0.4
	U Yin	Meiktila	6051	58-64	Alluvium	7023	0.7 ± 0.4
	Kyabetkon	Thazi	2760	171-190	Alluvium	7024	0.5 ± 0.4
	Phayanga Su	Thazi	6053	49-55	Alluvium	7025	13.9 ± 1.2
	Ywakonegyi	Thazi	4612	73-82	Irra Fm	7026	0.8 ± 0.4
	Thinbangone	Yamethin	3294	270-300	Irra Fm	7036	0.2 ± 0.4
	Pyanmadaw	Yamethin	6067	250-271	Irra Fm	7037	1.1 ± 0.4
	Khitaye	Tatkon	4267	21-26	Alluvium	7038	1.0 ± 0.4
Mandalay-Myittha area	Aungchantha	Amarapura	3325	15-21	Alluvium	7019	13.1 ± 1.1
	19th Street	Mandalay	-	46-55	Alluvium	7039	12.2 ± 1.0
	19th Street	Mandalay	-	91	Alluvium	7040	0.1 ± 0.4
	Chaungwun	Mandalay	-	18-21	Alluvium	7041	5.9 ± 0.5

TW No Tubewell number Irra FM Irrawaddy Formation AAEC No. Australian Atomic Energy Commission number

Recent Groundwater

Mixture Recent and Older Groundwater

Remainder- >30 years old Groundwater in 1986

Source: Drury (1986).

Table 17 Arsenic in Groundwater from Selected Townships in the Dry Zone

Region	Township	Total Samples	Concentration > 10 µg/L		Concentration > 50 µg/L	
			No.	%	No.	%
Sagaing	Chaung-U	500	34	6.8		
	Monywa	221				
	Shwebo	5,556	30	0.6	1	0.02
	Wetlet	563	91	16.2		
	Sagaing	1,809	264	14.6	9	0.5
	Myinmu	1,781	323	18.1	41	2.3
	Myaung	3,181	877	27.6	145	4.6
Mandalay	Kyauske	2,826	362	12.8	54	1.9
	Myingyan	614	60	9.8	17	2.8
	Mahlaing	500	102	20.4	6	1.2
	Amarapura	500	144	28.8	12	2.4
	Madayar	500	200	40	20	4.0
	Leway	2,782	809	29.1	63	2.3
	Sintgaing	4,650	765	16.5	82	1.8
	Myittha	6,061	933	15.4	37	0.6
	Tada-U	2,852	452	15.9	12	0.4
Magway	Yesagyo	522	96	18.4	7	1.3

Source: WRUD and UNICEF (2005), Bacquart et. al. (2015).

The highest arsenic concentrations exceeding 50 µg/L are from the Ayeyarwady River sediments (Myaung (4.6 percent) and Madayar (4 percent) followed by Myingyan, Amarapura, Leway, Myinmu, and Kyauske townships). Arsenic was below 10 µg/L in aquifers in the Mu and Chindwin river townships.

Table 18 indicates that of the 30,420 samples tested in the Dry Zone, arsenic levels above 50 µg/L occurred in 1.7 percent of groundwater, the highest being in Sagaing Region (2.3 percent), the lowest Magway Region (1.3 percent).

Table 18 Occurrence of Arsenic in Sagaing, Mandalay and Magway Regions

Region	Total samples	Samples	(%)	Samples	(%)	Samples	(%)
		< 10 µg/L		10-50 µg/L		> 50 µg/L	
Sagaing	8,611	6,796	78.9	1,619	18.8	196	2.3
Mandalay	21,257	17,127	80.6	3,827	18	303	1.4
Magway	552	449	81.3	96	17.4	7	1.3

Source: Pavelic et. al. (2015).

6 Chauk-Yenangyaung-Kyaukpadaung

6.1 Introduction

The Chauk-Yenangyaung-Kyaukpadaung area is located along the eastern edge of the Salin Sub-basin. It forms part of the Ayeyarwady River Corridor (ARC), which incorporates Study Area Zones 1, 2, 4, 8 to 11 **(Figure 13)**. To the east is the Bago Yoma Anticlinorium and southeast the Taungdwingyi Sub-basin. Kadaung Chaung is arbitrarily taken as the southern boundary. The Ayeyarwady River flows roughly north-south through the area and passes the oil producing regions of Chauk and Yenangyaung.

The geology of this region is described by several researchers[63]. Geologically the area is complex with many NNW-SSE orientated anticlines, synclines, faults and regional structural trends. These include the:

- Chauk, Yenangyaung and Yedwet anticlines;
- Chauk and Salin synclines (the latter west of **Figure 14**);
- Ngashandaung and Gwegyo hills;
- thrust faults along the Gwegyo Hills and Chauk Anticline; and
- Myaing Kyaukpadaung Structural Line.

These geological features have major controls on groundwater occurrence and movement.

Rocks of the Pegu Group (both Oligocene and Lower to Middle Miocene), Irrawaddy Formation, Alluvium and volcanics are present. The Pegu Group rocks form the axial core of the major anticlines and uplifted fault blocks. The Irrawaddy Formation crops out east of the Ayeyarwady River as a brown sandy soil. It is frequently covered by shallow Alluvium.

Along the Ayeyarwady River (mainly in the west) thick alluvial sediments overlie weathered Irrawaddy Formation — the contact boundary between these lithological units is sometimes hard to determine.

Igneous rocks of the Mount Popa Complex crop out near Kyaukpadaung.

Intense dry land agriculture takes place. Some small-scale groundwater based irrigation occurs along the alluvial flats, especially west of the river.

Badland topography is located along the trend of the Chauk and Yenangyaung anticlines in rocks of both the Pegu Group and Irrawaddy Formation. This area is barely arable and less inhabited.

Typical aquifer details and potential groundwater yield in various geological units are given on **Table 19**. Geological and hydrogeological features; water salinity; and areas of hot groundwater[64], deep drilling, difficulty in tubewell construction and high groundwater yield/low salinity[65] are shown on **Figure 14** and **Figure 15**. Hydrogeological cross sections are given on **Figure 16**. These figures present a summary of geological, hydrogeological and hydrochemical features. At specific sites variations from given detail should be expected.

No arsenic analysis from groundwater is reported (**Tables 17** and **18**) within Chauk–Yenangyaung–Kyaukpadaung township areas.

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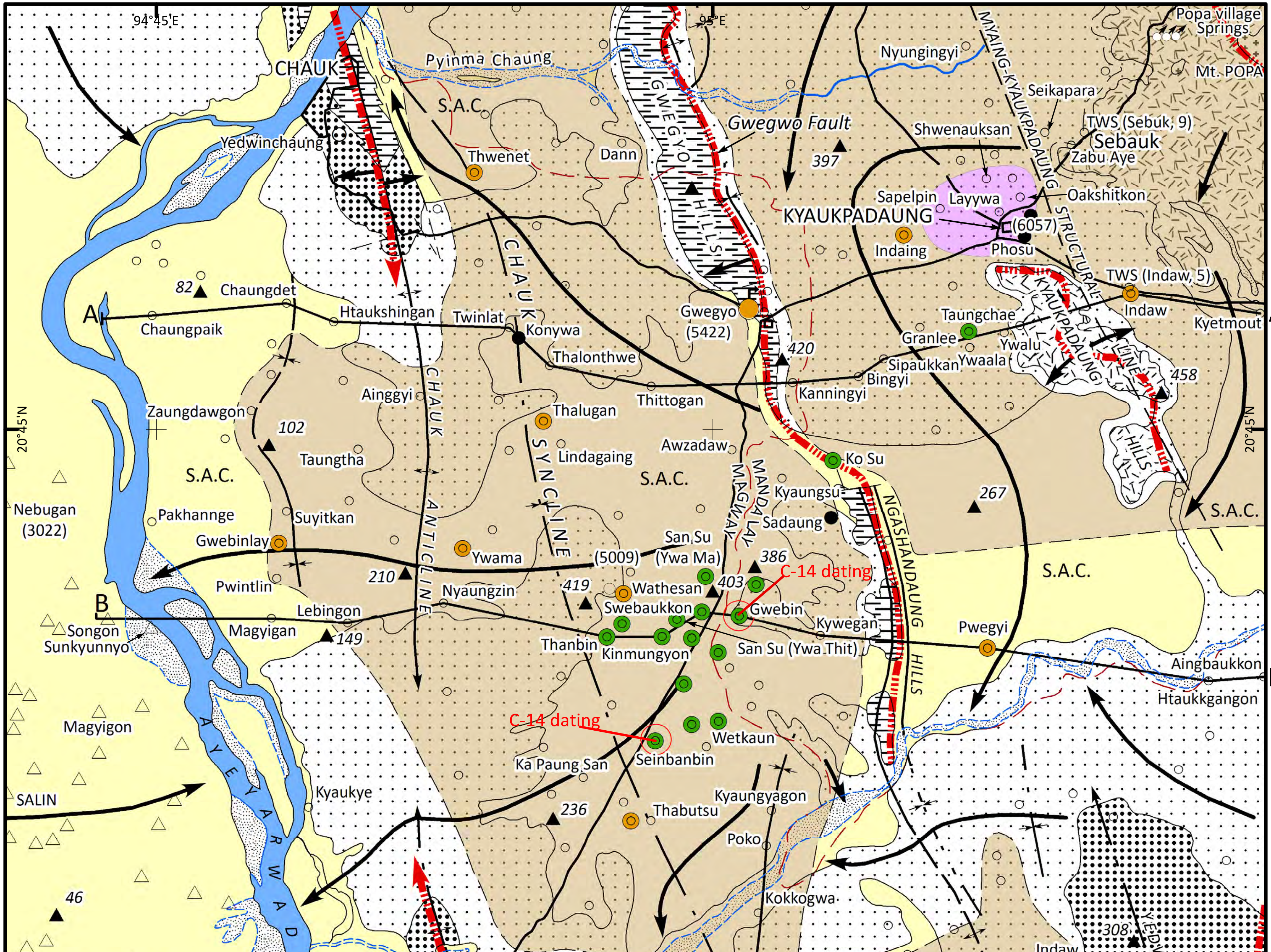
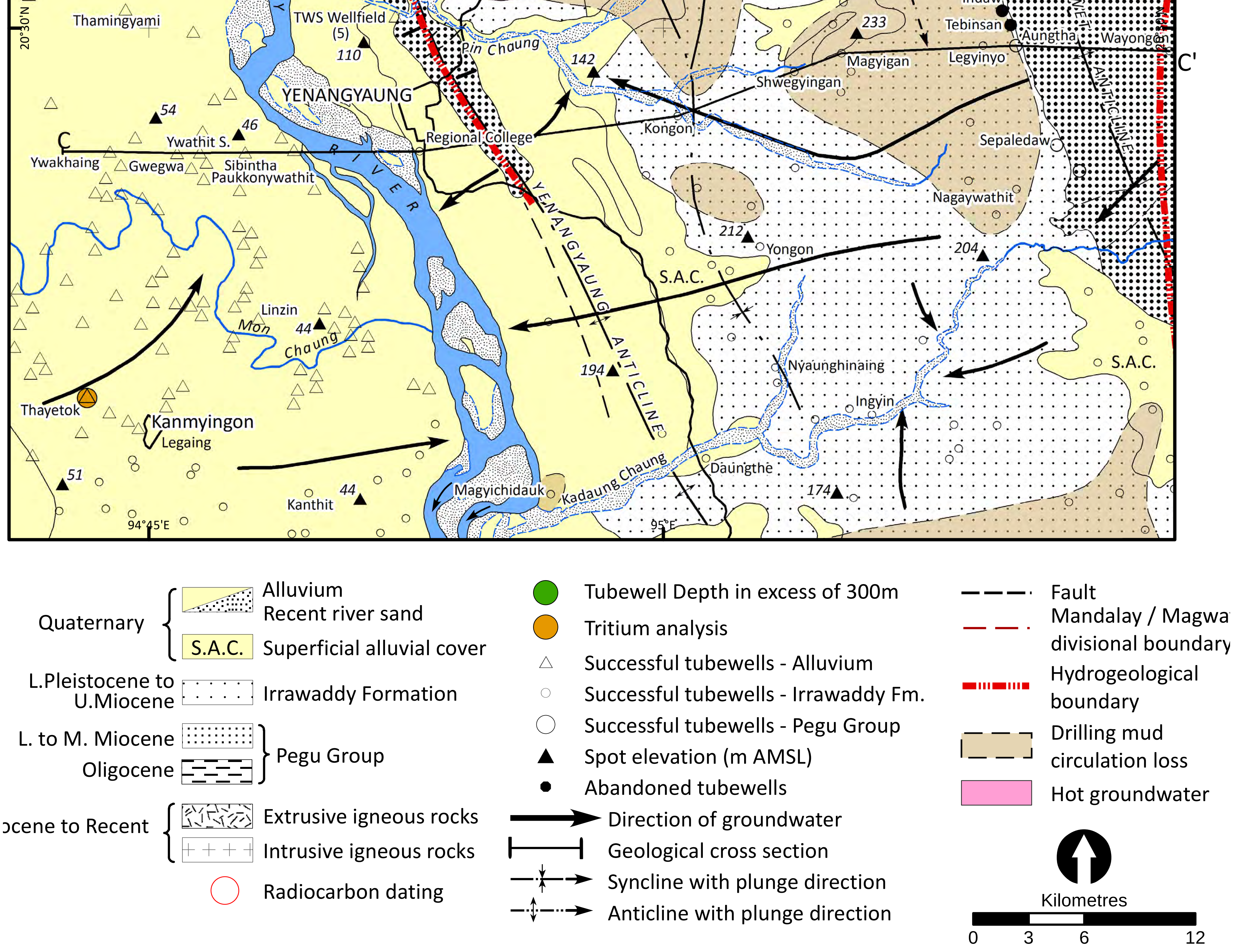
[63] Pilgrim (1904), Pascoe (1906a,b, 1907, 1908b), de Cotter (1909, 1910), Albert (1914), Rau (1921), Chhibber (1927c), Maung Nyan Min Naung (2008), Kyi Kyi Thwin (2011), Kyi Myo Khine (2011), Than Htike Oo (2012), Tin Lin (2014), Ridd and Racey (2016c-e)

[64] Assumed greater than 35° C

[65] Areas where groundwater for irrigation purposes may possibly be established from either Alluvium and/or Irrawaddy Formation. 6L/sec (0.5 ML/day) was assumed as a reasonable yield for small farmer paddy field. Areas of deep potentiometric surface and deep aquifers are excluded

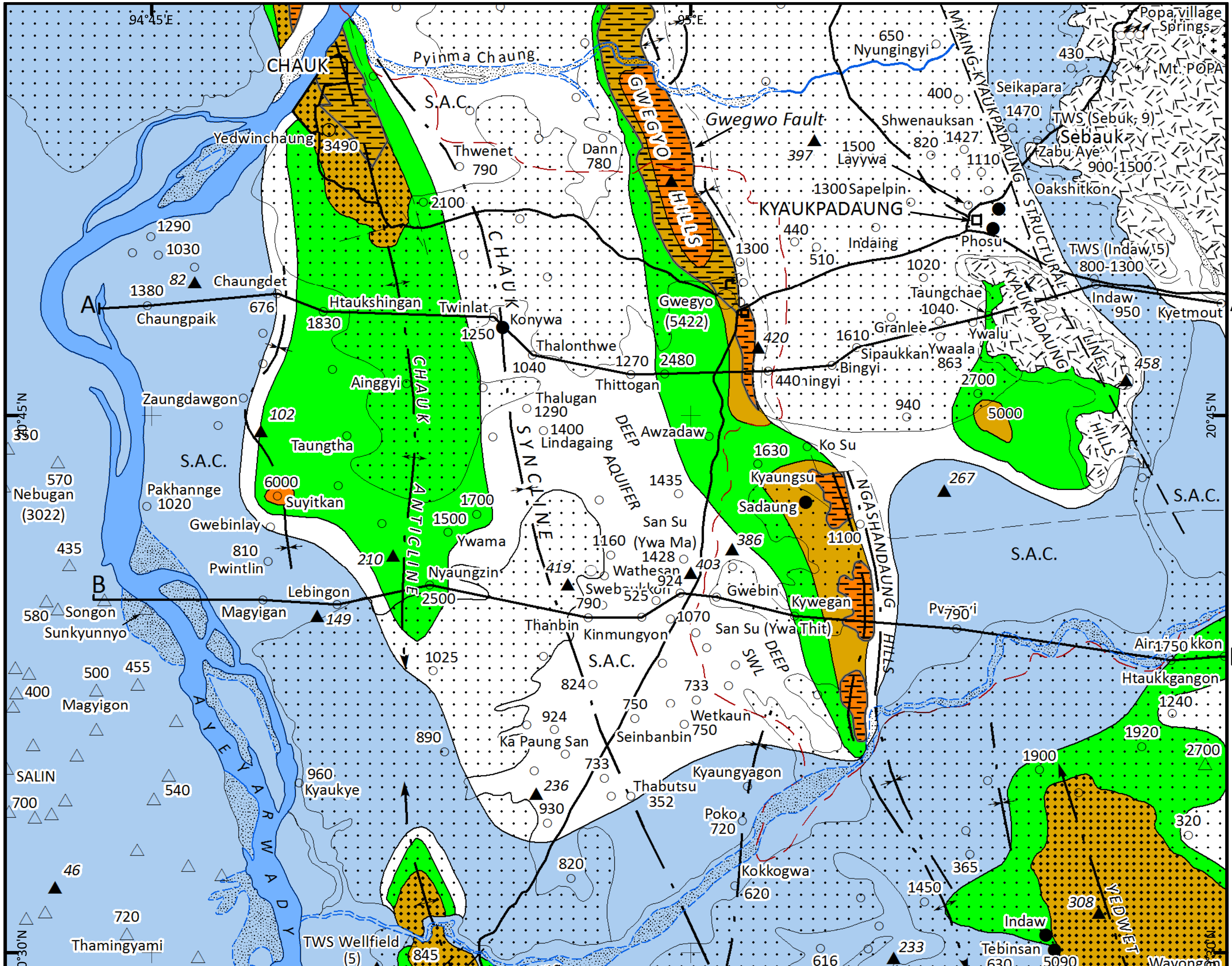
Figure 14 Schematic Geological and Hydrogeology Map: Chauk-Yenangyaung-Kyaukpadaung

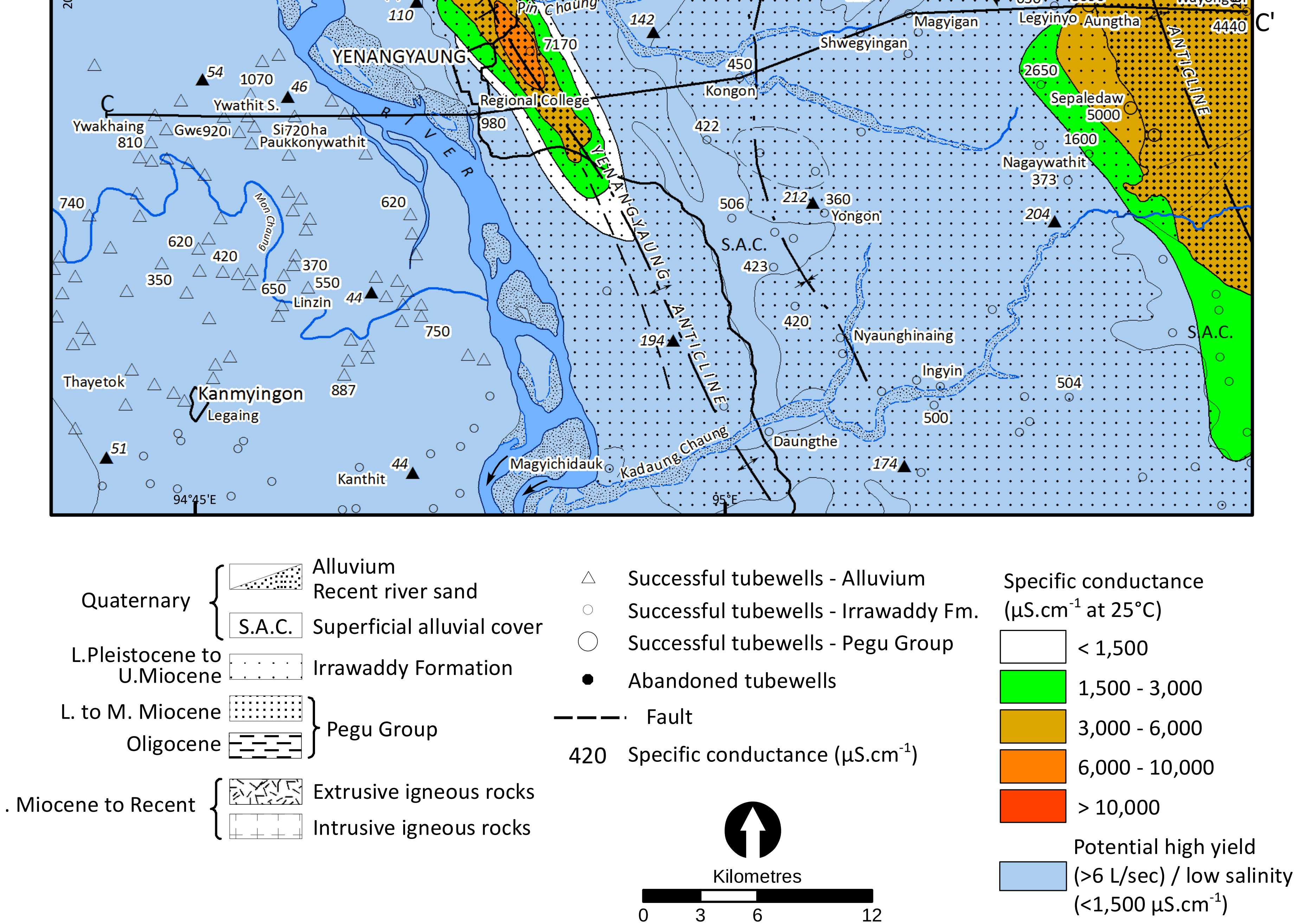




20°30'N
20°30'N
94°45'E
95°E
C
C'
Thamingyami
TWS Wellfield
(5)
110
YENANGYAUNG
54
46
Ywathit S.
Ywakhaing
Gwegwa
Sibintha
Paukkonywathit
RIVER
Regional College
Pin Chaung
142
Kongon
Shwegyingan
Magyigan
233
Tebinsan
Aungtha
Wayongon
Legyinyo
ANTICLINE
Sepaledaw
Nagaywathit
212
Yongon
204
S.A.C.
YENANGYAUNG ANTICLINE
194
Linzin
Mon Chaung
44
Thayetok
Kanmyingon
Legaing
51
Kanthit
44
Magyichidauk
Kadaung Chaung
Daungthe
174
Nyaunghinaing
Ingyin
S.A.C.
Quaternary
Alluvium
Recent river sand
S.A.C.
Superficial alluvial cover
L.Pleistocene to U.Miocene
Irrawaddy Formation
L. to M. Miocene
Oligocene
Pegu Group
Extrusive igneous rocks
Intrusive igneous rocks
Radiocarbon dating
Tubewell Depth in excess of 300m
Tritium analysis
Successful tubewells - Alluvium
Successful tubewells - Irrawaddy Fm.
Successful tubewells - Pegu Group
Spot elevation (m AMSL)
Abandoned tubewells
Direction of groundwater
Geological cross section
Syncline with plunge direction
Anticline with plunge direction
Fault
Mandalay / Magwa
divisional boundary
Hydrogeological
boundary
Drilling mud
circulation loss
Hot groundwater
Kilometres
0
3
6
12

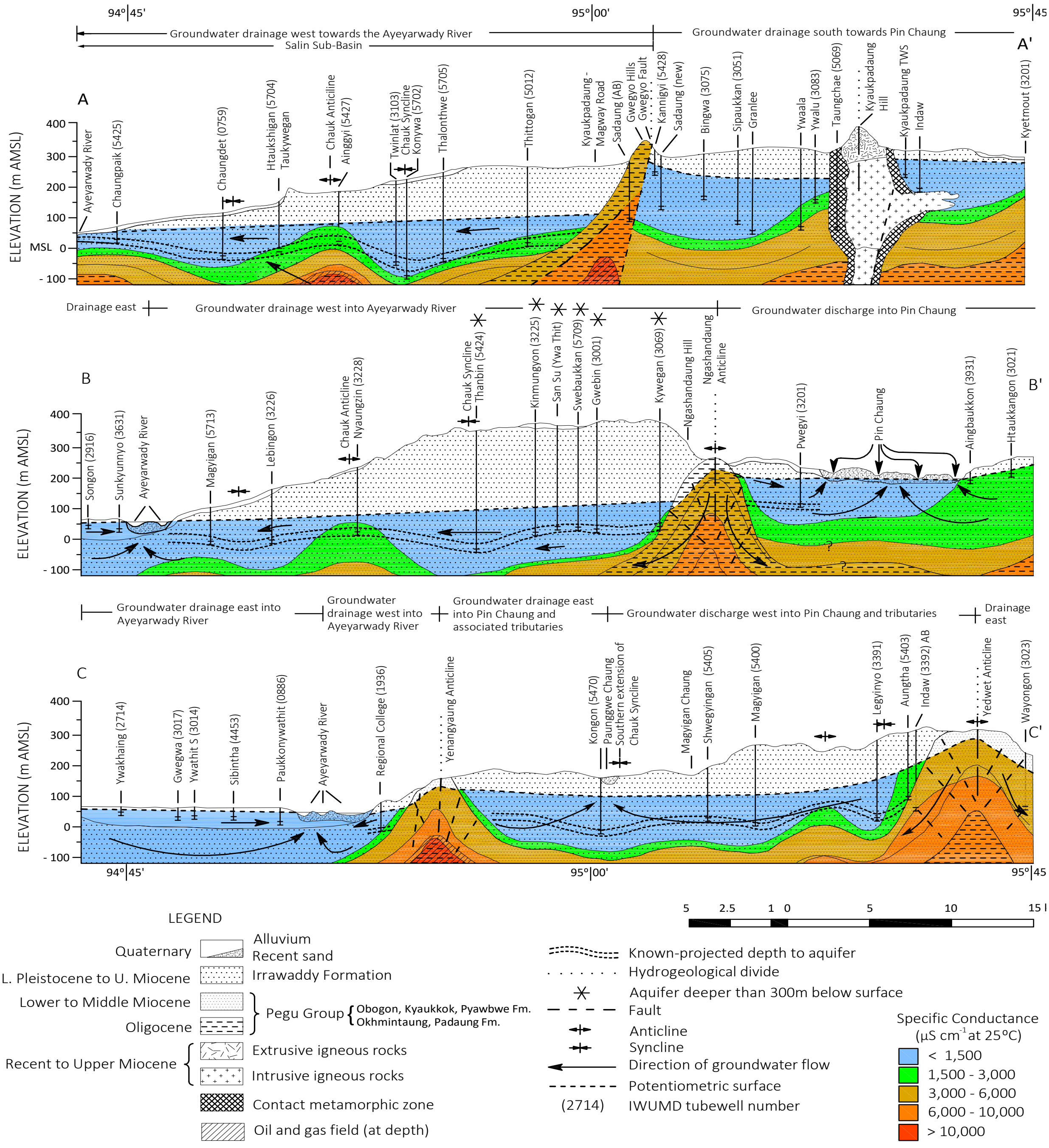
Figure 15 Chematic Hydrogeological and Hydrochemistry Map: Chauk-Yenangyaung-Kyaukpadaung





Note: This map shows regional hydrogeological and hydrochemical trends. At specific sites variations in detail may occur

Figure 16 Hydrogeological Cross Section and Specific Conductance: Chauk-Yenangyaung-Kyaukpadaung



Note: These cross sections give general trends. Irrawaddy Formation thickness is unknown. Variations in salinity may occur

Table 19 Aquifer Details on Selected Tubewells in the Chauk-Yenangyaung-Kyaukpadaung Area

Formation	Area	Village	Tubewell number	Surface Elevation (m AMSL)	All data from surface (m)				DD (m)	Airlift Yield# (L/sec)	Transmissivity (m^2/d)	Specific Conductivity ($\mu S.cm^{-1}$)
					Depth	Aquifer	SWL	DDL				
Pegu Group	Chauk Gwegyo	Yedwinchaung	5429	+ 137	168	147- 159	61	107	46	4.8	10	3,490
	Yedwet	Gwegyo	5422	+ 335	250	230- 238	Flow	76	76	0.3	1	2,420
	Anticline	Sepaledaw	5472	+ 280	251	131- 140	104	123	19	1.9	13	5,000
						220- 235						
Irrawaddy Formation	Chauk Anticline	Chaungdet	0729	+ 107	123	119- 122	51	54	3	9.1	417	676
	to Ayeyarwady	Chaungpaik	5425	+ 76	61	55- 61	21	24	3	8.8	298	1,380
	River	Pwintlin	5426	+ 99	89	78- 84	45	46	1	6.3	522	810
	Chauk Anticline	Kinmungyon	3225	+ 365	351	309- 340	241	259	18	1.9	15	525
	to Gwegyo Hills	Lingadaing	1946	+ 296	258	241- 250	209	232	23	0.4	2	1,400
	(Chauk	Ywama	3232	+ 249	247	211- 228	142	194	52	10	27	1,500
	Syncline)	San Su Ywa Thit	DJ (12)	+ 232	341	294- 312	232	233	1	2	360- 450*	1,435
		San Su (Ywa Ma)	DJ (17)	+ 340	315	284- 303	223	224	1	2	180*	1,428
		Ka Paung San	DJ (09)	+ 280	275	252- 271	173	175	2	2.5	300- 410*	924
		Kyaungsu	DJ (08)	+ 307	220	195- 214	192	198	6	1	21*	
		Dann	DJ (19)	+ 241	189	164- 176	151	155	4	2	140- 270*	
		Ko Su	DJ (16)	+ 317	303	270- 288	206	208	2	2.5	100*	1,630
	Kyaukpadaung	Nyungingyi	3282	+ 436	262	241- 250	170	198	28	1.6	6	650
		Oakshitkon	5057	+ 374	299	220- 226	111	134	23	3.2	37	1,190
		Pwegyi	3201	+ 221	122	113- 121	23	31	8	4.4	74	790
		Indaw No. 2	TWS	+ 396	107	73- 91	12	40	28	10.0	60	1,470
		Granlee	DJ (05)	+ 252	303	273- 293	124	126	4	2	680- 370*	865
		Ywaala	DJ (02)	+ 84	171	133- 153	84	102	18	3.5	35*	
	Yenangyaung	Kongon	5470	+ 152	175	149- 159	56	66	10	12.6	157	450
	to Yedwet	Kokkogwa	5458	+ 137	300	205- 223	38	52	14	10.7	97	620
	Anticline	Nagaywathit	5402	+ 254	260	232- 244	92	102	10	5.1	75	1,600
												1,780
Alluvium	West Bank	Ywathit South	3014	+ 49	34	31- 34	4	N/A	N/A	2.5	N/A	920
	Ayeyarwady	Magyigon	2919	+ 45	28	24- 27	5	N/A	N/A	3.8	N/A	550
	River	Linzin	2131	+ 49	23	18- 23	4	N/A	N/A	3.5	N/A	550

Source: IWUMD and DRD databases. Static water level (SWL), drawdown level (DDL) and drawdown (DD)
# indicates yield during pump-out test of 100 mm dia. tubewell. This does not necessarily indicate aquifer yield from large diameter production tubewell.
*JICA funded, Department of Rural Development pump-out test (2008-2009).

Pump-out tests from JICA funded village tubewells should accurately reflect aquifer hydraulic characteristics. Hydrogeological characteristics have also been assessed in some IWUMD tubewells by applying Logan's Method (Logan 1964)- such interpretation should be used with caution[66]. Overall the regional aquifer permeability trends may be considered as a reasonable indication.

Some hydrogeological reports on the Chauk–Yenangyaung-Kyaukpadaung area are available[67].

6.2 Pegu Group

Tubewells have been sunk into aquifers of the Pegu Group on the Chauk, Yedwet and Yenangyaung anticlines and the Gwegyo Hills. Most successful tubewells are sited in fractured sandstone aquifers of either the Okhmintaung or Kyaukkok formations. Drill depth ranges from 170 to 250 metres. The alternating shale formations usually act as impermeable hydrogeological barrier boundaries.

Potential groundwater yields from the fractured rock usually vary from 0.05 to 1 L/sec with transmissivity ranging 1 to 10 m^2/day. The salinity ranges from 2,420 to 7,170 $\mu S.cm^{-1}$, rendering water unsuitable for drinking purposes. The dominant chemical constituents are Ca^{2+}:SO_4^{2-} and Na^+:Cl^-, reflecting the host rock's marine origin and presence of gypsum along the fracture planes.

The lowest salinity (2,420 $\mu S.cm^{-1}$) is from a former 'artesian' aquifer (flow is 0.05 L/sec) at Gwegyo Village, located immediately west of the Gwegyo Hills. Groundwater ceased to flow in 1990. Aquifer recharge is from rainfall seeping into the westerly dipping Gwegyo Hills. Tritium analysis (**Table 16**) indicates that this water is pre-atmospheric atomic testing. Groundwater movement would be extremely slow.

Groundwater intersected in the Yenangyaung Anticline is a brackish (7,170 $\mu S.cm^{-1}$), alkaline (pH 9.2), Ca^{2+}:SO_4^{2-} type water with high total hardness 1,340 mg/L, thus unsuitable for any stock purpose. The salinity decreases away from the hill.

Salinities greater than 80,000 $\mu S.cm^{-1}$ occur in groundwater brine 900 to 1,200 metres below the surface in oil exploration wells at Chauk and Yenangyaung.

6.3 Irrawaddy Formation

Geological structure and hydrogeological barrier boundaries have significant impact on groundwater occurrence and depth to potentiometric surface and aquifer. Within the Irrawaddy Formation the shallow sediment is usually yellow-brown in colour whilst the deep aquifers are blue-grey in colour.

6.3.1 Chauk-Yenangyaung-Gwegyo Area

A feature along the Chauk Syncline is the significant depths to the potentiometric surface and the deep low salinity, blue/grey, fine to medium sand aquifers. For example:

- **Figure 16 A-A'**: south-east of Chauk the 250 metre-deep Konywa Village tubewell intersected a semi-consolidated confined aquifer at 220 metres; and
- **Figure 16 B-B'**: along the Gwegyo to Yenangyaung Road many tubewells have been drilled deeper than 300 metres before intersecting an aquifer. For example:
  - in Wathesan Village a deep tubewell sunk to 406 metres (13 m AMSL) intercepted a confined, sand and gravel aquifer at 377 to 390 metres (43 to 29 m AMSL);
  - at San Su (Ywa Thit) Village a tubewell terminated at 341 metres intersected a confined aquifer at 274 to 312 metres with a transmissivity range of 360 to 450 m^2/day. Specific conductance was 1,435 $\mu S.cm^{-1}$; and
  - the deepest potentiometric surface (280 metres) is at Swebaukkon Village.

[66] The static water level (SWL), drawdown level (DDL), total drawdown (DD) and groundwater yield are estimated during the airlift development of individual small diameter tubewells. The measurements cannot be considered accurate.

[67] Tahal (Water Planning) Ltd (1963), Tin Lin & Soe Win (1984), Coffey and Partners (1985b), Kyi Kyi Thwin (2011)

Seinbanbin Village Deep Tubewell: (May 2017)
Specific Conductance: 540 $\mu S.cm^{-1}$, Total Dissolved Solids: 390 mg/L, pH: 7.5, Temperature: 31° C.

Gwebin Village Deep Tubewell: (May 2017)
Specific Conductance: 770 $\mu S.cm^{-1}$, Total Dissolved Solids: 560 mg/L, pH: 7.4, Temperature: 31.5° C.

The depth to aquifer and yield are quite predictable. They are a function topography, geological structure and aquifer hydraulic characteristics. The east to west decline in surface elevation between the Gwegyo Hills and the Ayeyarwady River is over 300 metres. Over the same distance the potentiometric surface progressively shallows by 53 metres. The surface slope and hydraulic gradient are 0.012 and 0.002 respectively along the western half of cross section B-B'. The aquifer is usually less than 30 percent of the saturated stratigraphic column.

JICA's pump-out tests indicate that transmissivity within the deep aquifers range from 20 to 400 m^2/day (average 150 m^2/day). Potential groundwater yield ranges from 2 to 10 L/sec.

Fault systems play a significant role in groundwater occurrence and water quality. For example:

- the Gwegyo Fault separates the Irrawaddy Formation from the westerly dipping Oligocene Pegu rocks (Gwegyo Hills). At Gwegyo Village the brackish, former 'artesian' hole was replaced by two tubewells drilled east of the fault to depths of 110 metres (yellow sand) and 150 metres (blue gravel) in the Irrawaddy Formation. High groundwater yield and low salinity aquifers were intersected; and
- Sadaung Village – a tubewell penetrating to 210 metres in the Padaung Formation (Ngashandaung Hills) encountered no aquifer. Drilling in the fault fractured Irrawaddy Formation east of the hills to 150 metres encountered groundwater supplies (> 6 L/sec) of low salinity water.

Aquifer recharge at both successful Irrawaddy Formation sites is by direct infiltration of rainfall into the sandy soil and intermittent flow along the sandy chaungs. Saline groundwater in the adjacent Pegu Group rocks moves westwards away from the successful drill sites in conformity to the westerly dip of the strata.

The Irrawaddy Formation forms a regionally extensive aquifer directly draining to the Ayeyarwady River. Groundwater movement is:

- north-west around the Chauk Anticline to Pyinma Chaung;
- westwards where the Chauk and Yenangyaung anticlines plunge beneath the potentiometric surface of the Irrawaddy Formation; and
- southwards towards Pin Chaung.

Tritium analysis indicates that groundwater from the deep aquifer system is pre-thermonuclear.
The depth to aquifer, tritium results and low hydraulic gradient suggest that the water may be very old.

Radiocarbon dating results are given in **Table 20**. The results indicate an age of ≈ 2,565 to 3,600 years[68]. The distance between the two villages is 8,000 kilometres and aquifer depths are similar. Radiocarbon dating indicates that groundwater moves at a very slow rate of eight metres per year (assuming radiocarbon and calendar years are equivalent).

[68] The ages quoted are radiocarbon ages, not calendar ages

Table 20 Radiocarbon Dating of Groundwater in the Chauk-Yenangyaung-Gwegyo Area

Location	Depth (m)	Screen (m)	Formation	Sample Date (2017)	C-14 Dating (years)	Comment
Gwebin	320	260- 300	Irrawaddy Fm	11th May	2,565 ± 35	Seinbanbin down flow path from Gwebin
Seinbanbin	314	290- 310	Irrawaddy Fm	11th May	3,600 ± 30	

The specific conductance of groundwater is generally less than 1,500 µS.cm^{-1}. It is typically a Na^+:HCO_3^- type water. Evidence of groundwater recharge from the westerly dipping fractured sandstone of the Okhmintaung and Kyaukkok formations is indicated by the increase in salinity around the western flanks of the Gwegyo and Ngashandaung hills. Higher salinities are also measured on the flanks and direction of plunge of the Chauk and Yenangyaung anticlines. Here the chemical character changes to a Na^+:Cl^- or Na^+:SO_4^{2-} type water.

Photo 16: Drilling of New Tubewell. Source: *U Ngwe*

Photo 17: Checking Hydrogeological Maps at Drill Site

Due to the depth to the potentiometric surface (> 200 metres), depth to aquifer (> 300 metres) and moderate permeability, the low salinity aquifers within the Chauk Syncline are not considered suitable for large scale irrigation.

West of the Chauk Anticline to the Ayeyarwady River and near Pin Chaung, large groundwater supplies of low salinity (< 1,000 µS.cm^{-1}) should be expected. Drill depth ranges from 60 to 120 metres. Water level is less than 50 metres. The potential groundwater yield from appropriately designed deep tubewells may vary from 8 to 50 L/sec. High transmissivity values up to 450 m^2/day have been recorded.

6.3.2 Kyaukpadaung

The relatively impermeable Pegu Group shale isolates aquifers of the Irrawaddy Formation to the west and east of the north-south orientated Gwegyo and Ngashandaung hills. In addition, the Kyaukpadaung Hills and Mount Popa Complex act as localised groundwater divides in the northeast corner (see hydrogeological cross sections A-A' and B-B').

Within the smaller hydrogeological sub-basins the potentiometric surface and aquifer depth vary:

Sub-Basin	Depth to Potentiometric Surface (m)	Depth to Aquifer (m)
Gwegyo and Kyaukpadaung Hills	< 130	130- 250
Kyaukpadaung Hills and Mount Popa	< 50	80- 250
Kyaukpadaung Hills to Pin Chaung	< 30	< 150

The yellow sand and gravel aquifers form less than 20 percent of the stratigraphic sequence.

Transmissivity ranges from 10 to 700 m^2/day with an average of 200 m^2/day. Groundwater yields range from 1 to 10 L/sec, with the highest yields being within Kyaukpadaung Town.

Groundwater is recharged by surface runoff, discharge from fractured igneous rock aquifers around Mount Popa and direct infiltration of rainfall. Under a hydraulic gradient of 0.003 groundwater flow is southwards towards the elevated perennial Pin Chaung and eventually into the Ayeyarwady River.

The specific conductance of the Na^+:HCO_3^- type groundwater is generally less than 1,500 µS.cm^{-1}. For example, a 250 metre tubewell at Seikapara Monastery yields 3 L/sec with specific conductance of 1,470 µS.cm^{-1}.

Seikapara Monastery tubewell: November 2016
Specific Conductance: 1,470 µS.cm^{-1}, Total Dissolved Salts: 1,060 mg/L, pH: 6.9,
Temperature: 29.5° C.

Salinity up to 5,000 µS.cm^{-1} of Na^+:Cl^- or Na^+:SO_4^{2-} type water is encountered in hard rock aquifers along the western side of the Kyaukpadaung Hills. The presence of pyrite and chalcopyrite at Taungchae Village (220 metres) indicates proximity to underlying igneous rocks.

Kyaukpadaung Town Water Supply

Operator: Kyaukpadaung Township Development Committee operates the municipal water supply.

Sources: Springs

- Ye Tin- Ye Ngan: pumped 24 hours/day to town; and
- Kyo Chaung- Nga Wa: pumped (5pm to 7am) to town, remainder to farms.

Deep tubewells (DTWs)

- Sebuk Borefield: 9 x 200 mm dia. DTWs, 170 to 220 metres deep, equipped at 3 to 7 L/sec. Specific Conductance ranges from 900 to 1,500 µS.cm^{-1}. Total Yield: (15 hours pumping) = 2.4 ML/day; and
- Indaw Borefield: 5 x 200 mm dia. DTWs, 100 to 120 metres deep, equipped at 5 to 10 L/sec. Specific Conductance ranges from 800 to 1,300 µS.cm^{-1}. Total Yield: (15 hours pumping) = 1.9 ML/day.

Other: There are also hundreds of privately owned or community operated DTW in the town yielding 1.3 ML/day.

Town Water Demand: Assuming a population of 42,817 and water consumption of 130 Litres per day per person (L/d/p), the groundwater extraction from Kyaukpadaung Town is 5.6 ML/day

Hot groundwater is intersected by some deep tubewells near and within Kyaukpadaung Town **(Table 21).** The presence of elevated temperatures suggests that some volcanic activity may be present at considerable depth near the Mount Popa Complex.

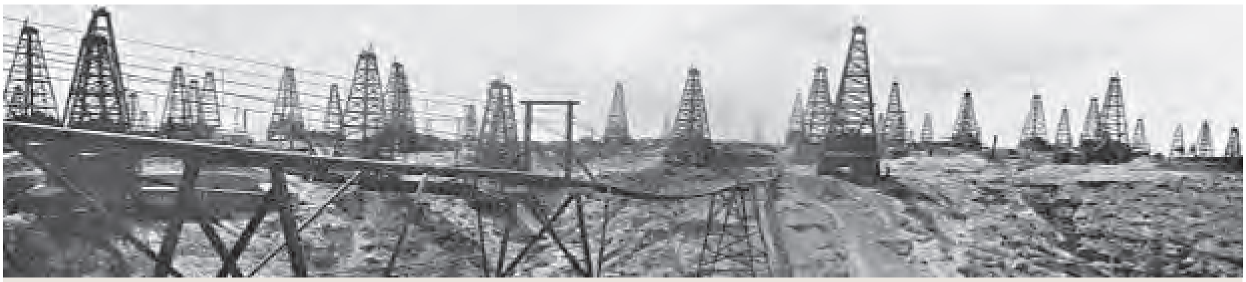
Large scale groundwater extraction between the Gwegyo and Kyaukpadaung hills is currently not considered economically viable due to the depth to the potentiometric surface (130 m) and aquifers (250 m), limited aquifer thickness and moderate transmissivity. In the shallow aquifers near Kyaukpadaung, Mount Popa and Pin Chaung high yields and low salinity supplies should be available.

Table 21 Tubewells Containing Hot Groundwater – Kyaukpadaung

Village Name	Tubewell No.	Aquifer from Surface (m)	SWL (m)	Potential Yield (L/sec)	Specific Conductivity ($\mu S.cm^{-1}$)	Temperature (° C)
Layywa	3,079	248- 257	167	1	1,500	44.2
Oakshitkon	5,057	220- 226	111	8	1,190	42
Phosu	5,059	159- 169	111	4	1,300	36.7
Sapelpin	3,081	169- 195	136	2	1,490	40.2
Shwenauksan	3,076	234- 245	135	6	1,100	36.7

Source: IWUMD database.

6.3.3 Yenangyaung to Yedwet Anticline Area



Yenangyaung Oilfield (circa 1940)

The Obogon Formation in the Yedwet Anticline hydrogeologically separates Irrawaddy Formation groundwater of the Yenangyaung area from the Taungdwingyi Sub-basin. The depth to aquifer near the anticline is about 240 metres below the surface, decreasing westwards to 80 metres (30 metres below mean sea level (m BMSL)) at the Ayeyarwady River. The potentiometric surface varies from 100 metres near Yedwet Anticline to river level near Pin Chaung, Kadaung Chaung and the Ayeyarwady River. Aquifer transmissivity is consistently between 20 and 150 m^2/day.

Recharge to the groundwater system is by direct rainfall infiltration on the sandy soil, infiltration of surface runoff on the Yedwet and Yenangyaung anticlines and groundwater discharge from Pegu Group aquifers. Groundwater movement is northwest, west and southwest to discharge into Pin Chaung, the Ayeyarwady River and Kadaung Chaung, respectively.

The specific conductance of the Na^+:HCO_3^- type groundwater is consistently less than 1,000 $\mu S.cm^{-1}$. As with the other areas, higher salinity, Na^+:Cl^-, Na^+:SO_4^{2-} and Ca^{2+}:SO_4^{2-} type waters are associated with aquifers near Pegu Group rocks. Kyi Kyi Thwin (2012) reports on elevated salinity adjacent to the Yenangyaung Anticline.

Irrawaddy Formation on flank of Yenangyaung Anticline: (Kyi Kyi Thwin 2012)
Specific Conductance: 2,920 $\mu S.cm^{-1}$, Total Dissolved Solids: 1,505 mg/L, pH: 7.7, Hardness: 710 mg/L.

West of the Yenangyaung Anticline, high yield, low salinity (980 $\mu S.cm^{-1}$) groundwater is encountered at depth below 50 metres at the Yenangyaung Regional College.

Elevated temperature 'hot spots' are occasionally reported along the western flank of the anticline.

Potential high yield, low salinity has been delineated over most of this area, especially from aquifers close to Pin and Kadaung chaungs and associated tributaries. Groundwater yields exceeding 40 L/sec may be available from properly constructed production tubewells.

Few tubewells have been abandoned. Exceptions are five drill holes at Indaw and one at Tebinsan Village (some drilled > 300 metres) close to the Yedwet Anticline. They were abandoned as no aquifer was encountered before intersecting Pegu Group rocks. Village water supplies should be available a few kilometres west at depth of 240 metres.

6.3.4 Loss of Circulation of Drilling Fluid

The thick unsaturated, uncemented, yellow coarse grain sand above the potentiometric surface has produced drilling problems for mud rotary rigs. Here loss of drilling mud circulation is a common problem. Drilling reports show major loss of drilling fluid in the Chauk and Yenangyaung areas **(Figure 14)**. The deeper blue grey sand and gravel usually occur below the potentiometric surface where mud loss is less of a drilling issue. Due to driller experience, improved drilling technology and the use of appropriate plugging materials, few drill holes are now abandoned.

6.4 Alluvium

Recent alluvial deposits are located along the perennial Pin Chaung and intermittent flowing Kadaung and Pyinma chaungs. Superficial Alluvial Cover (SAC) over the Irrawaddy Formation occurs in other areas east of the river.

West of the Ayeyarwady River thick deposits of unconsolidated, fluviatile sediment occur beneath the alluvial flats. Many tubewells intersect unconsolidated, semi-unconfined, sand and gravel aquifers at depths of six to 60 metres. The average depth of a village tubewell is about 30 metres. The upper sand aquifer is usually at 10 to 30 metres, underlain by five to 20 metres of thick yellow clay. Multiple coarse sand and gravel aquifers are intersected in the deeper tubewells. Depending on surface elevation, the water table is within 15 metres of ground level.

The specific conductance of groundwater is less than 1,000 $\mu S.cm^{-1}$. A Na^{+}:HCO_3^{-} type water is consistently encountered. Tritium analysis from Thayetok Village indicates that the shallow alluvial aquifer is Modern, thus within an aquifer recharge area.

Transmissivity values from shallow aquifers range from 12 to 300 m^2/day. Due to limited available drawdown, a maximum groundwater yield of 20 L/sec should be expected from appropriately constructed tubewells. Larger yields (>50 L/sec) might be available by the construction of large diameter gravel packed, multiple screened production tubewells, intersecting the deeper alluvial aquifers. Geophysical studies may be required to locate areas of thick alluvial aquifer.

At Yenangyaung, the Pin Chaung has cut a deep 20 metre channel through the Pegu rocks and infilled with medium to coarse sand. The Yenangyaung Oil Field is located on either side of this watercourse. Upstream groundwater discharge from the Irrawaddy Formation, volcanics and Alluvium maintains surface water baseflow during the Dry Season. Water is observed five to seven kilometres upstream of Yenangyaung, advancing upstream during the Wet Season and retreating during summer. At the Yenangyaung Bridge, baseflow in the 1986 Dry Season was measured in February (70 cusecs, 170 ML/day) and April (50 cusecs, 120 ML/day)[69]. At the end of the 2017 Dry Season (11th May) water flow was measured as 360 ML/day. This excludes throughflow in the underlying sand aquifer. The reason for this flow discrepancy is unknown.

Pin Chaung, Yenangyaung Anticline: (May 2017)
Specific Conductance: 420 $\mu S.cm^{-1}$, Total Dissolved Solids: 312 mg/L, pH: 8.3, Temperature: 32° C.

At Yenangyaung large groundwater extraction at shallow collector well systems in the Pin Chaung Alluvium occurs for town water supply purposes. Nearby the Myanmar Oil Corporation (MOC) operates four perforated infiltration wells for its oil production requirements (3 ML/day). These examples show that large supplies of low salinity groundwater may be established under favourable conditions in overall poor hydrogeological settings. With professional assessment, careful design and appropriate construction successful wellfield development may occur.

[69] Drury (1986)

Yenangyaung Town Water Supply

Operator: Yenangyaung Township Development Committee operates the municipal water supply from one groundwater wellfield.

Source: Collector Well System

The Well Field consists of:

- five x 4-metre dia. perforated concrete wells to 10 metres depth with telescopic 150 millimetres dia. screens set from 10 to 20 metres in Pin Chaung Alluvium;
- each well is 15 metres apart with pumps operating at 8 L/sec x 24 hours to cumulatively deliver 3.5 ML/day;
- all wells are adjacent to Pin Chaung for induced aquifer recharge; and
- salinity ranges from 800 to 1,000 µS.cm^{-1}.

Other: Due to the presence of the saline Pegu Group rocks and human waste pollution there are few privately owned DW and STW used for domestic purposes.

Yenangyaung Town Water Supply: (Kyi Kyi Thwin 2012)
Specific Conductance: 845 µS.cm^{-1}, Total Dissolved Solids: 430 mg/L, pH: 8.2, Hardness: 190 mg/L.

Large groundwater supplies should be available near the intermittently flowing Kadaung and Pyinma chaungs. Sand aquifer thickness and quantity of base flow in the Dry Season are unknown.

6.5 Aquifers in Fractured Igneous Rocks

Igneous rocks crop out at Mount Popa and in the Kyaukpadaung Hills. Several large springs emanate from the jointed and vesicular layers around the slope of the volcano at various levels, especially at and above Popa Village. These springs occur at the upper surface of relatively impervious tuffaceous, argillaceous rock. The Ca^{2+}:HCO_3^- type water has a specific conductance of less than 600 µS.cm^{-1}.

Few tubewells have been drilled into the igneous rock. Recharge of the fractured aquifer system is by direct rainfall and runoff over porous layers. No springs on the lower southern slopes are observed. The occurrence of springs due to the presence of fissures and vesicular layers indicates good prospects of obtaining high yielding aquifers.

6.6 Areas of High Groundwater Yield and Low Salinity

Figure 15 indicates the areas of potential high groundwater yield (> 6 L/sec) and low salinity (< 1,500 µS.cm^{-1}) within the Alluvium and Irrawaddy Formation. This assessment is based on current knowledge and the assumption that deep aquifers and potentiometric surfaces are not currently attractive targets for irrigation.

Photo 18: Yenangyaung TWS Well No.2, adjacent to Pin Chaung. Yenangyaung Oilfield on both sides of watercourse

Photo 19: Dry Season (May 2017) Groundwater Baseflow in Pin Chaung, upstream of Yenangyaung TWS Collector Wells

The area of potential high yield and low salinity occurs east of the Kyaukpadaung Hills; along Pin and Kadaung chaungs and both sides of the Ayeyarwady River. Groundwater extraction from Alluvium with shallow potentiometric surface may be from spearpoint batteries and collector well systems. Groundwater extraction from deep aquifers should be from large diameter, screened and gravel packed production bores. High yield potential may decrease towards Yedwet Anticline as depth to aquifer and potentiometric surface increases.

Excess groundwater extraction close to the Pegu Group rocks may induce saline water towards the pumping facility. In such cases the dip direction of the Pegu Group rocks is an important consideration. Where the Pegu Group underlies the Irrawaddy Formation or Alluvium, drilling should be terminated before saline aquifers are intersected.

6.7 Estimation of Water Balance

The Chauk-Yenangyaung-Kyaukpadaung region forms part of the ARC. A separate water balance model for individual sections is not considered. The water balance for the total Ayeyarwady River Corridor is discussed in **Chapter 17**.

Estimates of low salinity water in storage and concepts of safe and sustainable yield are also given in **Chapter 17**.

7 Hydrogeology of Magway-Minbu

7.1 Introduction

Agriculture is the main economic activity in the Magway-Minbu area. Magway is the headquarters of Magway Region, and is situated on the eastern bank of the Ayeyarwady River. The town's population is 94,038 (2014 census).

Small scale groundwater irrigation farming occurs along the alluvial flats of Yin and Mann chaungs and the Ayeyarwady River.

The Magway-Minbu area is situated near the southeast border of the Salin Sub-basin. To the east lies the Taungdwingyi Sub-basin and Bago Yoma; to the west is the Nwamataung Range and south the Thayetmyo Syntaxis.

Major structural features include the Ondwe, Mann-Minbu and Chaungtha anticlines, Ondwe and Minbu faults and the Salin Syncline. Mud volcanoes are associated with the Mann-Minbu Anticline and are produced by upward gas seepage from the underlying Mann and/or Htaukshabin oilfields.

To the south the broad alluvial flats terminate against the 20° N Uplift as the Ayeyarwady River cuts through Pegu group rocks of the Thayetmyo Syntaxis.

Groundwater studies have been carried out[70]. Examples of some aquifers are given in **Table 22.** Interpretation of hydrogeological data is shown on **Figure 17** and **Figure 18.** In contrast to the Chauk-Yenangyaung-Kyaukpadaung area the depths to aquifer and potentiometric surface are generally shallower.

7.2 Pegu Group

The marine rocks of the Pegu Group form the axial core of the NNW-SSE orientated Mann-Minbu, Chaungtha and Ondwe anticlines and crop out on the eastern part of the Nwamataung Range. The semi-confined to confined aquifers consist of fine grained fractured sandstone generally overlain by confining shale or siltstone layers.

Some tubewells intersect these aquifers on the Ondwe Anticline and southern areas near Minhla. No reliable tubewell data has been recorded on the Minbu Anticline. Groundwater yields are usually in the range of 0.5 to 3 L/sec. Pumping tests usually indicate multiple hydraulic barrier boundaries. At Ondwe Village the fractured aquifer system, with potential tubewell exceeding 10 L/sec, may be in direct hydraulic connection with Yin Chaung. A similar yield may be available from the nearby Salan Village tubewell.

Generally, groundwater in Pegu Group is saline and not suitable for human consumption. This is due to the soluble mineral content of the rock and long residence time of the groundwater in contact with the marine deposited sediment. A specific conductance of 550 $\mu S.cm^{-1}$ at Salan Village comes from shallow fractured rock adjacent to Yin Chaung where aquifer recharge occurs. Generally, the specific conductance is 2,500 to 4,000 $\mu S.cm^{-1}$, the highest measured at 4,600 $\mu S.cm^{-1}$. The water is typically a Na^+:Cl^- except close to the watercourses where Na^+:HCO_3^- type water is common.

[70] Tin Lin et. al. (1983a,b, 1984, 1985, 1986), JICA (1985), Htin Aung (1986), Dendena et. al. (2017)

The Ayeyarwady River cuts through Pegu Group rocks south of Magway. Tubewells sunk up to 300 metres at Sinbaungwe did not intersect any useable aquifer. For 10 kilometres east no successful tubewell is sited until Kyauksaungsan Village where low salinity Irrawaddy Formation aquifers are intersected.

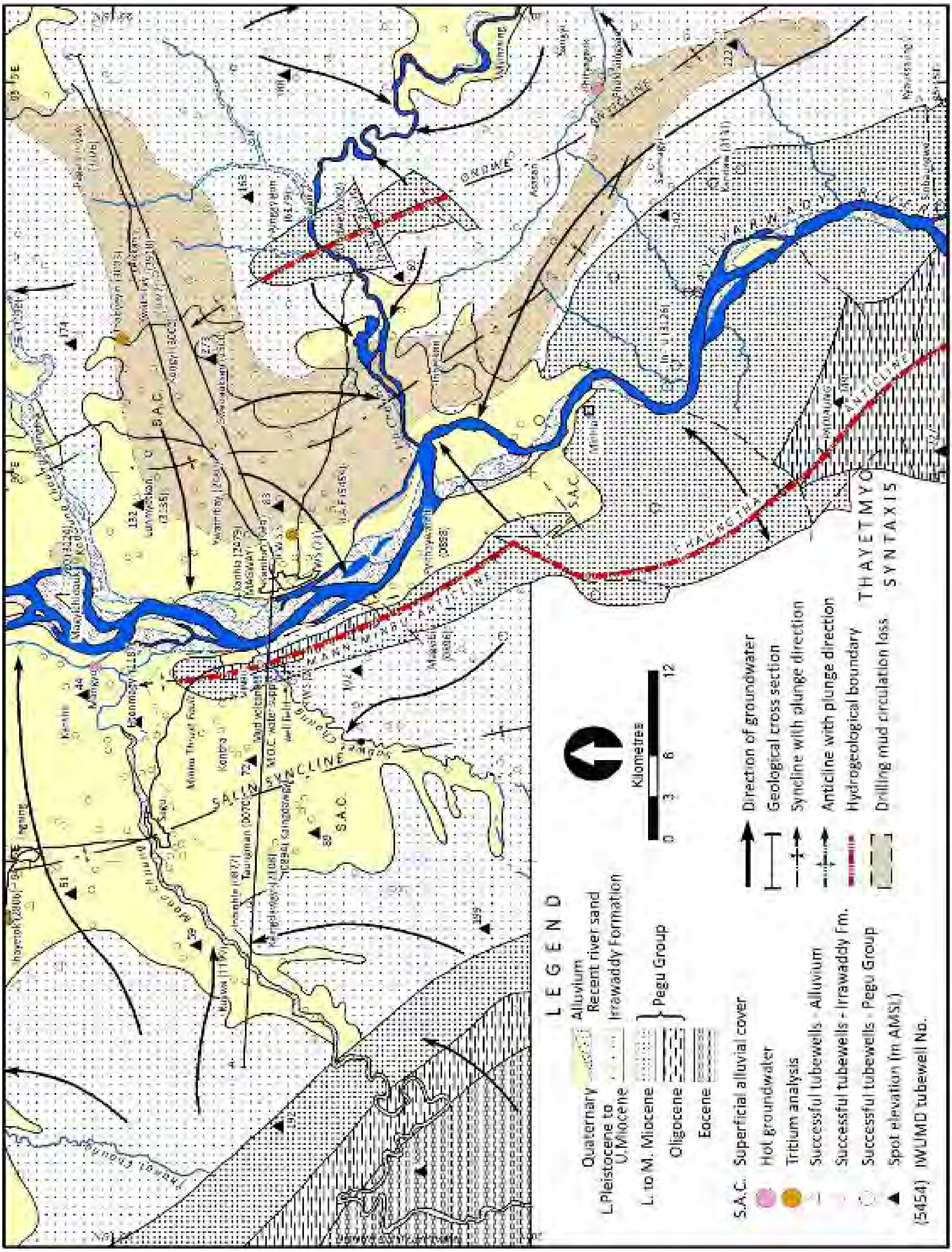
7.3 Irrawaddy Formation

The Pegu Group confining beds along the Mann-Minbu and Chaungtha anticlines, the Nwamataung Range and Thayetmyo Syntaxis form semi-impermeable barrier boundaries to groundwater flow in the Irrawaddy Formation.

Table 22 Details of Some Aquifers in the Magway-Minbu Area

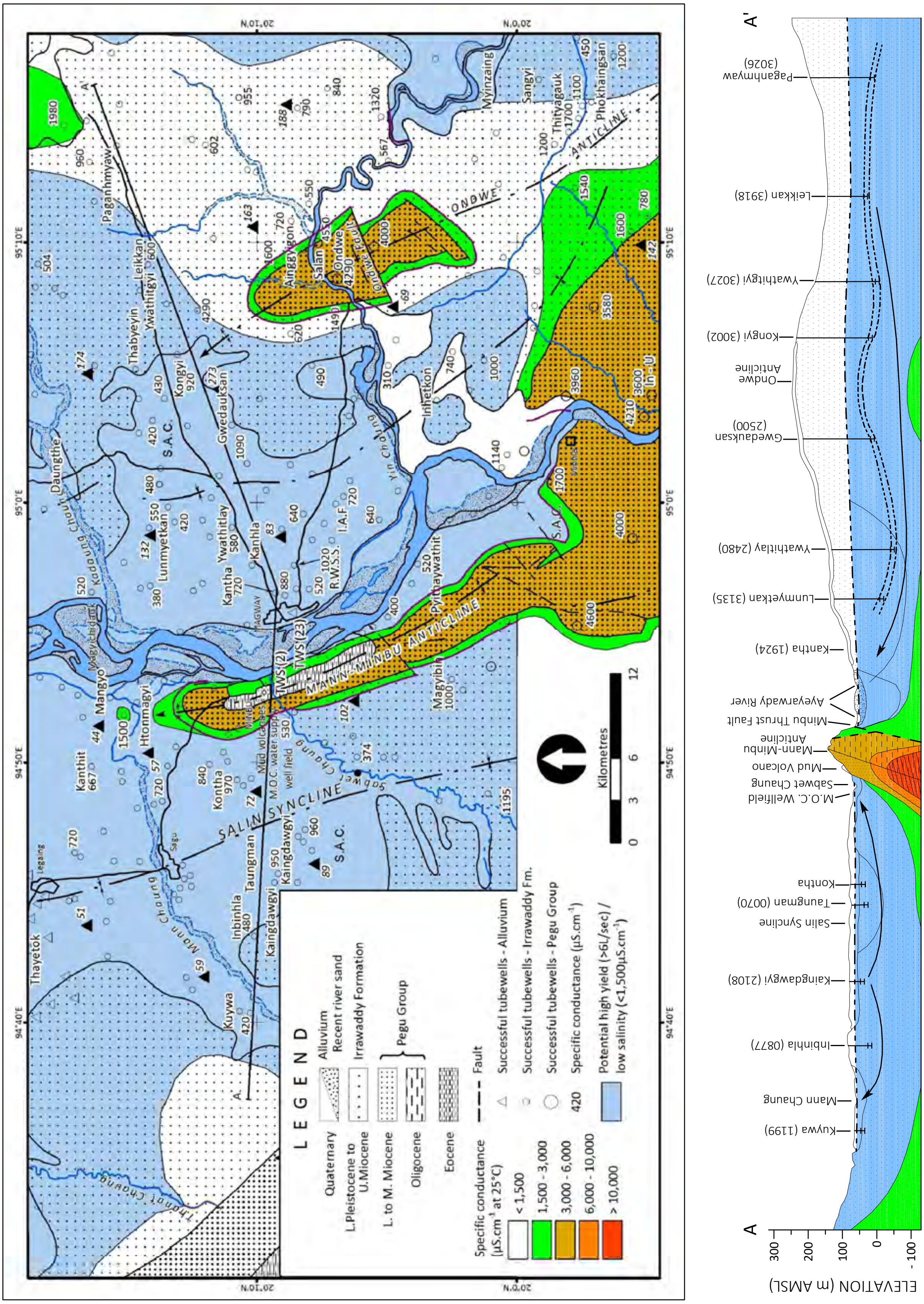
Formation	Area	Village	Tubewell number	Surface Elevation (m AMSL)	All data from surface (m)				DD (m)	Airlift Yield (L/sec)	Transmissivity (m^2/d)	Specific Conductivity ($\mu S.cm^{-1}$)
					Depth	Aquifer	SWL	DDL				
Pegu Group	Ondwe Anticline	Ondwe	6182	+ 64	165	146-152	6	15	9	8	107	4,290
		Salan	6183	+ 67	118	79-85	14	30	16	8	60	550
	Minhla	In U	3126	+ 73	95	66-74	10	48	38	5	16	1,100
	Aunglan-Thayet	Padaukpin	3362		31	27-31	19	7	9	0.3		'Saline, gas'
		Sakangyi	0910		34	29-34	11	30	20	0.1		'Saline'
		Kywechan	6733		98	61-67	10	30	21	1.5		'Saline'
Irrawaddy Formation	Kadaung Chaung	Daungthe	3132	+ 107	144	108-121	24	43	19	23	157	510
		Kanyin	3134	+ 55	89	77-82	5	21	16	11	86	560
	Magway	Kantha	1924	+ 79	67	55-67	15	17	2	5	417	720
		RWSD	3222	+ 76	95	65-83	14	31	17	19	142	1,020
		IAF	5454	+ 95	102	86-94	34	49	15	9	79	620
	Yin Chaung	Ainggyigon	6179	+ 76	77	65-70	12	18	6	9	179	720
		Myinzaing	3142	+ 95	77	43-66	11	46	35	15	45	920
	West bank of Ayeyarwady River	Pyithaywathit	0898	+ 60	31	27-31	9	10	1	11	2,340	520
		Htonmagyi	1187	+ 46	34	20-34	6	8	2	5	433	480
	West bank of the Minbu Anticline	Kaingdawgyi	0894	+ 76	34	30-34	17	26	9	9	128	950
		Magyibin	0896	+ 107	50	46-49	8	9	1	5	940	1,000
	SW and West of Ondwe Anticline	Kyauksaungsan		+ 240	200	160-190	120					< 1,000
		Sanmagyi		+ 232	193	132-183	130			6		670
		Asasan		+ 176	159	140-155	84			6		890
	Aunglan-Thayet	Yebwet	6218		81	61-73	31	46	15	8		620
		Aunglan Hospital	8307		82	70-78	12	27	15	5.5		
		Aunglan School	1957		40	31-40	13	27	14	5		
Alluvium	Aunglan-Thayet	Yemyet	3364		52	46-52	11	31	20	0.5		550
		Sankalay	5517		30	21-30	9	21	12	3		

Figure 17 Schematic Geological and Hydrogeology Map: Magway-Minbu



NOTE: This map gives generalised geological and hydrogeological features. At specific sites variations in detail may occur

Figure 18 Schematic Hydrogeological, Hydrochemistry Map and Cross Section: Magway- Minbu



NOTE: Regional hydrochemistry and cross sections give general trends only. At specific sites variations in detail will occur

The Irrawaddy Formation consists of a thick, current-bedded, poorly cemented sand and clayey sand sequence with minor clay, silt and gravel lenses. Silicified wood together with ferruginous and calcareous concretion[71] are commonly found.

7.3.1 Irrawaddy Formation – East Bank

On the eastern bank of the Ayeyarwady River the shallow, yellow, medium to coarse-grained sand aquifers change to a blue grey colour at about 45 m AMSL. The blue grey sand is intersected at a shallower depth near the Ondwe Anticline. High yielding aquifers are in both the yellow and blue aquifers.

Magway Town Water Supply

Magway's reticulated water supply system can deliver 8.9 ML/day.

Operator: The Magway Township Development Committee operates the municipal supply from three source types.

Sources:

- rainfall collection tanks;
- Ayeyarwady River water = 0.35 ML/day; and
- groundwater from Irrawaddy Formation = 8.55 ML/day. The wellfield is located throughout the northern part of town. 23 multiple-screened deep tubewells are sunk to 107 to 140 metres, each yielding between 7 to 10 L/sec; (average 8 L/sec).

Aquifers consist of coarse sand and fine to medium gravel.

The potentiometric surface is 10 to 12 metres beneath the surface.

Specific conductance varies from 850 to 1,410 µS.cm^{-1}, Total Hardness from 178 to 336 mg/L.

Other: Within Magway Township there are 452 deep tubewells, 4,130 shallow tubewells (hand pumps), 575 dugwells and 283 rainfall collection tanks, yielding 3.1 ML/day.

Town Water Demand: Assuming a population of 94,038 (Census 2014) and water consumption of 130 L/d/p, the town water supply demand is 12 ML/day. A combination of all water sources adequately meets the towns' requirements.

Industrial water supply comes from some of the private deep tubewells within the town municipal limits.

Magway Town Water Supply, Yan Way Quarter, Tubewell No. 5: November 2016
Specific Conductance: 1,410 µS.cm^{-1}, Total Dissolved Salts: 1,009 mg/L, pH: 7.1, Temperature: 31.5° C.

In the unnamed syncline to the south of Kadaung Chaung, and the elevated areas (> 240 m AMSL) west and south of the Ondwe Anticline, the depth to the primary aquifer exceeds 250 metres. With high surface elevation and good permeability characteristics, the potentiometric surface is deep. The multiple aquifers cumulatively occupy 20 to 40 percent of the saturated stratigraphic column. Groundwater moves from the south and west of the Ondwe Anticline (< 130 metres) under a low gradient towards the Ayeyarwady River, either directly or via Yin Chaung. Aquifer depth reduces towards Magway with potentiometric surface being 10 to 20 metres beneath the surface. The end of Dry Season (May 2017) baseflow of Yin Chaung cutting through the Ondwe Anticline is 1,700 ML/day (May 2017). The end of Dry Season Yin Chaung baseflow from the upstream Taungdwingyi Sub-basin is 127 ML/day **(Chapter 8)**. The excess 1,573 ML is sourced from groundwater discharge along the intervening 17 kilometres of watercourse entrenched through the Irrawaddy Formation. There is no Dry Season surface water flow contribution in this area.

[71] In outcrop exposure, calcareous concretions are usually taken as the Upper Irrawaddy Formation

Yin Chaung – Baseflow through Ondwe Anticline: May 2017
Specific Conductance: 620 µS.cm^{-1}, Total Dissolved Salts: 441 mg/L, pH: 8.7, Temperature: 34° C.

Typical hydrochemistry of groundwater under Magway town is given in **Table 23**. The specific conductance is consistently less than 1,500 µS.cm^{-1}. Regionally the salinity increases towards the Pegu Group outcrop.

Table 23 Hydrochemistry of Tubewells in the Magway Township Area[72]

Village	Depth (m)	pH	EC (µS.cm^{-1})	TDS	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}
				(mg/L)								
Ma Gyi Khan	91	6.7	850	550	13	50	30	5	82	91	80	ND
	93	6.7	900	585	12	77	44	5.5	81	104	84	ND
Kun Ohn Taung	80	6.7	1,350	875	53	26	27	7.6	125	82	130	ND
'East'	90	7.6	700	455	13	65	26	3.5	88	79	62	ND
'West'	90	7.7	1,000	650	41	43	22	5	142	69	94	ND

Source: Magway Town Development Committee.

Sanmagyi Village: May 2017
Specific Conductance: 670 µS.cm^{-1}, Total Dissolved Salts: 466 mg/L, pH: 7.4, Temperature: 33° C.

Transmissivities up to 350 m^2/day have been recorded, with many village tubewells exceeding a potential groundwater yield of 10 L/sec, some less than 20 L/sec. These high groundwater-yielding areas especially occur along Kadaung and Yin chaungs and in the Magway Town area.

Tritium analyses from Thabyeyin Village and the Magway IWUMD Station indicate that water is pre-thermonuclear.

Groundwater recharge is by direct precipitation, infiltration of surface runoff from elevated sandy soils, sandy watercourses, infiltration from the paddy fields and subsurface seepage from Pegu Group rocks.

Asasan Village: May 2017
Specific Conductance: 890 µS.cm^{-1}, Total Dissolved Salts: 637 mg/L, pH: 7.5, Temperature: 35° C.

Drilling mud circulation loss occurs in the unsaturated yellow sand and gravel horizons above the unnamed syncline[73]. Rotary rigs frequently encounter this drilling difficulty. In some cases, telescopic casing was inserted to regain mud circulation; in other cases, the drilling fluid was mixed with a plugging medium (sawdust, nut shell, clay ball or crushed muscovite flakes) to seal the voids within the porous material.

7.3.2 Irrawaddy Formation – West Bank

To the west of the Ayeyarwady River most tubewells intersect shallow, low salinity aquifers at depth of 20 to 50 metres within the Alluvium and Irrawaddy Formation. High transmissivity values (125 to 2,000 m^2/day) occur in some semi-confined aquifers which may be in direct hydraulic connection with the river. Of the domestic tubewells sunk, around 20 percent have a potential groundwater yield more than 10 L/sec. These are located along the western flank of the Minbu Anticline and adjacent to the Ayeyarwady River and Mann Chaung.

72 Ions and TDS do not balance (50 to 70 percent). Accuracy in Myanmar lab. results can be problematic. Field and lab EC values closely conform.

73 Tin Lin et. al. (1985, 1986)

Photo 20: KBZ Drilling Rig, Asasan Village, South of Ondwe Syncline

Photo 21: Magway TWS No. 5 Tubewell, Nov. 2016

Since large groundwater supplies are available at shallow depth, deep drilling is not required. Consequently, the thickness and depth to other underlying aquifers in the Salin Sub-basin is not known. The consensus is that the Irrawaddy Formation is greater than 500 metres thick. Large groundwater supplies should be available from appropriately constructed and developed deep tubewells.

On the west bank groundwater discharge is into the overlying Alluvium or towards the Ayeyarwady River and major tributaries, such as Mann and Sabwet chaungs.

7.3.3 Hot Groundwater

Hot groundwater is reported from two tubewells at Thityagauk and Mangyo villages with temperatures of 38.3° C and 41.6° C at depths of 180 and 30 metres below the surface respectively. The reason for such warm water at these two locations has not been adequately investigated. Maybe they are routed via greater depths within nearby tectonic features.

A recent replacement tubewell at Thityagauk Village has a lower groundwater temperature and higher salinity (1,100 µS.cm^{-1} (1986) and 1,680 µS.cm^{-1} (2016)).

Replacement tubewell in Thityagauk Village: November 2016
Specific Conductance: 1,680 µS.cm^{-1}, Total Dissolved Salts: 1,225 mg/L, pH: 7.2, Temperature: 33° C.

7.4 Alluvium

Superficial alluvial aquifers are located along the Ayeyarwady River, Kadaung and Yin chaungs and their tributaries. Reliable supplies of low salinity Na^+:HCO_3^- type water are usually available at a depth of 10 to 30 metres below the surface. Beneath the water table the unconsolidated aquifers usually occupy 30 to 60 percent of the stratigraphic column.

West of the Ayeyarwady River many village and small-scale irrigation tubewells are located within the thin alluvial cover. The general trend is for the yellow clay to thicken and the water table to increase southwards. Underlying blue sand is intersected at variable depth.

Minbu Town Water Supply

Operator: The Minbu Township Development Committee operates the reticulated municipal water supply.

Source: Two x four-metre diameter collector wells to depth of six to 12 metres in the Sabwet Chaung Alluvium between the Mann and Htaukshabin oilfields and adjacent Pegu Group rocks. The wells have 150 mm dia. perforated pipe extending two metres outwards from well portals. Each collector well is equipped with 25 L/sec pumps. The wellfield has a delivery capacity of 4.3 ML/day.

Town Water Demand: Assuming a population of 39,559 (Census 2014) and water consumption of 130 L/d/p, the town water supply demand is 5.1 ML/day. Operating full-time the collector well system can deliver 85 percent of the towns' requirements. The remainder comes from shallow private DWs and TWs. A stand-by collector well would be useful in case of failure of one pumping facility.

MOC Wellfield: The volume of groundwater extraction from the MOC Wellfield is not readily available.

The successful establishment and long-term operation of the Minbu Town Water Supply and MOC wellfields near the Pegu Group rocks indicates that large supplies of low salinity groundwater may be established where favourable conditions occur in a generally poor hydrogeological setting. Careful tubewell design and appropriate technology needs to be applied for successful wellfield development.

Photo 22: Minbu Town Water Supply Collector Well System

Photo 23: Yin Chaung Cutting Pegu Group- Ondwe Anticline

Future Research:

At Magway, there is no record of thick alluvial sediment in deep channels. The Irrawaddy Formation and Pegu Group crop out east and west of the Ayeyarwady River respectively. In contrast, a deep channel infilled with permeable Alluvium exists to 160 metres, upstream at Mandalay City. If a deep channel infilled with high yield aquifers occurs at Magway, it must be located beneath the river. In addition, the Alluvium is terminated further south of Magway as the Ayeyarwady River cuts through the Thayetmyo Syntaxis. Variance in interpretation of the Alluvium stratigraphy and depth requires further research so a better understanding of the anomalies and location of high yield aquifers can be achieved.

7.5 Groundwater Monitoring

Pressure transducers and data loggers were installed in groundwater monitoring piezometers in the Magway and Minbu IWUMD offices in late April 2017 **(Table 24)**. IWUMD will download the data each month and send to the Groundwater Department, Nay Pyi Taw for analysis and archiving.

Table 24 Groundwater Monitoring in Magway Area

Location	Formation	Depth (m)	Target
Magway	Irrawaddy Formation	61	Magway Town groundwater extraction
Minbu	Irrawaddy Formation	84	Regional groundwater behaviour

No long-term monitoring of groundwater behaviour has previously been carried out in this area.

7.6 Aunglan-Thayet Area

7.6.1 Introduction

The Aunglan-Thayet area is situated on the southern boundary of the Dry Zone. It is south of the 20° N Uplift Area and geologically isolated from the upstream Dry Zone Hydrogeological Basin. It includes Sinbaungwe, Aunglan and Thayet townships. It is bounded by a complex of anticlines, synclines and cross faults. Government and private oil and gas production occurs in the Padaukpin and Monatkon areas. Limestone extraction occurs in the Thayet Range.

7.6.2 Pegu Group

The Pwaybwe, Kyaukkok and Obogon formations are widely exposed. The Okmintaung Sandstone occurs within the anticlinal cores and north of Thayet.

There are over 100 IWUMD tubewells sunk into the Pegu Group. Those intersecting aquifers have a yield potential of 0.2 to 0.5 L/sec. Most tubewells are abandoned or of limited use due to their brackish to high salinity content. Depth to aquifer is usually less than 100 metres. The Thayet Government Technical Institute tubewell drilled to 180 metres into Pegu and Eocene rocks has a salinity of 9,000 $\mu S.cm^{-1}$.

7.6.3 Irrawaddy Formation

The Irrawaddy Formation consists of clay, silt, sand and gravel. It is exposed as clayey sand with lime nodules on both sides of the Ayeyarwady River. This geological unit is hydrologically isolated from the upstream Irrawaddy Formation by the encapsulating Pegu Group rocks.

There are 128 IWUMD tubewells drilled to depths of 60 to 180 metres with yields of 1.5 to 10 L/sec. The specific conductance is usually less than 1,500 $\mu S.cm^{-1}$.

7.6.4 Alluvium

The Alluvium consists of yellow fluviatile sand, gravel and clay located along the alluvial flats of the Ayeyarwady River and tributaries. Ten IWUMD tubewells have been drilled in low salinity alluvial aquifers with yields of 1 to 7 L/sec. Artesian tubewells occur in the Aunglan area.

7.7 Areas of High Groundwater Yield and Low Salinity

Based on borehole logs, pump-out tests, town water supply development and local professional hydrogeological advice, the area of potential high groundwater yield and low salinity from the Alluvium and/or Irrawaddy Formation in the Magway-Minbu region is shown on **Figure 18**. This includes:

- the confluence of Kadaung and Yin chaungs with the Ayeyarwady River and intervening area; and
- the Salin Syncline west of the Ayeyarwady River. The accuracy of the extent of irrigation potential in the Salin Sub-basin is limited by inadequate bore data.

High yield aquifers are located west and south of the Ondwe Anticline. However, as surface elevation rises the depth to aquifer and potentiometric surface increases. These areas are not considered part of the high yield / low salinity areas suitable for irrigation purposes.

7.8 Water Balance Annual Recharge Estimation

The Magway-Minbu region forms the southern part of the ARC. The water balance for the total ARC is discussed in **Chapter 17.**

Estimates of low salinity water in storage is given in **Chapter 17.**

8 Hydrogeology of the Taungdwingyi Sub-basin

8.1 Introduction

The Taungdwingyi Sub-basin is located on the southeast periphery of the Dry Zone. It comprises Taungdwingyi, Myothit and Natmauk townships. This irregular-shaped, elongated, sediment-infilled synclinal trough has:

- a north-south axis of about 110 kilometres and an east-west extent of 56 kilometres at the widest point;
- an eastern boundary formed by NNW-SSE orientated ridges of the Bago Yoma Anticlinorium. These highly contoured ridges rise from 290 to 600 m AMSL;
- a northwest border of the Yedwet Anticline. The highest point is Pingadaw at 480 m AMSL; and
- western and southern borders consisting of less elevated rocks of the Irrawaddy Formation.

The elevation of the fertile, medium to heavy-textured alluvial soil of the central valley varies from 150 m AMSL near Myothit to 100 m AMSL west of Taungdwingyi.

The Kandaw Dam has been constructed near Natmauk and is the primary water source for irrigation. Corn, sesame, groundnut, bean and rice are grown on the alluvial plain.

Some comment is given on groundwater potential for irrigation purposes[74]. Examples of aquifer data are given on **Table 25.** Over 300 tubewells have been sunk for domestic and irrigation supplies by the IWUMD and the Taungdwingyi Township Development Committee. This data forms the basis of hydrogeological assessment presented on **Figure 19** to **Figure 21.** Many thousands of private dugwells and tubewells have been constructed for domestic and irrigation purposes. Ponds and Yin Chaung are alternative sources of domestic water. The perennial Yin Chaung is the major watercourse. Its tributaries include Palin, Sun, Sadon, Ngamin, Seikpu and Yabe chaungs. All these branches flow intermittently with heavy bed loads during the Wet Season. Yin Chaung rises in the northern mountainous and drains southwards. It is the only watercourse that drains the Taungdwingyi Sub-basin. It flows westward to the Ayeyarwady River south of Magway. In May 2017 (end of Dry Season), groundwater-derived surface outflow in Yin Chaung was measured at the sub-basin's western exit point as 127 ML/day.

Yin Chaung – Baseflow at Taungdwingyi Western Exit Point: May 2017
Specific Conductance: 1,680 $\mu S.cm^{-1}$, Total Dissolved Salts: 1,225 mg/L, pH: 7.2, Temperature: 33º C.

There is little detail on the geology and hydrogeology of this area[75]. Three stratigraphic units crop out in the basin:

- Alluvium- thickening from the basin periphery to 75 metres along the basinal axis near Taungdwingyi;

[74] Thaik Nyunt (1981), SMEC (1986)
[75] Than Tun (1981), Tin Linn et. al. (1988), Tin Nyi Nyi Win (2013), JICA (2016)

- Irrawaddy Formation – greater than 450 metres thick in the synclinal trough. The percentage of aquifer within the stratigraphic sequence at Taungdwingyi is usually less than 10 to 25 percent, increasing southwards to 35 percent; and
- Pegu Group on the Bago Anticlinorium and Yedwet Anticline.

8.2 Pegu Group

The rocks in the Bago Yoma Anticlinorium contain numerous isoclinal folds and fault systems. They are predominantly of the Obogon Formation and consist of alternating bluish laminated shale, sandy clay with soft thinly bedded sandstone and calcareous conglomerate. Gypsum and sodium efflorescence are present, especially along the anticlinal axis. Lateral variation in lithological facies is common.

Table 25 Details of Aquifers in the Taungdwingyi Sub-basin

Formation	Area	Village	Tubewell number	Surface Elevation (m AMSL)	All data from surface (m)				DD (m)	Airlift Yield (L/sec)	Transmissivity (m^2/day)	Specific Conductivity ($\mu S.cm^{-1}$)
					Depth	Aquifer	SWL	DDL				
Pegu Group	Bago Yoma	Bangon	2455	+ 305	40	13- 40	6			1		4,240
		Thayetchin	3938	+ 247	109	92- 102	17			4		4,040
Irrawaddy Formation	North Natmauk	Kyetthit		+ 235	69	51- 68	4			2		3,010
		Pinn	2113	+ 244	44	21- 24	6			1		5,330
	Near Yedwet Anticline	Thayet-chaungyo										
		Gwechaung	2489	+ 335	191	177- 191	94			4		1,576
			5474	+ 229	199	174- 183	122			9		1,410
	Natmauk	Tamarbin	5315	+ 168	50	46- 49	6			4		510
		Aung San	0756	+ 170	46	43- 46	7			11		780
		Gwegyo		+ 179	164	145- 160	15			5		2,650
	Taungdwingyi	Inywag	0763	+ 101	253	223- 250	4	7	3	24	895	720
		Hingayaw	0764	+ 107	151	118- 147	+6			4		1,110
		Yewai	3249	+ 102	358	327- 341	10	39	29	4	18	750
		Kokkogwa	3248	+ 101	321	305- 314	9	21	12	4	45	700
		EPC Substation		+ 100	314	251- 300	+12			6		
		Taunbgbyin (Ward 2)		+ 102		125- 133	4	15	11	10	35	1,400
						165- 175						
	Southern area	Thetkegyin	6172	+ 158	141	117- 134	56	67	11	10	37	1,100
		Nyaung-bingwin	6175	+ 159	181	174- 180	44	64	20	6	40	920
		Theykegyin		+ 165	154	130- 141	76					640
		Thegyan		+ 125	35	31- 34	6					980
Alluvium	Taungdwingyi	Sipinthaya	3038	+ 127	80	48- 55	3	12	9	6	75	1,170
		Thitpoke-kone	5554	+ 122	31	61- 75	3	6	3	5	283	920
						20- 27						
	Myothit	Tamarbin	3904	+ 168	40	28- 34	14			9		540
		Sarde	3969	+ 137	27	20- 27	4			17		970

Source: IWUMD database; private drillers and U Tin Linn pers. comm.

Figure 19 Schematic Geological and Hydrogeology Map: Taungdwingyi Sub-basin

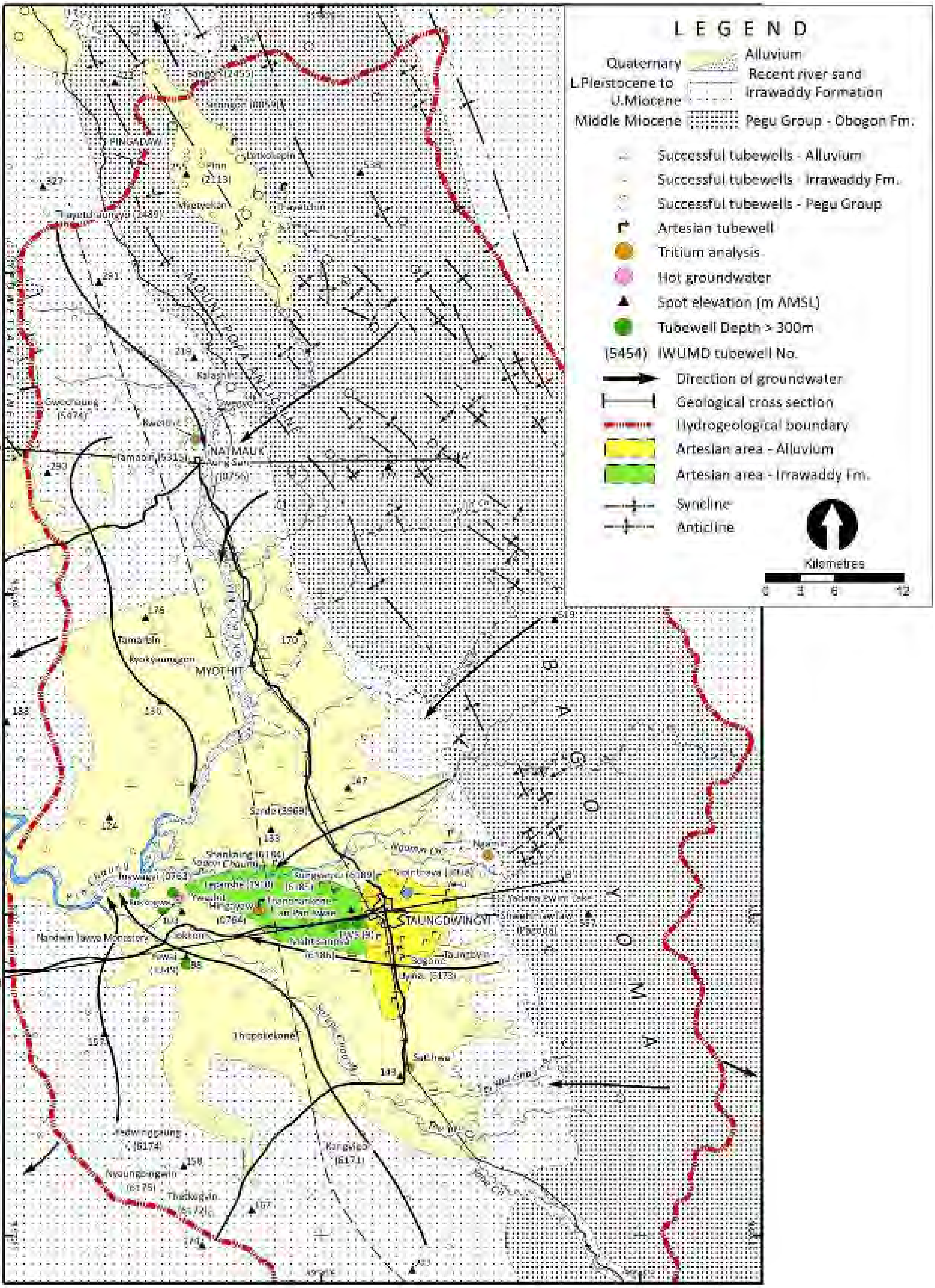
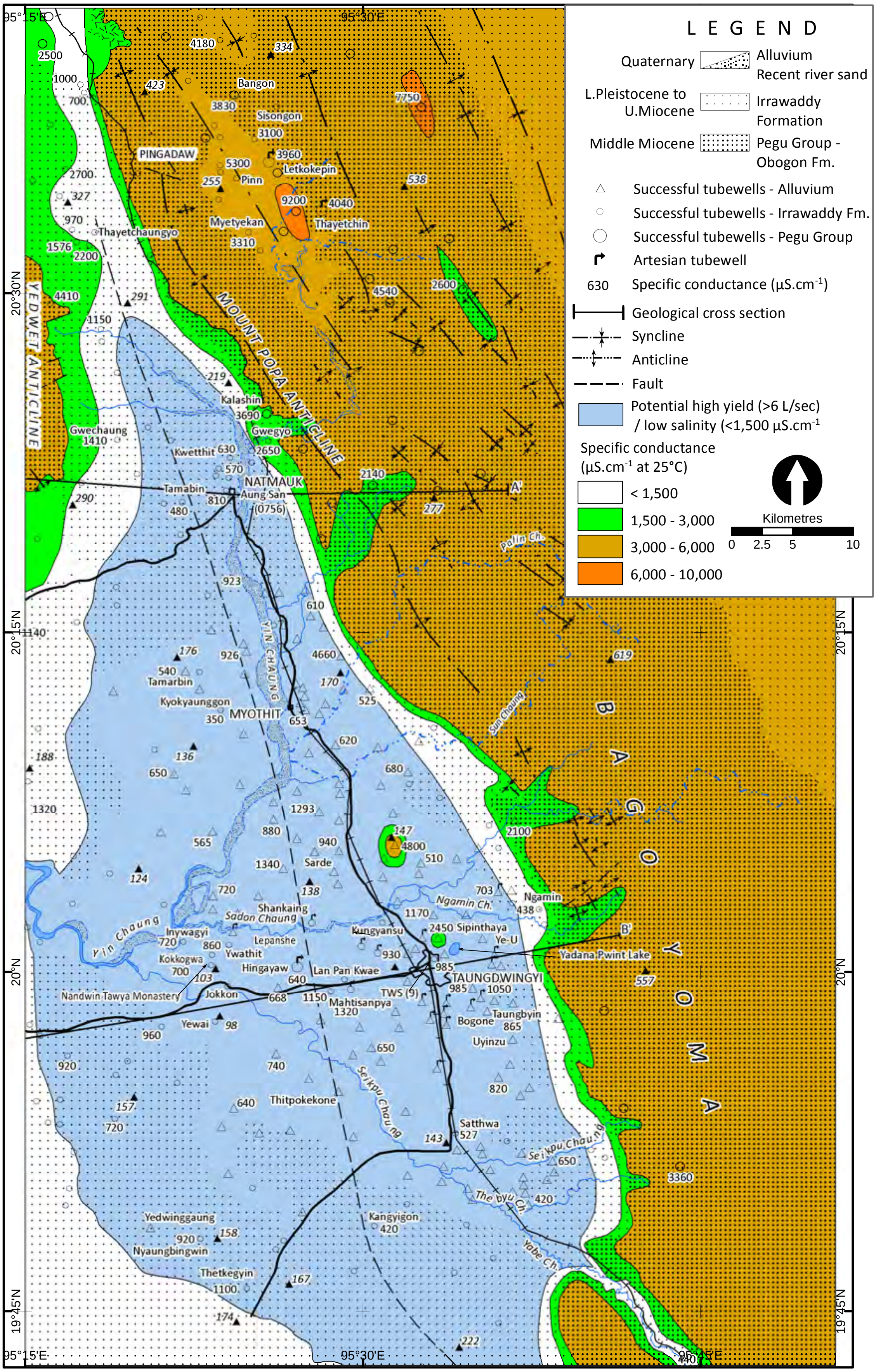
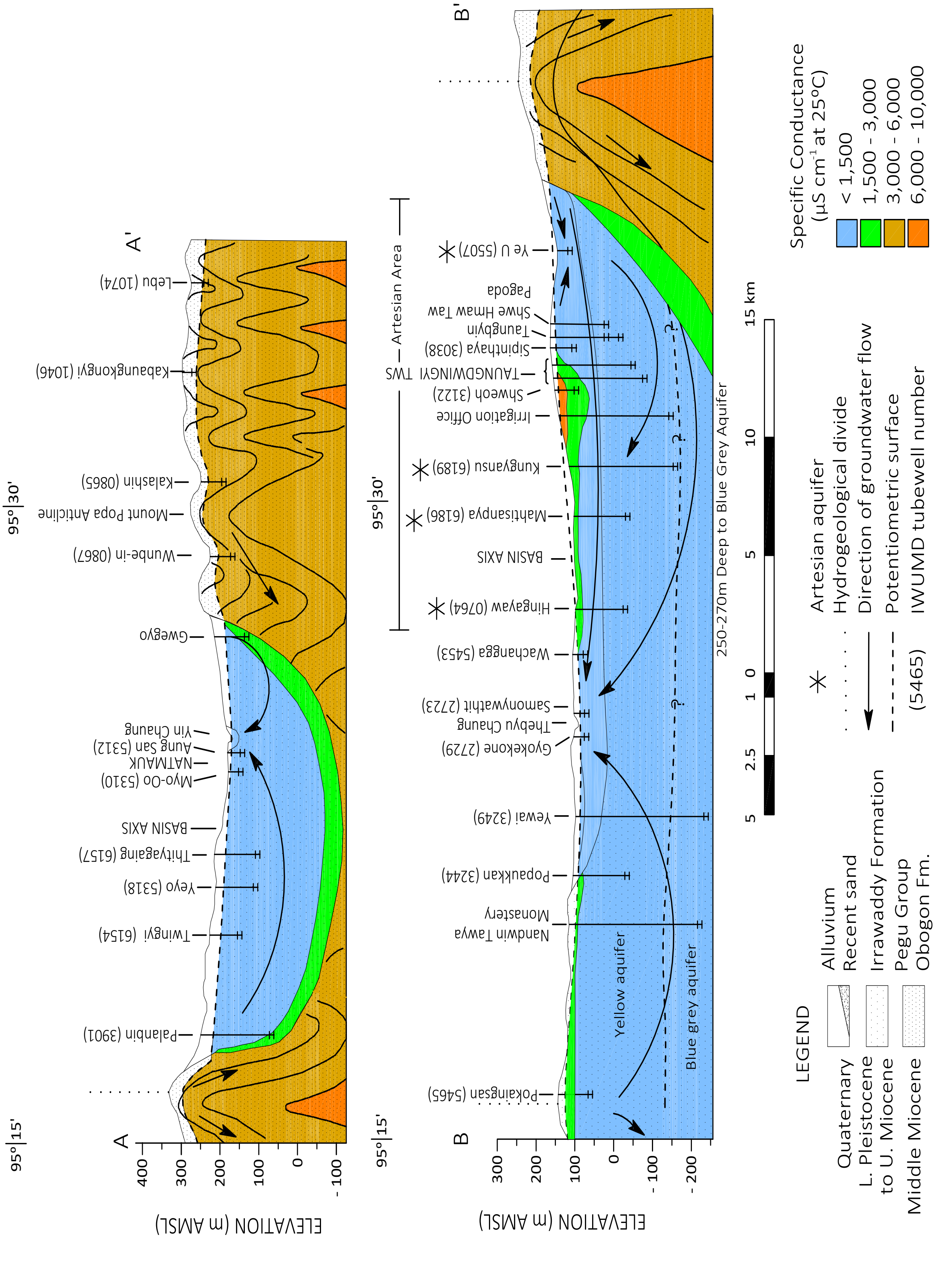


Figure 20 Schematic Hydrogeological and Hydrochemistry Map: Taungdwingyi Sub-basin



NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occur

Figure 21 Hydrogeological Cross Section and Specific Conductance: Taungdwingyi Sub-basin



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Photo 24: Exit of Yin Chaung from Sub-basin – Dry Season 2017

Photo 25: Low Flow DTW- Lat Pan Kwae Village. 2016

Historically the Pegu Group rocks of the Bago Yoma have been considered poor aquifers, in terms of both quality and quantity. Overall brackish to salty groundwater occurs in the synclinal structures which have low hydraulic characteristics. Groundwater is confined to joint and fracture systems within the various rock types.

North and northeast of Natmauk tubewells have intersected groundwater in fractured, semi-confined aquifers. The depth to aquifer varies from 25 to 140 metres, being dependent on topography and fracture location. Potential tubewell yield usually varies from 0.1 to 3 L/sec. Thayetchin Village is located on the flank of an unnamed syncline. This tubewell has a potential groundwater yield of 5 L/sec from fractured rock intersected at 92 to 101 metres. Nearby, deeper tubewells have only encountered smaller water supplies. The potentiometric surface is generally 10 to 20 metres below the surface during the dry period with a seasonal water level fluctuation of up to six metres.

The dominant chemical type of the Bago Yoma aquifers is $Na^+:Cl^-$. Sulphate rich water occurs in shallow aquifers along major anticlinal structures. Specific conductance ranges from 2,140 to 9,200 $\mu S.cm^{-1}$. Chemical analysis from a shallow tubewell in Kalashin Village, east of Natmauk indicates that the $Na^+:Cl^-$ type groundwater is brackish (3,690 $\mu S.cm^{-1}$), has high alkalinity (pH 10) and elevated sulphate content[76].

Low yielding, confined aquifers are intersected in fractured shale and fine sandstone on the Yedwet Anticline at depths of 150 to 240 metres. The potentiometric surface is 120 to 180 metres, depending on topographic relief. The specific conductance of groundwater ranges from 3,000 to 7,000 $\mu S.cm^{-1}$, the dominant chemical constituents being $Na^+:Cl^-$ and $Ca^{2+}:SO_4^{2-}$. Low salinity groundwater supplies are available from shallow dugwells constructed in the weathered zones. They usually dry up or become saline during January to May.

Groundwater movement from the Bago Yoma is west and southwest towards Yin Chaung. The Yedwet Anticline forms a hydraulic barrier boundary to the Sub-basin with groundwater movement west to the Ayeyarwady River. Recharge is by direct rainfall into the exposed weathered fracture systems.

8.3 Irrawaddy Formation

Based on colour the Irrawaddy Formation can be divided into two geological units[77]:

- Upper horizon- yellow / brown clay and fine to coarse sand
- western area- 75 to 270 metres thick; and
- eastern area- less than 300 metres.

[76] Tin Nyi Nyi Win (2013)
[77] Tin Linn et. al. (1988)

- Lower horizon- bluish sandy clay with minor medium to coarse sand
  - western area – 270 to greater than 400 metres thick; and
  - eastern area – below 300 metres.

The deeper sediments are located along the synclinal basin axis south of Myothit- mainly beneath and west of Taungdwingyi Town.

The Irrawaddy Formation consists of fluviatile, fine to medium quartzose and lithic (mainly feldspar and mica) sand, conglomerate, grit, clay and shale. Thick yellow and deep blue clay aquitards overlie the thin aquifers. The sand and clayey sand aquifers usually account for 10 to 20 percent of the lithological sequence. The aquifers are weakly consolidated with ferruginous, calcareous and argillaceous cement. Siliceous, calcareous and iron oxide concretions and fossil wood are abundant.

In the Natmauk and Myothit townships there is no record on groundwater discharge, potentiometric behaviour, long term pump-out tests or hydraulic parameters. In Taungdwingyi Township some drawdown and discharge data and pump-out tests are available, thus transmissivity can be estimated.

8.3.1 Northern Areas

North and northeast of Natmauk the semi-confined aquifers occur as a synclinal inlier within the Bago Anticlinorium. This area has partially been inundated by the Kandaw Dam. Aquifers are generally intersected within 160 metres (210 m AMSL) with yields invariably less than 5 L/sec. Depth to the potentiometric surface ranges from 12 to 50 metres, mainly being a function of surface topography. Brackish to saline groundwater is Na^+:Cl^- type.

On the alluvial flats, the Gwegyo Village tubewell intersected brackish water (2,650 µS.cm^{-1}) with high hardness (860 mg/L) and elevated calcium (574 mg/L) content.

In the elevated flanks of the Yedwet Anticline, the depth to aquifer is consistently 140 to 200 metres with the potentiometric surface at 75 to 120 metres. Most yields of the Na^+:HCO_3^- type, low salinity groundwater are below 5 L/sec. At Gwechaung Village the tubewell has a potential groundwater yield of 10 L/sec. The chemical type and low salinity is a marked contrast to that in neighbouring Peguan aquifers.

Natmauk Town Water Supply

No reticulated municipal water supply.

Source: Hundreds of small diameter private tubewells screened in both Alluvium (< 20 metres) and Irrawaddy Formation aquifers. Groundwater yield varies from 0.5 to 5 L/sec.

Town Water Demand:

Assuming a population of 18,818 (Census 2014) and water consumption of 130 L/d/p, the town water supply demand is 2.5 ML/day.

8.3.2 Central to Southern Areas

Between Taungdwingyi Town and Yin Chaung, tubewells intersect multiple yellow brown, semi-confined aquifers. Blue grey sands are encountered deeper at 270 metres, some exceeding 350 metres. At Kokkogwa Village the blue grey aquifer is 36 metres thick. Specific conductance of the Na^+:HCO_3^- water varies from 700 to 1,150 µS.cm^{-1}.

Nandwin Tawya Monastery (Depth: 350 m): November 2016
Specific Conductance: 860 µS.cm^{-1}, Total Dissolved Salts: 610 mg/L, pH: 8.3, Temperature: 38.5° C.

A recent completed tubewell in Taungbyin (2) Ward, Taungdwingyi intersected clayey Alluvium to 75 metres then yellow/brown clay with minor silty sand lenses (124 to 132, 165 to 175 metres) (see **Photo 26)**. The main lithology was clay and silt.

Photo 26: Taungbyin (2) Ward, Taungdwingyi. Yellow/Brown Clayey/Silty Sand Aquifer (165-175 m), Nov 2016

Artesian conditions occur west of Taungdwingyi over synclinal axis. The eastern area partially overlaps the Alluvium artesian zone. Groundwater flow is small, the maximum discharge being 1.5 L/sec at Hingayaw Village. Initial artesian pressures have not been recorded. Due to continuous, uncontrolled flow groundwater discharge and pressure has reduced over time. For example, since 2005 the flow from the Lan Pan Kwae Village tubewell (230 metres) has decreased from 1 to 0.05 L/sec with increased salinity. The specific conductance of the $Na^+:HCO_3^-$ type water is less than 1,500 µS.cm^{-1}. Groundwater from deep aquifers is quite warm (>35° C).

Lan Pan Kwae: November 2016
Specific Conductance: 1,150 µS.cm^{-1}, Total Dissolved Salts: 825 mg/L, pH: 8.6, Temperature: 39.3º C.

Larger artesian flows may be encountered if appropriately designed and constructed tubewells are sunk into the deep blue grey aquifers in the centre of the synclinal trough. Maintenance of artesian pressure by regulating groundwater flow is an important water management issue that is currently absent.

There is a general trend for brackish water (greater than 2,500 µS.cm^{-1}) to be in the yellow brown aquifers and better quality (< 1,000 µS.cm^{-1}) closer to Yin Chaung and in the deep, blue sand aquifers. For example, a dugwell (30 metres) and the deeper tubewell (305 to 314 metres) at Kokkogwa Village have specific conductances of 6,700 and 700 µS.cm^{-1} respectively.

A few pump-out tests have been carried out:

- yellow/brown aquifer
- transmissivity (6 to 75 m^2/day);
- average hydraulic conductivity (2.5 m/day).
- blue/grey silty fine to medium sand aquifer
- transmissivity (9 to 750 m^2/day);
- average hydraulic conductivity (21 m/day).

Some of the aquifers west of Taungdwingyi have moderate transmissivity values but provide high potential tubewell yield due to their large available water level drawdown. Some clean sand and gravel aquifers have high transmissivity values (for example, 750 m^2/day at Inywagyi Village). These aquifers close to Yin Chaung offer a potential groundwater yield from large diameter tubewells greater than 50 L/sec.

Taungdwingyi Town Water Supply

Operator: Taungdwingyi Township Development Committee.

Source: Nine JICA constructed tubewells (eight constructed in 1980s and one in 2016) supply 2.4 ML/day.

Depth ranges from 180 to 240 metres in yellow Irrawaddy Formation.

JICA anticipates a yield of 0.9 ML/day from the new tubewell. Total TWS supply is thus 3.3 ML/day.

The tubewells are located throughout the northern to central part of town, most close to Yadana Pwint Lake.

JICA (2016) suggests aquifer recharge is from this surface water body.

The slightly alkaline groundwater (pH 8.3 to 9.0) has TDS of 766 to 932 mg/L and hardness of 50 to 220 mg/L.

Other: Within Taungdwingyi Town there are 1,100 private DTW supplying 2.3 ML/day.

Town Water Demand:
Assuming a population of 43,023 (Census 2014) and water consumption of 130 L/d/p, the town water supply demand is 5.6 ML/day. The current mix of government and private tubewells can achieve the town's requirements.

To the south of Taungdwingyi low salinity Na+:HCO_3^- type groundwater is intersected 100 to 230 metres below the surface. These aquifers have a transmissivity range of 10 to 100 m^2/day. At the villages of Kangyigon, Thetkegyin, Yedwinggaung and Nyaungbingwin the tubewells have a potential yield greater than 20 L/sec.

Recharge to the aquifers is primarily by surface runoff from the Bago Yoma, direct infiltration of rainfall and surface water from the sandy chaungs during the Wet Season and permanent waterbodies (such as Yadana Pwint Lake).

Under a moderately steep hydraulic gradient groundwater movement is towards the basin centre with discharge directed towards Yin Chaung, the overlying alluvial sediment in the central valley and locally to the flowing tubewells.

Tritium analyses on five groundwater samples from the Irrawaddy Formation indicate that the water is pre-thermonuclear.

Photo 27: Drill Site, Taungbyin (2) Ward, Taungdwingyi Town

Photo 28: Taungdwingyi TWS Tubewell, Irrawaddy Formation

8.4 Alluvium

Due to the weathered nature and yellow colour of the shallow Irrawaddy Formation it is difficult to distinguish the contact zone with the overlying Recent Alluvium without palynological examination. An arbitrary depth of 75 metres is set as the boundary; this being based on similar depths in other nearby intermountain basins.

The Alluvium consists of:

- Younger Alluvium – three to 10 metres thick. Aquifers consist of sand, minor gravel; and
- Older Alluvium – < 75 metres thick. Aquifers consist of clayey sand and gravel.

In the central valley between Natmauk and Myothit the aquifers are shallow (10 to 50 metres) and water table close to the surface. Tubewell yields are generally below 5 L/sec. However, several tubewells near Natmauk (Aung San Village) have potential groundwater yields more than 10 L/sec. The specific conductance of the Na^+:HCO_3^- type water is less than 1,000 µS.cm^{-1}.

Shallow dugwells are constructed in unconsolidated sand beds close to Yin Chaung and associated tributaries to obtain reliable, low salinity domestic water supplies. The water table in the semi-unconfined aquifers varies from five to eight metres, with an annual fluctuation of 1.5 to five metres. High salinity groundwater is tapped by shallow dugwells away from the watercourses towards the Sub-basin boundaries.

Deeper alluvial sediments are intersected by tubewells from Myothit to south of Taungdwingyi. Some permeable, unconsolidated sand aquifers, less than 60 metres deep are located along Ngamin, Seikpu and Yabe chaungs. Transmissivity ranges from 45 to 200 m^2/day. Potential yields of low salinity water near chaungs may exceed 10 L/sec (for example Tamarbin and Sarde villages). Some farmers use solar powered pumps to extract 6 L/sec from shallow alluvial sand aquifers for irrigation purposes.

The specific conductance of deeper alluvial sediments ranges from 250 to 1,800 µS.cm^{-1}, the average being 1,000 µS.cm^{-1}.

In most parts of the Taungdwingyi Town, potential groundwater yields are below 5 L/sec. Water from deeper alluvial aquifers is of lower salinity. For example, a dugwell and a tubewell in Alluvium under Shwebo Quarter, Taungdwingyi have specific conductance of 5,138 and 2,450 µS.cm^{-1} respectively. Na^+:Cl^- are the major ions in the dugwell and Na^+:HCO_3^- in the tubewell.

Artesian flow from alluvial aquifers is encountered under Taungdwingyi at depths of 40 to 75 metres. Maximum natural groundwater discharge is 1.5 L/sec, the average being 0.7 L/sec. The specific conductance varies from 480 to 2,540 µS.cm^{-1}. The trend is for groundwater yield to decrease and salinity to increase towards the west.

Groundwater recharge into the Alluvium occurs by infiltration from sandy and gravelly, intermittently flowing chaungs; directly from precipitation and from the underlying Irrawaddy Formation.

Groundwater discharge from the Taungdwingyi Sub-basin only occurs as baseflow in Yin Chaung and westerly flowing throughflow in the underlying Alluvium and Irrawaddy Formation

8.5 Areas of High Groundwater Yield and Low Salinity

Potential high yield and low salinity aquifers are concentrated along the synclinal axis of the Sub-basin **(Figure 20)**. These include:

- shallow Alluvium along the perennial Yin Chaung and intermittently flowing tributaries through spearpoint batteries or collector well systems;
- lower sections of the yellow sand of the Irrawaddy Formation; and
- the deep blue sand and gravel of the Irrawaddy Formation along the Sub-basin axis. Large diameter, deep, screened and gravel packed pumping bores would be required.

8.6 Water Balance Annual Recharge Estimation

Future Research:

A water balance model for the Taungdwingyi Sub-basin was developed but not successfully completed. The large rainfall recharge (assumed 10 to 15 percent) through the extensive exposure of Alluvium and Irrawaddy Formation could not be balanced with known groundwater extraction and end of Dry Season baseflow measurements. Groundwater needs to exit the sub-basin either through either discharge to Yin Chaung or underflow through the Alluvium and Irrawaddy Formation at the narrow western exit point.

9 Hydrogeology of the Pakokku District

9.1 Introduction

The Pakokku area is geologically complex. It is situated in the upper part of the Minbu Basin towards the 22° N Uplift. Regional structures include the Kabet-Shinmataung Anticline, Shinmataung Fault, Pakokku Syncline, Myaing and Letpanto anticlinal complexes, Medin Fault, Myaing-Kyaukpadaung and Bahin-Pagan structural lines, Yenangyat Anticline and Yenangyat Thrust Fault. The axis of the Salin Syncline is to the west of the features shown on **Figures 22** to **Figure 24**.

The Eocene to Mid Miocene rocks of Myaing, Letpanto and Yenangyat are highly fractured. They appear as tight, ripple-like, elongated, symmetrical folds segmented by transverse faults. Major gas and oil fields occur in the Yenangyat and Letpanto areas.

The easterly dipping rocks of the Shinmataung Range also are highly faulted.

A few geological or hydrogeological reports have been written specifically on the Pakokku area[78]. Typical aquifer details in various rocks and geographical locations are given in **Table 26**.

9.2 Eocene Rocks

The Eocene rocks crop out along the Myaing and Letpanto anticlinal complexes and along part of the Shinmataung Range. They consist of massive fossiliferous sandstone and marine bluish/black shale of the Pondaung and Yaw formations.

Successful village water supply tubewells, intersecting semi-confined aquifers are located north of Letpanto to Myaing. These are located on both highly elevated plateaus and near the base of the escarpment slope. The depths to aquifers range from 41 to 93 metres, the higher elevated tubewells generally, although not consistently, being the deepest. On the hills, the depth to aquifer varies from 284 to 256 m AMSL, whilst along the escarpment base it ranges from 222 to 207 m AMSL. The depth of the potentiometric surface reflects the topographic elevation of the intersected aquifer. In the Letpanto area the water level varies between 310 to 293 m AMSL. The main direction of groundwater movement is north and northeast from recharge in the elevated plateau to discharge under the alluvial plain. Many abandoned tubewells also exist in the same area.

Transmissivity is low ranging from 3 to 30 m^2/day. Only a few of the deeper aquifers at Gokekon and Tanaunggon villages have a potential tubewell yield of 6 L/sec. Most tubewells yield less than 1 L/sec.

The tubewells on the plateau are in a hydrocarbon rich area. At Sinzwe, Gokekon and Tanaunggon villages the presence of methane gas is reported. High salinity occurs in some aquifers. For example, the specific conductance at Thinma and Nyaunggon villages is 8,000 and 12,530 $\mu S.cm^{-1}$. The main dissolved ions are

[78] United Nations (1978), Tin Shwe et. al. (1979), Tahal (Water Planning) Ltd (1963), UNICEF (1980), Aung Myint (1983), Wan Maung et. al. (1984), Aung Myint et. al. (1986), JICA (1985), Ko Ko Gyi (2012)

Photo 29: Pauk Khaung Village TW, Lepanto, Eocene Aquifer

Photo 30: Pondaung Sandstone Dipping South and Chaung

Na^+:Cl^- and Na^+:SO_4^{2}. The high salinity is probably due to the presence of brine associated with oil/gas accumulation and large deposits of gypsum observed along fractures within the anticlinal cores. Salinity decreases away from the structurally complex hydrocarbon areas as the fractured aquifers are recharged from rainfall and surface water runoff.

In marked contrast, lower salinity groundwater (740 to 2,000 µS.cm^{-1}) occurs in fractured Pondaung Sandstone lenses at Pauk Khaung and Wedaung villages respectively. In both cases upgradient intermittent watercourses traverse the Pondaung Sandstone outcrop which dips towards the villages. Other areas of low salinity within this overall saline environment may occur. In siting such tubewells consideration of geological structure, rock type, surface drainage systems and depth need to be considered.

Pauk Khaung Village: May 2017, Depth: 101- 114, 155 – 165 m
Specific Conductance: 740 µS.cm^{-1}, Total Dissolved Salts: 480 mg/L, pH: 8.3.

Eocene rocks are intersected along the Medin Fault at a depth less than 200 metres. Transmissivities up to 85 m^2/day are recorded with a potential groundwater yield of 8 L/sec. This is the highest recorded Eocene transmissivity in the Pakokku area and reflects the good groundwater yielding potential of fractured aquifer systems associated with major fault zones. The average groundwater salinity is 3,400 µS.cm^{-1}.

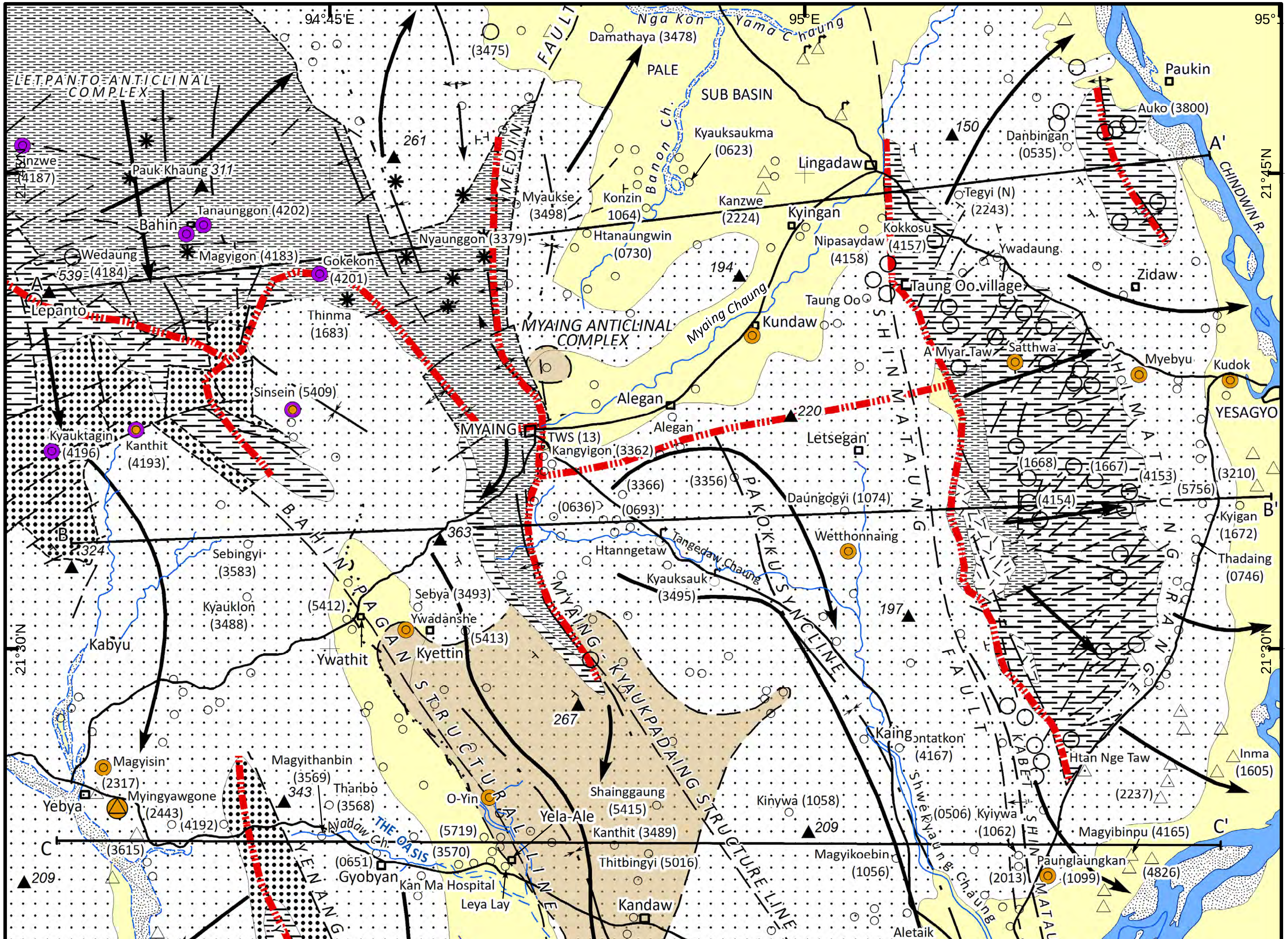
There is no tubewell data available in the Eocene rocks along the mid-western periphery of the Shinmataung Range.

9.3 Pegu Group

The Oligocene age Shwezetaw, Padaung and Okhmintaung formations are exposed in the Letpanto to Myaing area whilst the upper two formations crop out along the Yenangyat Anticline and Shinmataung Range. North of Yesagyo, the Oligocene age Pegu Group is superficially covered by Alluvium. The complete sequence of Lower to Middle Miocene rocks is exposed along the anticlinal flanks of the Yenangyat Anticline and south of Letpanto.

Aquifers in Pegu Group rocks of the easterly dipping Shinmataung Range usually provide high salinity and low yields. The specific conductance of the predominantly Na^+:Cl^- type water ranges from 1,100 to 10,100 µS.cm^{-1}, the average being 6,000 µS.cm^{-1}. The areal spread of salinity is erratic and appears confined to disjointed faulted blocks. The lowest salinity at A Nyar Taw Village (1,100 µS.cm^{-1}) is sited in a fault adjacent to an intermittent watercourse. Within the village old tubewells away from the fault have salinities up to 8,400 µS.cm^{-1}. Consideration of structural geology is critical to siting successful tubewells in the Pegu Group rocks.

Figure 22 Schematic Geological and Hydrogeology Map: Pakokku



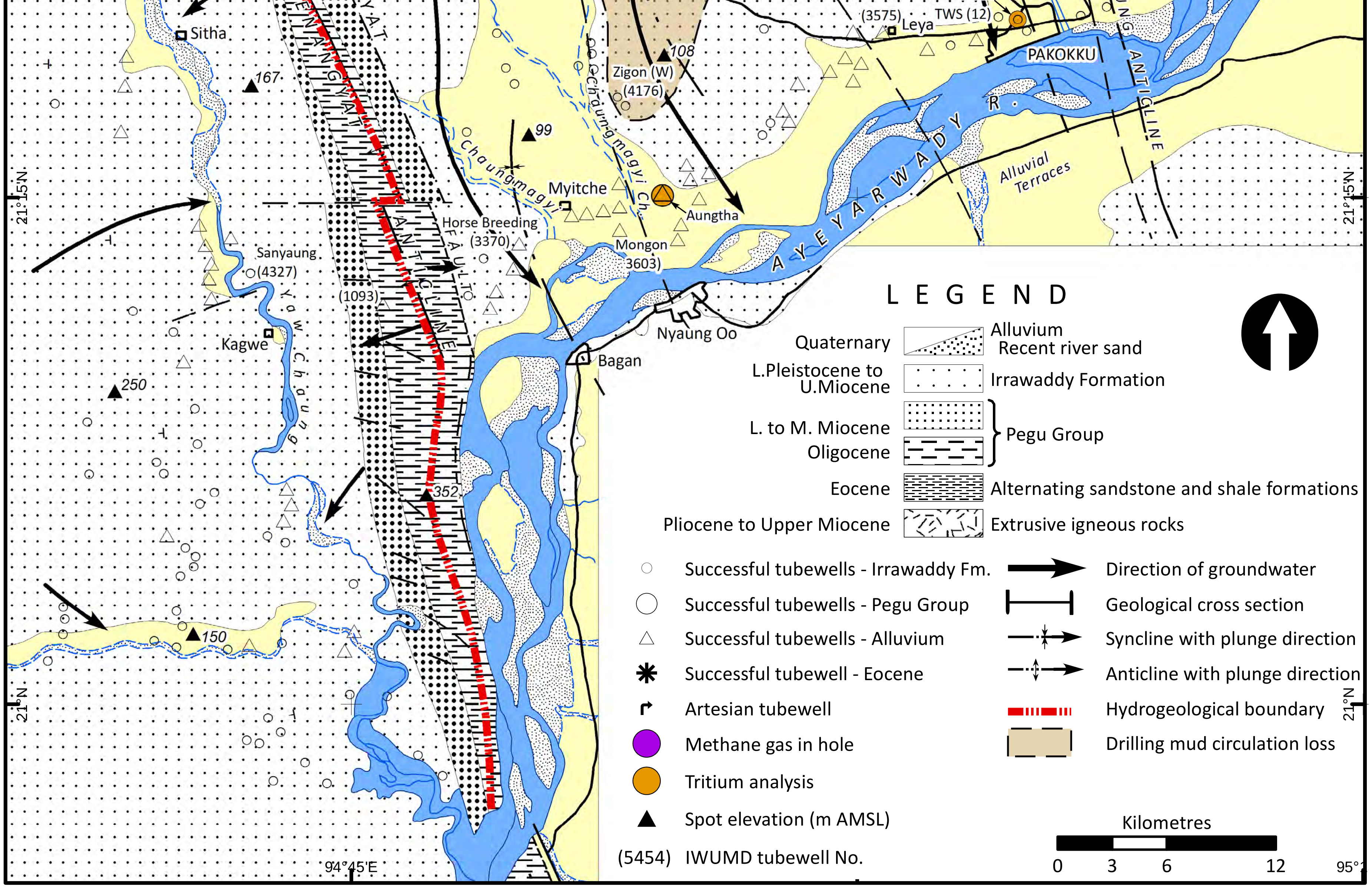
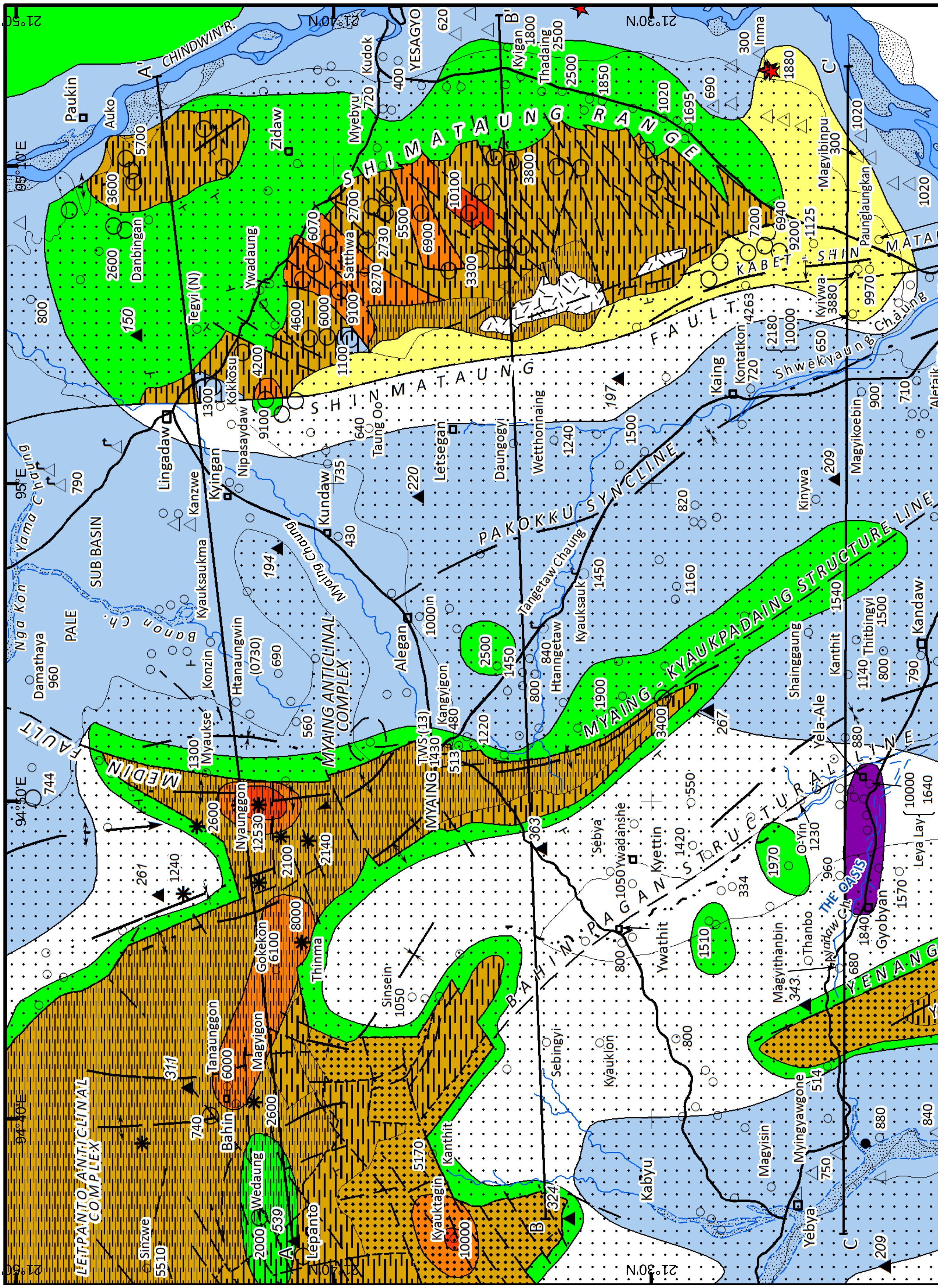
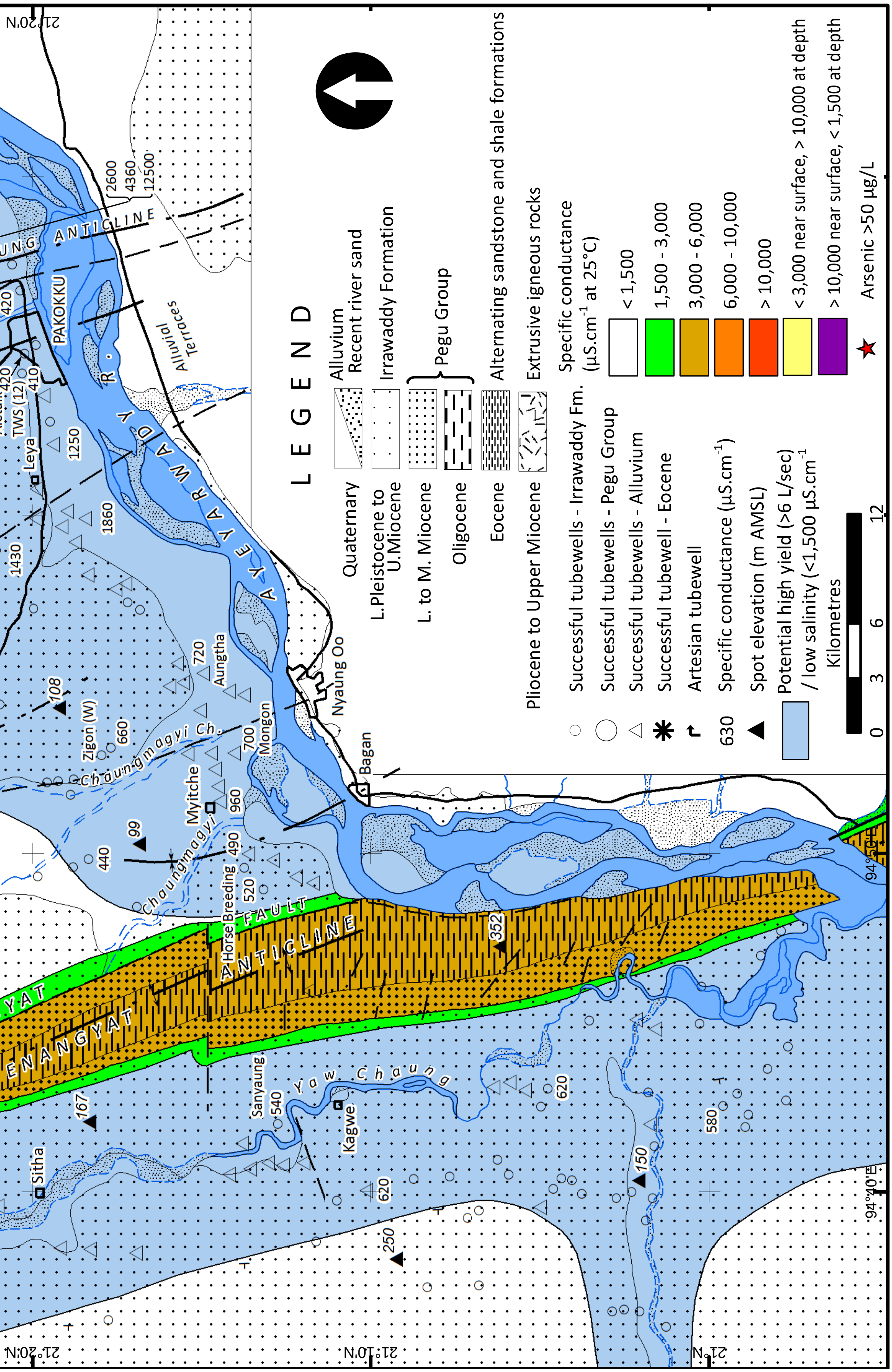

LEGEND
Quaternary
Alluvium
Recent river sand
L.Pleistocene to U.Miocene
Irrawaddy Formation
L. to M. Miocene
Oligocene
Pegu Group
Eocene
Alternating sandstone and shale formations
Pliocene to Upper Miocene
Extrusive igneous rocks
Successful tubewells - Irrawaddy Fm.
Successful tubewells - Pegu Group
Successful tubewells - Alluvium
Successful tubewell - Eocene
Artesian tubewell
Methane gas in hole
Tritium analysis
Spot elevation (m AMSL)
(5454) IWUMD tubewell No.
Direction of groundwater
Geological cross section
Syncline with plunge direction
Anticline with plunge direction
Hydrogeological boundary
Drilling mud circulation loss
Kilometres
0 3 6 12
PAKOKKU
Leya
TWS (12)
(3575)
Zigon (W)
(4176)
108
99
167
250
150
352
Sitha
Myitche
Aungtha
Mongon
3603)
Horse Breeding
(3370)
Sanyaung
(4327)
(1093)
Kagwe
Nyaung Oo
Bagan
AYEYARWADY R.
Alluvial Terraces
Chaungmagyi Ch.
Yaw Chaung
ANTICLINE
FAULT
21°15'N
21°N
94°45'E
95°

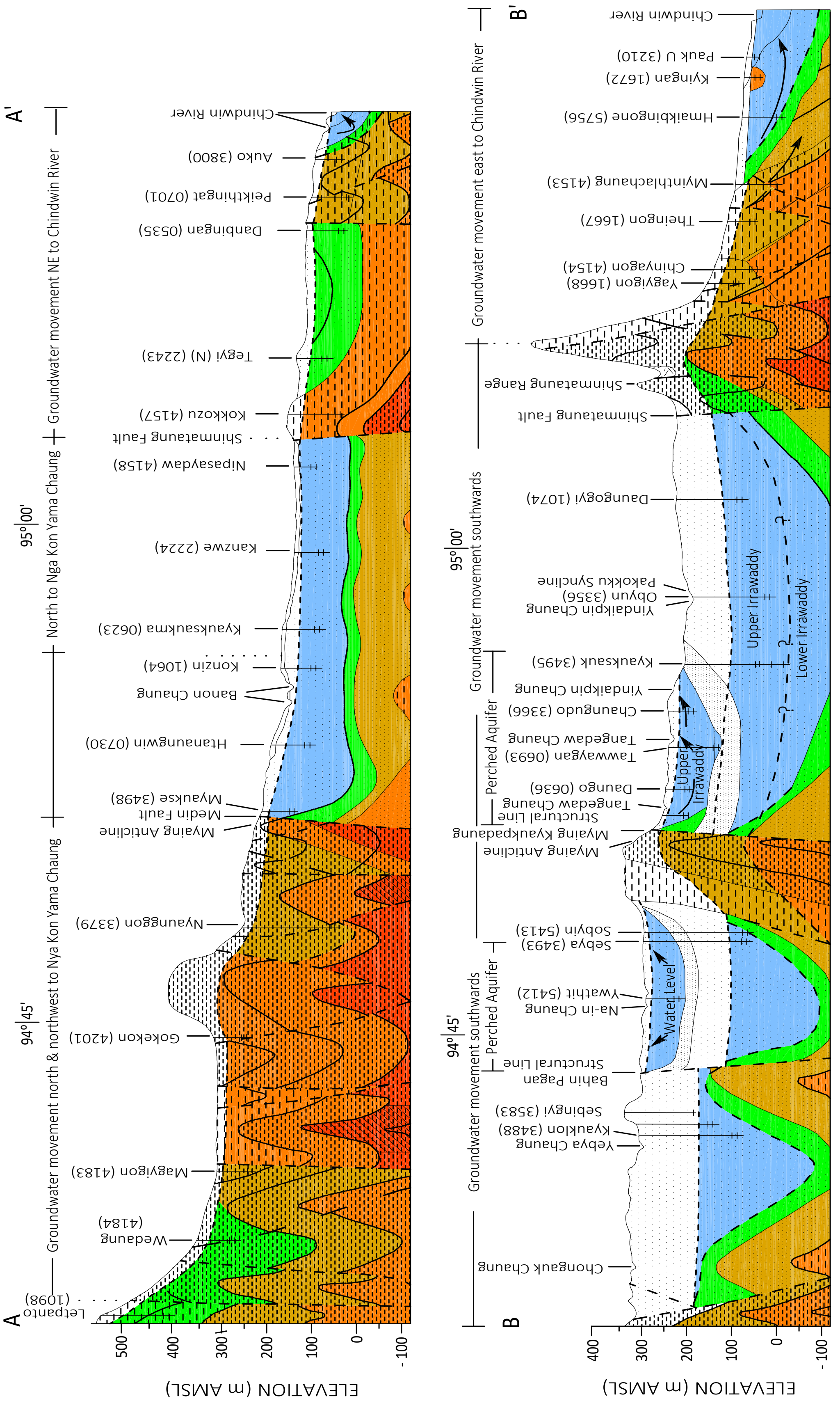
Figure 23 Schematic Hydrogeological and Hydrochemical Map: Pakokku





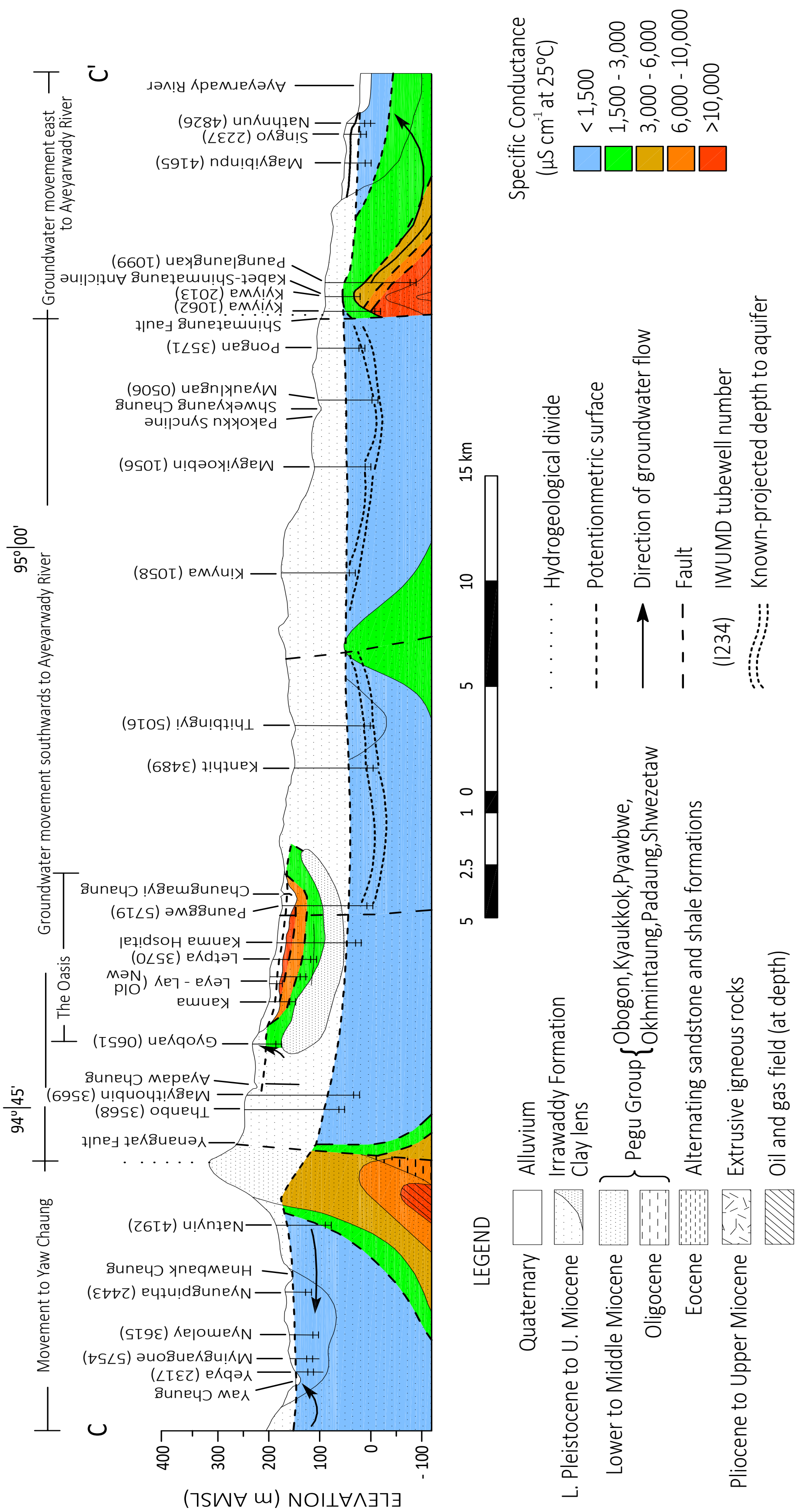
NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occur

Figure 24 Hydrogeological Cross Section and Specific Conductance: Pakokku



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Figure 24 (continued) Hydrogeological Cross Section and Specific Conductance: Pakokku



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Table 26 Aquifer Details from Various Rock Types in the Pakokku Area

Formation	Area	Village	Tubewell number	Surface Elevation (m AMSL)	All data from surface (m)				DD (m)	Airlift Yield (L/sec)	Transmissivity (m²/d)	Specific Conductivity (µS.cm⁻¹)
					Depth	Aquifer	SWL	DDL				
Eocene	Letpanto	Pauk Khaung			180	100-115 155-165	90	100	10	0.1	< 1	740[79]
Pegu/Irrawaddy	Shinmataung Anticline	Kyiywa Htan Nge Taw	1062	+ 86 + 90	92 146	83-91 27-37	32 22	36	4	7 3	246	13,000 6,940
Irrawaddy Formation	Myitche	Horse breeding Myit Chay Aing Gyi	3370	+ 61 + 60 + 58	58 43 40	17-55 38-41 35-38	12 9 5	15 13 12	3 4 7	13 7 9	514 240 180	520
	Chaungmagyi Chaung	Zigon West	4176	+ 102	104	82-101	44	48	4	6	179	660
	Pale Sub-basin	Damathaya (see Ch. 10)	3478	+ 138	202	174-195	24	31	7	9	179	900
	Pakokku Syncline	Kangyigon Kontatkon GTC station Industrial Zone	3362 4167	+ 128 + 122 + 135 + 120	95 128 91 79	62-92 101-125 55-61 64-70	13 56 26 23	16 59 29	3 3 6	13 5 8	513 206 200	480 720 680 820
	Bahin-Pagan	Shainggaung Ta Naung	5415	+ 205 + 210	198 50	177-186 38-41	122 19	129	7	6	107	1,500 1,200
	High Plateau	Sinsein	5409	+ 305	70	57-66	20	23	3	10	597	1,050
	Shinmataung Range	Thadaing Htan Nge Taw	0746	+ 76 + 90	36 146	32-35 28-36	8 22	11	3	6	239	2,500 6,940
	W. Fault Shinmataung	Taung Oo Kyauksauk		+ 145 + 150	135	75-90 101-110 60-66 91-105	20 18	 20	 2	5 3	 200	640 1,200
Alluvium	South Pakokku	Leya Mongon	3575 3603	+ 73 + 61	62 47	41-57 29-37	9 9	14 11	5 2	6 3	172 206	1,250 700
	North Pakokku	Magyibinpu Inma	4165 1605	+ 61 + 55	52 31	39-46 21-27	4 8	8 1	4 1	8 4	258 770	510 300
	Yaw Chaung	Sanyaun	4327	+ 173	40	24-34	6	7	1	4	606	540

Source: IWUMD database.

[79] Intermittent chaung recharge into Pondaung Sandstone

A Nyar Taw Village: May 2017, Depth: 107- 116, 122 – 128 m
Specific Conductance: 1,100 µS.cm^{-1}, Total Dissolved Salts: 720 mg/L, pH: 7.4.

The general trend is for salinity to increase with depth, but this is not always the case. The depth to aquifers is highly variable ranging from 24 to 214 metres. The potentiometric surface is located 7 to 28 metres below the surface in conformity with the topography. Some aquifers appear to be interconnected whilst others are likely to be isolated between fault blocks. Tritium analysis of groundwater from an aquifer at Satthwa Village indicates pre-thermonuclear water. The aquifers above 45 metres are clayey and yield below 5 L/sec; the majority less than 0.5 L/sec. Once the unweathered fracture zone is intersected the potential yield may exceed 10 L/sec. Transmissivity in the deeper aquifers ranges from 15 to 65 m^2/day, the average being about 35 m^2/day. Groundwater recharge occurs by rainfall onto the exposed fracture systems along the Shinmataung Range. Groundwater movement is east towards the Chindwin River and southeast towards the Ayeyarwady River.

Immediately south of the Shinmataung Range and east of the Shinmataung Fault and Kabet-Shinmataung Anticline, aquifers in fractured Pegu Group rocks are intersected beneath a thin cover of Irrawaddy Formation. Here multiple aquifer systems are encountered between 17 to 140 metres. The potentiometric surface in the shallow aquifer is 5 to 30 metres whilst the water levels in the deeper zones range between 34 to 69 metres. These aquifers have poor hydraulic interconnection. The fractured, semi-confined to confined aquifers contain weathered zones and yields are less than 5 L/sec. Transmissivity ranges from four to 30 m^2/day. The salinity of the Na+: Cl$^-$ type groundwater ranges from 5,000 µS.cm^{-1} in the shallow aquifers to more than 10,000 µS.cm^{-1} at depth.

West of the Shinmataung Fault the Pegu Group rocks are down-faulted and not encountered for at least 180 metres.

Northeast of the Shinmataung Range several tubewells intersect aquifers of the Pegu Group after passing through a superficial alluvial or Irrawaddy Formation cover. The depth to the fractured aquifer system is highly variable (17 to 100 metres) with tubewell yield below 5 L/sec. Transmissivity ranges from 10 to 30 m^2/day and the specific conductance from 1,300 to 5,700 µS.cm^{-1}.

Peguan aquifers are also intersected within the Letpanto oilfield at depths of 86 to 107 metres. Methane gas is frequently reported. The potentiometric surface in these low yielding aquifers slopes sharply to the south. The salinity of the Na^+:Cl^- and Na^+:SO_4^{2-} type groundwater at Kyauktagin Village exceeds 10,000 µS.cm^{-1}. The salinity and chemical characteristics of this water possibly result from a mixture of brine water (in association with the hydrocarbons) and the high solubility of the abundant gypsum deposits located within the fracture systems.

No successful groundwater tubewell is documented along the Yenangyat Anticline.

9.4 Irrawaddy Formation

Rocks of the Irrawaddy Formation consist of fine to medium-grained, poorly argillaceous cemented sand, conglomerate, gravel, shale, clay, fossil wood and lignite. These intermountain sediments are aligned along the orientation of the major regional features. In some areas, sediments of both the Upper and Lower Irrawaddy units can be identified. Both yellow brown and blue grey aquifers are present.

Groundwater movement and yield is strongly controlled by the regional geological structures and lithology within which they are associated. The depth to aquifers closely conforms to the associated tectonic structural features. Once these major structures are identified, confident prediction on depth, quality and yield should be possible.

Shallow perched aquifers (**Figure 24**) are located:

- south of Myaing along the upper catchment of Tangedaw Chaung;
- between Yela-Ale to Gyobyan villages- locally known as 'The Oasis'; and
- southwest of Ywathit.

The latter two are located within a broad synclinal area between the Bahin-Pagan Structural Line and the Yenangyat Anticline. Other small perched aquifer systems may be present. Most perched aquifers are of limited extent. They may be useful for shallow domestic water supplies, if the salinity is of acceptable quality.

Figure 22 indicates the hydrogeological boundaries and direction of groundwater movement. The location of the subsurface groundwater divide separating the Pale Sub-basin from the Pakokku Syncline passes near Kangyigon and Alegan villages to the east of Myaing.

9.4.1 Pakokku Syncline

Groundwater movement in aquifers within the Pakokku Syncline is mainly south towards the Ayeyarwady River; being bounded to the west by the Medin Fault and east by the Shinmataung Fault and the Kabet-Shinmataung Anticline. Due to the latter two tectonic structures, no groundwater movement occurs to the east towards the Ayeyarwady and Chindwin rivers.

To the west of the Shinmataung Fault, yellow clay and sand occurs to 200 metres and then blue grey sands and clay to at least 400 metres. Aquifers occupy 20 to 25 percent of the sediment. Groundwater yields are usually 2 to 10 L/sec. The specific conductance of the Na^+:HCO_3^- water is usually less than 1,500 µS.cm^{-1}. There are a few exceptions in some shallow aquifers where salinity varies from 1,500 to 3,000 µS.cm^{-1}. Salinity increases around the flanks of the Pegu Group and Eocene rock outcrops. Groundwater recharge occurs along the sandy Tangedaw Chaung and associated watercourses. Movement is into either the highly permeable, perched aquifers or direct into the deeper aquifers of the Pakokku Syncline. Some artesian flowing tubewells occur in topographic depressions.

Photo 31: Lithological Variation in Kyauksauk Village TW, Irrawaddy Formation (41-46, 55-60, 142-146 m), Pakokku Syncline

Taung Oo Village presents an excellent interpretation of hydrogeological conditions in the Pakokku Syncline. Several saline tubewells are in the village on the western flank of the Shinmataung Range. The new tubewell was sited 1.5 kilometres west of the Shinmataung Fault and intersected high yield, low salinity groundwater at depths of 75 to 110 metres. The potable water is pumped via pipeline back to the village.

Kyauksauk Artesian Tubewell: November 2016
Specific Conductance: 1,430 µS.cm^{-1}, Total Dissolved Salts: 1,037 mg/L, pH: 7.2.

Htanngetaw Village Artesian Tubewell: November 2016
Specific Conductance: 1,450 µS.cm^{-1}, Total Dissolved Salts: 1,039 mg/L, pH: 7.2, Temperature 28.8° C.

Taung Oo Village: May 2017, Aquifer Depth: 75- 90, 101 – 110 metres
Specific Conductance: 640 µS.cm^{-1}, Total Dissolved Salts: 322 mg/L, pH: 8.1.

Pakokku Town Water Supply

Operator: The Pakokku Township Development Committee.

Source: 12 deep tubewells located throughout town.

Depths: varying from 73 to 138 metres in Alluvium and Irrawaddy Formation.

Groundwater Yield: 2.5 to 14 L/sec. pumping 2 to 15 hours/day.

Total Yield Capacity: 5.4 ML/day.

Potentiometric surface: 10 metres (alluvial flats) to 50 metres (on hills).

Summary of Water Quality: pH: 6.5 to 6.94, Electrical Conductivity: 571- 1,865 µS.cm^{-1}, TDS 411- 1,320 mg/L.

Other: Within Pakokku there are over 1,000 private DTW and hundreds of DW supplying 6.4 ML/day.

Town Water Demand: For a population of 90,842 (Census 2014) the town water demand is 11.8 ML/day, supplied by municipal and private sources.

Pakokku Town Water Supply: Su Gyi Pan Quarter: November 2016
Specific Conductance: 700 µS.cm^{-1}, Total Dissolved Salts: 501 mg/L, pH: 7.1, Temperature: 32.1° C.

Photo 32: Myaing TWS Tubewell No. 2, Irrawaddy Fm.

Photo 33: Collecting Water, New DTW, Taung Oo Village, Irrawaddy Fm.

Myaing Town Water Supply

Operator: The Myaing Township Development Committee operates eight DTWs and has recently completed five new DTWs (not yet equipped).

The water supply scheme was paid by municipal funds and parliamentary budget.

Sources: When complete, the water supply system will consist of 13 DTWs screened in Irrawaddy Formation aquifers. The DTWs are in the eastern part of town away from the Eocene rocks.

Groundwater yield and water levels are declining, thus the need for the additional DTWs along Myaing Chaung.

The yield is also restricted by available electric power supply.

Tubewell log (No. 2 Quarter) indicates a depth of 128 metres with screens at 66 to 70, 90 to 99, 108 to 114 metres.

Depth: 125 to 150 metres.

Groundwater Yield: 1 to 6 L/sec; average 2 L/sec. Each new production tubewells yields 4 L/sec.

Current Wet Season Yield: 8 DTWs x 2 L/sec x 10 hours/day = 0.58 ML/day.

Current Dry Season Yield: 8 DTWs x 2 L/sec x 24 hours/day = 1.4 ML/day (if power consistently available).

Potentiometric surface: 20 to 27 metres.

Groundwater salinity: varies from 1,146 to 1,881 $\mu S.cm^{-1}$. New DTW near Myaing Chaung is 513 to 627 $\mu S.cm^{-1}$.

Town Water Demand: The water demand for a population of 7,706 (Census 2014) is around 1 ML/day. Assuming a reliable electricity power supply and pumps installed in new holes the municipal water supply should achieve the town's requirements.

Myaing Town Water Supply, Tubewell No. 2 Quarter (in town): November 2016
Specific Conductance: 1,340 $\mu S.cm^{-1}$, Total Dissolved Salts: 975 mg/L, pH: 7.1, Temperature: 28.9° C.

Myaing Town Water Supply, Tubewell No. 1 Quarter (in town): November 2016
Specific Conductance: 1,400 $\mu S.cm^{-1}$, Total Dissolved Salts: 1,000 mg/L, pH: 6.9, Temperature: 29.1° C.

9.4.2 Southwest of Shinmataung Range

Near the southwestern extent of the Shinmataung Range several tubewells intersect highly saline aquifers. Salinity increases with depth. For example, at Kyiywa Village (TW Nos 2013 and 1062) aquifers were intersected with a specific conductance of 2,180 and 10,000 $\mu S.cm^{-1}$ at depths of 40 to 47 metres and 85 to 90 metres respectively. A recently abandoned tubewell in Htan Nge Taw Village intersected brackish groundwater (6,940 $\mu S.cm^{-1}$) at 25 metres. The dominant soluble ions change from Na^+:HCO_3^- in the shallow aquifers to Na^+:Cl^- with depth. A similar change in salinity occurs at Paunglaungkan Village where at depths of four to six, 27 to 31, and 76 to 79 metres, the specific conductance increases from 2,660, 4,360 to 12,500 $\mu S.cm^{-1}$ respectively. The two shallow aquifers contain Na^+:HCO_3^- type water whereas the deeper groundwater is Na^+:Cl^-. Drilling for potable water in this area should be avoided. The increase in salinity with depth is assumed to be saline groundwater drainage from Peguan aquifers within the Shinmataung Range.

Htan Nge Taw Village: May 2017, Depth: 25 – 40 m
Specific Conductance: 6,940 µS.cm^{-1}, Total Dissolved Salts: 4,510 mg/L, pH: 8.2.

9.4.3 Bahin-Pagan and Myaing-Kyaukpadaung Structural Lines

In the broad trough between the Bahin-Pagan and Myaing-Kyaukpadaung structural lines groundwater movement is SSE to south from the elevated Letpanto and Myaing areas towards the Ayeyarwady River. Low salinity, Na^+:HCO_3^- type groundwater is usually intersected, except near Pegu Group rock outcrops.

Along the road west from Pakokku the depth to the regional aquifer increases from 60 to 100 metres as surface topography rises. In the Oasis, the perched and regional aquifers have different aquifer depth, potentiometric surface, yield and salinity variations (**Table 27**).

Table 27 Features of Perched and Regional Aquifers – The Oasis Area, Pakokku

Village	Depth	Screen	SWL	Airlift Yield (L/sec)	Specific Conductance (µS.cm^{-1})	Status
	(m)					
Local Perched Irrawaddy Formation Aquifer						
Leya Lay (new)	76	70- 76	19	2	1,640	Operational
Leya Lay (old)	61	50- 55	18	1	10,000	Abandoned
Gyobyan	91	70- 79	19	3	1,840	Operational
Regional Irrawaddy Formation Aquifer						
Kan Ma Hospital	132	119- 125	49	6	1,570	Operational
Paunggwa	147	104- 110	61	4	770	Operational
Magyithanbin	214	207- 213	61	6	680	Operational

Source: IWUMD database.

The abandoned Leya Lay Village tubewell intersected Na^+:Cl^- type water at a depth less than 55 metres with specific conductance more than 10,000 µS.cm^{-1}. The replacement tubewell, with the shallow aquifer sealed off, intersected better quality water (1,640 µS.cm^{-1}) at greater depth. The Gyobyan Village tubewell intersected Na^+:HCO_3^- type water with a specific conductance of 1,840 µS.cm^{-1}. The reason for such a marked change in chemical character and salinity within the perched aquifer system has not been adequately investigated. Evapotranspiration and lithological variations may need to be considered. Throughout the Oasis area, tubewells deeper than 100 metres intersect the regional aquifer system with Na^+:HCO_3^- type water below 1,600 µS.cm^{-1}. During tubewell construction, the upper aquifers should be cement-sealed to prevent the movement of saline water into the tubewell. Groundwater recharge occurs along the sandy watercourses.

Leya Lay (new): November 2016
Specific Conductance: 1,640 µS.cm^{-1}, Total Dissolved Salts: 1,198 mg/L, pH: 7.9, Temperature: 23.6° C.

Kan Ma Hospital: November 2016
Specific Conductance: 1,570 µS.cm^{-1}, Total Dissolved Salts: 1,164 mg/L, pH:8.1, Temperature:23.6° C.

To the west of the Yenangyat Anticline low salinity water in the Irrawaddy Formation moves towards Yaw Chaung.

The Irrawaddy Formation in the Letpanto area is located overlying hydrocarbon rich Eocene to Mid Miocene rocks. Methane gas is observed in Kanthit and Sinsein tubewells at depths of 110 to 134 metres and 57 to 66 metres respectively.

9.4.4 Loss of Mud Circulation

Loss of drilling mud circulation during tubewell construction has been recorded in unsaturated yellow, coarse sediment. The problem areas are in the broad synclinal trough between the Bahin-Pagan and Myaing-Kyaukpadaung structural lines and a small part of the Pakokku Syncline. Depths to aquifer and potentiometric surface in most cases are greater than 150 and 90 metres respectively.

9.4.5 Tritium Dating

Tritium analyses taken from nine tubewells indicate that most of the groundwater is pre-thermonuclear. The exception is at Paunglaunkgan Village (TW No 1099) where the shallow, saline water appears to be a mixture of both Modern and older groundwater.

9.5 Alluvium

Alluvial deposits of Pleistocene to Recent age are located along the Ayeyarwady and Chindwin rivers, and Chaungmagyi, Nga Kon Yama and Yaw chaungs. These unconsolidated sediments consist of clay, silt, sand and gravel. Alluvial terraces consisting of gravel and sand are observed southwest of Pakokku near the village of Leya. A proliferation of private shallow and deep tubewells occurs along these alluvial flats and terraces.

Southwest of Pakokku, tubewells intersect semi-unconfined, yellow brown sand and gravel aquifers at depths of 14 to 72 metres. The water level varies from five to 12 metres. Low salinity $Na^+:HCO_3^-$ type groundwater is located within the shallow alluvial aquifers. With a transmissivity range of 50 to 420 m^2/day and specific conductance of 400 to 1,250 $\mu S.cm^{-1}$ some aquifers are relatively permeable and high groundwater yields of low salinity water should be available. Recharge to the shallow aquifer is from the sandy tributaries that traverse the alluvial flats. Groundwater movement is towards the Ayeyarwady River. Groundwater levels adjacent to the Ayeyarwady River fluctuate with the river height[80] due to direct hydraulic connection. During flood periods, a localised reversal in groundwater movement may occur.

Tritium analyses of shallow groundwater at Aletaik and Aungtha villages, indicate a pre-thermonuclear age. These villages are two and four kilometres from the Ayeyarwady River and appear to be recharged upgradient from Shwekyaung and Chaungmagyi chaungs respectively.

Northeast of Pakokku semi-unconfined gravel and sand aquifers are located near the Ayeyarwady River. The depth to aquifer varies from 12 to 52 metres and potential yield frequently exceeds 10 L/sec. Transmissivity ranges from 25 to 650 m^2/day. Low salinity $Na^+:HCO_3^-$ water is available from shallow aquifers, especially close to the Ayeyarwady River where hydraulic interconnection is likely. Excessive groundwater withdrawals from the shallow aquifers close to Pegu Group rocks may induce salt water intrusion and result in a deterioration in water quality. Being along the flowpath of saline groundwater from the Shinmataung Range, deeper aquifers, if present may be unsuitable for irrigation or domestic purposes.

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80 Local farmers pers. comm.

Near Yesagyo the aquifers consist of clean sand and gravel at depths of 15 to 40 metres. The water level varies from five to nine metres. Transmissivity values range from 60 to 200 m^2/day. The yield of low salinity groundwater may exceed 10 L/sec. Tritium results from Kudok Village indicate Modern water and thus is in a recharge zone. IWUMD reports that since commencement of the Wayathazi River Pumping Scheme groundwater salinity has reduced and water levels risen due to vertical leakage from overlying irrigation water. **Table 17** indicates that from 522 dugwells and tubewells in Yesagyo Township arsenic exceeds the WHO and NDWQS standards of 10 and 50 $\mu S.cm^{-1}$ by 18.4 and 1.3 percent respectively. Most were from the shallow Alluvium.

In the Oasis area, the specific conductance of water from the shallow alluvial aquifers ranges from 4,500 to 15,000 $\mu S.cm^{-1}$.

An irrigation tubewell at the horse breeding farm at Myitche is equipped with an electrosubmersible pump capable of yielding 10 L/sec. Groundwater salinity near Chaungmagyi Chaung is 400 $\mu S.cm^{-1}$.

West of the Yenangyaung Anticline many dugwells and tubewells are sunk into unconfined to semi-confined, medium to coarse grained sand aquifers along Yaw Chaung. The depth to aquifer ranges from eight to 15 metres (shallow Alluvium) and 65 metres (older Alluvium). Transmissivity values range from 55 to 500 m^2/day. Water levels are from three to nine metres. The likely source of aquifer recharge is Yaw Chaung. Tritium dating at Myingyawgone Village indicates Modern water. The potential groundwater yield may exceed 20 L/sec, especially from the deeper aquifers. The specific conductance of this Na^+:HCO_3^- type groundwater is less than 1,000 $\mu S.cm^{-1}$.

9.6 Areas of High Groundwater Yield and Low Salinity

Figure 23 shows that high yielding aquifers of low salinity water should be located:

- around Myitche near the Ayeyarwady River (transmissivity up to 514 m^2/day);
- along Chaungmagyi Chaung and the Bahin-Pagan Structural Line passing the Pakokku-Pauk Road before reaching The Oasis (transmissivity up to 179 m^2/day);
- around Pakokku (transmissivity up to 513 m^2/day);
- between Pakokku and Myaing overlying the Pakokku Syncline (transmissivity up to 107 m^2/day);
- the Pale Sub-basin (see **Chapter 10**);
- west of Yenangyat Anticline along Yaw Chaung (transmissivity up to 200 m^2/day); and
- east of the Shinmataung Anticline and Shinmataung Range (transmissivity up to 250 m^2/day).

Groundwater in the Irrawaddy Formation and Alluvium close to the Pegu Group or Eocene rocks may be unsuitable for irrigation due to their high salinity.

The areas excluded are:

- The Oasis as the potentiometric surface usually exceeds 60 metres and is overlain by brackish areas; and
- the elevated area around Sinsein Village (transmissivity up to 600 m^2/day) due to the depth to aquifer and potentiometric surface and the upgradient high salinity groundwater of the Pegu Group.

9.7 Water Balance Annual Recharge Estimation

Water balance for the ARC and estimates of groundwater in storage are given in **Chapter 17**.

10 Hydrogeology of the Pale Sub-basin

10.1 Introduction

The agricultural-based Pale Sub-basin is situated within Yinmabin and Salingyi townships, Sagaing Region. Yinmabin and Pale are the main administrative centres.

Table 28 indicates geological equivalents to the stratigraphic column for the Pale Sub-basin. The nomenclature used here is based on the Standard Minbu Basin, the 2014 Geological Map (Myanmar Geosciences Society), IWUMD terminology and other references[81].

Some geological and hydrogeology reports on the Pale Sub-basin have been prepared[82]. The geology and hydrogeology are shown on **Figure 25** to **Figure 27**. Examples of aquifer details are on **Table 29**.

Table 28 Stratigraphic Column for Pale Sub-basin

	STAGE (assumed)[83]		PALE SUB-BASIN[84]	PRESENT REPORT		MINBU BASIN	
QUATERNARY	Holocene		Kangon Fm	Unconsolidated Sediment		Unconsolidated Sediment	
	Pleistocene	Upper Middle Lower		Kokkogon Fm including Kokkogon Aquifer			
TERTIARY	Pliocene		Magyigon Fm	Ywatha/Aungban Aquifer	Volcanics	Maw Gravel Upper Irrawaddy Fm	
	Miocene	Upper Middle Lower				Lower Irrawaddy Fm	
			Damapala Fm	Obogon Kyaukkok Pyawbwe		Obogon Kyaukkok Pyawbwe	Pegu Group
	Oligocene	Upper Middle Lower		Okhmintaung Padaung Shwezetaw		Okhmintaung Padaung Shwezetaw	
	Eocene	Upper Middle Lower	Pondaung Wazein Taung Fm	Yaw Pondaung Tabyin Tilin Laungshe		Yaw Pondaung Tabyin Tilin Laungshe	
	Palaeocene	Upper Middle Lower		Paunggyi		Paunggyi	
			Basement Complex	Basement Complex		Basement Complex	
	Cretaceous						

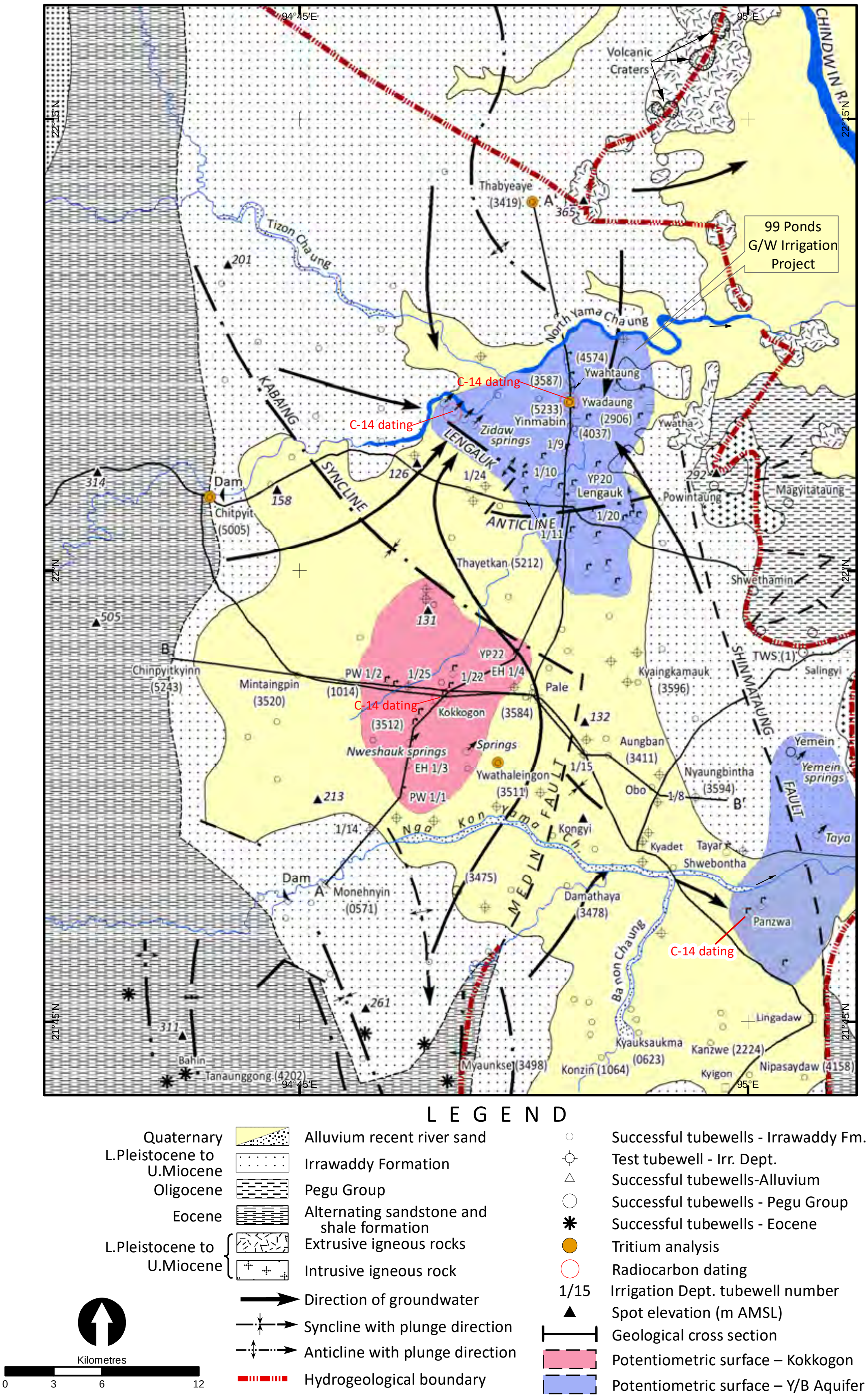
[81] GDC (1983), Tin Win (2016)

[82] Sein Myint et. al. (1970), Ahed (1979), Yin Swe et. al. (1979), Groundwater Development Consultants (1979, 1980a,b, 1981a-g, 1982a-c, 1983a,b, 1984a-c), Ko Ko et. al. (1980), Toe Yi (1980), Kyaw Aung (1984), Htet Wai Aung (2015), Myo Kyaw Tun (2015), Tin Win (2016), Aung Khaing Moe (2016), Hein Thu (2016)

[83] geological age (million years) is not given as author does not recognise method of determination

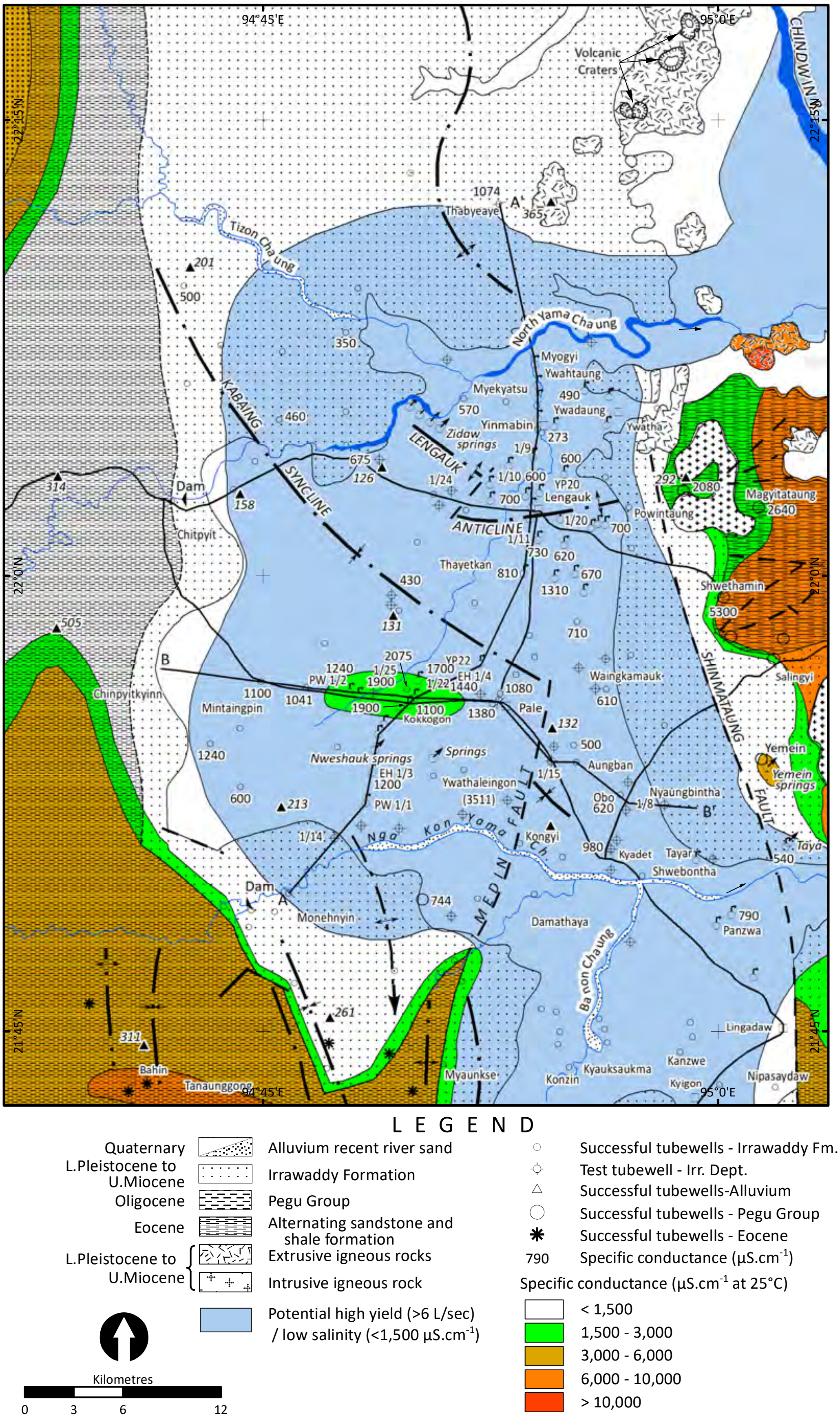
[84] Htet Wai Aung (2015), Myo Kyaw Tu (2015)

Figure 25 Schematic Geological and Hydrogeological Map: Pale Sub-basin



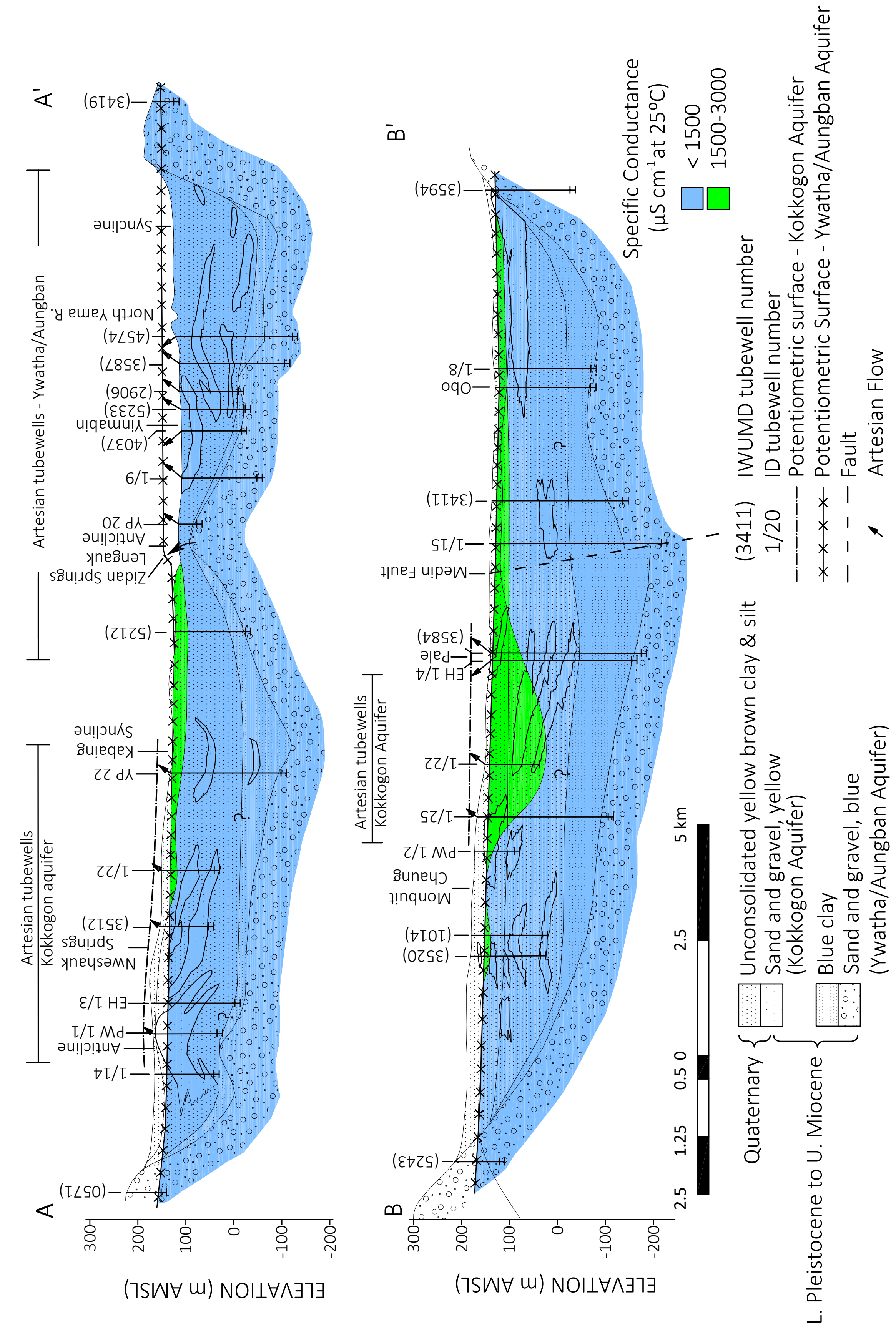
NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Figure 26 Schematic Hydrogeological and Hydrochemical Map: Pale Sub-basin



NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occur

Figure 27 Hydrogeological Cross Section and Specific Conductance: Pale Sub-basin



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Table 29 Examples of Aquifer Details from Selected Tubewells in the Pale-Yinmabin Area

Formation	Area	Village	Tubewell Number	Surface Elevation (m AMSL)	All data from surface (m)				DD (m)	Airlift Flow (L/sec)	Transmissivity (m²/d)	Specific Conductivity (µS.cm⁻¹)
					Depth	Aquifer	SWL *+	DDL				
Kokkogon Aquifer	Pale	Letpagan	PW1/2	+ 152	72	32- 45	+ 2	6	8	3	45	1,240
		Mintaingbin	3520	+ 178	144	138- 144	4	47	43	2	30	1,100
		Pale	3515	+ 133	189	180- 188	4	116	42	3	9	1,380
		Nyaungbingyi-su	EH1/3		78	56- 78	1.3	6.9	5.3	2	26- 88	1,200
		Kyadet	EH1/5		18	9- 18	8.1	11.9	3.8	1	26- 32	980
		Kokkogon	EH1/22		98	43- 74	+ 1					1,100
						89- 98						
		Letaunggyi	3584		267	258- 267	0	60	60	1	0.7- 1	1,080
		Pale	EH1/4	+ 135	249	113- 121	7					
						151- 166				0.1	2- 6	1,440
		Yoywa North	YP22	+ 131	116	91- 107				0.05		2,075
Ywatha / Aungban Aquifer	Yinmabin	Ywahdaung	2906	+ 111	158	146- 158	+ 11	0	11	98	1,059	273
		Ngamaung	1/9	+ 117	168	101- 119	+ 6	+ 1	5	15	388	600
		Tagayin	1/20	+ 125	140	104- 141	+ 3	+ 2	1	6	746	700
		Ywadaung	1/1		164	152- 164	+ 11	0	11	88	880	620
		Ngamaung	1/10		13	101- 131	+ 6	0.5	5.5	14	265	730
		Nyanugbingyisu	1/11		169	152- 159						810
						162- 162	+ 7	3.3	3.7	8	241- 1,040	
		Kyadet	1/24		239	199- 269						
						220- 239	6	5	1	41	282- 2,025	660
		Lengauk	YP20	+123	27	24- 27	+ 4.5	1	3.5	3		770
	Pale-Aungban	Kyaingkamuk	3596	+ 128	213	209- 216	2	3	1	26	2,100	510
		Tegyi Aungban	3411	+ 128	247	223- 248	6	13	7	39	664	500
		Kyadet	3401	+ 128	203	181- 201	6	11	5	19	700	510
		Kanni	0319		113	107- 113	13.8	17	3.2	3	97	720
		Sonda	3408		146	134- 146	6	9	3	9	329	650
Pegu Group	Salingyi	Powintaung	3413	+ 166	60	50- 62	40	42	2	1	58	2,080
		Shwethamin	3595	+ 154	136	49- 137	14	61	47	5	2	5,300
		Magyitataung	3591	+ 149	149	43- 108	11	64	60	1		2,640

*+ metres above ground surface

Source: IWUMD database and Umbrella Reports (GDC 1979-1984).

The Pale Sub-basin is located within the Western Trough. It is infilled with Recent intermountain alluvial sediment in topographic lows and underlain and surrounded by rocks of the Irrawaddy Formation (Kokkogon and Ywatha/Aungban aquifers). Eocene age rocks crop out on the western boundary. The Central Volcanic Line (granite, andesite, rhyolite and basalt) and Pegu Group rocks crop out to the east. This eastern 'Salingyi Uplift' forms a hydrogeological divide that partly isolates this sub-basin from the Chindwin River Basin. Groundwater resources are primarily located in the Irrawaddy Formation aquifers.

The NW-SE trending Kabaing Syncline crosses the centre of the sub-basin and is offset near Pale by the NNE-SSW orientated Medin Fault. Beneath Nga Kon Yama Chaung, Pegu Group bedrock has been uplifted to the east of the Medin Fault and down-dropped to the west.

The Lengauk Anticline trends NW-SE and is offset by faulting. This anticline is hydrogeologically significant since it is a conduit for groundwater flow[85]. Zidaw Springs emanates to the surface from this structure.

The perennial North Yama Chaung and intermittent Nga Kon Yama Chaung traverse west to east through the area. They are the only water discharge points from the sub-basin into the Chindwin River Valley. North Yama Chaung Dam (lower) and Nga Kon Yama Chaung Dam are used for irrigation and intentionally designed for groundwater recharge. Channels from the two dams supply irrigation water to the western part of the sub-basin (irrigation area of 40 x 52 kilometres).

North Yama Chaung Dry Season base flow was recorded at 2,400 L/sec (pre-dam construction)[86]. End of Dry Season discharge at the exit channel has recently been measured at 3,937 L/sec (2017). This latter measurement may include some water from the upstream dam.

10.2 Eocene and Pegu Group Rocks

Eocene rocks crop out on the basin's western periphery. This area has been intensely faulted, especially along the major fault systems:

- to the south, fractured sandstone aquifers are intersected at depths of 120 to 280 metres. They have moderate to high salinity (1,850 to > 10,000 µS.cm^{-1}, average being 3,800 µS.cm^{-1}), Na^+:Cl^- type water and low to moderate yields (0.5 to 5 L/sec). The general trend is for salinity to increase with depth; and
- further north block faulting has produced a highly fractured sandstone aquifer. Depth to aquifer is 60 to 80 metres, yield 1 to 10 L/sec, salinity below 1,000 µS.cm^{-1} and potentiometric surface of eight to 15 metres.

Tubewells in the Pegu aquifers have low yield and a salinity range of 1,500 to 5,500 µS.cm^{-1}.

10.3 Irrawaddy Formation

The Irrawaddy Formation has been subdivided into two units:

- Kokkogon Formation- Pleistocene age. The upper yellow brown sediment consists predominantly of clay, sandy clay and silt. Its thickness is 270 metres along the Kabaing Syncline. Saturated sand and gravel layers (known as the Kokkogon Aquifer) spasmodically occur within this predominantly clayey sequence, especially west of the Medin Fault towards Pale. The thickness of individual lenses is highly variable. Aquifer percentage varies from one to 46 percent of the stratigraphic column (average 20 percent). Due to the brown/yellow colour and weakly cemented nature, the contact with the overlying unconsolidated Alluvium is hard to determine; and

[85] Tin Win (2016)
[86] GDC (1984a)

- Ywatha/Aungban Aquifer- Pliocene to Upper Miocene. The deeper, blue grey sediment consists of highly permeable fine gravel and sand with minor clay and silt. It forms the regionally extensive and large groundwater yielding aquifer in this area. The aquifer is confined beneath clays and has strong artesian pressure in the north. Depth to aquifer is over 500 metres along the Kabaing Syncline and below 30 metres over the Lengauk Anticline. It has only been exploited in the northeast where drill depths are less than 310 metres. The aquifer comprises 25 to 30 percent of the borehole logs. This unit may continuously overlie basin bedrock.

The contact between the Kokkogon Formation and Ywatha/Aungban aquifers is variable, depending on geological structure and distance to the basin edge. Colour change within the strata usually occurs in a clay sequence, some five to 50 metres above the main blue grey sand and gravel zone.

10.3.1 Kokkogon Formation/Kokkogon Aquifer

Stratigraphically the Kokkogon Formation is considered 50 percent Alluvium and 50 percent Irrawaddy Formation (Minbu Basin nomenclature). On cross sections, the Alluvium/Kokkogon Formation interface is assumed at 250 m AMSL.

Photo 34: Artesian Kokkogon Aquifer, Kokkogon Village, 2017

Photo 35: Shallow Tubewell, Panzwa, Ywatha/Aungban

Because of its stratified nature and dominance of silt and clay the multiple aquifers possess less favourable hydraulic characteristics and groundwater yield than the underlying Ywatha/Aungban Aquifer. An average permeability of the Kokkogon Aquifer is in the order of 30 m/day (range 1 to 65 m/day). Groundwater yield is 1 to 5 L/sec. The depth to aquifer is variable at 10 to 270 metres depending on lithology and tectonic structure.

Artesian STW Kokkogon Village, Pale Sub-basin: May 2017
Specific Conductance: 1,130 $\mu S.cm^{-1}$, Total Dissolved Salts: 814 mg/L, pH: 7.9, Temperature: 28º C

Artesian tubewells are located to the west and southwest of Pale. Flows are dependent on surface topography and hydraulic head. The initial groundwater flow from all tubewells has gradually declined to being negligible in 2017. Most tubewells are sub-artesian.

Groundwater moves from the west and southwestern hills towards the sub-basin centre. Discharge points are located at the Nweshauk Springs, Nga Kon Yama Chaung, artesian and sub-artesian tubewells and marshes over the Lengauk Anticline west of Yinmabin. The specific conductance of the predominantly $Na^+:HCO_3^-$ type water ranges from 600 to 1,900 $\mu S.cm^{-1}$. The general trend is for salinity to increase down the flowpath towards the Pale artesian area. The shallow water bearing layers are slightly more saline than the deeper aquifers.

Tritium analyses at Ywathaleingon and Chitpyit villages (TW Nos 3511 and 5005) are dated as pre-thermonuclear. The radiocarbon age of groundwater from the Kokkogon artesian area in the sub-basin centre is about 6,400 years.

Table 30 Radiocarbon Dating of Groundwater in the Kokkogon Aquifer, Pale Sub-basin

Location	Depth (m)	Screen (m)	Formation	Sample Date '17	C-14 Dating (years)	Comment
Kokkogon Village	98	43- 74	Kokkogon	12^{th} May	6,415 ± 35	Kokkogon artesian area

10.3.2 Ywatha/Aungban Aquifer

10.3.2.1 Aquifer Occurrence

The semi-confined, blue grey Ywatha/Aungban Aquifer consists of porous and highly permeable, poorly cemented (sometimes cement absent) quartzose sand and gravel. The grain size becomes finer towards the centre of the sub-basin. Pyrite crystals are sometimes present.

Kabaing Syncline - within the Kabaing Syncline this aquifer is not usually utilised for domestic purposes due to its depth (750 metres) and tubewells are sub-artesian (potentiometric surface five to 30 metres beneath the surface). Most village tubewells have been successfully completed in the overlying Kokkogon Aquifer.

Lengauk Anticline - the Ywatha/Aungban Aquifer is extensively exploited for both irrigation and domestic purposes in the east where the aquifer is relatively shallow and artesian aquifer thickness is frequently greater than 60 metres. In this area:

- depth of aquifer varies from 30 to 310 metres, depending on the sub-surface geological structure;
- initial artesian flows are up to 80 L/sec (Ywadaung Village) with maximum recorded artesian pressure head of 15 metres (135 m AMSL);
- transmissivity ranges from 200 to 1,500 m^2/day;
- a representative permeability value is 100 m/day (range from 30 to 2,600 m/day);
- large gravel packed, screened and developed tubewells may have yield capacity > 100 L/sec; and
- specific conductance is 400 to 900 µS.cm^{-1}. The main anion is HCO_3^-, the cations vary between Na^+, Mg^{2+} and Ca^{2+} dominance.

Zidaw Spring, Pale Sub-basin: May 2017
Specific Conductance: 400 µS.cm^{-1}, Total Dissolved Salts: 390 mg/L, pH: 7.5, Temperature: 31.3° C.

Nga Kon Yama Chang - numerous artesian tubewells in topographic lows are used for small scale irrigation. For example, over 100 artesian shallow tubewells exist around the base of Panzwa Village, each flowing low salinity water at 1 L/sec for irrigation purposes. All tubewells intersect aquifers between 30 to 50 metres.

Artesian STW Panzwa Village, Pale Sub-basin: November 2016
Specific Conductance: 790 µS.cm^{-1}, Total Dissolved Salts: 556 mg/L, pH: 7.6, Temperature: 30.5° C.

The Ywatha/Aungban Aquifer is in hydraulic connection with the coarse-grained sandstone of the Irrawaddy Formation that crops out around the basin periphery.

Regional groundwater movement is from the recharge areas in the surrounding hills towards the Lengauk Anticline in the basin centre. Groundwater discharge is mainly to Zidaw Springs (along the anticline), the North Yama River and the artesian tubewells.

The high potentiometric surface exists due to:

- groundwater recharge in the regionally extensive outcrops around the elevated basin periphery;
- low topographic surface of the alluvial plain; and
- the two-narrow groundwater exit channels from the Pale Sub-basin (North Yama and Nga Kon Yama chaungs), through Pegu Group and volcanics, partially retard groundwater flow leaving the basin.

Salingyi Town Water Supply

Operator: Salingyi Township Development Committee.

Salingyi is sited over Pegu Group rocks. The town and environs are within a saline environment. Groundwater is piped 14.5 kilometres from the Pale Sub-basin to the town.

Source: Groundwater – One x 150 mm dia. production tubewell is sited on the eastern limb of the Ywatha/Aungban Aquifer underlain by Pegu Group rocks. Drilled to 50 metres and screened between 10 to 46 metres the DTW can be pumped at 25 L/sec for 22 hours/day (2.1 ML/day), if required. Static potentiometric surface is three metres.

Surface Water – pumping from the Chindwin River is an alternative water supply option.

Other: Within Salingyi there are a few large diameter dugwells and private shallow tubewells in weathered volcanics and Pegu Group containing brackish water.

Town Water Demand: Assuming a population of 5,553 (Census 2014) and water consumption of 130 L/d/p, the town water supply demand is < 1 ML/day.

Salingyi Town Water Supply Tubewell: May 2017
Specific Conductance: 810 $\mu S.cm^{-1}$, Total Dissolved Salts: 582 mg/L, pH: 7.6, Temperature: 31.7° C.

10.3.2.2 Groundwater Irrigation Activity - Pre-1986

Before 1986 there was some groundwater irrigation activity in the Yinmabin to Lengauk area[87]:

- 480 L/sec was being extracted from 42 uncontrolled, artesian tubewells;
- three ponds (flow of 150 L/sec from 16 artesian tubewells) irrigated 240 hectares of rice; and
- the ID had also constructed artesian and sub-artesian irrigation tubewells.

10.3.2.3 99 Ponds Groundwater Irrigation Project

The '99 Ponds Irrigation Project' was constructed in August 1994 to February 1995. The objective was to irrigate a proposed command area of 1,335 hectares. Each pond was designed to receive 2,500 m^3/day (1 cusec) from two to five artesian tubewells constructed within each impoundment. The ponds were 60 x 60 x 2.5 metres and were slightly elevated for gravity water delivery through channels.

[87] Drury (1986)

99 Ponds Groundwater Irrigation Project

Stage 1

Construction Date: 1994 – 1995.

Ponds: 99 (N3-N5, N8-N14, N6-20, N22-N23, N25-26, N28-29, N31-N33, N38-N46, N50-51, L1-L10, L15, L17-L20, L23, R1-R9, R14-R15, R18-R23, R25-R30, R34-R36, R38, R40, R46, R50-58, R60-61, R64)[88].

Number of Tubewells: 417 (each of the 99 ponds contains 3 to 5 artesian tubewells).
Ponds: 99; Irrigation Command: 3,300 hectares.
Canals: 99 Nos.
Implementing Agency: Government.
Operator: IWUMD.
Aquifer: Ywatha/Aungban Formation.
Piezometric Surface: two to 12 metres above ground.
Artesian Flow: 1 to 18 L/sec, average 6 L/sec.

Stage 2

Construction Date: 2000.
Number of Tubewells: 32.
Ponds: 8 (A1-A8).
Total Irrigation Ponds: 107.
IWUMD Groundwater Extraction: Flow of 44.7 $Mm^3 yr^{-1}$ (2017)
Private Tubewell Extraction: 43.4 $Mm^3 yr^{-1}$.
Total Extraction: 96 $Mm^3 yr^{-1}$

Geology	Aquifer	Depth (m)	Lithofacies	Potential Yield (L/sec)	Transmissivity (m^2/day)	Extraction Method
Holocene	Alluvium		brown clay, sandy clay			
Lower Pleistocene Pliocene to Mid Miocene	Kokkogon Fm	20 – 100	Yellow sand/ gravel	1- 10	250	Artesian/ Pumping
	Ywatha-Aungban Fm	60 – >240	blue grey sand / gravel	10- 100	200- 1,500	Artesian / pumping

Pressure Head Decline: two to 10 metres (1996 – 2016).
Summary of Average Stage 2: 32 Borehole Logs over Lengauk Anticline.

	Depth (m)	Clay Thickness (m)	Aquifer Thickness (m)	Comment
Range	60 – 240	12 – 150	8.8 – 74.7	21 holes contain a single continuous aquifer
Average	117	74	36	18 aquifers continue at hole bottom

Chemistry: Ywatha/Aungban Aquifer

	TDS	EC	pH	Na^+	K	Ca^{2+}	Mg^{2+}	Fe^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
	(mg/L)	$\mu S.cm^{-1}$		(mg/L)							
Minimum	260	400	6.47	19	1.5	19.23	9.6	0.5	33	28.8	40
Maximum	510	790	6.35	51	4.5	93.78	1824	4	97	6,004	104
Mean	367	566	7.61	31	2.5	46	49.7	2	54	115	67

References: Pavelic et. al. (2015), Aung Khaing Moe (2016), Win Tin (2016), unpublished data IWUMD.

[88] 'R' and 'L' designated ponds right and left of Yinmabin-Pale Road. 'N' is north of Yinmabin. 'A' specify Stage 2 new ponds

Photo 36: Pond R-1 with Artesian DTW. Y/A Aquifer, Yinmabin

Photo 37: Uncontrolled Flow from Rusted Tubewell, Lengauk

Due to the lack of groundwater flow control with a subsequent decrease in potentiometric surface, eight ponds ceased flowing by Year 2000. Replacement tubewells and ponds were constructed in the Stage 2 development. The location of Project irrigation ponds and their current operational status is shown on **Figure 28**.

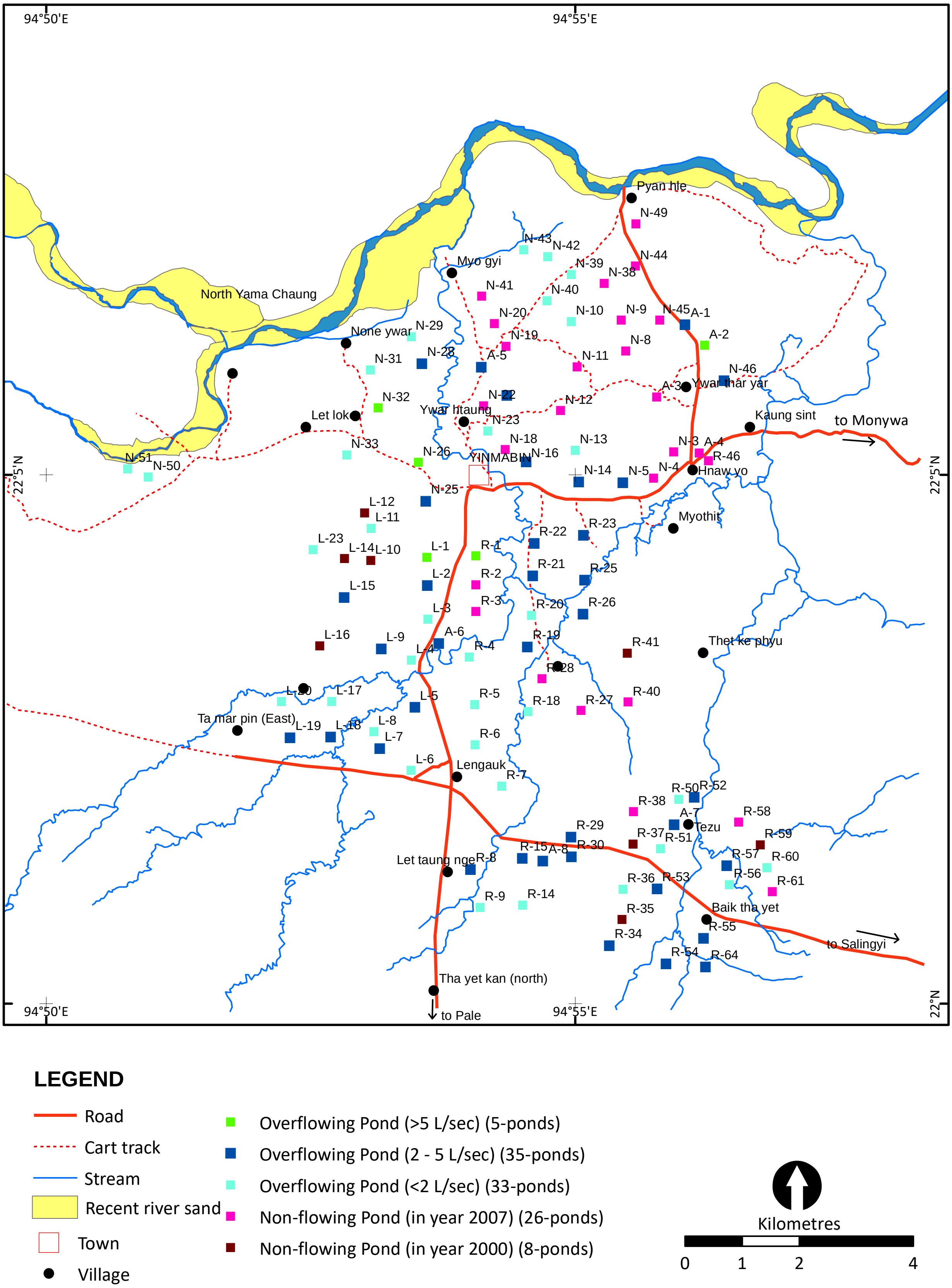
Based on the geological borelogs from Stage 2:

- the tubewells are 60 to 240 metres deep (average 117 metres);
- overlying clay horizon is 12 to 150 metres thick (average 74 metres);
- Ywatha/Aungban Aquifer has an average thickness of 36 metres;
- the aquifer acts as a single continuous unit (65 percent of cases); and
- 56 percent remain in the aquifer at hole termination.

Photo 38: Artesian Tubewell in Pond, Y/A Aquifer.
Source: *U Ngwe*

Photo 39: Ywahtaung Irrigation DTW, Y/A Aquifer Yinmabin

Figure 28 Location of 99 Ponds Irrigation Stages 1, 2: Pale Sub-basin



10.3.2.4 Post 99 Ponds Groundwater Behaviour

The status of the 107 IWUMD ponds is:

- eight ponds quickly went dry (pre-2000) and replaced under Stage 2;
- 26 ponds have subsequently become dry;
- 33 ponds have significant lower flow (< 1 L/sec);
- 35 ponds have reasonable flow (1 to 5 L/sec); and
- five ponds maintain original flow (> 5 L/sec).

Since Project construction there has been a steady decline in potentiometric pressure and flow (**Figure 29** and **Table 31**) and a significant reduction of effective command area. By 2016 the potentiometric pressure in the Ywatha/Aungban Aquifer had declined from 131 to 121 m AMSL. This has been due to:

- IWUMD irrigation tubewells installed on elevated topography;
- hundreds of private artesian irrigation and domestic tubewells drilled in low lying areas;
- uncontrolled groundwater flow by government and private irrigators. There is no control of artesian flow in non-irrigation periods;
- lack of an effective water management strategy; and
- no groundwater legislation and regulation. Enforcement can only occur through public liaison and community support.

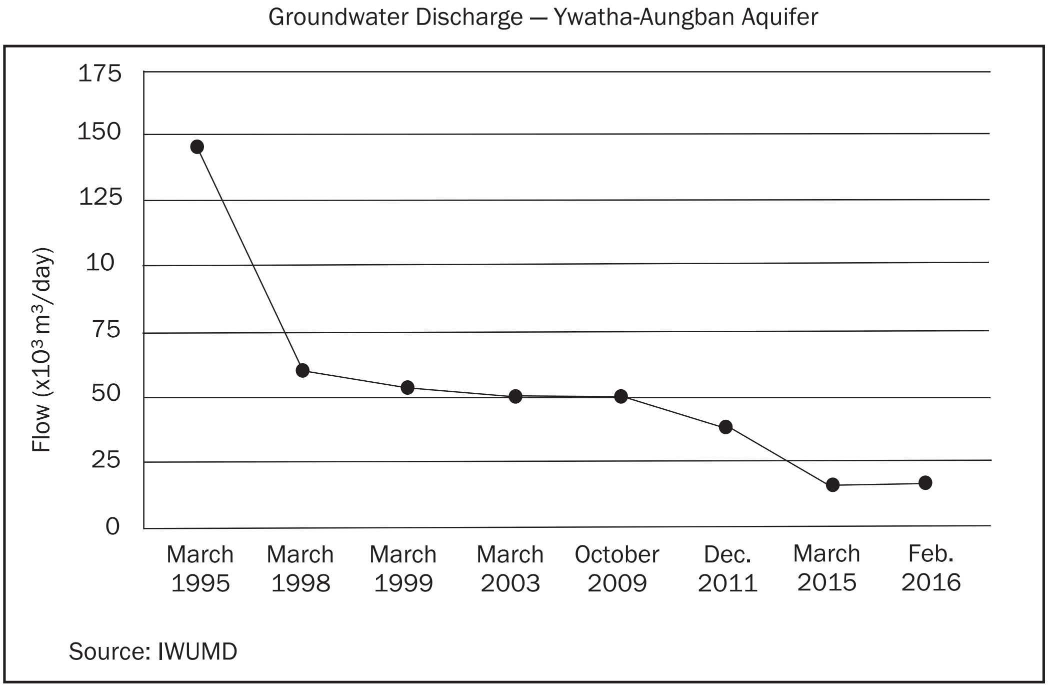
Table 31 Discharge and Well Status of the Ywatha-Aungban Aquifer in 1999 and 2009

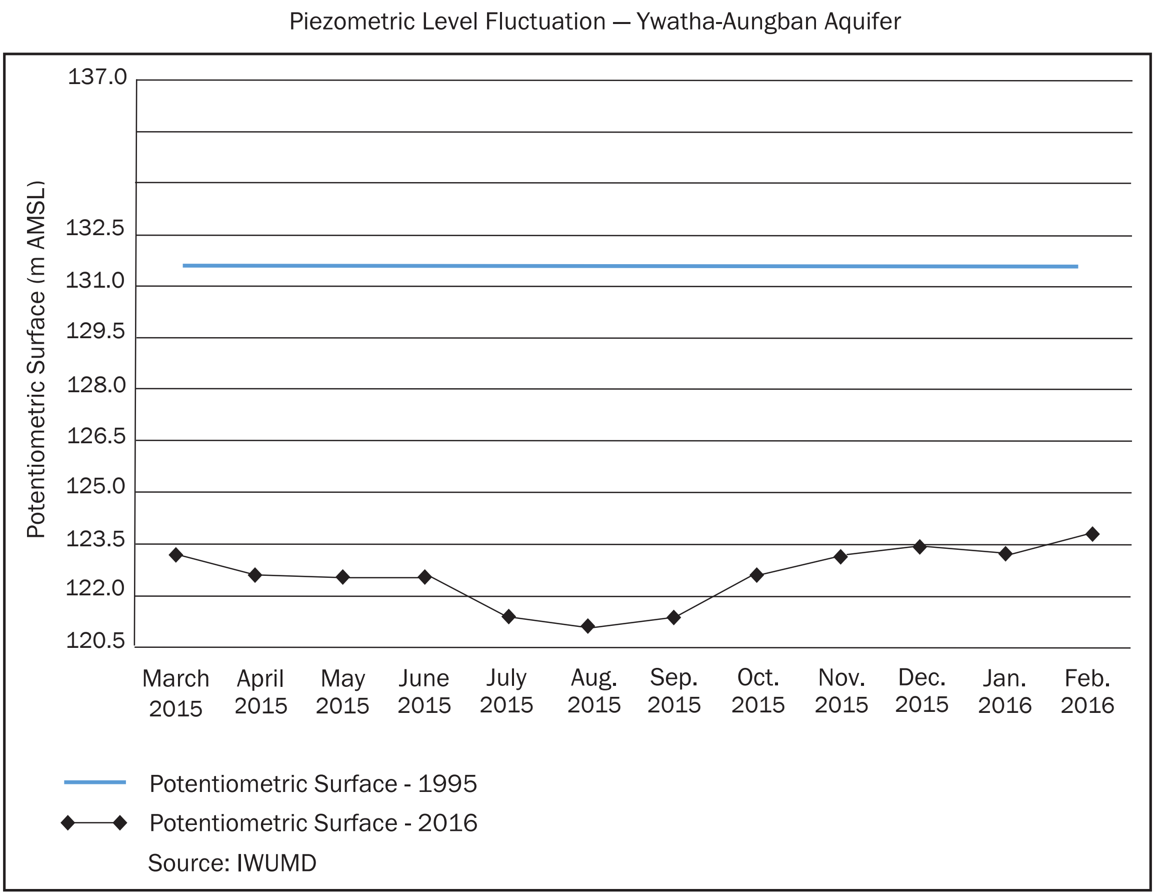
Purpose	Tubewell Type	1999		2009		Increase Tubewell (%)	Yield Difference (%)
		Artesian Wells	Discharge (m^3/day)	Artesian Wells	Discharge (m^3/day)		
Irrigation	99 Ponds (IWUMD)	449	52,161	449	48,932	0	-6.2
	Test Holes (IWUMD)	10	2,936	10	2,447	0	-16.7
	Private (farmers)	205	39,145	753	61,581	267	+ 57.3
	TOTAL	664	94,242	1,211	112,960	82.3	+ 19.9
Domestic		85	7,340	187	9,933	120	+ 35.3

Source: IWUMD data (2017).

From 1999 to 2009 the total number of flowing irrigation tubewells increased by 82.3 percent but yield increased by only 19.9 percent. A combined irrigation and domestic tubewell increase of 86 percent resulted in only 21 percent more artesian flow. Over 10 years the average artesian flow decreased from 136 m^3/day to 88 m^3/day due to the gradual decline in artesian pressure. As groundwater flow further decreases and the number of private tubewells increases, artesian conditions will eventually cease and mechanical pumping will be required. IWUMD has not commenced pumping from the non-flowing tubewells and many ponds remain dry. By March 2016 there were 1,982 artesian tubewells in the Ywatha/Aungban Aquifer with flows of 0.1 to 10 L/sec, average of 4 L/sec (IWUMD 2017).

Figure 29 Decline in Potentiometric Surface Ywatha /Aungban Aquifer: Pale Sub-basin





Source: IWUMD data (2017).

Groundwater production trends appear to be:

- consistent high yield ponds (L-1, R-2, N-31 and N-32) are located on the north-western periphery and A-2 north-eastern artesian flow boundary;
- lower yielding ponds are concentrated to the south; and
- non-flowing ponds tend to be located within the north-centre of the Project area.

Both shallow and deep tubewells have ceased to be artesian whilst others continue to flow (**Table 32**). Such reduction in flow appears to be due to the proliferation of uncontrolled farmer-owned tubewells near the impacted ponds and non-flow control by the IWUMD. The ponds around the periphery appear to have more sustainable flows.

Table 32 Artesian Flow and Declines in '99 Ponds Tubewells' with Increasing Depth

Pond Number	Village Name	Tubewell			Pond		
		Pond Number	Depth (m)	Initial Yield (m^3/day)	Initial Yield (m^3/day)	Current (m^3/day)	Loss %
R58	Min Zuu	4	31.3	547	2,186	91	95.8
R46	Hnaw Yoe	5	38.8	391	1,954	0	100
R19	Zee Phyu	3	57	864	2,591	136	94.8
R15	Tan Kharr	4	74.5	454	1,817	182	90.0
R30	Bya Ma Da	4	74.7	538	2,154	227	89.5
R5	Lei Ngauk	4	96	443	1,771	64	96.4
R2	Lei Ngauk	5	112	758	3,792	0	100
R4	Lei Ngauk	5	129	610	3,049	45	98.5
R1	Yinmabin	4	137	774	3,094	935	69.8
R21	Zee Phyu	4	145	803	3,210	227	92.9
R22	Myoh Thit	4	181	368	1,472	182	87.6
N23	Myoh Thit	4	200	487	1,949	136	93
L19	Nyaung Pin Khee	4	202	368	1,472	0	100
N20	Myay Kyat	4	218	502	2,007	0	100
L12	Ngarr Mou	4	234	341	1,364	109	92
N33	Pyaung Pya	4	246	418	1,670	0	100
N31	Myoh Paw	2	256	1,191	2,381	91	96.2

Source: IWUMD data (2017).

10.3.2.5 Aquifer Rehabilitation

Table 33 gives some examples where tubewell rehabilitation by IWUMD has taken place.

Table 33 Examples of Tubewell Rehabilitation Results, Pale Sub-basin

Pond No.	Location within Pond	Depth (m)	Initial Artesian Flow	Pre-Rehabilitation Flow		Post-Rehabilitation		
						Increase in flow		Deficit from Initial Flow
			(m³/day)	(m³/day)	(% Loss)	(m³/day)	(%)	(m³/day)
R29	NE	58	455	9	98	23	2.6	-432
	NW	58	545	24	95.6	25	1.1	-520
	SE	58	455	102	77.6	126	1.2	-329
	SW	55	545	8	98.5	9	1,1	-536
R30	NE	72	455	39	91.4	43	1.1	-412
	NW	73	491	164	66.6	234	1.4	-257
	SE	76	500	17	96.6	34	2	-466
	SW	55	545	8	98.5	9	1.1	-536
R21	NE	165	727	22	97.0	22	1	-705
	NW	165	393	0	100	3	3	-390
	SW	165	1,000	55	94.5	98	1.8	-902
	SE	165	1,091	78	92.3	131	1.7	-960
R22	NE	184	190	39	79.5	39	1	-151
	NW	179	145	39	73.1	39	1	-106
	SW	184	145	40	72.4	66	1.7	-79
	SE	184	123	55	55.2	104	1.9	-19

Source: IWUMD data (2017).

Rehabilitation for removal of fine sediment and encrustation from the screens has marginally increased the groundwater flow in most tubewells but not back to initial flow conditions. The principal cause of decrease in flow is the reduction in potentiometric surface not encrustation. Efforts to rehabilitate some irrigation ponds may be a short-term solution however, the key long-term issue of uncontrolled flow and water management of this valuable resource should be addressed.

10.3.2.6 Groundwater Quality

The specific conductance of groundwater from the Ywatha/Aungban Aquifer varies from 250 to 900 µS.cm^{-1}, (400 to 790 µS.cm^{-1} in the '99 ponds' area). The salinity increases to 1,500 µS.cm^{-1} towards the hard rock outcrops.

Tayar Village Tubewell: November 2016
Specific Conductance: 540 µS.cm^{-1}, Total Dissolved Salts: 390 mg/L, pH: 7.7, Temperature: 31.8° C.

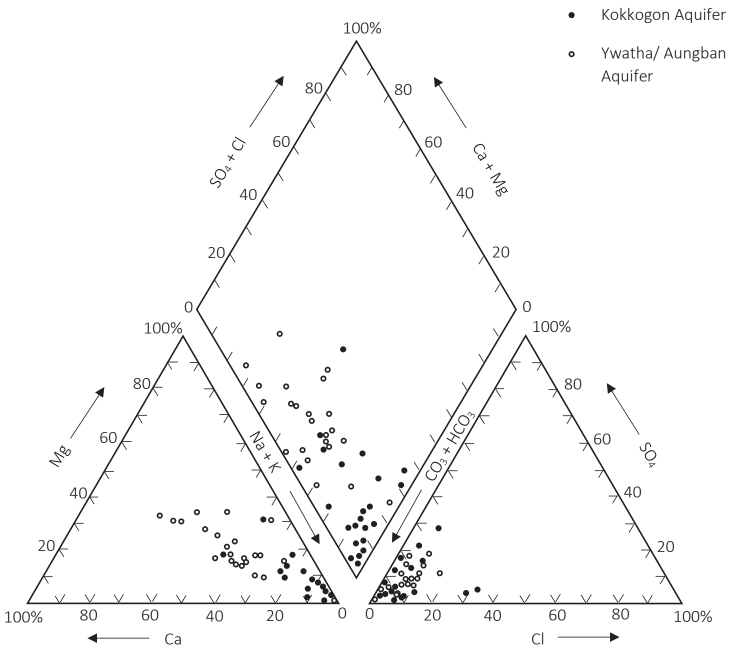
Tayar Village Tubewell: May 2017
Specific Conductance: 370 µS.cm^{-1}, Total Dissolved Salts: 270 mg/L, pH: 7.7, Temperature: 33° C.

Ywahtaung Village Tubewell: November 2016
Specific Conductance: 470 µS.cm^{-1}, Total Dissolved Salts: 325 mg/L, pH: 7.3, Temperature: 31.5° C.

Ywahtaung Village Tubewell: May 2017
Specific Conductance: 390 µS.cm^{-1}, Total Dissolved Salts: 280 mg/L, pH: 7.4, Temperature: 31.4° C.

The Piper-Palmer diagram **(Figure 30)** indicates that the major anion is bicarbonate. The main cation is sodium in the Kokkogon Aquifer and sodium with calcium and/or magnesium in the Ywatha/Aungban Aquifer.

Figure 30 Piper-Palmer Diagram for Kokkogon and Ywatha/Aungban Aquifers: Pale Sub-basin



Source: GDC (1984c).

The plot of electrical conductivity versus sodium absorption ratio indicates that water from the Ywatha/Aungban Aquifer is better suited to irrigation than the Kokkogon Aquifer **(Figure 31)**. Hardness in the Kokkogon Aquifer varies from 50 to 410 mg/L, whilst in the Ywatha/Aungban Aquifer the range is from 80 to 200 mg/L.

10.3.2.7 Age of Groundwater

Tritium dating of groundwater from a shallow Ywatha/Aungban aquifer in the hills at Thabyeaye Village indicates a Modern recharge water, whilst that from Ywadaung Village is pre-thermonuclear.

Radiocarbon dating results are given in **Table 34**. The ages of groundwater range from 2,455 to 4,000 years, the youngest being in the Lengauk Anticline and the oldest near the sub-basin exit near Nga Kon Yama Chaung.

Table 34 Radiocarbon Dating of Groundwater in the Ywatha/Aungban Aquifer, Pale Sub-basin

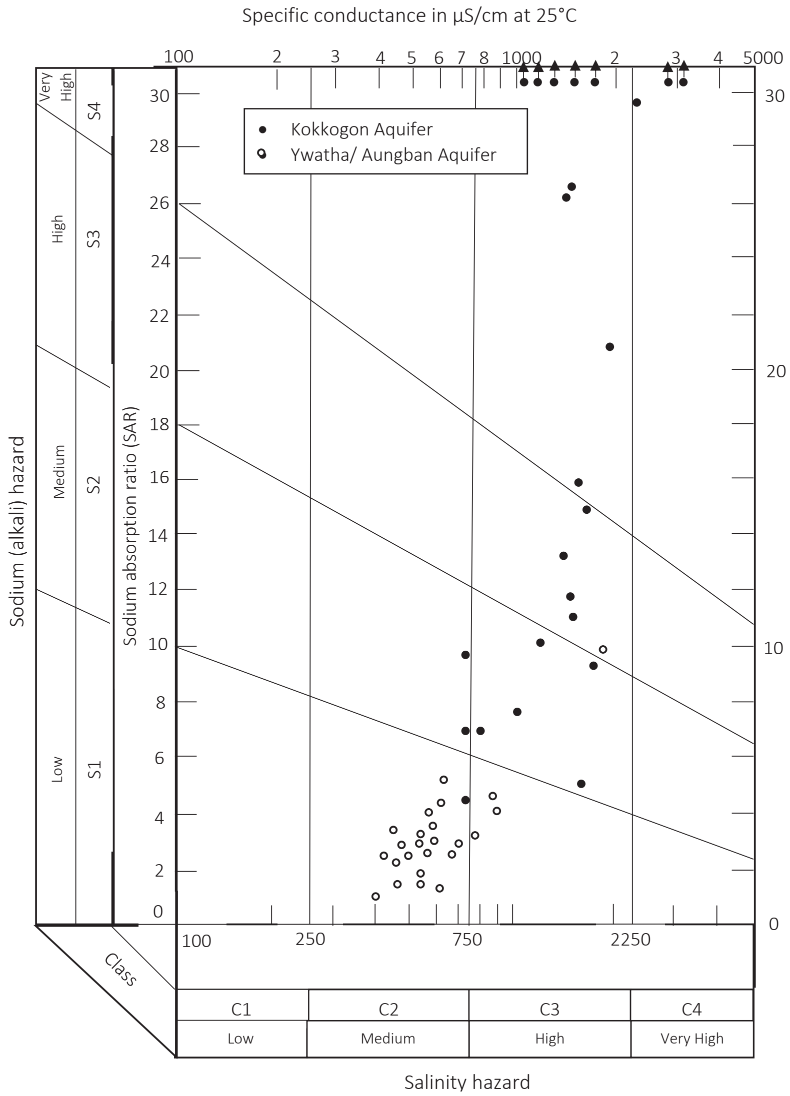
Location	Depth (m)	Screen (m)	Formation	Sample Date 2017	C-14 Dating (years)	Comment
Ywahtaung	159	146 – 158	Ywatha/Aungban	12th May	2,800 ± 25	99 Pond Irrigation area
Zidaw Village	30	25 – 30	Ywatha/Aungban	12th May	2,455 ± 25	Western flank of anticline
Tayar Village	223	200- 223	Ywatha/Aungban	12th May	4,000 ± 30	Southern artesian area

The radiocarbon dating indicates a substantial aging of groundwater along the flow path:

- the youngest groundwater is at the shallow Zidaw tubewell (Lengauk Anticline); to
- the deep, high yielding Ywahtaung tubewell near Yinmabin down; then
- Tayar Village tubewell near the Nga Kon Yama Chaung exit from the sub-basin.

The overlying sand stringer Kokkogon Aquifer within a clay matrix has the oldest age of ≈ 6,400 years (**Table 30**).

Figure 31 Salinity Hazard Diagram for Kokkogon and Ywatha/Aungban Aquifer: Pale Sub-basin



Source: GDC (1984c).

10.4 Alluvium

Shallow alluvial deposits are found in low-lying areas of the Pale-Yinmabin plain, especially adjoining North Yama Chaung and major tributaries. These areas are subject to flood during the rainy season. The soil is a brownish yellow and red sandy loam near Yinmabin becoming more clayey to the south. The underlying sediments are composed of unconsolidated sand and silt. The colour is commonly brownish yellow or red in places. The geological age of this unit is Recent. Dugwells in most towns are used for domestic purposes but may go dry during the Dry Season. The salinity is low. If the dugwell is poorly constructed the aquifer may be subject to surface water contamination.

10.5 Areas of High Groundwater Yield and Low Salinity

The area assumed to contain high groundwater yields and low salinity is shown on **Figure 26**. High groundwater yields at shallow depth from the Ywatha/Aungban Aquifer are well documented along the Lengauk Anticline and at Yinmabin. Hydrogeological data from the west of Yinmabin and south of Pale is scant. However, since the Ywatha/Aungban Aquifer is expected to extend under most of the Sub-basin, the area of high yield and low salinity is assumed extensive.

There are only two narrow exit points for the Pale Sub-basin, through gaps in the volcanic and Pegu Group rocks along North Yama and Nga Kon Yama chaungs. Large groundwater yield areas may be available in these gaps to join the high yield and low salinity areas of the Chindwin River Valley.

10.6 Water Balance

The water balance was developed during the June 2017 Hydrogeological Workshop. Main contributors were Tin Win, U Ngwe, Than Zaw and IWMI. **Figure 32** shows the water balance for the Pale Sub-basin.[89] Base assumptions are:

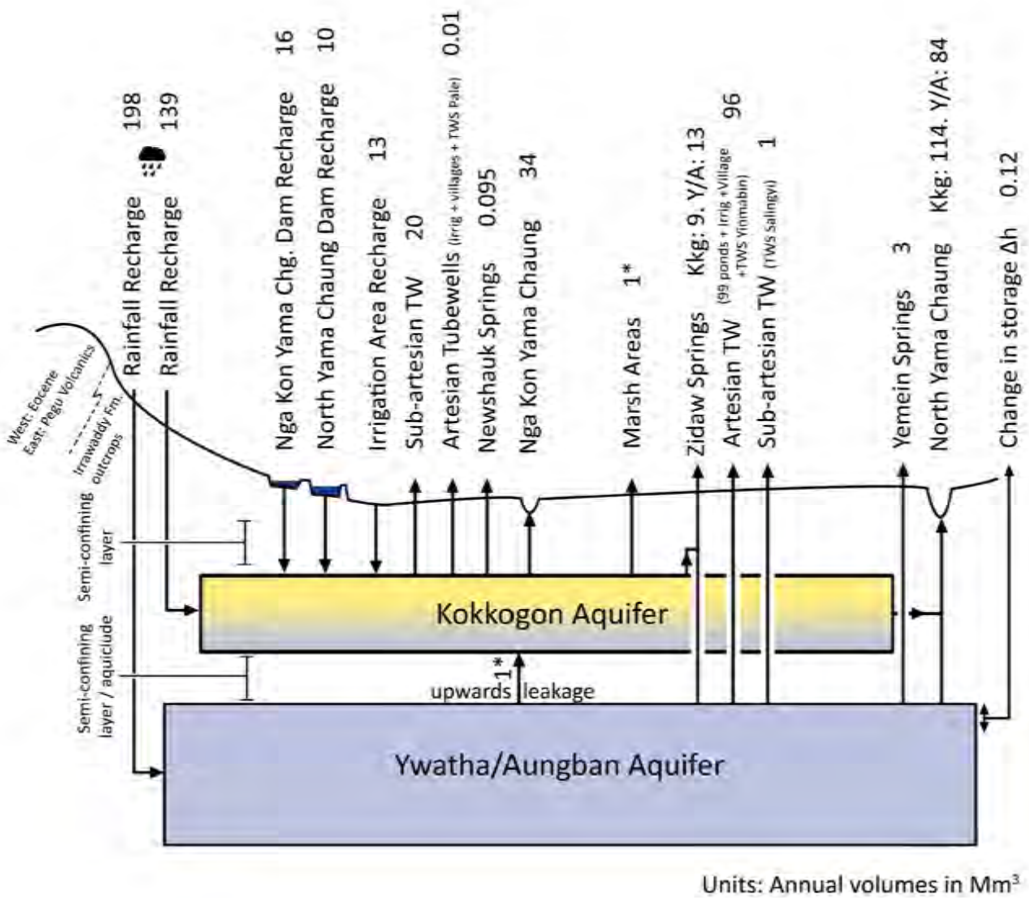
- Aquifer Inputs:
- Recharge:
  - average rainfall of 914 millimetres (36 inches);
  - 15 percent of rainfall[90] for the Ywatha/Aungban Aquifer; and
  - 10 percent for the Kokkogon Aquifer due to high clay content and low aquifer occurrence.
- Surface Water Infiltration:
  - dams- based on IWUMD *'Evaporation and Other Losses'* records for the sub-basin reservoirs; and
  - irrigation return flow- calculated using total irrigation volume extracted (from both aquifers) and a return vertical infiltration of 15 percent. This low return flow value assumes high clay content.

- Aquifer Outputs:
- groundwater withdrawal- combined artesian, sub-artesian and spring extraction based on tubewell numbers (recorded and estimated), flowing/pumping times and discharge;
- springs- measured by IWUMD (June 2017), others based on field knowledge and local experts;
- marsh area- flow from the Kokkogon Aquifer to the swampy terrain near Yinmabin was particularly difficult to assess. However, it is not a large component in the hydrogeological system; and
- baseflow:

[89] Any information imbalance in Figure 32 is due to rounding of decimals in the calculations
[90] GDC (1984c), Than Zaw (2010, van Ramshorst (2017)

- North Yama Chaung- discharge was measured at the end of the Dry Season, then increased to allow for Wet Season groundwater discharge;
- Nga Kon Yama Chaung- flows intermittently; and
- baseflow was fine-tuned to close the balance, considering baseflow from these two watercourses are the only output of groundwater in the basin.

Figure 32 Groundwater Budget Model: Pale Sub-basin



The water balance model includes a groundwater loss to the system (ΔS =- 0.12 $Mm^3.yr^{-1}$), which is supported by the IWUMD documented reduction in piezometric pressure (**Figure 29**).

The water balance suggests that if the government and private artesian tubewells were closed when not required (assume 25 percent of time), a groundwater saving of 22.5 $Mm^3.yr^{-1}$ would occur. Since the change in aquifer depletion has been slow (average 0.12 $Mm^3.yr^{-1}$ versus 96 $Mm^3.yr^{-1}$ extraction), aquifer repressurisation would be reasonably expected with subsequent flow increase in springs, tubewells and river discharge. Alternatively, additional groundwater development elsewhere in the basin may be possible.

Photo 40: IWUMD Piezometer Briefing Hall

10.7 Groundwater Management

The development of the high yielding artesian aquifers by government agencies, farmers and others has produced a significant change to the regional groundwater flow system. With poor construction and lack of operational flow regulation valves, the artesian tubewells flow continuously from both aquifer systems. Most of this resource is wasted (especially during the Wet Season) and aquifer pressure will continue to decline unless government authorities and local communities take remedial action.

There is also concern that such water wastage may contribute to water logging of agricultural land and the increase in salinity of the shallow aquifer. Several studies recommend remedial and legislative action to protect and manage this valuable resource[91].

The Pale Sub-basin has the only long-term pressure monitoring tubewell in the Dry Zone sited at the IWUMD Briefing Hall[92].

The IWUMD has implemented community consultation and education programmes. Some farmers are afraid that artesian flows will cease if their tubewell is temporarily sealed during periods of none use or non-participating neighbours will steal their water. Others appear to understand the importance of maintaining artesian pressure and groundwater flow conservation. In 2016 some farmers capped their flowing tubewells during the harvest period. Some repressurising of the aquifer resulted. Nearby dry ponds began to infill with water once their contained IWUMD tubewells began to flow. The confined aquifer appears responsive to groundwater flow management.

In 1984 the 'Yinmabin Well Killing Proposal' was considered. The proposal was to plug 45 uncontrolled flowing tubewells and replace them with 90 artesian wells of appropriate design and flow control mechanism. The new tubewells would be closed in non-irrigation periods. Due to perceived poor economic returns to the larger Umbrella Project and 'administrative and social issues' it never proceeded.

Based on water management, agricultural and conservation grounds, there is a strong case for plugging corroded holes and replacing them with properly constructed tubewells fitted with flow control devices. This will ensure that flow will be regulated, water wastage minimised and artesian life of this valuable resource preserved. Observation piezometers fitted with pressure gauges should be installed to measure changes within the aquifer system.

The implementation of Groundwater Laws and Regulations, with development of a management plan, community workshops and publicity campaigns are critical for the long-term utilisation of this valuable groundwater resource within the Pale Sub-basin.

The Great Artesian Basin, Australia, is a good example of National Government action to restore potentiometric pressure for long-term viability of an important artesian aquifer system (**Chapter 17**).

Future Research:

It is recommended that pressure transducers and data loggers be installed in several monitoring piezometers in the Kokkogon and Ywatha/Aungban aquifers to better understand the hydrodynamics of the aquifer systems.

A groundwater model of the Pale Sub-basin should be developed to simulate operational scenarios on the hydrodynamics of the aquifer systems; such as uncontrolled flow and tubewell closure during the non-irrigation season.

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[91] GDC (1984c), Drury (1986), Tin Win (2016)

[92] Five water level and salinity pressure transducers/data loggers were installed in tubewells elsewhere in the Dry Zone at end of April 2017

11 Hydrogeology of the Lower Chindwin River Valley

11.1 Introduction

Some geological and hydrogeology investigations in the Lower Chindwin River Valley (Budalin to Chaung-U) have been reported[93]. **Table 35** indicates the stratigraphic column used in this text (Minbu Basin stratigraphy) and some equivalents. The Dry Zone does not extend into the Upper Chindwin River Valley.

Table 35 Stratigraphic Column for the Chindwin River Valley

	STAGE		CHINDWIN BASIN[94]	SABE - SALINGYI[95]	POWINTAUNG -SILAUNG AREA[96]	MINBU BASIN – PRESENT REPORT	
QUATERNARY	Holocene			Kangon Fm	Kangon Fm	Unconsolidated Sediment	
	Pleistocene	Upper					
		Middle				Maw Gravel	Volcanics
		Lower				Upper Irrawaddy	
TERTIARY	Pliocene		Mingin Fm	Magyigon Fm	Magyigon Fm	Lower Irrawaddy	
	Miocene	Upper					
		Middle	Shwethamin Fm	Damapala Fm	Damapala Fm		
		Lower	Natwa Fm			Obogon Kyaukkok Pyawbwe	Pegu Group
	Oligocene	Upper	Letkat Fm			Okhmintaung	
		Middle				Padaung	
		Lower				Shwezetaw	
	Eocene	Upper	Yaw Pondaung Tabyin		Wasintaung Fm	Yaw Pondaung Tabyin Tilin Laungshe	
		Middle					
		Lower	Tilin Laungshe				
	Palaeocene	Upper	Kebaw Fm	Basement Complex	Basement Complex	Paunggyi	
		Middle				Basement Complex	
		Lower					
	Cretaceous						

[93] GDC (1980a,b, 1982b,1984a,c), Nyunt Lwin (1980b), Maung Tun Lwin (1981), Tun Lwin (1981), Soe Aung et. al. (1982b), World Bank (1983), Myint Soe et. al. (1984), Ngwe et. al. (1986), Thaik Nyunt (1986a,b,d), Ma Theingi Oo (2006), Ngwe (2013), Nyi Nyi Tun (2013), Aung Khaing Moe (2016), Zaw Myo Oo (2017)

[94] Aung Khin & Kyaw Win (1968)

[95] Myint Zaw Han (1993)

[96] Min Aung (1994)

The alluvial plain is bounded to the west by the Pale Sub-basin and east by the Kyaukka Range, the latter forming part of the western watershed of the Mu River Valley. To the south, the flats become swampy near the confluence of the Chindwin and Ayeyarwady rivers (**Figure 33**). Ground elevation of the alluvial plains gradually rises from 65 metres near Monywa to 120 metres towards the base of the Kyaukka Hills (elevated 150 to 375 m AMSL).

The Lower Chindwin River Valley is located along the Central Volcanic Line (west) and in the southwest corner of the Shwebo-Monywa Basin of the Eastern Trough.

Photo 41: Volcanic Craters, Lower Chindwin. Source: Google Earth

The geological units are:

- Pegu Group- that crop out along the Kyaukka Range. Easterly dipping shales are exposed west of the Chindwin River near Salingyi;
- Irrawaddy Formation- exposed along the alluvial boundary east and west of Budalin and at the base of the Kyaukka Range;
- Igneous rocks- strike NNW along two structural lines;
- Central Volcanic Line:
    - extinct volcanic craters of Twin Taung East, Twin Taung West, Taungbauk and Leshe;
    - copper ore volcanics at Sabe Taung, Kyising Taung and Letpadaung Taung; and
    - intrusive rocks at Powintaung and Salingyi.
- Secondary Volcanic Line: olivine basalts on Kyaukka Range; and
- Alluvium- unconformably overlies weakly cemented sand of the Irrawaddy Formation.

Faulting and folding has strongly influenced the distribution of the various formations. The Alluvium and Irrawaddy Formation are truncated in the east by the north-south orientated Kyaukka Fault coinciding with the uplifting of the southward plunging, anticlinal folded Pegu Group rocks along the Kyaukka Range. Minor cross fault systems are present.

The northward plunging Chaung-U Syncline has been infilled with a thick sequence of alluvial sediment along its axis.

Drainage to the NNW-SSE flowing Chindwin River is from a series of ephemeral, sinusoidal gravel bedded streams, including Paunggada, North Yama, Chaungmagyi, Myothit, Thazi, Buga, Ywathitpauk and Daing chaungs. Drainage is mainly east-west with all intermittent chaungs becoming braided as they cross the plain. The exception is the ephemeral Thade Chaung that flows north-south and is deeply incised.

South of Chaung-U, the alluvial plain is flooded for several months. Major flooding upstream of Monywa is rare. The average annual rainfall at Monywa is 80 centimetres.

Due to the presence of shallow, low salinity groundwater very few villages use surface ponds for domestic water supplies.

People living along the banks of the Chindwin River use it as a source of domestic and stock water supply. There are many surface water pumping schemes that utilise the Chindwin River for irrigation purposes. No impounding dam nor diversion weir has been built on the tributaries (except North Yama Chaung and Nga Kon Yama dams - Pale Sub-basin).

The 1,200-megawatt Tamanthi Dam[97] is proposed on the Chindwin River but the decision to proceed is currently postponed.

Examples of aquifer details for various rock types are given in **Table 36**. **Table 37** gives chemical analysis for various aquifers. Hydrogeological information is presented on **Figures 33** to **35**. The main aquifers are located within the unconsolidated Alluvium. Groundwater bearing sediments also exist in the Irrawaddy Formation and Pegu Group.

Hundreds of Government and thousands of private tubewells and dugwells have been constructed. Some dugwells need to be progressively deepened, due to groundwater extraction for irrigation purposes from underlying aquifers.

11.2 Pegu Group

Tubewells have been sunk into fractured Pegu Group aquifers in the Salingyi area. Potential groundwater yields vary from 0.5 to 9 L/sec (Yemein and Pyawbwe villages). Multiple aquifers are usually intersected between 45 to 90 metres. The transmissivity range is 0.5 to 70 m^2/day. The specific conductance varies from 2,080 to 5,400 $\mu S.cm^{-1}$ at Powintaung and Kywekotaw villages. The general trend is for the lower salinity, $Na^+:HCO_3^-$ type groundwater to be in higher elevated aquifers and more saline, $Na^+:Cl^-$ water at lower elevations around the outcrop periphery. Due to topography and the easterly dipping rocks, the hydrogeological boundary is located near the western edge of the range. Groundwater movement is mainly east towards the Chindwin River.

Pegu Group bedrock occurs at a shallow depth under Monywa Town.

Along the Kyaukka Range, many tubewells penetrating marine shale and fine sandstone have been abandoned. Highly saline, $Na^+:Cl^-$ rich, low yielding aquifers are intersected. For example, at both Kyaukka North and Chaungma villages groundwater with specific conductance exceeding 10,000 $\mu S.cm^{-1}$ has been encountered. The general trend is for salinity to increase with depth. Low yielding dugwells usually contain less saline water in the weathered marine rock near watercourses. At Kyaukka North Village the specific conductance of groundwater from eight dugwells (nine metres deep) ranges from 2,980 to 8,240 $\mu S.cm^{-1}$. Groundwater movement along the easterly dipping Pegu Group fractured rock is eastwards from the Kyaukka Fault into the Mu River Valley.

South of Chaungma Village the Pegu Group plunges under a shallow alluvial cover. Tubewells encounter brackish water at shallow depths.

11.3 Irrawaddy Formation

Tubewells screened in blue grey sand aquifers are located west of the Kyaukka Fault, near Budalin and underlying the central valley Alluvium. Aquifers are usually intersected 60 to 200 metres below the surface, shallowing towards the basin periphery. Transmissivity values range from 12 to 125 m^2/day. Small diameter village tubewells yield up to 6 L/sec with a water level drawdown of nine metres. The specific conductance of the typically $Na^+:HCO_3^-$ type groundwater is usually below 1,500 $\mu S.cm^{-1}$ except close to the flanks of the Kyaukka Range, where salinity increases.

[97] Outside Figure 33

Table 36 Aquifer Details for Various Rock Types – Chindwin River Valley

Formation	Area	Village	Tubewell number	Surface Elevation (m AMSL)	All data from surface (m)				DD (m)	Airlift pump-test (L/sec)	Transmissivity (m^2/d)	Specific Conductivity ($\mu S.cm^{-1}$)
					Depth	Aquifer	SWL	DDL				
Pegu Group	Kyaukka Range	Kyaukka North	3813	+ 152	98	70- 76	52	68	16	0.4	2	> 10,000
	Salingyi	Pyawbwe	5203	+ 119	125	43- 48	6	18	12	9	70	4,100
		Powintaung	3413	+ 166	60	50- 62	40	42	2	1	48	2,080
Irrawaddy Formation	Kyaukka Range	Kyaukka South	4008	+ 146	189	168- 171	44	52	8	2	23	1,120
		Bawga	4026	+ 168	155	135- 151	72	76	4	3	78	1,200
Alluvium	Central Alluvium	Lezin	2160	+ 91	25	6- 25	5	6	1	4	260	2,100
		Magodaw	2163	+ 79	26	11- 26	9	10	2	4	224	1,150
		Ettaw	2129	+ 80	46	25- 46	9	N/A	N/A	66*	358	1,120
		Kyweye	EH2/30	+ 80	46	25- 46	6	10.6	4.6	63	2,136	1.002
		Kyweye	EH2/33	+ 81	40	21- 40	5.5	11.3	5.8	68	1,208	980
		Ma U	EH2/2	+ 79	30	14- 17						
						23- 30	4.8	6.8	2	06	241	1100
	South of Chaung-U	Chaung-U	2120	+ 88	70	55- 70	18	N/A	N/A	43*	358	1,080
		Nyaungbintha	4116	+ 70	23	12- 23	6	8	2	12	805	1,000
		Kyigon	4117	+ 67	26	11- 26	3	4	1	12	1,014	1,800

* Result based on pumping test report

Source: IWUMD database and Umbrella Reports (GDC 1979-1984).

Table 37 Examples of Chemical Analysis from Alluvium and Irrawaddy Formation Aquifers – Chindwin River Valley

ID Tubewell Number	Location	Interval Sampled (m)	Milliequivalents/litre								Error (%)	SAR	TDS (mg/L)	EC ($\mu S\ cm^{-1}$)	pH
			Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	SO_4^{2-}	Cl^{-}					
EH 2/2	Zalok Farm	29- 32 (All.)	1.6	2.8	13.2	0.1	Nil	14.0	1.6	2.0	0.1	8.9	1,109	1,140	8.5
		84- 88 (Irr. Fm.)	1.8	3.7	9.6	0.1	Nil	9.0	4.8	1.4	0.5	5.8	1,109	1,345	7.8
EH 2/3	Tanaunggon	34- 37 (All.)	1.8	1.8	12.7	tr.	1.3	16.8	1.4	1.1	0.4	12.7	1,182	1,750	8.4
		105- 108 (Irr.)	2.2	0.6	12.2	0.1	Nil	13.0	tr.	1.5	1.4	10.3	866	1,500	8.0
EH 2/24	Myobaw	34- 37 (All.)	1.0	1.4	12.1	tr.	0.8	12.4	0.4	0.4	2.1	11.0	804	1,000	8.5
		61- 67 (Irr. Fm.)	0.5	0.7	13.0	0.1	1.2	12.5	0.3	0.6	0.1	17.0	816	990	8.4
PW 2/4	Mangyo	12- 21 (All.)	6.6	1.2	25.0	0.2	Nil	19.0	7.0	7.0	3.4	12.7	1,841	3,000	7.3

(All.)– Alluvium
(Irr. Fm.)– Irrawaddy Formation

Source: IWUMD database and Umbrella Reports (GDC 1979-1984).

Figure 33 Schematic Geological and Hydrogeological Map: Lower Chindwin River Valley

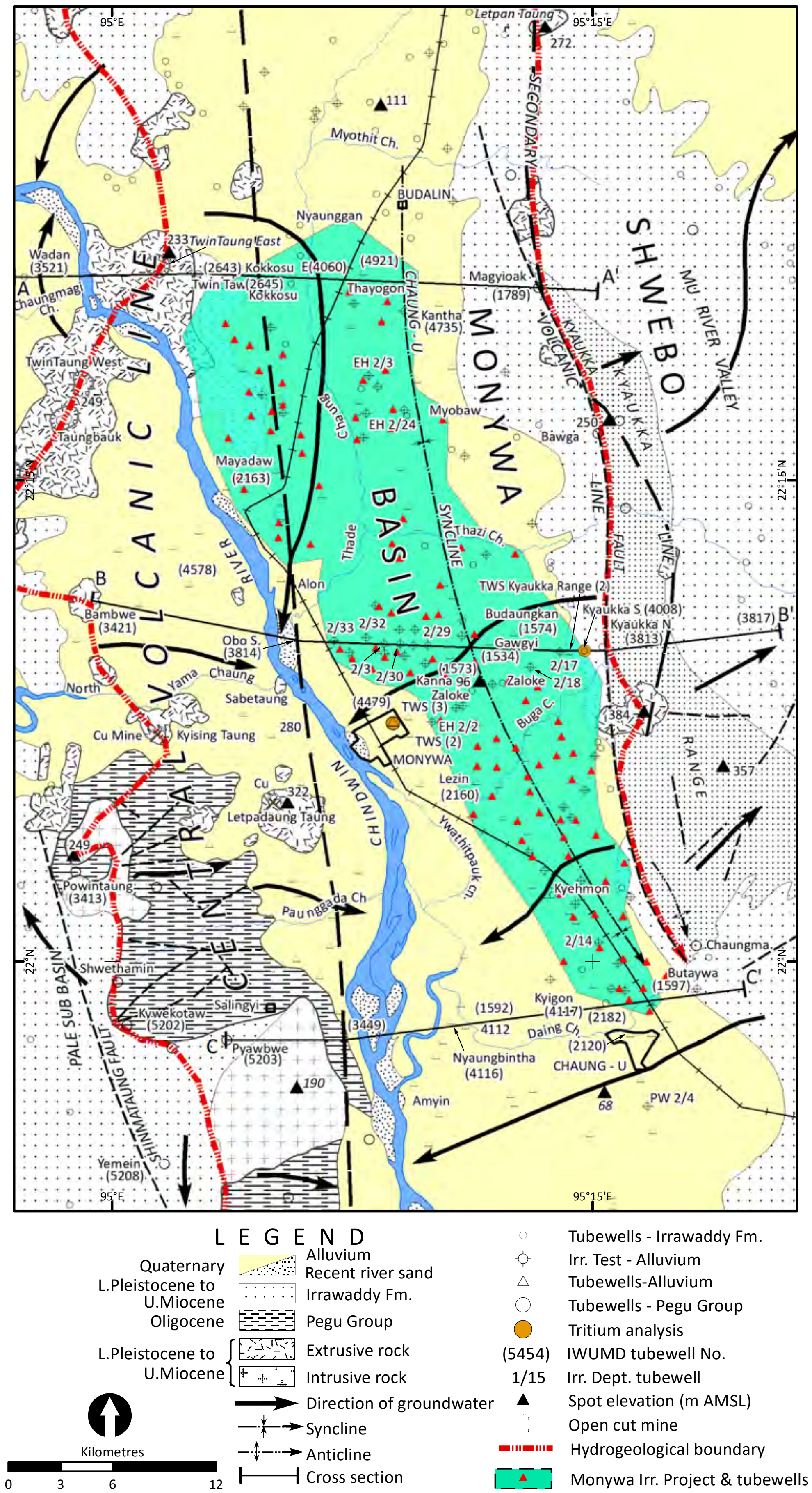
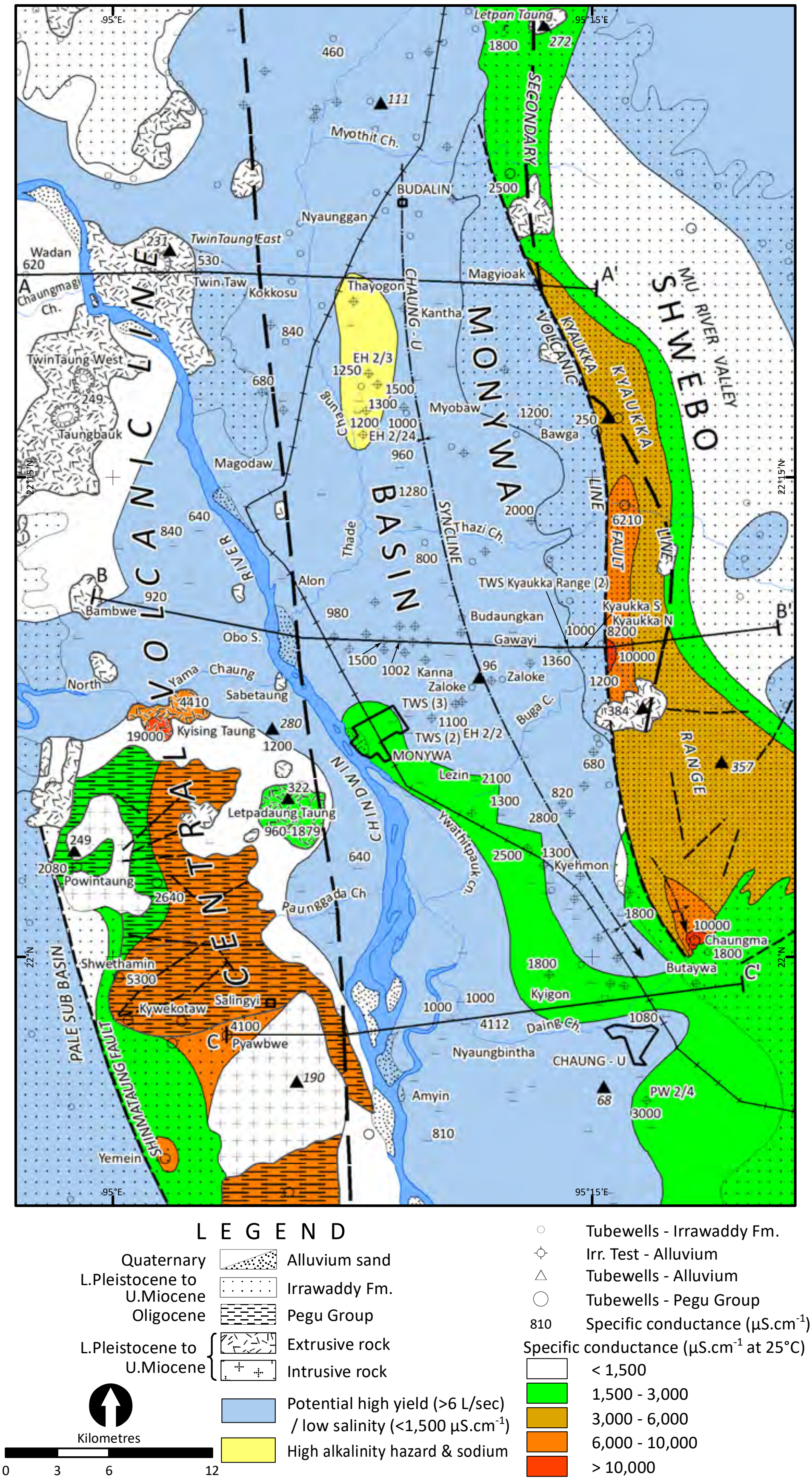
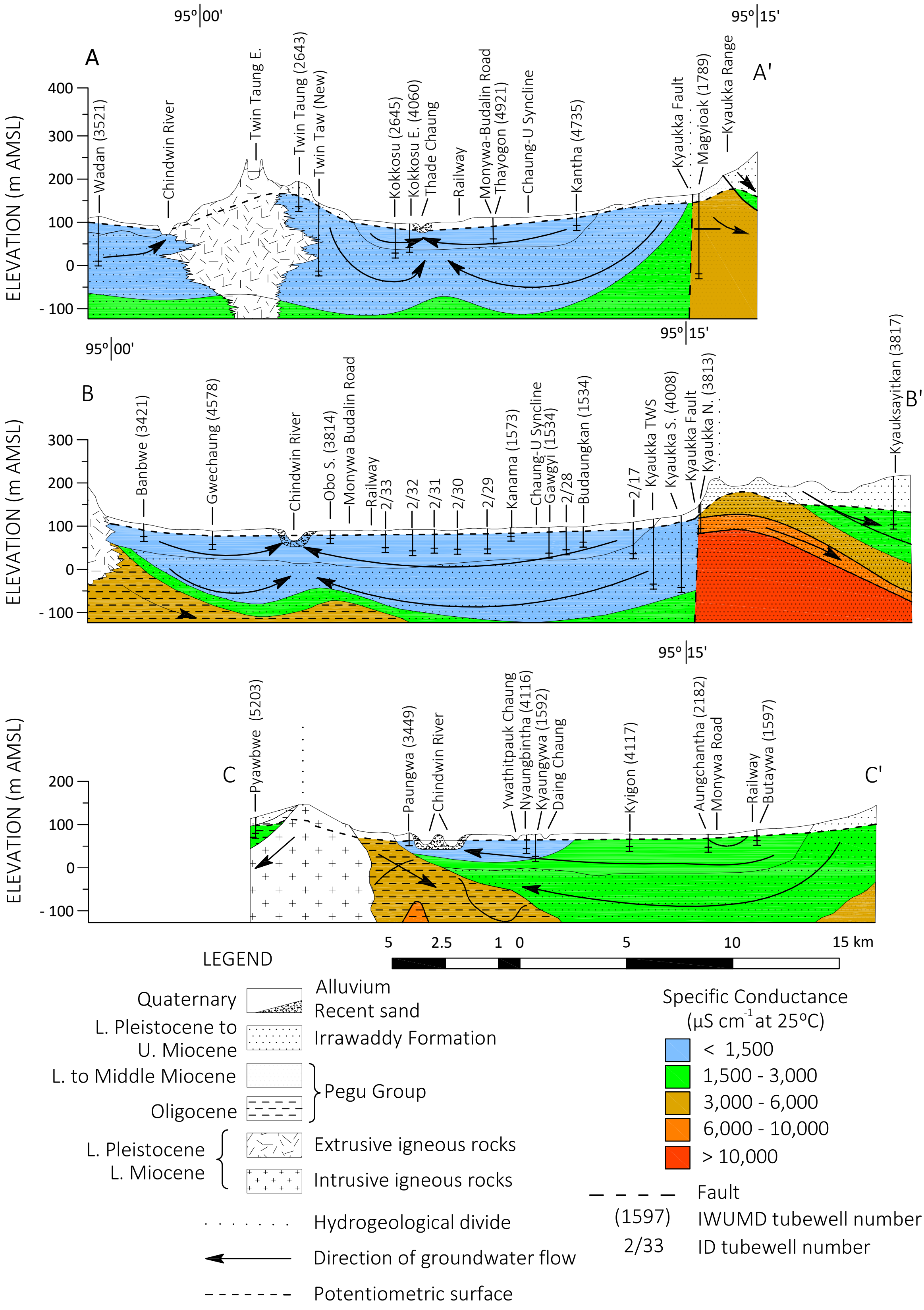


Figure 34 Schematic Hydrogeological and Hydrochemical Map: Lower Chindwin River Valley



NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occur

Figure 35 Hydrogeological Cross Section and Specific Conductance: Lower Chindwin River Valley



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Higher groundwater yields should be available in certain areas from properly constructed production tubewells. For example: a recently completed (November 2016), 150-millimetre diameter IWUMD tubewell at Twin Taw (near Twin Taung East volcano), drilled to 160 metres intersected a thick (105 metre) blue gravel and sand aquifer. Screened from 131 to 150 metres the low salinity groundwater was airlifted at 25 L/sec. During drilling two pyroclastic flows (presumably from the Twin Taung Volcano Complex) were penetrated near the top of the formation.

The Kyaukka South Village tubewell intersected a semi-confined aquifer at 165 to 170 metres (21 to 24 m BMSL) within the Kyaukka Fault. The Na^+:HCO_3^- type water has a specific conductance of 1,120 µS.cm^{-1}. Tritium analysis indicates Modern water. There appears to be good recharge conditions along the fault line. Geological structure and stratigraphy strongly control groundwater occurrence over short distances (for example: between Kyaukka South and Kyaukka North villages).

Budalin water supply is sourced from four 150-millimetre diameter tubewells, each sunk to 130 metres in blue coarse sand and gravel. Each tubewell is equipped at 8 L/sec and collectively yield 3 ML/day.

Photo 42: Airlift Production Tubewell – Twin Taw Village, 2016

Twin Taw Village Tubewell: November 2016
Specific Conductance: 530 µS.cm^{-1}, Total Dissolved Salts: 382 mg/L, pH: 8.4, Temperature: 25.7° C.

The direction of groundwater flow is towards the Chindwin River. The extent to which groundwater flow occurs between the Alluvium and Irrawaddy Formation aquifers is controlled by the vertical permeability of the clay aquicludes, its thickness and head differences. The piezometric surface of the Irrawaddy Formation is like the Alluvium. They have a maximum head difference of only 0.6 metres. The uncertainty in distinguishing origin of aquifer heads beneath the alluvial plain makes the piezometry of the Irrawaddy Formation poorly defined.

Photo 43: Coarse Sand and Fine Gravel from Twin Taw Village Tubewell, Irrawaddy Formation (137- 181 m)

11.4 Alluvium

11.4.1 Hydrogeological Characteristics

Considerable lateral lithological variation occurs in the fluviatile, unconsolidated Alluvium and the underlying weathered, weakly cemented sand of the Irrawaddy Formation. Colour changes, differences in drilling rate and grain grading are not sufficiently definitive to separate the two formations. The subdivision of the subsurface geology presented here is made on the blue grey colour of the Irrawaddy Formation, however this may not necessarily be the lithological contact. Hydraulic connection between the two geological units occurs throughout the area.

The Alluvium contains multiple aquifers and aquicludes. Unconsolidated alluvial thickness is quite variable ranging up to 75 metres in the Chaung-U Syncline to less than 15 metres at Monywa (underlain at shallow depth by Pegu Group bedrock). The average aquifer thickness is 45 metres (63 percent of stratigraphic column); increasing to 68 metres (90 percent) in the central area and thinning to 30 metres (40 percent) to the south and towards the eastern and western basin peripheries. The thickness of semi-confining aquitard layers varies from six to 12 metres over most of the area increasing to 25 metres over the synclinal trough and near the Kyaukka Fault.

On the alluvial plain, there are thousands of dugwells and tubewells, many of which are used for irrigation. The unconsolidated aquifers have transmissivities up to 15,000 m^2/day, average around 300 m^2/day. As in most alluvial valleys, lithological variation occurs over small distances. In general, aquifers in the Chaung-U Syncline appear less permeable (presumably due to the inflow of silt and clay from the Pegu Group in the Kyaukka Hills), although tubewell yields up to 8 L/sec can usually be extracted. Tubewells screened in multiple alluvial aquifer systems in the more transmissive zones usually yield 10 to 50 L/sec, with water level drawdowns of one to six metres.

The shallow saturated alluvial sediments behave as unconfined aquifers over long pumping periods with storage coefficient values around 0.16. Deeper aquifers are semi-confined (Storage Co-efficient (SC) = 8.4×10^{-3}). Occasionally long-term pump-out tests intersect recharge boundaries. No value for vertical permeability through the clay aquicludes is available. GDC (1984) suggests a range of 10^{-4} to 10^{-2} $ft.d^{-1}$ (3×10^{-5} to 6×10^{-3} m/day).

The specific conductance is usually below 1,500 $\mu S.cm^{-1}$. A Piper-Palmer diagram (**Figure 36**) indicates a strong Na^+:HCO_3^- type water. Quality variation with depth appears marginal. Being a single hydrochemical type, the water is interpreted as a moderately juvenile water. The Langlier Index indicates a slight tendency for encrustation.

A plume of slightly saline water (> 2,000 $\mu S.cm^{-1}$), extends from Monywa southeast past Chaung-U and links with brackish water south of Chaungma Village. The Alluvium overlies shallow Pegu Group bedrock containing saline groundwater. Tritium analysis of groundwater at Monywa indicates a pre-thermonuclear age.

Close to the Kyaukka Range the specific conductance in some alluvial aquifers increases to 5,000 $\mu S.cm^{-1}$. High salinity infers local recharge by throughflow from the Pegu Group into the Alluvium.

On the western bank, including the Monywa Copper Mine, the alluvial aquifer is of low salinity, with neutral pH and Na^+:Cl^- dominant.

A plot of sodium absorption ratio (SAR) versus specific conductance for both Alluvium and Irrawaddy Formation aquifers is shown on **Figure 37**. Most groundwater falls into the S1C3 and S2C3 groups. Irrigation tubewells usually yield water with a specific conductance of 1,000 to 1,500 $\mu S.cm^{-1}$. Overall the existing irrigation scheme does not appear to be constrained by the SAR ratio or specific ion toxicity. Some exceptions exist.

Table 17 indicates that from the 721 dugwells and tubewells sampled for arsenic in Chaung-U and Monywa townships none exceeded 50 µg/L.

Figure 36 Piper-Palmer Diagram: Lower Chindwin River Valley

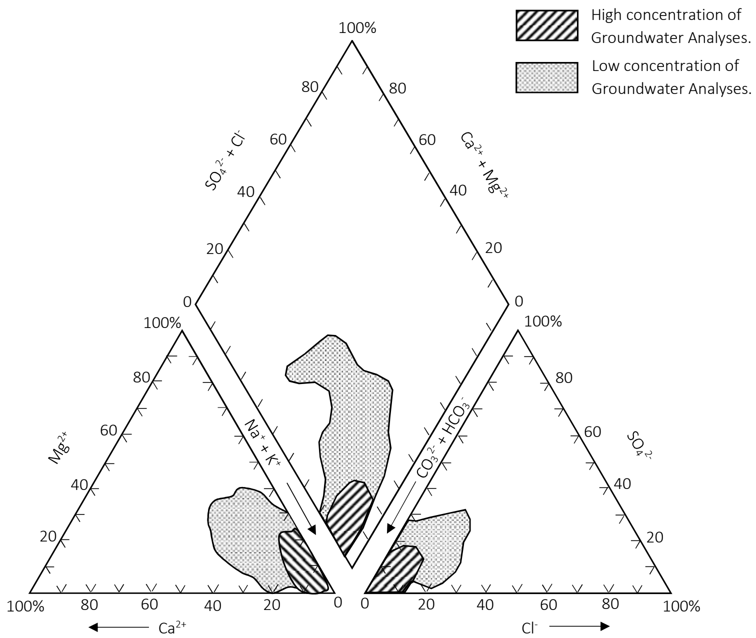
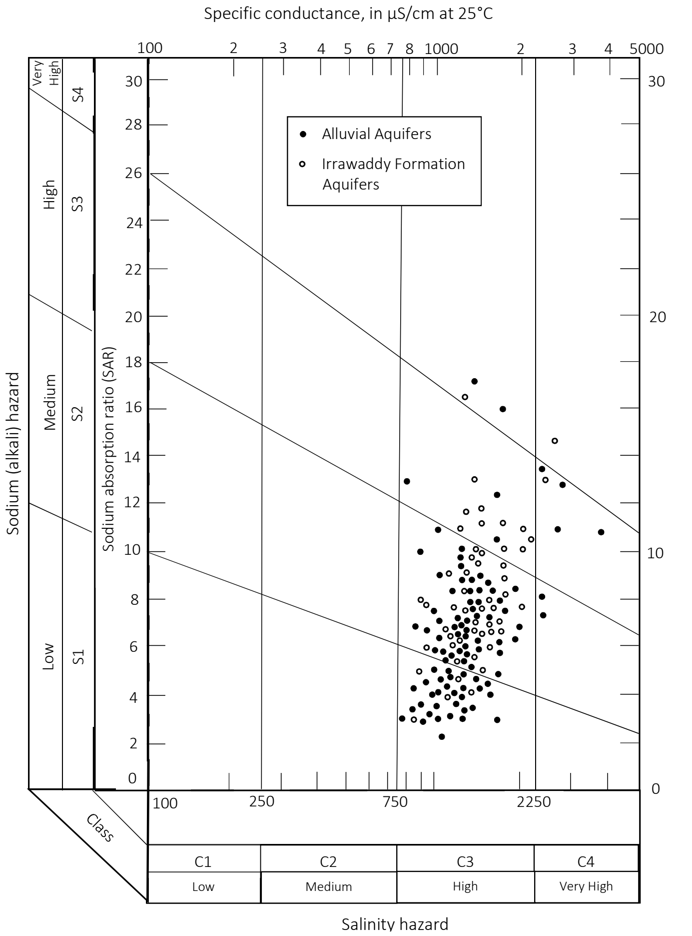


Figure 37 Salinity Hazard Diagram: Lower Chindwin River Valley



Source: GDC (1984c).

Monywa Town Water Supply

Operator: Monywa Township Development Committee.

Sources: municipal water from both the Chindwin River and groundwater:

- Chindwin River Pumping Station- developed and operated by Private Developers – pumping 1,150 m^3/day.
- Groundwater – two borefields:

Borefield 1: three JICA tubewells, each yielding 18 L/sec (2 operating x 12 hours/day); and

Borefield 2: two government tubewells, each pumping 25 L/sec (2 operating x 6 hours/day).

Total Yield: 3.2 ML/day.

Pegu Group bedrock occurs at a shallow depth under Monywa. The two borefields are sited to the east of town around Ranthaupit Lake.

Drill depth: around 30 metres in Alluvium.

Potentiometric surface: 15 metres.

Other: Within Monywa and away from the brackish groundwater zone there are thousands of private DTW and hundreds of DWs.

Town Water Demand:
With a city population of 207,489 (Census 2014), the water demand is 27 ML/day (assuming 130L/d/p). The reticulated water system is 16 percent of water demand, the remainder coming from the private sources.

Kyaukka Range Water Supply

Pegu Group groundwater on the Kyaukka Anticline is saline. Deep tubewells in Alluvium and Irrawaddy Formation aquifers west of the Kyaukka Fault supply water to villages and monasteries in the Kyaukka Range.

Kyaukka Village:
1 x 150 mm dia. DTW: Depth 41 metres, SWL 16 metres, Alluvium Aquifer, Yield 2 L/sec, salinity < 1,000 $\mu S.cm^{-1}$.

1 x 100 mm dia. DTW: Depth 120 metres, Alluvium and Irrawaddy Fm., Yield 4 L/sec, salinity 1,130 $\mu S.cm^{-1}$.

Monastery:
1 x 200 mm dia. DTW: Depth 210 metres, Irrawaddy Fm., Yield 5 L/sec, salinity 1,360 $\mu S.cm^{-1}$.

11.4.2 Monywa Irrigation Project

Figure 33 shows the location of the Monywa Groundwater Irrigation Project (MGIP). It covers parts of Budalin, Monywa and Chaung-U townships. Construction commenced in 1983[98].

The Project objectives were:

- to increase crop production and farm incomes by expanding irrigation area to 8,100 hectares through development of groundwater resources; and
- increase the institutional capability of the ID in groundwater exploration and development.

There are currently no Hydrogeologists working on Project operation. There is no groundwater modelling to manage the groundwater resource.

[98] World Bank (1983)

Photo 44: Electro-Turbine Pump, Monywa Irrigation Area

Photo 45: Production Tubewell, Ring 4, Alluvium Aquifer, 2016

Monywa Groundwater Irrigation Project between Monywa, Chaung-U and Budalin

Construction Date: 1983 to 1992.

Irrigation Command: Originally 810 ha. (1980) to 6,100 ha (2016). Initial plan 8,100 ha.

Number of Tubewells: Initially 157 constructed. Of the 141 DTW available, (105 @ 50 L/sec + 36 @ 25 L/sec) 120 DTW operational in 2016.

Potentiometric Surface: Minimum: 15 metres (north); maximum: 45 metres (central and south).
Operation: The system pumps 14 hours/day or longer to meet water demands.

Total Groundwater Extraction: 120 MCM – 53 MCM government, 67 MCM private

Crop Demand: 1,200 mm for paddy and 600 mm for other.

Implementing Agency: Funded by United Nations Development Programme (UNDP), International Development Association (IDA) and World Bank (WB).

Operator and Major Maintenance: Irrigation Department (now IWUMD) with local pump operations by trained farmers.

Cost Recovery: Capital Cost: an indirect agricultural tax through procurement of 'controlled' crops (cotton, wheat and mung beans) at below the export or import prices.

Operation and Maintenance Cost: Farmers pay a water fee of MMK 6,000, 9,000 and 3,000/acre for wet paddy, dry paddy and other crops through a Water User Group.

Geology: Aquifers: Two distinct aquifers

Geology	Unit	Aquitard Thickness (m)	Aquifer Depth (m)	Lithofacies	Aquifer/Aquitard
Holocene	Alluvium	6-12 most areas 24-27 syncline and fault		Silty clay	Semi-confining aquitard
			24-27 most areas 30-37 syncline 55 northern basin	Yellow brown sand and gravel	Main aquifer in Monywa Irrigation area
Mid Pleistocene	Irrawaddy Formation	2 (central), 35 (east)			Clay aquitard
			> 50	Blue sand	Aquifer

Aquifer: Hydraulic Conductivity: Alluvium: near hills (8 to 15 m/day), near Chindwin River and north (200 m/day) and south to Chaung-U (100 m/day). Irrawaddy Fm: uniform at 8 to 15 m/day.
Transmissivity: Alluvium: 1 to 15,000 m^2/day. Irrawaddy Fm: 20 to 170 m^2/day.

Storage Co-efficient: Alluvium 0.16 to 8 x 10^{-3}, Irrawaddy Fm. 10^{-4}.

Groundwater Yield: average: 330 ML/day

Water Level Response: Monitoring of 16 x 50 mm diameter wells for 2 years (GDC 1984) indicated no deterioration in water level, quality or yield. Monitoring then ceased for 33 years. Water level and salinity observation recommenced in April 2017 in one piezometer with pressure transducer and data logger.

Summary of Water Quality: (126 samples)

	TDS	EC	pH	Na^+	K	Ca^{2+}	Mg^{2+}	Fe^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
	(mg/L)	µS.cm^{-1}		(mg/L)							
Monywa (Number of analysis 126)											
Minimum	430	670	6.07	40	2.4	26.45	5.76	0.5	103	51.84	62
Maximum	2,000	3,150	8.45	1,580	25	177.8	64.92	4	516	295.6	284
Mean	938	1,452	7.55	146	7.1	66.1	23.8	1.8	226	158.5	122

Source: unpublished data from the Irrigation and Water Utilization Management Department (IWUMD)

Salinity generally increases from east to west. Pockets of high salinity (2,000 to 5,000 µS.cm^{-1}) on the eastern margin. Little variation in salinity at depth.

The MGIP has the following chemistry characteristics: EC 1,000 to 1,500 µS.cm^{-1} exceptions up to 2000 µS.cm^{-1}; RCS: 5 to 10 meq/L; and SAR: 2.5 to 7.5, some up to 12.5.

References: GDC (1983, 1984a-c), Pavelic et. al. (2015), Aung Khaing Moe (2016), IWUMD pers. comm.

Well No 3/12, Ring 3, Zaloke Village: November 2016
Specific Conductance: 1,300 µS.cm^{-1}, Total Dissolved Salts: 928 mg/L, pH: 7.4, Temperature: 30.2° C.

Well No 4/25, Ring 4, Kyehmon Village: November 2016
Specific Conductance: 1,290 µS.cm^{-1}, Total Dissolved Salts: 885 mg/L, pH: 7.3, Temperature: 29.4° C.

The actual command area (6,100 hectares) is substantially less than design. Problems include:

- 16 wells (> 10 percent) have been abandoned due to poor construction, mechanical/electrical failure or land rezoning. Of the 141 available tubewells, 120 are currently operational;
- regular power shortages and poor reliability due to overloads on the grid system;
- some farmers not paying for water and use their own tubewells;
- concerns about water quality. Some tubewells have:
- (2/67, 2/80, 2/141) near Chaung-U: moderate salinity hazard (> 2,250 µS.cm^{-1});
- in the north:
    - high alkalinity with Na > 80 percent (2/8, 2/51, 2/52, 2/73, 2/76, 2/77);
    - high sodium hazard (C3S4 – 2/52, 2/76 and C3S3- 2/8, 2/51, 2/73, 2/77); and
    - soil analyses show increase in pH and SAR (even during the Monsoon Season).

To improve irrigation efficiency many farmers (either individually or collectively) operate their own shallow tubewells, especially at the tail-end of the MGIP. Typically, 75-millimetre diameter cased holes are screened in the alluvial sand aquifer. Irregular power supply constrains pumping duration and water delivery to the tail-end users[99].

In the early 1980s many shallow gravel infilled wells were installed north and south of Monywa adjacent to the Chindwin River. The MGIP concept was for flood water to pass through the gravel and into the Alluvium. Due to the lack of maintenance the scheme is no longer functional and most infiltration wells have been infilled.

In April 2017, a data logger and pressure transducer were installed in a monitoring piezometer at the IWUMD office, Monywa to observe groundwater behaviour (salinity and water level) in the Alluvium Aquifer.

11.5 Copper Mining

The Monywa Copper Project (Sabe Taung, Kyising Taung and Letpadaung Taung ore bodies) is located west of Monywa and the Chindwin River along the Central Volcanic Line.

Alluvial sediments are deposited around the flanks of the copper (chalcocite) bearing volcanics. Groundwater studies have been reported[100]. The open cut mines are operated by Myanmar Wanbao Mining Copper Limited.

The volcanic rocks contain mainly compressional fractures and tight fault zones. **Table 38** indicates that hydraulic characteristics and groundwater yields are low due to the confining nature of the narrow fractures. Specific conductance varies from 1,000 to 19,000 µS.cm^{-1}.

Table 38 Aquifer Characteristics and Open Cut Inflow Calculations – Monywa Copper Mine

Geology	Aquifer Occurrence	Lithology	Thickness (m)	Permeability (m/day)	Unit Inflow (L/sec/m)
Quaternary Alluvium	Eluvial slope scree	silty clay, gravel, breccia	1- 22	0.1- 7.5, av. 3.4	
	Alluvium	Clay, sand, gravel, cobbles	12- 50	18- 44, av. 24	
Volcanic Rock Mass	Intensely weathered fissures	andesite – dacite	25- 140	2.9×10^{-4} - 6.7×10^{-2}, av. 1.60×10^{-2}	0.002 ~ 0.41, av. 0.080
	Weathered fissures	andesite – dacite	18 ~ 620, av. 250	2.8×10^{-4} - 2.4×10^{-3}, av. 1.80×10^{-3}	0.002~0.052, av. 0.032

Source: Coffey Partners International (1997), Knight Piésold (2013).

Groundwater inflow from the volcanics to the final planned depth at the Letpadaung Mine is predicted to be 37 L/sec. The volcanics are in hydraulic connection with the Alluvium. During mine dewatering, the water quality may be affected by acid rock drainage (ARD), resulting in low pH and high dissolved metal concentrations (Fe and Cu) in the brackish to saline water. A water management plan has been prepared.

Like other copper projects close to alluvial deposits there is potential for soil and groundwater contamination centered under the heap leach pad; other mineral processing and rock dump areas; and waste water facilities. No water quality reports on the mining operation have been made available for review.

99 Pavelic et. al. (2015)

100 Minproc Engineers Ltd (1996), AATA International Inc. (1996), Coffey Partners International (1997), Muir Environmental (1997), Knight Piésold (2000, 2013, 2015), MICCL (2004), MWMCL (2011), NFMKSDI (2011), SWNFDIC (2011) and SWNFKDIC (2012)

Fractured Andesite - Dacite Volcanics: Letpadaung
Total Dissolved Salts: 960 to 1,878 mg/L, pH: 3.3 to 8.3, Total Hardness: 340 to 421 mg/L. Trace metals: As, Cr, Cu, Fe and Mn occur at higher than guideline values.

Fractured Andesite - Dacite Volcanics: Heap Leach Pad
Total Dissolved Salts: 1,016 to 19,386 mg/L and pH: 6.9 to 8.7. Total Hardness and trace metals (As, Cr, Cu, Fe and Mn) are above guideline values.

Photo 46: Copper Workings, Kangone Village.
Source: *minesandscommunities.org*

Photo 47: Monywa Copper Mining and Plant.
Source: *Google Earth*

11.6 Groundwater Contamination

Like most large towns Monywa generates municipal and industrial wastes[101]:

- 52 tons of solid waste (paper, organic waste, glass, plastic, textile, metal and ash) is generated daily;
- over 20,000 septic tanks collectively generate one million litres per year;
- 588 industries generate metal contamination (sodium, potassium, iron, zinc, copper, cobalt), acids and alkalines, oils, solvents, food wastes and paints; and
- agricultural waste (animal effluent and agrochemicals) are stored and distributed.

Large agricultural areas grow watermelon for the China market. It appears that unregulated volumes of pesticides and fertilisers are applied to the crop. Where dugwells and tubewells are poorly sealed at the surface, urban and rural pollutants may contaminate soil and the underlying shallow aquifers. Chemical analysis of such contamination has not been undertaken.

11.7 Areas of High Groundwater Yield and Low Salinity

Figure 34 indicates the likely extent of high yield and low salinity areas. These are:

- the MGIP which is well documented by its 30-year operation;
- further north of Twin Taw Village and Budalin north; and
- the western alluvial flats close to the Chindwin River.

The brackish groundwater plume between Monywa and Chaung-U restricts the high yield and low salinity water to the south. The narrowing of the Chindwin River alluvial flats upstream of the volcanic craters limits the widespread irrigation potential to the northwest.

[101] Ma Theingi Oo (2006)

11.8 Water Balance Annual Recharge Estimation

Figure 38 shows the water balance. Base assumptions are:

- Aquifer Inputs:
- Recharge:
  - average rainfall of 914 millimetres (36 inches); and
  - 15 percent from rainfall[102] for the Alluvium and Irrawaddy Formation aquifers.
- Surface Water Infiltration:
  - irrigation return flow- calculated using total irrigation volume extracted (from both aquifers) and a return vertical infiltration of 30 percent;
  - assuming 75 percent of rainfall reaches the chaungs as surface flow, vertical infiltration from the sinusoidal and braided gravelly watercourses interconnecting with the unconfined aquifer is taken as 25 percent;
  - flooding for two to three months in the southern area is likely to enhance recharge. Calculating such input has proven complex. Since this area is in the southern periphery it is assumed that its flow will be southwards to outside of study area.
- Aquifer Outputs:
- groundwater withdrawal- based on known and assumed tubewell numbers (recorded and estimated), pumping times and discharge; and
- upward leakage is likely to occur (but without monitoring data it is speculative). A low number has been assigned (* in **Figure 38**), indicating it is not likely to influence the groundwater system.
- Change in Storage: There has been no hydrogeological monitoring. However, the long-term operation of the MGIP suggests that
- input flow = outflow flow; and
- there is no change in aquifer storage.

The shallow, unconsolidated Alluvium receives a large volume of water by infiltration recharge. The water balance model indicates that 27 percent of rainfall recharge is extracted by pumping from the Alluvium whilst 73 percent is discharged into the Chindwin River. It suggests that more groundwater could be extracted but caution is required in respect to impact to shallow tubewells, water quality and environmental requirements. North of Twin Taung East could be a new development area but need to look at soil types and water quality.

The MGIP has been operational for 30 years. Even though no hydrogeological monitoring has occurred since 1984 and water level decline in some shallow aquifers is reported, it appears that the groundwater irrigation system is possibly manageable.

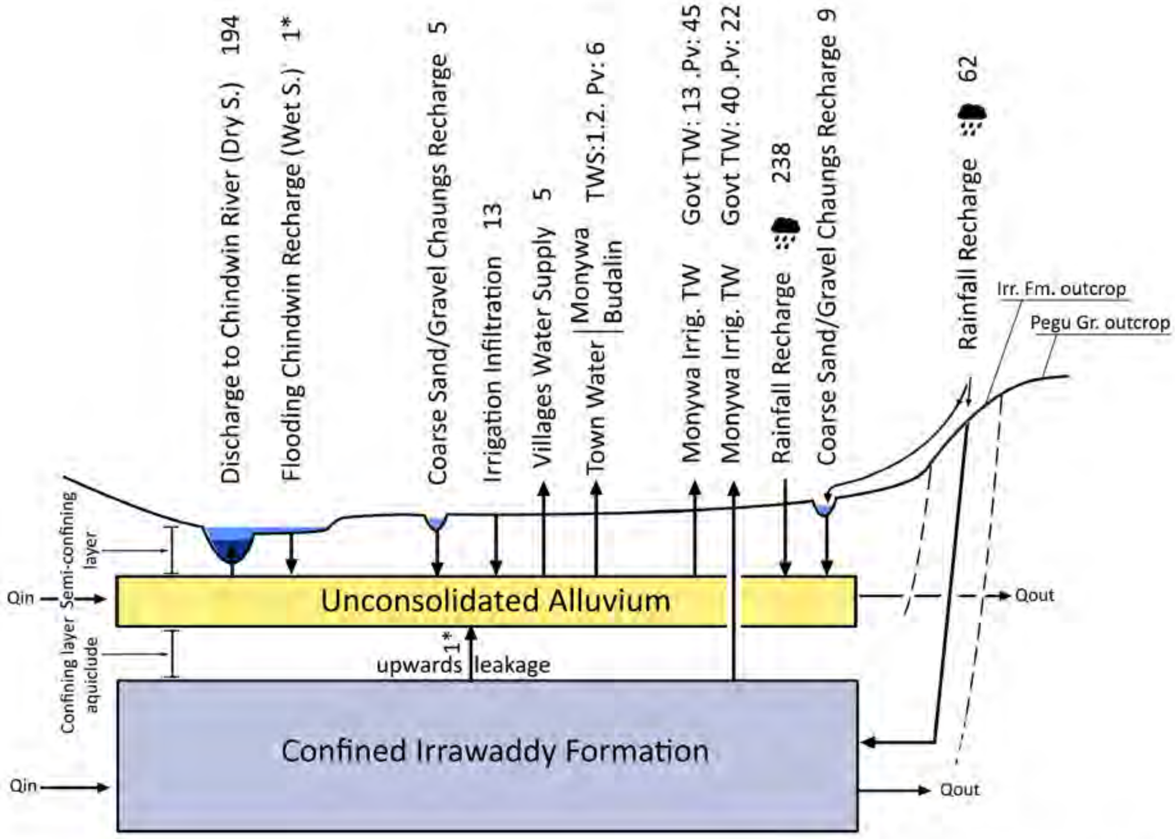
Future Research:

Due to a lack of long-term monitoring data the water balance has a myriad of assumptions. It is recommended that IWUMD install a series of long-term monitoring piezometers into Alluvium and Irrawaddy Formation aquifers. Individual piezometers targeting different aquifers would be required. This long-term data would assist in assessing if the water balance assumptions are reasonable. Vertical aquifer recharge from flooding and the chaungs need closer assessment.

In addition, a groundwater model should be developed to optimise MGIP wellfield operations.

[102] GDC (1984c), Than Zaw (2010), van Ramshorst (2017)

Figure 38 Water Balance for Main Aquifers in the Lower Chindwin River Valley



Units: Annual volumes in Mm^3

12 Hydrogeology of the Lower Mu River Valley

12.1 Introduction

Sagaing is the administrative centre of the Sagaing Region. It is mainly built around Sagaing Ridge which attains an elevation of 406 m AMSL. Annual average rainfall at Shwebo and Ayadaw is around 800 millimetres.

Since the ninth century surface water irrigation has been developed with rice extensively grown. Diversion weirs on the Mu River supplied water to a multiplicity of distribution canals. A major transformation in irrigation development was the 2001 construction of Thaphanseik Dam (located north of the Dry Zone). This multipurpose dam is six kilometres long making it one of the largest dams in South East Asia. The dam enables year-round irrigation (three crops) over a potential command area of half-a-million hectares with feeder canals extending to eight townships. This Mu River Irrigation Project is one of the largest in Myanmar. Recently river pumping stations have been constructed near Ayadaw to increase the area of surface water irrigation. Due to the availability of perennial surface water there is little need to develop groundwater irrigation areas, except near Ayadaw.

The Mu River drains the Kabaw Valley (north of Dry Zone) and then meanders roughly north-south through the valley centre to meet the Ayeyarwady River near Myinmu.

The Mu River Valley occupies most of the Shwebo-Monywa Basin of the Eastern Trough. It is located on the northern extension of the Bago Yoma Anticlinorium; east of the Central Volcanic Line along the Kyaukka Range; west of the Shan Plateau and the Sagaing Fault; and bounded northwards by the Wuntho Massif[103] (north of **Figure 39**). The Lower Mu River Valley consists of undulating peripheral hills and the central alluvial plain. The surface elevation of the alluvial flats varies between 76 to 120 m AMSL.

There are several geological and hydrogeological reports on the Mu River Valley[104]. A summary of geological and hydrogeological information between Taze and Sagaing is shown on **Figures 39** to **41**. The area is not structurally complex. Two long NNW-SSE orientated multiple plunging synclines are present (Ayadaw and Shwebo synclines) separated by a slightly elevated bedrock ridge. The western hydrogeological boundary is the easterly dipping Pegu rocks along the Kyaukka Range and further north by the Irrawaddy Formation. The eastern boundary includes metamorphic, igneous and Eocene rocks associated with the north-south orientated strike-slip Sagaing Fault. To the south the hydrogeological boundary is the northern extensions of the Bago Yoma (including the Legyi Anticline). All the boundaries and internal geological structures have an impact on groundwater occurrence and quality.

Table 39 gives examples of tubewell and aquifer data in various rock types within the valley. Significant groundwater resources exist within this valley.

[103] North of study area

[104] Fermor (1934), Aung Ba (1962), Italconsult (1970), Nyunt Lwin (1980a,b, 1981), Nyunt Lwin et. al. (1980, 1984a,b), Soe Aung et. al. (1982, 1984, 1985), Thein Nyunt (1982), GDC (1983b, 1984c), Myint Soe et. al. (1984), Thein Tun & Shwe Ko (1984), Kyaw Shwe (1985), Thein Tun & Kyaw Shwe (1985), JICA (1985), Ngwe et. al. (1986), Win Naing (1988), Than Zaw (2010), Khin Chan Myae Cherry Maung (2014), Aung Khaing Moe (2016), Khin Aung Thein (2016), Than Zaw (2016), Than Zaw et. al. (2016)

12.2 Pegu Group

Lower to Middle Miocene age rocks form the core of the anticlinal axis along the Kyaukka and Legyi anticlines and bedrock at a shallow depth as these rocks plunge beneath the Alluvium.

Many tubewells sunk into the Pegu Group rocks on the low lying Legyi Anticline have been abandoned due to the poor groundwater yields and salinity (3,000 to more than 15,000 µS.cm^{-1}). The dominant ions are Na+:Cl$^-$ and Ca^2+:SO4^{2-}. The Sadaung Village monastery tubewell intersected two Pegu Group aquifers (137 and 200 metres) beneath a shallow alluvial cover. The combined salinity of the Na+:Cl$^-$ type waters was 17,200 µS.cm^{-1}. Consequently, the hole was abandoned. A privately donated tubewell in the same compound (30 metres away) intersected a shallow alluvial aquifer from 34 to 45 metres containing Na^+:Cl^- type water with a lower salinity of 4,520 µS.cm^{-1}. The high salinity and type of ion dominance suggests an upward movement of groundwater from the Pegu Group into the Alluvium. Groundwater from all aquifers beneath Sadaung are saline and unsuitable for human consumption. Two kilometres north, low salinity water is available from dugwells in shallow alluvial aquifers.

The salinity of groundwater between Sadaung to Yemyet In and north to Halin is usually between 2,000 to greater than 10,000 µS.cm^{-1}.

A few tubewells are located along the elevated Kyaukka Range. Most have been abandoned as the electrical conductivity of the Na^+:Cl^- type water usually exceeds 3,000 µS.cm^{-1}. Along the base successful tubewells have intersected easterly dipping fractured rock aquifers of the Pegu Group, after penetrating a thin, unsaturated sequence of Irrawaddy Formation. The rocks consist of fine-medium grained, micaceous sandstone, and laminated shale with some hard-ferruginous bands. Aquifers are intersected between 90 to 180 metres. Most yield less than 4 L/sec from aquifers with a transmissivity range of three to 20 m^2/day. Tubewells at Wetkya and Letpankyin, encountered highly fractured aquifers between 124 and 141 metres associated with faults with a potential tubewell yield of 10 L/sec. The specific conductance is below 1,500 µS.cm^{-1}. In contrast to other Pegu Group aquifers, the water is dominantly Na^+:HCO_3^-, probably indicating a short residence time of the water in contact with the marine deposit.

12.3 Irrawaddy Formation

The Irrawaddy Formation is composed of weakly consolidated medium to coarse sand, sandstone, clay and intercalated gravel. Colour variations are yellow, brown to blue.

Sediments in the Ayadaw Syncline consist of shallow yellow brown sand, silt and clay overlying deep blue grey, medium to coarse grained sand, fine gravel and clay. Some deep aquifers are up to 30 metres thick. By contrast the Shwebo Syncline consists of finer grained, thinner bedded aquifers. Due to its extensive nature and variability in aquifer characteristics the Irrawaddy Formation has been divided into several geographical locations.

12.3.1 Ayadaw Syncline

12.3.1.1 Groundwater Occurrence

There are many tubewells intersecting porous granular aquifers at depths of 40 to 400+ metres, with potential tubewell yields exceeding 50 L/sec. Most high yield aquifers are aligned along or near the axis of the Ayadaw Syncline where many aquifers are artesian. The whole western side of the Mu River Valley may contain one continuous deep confined aquifer system with salinity less than 1,500 µS.cm^{-1}.

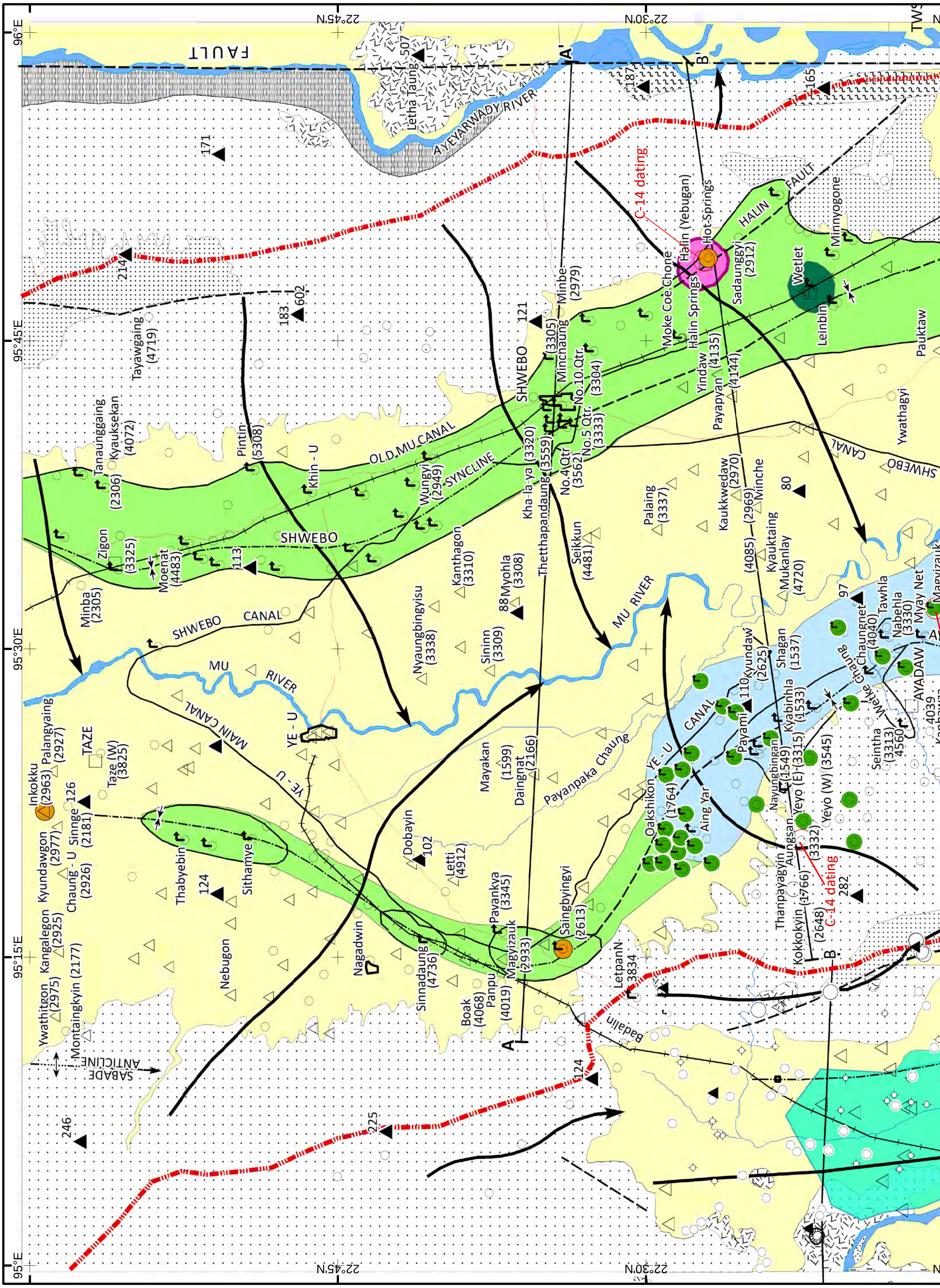


Figure 39 Schematic Geological and Hydrogeological Map: Lower Mu River Valley

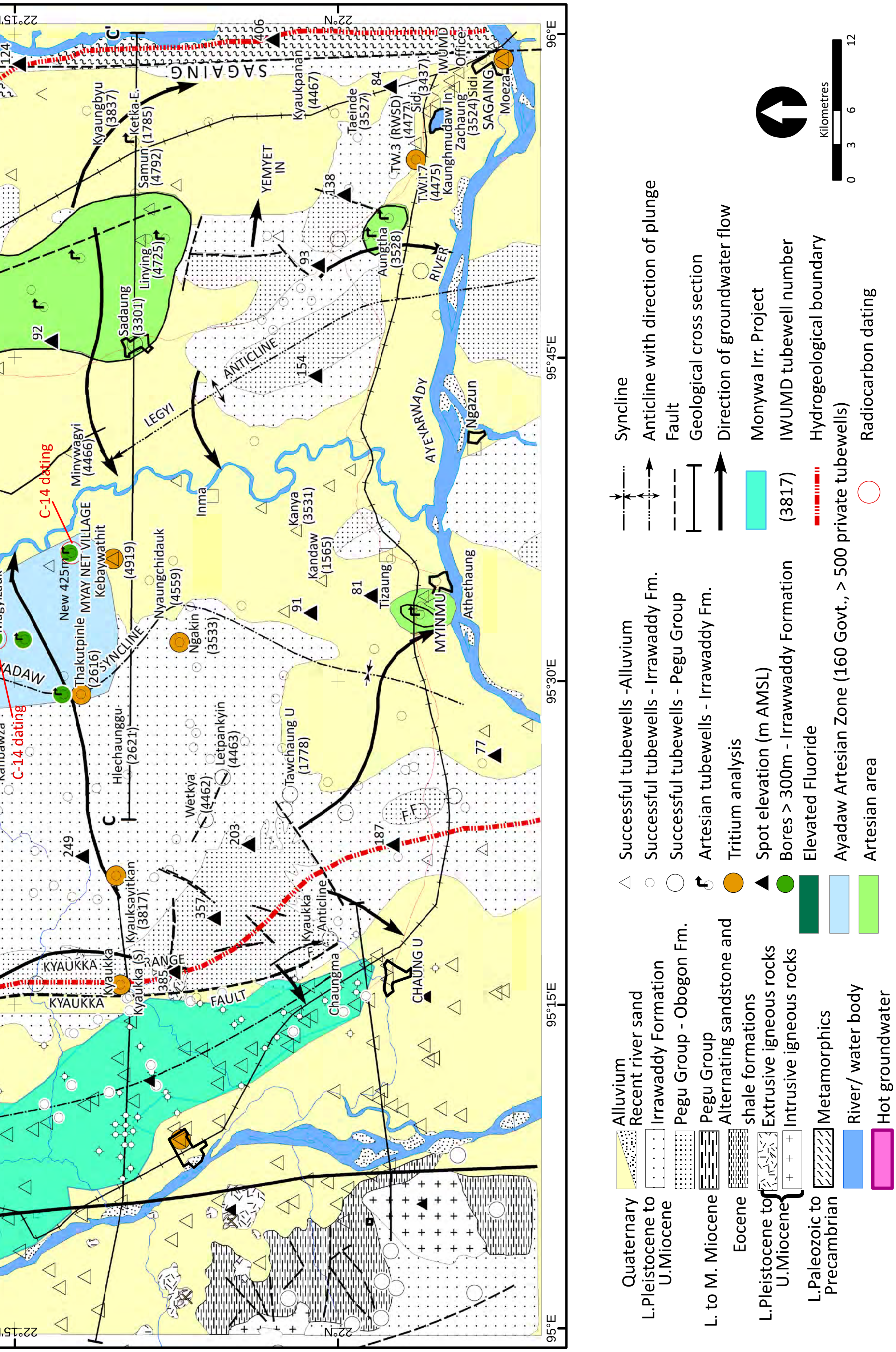
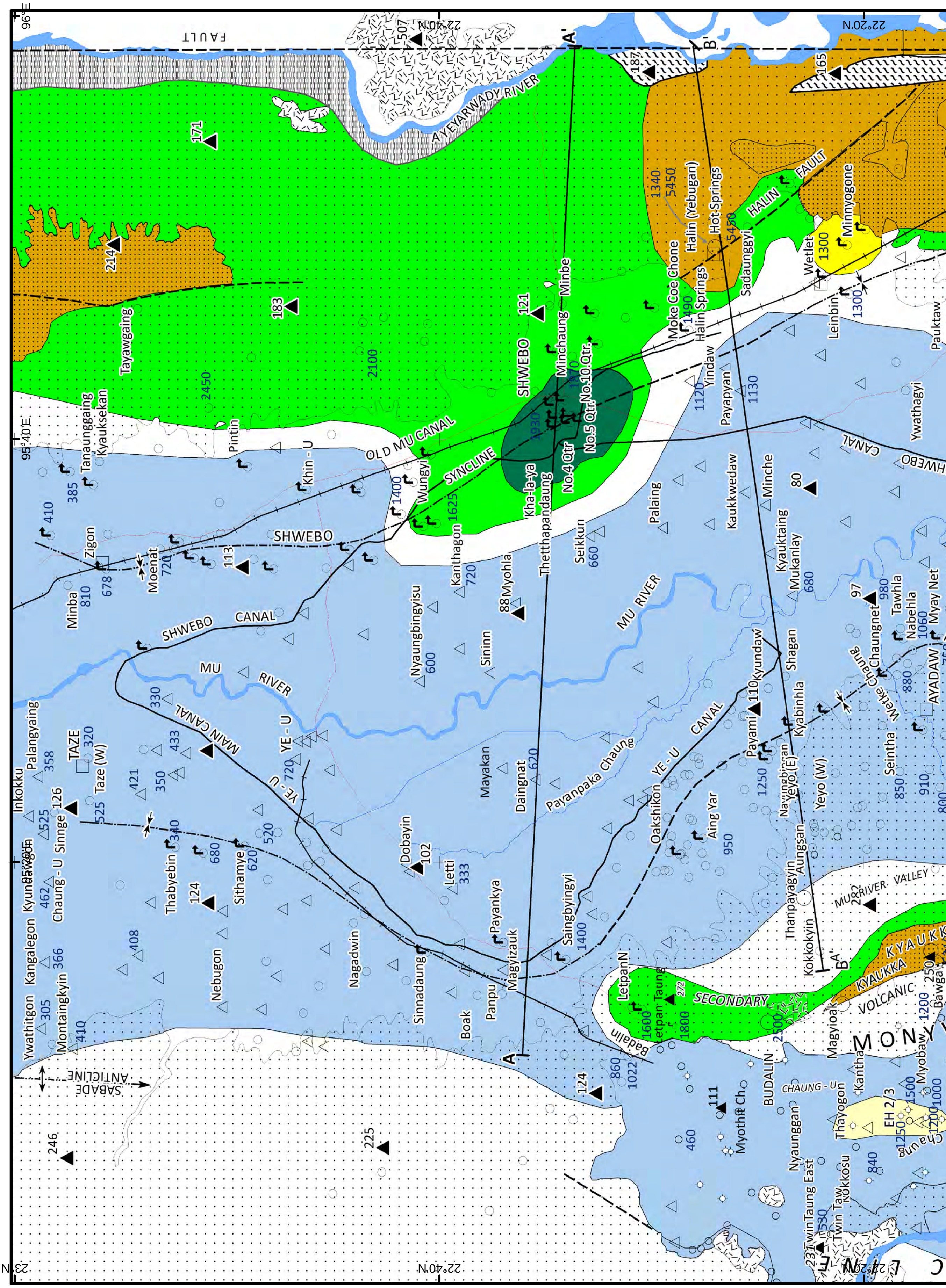
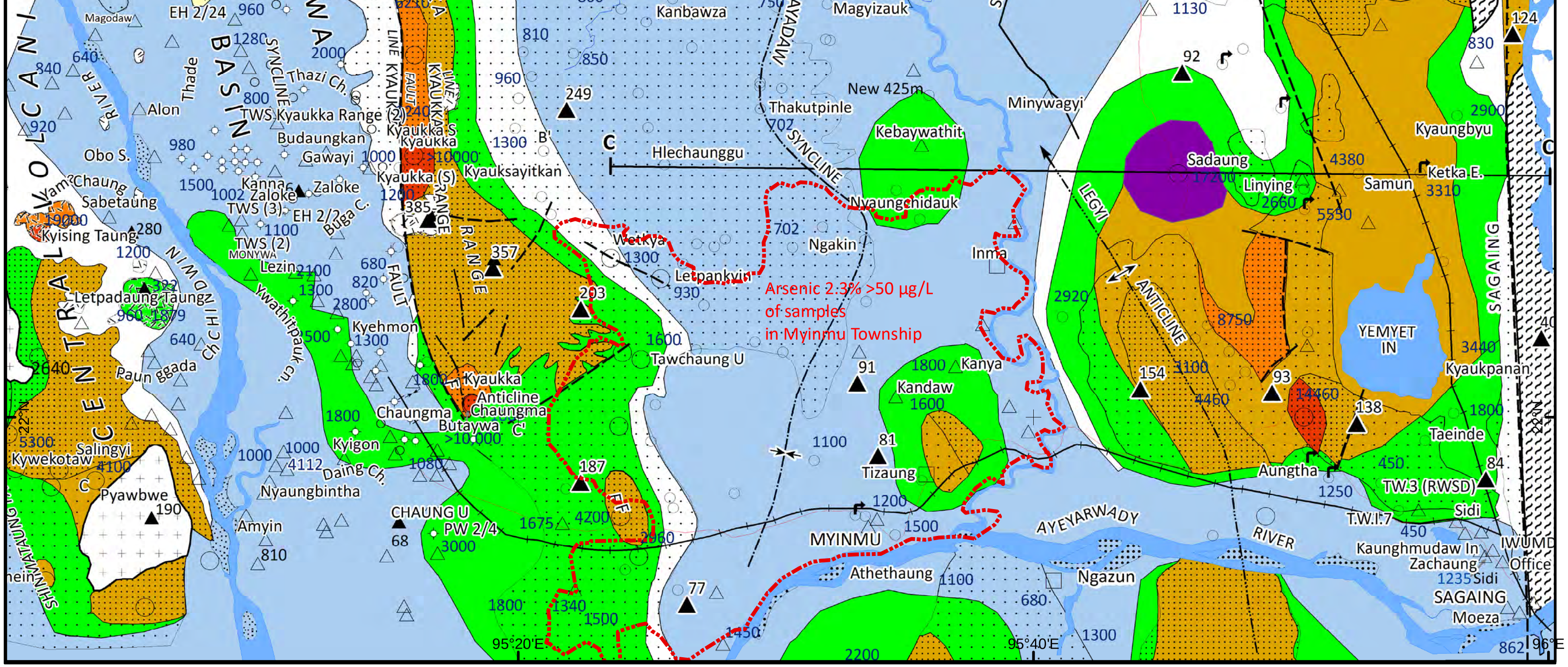

Quaternary
Alluvium
Recent river sand
L.Pleistocene to U.Miocene
Irrawaddy Formation
Pegu Group - Obogon Fm.
L. to M. Miocene
Pegu Group
Eocene
Alternating sandstone and shale formations
L.Pleistocene to U.Miocene
Extrusive igneous rocks
Intrusive igneous rocks
L.Paleozoic to Precambrian
Metamorphics
River/ water body
Hot groundwater
Successful tubewells -Alluvium
Successful tubewells - Irrawaddy Fm.
Successful tubewells - Pegu Group
Artesian tubewells - Irrawaddy Fm.
Tritium analysis
Spot elevation (m AMSL)
Bores > 300m - Irrawaddy Formation
Elevated Fluoride
Ayadaw Artesian Zone (160 Govt., > 500 private tubewells)
Artesian area
Syncline
Anticline with direction of plunge
Fault
Geological cross section
Direction of groundwater flow
Monywa Irr. Project
(3817) IWUMD tubewell number
Hydrogeological boundary
Radiocarbon dating
Kilometres
0 3 6 12
C-14 dating
SAGAING
MYINMU
CHAUNG U
KYAUKKA
AYEYARWADY RIVER
LEGYI ANTICLINE
SYNCLINE
KYAUKKA FAULT
95°E
95°15'E
95°30'E
95°45'E
96°E
22°N
22°15'N

Figure 40 Schematic Hydrogeological and Hydrochemical Map: Lower Mu River Valley





Geology (see Figure 39)

Specific Conductance (μS.cm^{-1} at 25°C)

- <1,500
- 1,500 - 3,000
- 3,000 - 6,000
- 6,000 - 10,000
- >10,000
- <2,500 near surface, >10,000 at depth
- >10,000 near surface, <1,500 at depth
- >6,000 near surface, <2,000 at depth

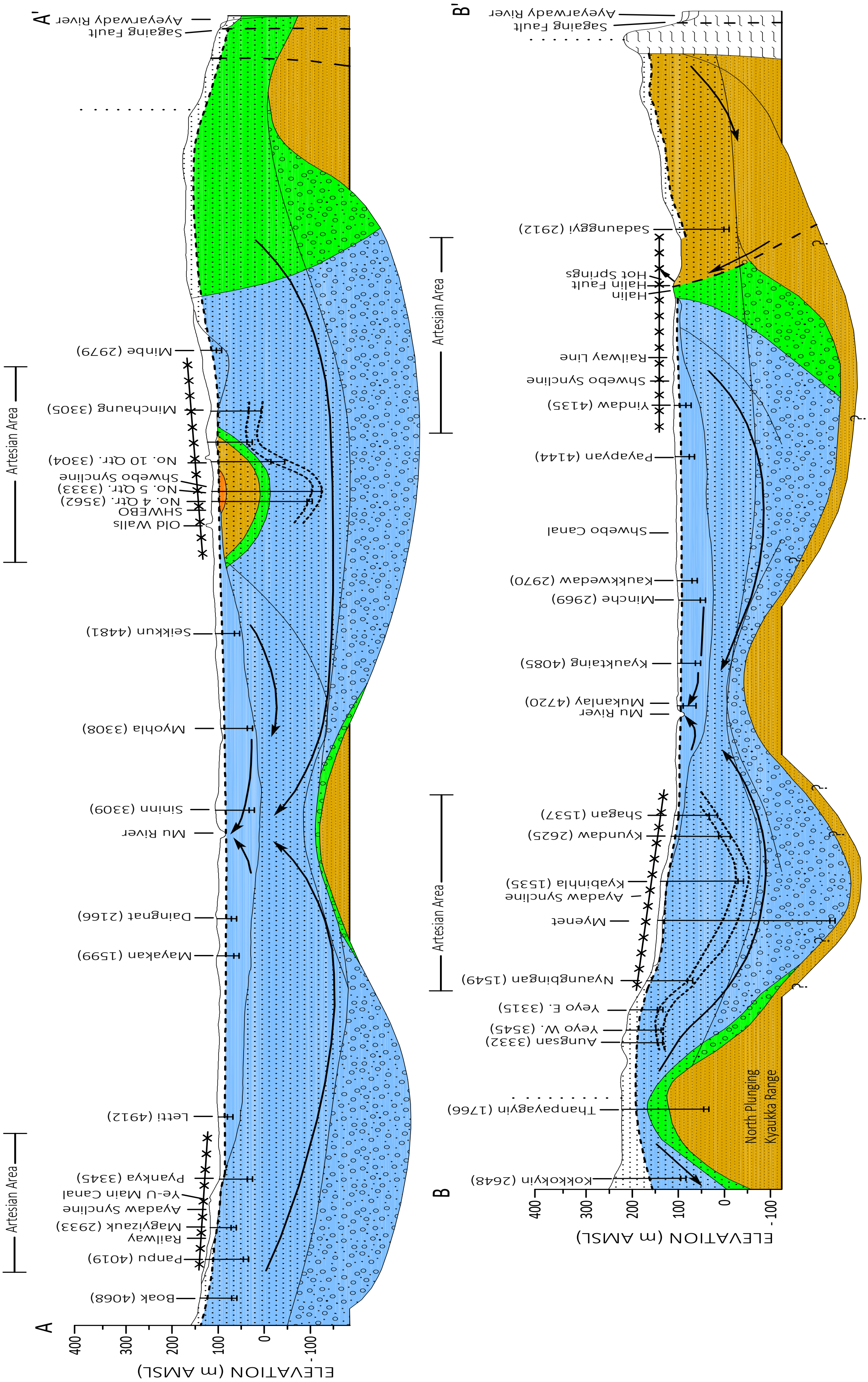
- High alkalinity hazard & sodium
- Potential high yield (>6 L/sec) / low salinity (<1,500 μS.cm^{-1})

- △ Successful tubewells -Alluvium
- ○ Successful tubewells - Irrawaddy Fm.
- ◯ Successful tubewells - Pegu Group
- ↱ Artesian tubewells - Irrawaddy Fm.
- 1100 Specific conductance (μS.cm^{-1})
- Arsenic >50 μg/L within township

Kilometres
0 3 6 12

NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occur

Figure 41 Hydrogeological Cross Section and Specific Conductance: Lower Mu River Valley



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Figure 41 (continued)   Hydrogeological Cross Section and Specific Conductance: Lower Mu River Valley

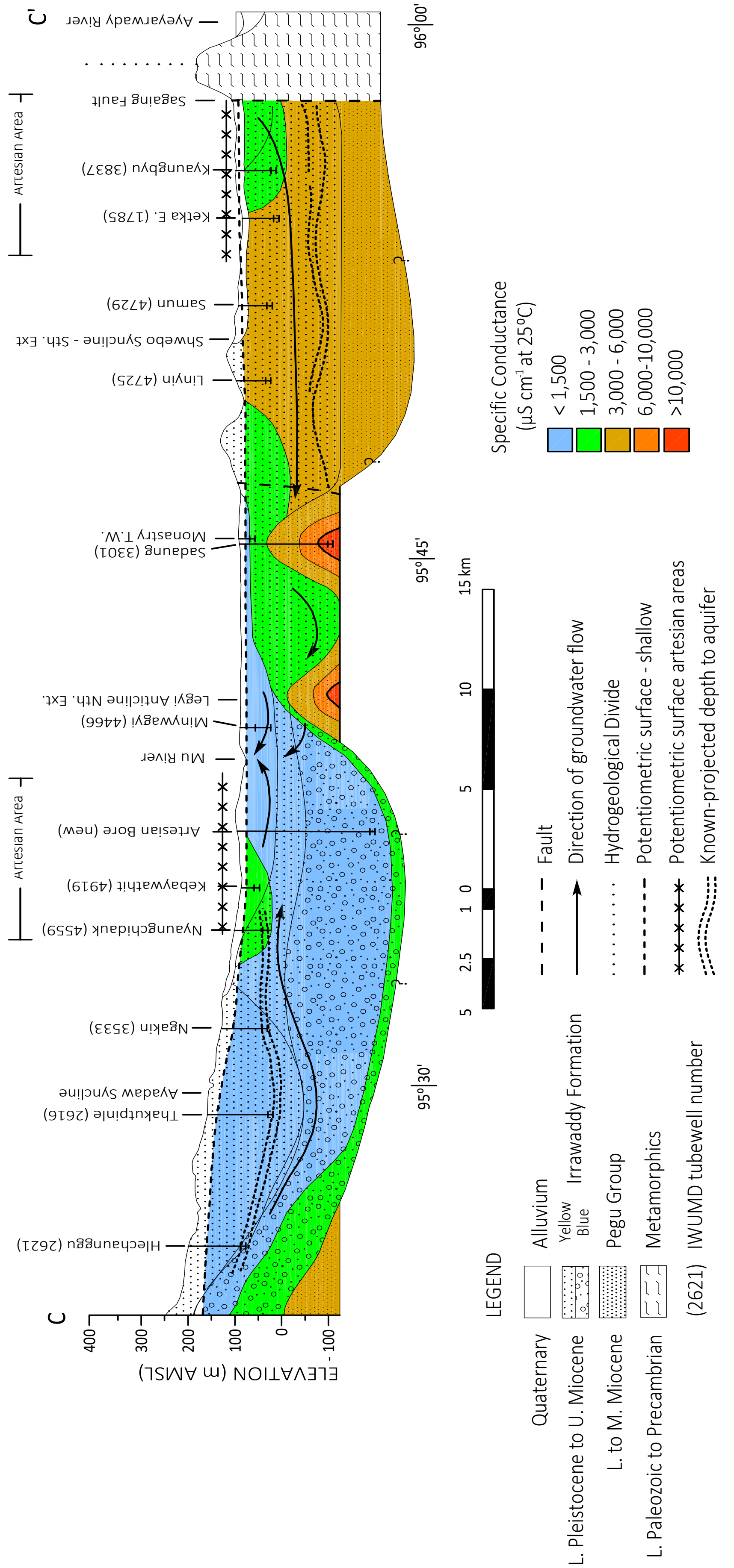


Table 39 Details of Aquifers in Various Rock Types in Different Areas of the Mu River Valley

Formation	Area	Village	Tubewell number	Surface Elevation (m AMSL)	All data from surface (m)					Airlift Yield (L/sec)	Transmissivity (m^2/d)	Specific Conductivity ($\mu S.cm^{-1}$)
					Depth	Aquifer	SWL	DDL	DD			
Pegu Group	Legyi Anticline	Sadaung	3301	+ 84	204	144- 166 177- 200	0	159	159	1 flow	1	17,200
	Kyaukka Anticline	Letpankyin	4463	+ 206	142	137- 141	48	61	13	8	58	930
		Taw Chaung-U	1778	+ 152	134	79- 85 122- 131	98	111	13	1	5	1,600
Irrawaddy Formation	Ayadaw	Aungsan	3332	+ 190	83	75- 82	43	48	5	3	60	770
		Seintha	3313	+ 183	76	74- 76	0	24	4	28	790	850
		Chaungnet	4040	+ 137	159	140- 156	> + 15			10 flow	1,080	880
		Myay Net No.1	21287	+ 140	396	366- 385	+ 15			22 flow		750
		Myay Net Village		+ 134	430	405- 423	+ 13			25 flow		820
		Oakshitkyi	21290	+ 156	410	367- 385	+ 10			22 flow		1,060
		Tawhla	21297	+ 155	360	338- 353				16 flow		980
	Dabayin	Saingbyingyi	2613	+ 119	168	156- 165	0	-	-	23 flow	-	1,400
		Letpan North	3834	+ 145	61	47- 58	+ 2	6	4	14	350	1,600
	Khin U	Wungyi	2949	+ 110	78	52- 76	0	3	3	4 flow	137	1,400
		Moenat	4483	+ 127	113	105- 111	5	14	9	9	107	720
	Shwebo town	Thetthapan-daung	3559	+ 111	256	229- 250	0	-	-	1 flow	-	1,930
		Kha-la-ya	3302	+ 115	198	157- 190	0	7	7	1 flow	11 flow	1,870
	Sagaing	Taeinde	3527	+ 99	111	91- 109	9	15	6	12	200	1,800
		Aungtha	3528	+ 90	84	34- 79	0	18	18	3 flow	18	1,240
Alluvium	Dabayin	Daingnat	2166	+ 95	41	30- 38	1	2	1	4	450	620
	Taze	Palangyaing	2927	+ 121	41	24- 38	3	5	2	7	277	358
	Myinmu	Kandaw	1565	+ 78	47	36- 44	9	11	2	3	188	1,600
		Kanya	3531	+ 88	49	24- 44	18	21	3	7	277	1,800
	Northwest Shwebo	Nyaungbin-gyisu	3338	+ 95	66	49- 62	1	6	5	23	555	600
		Kanthagon	3310	+ 96	110	102- 106	23	30	7	19	282	720
	West Shwebo	Seikkun	4481	+ 91	49	15- 44	2	3	1	15	1,035	660
	Southwest Wetlet	Minywagyi	4466	+ 79	64	26- 60	8	15	7	26	358	1,100
	Northwest Wetlet	Yindaw	4135	+ 88	24	15- 21	2	3	1	4	647	1,120
	Sagaing	Zachaung	3524	+ 79	43	25- 37	12	13	1	21	3,550	1,235
		Test Well 3	4477	+ 85	43	31- 38	13	14	1	19	2,177	450

Source: IWUMD database, Than Zaw (2010) and Umbrella Reports (GDC 1979-1984).

12.3.1.2 Taze to Ye-U

High groundwater yielding aquifers from both Irrawaddy Formation and Alluvium are located near the towns of Taze and Ye U. Individual sand and gravel units may be greater than 50 metres thick over the synclinal axis. The aquifers should be considered as one hydrogeological unit where vertical leakage and lateral flow are equally important. There is considerable heterogeneity within the sediment column, with aquifers occupying 10 to 90 percent of a tubewell log. This area can be subdivided into two regional aquifer units[105]:

- east of Taze and Ye U – 'Unit A'- upper clay thickness is six metres overlying 70 percent aquifer availability (permeability 100 to 150 m/day); and
- west of Taze and Ye U – 'Unit B' – upper clay thickness is around 50 metres.
  - where the water table is zero to six metres below the surface, the upper 140 metres of sediment should have 30 percent aquifer availability. At greater depth, there may be 70 percent aquifer availability (permeability 10 to 40 m/day); and
  - where the water table is six to 12 metres below the surface, the sediment above 75 metres should have 30 percent aquifer availability. Deeper profiles should contain 70 percent aquifer availability (permeability 10 to 40 m/day).

Along the synclinal axis many tubewells are artesian. They intersect blue grey sand and gravel at depths of 34 to 320 metres, with flow exceeding 20 L/sec and potentiometric heads of 10 metres. Transmissivity ranges from 13 to 1,200 m^2/day, the average around 280 m^2/day. Combined aquifer thickness varies from 30 to 220 metres. Specific conductance is below 1,500 $\mu S.cm^{-1}$.

Groundwater yields from individual production tubewells in Units 'A' and 'B' should exceed 50 and 25 L/sec respectively. Both aquifer types have a $Ca^{2+}:HCO_3^-$ dominance with salinity less than 1,500 $\mu S.cm^{-1}$. Groundwater throughflow may be 150 L/sec/linear kilometre. Due to surface clay thickness, rainfall recharge to Units 'A' and 'B' is assumed to be 14 and seven percent respectively.

Some low yielding aquifers occur in the Chindwin River Valley border area.

12.3.1.3 Ayadaw Artesian Zone

A continuous clay and sandy clay sequence, up to 180 metres thick is located beneath the town of Ayadaw and extends for one kilometre to the east and southeast. Discharge from tubewells in this area is usually below 1 L/sec. Most low yielding aquifers are encountered 37 to 90 metres below the surface[106]. Average transmissivity varies from 10 to 70 m^2/day. The specific conductance of the $Na^+:HCO_3^-$ type water is less than 1,500 $\mu S.cm^{-1}$.

Aungsan Village Tubewell, Recharge area to Ayadaw Artesian Zone: May 2017
Specific Conductance: 460 $\mu S.cm^{-1}$, Total Dissolved Salts: 331 mg/L, pH: 7.1, Temperature: 31° C.

The 'Ayadaw Artesian Zone' (AAZ) is located several kilometres to the east and north of Ayadaw over the synclinal axis. There are three aquifers:

- Aquifer 1- shallow, unconfined laterally discontinuous, shallow yellow sand aquifer, flow 2 to 10 L/sec;
- Aquifer 2- confined, laterally discontinuous yellow/brown sand and gravel, flow of 2 to > 20 L/sec; and

[105] GDC (1983b)
[106] Nyunt Lwin (1981)

- Aquifer 3- confined, laterally continuous, deep blue/grey sand and gravel, flow 4 to > 30 L/sec.

The AAZ contains:

- > 60 large-diameter, deep government tubewells supplying village and irrigation water supplies; and
- some 500 private, smaller tubewells for similar purposes.

Drilling depth exceeds 300 metres in 23 of the government tubewells (**Figure 39**), the deepest being 425 metres. The aquifer is usually open at drilling termination.

Hydrogeological studies[107] on the AAZ have recently been reported.

The general trend is for higher artesian discharge from the deeper tubewells with thick aquifer systems (> 30 metres). Within Aquifer 3 the northern and south-eastern areas have the highest groundwater flow. Between Oakshitkon and Thakutpinie villages the potential pumping yield capacity is more than 100 L/sec. The deep aquifer system extends at least 15 kilometres east of the axis to Myay Net Village.

Artesian flows have reportedly declined in the AAZ but not as much as the Pale Sub-basin (IWUMD pers. comm.).

The average salinity from the shallow and deeper Na^+:HCO_3^- type aquifers are similar (800 to 1.500 $\mu S.cm^{-1}$). Forty two percent of groundwater from 'Aquifer 2' lies within classification C3-S3, C3-S4, C4-S2, indicating poor quality for irrigation purposes. Thirty three percent of groundwater from the deeper aquifer fits the same classification.

Most farmers do not comprehend water management issues. Although some have gate valves fitted, flow is not terminated during the non-irrigation periods. Many discharge points are overgrown with weed and reeds.

Photo 48: Myay Net Village DTW, Irrawaddy Fm. Source: U Ngwe

Photo 49: Myay Net No. 1 Irrigation DTW. Source: U Ngwe

Aquifer recharge in the AAZ is in excess of 120 million m^3/annum (15 percent of rainfall)[108].

107 Than Zaw (2010), Aung Khaing Moe (2016), Khin Aung Thein (2016), Than Zaw (2016), Than Zaw et. al. (2016)
108 Than Zaw (2010)

Project: Ayadaw Artesian Zone

Number of Tubewells: 60+ artesian tubewells.

Implementing Agency: IWUMD.

Operator and Major Maintenance: Village water groups.

Artesian Flow: Variable groundwater discharge flows from 2.5 to 30 L/sec; average 12 L/sec.

Total Artesian Flow: Collectively 80 MCM (40 MCM from Government DTW and 40 MCM by private TW).

Potentiometric Surface: Minimum: one metre, maximum: 50 metres, average 15 metres- depending on depth to aquifer and topographic relief.

Pressure Drop: zero to three metres. All tubewells still flowing but pressure head and yield less.

Depth to Base of Aquifer 3: Assume 500 metres.

Aquifer Systems:

1. unconfined Alluvium;

2. confined Irrawaddy Formation; and

3. confined Irrawaddy Formation.

Photo 50: Myay Net No. 1 Irrigation DTW. Pressure Head > 50 m

Potentiometric Surface Response: IWUMD has no monitoring program for this aquifer system.

Geology

Geology	Unit		Aq. Condition / Depth (m)	Lithofacies	Location	Flow (L/sec)
Holocene	Alluvium		Unsaturated	Brown/yellow sand	Widespread, variable thickness	
		1	Unconfined Aquifer / 15	Brown yellow sand	E., N. and SE of Ayadaw. Absent to W. Thins E. Laterally discontinuous	2 – 16
Lower Pleistocene to Mid Miocene	Irrawaddy Formation	1	Aquitard	Yellow clay / silt	Laterally discontinuous	
		2	Confined Aquifer / 120-180	Yellow brown sand, minor gravel	Mainly N and E of Ayadaw. Laterally discontinuous	2 – > 20
		2	Aquitard	Blue clay / silt	Laterally continuous	
		3	Confined Aqu. 240-> 450	Grey / blue sand and gravel	Thins to west and east. Laterally continuous	4 – > 30

Aquifer Parameters:

	Aquifer 1	Aquifer 2	Aquifer 3
Hydraulic Conductivity (m/day)	15- 100	2- 100	Not tested
Transmissivity (m^2/day)	58-1,035, av. 680	20- 280, av. 48	20 to 1,000, av. 210
Storage Co-efficient	0.2	10^{-4}	10^{-4} to 10^{-5}
Specific Capacity (L/sec/m)	4.5	2- 400	Not tested

Water Quality for Aquifers 2 and 3: See **Table 40**

Myay Nat No. 1 Artesian Tubewell: November 2016
Specific Conductance: 1,060 $\mu S.cm^{-1}$, Total Dissolved Salts: 760 mg/L, pH: 8.1, Temperature: 35.9° C.

Myay Nat No. 1 Artesian Tubewell: May 2017
Specific Conductance: 770 $\mu S.cm^{-1}$, Total Dissolved Salts: 530 mg/L, pH: 7.9, Temperature: 35.7° C.

Myay Nat Village Artesian Tubewell: May 2017
Specific Conductance: 820 $\mu S.cm^{-1}$, Total Dissolved Salts: 585 mg/L, pH: 8.4, Temperature: 36.5° C.

Payami Village Artesian Tubewell: November 2016
Specific Conductance: 1,250 $\mu S.cm^{-1}$, Total Dissolved Salts: 900 mg/L, pH: 8.4, Temperature: 30.4° C.

Aing Yar Village Artesian Tubewell: November 2016
Specific Conductance: 950 $\mu S.cm^{-1}$, Total Dissolved Salts: 687 mg/L, pH: 7.8, Temperature: 29.8° C.

Typical chemistry analysis for groundwater within the Ayadaw Artesian Zone is given on **Table 40**.

Table 40 Summary of Chemical Analyses for Aquifers 2 and 3, Ayadaw Artesian Zone

Chemical parameter	Units	Shallow Irrawaddy Fm – Aquifer 2			Deep Irrawaddy Fm – Aquifer 3		
		Range	Average	St Dev.	Range	Average	St Dev.
pH		7.2 – 7.7	7.5	0.2	6.1- 8.1	7.1	0.6
EC	$\mu S.cm^{-1}$	697- 1,244	997	176	231 – 1,288	999	237
Ca^{2+}	mg/L	12- 106	59	29	6 – 95	42	20
Mg^{2+}		2- 19	7	5	0 – 16	4	4.1
K^+		3- 9	3.5	1.8	1 – 4	2.8	1.2
Na^+		56- 464	352	130	77- 321	331	56.9
CO_3		29- 66	10.3	8.8	19- 52	36	9.8
HCO_3^{2-}		300- 508	402	60	377- 483	431	03.9
SO_4^{2-}		7- 180	81.4	44.3	3- 141	40	40.0
Cl^-		34- 118	66	24	28- 99	63.8	18.7
SAR		1.3- 31.7	10.2	8.8	3.1- 23	10.1	5.2

Source: Than Zaw (2010).

12.3.1.4 Age of Groundwater

Tritium analysis of groundwater from Ngakin, Saingbyingyi, Inkokku, Kyauksayitkan and Kebaywathit villages around the Ayadaw Syncline indicates a pre-thermonuclear age.

Radiocarbon dating of groundwater from Aungsan Village, Myay Net No.1 Irrigation and Myay Net Village tubewells are shown on **Table 41**. Along the flowpath the C-14 age ranges from 1,350 to 9,800 years, indicating that recharge takes place in the Irrawaddy Formation near the Kyaukka Range (Aungsan Village) and move slowly downgradient to the deep sediments in the Ayadaw Syncline (Myay Net No.1 Irrigation and Myay Net Village). Groundwater movement between the latter two tubewells is 20 metres per year.

Table 41 Radiocarbon Dating of Groundwater in the Mu River Valley

Location	Depth (m)	Screen (m)	Formation	Sample 2017	C-14 Dating (years)	Comment
Aungsan Village	83	75- 82	Irrawaddy Fm.	13th May	1,355 ±30	Recharge Area
Myay Net No. 1	396	366- 385	Irrawaddy Fm.	13th May	9, 175 ± 40	In Ayadaw Synclinal axis
Myay Net Village	430	405- 423	Irrawaddy Fm.	13th May	9,790 ± 40	East of syncline axis
Yebugon Village Halin Hot Spring	+1		Pegu Group	13th May	26,120 ± 120	Intersection of Halin and Sagaing Faults

12.3.2 Shwebo Syncline

12.3.2.1 Shwebo Area

Only a small number of high yielding aquifers are located east of the Mu River, mostly in the Shwebo Syncline at depths ranging from 37 to 227 metres. These aquifers are composed of yellow-brown, fine to coarse-grained sand overlying blue, finer grained sediment with increased clay content. They have lower aquifer hydraulic characteristics and lower potential yield than the AAZ. The average transmissivity is 75 m^2/day (compared to 210 m^2/day in the Ayadaw Syncline).

Artesian aquifers at depths of 55 to 240 metres occur along the full length of the syncline. Artesian flow is between 0.3 to 5 L/sec. The specific conductance of the Na^+:HCO_3^- type water is usually below 1,500 µS. cm^{-1}.

> **Shwebo Town Water Supply**
>
> **Operator:** Shwebo Township Development Committee.
>
> **Sources:** municipal water from both surface water and groundwater:
>
> **Surface Water:** with the construction of Thaphanseik Dam (2001) 80 percent of Shwebo's reticulated municipal water supply comes from surface water.
>
> **Groundwater:** between 1980 and 2000 Shwebo received its total municipal water supply from low yielding (1 to 5 L/sec) artesian tubewells sunk to 130 metres in the Irrawaddy Formation. In 2016 one JICA and three Committee DTWs remain operational, cumulatively yielding 680 m^3/day.
>
> **Other:** Within Shwebo Town there are 1,430 STWs and 460 DTWs, cumulatively yielding 3,600 m^3/day. By 2020 it is planned to fully reticulate surface water to the town.
>
> Community dugwells in Shwebo Township report faecal and total coliforms from villages and urban/market areas.

In Shwebo Town artesian aquifers are encountered at 60 to 140 metres. They could be pumped at 20 L/sec, however the salinity of this Na^+:Cl^- type water is 4,000 to 6,000 µS.cm^{-1}. Finer grained aquifers containing lower salinity Na^+:HCO_3^- type water are intersected below 150 metres, but hydraulic parameters and yields are less.

Deep drilling from 240 to 450 metres along the Shwebo Syncline has not occurred. It is unknown if a deep AAZ equivalent occurs along this synclinal axis near Shwebo. Due to the northern extension of the Legyi Anticline the Shwebo Syncline is terminated near Sadaung.

12.3.2.2 Halin to Sagaing

Many hot artesian tubewells exist in Yebugon Village, the ancient capital city of Halin. Four different springs are located within nine metres of each other. The surface temperature ranges from 29.9 to 46° C with respective salinities of 1,340 to 5,450 µS.cm^{-1}. The estimated subsurface temperature for the hottest is 66° C[109]. Combined spring water flow of 2 L/sec. The springs appear to be associated with the Halin Fault complex which is an offshoot of the Sagaing Fault. The more saline groundwater flows are used for salt production in evaporation basins.

It is verbally reported that immediately after a 2013 earthquake the springs initially pulsated with strong flows along the fault lines, then receded to historical flow volumes. The source of the springs is unknown, but the variation in temperature and salinity suggests variable depths and sources[110].

[109] Win Khaing (2008)

[110] Other hot water occurrence along the Sagaing Fault are south in the Wundwin to Yamethin Area **(Chapter 15)**

Photo 51: Multiple Hot Springs, Halin (Yemugon Village) Halin Fault

Photo 52: Measuring Temperature and Salinity in Hot Springs

A tritium analysis on the hottest spring indicates a pre-thermonuclear water. Dating by ANSTO indicates an age of 26,120 ± 120 radiocarbon years (**Table 41**). The hot groundwater is very old, its conduit along the fault systems and heating mechanism at depth are unknown.

Hot Saline Spring, Yebugon Village, Halin: November 2016
Specific Conductance: 5,450 µS.cm^{-1}, Total Dissolved Salts: off scale, pH: 7.9, Temperature: 45.2° C.

Hot Saline Spring, Yebugon Village, Halin: May 2017
Specific Conductance: 5,180 µS.cm^{-1}, Total Dissolved Salts: off scale, pH: 7.9, Temperature: 46.0° C.

Hot Lower Salinity Spring, Yebugon Village, Halin: November 2016
Specific Conductance: 1,340 µS.cm^{-1}, Total Dissolved Salts: 998 mg/L, pH: 8, Temperature 29.9° C.

Between Halin and Wetlet there are many low salinity and low yielding artesian aquifers.

Basic Education High School, Moke Coe Chone Village Artesian Tubewell, Wetlet: November 2016
Specific Conductance: 1,490 µS.cm^{-1}, Total Dissolved Salts: 1,057 mg/L, pH: 7.9, Temperature: 29.0° C.

Leinbin Village Artesian Tubewell, Wetlet: November 2016
Specific Conductance: 1,300 µS.cm^{-1}, Total Dissolved Salts: 932 mg/L, pH: 8.3, Temperature: 31.2° C.

Wetlet Elevated Fluoride Concentration

Elevated fluoride concentration in groundwater is reported in Wetlet Township (Kyi Lwin Oo (2014)). Out of 1,114 drinking samples tested, 394 (35 %) exceeded 1.5 mg/L and 10 (≈1 %) was above 2.5 mg/L. Most elevated samples came from dugwells and shallow tubewells. High fluoride was also identified at depths up to 130 metres in the Irrawaddy Formation. From a sampling of 702 students, 91 percent had evidence of fluorosis.

The cause of fluoride prevalence is not determined. Fluorite (CaF_2) and apatite ($Ca_{10}(PO_4)_6(OH,F,Cl)_2$) exist in igneous, metamorphic, and sedimentary rocks. Mobilisation of fluoride may occur along the Halin hot spring line, Sagaing Fault or the underlying Pegu Group rocks. Fracture systems may provide the conduit for mobilisaton of high temperature fluid into the Irrawaddy Formation aquifer with upward leakage into the overlying Alluvium.

Pegu Group bedrock underlies Wetlet at 90 metres where shallow saline groundwater is encountered. Artesian tubewells to 180 metres are located on the town periphery where the Irrawaddy Formation is deeper (for example, Leinbin Village).
Many tubewells have been abandoned close to Pegu Group rocks and the Halin hot springs. The general hydrogeological principals in the Halin to Wetlet area are:

- avoid shallow Pegu Group bedrock;
- if shallow aquifers (< 60 metres) are brackish, go deeper (> 150 metres) or west; and
- artesian flow increases and salinity decreases with depth.

South of Wetlet the salinity increases due to the proximity of the marine Pegu rocks:

- at Minnyogone Village, a shallow aquifer containing Na^+:Cl^- type water with salinity of 10,000 µS.cm^{-1} was intersected at 24 metres. One hundred metres deeper a Na^+:HCO_3^- type aquifer had a salinity of 1,200 µS.cm^{-1}; and
- near Yemyet In and Aungtha the fractured Legyi Anticline aquifers contain both Na^+:Cl^- and Na^+:HCO_3^- type water with specific conductance up to 9,000 µS.cm^{-1}.

The specific conductance of groundwater near Sagaing Hill exceeds 4,500 µS.cm^{-1}, reducing to 1,500 µS.cm^{-1} near the Sagaing to Monywa Road.

Sagaing Region IWUMD District Office: November 2016
Specific Conductance: 1,520 µS.cm^{-1}, Total Dissolved Salts: 1,104 mg/L, pH: 6.9, Temperature: 26.4° C.

12.4 Alluvium

To the west of the Mu River the Alluvium contains fluviatile, high groundwater yielding sediment. Near the towns of Taze, Ye U and Dabayin, the unconfined to semi-confined aquifers have a potential yield exceeding 20 L/sec at depths of 20 to 40 metres. The specific conductance of the Na^+:HCO_3^- type water is usually below 1,500 µS.cm^{-1}. Transmissivity values range from 60 to 1,000 m^2/day and hydraulic conductivity from 15 to 100 m/day.

Table 42 indicates that the specific conductance of the shallow groundwater in the AAZ is variable (572 to 3,290 µS.cm^{-1}). The average is around 1,000 µS.cm^{-1}.

Table 42 Chemistry of Groundwater from Alluvial Aquifers in the Ayadaw Artesian Zone

No.	Village Name	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-
			µS.cm^{-1}								
DW1	Kangyi Monastery	6.1	1,051	673	124	16	122	7	498	7	59
DW2	Mya Yeik	6.5	914	585	47	20	56	3	411	11	28
DW3	Ngwe Twin Gone	6.3	677	581	135	4	127	1	435	18	29
DW4	Ya Tha	6.4	1,063	680	74	46	87	7	488	11	62
DW5	Chin Bin	6.6	572	366	52	29	71	1	290	33	17
DW6	Wa Taw Ma	6.0	3,290	2,106	380	22	245	1	503	11	378
DW7	Nwq Ma Thin	6.9	2,050	1,312	95	5	367	19	923	1	130
DW8	Min Ywa	7.5	948	607	15	5	229	1	406	94	35
DW9	Htan Gyi	6.9	1,150	755	120	5	204	2	469	11	65
DW10	Tha Khut Pin Le	6.9	819	524	117	2	117	3	333	80	45

Source: Than Zaw (2010).

To the southeast and south of Ayadaw and west of the Mu River, groundwater yields are generally less than 5 L/sec. This is due to shallow aquifer depth and poor hydraulic characteristics. The exceptions are Kandaw and Kanya villages near Myinmu, where shallow sand and gravel lenses have transmissivities of 200 m^2/day. The specific conductance of alluvial aquifers in this area usually exceeds 1,500 $\mu S.cm^{-1}$, especially in the Myinmu township and south of Chaungma village, presumably due to the presence of Pegu Group bedrock at shallow depth.

East of the Mu River, several tubewells have intersected semi-confined alluvial aquifers which provide potential yields exceeding 20 L/sec. These areas are located between Kanthagon, Nyaungbingyisu, Seikkun and Palaing villages (northwest and southwest of Shwebo). The specific conductance of the $Ca^{2+}Na^{+}:HCO_3^{-}$ type water is usually below 1,000 $\mu S.cm^{-1}$. High transmissivity values (>500 m^2/day) are calculated for some aquifers. For the remainder of this area the shallow lithology is quite variable although the depth to aquifer is relatively consistent. The water level fluctuation in alluvial aquifers is reported as 1.3 and 2.1 metres [111].

Surface water from the Mu River Irrigation Project has infiltrated through the soil into the shallow alluvial aquifer. The general opinion is that the water table has risen two to four metres since Year 2000.

Near Sagaing the Alluvium consists of yellow clay and silt with thick zones of coarse grained sand and gravel. This deposit is located south of the Sagaing to Monywa Road and thickens towards the river. The semi-confined water bearing zones are 24 to 160 metres deep and are up to 35 metres thick. The aquifers are usually highly permeable, the transmissivity ranges from 100 to 3,500 m^2/day at Zachaung and Sidi villages respectively. The potentiometric surface is six to 18 metres. Groundwater salinity south of the Sagaing to Monywa Road ranges from 150 to 980 $\mu S.cm^{-1}$. Highly permeable aquifers southwest to west of Sagaing should yield over 60 L/sec of low salinity water suitable for municipal purposes from appropriately designed tubewells.[112]

Sagaing Town Water Supply

Operator: Sagaing Township Development Committee.

Sources:

- Surface Water – operates 11 pumping sites from the Ayeyarwady River.
- Groundwater – three tubewells in Alluvium and Irrawaddy Formation. Combined pumping capacity is 2,900 m^3/day.

Other: Private Tubewells (2016): 1,466 deep tubewells (Irrawaddy Formation), 424 shallow tubewells (Alluvium) and 201 dugwells (Alluvium). Total groundwater yield of 31,900 m^3/day.

Cumulative Yield: Cumulative government and private groundwater yield is around 34,800 m^3/day.

Towards the Sagaing Hill the specific conductance in the alluvial aquifers increases.

Tritium analyses on three water samples from alluvial aquifers at Taze, southeast of Ayadaw and at Sagaing indicate a pre-thermonuclear age.

Yemyet In near Sagaing is 10.5 kilometres long and 6.5 kilometres wide. Due to the internal surface drainage, underlying Pegu Group rock and high evaporation, salinity in the 1984 Dry Season was 15,300 $\mu S.cm^{-1}$. Shallow dugwells in alluvial aquifers surrounding the lake also contain highly saline water. In contrast, the artificially built Kaunghmudaw In has a low salinity of 160 $\mu S.cm^{-1}$ and is annually replenished by flood waters.

[111] GDC (1984c), Italconsult (1970)

[112] These aquifer characteristics are equivalent to the Alluvium in the Mandalay City Water Supply (Chapter 12)

12.5 Groundwater Movement

Groundwater flow is from the watersheds towards the Mu River or Ayeyarwady River. Flow is more complex with vertical leakage between the more permeable layers being as important as lateral flow towards the discharge areas. The overall gentle gradient beneath the Mu River Valley is indicative of high permeability. Groundwater recharge is from direct rainfall; infiltration of surface irrigation and surface runoff; and upward leakage from underlying aquifer systems. Discharge is towards the watercourses, shallow alluvial aquifers and artesian tubewells.

12.6 Arsenic in Groundwater

Table 43 indicates the presence of arsenic in groundwater from four townships within or on the periphery of the Mu River Valley. The highest arsenic concentrations were in townships of Myaung (4.6 percent exceeding 50 µg/L) and Myinmu (2.3 percent), both close to the Ayeyarwady River. Of the 5,556 samples taken in the Shwebo Township one sample (0.02%) exceeded 50 µg/L and Wetlet Township was nil. It appears that high arsenic in groundwater is associated with the Ayeyarwady River sediments and below acceptable limits in sediments of the townships tested within the Mu River catchment.

Table 43 Arsenic in Groundwater from Four Townships in Proximity to Mu River Valley

Township	Total Samples	Concentration > 10 µg/L		Concentration > 50 µg/L	
		No.	%	No.	%
Shwebo	5,556	30	0.6	1	0.02
Wetlet	563	91	16.2		
Myinmu	1,781	323	18.1	41	2.3
Myaung	3,181	877	27.6	145	4.6

Source: WRUD and UNICEF (2005).

12.7 Areas of High Groundwater Yield and Low Salinity

Figure 40 indicates that a large percentage of the Alluvium and/or Irrawaddy Formation could be considered as potential sources of high yield and low salinity groundwater for irrigation purposes. This is especially the case in the deep gravels and sand along the Ayadaw Syncline (especially within the AAZ) and to a lesser extent along the Shwebo Syncline.

East of the Mu River there are many areas where brackish water, elevated temperature, arsenic and fluoride are encountered at variable depth within the Irrawaddy Formation and rocks of the Pegu Group. Approaching the northern extension of the Bago Yoma and the Ayeyarwady River the width of good aquifers significantly decreases.

The width of potential high yield, low salinity aquifers on either side of the Ayeyarwady River is a narrow five kilometres strip from Sagaing downstream to Myinmu.

12.8 Water Balance Annual Recharge Estimation

Figure 42 shows the water balance for the Lower Mu River Valley.

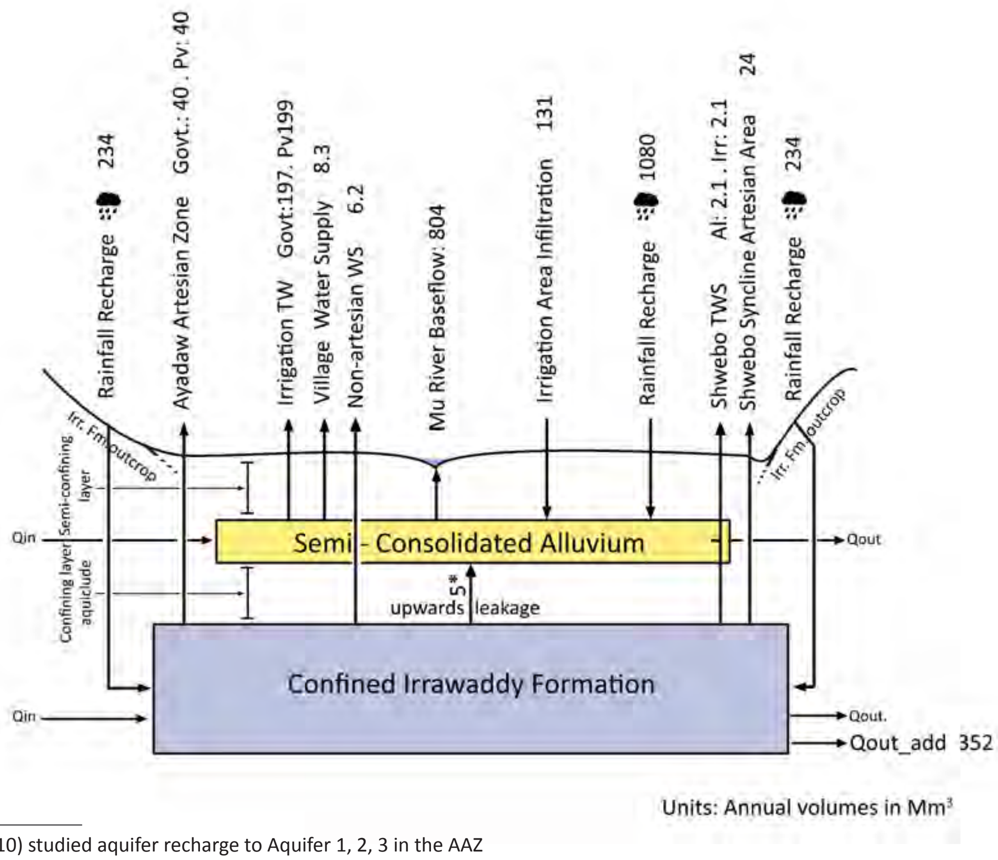
The basic assumptions for the Mu River water balance model are:

- Aquifer Inputs:
- Recharge:
    - average rainfall of 914 millimetres (36 inches); and

  - 15 percent from rainfall for the Alluvium and Irrawaddy Formation aquifers[113]. Due to extensive outcrop there is a large volume of water recharge into the two aquifer systems.
- Surface Water Infiltration:
  - irrigation return flow- calculated using total irrigation volume extracted (from both aquifers) and a return vertical infiltration of 30 percent.
- Aquifer Outputs:
- groundwater withdrawal- based on known and assumed artesian and sub-artesian tubewell numbers (recorded and estimated), flowing/pumping times and discharge;
- upward leakage is likely to occur but may not be accurate due to the lack of monitoring data;
- contribution to baseflow was used to close the water balance (considering baseflow is the main output for recharge in the alluvial aquifer); and
- the extensive outcrop of Irrawaddy Formation, the depth of aquifer, confining overlying clay aquitard and the relatively low abstraction rate creates a condition for an increase in outflow, here referred to as an additional outflow (Q_{out_add})[114].
- Change in Storage: There is an assumption that:
- input flow = outflow flow, assuming there is no change in aquifer storage.

From rainfall and irrigation return, the vertical recharge to the shallow Alluvium is 1,211 $Mm^3.yr^{-1}$. Around 33 percent is utilised by groundwater extraction (404.3 $Mm^3.yr^{-1}$), the remainder discharges into the Mu River (804 $Mm^3.yr^{-1}$). Similarly, for the deeper Irrawaddy Formation 25 percent of rainfall water recharge is utilised by groundwater extraction, the remainder is assumed to discharge into the ARC.

Figure 42 Water Balance for Main Aquifers in the Lower Mu River Valley



[113] Than Zaw (2010) studied aquifer recharge to Aquifer 1, 2, 3 in the AAZ
[114] This outflow is incorporated into the ARC Water Balance Model (Chapter 17)

13 Hydrogeology of Nyaung Oo-Kyaukpadaung

13.1 Introduction

The Nyaung Oo-Kyaukpadaung area forms part of the ARC. It is in the driest and hottest part of the Dry Zone, with an average annual rainfall below 50 centimetres and temperature exceeds of 37.5° C during the Dry Season.

The surface elevation is 70 m AMSL at Bagan and 90 m AMSL near Nyaung Oo Airport, gradually rising southeast to 500 m AMSL at Byugyi Village and 1,500 m AMSL at Mount Popa. The NNW-SSE striking Pagan and Gwegyo hills rise 240 m AMSL from the surrounding plain. Over 60 percent of the area has an elevation above 300 m AMSL.

The intermittent watercourses are the Pyinma, Chaungmagyi (North and South), Seikkwa, Nalataw and Yeosin chaungs. These streams flow during the Wet Season towards the Ayeyarwady River. Floods are of short duration and of great intensity.

The plain is covered by light sandy loam. A large proportion is under cultivation. Badland topography is developed in some of the higher elevated areas where soil cover is thin or non-existent.

The Nyaung Oo-Kyaukpadaung area is in a region of broad folds and structural lines. These include:

- the Bahin-Pagan and Myaing-Kyaukpadaung structural lines which are exposed on the eastern bank of the Ayeyarwady River as an eroded fault plane in the Irrawaddy Formation;
- the Pagan, Gwegyo and Yenangyat thrust faults and associated cross faults; and
- the NNW-SSE orientated Pagan Syncline located west of the Pagan Hills extending north through Bagan.

Groundwater development has been carried out by national and foreign governments and NGOs. However, there are only a few hydrogeological reports[115]. Since 2002 the DRD, through JICA funding, has conducted groundwater drilling programs in the Nyaung Oo, Kyaukpadaung and Chauk areas.

Geological and hydrogeological data are presented on **Figure 43** to **Figure 45**. Details of some tubewells are given on **Table 44**. Some pump-out tests conducted by DRD are included.

[115] Tahal (Water Planning) Ltd (1963), Hla Tint (1979), Coffey and Partners (1984a)

Figure 43 Schematic Geological and Hydrogeological Map: Nyaung Oo-Kyaukpadaung

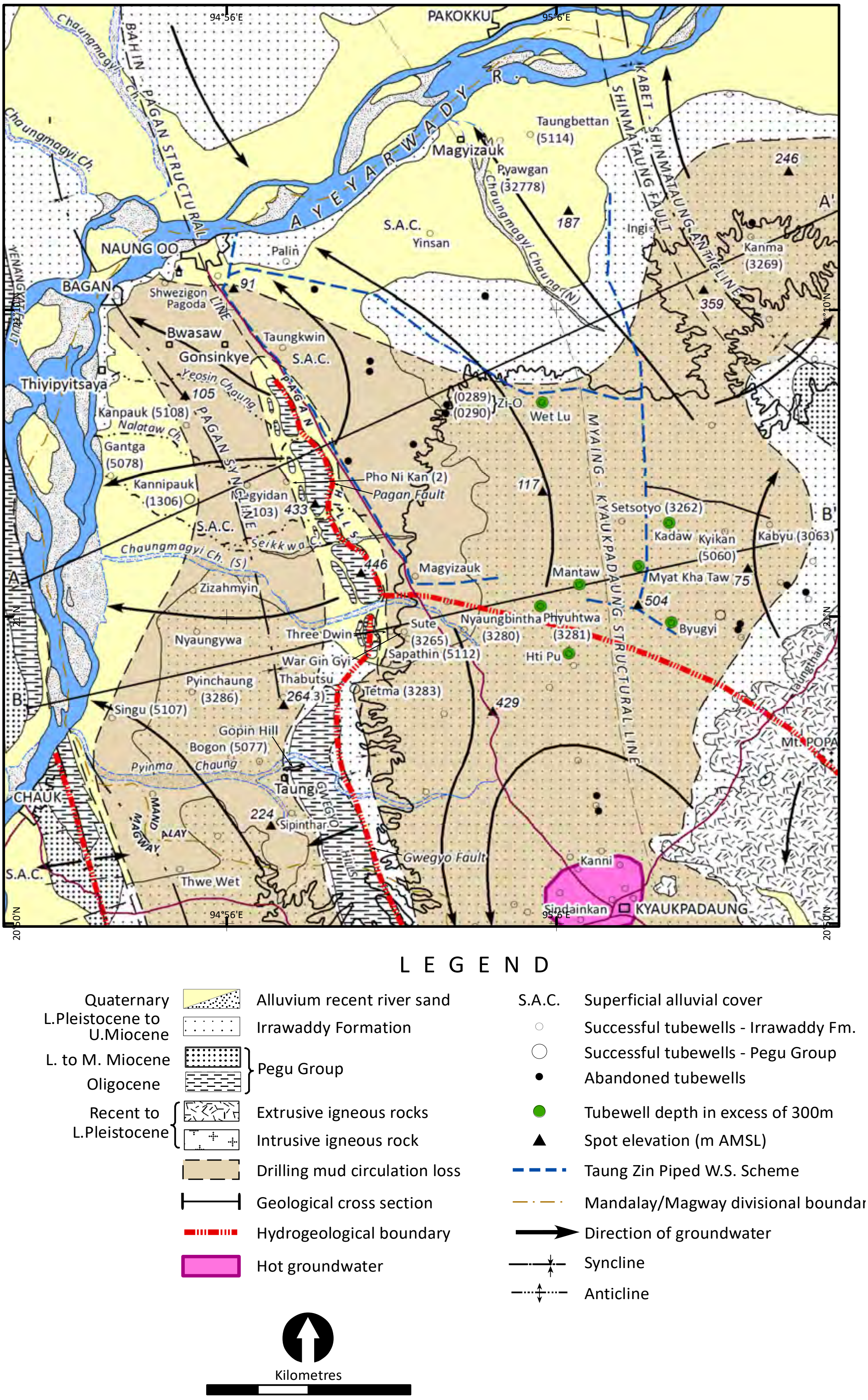
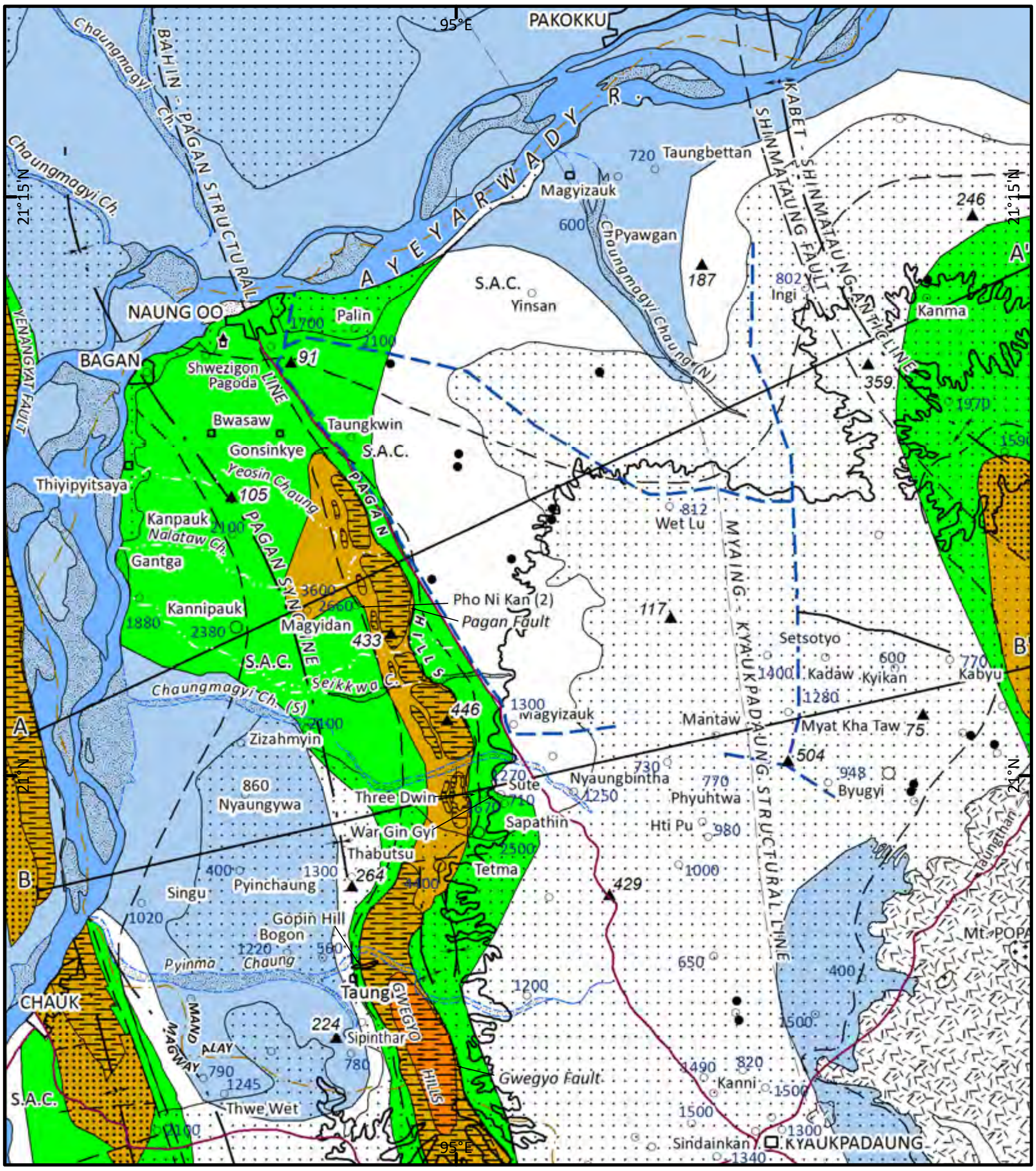


Figure 44 Schematic Hydrogeological and Hydrochemical Map: Nyaung Oo-Kyaukpadaung



L E G E N D

Quaternary		Alluvium
		Recent river sand
L.Pleistocene to U.Miocene		Irrawaddy Formation
L. to M. Miocene		Pegu Group
Recent to L.Pleistocene		Extrusive igneous rocks
		Intrusive igneous rock

Specific Conductance (µS.cm^{-1} at 25^{o}C)

- <1,500
- 1,500-3,000
- 3,000-6,000
- 6,000

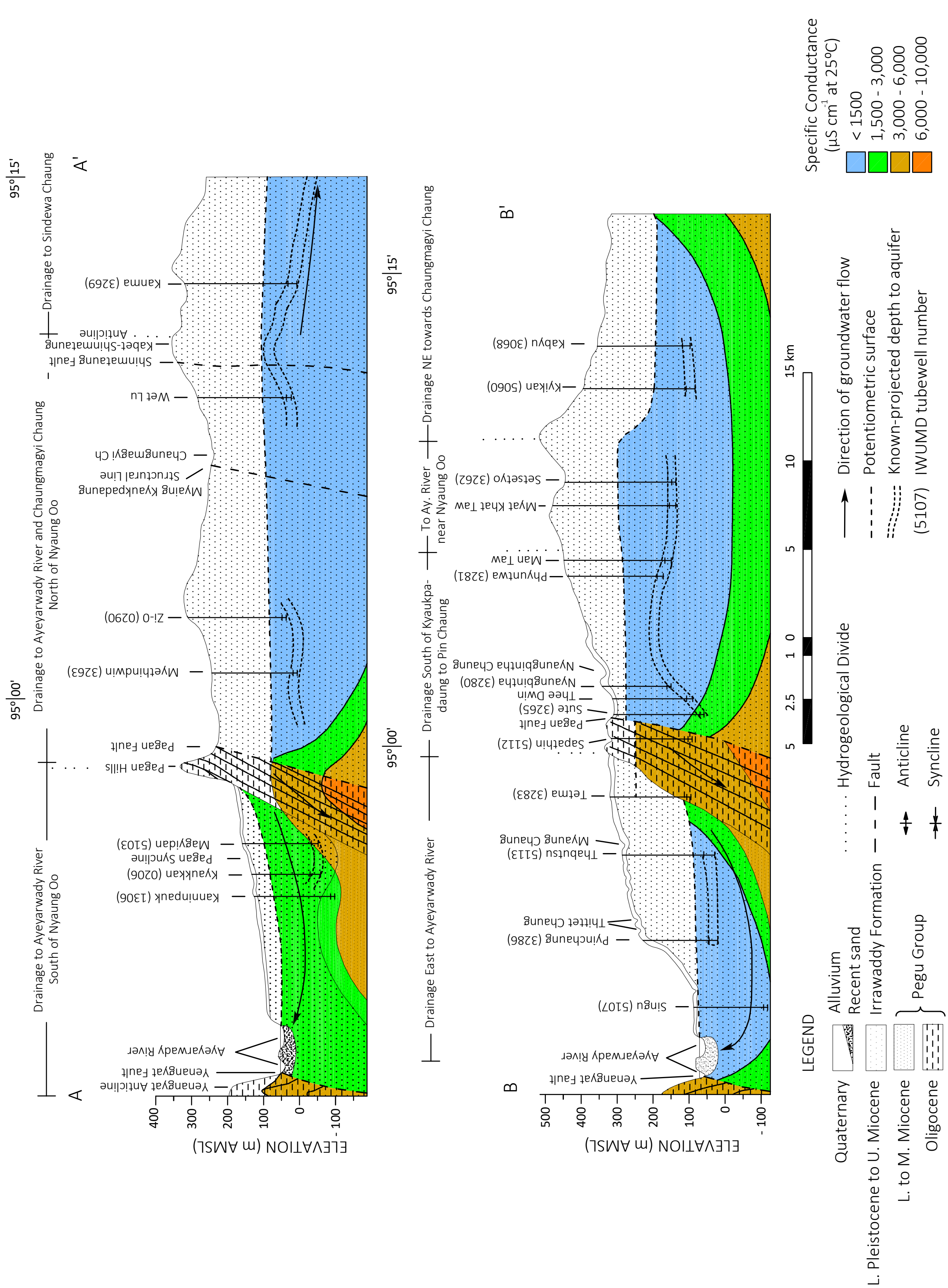
S.A.C.	Superficial alluvial cover
○	Successful tubewells - Irrawaddy Fm.
○	Successful tubewells - Pegu Group
├─┤	Geological cross section
1200	Specific conductance (µS.cm^{-1})
	Potential high yield (>6 L/sec) / low salinity (<1,500 µS.cm $^{-1}$)

Kilometres

0 3 6 12

NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occur

Figure 45 Hydrogeological Cross Section and Specific Conductance: Nyaung Oo-Kyaukpadaung



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Table 44 Details of Tubewells in the Nyaung Oo–Kyaukpadaung Area

Formation	Area	Village	Tubewell Number	Surface Elevation (m AMSL)	All data from surface (m)				DD (m)	Airlift Yield# (L/sec)	Transmissivity (m^2/d)	Specific Conductivity ($\mu S.cm^{-1}$)
					Depth	Screen Aquifer	SWL	DDL				
Pegu Group	Pagan Hill	Kannipauk	1306	+ 125	216	198- 216	55	76	21	5	25	2,380
Irrawaddy Formation	Pagan Syncline	Zizahmyin	5104	+ 170	186	156- 174	109	123	14	6	268	2,100
		Magyidan	5103	+ 166	277	261- 277	12	17	5	5	90	3,600
		Kanpauk	5108	+ 111	247	184- 192	41	46	5	6	134	2,100
		Pho Ni Kan	DJ (21)		72	21- 39	14	18.25	4.25	3.5	52-142*	2,660
	Myaing-Kyaukpadaung Structural Line	Pyawgan	3278	+ 122	146	128- 146	55	64	9	7	87	600
		Taungbettan	5114	+ 81	134	98- 134	17	31	14	9	66	720
		Byugyi	DJ (07)	+ 497	310	285- 304	236	240	4	2	30- 70*	948
		Hti Pu	DDA (1)	+ 462	300	273- 292	240	244	4	1.8	60- 90*	
		Man Taw	DJ (01)	+ 431	243	209- 228	187	189	2	3	200- 350*	770
		Ingi	DJ (15)	+ 260	228	180- 198	123	127	4	3.5	50- 150*	802
		Myat Khat Taw	DJ (16)	+ 477	353	294- 336	251	257	6	2	35- 60*	1,280
		Kanni	DJ (04)	+ 438	237	209- 228	151	165	14	3	50- 70*	1,500
		SIndainkan	DJ (3)	+ 370	219	191- 211	122	125	3	4	30- 600*	1,390
		Wet Lu	DJ (14)	+ 236	305	274- 292	236	237	1	1.5	100- 220*	812
		Thee Dwin	DJ (10)	+ 307	220	183- 201	57	70	13	4	50- 100*	1,670
		Wai Gin Gyi	DJ (11)	+ 320	202	170- 188	76	81	5	4	145- 165*	1,270
		Palin (W)	Private		110	70 – 85	18	42	24	12		2,100
		Kudaw	JICA 87	+ 430	360	343-355	243			2		
	North of Chauk	Singu	5107	+ 69	90	58- 72	18	46	28	4	34	1,020
		Thwe Net	DJ (06)	+ 238	198	170- 176 182- 195	151	152.5	1.5	3.5	221*	1,245
		Sipinthar	DJ (20)	+ 204	144	122-134	126	137.4	11.4	2	70- 120*	

Source: IWUMD and DRD databases.
# indicates yield during pump-out test of 100mm dia. tubewell. This does not necessarily indicate aquifer yield from large diameter production tubewell.
*JICA funded, Department of Rural Development pump-out test (2008-2009).

Surface Water Supply Schemes

The towns of Bagan and Nyaung Oo obtain untreated reticulated water supply from the Ayeyarwady River. The river pumping station for the Taung Zin Piped Water Supply Project is located next to the Nyaung Oo pumping site.

Nyaung Oo Town Water Supply:

Source: Ayeyarwady River- delivering 2,273 m^3/day.

Bagan Town Water Supply:

Source: Ayeyarwady River – separate pumping station delivering 1,800 m^3/day.

Taung Zin Village Water Supply:

Technical reports have been prepared. The Taung Zin Piped Water Supply Project (TZPWSS) delivers untreated river water to 103 villages in hydrogeological difficult environments. First established in 1965 to provide piped water to 35 villages, the scheme was expanded in the mid-1980s with AusAID funds to include an additional 68 villages through a 100-kilometre pipeline system. The scheme currently delivers 1,455 m^3/day (pers. comm. IWRUMD).

World Health Organisation (1980), Coffey & Partners (1981, 1983b, 1985f), Coffey & Partners and Sinclair Knight & Partners (1982, 1984)

13.2 Pegu Group

The westerly dipping Pegu Group rocks along the Pagan and Gwegyo hills consist of relatively impervious shale, mudstone and minor fine-grained sandstone. They form a NNW-SSE orientated hydrogeological flow boundary. The semi-confined aquifers, where present, usually occur in fractured Kyaukkok Formation sandstone associated with faults and anticlinal folds. These aquifers are intersected less than 200 metres below the surface. The transmissivity is low (three and 25 m^2/day), brackish salinity (3,000 to 6,000 µS. cm^{-1}) and village tubewells yield below 2 L/sec. These rocks are marine in origin. The groundwater residence time is long, especially in the structural traps along the fold axis.

The specific conductance of the Na^+:Cl^- and Na^+:SO_4^- groundwater from tubewells at the base of the Pagan and Gwegyo hills vary from 2,500 to 4,440 µS.cm^{-1} at Sapathin and Tetma villages.

Shallow aquifers under chaungs emanating from the hill slopes, where localised recharge occurs, may contain lower salinity groundwater suitable for human consumption.

13.3 Irrawaddy Formation

The Irrawaddy Formation consists of loosely cemented, fine to coarse grained sand with minor gravel, clay, silt, petrified wood and calcareous nodules. The semi-confined to confined water bearing sediments form the regionally extensive aquifer system.

13.3.1 Deep Aquifer along Myaing-Kyaukpadaung Structural Line

East of the Pagan Hills the surface elevation rises to over 500 m AMSL. The average depth to the Irrawaddy Formation aquifer exceeds 200 metres near the Pagan Hills and above 300 metres along the Myaing-Kyaukpadaung Structural Line (for example, 343 to 355 metres at Kadaw Village). **Figure 43** indicates the location of the deep aquifer hydrogeological boundary (near Phyuhtwa, Hti Pu and Byugyi villages), draining north to the Ayeyarwady River and south to Pin Chaung. There is an extensive area of deep aquifers north of this boundary. Aquifer depth is a function of the elevated surface topography, geological structure, hydraulic characteristics (transmissivities of 30 to 220 m^2/day) and hydraulic gradient (draining to the Ayeyarwady River (distant)[116] and a steeper gradient to the closer Chaungmagyi Chaung (N)). These deep aquifers are usually described as clayey sand, with transmissivity range from 30 to 350 m^2/day and specific conductance below 1,500 µS.cm^{-1}. They comprise 35 to 65 percent of the saturated stratigraphic column.

In the 1980s, due to limited drilling rig capacity and drill mud circulation loss into the thick unsaturated, unconsolidated, yellow sand most attempts to obtain groundwater from the deep aquifers failed. Due to the lack of success the TZPWSS was implemented to deliver surface water from Nyaung Oo to this rural community. Recent JICA funded drilling has successfully developed village water supplies in these deep aquifers using higher capacity rigs and appropriate mud control techniques.

13.3.2 Nyaung Oo and Pagan Syncline

All tubewells in the Nyaung Oo and Bagan town areas intersect aquifers in the Irrawaddy Formation. The specific conductance of the Na^+:HCO_3^- type water varies from 630 to 2,980 µS.cm^{-1}, depending on proximity to the Pegu Group rocks.

At Palin Village two 200 millimetres diameter production bores, each drilled to 100 metres, yield 12 L/sec. The specific conductance is 2,100 µS.cm^{-1} indicating marginal suitability for irrigation purposes. A slight smell of hydrogen sulphide (H_2S) was detected during pumping for groundwater sampling.

Sharkey Irrigation Farm, Palin Village, Nyaung Oo: November 2016
Specific Conductance: 2,100 µS.cm^{-1}, Total Dissolved Salts: 1,499 mg/L, pH: 6.9, Temperature: 32.4° C.

Saturated, permeable blue sand aquifers are located at depths of 150 to 250 metres within the Pagan Syncline. Near the Ayeyarwady River drilling depth is below 90 metres. The transmissivity of 50 to 250 m^2/day suggests favourable groundwater yielding potential. High resistivity soundings (5,600 to 9,500 Ω cm)[117], indicate that saturated sand and gravel to a depth of 146 metres occur at Bwasaw and Kanpauk villages, increasing eastwards to 250 metres as surface topography increases. Aquifer salinity is quite variable:

- the specific conductance of the dominant Na^+:HCO_3^- type groundwater north of Chaungmagyi Chaung (S) ranges from 1,880 to 3,600 µS.cm^{-1}. The salinity increases and ion dominance changes to Na^+:SO_4^{2-} towards the Pagan Hills, indicating water mixing with groundwater discharge from rocks of the Pegu Group; and
- between Chaungmagyi Chaung (S) and Pyinma Chaung, the specific conductance of the Na^+:HCO_3^- type water is below 1,500 µS.cm^{-1}, except close to the Gwegyo Hills where salinity increases.

The hydrogeological barrier on the eastern edge of the Pagan to Gwegyo hills separates the aquifer system into two distinct regions. **Figure 45** indicates that the potentiometric surface:

- west of the Pagan Hills varies from 120 to 60 m AMSL, draining directly west into the Ayeyarwady River;
- to the east varies from 60 m AMSL near the Ayeyarwady River (A-A') and more than 240 m AMSL in the higher topographic areas (B-B').

Groundwater recharge occurs as:

- surface runoff along the Pegu Group ridges;
- direct infiltration of precipitated water into the sandy soils;
- infiltration of surface runoff along the sandy chaungs during the Wet Season; and
- saline groundwater discharge from aquifers in the Pegu Group.

[116] This is a similar hydrogeological situation to the deep Irrawaddy Formation aquifers in the Chauk Syncline (Chapter 6)
[117] Tahal (Water Planning) Ltd (1963)

Photo 53: Sharkey Irrigation Tubewell, Palin Village

Photo 54: Irrawaddy Fm. Aquifer Development, Myaynegyi Village. Source: *DRD*

13.4 Alluvium

Dugwells are sited in the shallow Alluvium near Bagan and west of the Pagan Hills. These wells are lined with stone, brick, petrified wood or concrete blocks. They rarely penetrate more than a few metres below the water table. The salinity is below 800 $\mu S.cm^{-1}$. Water levels fluctuate according to river height indicating good hydraulic interconnection.

West of the Pagan Hills, a shallow perched water horizon is intersected by large diameter dugwells in the sandy Alluvium overlying the relatively impermeable Pegu Group rocks. This perched aquifer extends along the base of the westerly dipping ridge from the villages of Thabutsu to Gonsinkye. Salinity is in the order of 400 to 2,500 $\mu S.cm^{-1}$. Low salinity water is located adjacent the chaungs and increases towards the hills. Dugwells deepened to the Pegu Group rocks contain saline groundwater (8,000 to 11,500 $\mu S.cm^{-1}$). The water table slopes steeply west and northwest closely following the configuration of the impervious base.

Few dugwells are located east of the Pagan Hills. Successful dugwells are in coarse grained sand deposited along intermittently flowing chaungs. These dugwells frequently run dry during the Dry Season. An exception is along the sandy Chaungmagyi Chaung (N) where dugwells six metres deep supply low salinity drinking water to villages throughout the year.

River terrace deposits consisting of sandy loam, gravel and minor silt and sandy silt occur near Nyaung Oo. Their thickness is generally below 30 metres. Frequently the base of the deposit is near river level, thus groundwater yielding potential is poor, especially in the Dry Season.

13.5 Areas of High Groundwater Yield and Low Salinity

Figure 44 indicates the areal extent of potential high yield and low salinity groundwater for irrigation purposes in the Nyaung Oo-Kyaukpadaung area. These mainly occur along the ARC. They include Alluvium and Irrawaddy Formation aquifers:

- from Pyinma Chaung to Chaungmagyi Chaung (S) in the Pagan Syncline;
- at Chaungmagyi Chaung (N) near Pyawgan and Taungbettan villages extending northeast along the Ayeyarwady River; and
- close to Mt Popa.

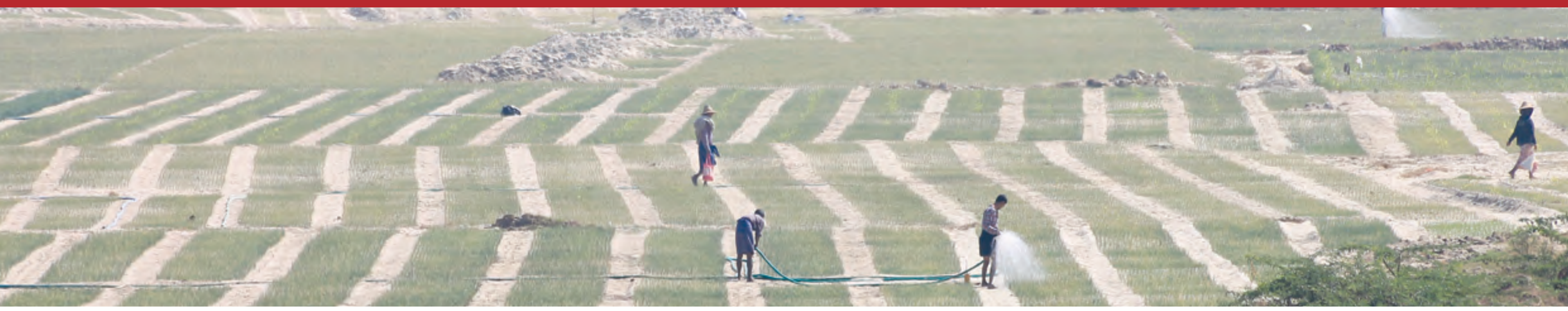
The width of good quality, high yield aquifers between the Chauk and Yenangyat anticline is less than two kilometres.

Although the Irrawaddy Formation aquifers along the Myaing-Kyaukpadaung Structural Line contain low salinity and reasonable yields, the depths to the potentiometric surface and aquifer precludes consideration for irrigation potential.

13.6 Water Balance Annual Recharge Estimation

The Nyaung Oo region is within the ARC. The combined water balance is given in **Chapter 17**.

Estimates of low salinity water in aquifer storage is also presented in **Chapter 17**.



14 Hydrogeology of Myingyan-Ngazun-Mahlaing

14.1 Introduction

The Myingyan-Ngazun-Mahlaing area is situated in the centre of the Dry Zone. Historically this area has been hydrogeologically renowned for its high salinity, low groundwater yielding aquifers and low success rate in locating potable water suitable for irrigation and human consumption (**Table 45**). This is still the case in most of the fractured marine shale and fine sandstone aquifers of the Obogon and Kyaukkok formations and adjacent Irrawaddy Formation aquifers. Acute water shortages for both rural and urban domestic purposes still occur in most parts of this area, especially during the Dry Season even though emergency groundwater drilling programs have taken place. Overall there are poor prospects of intersecting high water yielding, low salinity aquifers. However, with careful hydrogeological assessment, the success rate over time has improved.

The Ayeyarwady River is the main source of irrigation water. It forms the north and northwest boundary of this area. Sindewa Chaung, sourced from low salinity springs from Mount Popa aquifers, is the only other perennial watercourse.

There are many large-scale river pumping stations for irrigation between Nyaung Oo and Myingyan. Operational problems include river level fluctuations, shifting sand bars, absence of stable banks, widespread floods, high bed load, power availability, lack of water delivery to the channel ends and farmer affordability or willingness to pay. Domestic water supply from the Ayeyarwady River also faces additional constraints, including bacteriological and agricultural pollution, turbidity and high cost of treatment. Other surface water sources come from reservoirs, tanks, lakes and ponds.

Most regional groundwater assessments of the Dry Zone include some comment on the Myingyan-Ngazun-Mahlaing area. Groundwater reports specifically written on this area are available[118]. Geological studies have been carried out[119]. This area is located near the northern extent of the Bago Yoma Anticlinorium. Most anticlinal structures trend NNW-SSE in the direction of the strike of the rocks. The highest peak is Taungtha Taung (545 m AMSL). Other major hills include Magyizu, Taungtalon and Mingon (474, 448 and 398 m AMSL respectively). Salient structural features include:

- the ripple-like asymmetrical anticlinal folds plunging to the north;
- major regional faults parallel to the general north-south or NNW-SSE strike of the strata. The largest is the Mahlaing Fault which passes west of Ngazun, Natogyi to Mahlaing. It is clearly recognisable by strata nonconformities with downthrow to the east and salt springs along the fault line; and
- minor faults, especially where the Pegu Group is intensely folded.

Tectonic activity is Upper Pliocene to Lower Pleistocene[120].

Groundwater occurs in the Pegu Group, Irrawaddy Formation and unconsolidated Alluvium. Hydrogeological maps are presented on **Figure 46** to **Figure 48**. Some transmissivity and estimated groundwater yield from domestic tubewells are given in **Table 45**. Typical chemistry is given in **Table 46**.

118 Nyo Lwin (1976), Myint Soe et. al. (1981), Nyo Lwin & Maung Thin (1981), Soe Win et. al. (1983), Soe Win & Shwe Ko (1982), Soe Win (1984a,b), Coffey and Partners (1984f, 1985a), Water Resources Utilization Department in Collaboration with UNICEF (2005), Bacquart et. al. (2015), Pavelic et. al. (2015), Aye Aye Min (2016), Wai Wai Phyo (2016)

119 Cotter (1908a), Brown (1927), Sein Myint (1958), Ngwe Thein (1958, 1959, 1960), San Lwin (1962, 1968), Chit Saing (1962), Nedelcu et. al. (1965)

120 Aung Khin & Kyaw Win (1968)

Table 45 Transmissivity and Potential Yield of Aquifers in Myingyan-Ngazun-Mahlaing Area

	Area	Transmissivity (m^2/day)								Groundwater Yield (L/sec)						Abandoned Drill hole				
		< 40		40-150		150-600		> 600		< 5		5-25		> 25						
		No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	*	**	***
Alluvium	East Bank Ayeyarwady	8	21.6	25	67.5	4	10.9	-	-	20	54	17	48	-	-	-	-	-	-	-
	Sindewa Chaung	-	-	-	-	3	50	3	50	-	-	6	62.5	3	37.5	-	-	-	-	-
	Thinbon Chaung	20	45.5	20	45.5	3	6.8	1	2.2	31	55.4	21	37.6	4	7	2	3.4	2	-	-
Irrawaddy Fm	Chaunggwa-Myingyan	18	90	2	10	-	-	-	-	17	65.4	9	34.6	-	-	11	30	11	-	-
	Myingyan-Nabuaing	20	64.5	10	32.5	1	3	-	-	20	57.1	15	42.9	-	-	4	10.3	4	-	-
	Natogyi-Mahlaing	24	61.5	14	35.9	1	2.6	-	-	26	60.5	7	39.5	-	-	-	-	-	-	-
Pegu Group	Taungtha Anticline	12	92	1	8	-	-	-	-	13	100	-	-	-	-	3	19	1	2	-
	Natogyi-Mahlaing	20	67	9	30	1	3	-	-	30	75	10	25	-	-	5	11	2	2	1
	Legyi Anticline	20	84	4	16	-	-	-	-	20	83.3	4	16.7	-	-	1	4	-	1	-
	Mingon-Indaw Anticline	15	78	3	17	1	5	-	-	21	95.5	1	4.5	-	-	12	35	1	5	6

Source: RWSD (1986).
* Construction problem (for example, wrong drilling rig for rock type or depth, or loss of drilling mud circulation).
Usually new successful tubewell drilled by larger capacity rig and appropriate drilling fluid.
** Saline groundwater. Frequently tubewell too deep, shallower aquifer less salty (usually brackish).
*** No aquifer encountered. Drilling depth 250 metres to greater than 300 metres.

Table 46 Typical Chemistry of Groundwater in the Myingyan-Ngazun-Mahlaing Area

Tubewell	Formation	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-
			µS.cm^{-1}	mg/L							
TW5	Alluvium	7.8	1,480	955	Pumped volume 11 m^3						
TW5	Alluvium	7.5	1,520	910	Pumped volume 5,455 m^3						
TT1	Irrawaddy	8.2	1,002	739	96	25	12	10	70	81	96
TT2	Irrawaddy	7.6	950	650	70	24	14	12	62	123	158
TT5	Irrawaddy	7.7	1,570	1,000	89	41	32	27	110	96	220
TT6	Irrawaddy	7.7	1,370	890	87	39	20	17	68	227	109
T11	Pegu Group	8	2,800	1,820	214	52	288	245	76	584	720
T12	Pegu Group	7.6	3,400	2,200	181	168	123	104	74	200	900

Source: Alluvium = Coffey (1984f, 1985a), Irrawaddy Fm. and Pegu Group = Aye Aye Min (2016).

14.2 Pegu Group

The anticlinal structures consist of Lower to Middle Miocene age Pegu Group rocks. The Obogon Formation usually occupies the flanks whilst the Kyaukkok Formation forms the anticlinal cores. These highly folded, faulted and contorted rocks consist of well-bedded shale, siltstone and yellow-brown sandstone with gypsum in fractures along the anticlinal axis. Dips vary from 25 to 85 degrees east and west. Aquifer depth is largely controlled by geological structure and topography. For example:

- a Kyaukkok Formation sandstone aquifer is asymmetrically folded in the core of the Taungtha Anticline with fractured shale above and below. The aquifer dips 50 to 70 degrees west and 25 to 45 degrees east from the axis. The San Oo Village tubewell (western flank), intersected a Kyaukkok

Formation aquifer at 18 m BMSL, whilst the Gwaepinyoe Village hole (at a similar distance to anticlinal axis and surface elevation, but on the eastern flank) encountered the aquifer at 116 m AMSL; and

- along the Legyi Anticline axis typical aquifer depths are around 150 metres, and drilling depths on the flanks are generally less than 75 metres.

A few tubewells in the Kyaukkok Formation have potential groundwater yields more than 5 L/sec and none exceeding 10 L/sec. Most aquifers have a transmissivity value below 60 m^2/day, the overall lowest being around the Taungtha Anticline. Transmissivity beneath Inde Village (west of Taungtha) is 35 m^2/day[121]. The highest number of abandoned holes are in the Mingon area where marine shales of the Obogon Formation crop out. Of these around 50 percent failed to intersect an aquifer (drilled up to 250 metres) and five were abandoned due to the intersection of highly saline water.

Groundwater flow within the Pegu Group is complex. The relatively impermeable marine shales form distinct hydrogeological boundaries throughout the area. Flow is from the anticlines to the downgradient Irrawaddy Formation located along the anticlinal flanks and in the adjacent synclines. The exception appears to be the highly-faulted region north of the Indaw Anticline, where groundwater flow is east through rocks of the Kyaukkok and Obogon formations towards Thinbon Chaung.

Recharge to the elevated fractured aquifers occurs as rainfall and intermittent surface flow on rock outcrops.

Groundwater discharge occurs as saline soda springs along fault lines, throughflow into the more permeable Irrawaddy Formation or sandy chaungs and artificially from tubewells and dugwells.

The specific conductance of the $Na^+:Cl^-$, $Na^+:SO_4^{2-}$ and $Ca^{2+}:SO_4^{2-}$ type groundwater near Taungtha Taung usually exceeds 4,000 µS.cm^{-1}. Lesser salinities occur in fractured rock crossing watercourses (for example, Nan Myint Taung Monastery tubewell).

Nan Myint Taung Monastery Tubewell: November 2016
Specific Conductance: 2,240 µS.cm^{-1}, Total Dissolved Salts: 1,843 mg/L, pH: 8.7, Temperature: 23.7° C.

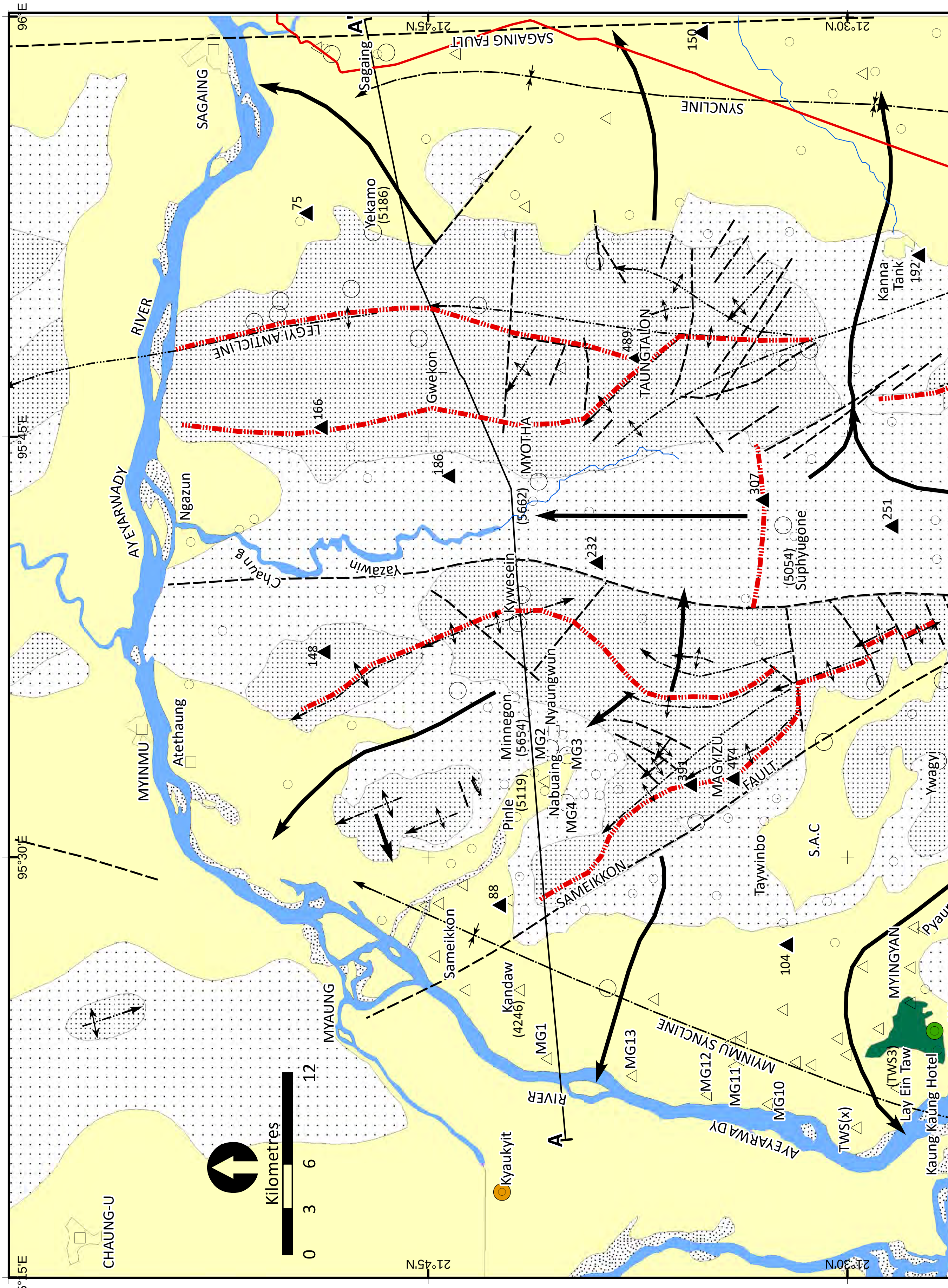
Brackish to saline $Na^+:Cl^-$ and $Na^+:SO_4^{2-}$ type groundwater occurs around the periphery of the Pegu Group ridges, especially along the Mahlaing Fault (near Mahlaing and Natogyi) and the Sameikkon Fault. Groundwater salinities of 10,000 µS.cm^{-1} occur in geological structurally complex areas along the Taungtha Ridge. High salinity indicates poor hydraulic characteristics, long residence time and the presence of soluble salts in the marine rocks.

Groundwater quality varies over short distances due to depth and fracture locations. At Kuywa Village a dugwell sunk nine metres in fractured sandstone yielded 0.1 L/sec of $Na^+:HCO_3^-$ type water with specific conductance of 1,400 µS.cm^{-1} (which the villagers use for drinking purposes). Another dugwell sunk to 15 metres intersected $Na^+:Cl^-$ type water of 5,200 µS.cm^{-1}. The village tubewell intersected $Na^+:Cl^-$ type groundwater with salinity of 13,850 µS.cm^{-1} at a depth of 43 to 60 metres.

In 2014 the IWUMD constructed many small diameter tubewells in Taungtha and Mahlaing townships as an emergency drought relief program. The locations of some are shown on **Figure 46**. Some hydrogeological data of Pegu aquifers are given in **Table 47**. The specific conductance varies from 2,600 to 3,750 µS.cm^{-1}.

[121] Aye Aye Min (2016)

Figure 46 Schematic Geological and Hydrogeological Map: Myingyan-Ngazun-Mahlaing



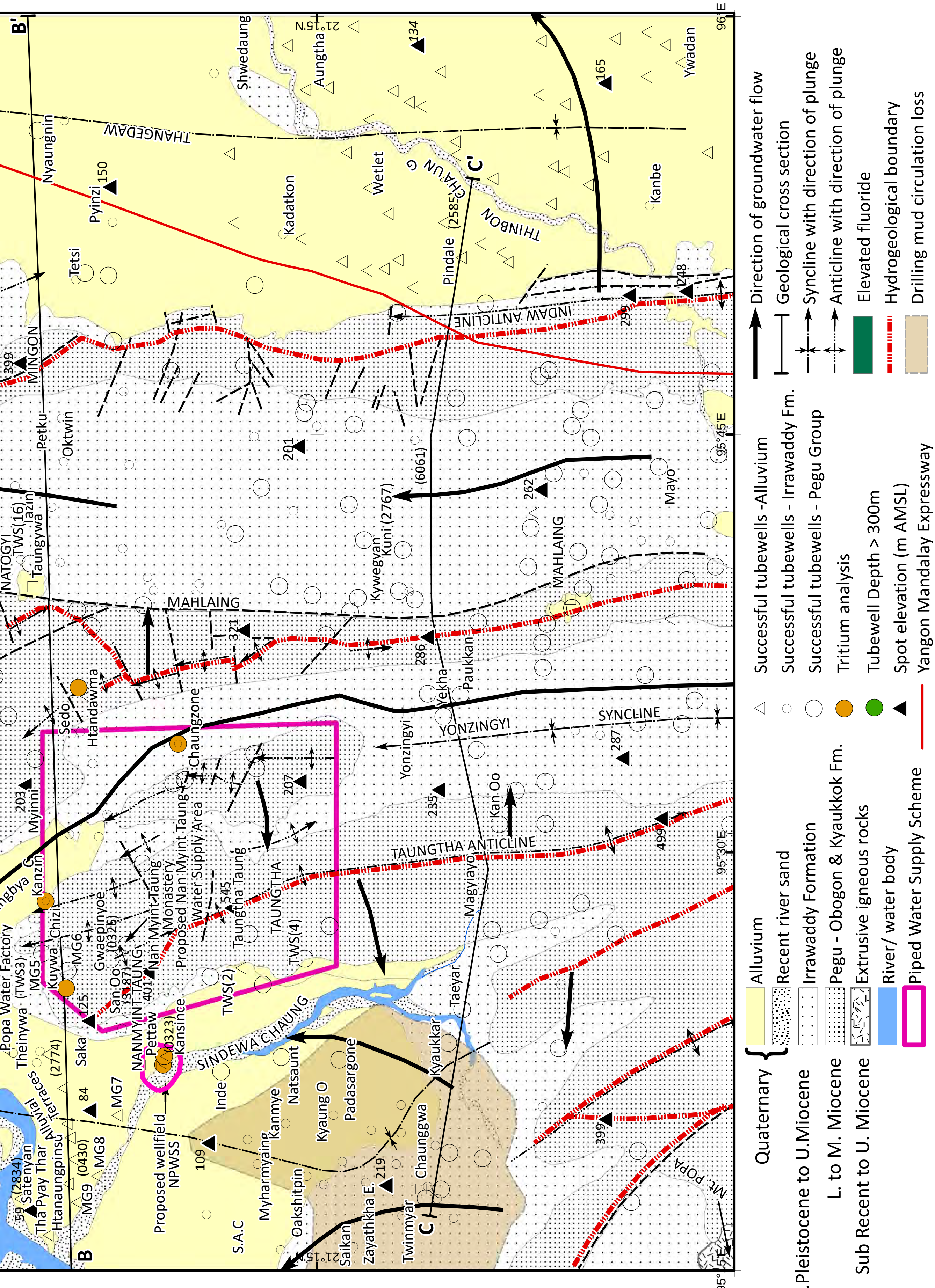
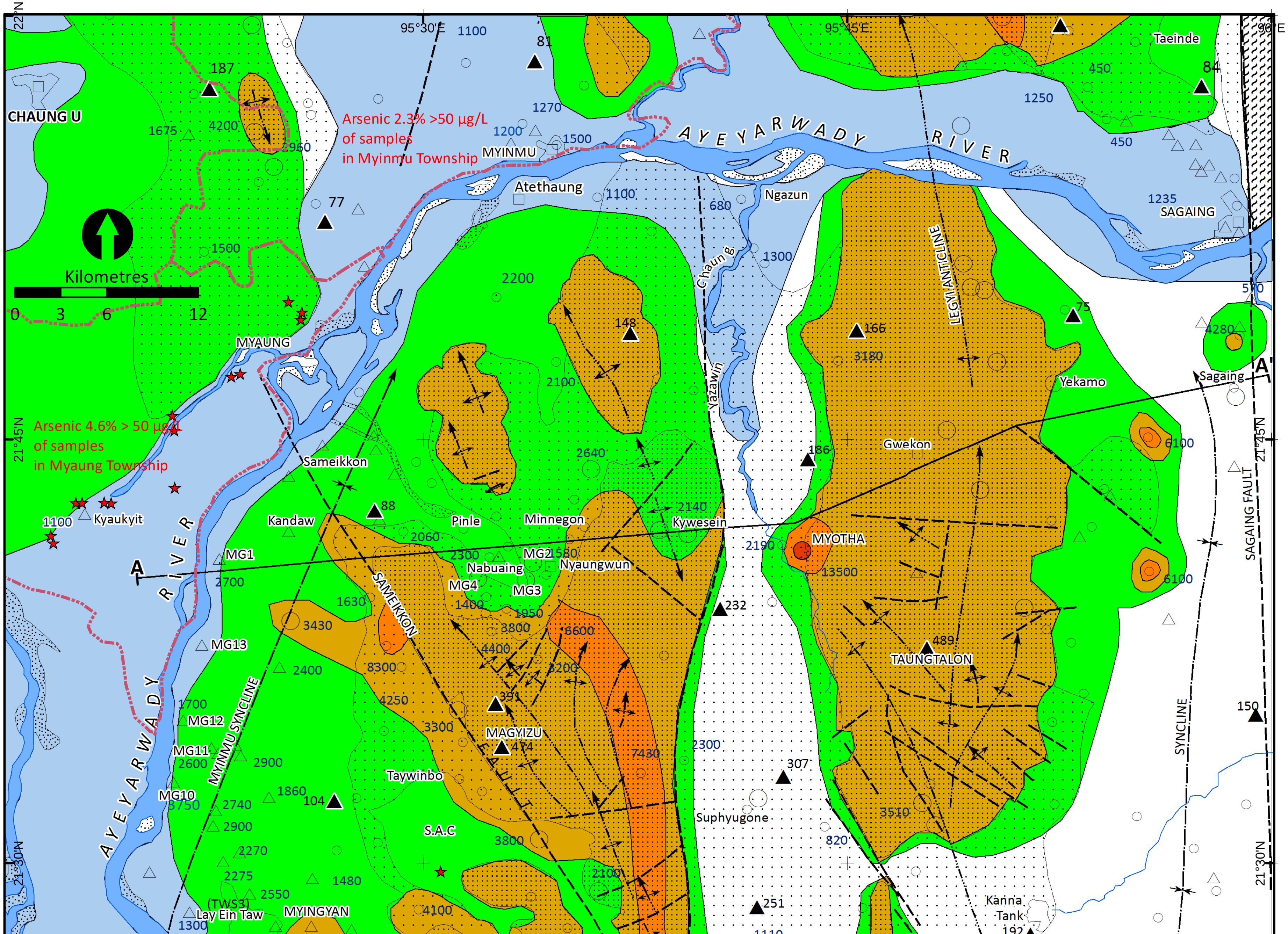
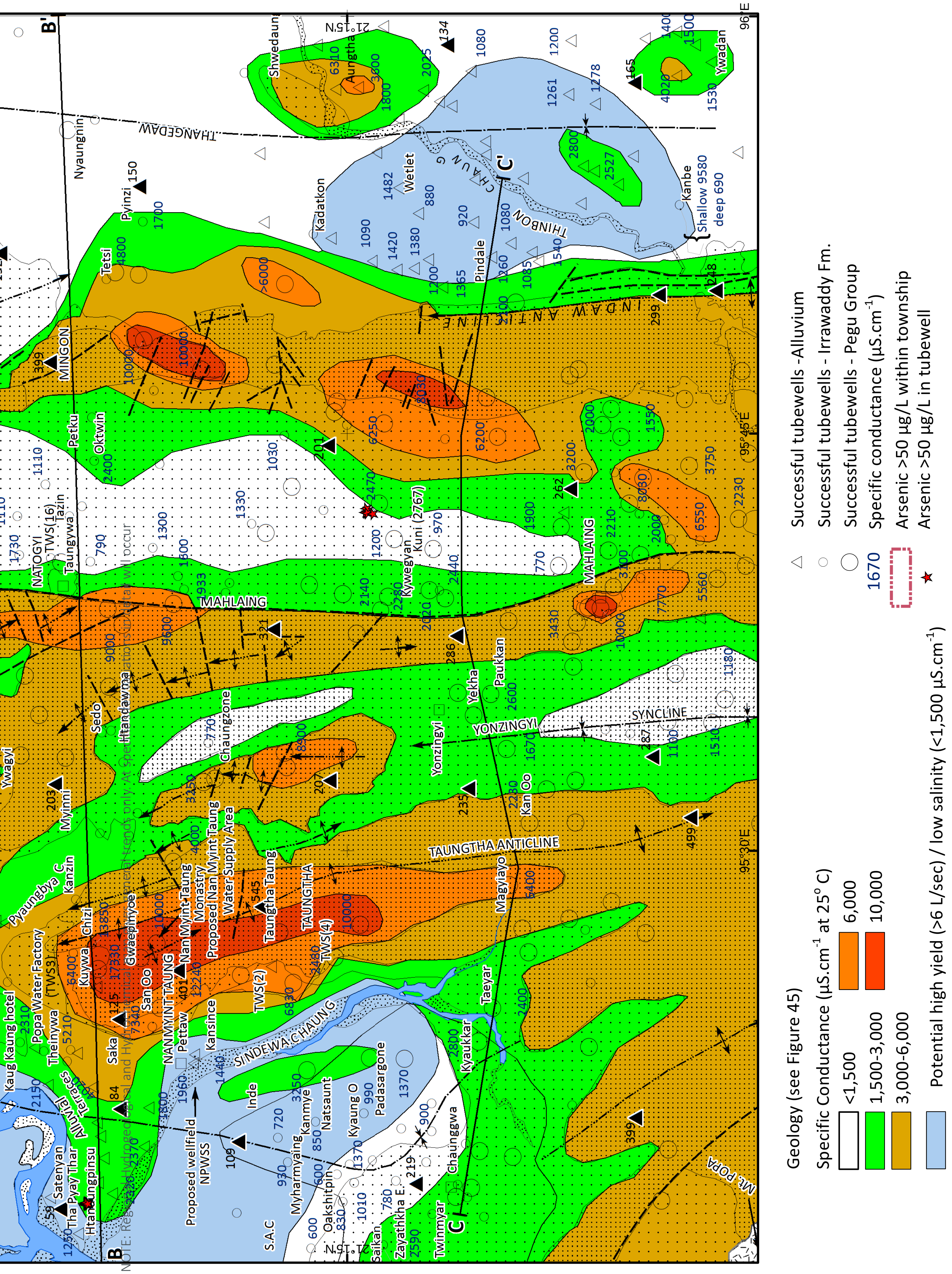

Quaternary
Alluvium
Recent river sand
L.Pleistocene to U.Miocene
Irrawaddy Formation
L. to M. Miocene
Pegu - Obogon & Kyaukkok Fm.
Sub Recent to U. Miocene
Extrusive igneous rocks
River/ water body
Piped Water Supply Scheme
Successful tubewells -Alluvium
Successful tubewells - Irrawaddy Fm.
Successful tubewells - Pegu Group
Tritium analysis
Tubewell Depth > 300m
Spot elevation (m AMSL)
Yangon Mandalay Expressway
Direction of groundwater flow
Geological cross section
Syncline with direction of plunge
Anticline with direction of plunge
Elevated fluoride
Hydrogeological boundary
Drilling mud circulation loss
TAUNGTHA ANTICLINE
YONZINGYI SYNCLINE
MAHLAING
INDAW ANTICLINE
THANGEDAW
SINDEWA CHAUNG
THINBON
MT. POPA
Proposed wellfield NPWSS
Proposed Nan Myint Taung Water Supply Area
95°15'E
95°30'E
95°45'E
96°E
21°15'N

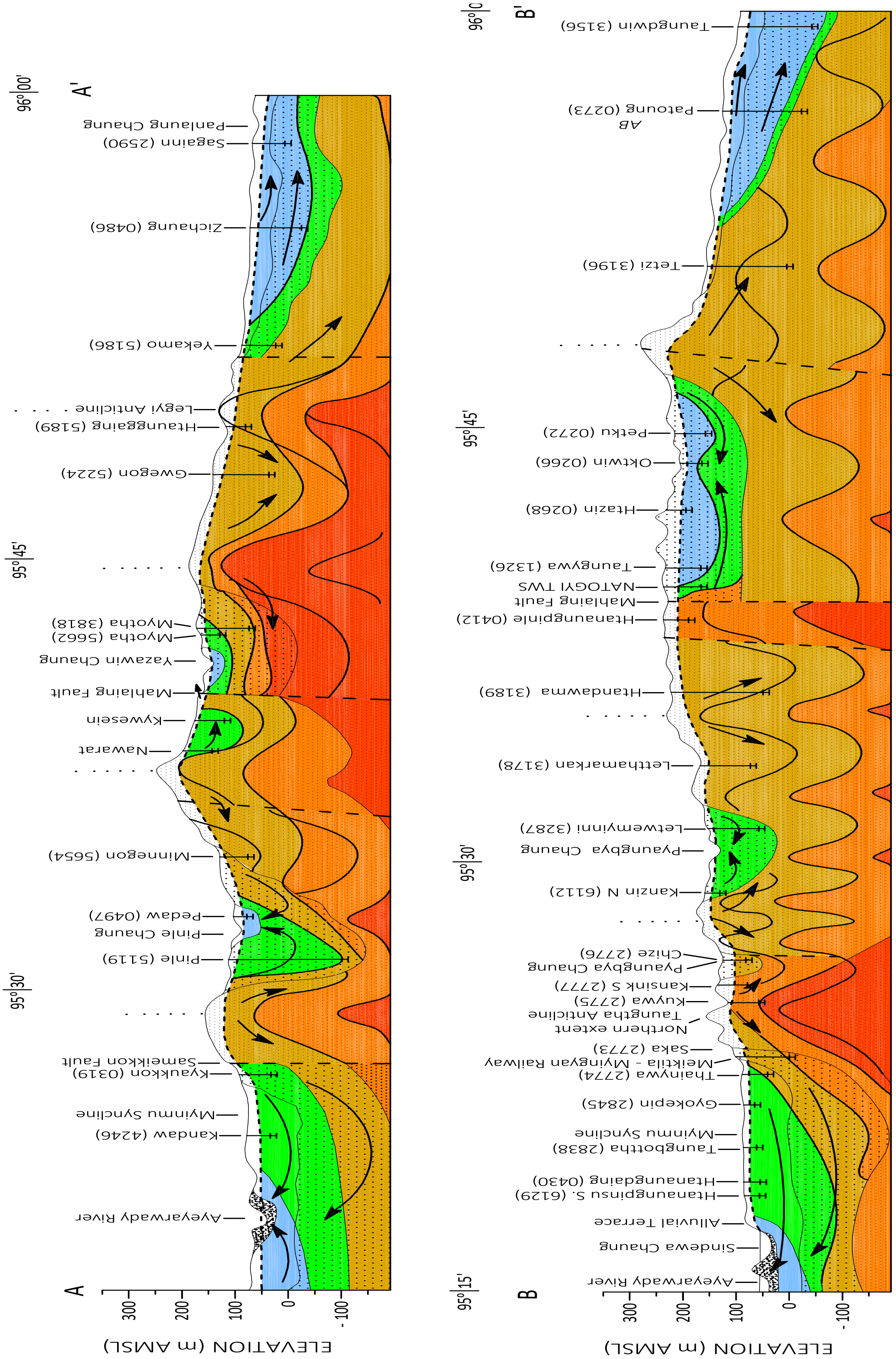
Figure 47 Schematic Hydrogeological and Hydrochemical Map: Myingyan-Ngazun-Mahlaing





Geology (see Figure 45)
Specific Conductance (µS.cm⁻¹ at 25° C)
<1,500
1,500-3,000
3,000-6,000
6,000
10,000
Potential high yield (>6 L/sec) / low salinity (<1,500 µS.cm⁻¹)
Successful tubewells - Alluvium
Successful tubewells - Irrawaddy Fm.
Successful tubewells - Pegu Group
1670 Specific conductance (µS.cm⁻¹)
Arsenic >50 µg/L within township
Arsenic >50 µg/L in tubewell
NOTE: Regional hydrogeological and Hydrochemical trends only. At specific locations anomalous situations will occur
THANGEDAW
THINBON CHAUNG
INDAW ANTICLINE
MAHLAING
MAHLAING
YONZINGYI SYNCLINE
TAUNGTHA ANTICLINE
SINDEWA CHAUNG
NATOGYI
MINGON
TAUNGTHA
NANMYINTTAUNG
MT. POPA
95°30'E
95°45'E
96°E
21°15'N
B
B'
C
C'

Figure 48 Hydrogeological Cross Section and Specific Conductance: Myingyan-Ngazun-Mahlaing



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Figure 48 (continued) **Hydrogeological Cross Section and Specific Conductance: Myingyan-Ngazun-Mahlaing**

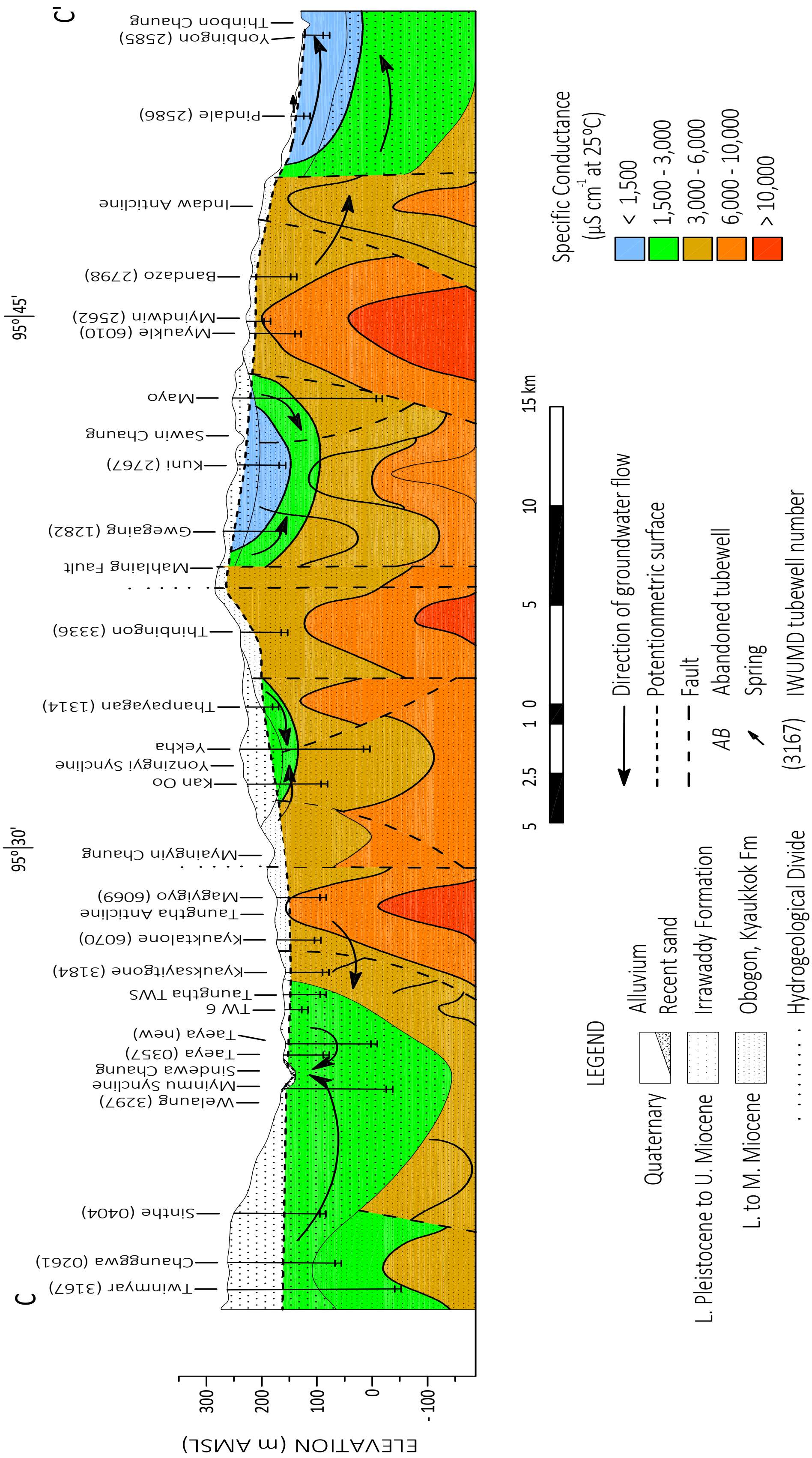


Table 47 Examples of Drought Relief Tubewells (2014) in Pegu Group Aquifers

Village	Depth	Screen Length	SWL	DDL	Yield (L/sec)	Specific Conductance ($\mu S.cm^{-1}$)
	(m)					
Yekha	213	14	3	6	5	2,950
Kan Oo	137	24	4.5	30	2	3230
Paukkan	215	13	15	24	3	2,600
Mayo	277	6	1.2	24	2	3,750
Kyaukkar	182	23	10	24	2	2,800
Taeyar	177	31	18	61	0.3	3,400
Natsaunt	230	23	38	6	5	3,250

Source: IWUMD data (2017).

Tritium analyses from the Obogon Formation (Kuywa and Htadawma villages) indicate pre-thermonuclear age.

General principles for developing successful water supplies in Pegu Group aquifers are:

- drilling should be terminated at the first aquifer intersected. The ion dominance changes from a brackish Na+:HCO_3^- type water in shallow aquifers to a more saline Na+:Cl^- and Ca^{2+}:SO_4^{2-} with depth;
- expect low groundwater yield. Several shallow brackish tubewells is more beneficial than one deep saline hole; and
- practice multi-sourcing – use shallow groundwater in the Dry Season and rain harvesting and surface water catchments in the Wet Season.

14.3 Irrawaddy Formation

The Irrawaddy Formation is in synclinal basins between the Pegu Group hills and on the flanks. These rocks of Upper Miocene to Lower Pleistocene age consist of poorly cemented, massive, current-bedded, medium to coarse grained sand, poorly bedded clay and shale and calcareous nodules. Fossil wood, up to 15 metres in length is occasionally observed.

14.3.1 Bago Yoma Anticlinorium

The depth to aquifers generally conform to the structure in which they are associated:

- there is a general trend for aquifers along the Yonzingyi Syncline to be shallower towards the edge of the hills (24 to 60 metres towards the Taungtha Anticline) and deeper (>150 metres) and thicker along the synclinal axis increasing to the north;
- in the Mahlaing to Natogyi trough the Irrawaddy Formation superficially overlies an easterly dipping Pegu bedrock. Most tubewells penetrate the Irrawaddy Formation and then enter the underlying Obogon Formation; and
- from Suphyugone Village northwards to Ngazun the aquifer slopes from 180 to 30 m AMSL.

Recharge occurs by direct rainfall on the permeable sandy soil, surface runoff along chaungs during the Wet Season or throughflow of saline water from the Pegu Group.

Salinity is quite predictable and dependent on proximity to the Pegu Group:

- to the east of Sindewa Chaung groundwater salinity increases. The Na^+:HCO_3^- dominance changes to a Na^+:Cl^- and Na^+:SO_4^{2-} type water. At Natsaunt Village alluvial aquifers are less than 30 metres thick contain low salinity water (1,290 $\mu S.cm^{-1}$). A deep tubewell in the underlying Irrawaddy Formation aquifer yields brackish water (3,250 $\mu S.cm^{-1}$);

Natsaunt Village Dugwell: May 2016 (Source: Aye Aye Min (2016))
Specific Conductance: 1,290 µS.cm^{-1}.

Natsaunt High School Deep Tubewell: November 2016
Specific Conductance: 3,250 µS.cm^{-1}, Total Dissolved Salts: over detection limit, pH: 8.3

- overlying the Yonzingyi Syncline axis some tubewells intersecting shallow aquifers yield $Na^+:HCO_3^-$ type water with a specific conductance below 2,000 µS.cm^{-1} (the groundwater at Chaungzone Village has a salinity of 770 µS.cm^{-1}). Tritium analysis indicates a pre-thermonuclear age. Water quality deteriorates both to the east and west of the synclinal axis towards the Pegu Group outcrop; and
- east of the Mahlaing Fault the specific conductance of the $Na^+:Cl^-$ and $Na^+:HCO_3^-$ type water from the shallow aquifers varies from 730 to 2,470 µS.cm^{-1}, at Taungywa and Kywegyan villages respectively. Groundwater from the underlying marine Obogon Formation ranges up to 10,000 µS.cm^{-1}.

Natogyi obtains its water supply from groundwater in the Irrawaddy Formation close to the Mahlaing Fault. It extracts 3 L/sec from 16 shallow tubewells with specific conductance of 1,930 µS.cm^{-1}.

Mahlaing's water supply is sourced by private tubewells at 100 to 120 metres deep in Irrawaddy Formation and weathered Pegu Group rocks. Salinity is between 1,900 and 2,300 µS.cm^{-1}.

Another example of the importance of locating shallow aquifers of the Irrawaddy Formation before intersection of Pegu rocks is given for Myotha Village. A tubewell on the Obogon and Irrawaddy formations boundary intersected a $Na^+:Cl^-$ type groundwater from 98 to 104 metres with a specific conductance of 13,500 µS.cm^{-1}. A new hole (TW No 5662) was sunk west of this geological boundary and terminated in the Irrawaddy Formation at 45 metres. This new hole yielded $Na^+:HCO_3^-$ type water with a specific conductance of 2,190 µS.cm^{-1}.

Taungtha Town Water Supply:

Operator: Taungtha Township Development Committee.
Sources: municipal water from both surface and groundwater. The municipal pumping capacity is 2.7 ML/day.

Surface Water – Taungtha and Bonsinyoe dams used in the Wet Season.

Groundwater (Source 1) – four x 100 mm dia. DTWs (Ne Thayar Village) at the base of the Taungtha Anticline drilled through Alluvium and into Irrawaddy Formation. The water is slightly brackish. SWL: 12 metres.

Drill depth: 65 to 120 metres, Screen depth: 45 to 60 (min.), 93 to 100 metres (max.).

During the Dry Season, the tubewells are each pumped @ 4 L/sec x 18 hours/day (1 ML/day).

Specific conductance: 1,500 to 2,500 µS.cm^{-1}.

Groundwater (Source 2) – two x 4 metre dia. dugwells near Taungtha Chaung dams.

Town Water Demand:

Assuming a population of 17,528 (Census 2014) and water consumption of 130 L/d/p, the town water supply demand is 2.3 ML/day.

Taungtha TWS Ne Thayar Village: November 2016
Specific Conductance: 2,460 µS.cm^{-1}, Total Dissolved Salts: 1,892 mg/L, pH: 7.8, Temperature: 26.3° C.

In this saline environment, the general rules to locate low salinity water include:

- drill away from Pegu Group outcrop;
- avoid areas where the Obogon Formation occurs at a shallow depth; and
- terminate drilling in the shallowest aquifer of the Irrawaddy Formation, geophysical log the tubewell and test for quality and quantity. Do not drill deeper unless necessary.

In April 2017, a data logger and pressure transducer were installed in a monitoring piezometer at the IWUMD office, Myingyan to observe groundwater behaviour (salinity and water level) in the Irrawaddy Formation.

14.3.2 Regional Impact of the Bago Yoma Anticlinorium

From the elevated Bago Yoma Anticlinorium brackish groundwater slowly moves outwards into the regionally extensive Irrawaddy Formation. Recharge of low salinity water occurs from watercourses, such as Sindewa Chaung. **Figure 47** and **Figure 48** indicate the impact that both recharge systems have on the Irrawaddy Formation aquifers.

A plume of brackish groundwater moves towards Myingyan Town and environs, progressively becoming less saline with distance from the Pegu rocks. At Theinywa Village, south of Myingyan the water chemistry profile is:

Theinywa Village 25-metre-deep Dugwell: November 2016
Specific Conductance: 2,250 µS.cm^{-1}, TDS: 1,892 mg/L, pH: 8.6, Temperature: 23.7° C.

Theinywa Village 75 metre Tubewell: November 2016
Specific Conductance: 4,020 µS.cm^{-1}, pH: 8.3, Temperature: 28.5° C, SWL 15 metres.

Theinywa Village 180 metre Tubewell (sample taken during development airlift): November 2016
Specific Conductance: 5,210 µS.cm^{-1}, pH: 7.8, Temperature: 28.5° C, SWL 12 metres.

At Myingyan less saline water (2,730 µS.cm^{-1}) is encountered in the 390 metre-deep Kaung Kaung Hotel tubewell overlying multiple salty yellow fine sand aquifers. The 365 to 385 metre, medium to coarse sand yields 2.5 L/sec.

Kaung Kaung Hotel, Myingyan: November 2016
Specific Conductance: 2,730 µS.cm^{-1}, pH: 7.8, SWL 12 metres.

Water salinity less than 2,500 µS.cm^{-1} should not be anticipated with depth beneath Myingyan Town. To the west groundwater salinity progressively decreases.

Hydrogeological details of some emergency drought relief tubewells west of Taungtha are given in **Table 48.**

Table 48 Examples of Drought Relief Tubewells (2014) in Irrawaddy Formation Aquifers

Village	Depth	Screen Length	SWL	DDL	Yield	Specific Conductance
	(m)				(L/sec)	(μS.cm^{-1})
Zagyan	274	23	99	130	3.5	1,002
Kanmye	262	23	102	12	3.3	950
Kyaung O	280	17	105	128	3	1,370
Oakshitpin	274	17	101	131	5	830
Kantonesint	274	23	116	143	3	1,200
Zayathkha E	244	31	143	177	3.5	780
Sinkan	284	23	177	220	1.5	2,590

Source: IWUMD database.

Tubewells immediately downgradient of Pegu Group outcrops have elevated salinity. To the west and north away from the Bago Yoma Anticlinorium groundwater salinity decreases (< 1,500 μS.cm^{-1}). Aquifer depth increases over the Myinmu Syncline to 280 metres. Most deep tubewells intersect Na^+:HCO_3^- type water. Some aquifers have a potential yield greater than 10 L/sec.

14.4 Alluvium

The fluviatile sediment of Thinbon Chaung and tributaries (eastern periphery of map), are discussed in **Chapter 15**.

A narrow strip of Alluvium is located along the Ayeyarwady River and associated tributaries. Its thickness is poorly documented as tubewells are usually terminated in shallow unconsolidated aquifers. Depth to the underlying Irrawaddy Formation is assumed to be 75 metres. The Alluvium consists of brown and grey clay, silt, sandy clay and sand, minor fossil wood fragments and fresh water gastropods.

Several alluvial terraces, at elevations of 76 to 55 m AMSL occur to the southwest of Myingyan. The depth to the water table in the lowest terrace is about 1.5 metres; the upper terrace between 12 to 24 metres. Simultaneous fluctuations in both river and aquifer water levels indicate direct hydraulic connection between the two water systems.

Semi-unconfined aquifers are usually encountered at a shallow depth (30 to 45 metres) along the Ayeyarwady River. Small scale irrigation takes place from thousands of shallow, small diameter tubewells, with individual yields around 2 L/sec.

Photo 55: Maharmying Village Tubewell, Irrawaddy Fm, Taungtha

Photo 56: Sindewa Chaung near Pettaw Village, Taungtha

Fluviatile deposits along the perennial Sindewa Chaung extend 30 kilometres from the Ayeyarwady River towards Mount Popa. These sediments are recharged by low salinity water during the Wet Season and continuously from Mount Popa springs. Hydrogeological testing has been carried out at the proposed Nanmyinttaung Piped Water Supply Scheme (NPWSS) near Pettaw Village[122]. The alluvial thickness is 41 metres. The sand and gravel aquifers have high transmissivities (400 to 1,000 m^2/day) and a storage coefficient of 1.3 x 10^{-3} to 2 x 10^{-4} (semi-confined to confined conditions). Groundwater yield from properly constructed production tubewells should exceed 40 L/sec. Throughflow and groundwater storage are estimated as 3 ML/day and 6.6 x 10^8 Litres/km^2 respectively. The specific conductance of the deeper alluvial aquifers is 1,400 µS.cm^{-1}. Tritium analyses for the deeper aquifers indicate a pre-thermonuclear water. Base flow from the underlying Pegu Group or Irrawaddy Formation may occur.

Beneath Myingyan the specific conductance of alluvial aquifers varies from 2,000 to 6,000 µS.cm^{-1}. Lower salinity, high groundwater yielding alluvial aquifers have been located to the west of that town[123].

Brackish water occurs where watercourses drain the Pegu Group watersheds. Pyaungbya Chaung Alluvium is recharged by low salinity water during flood events. During the Dry Season, a saline plume moves slowly westwards as the low salinity water drains under a low hydraulic gradient back into the Ayeyarwady River.

'Recession farming' is carried out on sandy riverbeds during the Dry Season. Farmers are allocated small parcels of land. They dig temporary shallow dugwells (supported with bamboo reinforcing) in a grid pattern to minimise energy in water distribution. Typically, dual watering cans of low salinity groundwater are used to spread water on a few square metres of crop per application. Due to the sandy soil, frequent irrigation is necessity.

Myingyan Town Water Supply

Operator: Myingyan Township Development Committee.
Source: Groundwater:

Popa Water Factory

- 3 x 100 mm dia. tubewells; 52 metres deep, SWL 16 metres; multiple sand and gravel Alluvium aquifers; screened 35 to 50 metres; Specific Conductance: 2,160 µS.cm^{-1}. Total yield 25 L/sec.

Lay Ein Tan Village

- 2 x 200 mm dia. tubewells; 55 metres depth; SWL eight metres; multiple Alluvium aquifers, screened 40 to 52 metres. Transmissivity range 3,500 to 3,700 m^2/day- with hydraulic barrier boundary.
- 1 x 250 mm dia. tubewell; 55 metres deep, SWL 7.6 metres; Specific Conductance: 1,300 µS.cm^{-1}.
- combined yield from Lay Ein Tan Village is 35 L/sec.

Town Water Demand:

Assuming a population of 87,708 (Census 2014) and water consumption of 130 L/d/p, the town water supply demand is 11.4 ML/day. The municipal groundwater supply of 5.2 ML/day supplies 46 percent of the town's water demand, the remainder comes from brackish dugwells, shallow tubewells, rainfall storage and ponds.

122 Soe Win et. al. (1983, 1985), Soe Win (1984a,b), Coffey and Partners (1985a)
123 Sir Alexander Gibb and Partners (1986)

Photo 57: Temporary Shallow Dugwell in Recent Sand, along Ayeyarwady River and Tributaries in Dry Season

Hundreds of other farmers have permanent small diameter, shallow tubewells in the Alluvium, equipped with centrifugal pumps.

14.5 Dissolved Metals in Groundwater

Table 49 and **Figure 47** show arsenic in groundwater from four townships in three regions. The high concentrations from Myaung Township have previously been discussed (**Chapter 12**). Arsenic exceedance of 50 µg/L in the Ayeyarwady River Alluvium beneath Myingyan and Yesagyo townships is 2.8 and 1.3 percent respectively.

Table 49 Arsenic in Groundwater from Myingyan and Environs

Township (Region)	Total Samples	Concentration > 10 µg/L		Concentration > 50 µg/L	
		No.	%	No.	%
Yesagyo (Magway)	522	96	18.4	7	1.3
Myingyan (Mandalay)	614	60	9.8	17	2.8
Mahlaing (Mandalay)	500	102	20.4	6	1.2
Myaung (Sagaing)	3,181	877	27.6	145	4.6

Source: WRUD and UNICEF (2005).

Table 50 indicates the dissolved metal content in groundwater from Myingyan Town. Of the 12 groundwater samples tested none exceeded NDWQS arsenic standard of 50 µg/L. Forty-two percent exceeded WHO standards for fluoride (compared to 35 percent at Wetlet). Uranium exceeded WHO standards in 16 percent of groundwater samples.

Table 50 Dissolved Metal Content of Groundwater from Myingyan Town

WHO	10	2,400	700	50	1,500	2,000	400	10	40	30	100	Depth (m)
Metal	As	B	Ba	Cr	F	Fe	Mn	Pb	Se	U	V	
	(µg/L)											
SA	22*	130	< 10	< 10	1,500	< 100	< 5	< 1	< 5	14	< 5	37
SB	2	120	< 10	< 10	800	< 100	< 5	< 1	< 5	18	< 5	61
SC	2	30	30	< 10	900	< 100	< 5	< 1	< 5	13	7	55
SD	1	110	< 10	< 10	1,400	< 100	< 5	< 1	< 5	5	6	40
SE	1	59	20	10	1,100	1,180	14	< 1	< 5	8	9	55
SF	3	< 20	20	30	2,000*	< 100	< 5	< 1	7	45*	14	61
SG	2	120	10	< 10	900	260	< 5	< 1	< 5	16	< 5	35
SH	1	140	20	< 10	1,100	< 100	< 5	< 1	< 5	10	< 5	31
SI	2	< 20	20	< 10	1,500*	< 100	< 5	< 1	< 5	11	< 5	55
SJ	3	170	20	< 10	2,500*	< 100	< 5	< 1	14	10	7	61
SK	2	< 20	20	20	1,700*	< 100	< 5	< 1	7	33*	6	46
SL	3	360	< 10	< 10	3,600*	< 100	< 5	< 1	< 5	16	< 5	55

Source: Bacquart et. al. (2015). * sample exceeded health based reference (WHO Guidelines).

There are around 60 shallow tubewells (eight to 15 metres deep with static water level of three metres) near Tha Phay Thar Village. Groundwater is of low salinity however contains high concentrations of arsenic, iron and manganese (**Table 51**). All groundwater samples exceed the arsenic WHO Standard of 10 µg/L. Informed of this hazard, the villagers now only use one designated low arsenic tubewell within the village for drinking purposes.

Tha Pyay Thar Village Tubewell: November 2016, SWL three metres
Specific Conductance: 1,250 µS.cm^{-1}, Total Dissolved Salts: 905 mg/L, pH: 7.2, Temperature: 24.3° C.

Table 51 Dissolved Metal Analyses from Tha Pyay Thar Village Tubewells

WHO	10	2,400	700	50	1,500	2,000	400	10	40	30	100	Depth (m)
Metal	As	B	Ba	Cr	F	Fe	Mn	Pb	Se	U	V	
Unit	(µg/L)											
S1	134*	< 20	120	< 10	< 300	3,320*	1,140*	< 1	< 5	< 1	< 5	18
S2	20*	42	250	< 10	300	4,160*	390	2	< 5	< 1	< 5	23
S3	14*	62	150	< 10	400	1,930	750*	< 1	< 5	< 1	< 5	19
S4	46*	< 20	60	< 10	400	1,320	1,580*	< 1	< 5	< 1	< 5	20
S5	48*	38	160	< 10	< 300	1,110	1,748*	2	< 5	< 1	< 5	15
S6	10	< 20	190	< 10	< 300	3,680*	541*	< 1	< 5	< 1	< 5	17

Source: Bacquart et. al. (2015). * sample exceeded health based reference (WHO Guidelines)

Dissolved metal content is not usually analysed. Other locations of high dissolved metal may occur in groundwater of the Myingyan-Ngazun-Taungtha area.

14.6 Areas of High Groundwater Yield and Low Salinity

Due to the dominance of brackish to saline groundwater in the Pegu Group and seepage into the downgradient Irrawaddy Formation and Alluvium, there is overall poor prospects in obtaining large supplies of low salinity water for irrigation purposes.

Small scale farm irrigation and testing for the NPWSS indicate that high yield and low salinity Alluvium and Irrawaddy Formation aquifers may occur in the downstream sections of Sindewa, Yazawin and Thinbon chaungs and a narrow strip of alluvial flats along the Ayeyarwady River. The total area of potential high groundwater yield and low salinity is less than 20 percent of the Myingyan-Ngazun-Mahlaing area.

Heavy groundwater extraction may induce salt water intrusion to the pumping facility if the pumping facility was located too close to existing brackish areas.

Figure 47 indicates that there is a narrow six to 10-kilometre width of low salinity groundwater between Sagaing to downstream of Myaung.

14.7 Estimation of Water Balance

The Myingyan-Ngazun-Mahlaing area forms part of the ARC. The water balance for the total Ayeyarwady River Corridor is discussed in **Chapter 17**, along with estimates of low salinity water in storage.

15 Hydrogeology of Wundwin-Thazi-Tatkon

15.1 Introduction

The Wundwin-Thazi-Tatkon area is located within the Eastern Trough. Meiktila is the largest town. Other important centres include Wundwin, Thazi, Pyawbwe, Yamethin and Tatkon. Samon Chaung starts at Yamethin with all intermittent tributaries flowing northwards. South of Yamethin surface water drainage is southwards in the Sittaung River Valley. Agricultural pursuits along the north-south orientated, fertile, alluvial flats include rice, sugar cane, corn, sesame and peanuts. Substantial surface water and groundwater irrigation projects have been developed.

Major regional structural features include the Sagaing Fault, Thazi Anticline and Shan Boundary Fault Complex. The Thangedaw Syncline occurs to the west of Wundwin. A whole series of buried bedrock structures (step faulting or graben valleys associated with the Sagaing Fault) may be present. Anomalous Bouguer highs between Wundwin and Thazi and north and south of Tatkon[124] indicate magma intrusions at depths associated with the fault complex. The Wundwin-Thazi-Tatkon area is a hydrogeological complex region. It contains deep hot water; multiple artesian zones; heterogeneity in aquifer occurrence; thick clay horizons; thin sand lenses; highly variable potentiometric surfaces; shallow and deep bedrock; saline seepages and gas zones. Groundwater studies have been carried out.[125] Tens of thousands of dugwells and tubewells are in this area. The three primary aquifers are:

- Alluvium - fluviatile transported sediment along both sides of the Thazi Anticline;
- Colluvial Piedmont Complex - from the Shan Plateau; and
- Irrawaddy Formation - along the Thazi Anticline, the eastern flank of the Bago Yoma and underlying the Alluvium.

This subdivision is not definitively accurate as longitudinal and laterally transported sediment intertongue and are hydraulically interconnected. Lesser aquifers in fractured rock occur along the Shan Plateau and in the Pegu Group on the eastern edge of the Bago Yoma Anticlinorium.

Examples of aquifer details for various rock types are given on **Table 52**. Water supply tubewells to villages, towns and military camps have been drilled by various government authorities or private contractors. Most towns (Yamethin, Pyawbwe, Wundwin and Thazi) obtain their municipal water requirements from groundwater. Meiktila Town, sited on Pegu Group rocks obtains its water from surface water sources. Groundwater irrigation areas have been developed in the Meiktila-Thazi, Pyawbe-Payangazu and Takton areas. Elsewhere farmers use dugwells and small diameter tubewells with centrifugal pumps for their small-scale irrigation requirements. During the Dry Season, many dugwells go dry as the water table declines. The quality also deteriorates due to pollution through the lack of sanitation, and by salt water encroachment from upgradient saline aquifers in the Pegu Group rocks.

Hydrogeological maps and cross sections are given on **Figures 49** to **53**.

[124] GDC (1984c)

[125] Aung Ba (1958, 1960), Ivanitsin (1962a), Than Tun (1966), Maung Thin (1971), Irrigation Department (1972), FAO (1973), Khaing Shin (1973), Tin Maung Nyunt et. al. (1976), Aung Kyaw Htoon (1979), Ba Khaing (1979), Thein Win (1979), Thein Htay (1980), Tin Maung Nyunt (1980), Myint Soe et. al. (1981), Soe Win et. al. (1981), Thein Soe et. al. (1981), Kyaw Shwe et. al. (1982), GAD (1983), Soe Win (1983), GDC (1984c), Hla Kyi & Shwe Ko (1984), JICA (1985), Soe Win & Tin Tun (1985), Zaw Thay et. al. (1985), Cho U (1986), Hla Kyi et. al. (1986), Thaik Nyunt (1986c,d), Su Mon Win (2013), Aung Khaing Moe (2016), Khin Nilar Tin (2016), Tun Aung (2016), Zaw Htay et. al. (2016)

Table 52 Examples of Aquifer Details from Selected Tubewells in the Wundwin-Thazi-Yamethin Area

Formation / Irrigation Area	Area	Village	No.	Surface Elevation (m AMSL)	All data from surface (m)				DD (m)	Flow/pump Yield (L/sec)	Transmissivity (m^2/d)	Specific Conductivity ($\mu S.cm^{-1}$)
					Depth	Aquifer	SWL	DDL				
Metamorphic	Thazi	Hngetmie	2791	+ 292	79	70- 79	43	55	12	1	8	480
Pegu Group	Bago Yoma to Pyawbwe	Thapanchaug	2795	+ 318	88	73- 79	2	24	22	2	13	1,100
		Ido	0363	+ 305	18	16- 18	8	15	7	1	9	670
	Meiktila	Kya Inn	2754	+ 234	43	32- 37	10	16	6	2	52	12,000
		AMD Station	1330	+ 244	197	183- 197	17	37	20	4	24	4,400
Irrawaddy Formation	Wundwin	Ingangon	3088	+ 116	325	299- 323	45	59	14	13	113	2,140
		Baho	0447	+ 133	22	20- 22	7	12	5	1	30	1.520
		Natkan (E)	1618	+ 136	68	61- 68	7	N/A	N/A	3	N/A	> 10,000
		Dahattaw	6501	+ 128	457	368- 374	82	N/A	N/A	8	N/A	1,600
	Meiktila	Zidaw	4346	+ 180	61	58- 61	Artesian	21	21	8	45	920
	Thazi	Zibinbauk	2759	+ 156	116	76- 79	7	44	37	1	5	2,420
		Ywapale (W)	6502	-	183	176- 180	24	59	35	3	8	10,000
	Yamethin to Tatkon	Thinbannone	3294	+ 197	299	270- 299	6	42	36	8	27	480
		Sepalego	0400	+ 183	52	49- 51	5	23	18	1	5	440
		Pyinmadaw		+ 190	279	239- 260	Artesian	0		5 (flow)		780
		Yamethin (S)	EH3/12	+ 195	180	No G/W						
Piedmont Sediment	Wundwin	Dainggaungkan	2569	+ 75	29	18- 29	1	4	32	8	448	820
	Thazi	Myaingtha	4250	+ 116	52	46- 52	8	12	4	5	131	840
	Pyawbwe	Pinthaung	2790	+ 75	84	72- 78	Artesian	11	11	2	22	580
Alluvium Central Valley	Samon Chaung	Dongon	2582	+ 80	41	29- 41	7	9	2	4	224	1,300
		Kabamyint	1617	+ 173	24	16- 24	7	14	7	1	24	890
		Paukmyaing	6106	+ 88	27	21- 27	2	5	3	11	448	
	Nawin Chaung	Shaukkon	3/19	+ 134	47	33- 46	1	6	5	23	552	440
		U Yin	4374	+ 142	19	13- 19	6	9	4	1	31	400
	Thinbon Chaung	Myaukseywa	4238	+ 152	74	72- 74	7	13	6	5	87	1,090
		Kanbe	2588	+ 157	43	19- 27	9	12	3	2	66	690
	Tatkon	Thaya-aing	3/15		65	19- 22 47- 65	4	11	7	20	JICA 150-325 K = 25-50m/day	520
Meiktila Irrigation Project	Meiktila	Magyi Pin Pu			110	34- 38 47- 52 71- 76 96- 107	5	4	1	6	JICA 500-650 K = 112-124 m/d IWUMD K= 150-200 m/d	1,300
Pwaybwe Irrigation Project	Twin Ywa	Twin Ywa	PB001	+ 80	91	40- 46	Artesian	+ 4	N/A	7.5 /12		240
	Oak Sar Nwe	Hta Aung Pin	PB003	+ 78	213	192- 198	Artesian	+ 4	N/A	1.5 / 10		449
	Oak Sar Nwe	Lin Sin Kone	PB009	+ 75	146	134- 136	Artesian	+ 4	N/A	1 / 7		210

Source: IWUMD database and Umbrella Reports (GDC 1979-1984).

Figure 49 Schematic Geological and Hydrogeological Map: Wundwin-Thazi-Tatkon (North)

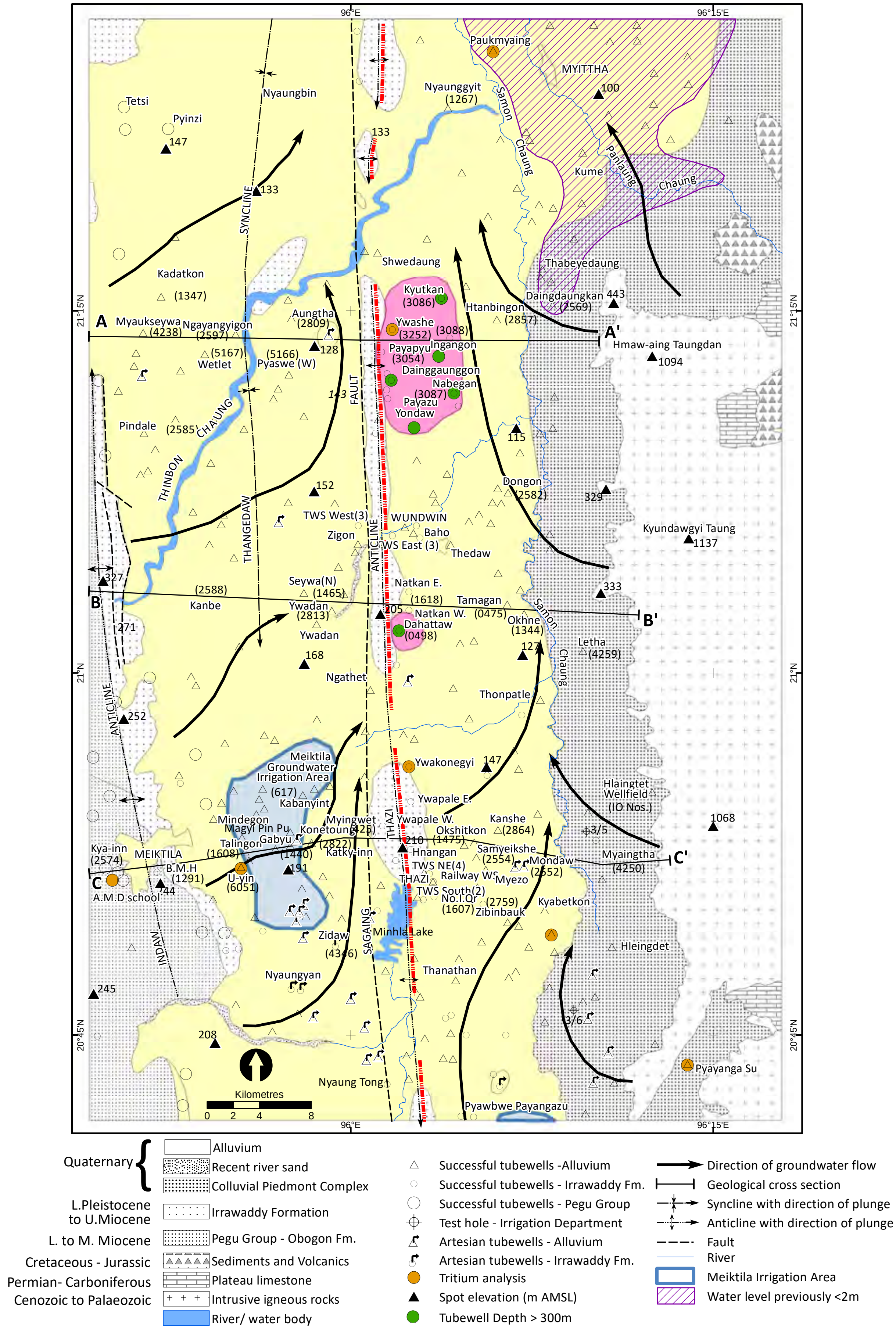
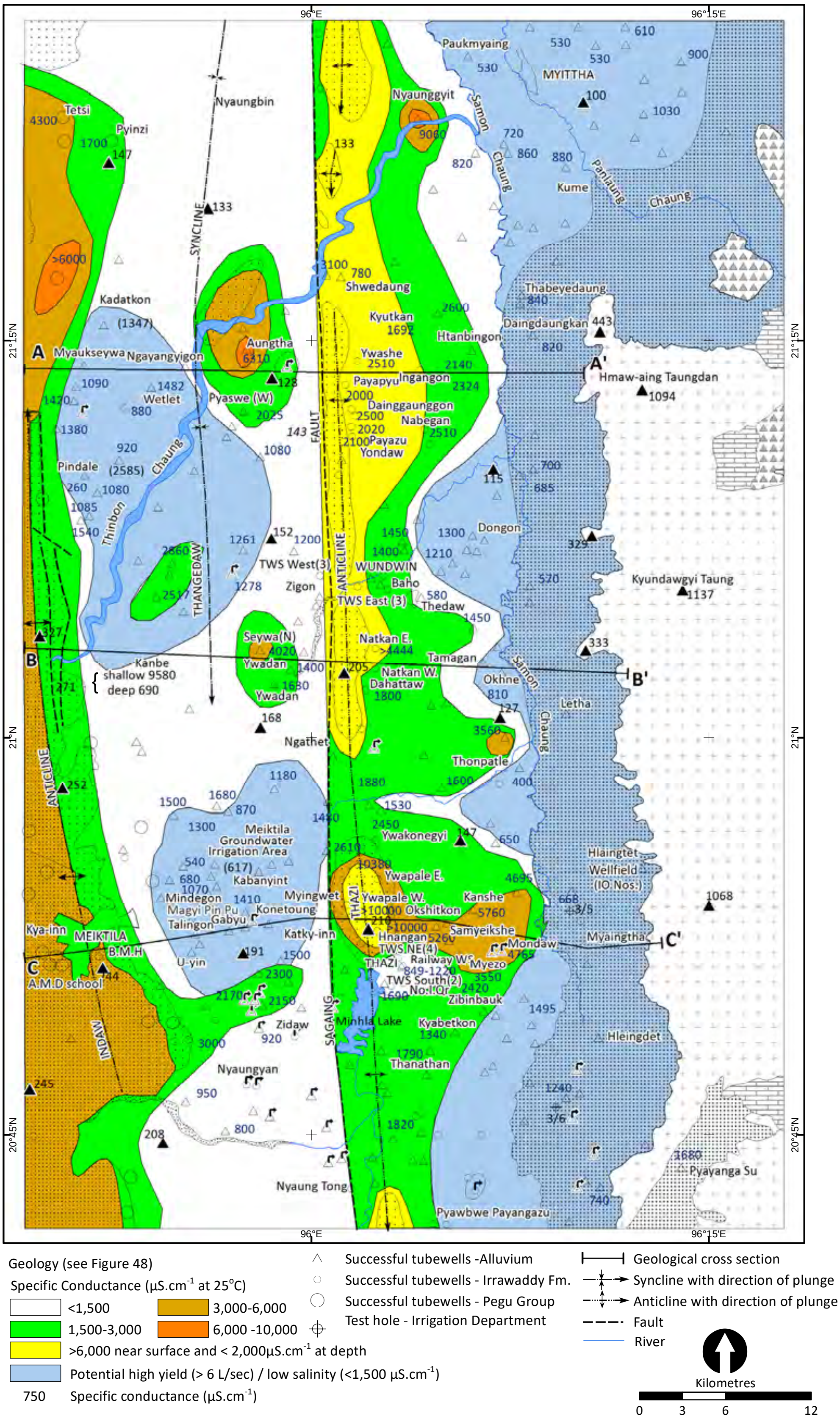


Figure 50 Schematic Hydrogeological and Hydrochemical Map: Wundwin-Thazi-Tatkon (North)



NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occur

Figure 51 Schematic Geological and Hydrogeological Map: Wundwin-Thazi-Tatkon (South)

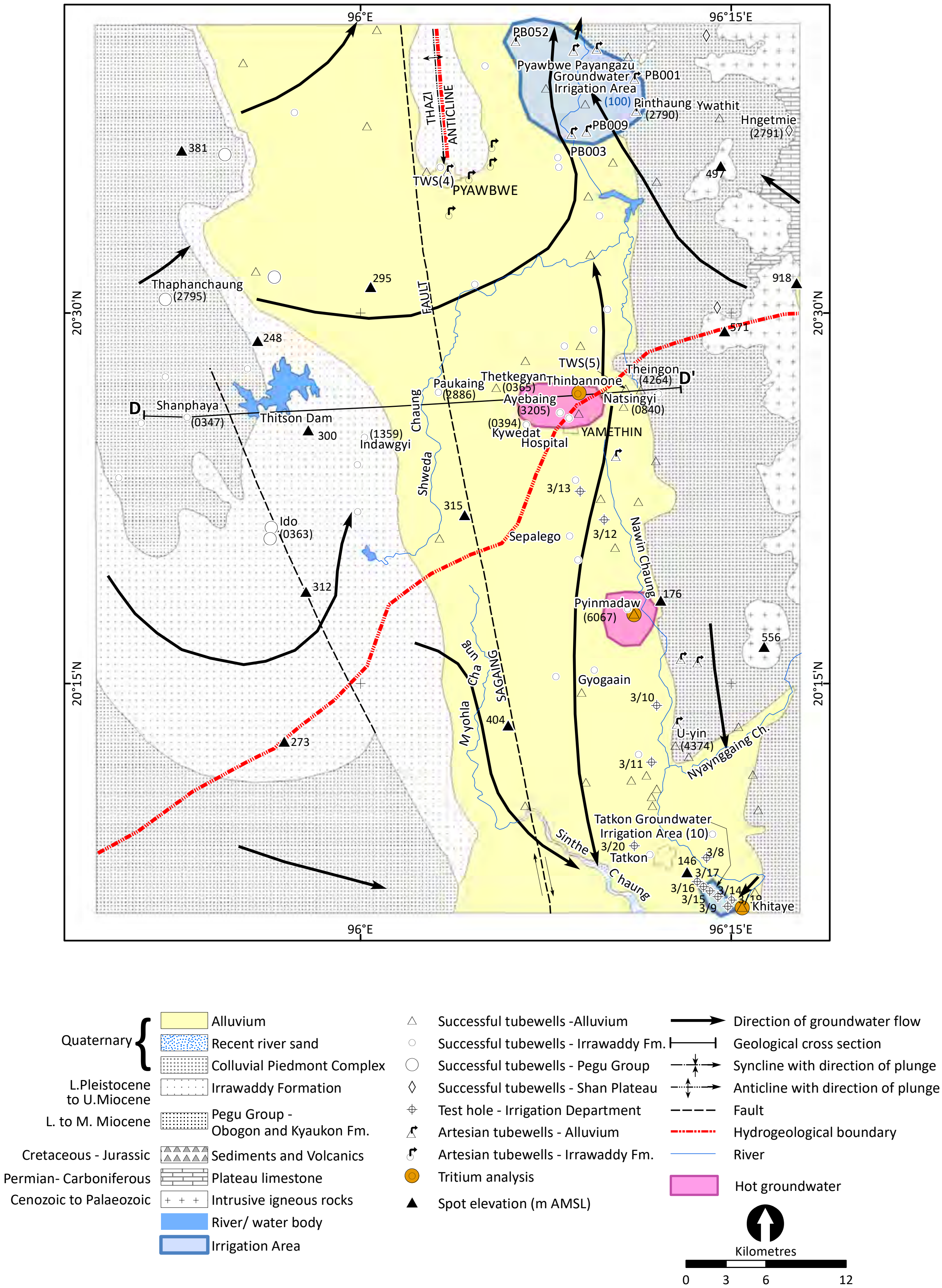
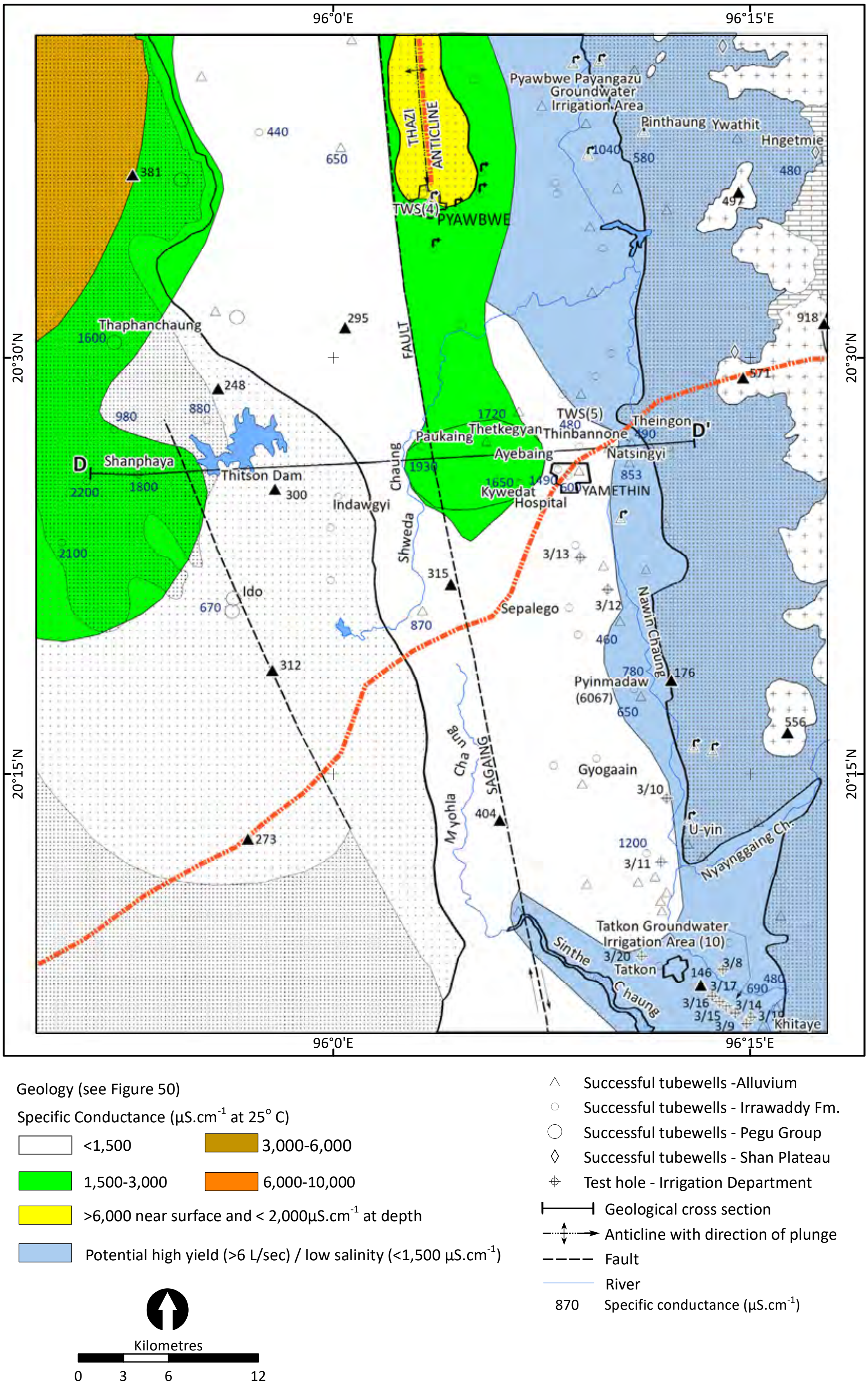
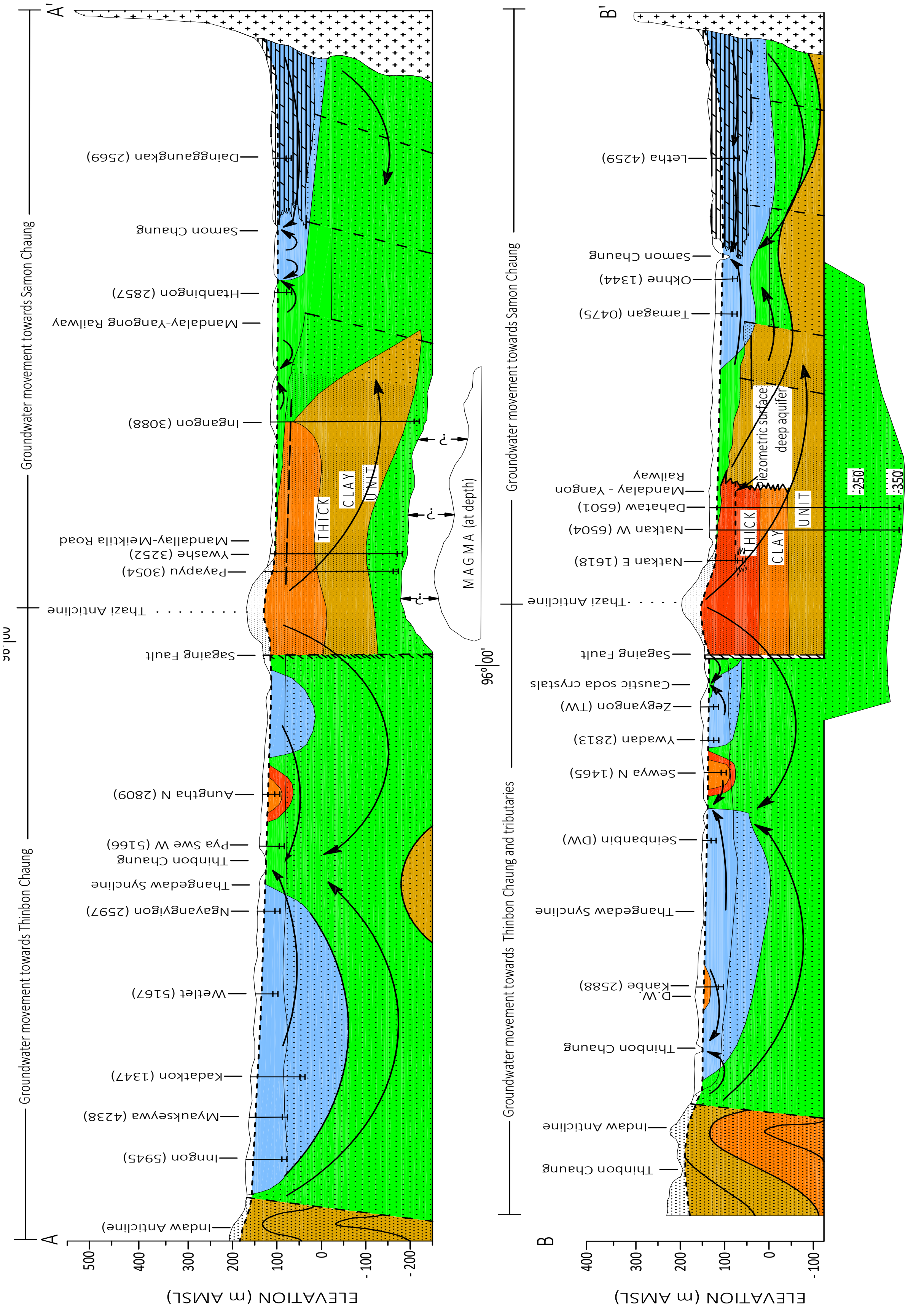


Figure 52 Schematic Hydrogeological and Hydrochemical Map: Wundwin-Thazi-Tatkon (South)



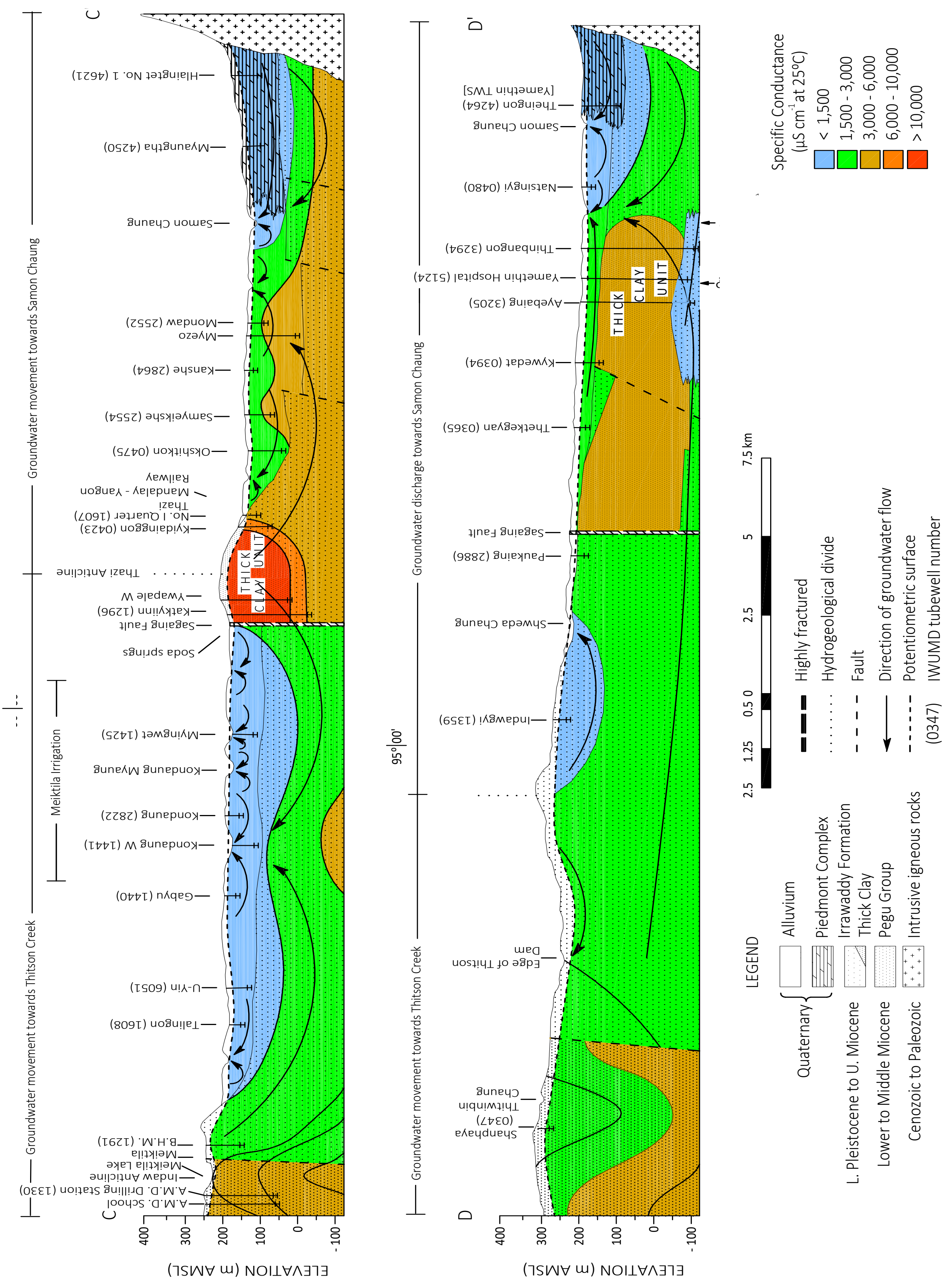
NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occc

Figure 53 Hydrogeological Cross Section and Specific Conductance: Wundwin-Thazi-Tatkon



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

Figure 53 (continued) Hydrogeological Cross Section and Specific Conductance: Wundwin-Thazi-Tatkon



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

15.2 Shan Plateau

Palaeozoic crystalline metamorphic and igneous rocks (gneiss, marble, schist, granite) and Mesozoic sedimentary rocks (shale, siltstone, sandstone, limestone) are located along the western edge of the Shan Plateau. All rocks are intensely folded and faulted. Some low yielding tubewells have been sunk in both the metamorphic and igneous rocks on the escarpment. Most tubewells are abandoned either because the selection of available drilling rigs was not appropriate or fracture systems were not encountered. Those successfully completed yield Ca^{2+}:HCO_3^- dominant water supplies below 2 L/sec. Some tubewells at the base of the escarpment are flowing. The absence of extensive aquifers in metamorphic and igneous rocks along the western edge of the Shan Escarpment limits their regional hydrogeological importance. Limestone forms an important aquifer on the Shan Plateau. Limestone springs are frequently used for village water supplies. Shan Plateau hydrogeology is described by several investigators[126]. The depth of drilling in limestone around Bawsaing, Kalaw Township ranges from 100 to 250 metres with groundwater yields from 1 to 50 L/sec (**Table 53**). The piezometric surface is 30 to 120 metres, generally in accordance with topographic relief.

Table 53 Limestone Aquifers in Bawsaing Village Tract, Kalaw Township

Village	Date Completed	DTW Depth (m)	Water Level (m)	Yield (L/sec)
Kone Mying Tha Yar	31/03/2014	192	55	1
Shwe Mya Se (Monastery)	15/05/2015	178	49	1.5
Tha Phan Pin (2)	06/04/2014	157	64	2.5
Ye Phyu Kan (1)	07/03/2014	145	52	2.5
Ye Phyu Kan (2)	08/09/2014	100	31	3.7
Ye Boke	19/11/2014	180	91	2.0
Kan Thar	30/04/2014	96	71	2.3
Kyauk Htet	10/02/2014	160	117	2.0
Naung Lwe (Monastery)	02/05/2016	250	109	50

Source: IWUMD data (2017).

Deep tubewells in Heho, Pindaya, Aungban, Kalaw, Taunggyi and Namsam of Southern Shan State obtain groundwater from limestone aquifers.

15.3 Pegu Group

Rocks of the Kyaukkok and Obogon formations crop out to the west at Meiktila along the eastern edge of the Bago Yoma. Some tubewells sunk into the marine sediments have been abandoned as no aquifer was intercepted. Aquifer depth in successful holes varies from 10 to 120 metres, the depth being largely dependent on topography and geological structure. Groundwater yield ranges from 0.4 to 5 L/sec. The highest yield has a specific conductance below 1,600 $\mu S.cm^{-1}$ and is sited in a fractured Kyaukkok Sandstone aquifer. Most other tubewells encounter Na^+: HCO_3^- and Na^+:Cl^- type groundwater with specific conductance of 3,250 to 9,000 $\mu S.cm^{-1}$. The general trend is for salinity to increase with depth. Potable water supplies are obtained from shallow sand and weathered rock.

Groundwater flow is east from the elevated recharge areas towards the alluvial valley. Caustic soda crystals are commonly found during the Dry Season in intermittent chaungs draining the Bago Yoma.

Tritium analysis of groundwater taken from 180 to 195 metres at Meiktila indicates a pre-thermonuclear water.

[126] Soe Min (2010), Myanmar Institute for Integrated Development (2015), Ma Ma Chaw (2016)

15.4 Irrawaddy Formation

Rocks of the Irrawaddy Formation crop out:

- as a series of folded inliers along the north-south orientated Thazi Anticline, east of the Sagaing Fault;
- as an almost continuous outcrop along the base of the Bago Yoma; and
- east of Meiktila where it is overlain by Meiktila Lake.

It does not crop out along the Shan Plateau. It may be buried by the Piedmont sediments or is absent.

The Irrawaddy Formation consists of both fluviatile and deltaic sediments. These deposits comprise of fine-medium grained, loosely cemented sandstone, gravel, sand, sand clay, clay, silt and petrified wood. Surface outcrop consists of soft, yellow-brown, fine to medium grained sandstone, loosely cemented and iron stained with appreciable amounts of silt and clay. The aquifers are semi-confined to confined. In some areas, artesian conditions occur.

15.4.1 Along and East of Thazi Anticline

Drilling near Wundwin and Thazi indicates that the thickness of Irrawaddy Formation is greater than 400 metres. The depth to the underlying bedrock is unknown.

A thick yellow-brown clay exists along the full length of the Thazi Anticline. From the surface, the clay horizon is less than 240 metres thick at Wundwin and Thazi; more than 150 metres southwards at Pyawbye; and below 250 metres near Yamethin. Aquifers are usually located beneath this thick clay horizon. It forms a north-south groundwater flow boundary meridionally dividing the valley into two distinct hydrogeological regimes.

Within this clay unit thin, confined sand lenses of variable salinity occur. At Natkan East Village (near Wundwin), the specific conductance of the Na^{+}:HCO_3^{-} type water at depth of 67 to 85 metres is more than 10,000 µS.cm^{-1}. Deeper (but less than 240 metres), isolated sand aquifers are also highly saline. For example, at Ywapale West, Ywapale East and Hnangan villages (Thazi) the specific conductance of the Na^{+}:HCO_3^{-} type water exceeds 10,000 µS.cm^{-1}. Groundwater quality gradually improves with depth. Nearby to these villages, lower salinity sand lenses beneath Katkyi-inn Village at 258 to 264 metres have a salinity of 3,560 µS.cm^{-1}. Similar brackish aquifers occur along the Thazi Anticline at Pyawbwe. The reason for this lithological and salinity occurrence has not been assessed. The potentiometric surface of the sand lenses is less than 15 to 30 metres. The potential tubewell yield varies from 0.1 to 5 L/sec.

Confined, easterly dipping blue grey sand and gravel aquifers (**Table 54**) occur under this thick, saline clay sequence. The depth to the blue grey aquifer in the Wundwin area varies from 200 to 380 metres. The aquifer progressively deepens in an easterly direction away from the Sagaing Fault. The maximum known aquifer thickness is 82 metres at Ywashe Village. The deep aquifers have a transmissivity around 100 m^2/day and contain elevated temperatures. These abnormally high temperatures may be due to proximity of the deep aquifers to magmatic activity identified by Bouguer anomalies associated with the Sagaing Fault. The specific conductance of the Na^{+}:HCO_3^{-} type water varies from 1,600 to 2,510 µS.cm^{-1}. The potential yield from the deep, confined aquifer varies from 10 to 20 L/sec. Large diameter tubewells should yield 50 L/sec.

Table 54 Aquifers Containing Hot Groundwater in the Wundwin-Thazi-Yamethin Area

Township	Village	Tubewell Number	Aquifer Depth (m)	Airlift Yield (L/sec)	SWL (m)	Measured Temperature (º C)	Specific Conductance (µS.cm^{-1})
Wundwin	Dainggaungon	3067	305- 317	10	55	42	2,000
	Ingangon	3088	289- 323	13	45	40	2,140
	Kyutkan	3086	317- 332	10	38	41	1,692
	Nabegan	3087	305- 316	3	44	40	2,510
	Payapyu	3054	265- 293	6	64	42	2,500
	Yondaw	6077	305- 341	8	N/A	42	2,100
	Ywashe	3252	217- 299	10	54	42	2,510
	Payazu	3055	195- 220	2	N/A	42	2,020
	Dahattaw	6501	368- 374	8	82	38	1,600
Yamethin	Ayebaing	3205	251- 293	8	20	35	1,770
	Hospital	5124	274- 287	13	11	39	600
	Thinbannone	3294	270- 300	8	6	38	480
	Pyinmadaw	6067	250- 271	4	0	38	400

Source: IWUMD database.

At Thazi and Wundwin the potentiometric surfaces of the shallow (15 to 30 metres) and deep (45 to 55 metres) aquifers are quite distinct suggesting that the aquifers may occur in discrete blocks, possibly separated by transverse faults and/or that some interaction with deeper aquifers produces a significant component of vertical flow. The difference in potentiometric surface between the saline, shallow aquifers and the lower salinity, deep aquifer at Wundwin indicates a lack of hydraulic interconnection.

The sources of recharge to the deep aquifers is unknown. It may be hydraulically connected to the:

- Irrawaddy Formation cropping out along the western edge of the study area and vertically displaced by the Sagaing Fault; and/or
- Piedmont Colluvial and springs along the Shan Plateau.

The deep tubewells were drilled in 1984 to 1986. No additional holes have been sunk, thus the areal extent of this aquifer system in unknown. Only the Payazu tubewell remains operational. The others have been replaced by better quality surface water from nearby irrigation canals. After 30 years of groundwater extraction the temperature in the Payazu tubewell has declined from 42º C to 35º C and specific conductance improved from 2,020 to 550 µS.cm^{-1}. Pumping at 3 L/sec for five hours per day for 30 years has apparently drawn in cooler and different quality groundwater from other sources.

Payazu Village Tubewell: November 2016
Specific Conductance: 550 µS.cm^{-1}, Total Dissolved Salts: 388 mg/L, pH: 8.3, Temperature: 35º C.

Between Pwaybwe and Yamethin the Thazi Anticline plunges southwards. The thin sand stringers within the clay horizon comprise less than 12 percent of the stratigraphic column. The Na^{+}:Cl^{-} type groundwater salinity of the clayey sand underlying Shweda Chaung, Yamethin and the western part of the Pyawbwe – Payangazu Groundwater Irrigation Project is more than 1,500 to 3,000 µS.cm^{-1}.

Warm groundwater in deep aquifers (> 250 metres) occur under a thick clay aquitard at Yamethin and Pyinmadaw, (**Table 54**). Temperatures range from 35° to 39° C with specific conductance of 400 to 1,930 µS.cm^{-1}. Tubewells at Wundwin are hotter than those at Yamethin.

Pyinmadaw Village Tubewell: November 2016
Specific Conductance: 780 µS.cm-1, Total Dissolved Salts: 456 mg/L, pH: 7.0, Temperature: 39.0º C.

Wundwin Town Water Supply

Operator: Wundwin Township Development Committee.

Source: Groundwater:

Eastern Wellfield and Western Wellfield – Three production bores in each wellfield (total six), all drilled to 180 metres in Alluvium and Irrawaddy Formation. Water quality is marginal to poor. Average yield is 2 L/sec.

Better quality and higher yield should be available further east or west, some two kilometres from the Thazi Anticline.

Thazi Town Water Supply

Operator: Thazi Township Development Committee.

Source: Surface and groundwater is mixed before reticulation.

Surface Water: Raw water from nearby Minhla Dam (when available). This water is turbid and no treatment available.

Groundwater: Southern Wellfield (southeast of Thazi Anticline) – Two JICA tubewells are operational (+ 1 standby) at 6 L/sec for 15 hours/day, yielding 0.65 ML/day. Each hole is sunk to 90 metres (aquifers 40 – 46, 61 – 64 and 79-85 metres).

Northeast Wellfield (east of Thazi Anticline) – Four production bores drilled to 85 to 90 metres with local government funding. Groundwater yield is between 3 and 7 L/sec. Groundwater salinity and yield fluctuates: better in the Wet Season and more saline (> 2,000 µS.cm^{-1}) during the Dry. Average wellfield yield is 1.7 ML/day.

Cumulative Yield: Cumulative wellfield yield is 2.35 ML/day.

Other: There are many private shallow tubewells in Thazi.

Town Water Demand: Assuming a population of 20,561 (Census 2014) and water consumption of 130 L/d/p, the town water demand is 2.7 ML/day. The current reticulated water supply accounts for 87 percent of the town's requirements in the Wet Season but less in the Dry. If additional tubewells are required a wellfield further to the west (Meiktila Groundwater Irrigation Area) or two kilometres east may be viable options.

Photo 58: Thazi TWS, Southern Wellfield, Nov. 2016

Photo 59: Thazi TWS, Northeast Wellfield, Nov. 2016

South of Thazi, the Nyaung Tong Village tubewell sited in the Sagaing Fault penetrated 175 metres of clay, then blue sand before encountering 'gas' at 210 metres. The hole was subsequently abandoned.

Deep groundwater at Ywashe, Ywakonegyi, Thinbangone and Pyinmadaw are pre-thermonuclear (tritium analysis).

Thazi TWS Northeast: November 2016
Specific Conductance: 849 $\mu S.cm^{-1}$, Total Dissolved Salts: 604 mg/L, pH: 7.7, Temperature: 28° C.
Specific Conductance: 1,220 $\mu S.cm^{-1}$, Total Dissolved Salts: 876 mg/L, pH: 8.2, Temperature: 28° C.

Thazi TWS Southern Borefield: November 2016
Specific Conductance: 1,640 $\mu S.cm^{-1}$, Total Dissolved Salts: 1,192 mg/L, pH: 7.6, Temperature: 27° C.

15.4.2 West of Thazi Anticline

West of the Thazi Anticline the yield of low salinity groundwater from small diameter tubewells ranges from 1 to 10 L/sec at depths of 75 to 100 metres. Close to the Obogon Formation the specific conductance of the Na^+:HCO_3^- type water increases to 3,000 $\mu S.cm^{-1}$. Due to topographic relief, some aquifers are artesian. The maximum transmissivity value is 70 m^2/day.

15.4.3 Principle of Hydrogeological Success near Thazi Anticline

The hydrogeological principle for a success tubewell is to stay away from the Thazi Anticline and to drill in the Alluvium or Irrawaddy Formation to the east, west or south of the inliers.

15.5 Alluvium

Heterogeneous Alluvium deposits continuously crop out throughout the Samon Chaung Valley. The aquifers consist of sand and gravel channel deposits within a clayey matrix. The north-south orientated Thazi Anticline hydrogeological barrier has a strong impact on groundwater occurrence and movement (**Figure 49** and **Figure 51**).

15.5.1 West of Sagaing Fault

15.5.1.1 Meiktila – Thazi Groundwater Irrigation Project

Within the Meiktila – Thazi Groundwater Irrigation Project (MTGIP)[127] area groundwater is extracted from Alluvium aquifers to depths of 65 metres. Deeper holes intersect the Irrawaddy Formation.

[127] Su Mon Win (2013), Aung Khaing Moe (2016), Khin Nilar Tin (2016), Tun Aung (2016), Zaw Htay et. al. (2016)

Meiktila – Thazi Groundwater Irrigation Project

Construction Date: 2008.

Number of Tubewells: 485.

Command Area: 2,600 hectares.

Implementing Agency: IWUMD / FAO / Italian Development Corporation.

Operator: Individual farmers.

Purpose: Improve farmer socio-economic status by increasing agriculture productivity.

Management: No flow monitoring.

Hole Design: diameter: 50 and 100 mm; depth: 25 to 130 metres.

Geology: Alluvial clay, silt, sand, gravel and Irrawaddy Formation.

Aquifers: Four distinct aquifers

Geology	Unit	Depth (m)	Lithology	Aquifer/Aquitard	Extraction
Holocene	Alluvium	37	Fine to medium sand	Unconfined Aquifer 1	Pump
			Clay, silty	Aquitard 1	
		65	Yellow medium sand	Confined Aquifer 2	Pump
L. Pleistocene M. Miocene	Irrawaddy Formation		Clay, silt	Aquitard 2	
		80	Blue sand, gravel	Confined Aquifer 3	Artesian and/or pump
			Blue clay	Aquitard 3	
		130	Blue sand, gravel	Confined Aquifer 4	

Groundwater Yield: Tubewells equipped at 5 to 10 L/sec.

Aquifer Characteristics:

Parameter	Aquifer 2 (Reference)	Aquifer 3 (Reference)
Transmissivity (m^2/day)	44 to 54 (Tun Aung 2016)	498 to 647 (Zaw Htay et. el. 2016) 532 to 639 (Su Mon Win 2013) 647 to 1,078 (Khin Nilar Tin 2016)
Hydraulic Conductivity (m/day)		20 to 27 (Zaw Htay et. al. 2016)

Static Water Level: + three to seven metres below surface.

Of the initial 22 artesian tubewells recorded in 2008 only one was still flowing in November 2016. Flows were not turned off during the non-irrigation season to partially repressurise the aquifer system. Like most groundwater irrigation projects in the Dry Zone there is no Project Hydrogeologist. Thus, there is neither monitoring of potentiometric surface or extraction, nor numerical modelling to enable effective management of this valuable resource.

At U Yin Village tritium analysis from 58 to 64 metres indicates a pre-thermonuclear age.

MTGIP Flowing Tubewell: November 2016
Specific Conductance: 800 $\mu S.cm^{-1}$, Total Dissolved Salts: 680 mg/L, pH: 8.2, Temperature: 30° C.

MTGIP Magyi Pin Pu: November 2016
Specific Conductance: 1,300 $\mu S.cm^{-1}$, Total Dissolved Salts: 777 mg/L, pH: 8.1, Temperature: 28° C.

15.5.1.2 Thinbon Chaung Alluvium

Thinbon Chaung Alluvium consists of brown clay, pebble, sand, gravel, fossil wood and silt. The maximum known thickness is 70 metres. Tubewells intersect semi-unconfined to semi-confined alluvial aquifers at depths more than 12 metres. The Alluvium thickens to the north. Potential tubewell yields range from 1 to 20 L/sec. Most tubewells obtain adequate domestic water supplies from shallow aquifers but higher yields may be available at depth. The specific conductance of most aquifers is below 1,500 $\mu S.cm^{-1}$. Some anomalous higher values are recorded (Thitpalwegon, Seywa (N) and Aungtha (N) villages). Salinity decreases with depth- the Kanbe Village tubewell yields $Na^{+}:HCO_3^{-}$ type water with a specific conductance of 690 $\mu S.cm^{-1}$, whilst adjacent dugwells have $Na^{+}:Cl^{-}$ type water with a salinity of 3,160 to 9,580 $\mu S.cm^{-1}$.

Groundwater discharge in the Dry Season is towards Thinbon Chaung and associated tributaries. During the Wet Season, these sandy watercourses are the main sources of recharge.

Between Ngathet and Zigon villages white sodium bicarbonate crystals are harvested for soap production. Caustic soda crystals are usually derived from Pegu Group rocks and as sodic springs along the Sagaing Fault. The salinity of water in the nearby unnamed creek is 2,500 $\mu S.cm^{-1}$, that is, twice that of the underlying Alluvium.

A saline groundwater plume (> 2,000 $\mu S.cm^{-1}$) is located southeast of Meiktila. Leakage from Meiktila Lake through the Pegu Group and Irrawaddy Formation and into the Alluvium may be the source of this elevated salinity.

15.5.2 East of Sagaing Fault

Groundwater movement closely follows the topography and surface drainage. Samon and Sinthe chaungs and their tributaries are the drainage foci. This simple pattern is much more complex when considered in detail. Groundwater flow occurs through preferential paths and these can be isolated from each other both laterally and vertically giving rise to an observed range of apparently anomalous depths to the potentiometric surface.

The unconsolidated sediments deposited by Samon Chaung east of Thazi and Wundwin are thicker than those in the MTGIP. A thickness between 120 and 180 metres is usually reported. Such thickness could include the weathered Irrawaddy Formation and due to block faulting in the underlying bedrock. The sediments consist of red-yellow brown, fine to coarse grained sand and clay. They intertongue to the east with the Colluvial Piedmont sediments. Tubewell yields of 10 L/sec should be available in some areas (Oakshitkon, Thanathan, Dangon and Paukmyaing villages). Most shallow aquifers have a potential yield less than 6 L/sec. The highest transmissivity is 370 m^2/day at Paukmyaing Village.

The salinity of the dominantly $Na^{+}:HCO_3^{-}$ and $Na^{+}:Cl^{-}/HCO_3^{-}$ type water is quite predictable. The range in specific conductance of the alluvial aquifers is:

- usually 2,000 to 5,000 $\mu S.cm^{-1}$ east of the Thazi Anticline (for example, Mondaw and Samyeikshe villages), close to the shallow saline aquifers of the Irrawaddy Formation;
- below 1,500 $\mu S.cm^{-1}$ near Samon Chaung and the Colluvial Piedmont sediments; and
- less than 1,000 $\mu S.cm^{-1}$ in the Myittha area.

Tritium analyses taken from shallow and deep alluvial aquifers at Paukmyaing and Kyabetkon villages respectively, adjacent to Samon Chaung indicate that both aquifers contain pre-thermonuclear water.

15.5.2.1 Pyawbye – Payangazu Groundwater Irrigation Project (PPGIP)

With annual rainfall less than 500 mm and drought common, a co-operative effort between the IWUMD, JICA, local farmers, NGOs and INGOs resulted in the construction of 100 irrigation tubewells into Alluvium, Irrawaddy Formation and colluvial aquifers. This project is close to the Shan Plateau, thus artesian flow was anticipated.

The overall development goal of the PPGIP[128] was to:

- improve the living condition and enhance the socio-economic status of local people; and
- boost the agricultural production and increase the income of the local farmers.

Pyawbwe – Payangazu Groundwater Irrigation Project

Construction Date: 2009 to 2011.

Number of Tubewells: 100 (initially 75 artesian and 25 pumping). By 2014 only 23 were still flowing.

Groundwater Yield:
Artesian flow (drop in pressure): 2010: 2 to 8 L/sec; 2015: 1 to 3 L/sec.
Sub-artesian pumping: 2010: 3 to10 L/sec; 2015: 3 to 8 L/sec.

Irrigation Command: 500 hectares.

Implementing Agency: IWUMD, JICA, NGOs, INGOs and farmers.

Operator: Farming Community- 30 villages.

Drill Depth: 45 to 212 metres.

Geology: Clay, silt, sand, gravel and cobbles from Alluvium, Colluvium and Irrawaddy Formation.

Aquifer: Shallow: 10 to 75 metres. Medium: less than 75 metres. No testing of aquifers.

Water Quality:

Specific Conductance: Shallow Aquifer: less than 1000 µS.cm^{-1} Na^+:HCO_3^- type water; and Medium Aquifer: less than 1,000 to more than 2400 µS.cm^{-1} (increases westwards).

Salinity has increased over time:

TW Number	Specific Conductance (µS.cm^{-1})	
	2011	2014
PB001	141	242
PB013	119	339
PB033	99	250

Problems:

- increase in salinity and SAR (C3:S1 and C3:S2); and
- reduction in artesian and non-artesian yield.

References: Aung Khaing Moe (2016).

Pyawbye Borefield: November 2016
Specific Conductance: 1,040 µS.cm^{-1}, Total Dissolved Salts: 750 mg/L, pH: 8.4, Temperature: 29.2° C.

Pyawbwe Town Water Supply

Operator: Pyawbwe Township Development Committee.

Source: Groundwater

Consists of four deep tubewells in the southern part of town, just off the Thazi Anticline inlier and away from the brackish groundwater (> 3,000 µS.cm^{-1}) of the Irrawaddy Formation.

150 to 200 mm diameter holes drilled between 60 and 70 metres in Alluvium, each equipped at 5 L/sec and pumped 10 hours per day (0.7 ML/day). Specific Conductance: less than 1,500 µS.cm^{-1}.

[128] Water Resources Utilisation Department (2015), Aung Khaing Moe (2016)

Photo 60: Artesian Tubewell, MTGIP

Photo 61: Artesian DTW, PPGIP

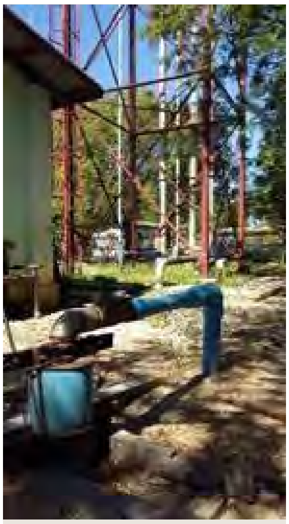


Photo 62: Pyawbye TWS DTW

15.6 Colluvial Piedmont Complex

The Colluvial Piedmont Complex consists of an almost continuous series of laterally transported outwash fans at the base of the Shan escarpment. It is usually less than 10 kilometres wide and thins adjacent to the granite batholiths. Large quantities of ill-sorted, felspathic and quartzose cobble, gravel and sand with minor clay beds have been deposited, interdigitising with the alluvial sediments. The semi-unconfined to semi-confined aquifers are hydrogeologically characterised by their heterogeneity, variable permeability, steep hydraulic gradient, low salinity and large water level fluctuations. There is a general trend for clay content to increase to the west and with depth.

Artesian conditions exist due to groundwater in the permeable colluvium becoming confined by the downgradient, less permeable Alluvium. Sufficient pressure head exists to push the potentiometric surface above ground level.

In the Thazi-Wundwin area colluvial aquifers up to 100 metres thick have potential yields of 5 to 10 L/sec (Dainggaungkan Village may exceed 20 L/sec). The specific conductance is below 850 $\mu S.cm^{-1}$. Transmissivity values range from 15 to 370 m^2/day and permeability from three to 75 m/day. The combined aquifers occupy around 40 percent of the stratigraphic column.

At the Hlaingdet Mango Plantation eight production tubewells intersect highly permeable medium to coarse sand and gravel aquifers at depths of 60 to 90 metres. Aquifer thickness varies from 35 to 92 percent of the stratigraphic column (average 68 percent) and tends to thin westwards. The potentiometric surface is about eight metres below the surface and seasonally fluctuates from 1.2 to 3.6 metres. Tubewells yield between 7 to 10 L/sec of low salinity water. The farm irrigates for four months per year with annual groundwater withdrawal of around 500 ML.

South of Hlaingdet the specific conductance of the $Na^+:HCO_3^-$ and $Ca^{2+}:HCO_3^-$ type groundwater increases away from the escarpment to be 1,000 to 1,500 $\mu S.cm^{-1}$ near the contact with the alluvial plain sediments. Electrical conductivities are usually consistent along flow lines parallel to the escarpment. Groundwater from these aquifers is generally suitable for irrigation purposes with a low SAR and a low to moderate salinity hazard.

There are thousands of small diameter domestic tubewells fitted with hand, air and electrosubmersible pumps.

Recharge to the Piedmont Complex is mainly by surface runoff along the sandy and gravelly chaungs draining the Shan Plateau and by direct precipitation. Lesser recharge may occur from hard rock aquifers. Tritium analysis from Pyayanga Su Village indicates that the aquifer contains Modern recharge water.

Groundwater discharge is west into the alluvial aquifers, to springs and artesian and sub-artesian tubewells. Natural groundwater flow is estimated as 20 L/sec per kilometre along the escarpment.

15.7 Upper Sittaung River Valley

A groundwater divide exists near Yamethin, separating groundwater drainage to Samon Chaung (Ayeyarwady River Valley) from that to Sinthe Chaung (Sittaung River Valley). This hydrogeological boundary occurs near the south-eastern corner of the Central Dry Zone.

Large groundwater supplies of good quality water are available from the alluvial and colluvial aquifers.

Photo 63: Deep Tubewell, Pyinmadaw Village, Nov. 2016

Photo 64: Yamethin TWS from Thein Gone Village DTW

Groundwater occurrence in the Irrawaddy Formation is erratic:

- beneath Yamethin aquifers are intersected at depths less than 250 metres under thick clay horizons;
- at Pyinmadaw Village two tubewells were drilled up to 299 metres. Warm groundwater initially flowed at 5 L/sec with initial piezometric surface of five metres above ground level. Aquifer pressure has declined and flow no longer occurs; and
- no aquifers were intersected in test holes EH3/10, 3/11 and 3/12, drilled 80 to 180 metres south of Yamethin. Deeper drilling may have proven successful.

Pyinmadaw Village: Two Former Artesian Tubewells: November 2016
Specific Conductance: 780 $\mu S.cm^{-1}$, Total Dissolved Salts: 550 mg/L, pH: 7.1, Temperature: 38° C.
Specific Conductance: 650 $\mu S.cm^{-1}$, Total Dissolved Salts: 456 mg/L, pH: 7.0, Temperature: 39° C.

Thein Gone Borefield: November 2016
Specific Conductance: 490 $\mu S.cm^{-1}$, Total Dissolved Salts: 347 mg/L, pH: 6.9, Temperature: 31° C.

Yamethin Town Water Supply

Operator: Yamethin Township Development Committee.

Source: Groundwater:

- Location- Thein Gone Village, four kilometres east of Yamethin.
- Aquifers- Piedmont and Alluvium aquifers.
- Tubewells- Eight x 350 mm diameter holes drilled to depths of 88 to 160 metres. The primary permeable horizon is around 130 to 140 metres (18 metres thick).
- Yield- at least 10 L/sec.

Groundwater Production- Five tubewells are operational, pump-equipped at 3 and 7 L/sec. Pumping 24 hours/day the water delivery is around 1.8 ML/day.

Other: With improve drilling techniques there are now many deep tubewells within Yamethin.

Town Water Demand:

Assuming a population of 27,698 (Census 2014) and water consumption of 130 L/d/p, the town water demand is 3.6 ML/day. The Thein Gone Village Wellfield supplies around 50 percent of the town's water requirements.

15.7.1 Tatkon Groundwater Irrigation Project (TGIP)

At Takton a small groundwater irrigation area has been developed in shallow alluvial aquifers. Ten 250 mm diameter production tubewells have been constructed to depths of 50 metres with average yield of 25 L/sec. These sediments had previously been identified as high groundwater yielding potential[129].

The Alluvium aquifer occupies 30.4 percent (GDC 1984) and 32 percent (IWUMD bore logs) of the stratigraphic column. West of Tatkon the semi-confined Alluvium aquifer comprises three percent. Groundwater chemistry is given on **Table 55**.Tritium analysis of groundwater from the Alluvium at Khitaye Village indicates a pre-thermonuclear age.

Table 55 Hydrochemistry of Alluvium Aquifers, Takton Irrigation Area

No.	EC	TDS	pH	Na^+	Ca^{2+}	Mg^{2+}	K^+	Fe^+	Cl^-	SO_4^{2-}	HCO_3^{2-}	CO_3^-	As^{3+}
	$\mu S.cm^{-1}$	mg/L		(mg/L)									
TW001	690	440	7.4	15.2	57.7	19.7	0.36	0.1	40	49.9	54	ND	ND
TW003	480	310	7.5	13.3	56.9	4.3	0.45	0.2	28	84.5	44	ND	ND
TW006	670	430	7.8	11.2	91.4	7.7	0.31	0.01	57	23	58	ND	ND
TW007	480	310	7.7	6.6	53.7	13.4	0.49	0.2	37	57.6	28	ND	ND

Source: IWUMD data (2017).

Photo 65: TGIP Tubewell, Takton, Shan Plateau in Background

Photo 66: Irrigation Activity in the TGIP

[129] GDC Ltd (1979 to 1984), Drury (1986)

Tatkon Groundwater Irrigation Project

Construction Date: 2014 to 2015.

Number of Tubewells: 10 equipped with electrosubmersible pumps.

Purpose: Emergency water supply and to improve the socioeconomic status of farmers.

Implementing Agency: Government of Myanmar.

Operator: Village Water Committee.

Command Area: 12 hectares per tubewell.

Geology: Alluvial sand and gravel aquifers.

Construction Details: 400 mm dia. holes with 250 mm dia. casing and stainless-steel screen.

Groundwater Yield: All tubewells are equipped at 2 ML/day (24 L/sec).

Aquifer:

- Hydraulic Conductivity: 150 to 200 m/day (IWUMD), 14-18 m/day (GDC 1984);
- Transmissivity: 2,810 to 4,000 m^2/day, 270 m^2/day (GDC 1984); and
- Storage Co-efficient: 0.05 to 10^{-4}.

Water Level Response: static water level seven metres below surface.

Water Quality: (see **Table 55**)

Geological Profile:

Geology	Unit	Thickness (m)	Lithofacies	Aquifer/Aquitard	Extraction Method
Holocene	Alluvium	0 to 11	Yellow Clay	Soil	Submersible pump power by 11 Kv HT Line Transformers 0.4 Kv LT Line
		11 to 20	Sand and gravel	Aquifer 1	
Upper Pleistocene		20 to 39	Blue clay	Aquitard 1	
		39 to 46	Sand, gravel	Aquifer 2	
		46-51	Grey clay.	Aquitard 2	

References: Aung Khaing Moe (2016), IWUMD (2016).

15.8 Areas of High Groundwater Yield and Low Salinity

Along the longitudinally extensive Wundwin-Thazi-Tatkon region there are distinct areas where high yield and low salinity groundwater may be available (**Figure 50** and **Figure 52**). These include:

- west of the Sagaing Fault- the MTGIP and near Thinbon Chaung. Caution is required to avoid saline water intrusion by over pumping the Alluvium and Irrawaddy Formation aquifers; and
- east of the Sagaing Fault- along the extensive Colluvial Piedmont Complex and adjacent Alluvium. This includes the PPGIP and TGIP, Hlaingdet Irrigation Farm and private farmer irrigation in Myittha Township (**Chapter 16**).

The deep high yield Irrawaddy Formation aquifers located near Wundwin and Yamethin are not considered, as the salinity exceeds 1,500 µS.cm^{-1} and they are overlain by thick clays with saline aquifers.

16 Hydrogeology of Myittha-Mandalay

16.1 Introduction

The Myittha-Mandalay area is situated in the southeast part of the Shwebo-Monywa Basin of the Eastern Trough. Frequent earth movements occur along the Sagaing Fault and the Shan Plateau Fault Complex. The Thazi Anticline continues north from the Wundwin area and terminates near the Ayeyarwady River.

Mandalay is the second largest city and the commercial centre of Upper Myanmar. The city was established in the nineteenth century by King Mindon and was for a time the capital.

The southern area is mainly located on the fertile alluvial plain of Samon, Panlaung and Zawgyi chaungs. These and their associated watercourses drain to the north towards the perennial Myitnge (Doke Hta Wadu) and the Ayeyarwady rivers. The surface elevation of the alluvial plain varies from 90 m AMSL near Myittha to 64 m AMSL near the Ayeyarwady River.

Irrigation by surface water dates to the early Pagan Dynasty. Details of construction for irrigation purposes can be found in various historical records. Many dams, weirs and irrigation canals have been constructed.

Most hydrogeological reports are centred on the Mandalay City Water Supply[130]. Hydrogeological and hydrochemical maps and cross sections are given on **Figure 54** to **Figure 55**.

East of the Thazi Anticline there is a proliferation of private dugwells and shallow tubewells used for irrigation and domestic purposes. Over 50,000 domestic tubewells exist within Mandalay City.

With an abundance of surface water storage, irrigation canals and shallow low salinity groundwater, this area may be the least water deficient part of the Dry Zone.

16.2 Shan Plateau

Along the base of the Shan Plateau:

- igneous rocks (granite, dacite, porphyry, granodiorite, dolerite and pegmatite dykes);
- Jurassic to Cretaceous rocks (limestone, dolomite, chert, calcareous sandstone, quartz and quartzite); and
- metamorphic rocks (marble, calc-silicates, gneiss, schist and graphite of Lower Cambrian age) crop out between Kyaukse and Mandalay.

Few tubewells have been sunk into these rocks. There is poor groundwater potential in the metamorphic and igneous rocks. Fracturing and large storage capacity of the karst system may provide good groundwater prospects. Limestone spring discharges have been measured at 50 to 500 L/sec. They form the base flow for the westward flowing perennial watercourses. The spring water is potable although moderately hard due to the presence of calcium carbonate. Mandalay Hill forms an isolated metamorphic inlier within the city. Metamorphic rocks form Sagaing Hill west of the Ayeyarwady River.

Groundwater flow is westwards into the unconsolidated sediments of the Piedmont Complex and alluvial plain.

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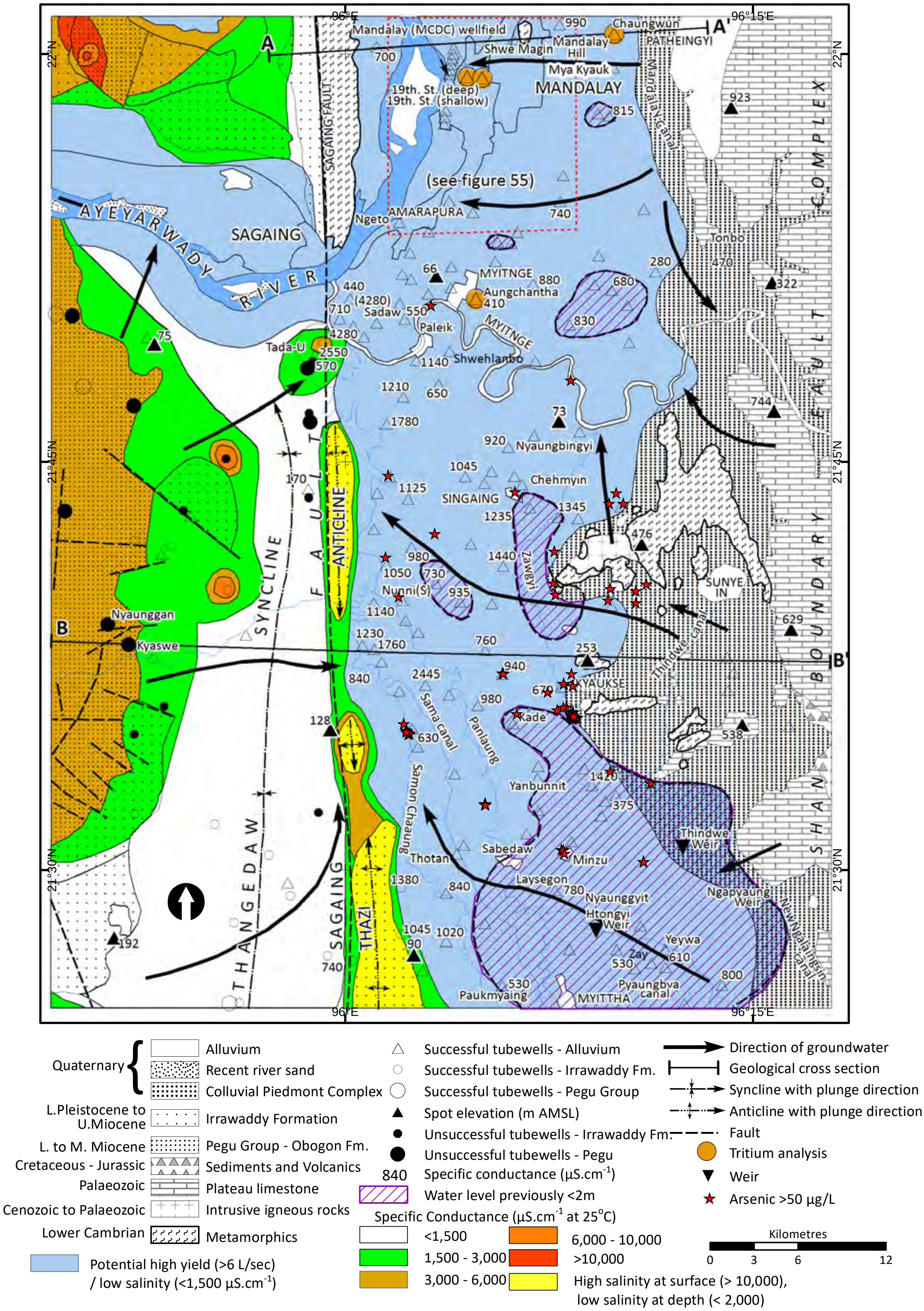
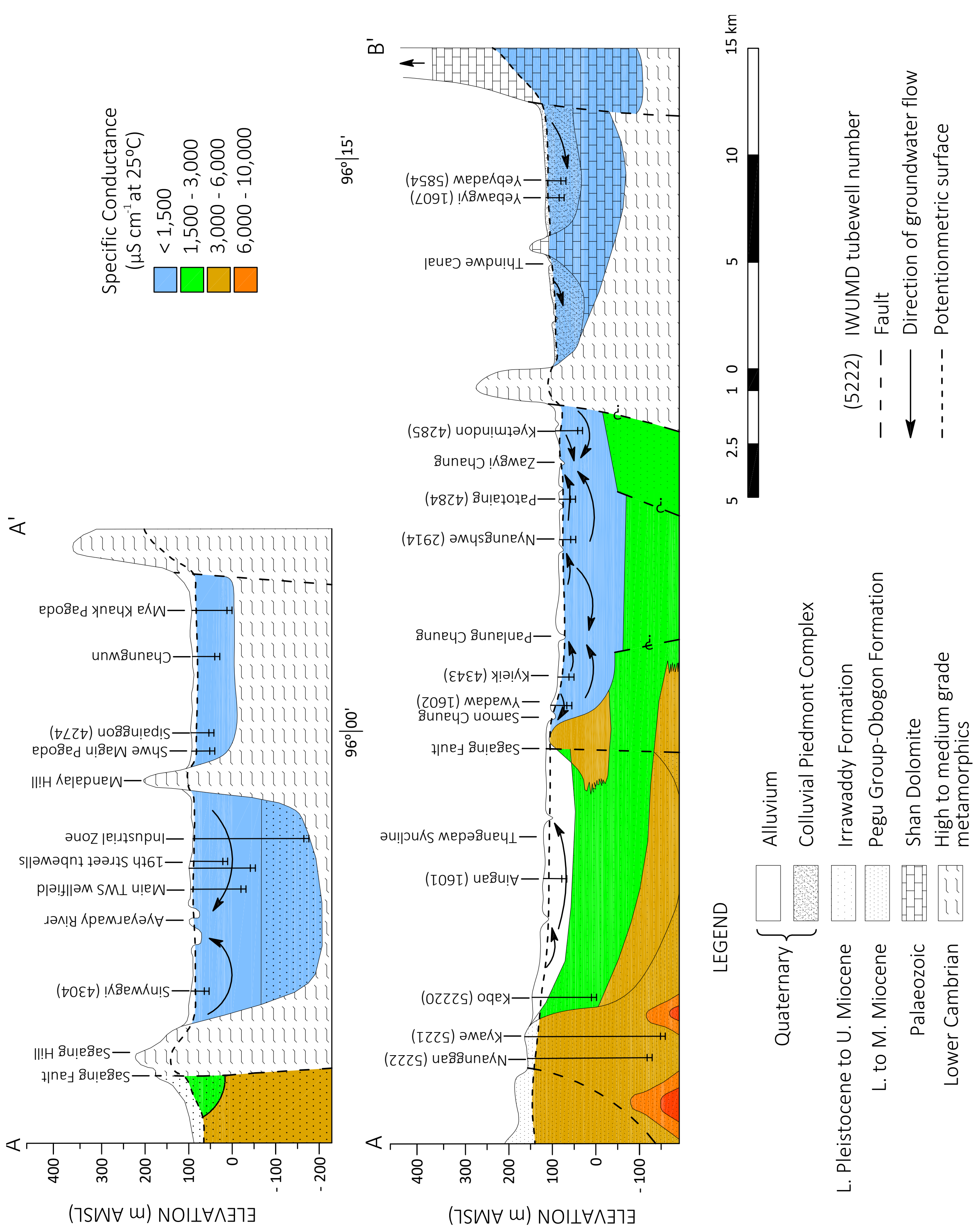
130 Lotti and Associati (1982), Department of Applied Geology (1983), Coffey et. al. (1984b, 1985), JICA (2003, 2015), Mandalay City Development Committee (1989), Ministry of Home and Religious Affairs (1984), San Lwin et. al. (1988), Tun Win (2016a-c)

Figure 54 Schematic Hydrogeological and Hydrochemical Map: Myittha-Mandalay



NOTE: Regional Hydrogeological and Hydrochemical map gives general trends only. At specific sites variations in detail will occur

Figure 55 Hydrogeological Cross Section and Specific Conductance: Myittha-Mandalay



NOTE: Regional cross sections give general trends only. Thickness of Irrawaddy Formation unknown. At specific sites variations in detail will occur

16.3 Pegu Group

Marine shale and fine sandstone of the Obogon Formation crop out along the western boundary. At Kyaswe and Nyaunggan villages, holes that were sunk to 275 metres encountered no aquifer. Many drill holes have been abandoned due to the brackish (5,000 µS.cm^{-1}) Na^+:Cl^- groundwater. Where lower salinity water is intersected, yields vary from 1 to 3 L/sec.

16.4 Irrawaddy Formation

Due to the proliferation of shallow high yield, low salinity aquifers, there is little need to drill deep tubewells for domestic village or irrigation supplies. Overall the hydrogeology of the Irrawaddy Formation is poorly documented, except under Mandalay City and environs where large municipal groundwater extraction occurs.

The Irrawaddy Formation forms a series of inliers along the north-south orientated Thazi Anticline to the east of the Sagaing Fault. The outcrops consist of poorly cemented sand, clay horizons, ferruginous bands and calcareous nodules. The thick clay unit across the Thazi Anticline forms a partial barrier to groundwater flow. Many shallow tubewells have been abandoned along this inlier because of the occurrence of highly saline groundwater (6,000 µS.cm^{-1}) within the isolated, thin sand lenses. Lower salinity water occurs at depth.

At Tada-U a recent hole over the Sagaing Fault intersected low yield and good quality water (570 µS.cm^{-1}) at 50 metres, with salinity increasing with depth. 'Gas' was encountered in this hole.

West of the Sagaing Fault a few shallow tubewells have been successfully completed. The sediment consists of reddish brown silt, clay, sand and calcareous concretions. The Na^+:HCO_3^- type water has a specific conductance range of 800 to 2,000 µS.cm^{-1} except close to the Pegu Group rocks where salinity increases. Overall salinity increases with depth.

No deep drilling has taken place east of the Thazi Anticline between Myittha and Tada-U. In Mandalay City deep tubewells (> 250 metres) have recently been sunk into blue /grey sand and fine gravel aquifers of considerable thickness (> 30 metres) and yield (> 20 L/sec). These aquifers underlie thick clay and sandy clay units. The successful deep tubewell drilling at Wundwin and Mandalay City may suggest substantial groundwater reserves east of the Thazi Anticline.

16.5 Alluvium

Photo 67: Alluvium Lithological Variation in Zay Village Tubewell, Pone Hnyat Village Tract, Myittha (50 to 64 m), Nov. 2016

Extensive alluvial deposits of clean, subangular, brown to grey coarse sand and fine gravel with minor clay and silt are located between Myittha and Mandalay, east of the Thazi Anticline.

Low salinity groundwater from shallow alluvial aquifers are used by farmers for irrigation. Ninety percent of Mandalay City water supply is pumped from these aquifers. The thickness of Alluvium varies from 120 metres at Myittha to at least 160 metres at Mandalay.

Recharge to these saturated, fluviatile sand and gravel deposits is by vertical infiltration of rainfall, flood and irrigation waters; throughflow from limestone, Piedmont Colluvium and Alluvium; and upflow from underlying aquifers. Groundwater movement is north-west and northwards towards Samon and Panlaung chaungs and the Ayeyarwady and Myitnge rivers.

Tritium analyses from shallow aquifers (Aungchantha and Chaungwun villages and at 19th Street, Mandalay), indicate Modern recharge water. A deep alluvial aquifer (90 metres) from 19th Street, indicates a pre-thermonuclear age.

16.5.1 Kyauske and Environs

A regional government-financed and farmer-operated shallow tubewell project has been established between Kyaukse to Myittha. In this area, there are 5,016 (50 to 100-millimetre diameter) tubewells, each yielding 4 to 6 L/sec from depths less than 40 metres. Potential yield from properly constructed tubewells screened in multiple alluvial aquifers should exceed 50 L/sec. Specific conductance is usually below 800 $\mu S.cm^{-1}$.

Groundwater irrigation generally occurs in the Dry Season. Wet Season irrigation mainly relies on rainfall. During the latter period, the shallow tubewells are capped and centrifugal pumps removed due to theft concerns. Before Year 2000 the potentiometric surface in the Kyauske area was frequently around one metre below the surface (**Figure 54**) with the threat of water logging and soil salinisation. Since implementation of intensive groundwater irrigation, the water table has declined by three metres. A pressure transducer/data logger was installed by IWUMD in one observation hole for water level and salinity monitoring purposes in April 2017.

Arsenic is present in alluvial aquifers associated with the Ayeyarwady River. For example, of the 2,826 sites tested within Kyaukse Township (**Table 56** and **Figure 54**)[131], arsenic exceeded 50 µg/L in 2.17 percent of shallow tubewells (mainly in the town) and 1.23 percent of dugwells. Notably, two shallow tubewells contain concentrations higher than 200 µg/L. Several 'hot spots' had 75 percent of their water sources contaminated and emergency response for arsenic mitigation was implemented. Kyaukse and most villages obtain reticulated water supply from the local flowing chaungs or canals.

Table 56 Arsenic Contamination in Kyaukse Township

Arsenic (µg/L)	STW	DW	DTW	SW	Pond	TOTAL
> 100	5	-	-	-	-	5
51-100	40	9	-	-	-	49
11-50	186	119	1	-	2	308
1-10	449	176	2	1	1	629
Nil	1,394	428	8	4	3	1,835
TOTAL	2,074	730	11	5	6	2,826

Source: WRUD and UNICEF (2015).

Table 57 indicates that other nearby townships (Amarapura, Leway, Madayar and Sintgaing) have higher or similar arsenic levels. The highest 50 µg/L exceedance is in Madayar Township (north of **Figure 54**).

131 WRUD and UNICEF (2005)

Table 57 Arsenic Concentration in Shallow Aquifers between Myittha-Mandalay

Region	Township	Total Samples	Concentration > 10 µg/L		Concentration > 50 µg/L	
			No.	%	No.	%
Mandalay	Kyauske	2,826	362	12.8	54	1.9
	Amarapura	500	144	28.8	12	2.4
	Madayar	500	200	40	20	4.0
	Leway	2,782	809	29.1	63	2.3
	Sintgaing	4,650	765	16.5	82	1.8
	Myittha	6,061	933	15.4	37	0.6
	Tada-U	2,852	452	15.9	12	0.4

Source: WRUD and UNICEF (2015)

16.5.2 Mandalay City Water Supply (Alluvium and Irrawaddy Formation Aquifers)

Many hydrogeological and geophysical studies have been carried out in Mandalay City. They demonstrate that the occurrence and characteristics of 'simple' Alluvium, Piedmont and Irrawaddy Formation aquifers are quite complex. Fluviatile, unconsolidated Alluvium of the Ayeyarwady River and tributaries interfinger with coarser Piedmont Deposits from the Shan Plateau. Geophysical studies indicate a thickening of sand and gravel from Mandalay Hill towards the Ayeyarwady River. These permeable sands and gravels of the northwest become finer southwards, as clay content increases. The maximum thickness of Alluvium is around 160 metres, underlain by the Irrawaddy Formation which overlies bedrock. Groundwater flow is east-west across the city towards the rivers.

Photo 68: Developing Deep All. Aquifer, Mandalay. Source: *MDC*

Since 2002 the number of tubewells in the city has increased 44 percent (from 17,508 to 25,257), including 1,522 in the industrial zone alone. There are four known aquifers:

- Aquifer 1- private dugwells and shallow tubewells < 30 metres;
- Aquifer 2- private tubewells screened < 70 metres;
- Aquifer 3 – source for municipal MCDC production tubewells < 160 metres; and
- Aquifer 4 – private industrial bores < 300 metres (recently developed).

Mandalay City Water Supply

Population: 1.28 million.

Operator: Water and Sanitation Department, Mandalay City Development Committee (MCDC).

Location: East bank of Ayeyarwady River towards Shan Plateau. Altitude around 70 m AMSL.

Water Source: In 2017 – 136,364 m^3/day (30 MGD) is consumed, comprising:

- 90 percent groundwater- 122,727 m^3/day (27 MGD) from 116 DTW; and
- 10 percent surface water- 13,637 m^3/day (3 MGD) from the Ayeyarwady River/Sedawgyi Dam.

The future MCDC plan is 60 percent groundwater and 40 percent surface water.

Supply System: Tubewell → Water Transmission → Pipeline → Reservoir → Disinfection → Distribution Pump → Reticulated Water Supply.

Geological Units:

Geology	Unit	Thickness (Depth m)	Lithofacies	Aquifer type / Aquitard	Extraction Method
Alluvium	Aquifer 1	30 (30 / 40)	Yellow silty sand bands	Unconfined	Dugwell
Holocene	Aquitard 1	Not laterally continuous	Yellow, brown clay	Confining layer where present	
Upper – mid Pleistocene	Aquifer 2	40 (70 / 72)	Yellow brown silty sand	Shallow partially confined	Private shallow tubewell
	Aquitard 2	20 (90 / 97)	Brown clay	Confining layer	
Pliocene	Aquifer 3	70+ (max.160)	Yellow sand, gravel	Confined	Deep tubewell
	Yield (m^3/day): 5,000 (NW), 2,000- 3,000 (Central), 800 (South) Well Efficiency: 80-90%				
Irrawaddy Fm.	Aquitard 3		Blue clay, silt	Confining layer	
L. Pleistocene to U. Miocene	Aquifer 4	30 (> 250-300m)	Sand/gravel	Deep Confined	Deep tubewell

Aquifers: Four distinct aquifers and three aquitards. Aquifer 4 recently found in deeper drilling.

Borefield: Deep production tubewells screened in Aquifer 3 throughout city (location see **Figure 56**). MCDC add two to four tubewells/year. Industrial areas have private tubewells only.

Water Level Decline: 0, 30 and 60 metres in north-west, central/south and eastern/south-eastern areas

Variation in Hydrogeological parameters: See **Table 58** and **Table 59.**

Water Quality: See **Table 60**. Waters from Aquifers 1 and 3 are slightly hard.

The city can be areally divided into three zones based on groundwater occurrence and yield (**Table 58** and **Figure 56**). Overall the high permeability and steady potentiometric surface of Aquifer 3 in the northwest decreases towards the centre and south of town.

Table 58 Subdivision of Mandalay City Aquifers based on Groundwater Occurrence and Yield

Zone	Description
Zone 1 Best wellfield area	Adjacent to the Ayeyarwady River. Good yield (> 50 L/sec), low salinity in thick alluvial aquifers (80 percent of borehole log) to depth of 160 metres. From 50 to 90 metres the water is of low salinity (< 1,000 µS.cm^{-1}) but high in calcium and hardness in yellow sands. Within Aquifer 3 the blue sand and gravel of the Alluvium/ Irrawaddy Formation is less hard. Near Mandalay Hill metamorphic bedrock is intersected at 250 metres. Water levels are drawn down from 10 to 12 to 40 metres at 36 L/sec. On cessation of pumping water level recovery is almost instantaneous. Submersible pumps are installed at 45 to 50 metres.
Zone 2 Moderate area	The silty sand alluvial aquifers (around 25 percent of the saturated stratigraphy) have less permeability and lower groundwater yield. From 90 to 140 metres groundwater is of low salinity (< 1,000 µS.cm^{-1}) with elevated calcium and hardness. The original SWL (10 to 22 metres) has declined to 21 to 46 metres. Deep drilling into the underlying Irrawaddy Formation indicates high yield and low salinity at depth. The static water level (10 to 18) indicates that the confined aquifer is isolated from the overlying heavily pumped alluvial aquifers. Yield should be least 50 L/sec.
Zone 3 Poor wellfield area	Historically considered less favourable hydrogeological conditions for Aquifer 1 to 3 (15 percent of lithological log). The discovery of the permeable, blue grey sands of Aquifer 4 (250 to 300 metres) indicates high yield of low salinity groundwater at depth. The SWL in Aquifer 3 has dropped from near the surface to 56 to 76 metres. Tubewell pumping level is 120 metres. Due to Aquifer 4, Zone 3 may have high yield potential at depth.

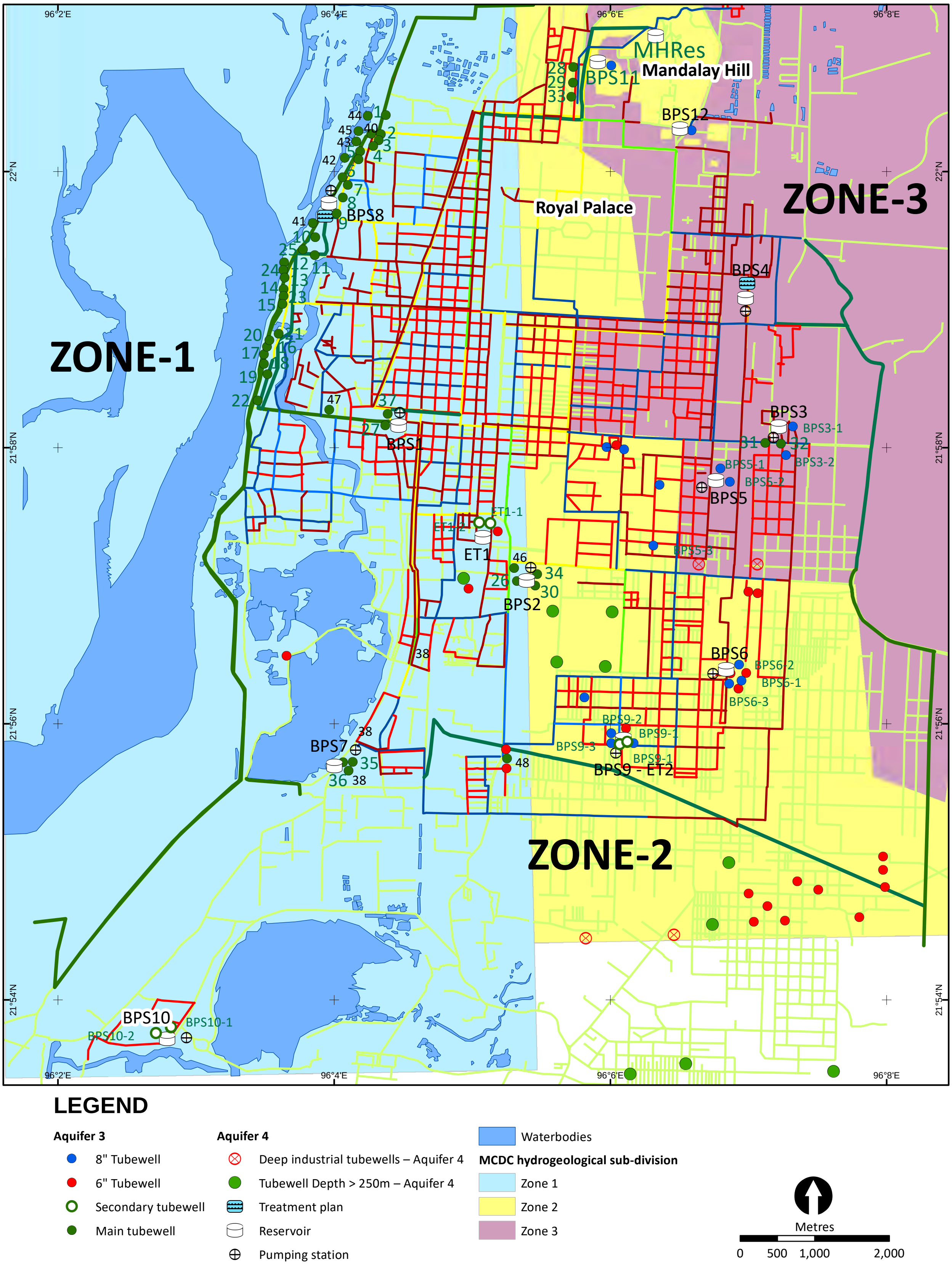
There have been many pump-out tests in Zone 1. Combined with computer modelling, hydraulic characteristics of most aquifers are well documented. Pump tests have not been carried out in Aquifer 4. A summary of aquifer characteristics is given on **Table 59.**

Table 59 Aquifer Hydraulic Characteristics, Mandalay City

	Condition	Top to Bottom (m AMSL)	Ø	SC	k (m/day)	T (m²/day)	SWL (m)	Recharge (mm/day)
Aquifer 1	Unconfined	+ 65 to + 96 + 45 to + 72	0.12	2.4 x 10^{-3}	0.89		10 to 12	0.84 Mandalay 1.05 other
Aquifer 2	Confined	+ 45 to + 77 - 29 to + 47	0.25	5.4 x 10^{-5} 1.4 x 10^{-3}	27-140	1,900	21 to 46	0
Aquitard	Confined	- 29 to + 47 - 70 to + 1	0.06	6.1 x 10^{-5}	0.08			0
Aquifer 3	Confined	- 70 to + 1 - 90 to- 18	0.25	7.4 x 10^{-5} 1.3 x 10^{-3}	220 (NW) 43-70 (C) 1.3 (S)	15,000 2,000- 5,000 100	12 (NW) 50 (C) 76 (S)	0

Source: Coffey et. al. (1984b, 1985), JICA (2003, 2015)
Ø = porosity, S = storage coefficient, T = transmissivity, SWL = static water level, C = Central, S = South

Figure 56 Mandalay City Water Supply Borefield and Hydrogeological Sub Divisions



SOURCE: Modified from MCDC 2017

Table 60 indicates that groundwater from all aquifers is of low salinity (330 to 850 µS.cm^{-1}) with deeper aquifers best suited for human consumption. Aquifers 1 and 2 have elevated calcium and hardness content. Deeper aquifers have lower salinity. Aquifer 4 has the lowest specific conductance and hardness.

Faecal coliform and dissolved metals have not been analysed. It is likely that the shallow aquifer may have high organic contamination in areas of high population density (for example, Central Zagro Market) and dissolved metals (underlying industrial areas) where there is an absence of adequate surface sealing around the dugwells or lack of waste water disposal protocol. No faecal coliforms or dissolved metals are recorded in the municipal production tubewells (MDCD pers. comm.).

Table 60 Water Chemistry of Aquifers Underlying Mandalay City and Environs

Parameter		Dugwell (15 m)	Tubewell				
			Aq. 1 (30-40 m)	Aq. 2 (< 70 m)	Aq. 3 (< 160 m)	Aq. 4 (250-300 m)	Jade Pagoda (195-205 m)
pH		8	7.5	7.6	7.5	7.1	7.7
Colour		5	5	5	5	5	5
Turbidity (mg/L)		4.75	5.3	5.1	5.1	5.1	-
Conductivity (µS.cm^{-1})		720	519	703	390	336	823
Calcium	mg/L	120	24	80	32	8	24
Hardness	mg/L	480	100	340	100	24	120
Magnesium	mg/L	44	10	44	5	1	7.2
Chloride	mg/L	60	8	60	8	15	40
Total Alkalinity	mg/L	500	288	320	220	188	520
Iron Total	mg/L	0.01	0.01	0.01	0.01	0.01	-
Manganese	mg/L	0.01	0.01	0.01	0.01	0.01	0.01
Sulphate	mg/L	< 300	< 200	< 200	< 200	< 200	176

Source: Tun Win (2016a-c).

Outside the city there are many high groundwater yielding areas. For example:

- south – Amarapura. Tubewells in Alluvium and Irrawaddy Formation to 240 metres yield less than 20 L/sec of low salinity water in medium to coarse sand (82 percent of borehole lithology). The water level is three metres;
- west – Jade Pagoda. This 213-metre deep tubewell is screened from 195 to 205 metres with high yield (> 20 L/sec) and low salinity (823 µS.cm^{-1}) from thick coarse sand and gravel (98 percent of borehole lithology). The static potentiometric surface is eight metres beneath the surface; and
- far west – Sagaing Township. Alluvial aquifers have transmissivities up to 2,500 m^2/day, storage coefficient of 2 x 10^{-4}, groundwater yield more than 50 L/sec. and 80 percent of stratigraphic column.

The alluvial flats are only developed for 65 kilometres upstream of the city (location on **Figure 39**). The alluvial sediments under Mandalay City (Zone 1) and environs show lithologic and hydrogeological characteristics that are different from most of the Dry Zone. They contain highly permeable, coarse sand and gravel deposits that occupy 60 to 95 percent of the stratigraphic column. It appears that this thick sand and gravel sequence was deposited in the western part of Mandalay City, Sagaing and Amarapura areas as the fast flowing Ayeyarwady River turns sharply westwards past Sagaing Hill. Away from the high energy area the grained size and aquifer thickness thins. Lesser groundwater yields of low salinity are encountered:

- in Mandalay City- Zone 2 (24 percent of strata) and Zone 3 (16 percent);
- south of the Myitnge River- in the Samon Chaung Valley (12 percent of lithology);
- Zone 2, near of Mandalay Hill – the Shwe Magin Pagoda tubewell intersected coarse sand and gravel Alluvium at 45 to 50 metres (< 25 percent of lithology). Salinity is below 500 µS.cm^{-1}; and
- Zone 3, east of Mandalay – the aquifer under Mya Khauk Monastery (90 to 110 metres) occupies 28 percent of the Alluvium. Limestone bedrock was intersected from 110 to 220 metres.

Mya Khauk Monastery Tubewell: (chemical analysis inscribed in marble tablet) November 2016
Specific Conductance: 710 µS.cm^{-1}, Total Dissolved Salts: 393 mg/L, Hardness: 76 mg/L.

The IWUMD has recently established surface water irrigation projects along Myitnge River.
Farmers indicate that the water level in the shallow Alluvium aquifer has risen three metres over the last few years, probably due to vertical recharge from surface irrigation water.

16.5.3 MCDC Aquifer Management

Since the Year 2002 MCDC has implemented an interim aquifer management system (Ground Water Rule and Regulation) to control and manage tubewell construction and withdrawal. Basically, an application form is required outlining expected yield, intended use, closest neighbouring tubewells, distance to septic and depth. If approved, interim permission to proceed is given by a MCDC Panel. A permanent license may be approved once lithology, final depth, water quality and tested yield is supplied. This appears to be the most advanced form of private and industrial groundwater registration in Myanmar.

Water levels are intermittently measured at selected MCDC production bores and observation piezometers. Long-term pump-out tests are carried out on completion of each town water supply production tubewell.

16.6 Colluvial Piedmont Complex

The subdivision between the colluvial and alluvial deposits is not absolute and transitional zones exist. Both zones are hydraulically interconnected.

The Colluvial Piedmont Complex consists of a series of laterally transported outwash fans at the base of the Shan Plateau. The polymictic sediment is poorly sorted and its potentiometric surface slopes downwards to the west. The maximum thickness of this deposit is probably 90 metres.

Towards the base of the Piedmont Complex the potentiometric surface is shallow. The upper aquifer is usually intersected at depths of five to 20 metres. The specific conductance of the Na^+:HCO_3^- and Ca^+:HCO_3^- type water varies from 300 to 1,000 µS.cm^{-1}. Groundwater yields up to 20 L/sec may be extracted from sand, gravel and cobble aquifers.

16.7 Areas of High Groundwater Yield and Low Salinity

Figure 54 shows the high yield and low salinity groundwater system east of the Sagaing Fault and Thazi Anticline. This area is well documented by the large-scale farmer groundwater irrigation activity around Myittha and Mandalay City Water Supply. With the recent interception of Aquifer 4, 'Zone 2' and 'Zone 3' should be considered as high yield areas.

The high groundwater yield and low salinity area extends northwards to termination of the alluvial flats near Letha Taung (**Plate 3**). This is the northern extent of the Irrawaddy River Alluvium within the Dry Zone.

Downstream of Mandalay the width of low salinity Alluvium decreases as the Ayeyarwady River cuts through the northern extension of the Bago Yoma.

17 Regional Hydrogeology and Groundwater Resources Management

17.1 Hydrogeological Understanding of the Dry Zone

The Dry Zone is effectively encapsulated within a sedimentary basin. A summation of the geological features of the Dry Zone is presented on **Figure 57** to **Figure 60**. Within this complex geological setting the associated hydrogeological characteristics can be reasonably understood and interpreted.

The Alluvium commences 65 kilometres upstream of Mandalay (near Letha Taung), is joined by extensive sedimentary deposits from the Mu and Chindwin river systems (plus a myriad of tributaries) and terminates on the 20° N Uplift Syntaxis. It is enclosed to the east by the Shan Plateau and west by the Chin Hills- Rakhine Yoma. Centrally it is split by the Bago Yoma Anticlinorium. To the southeast, the hydrogeological boundary near Yamethin separates groundwater flow between the Samon Chaung (Ayeyarwady River) and Sinthe Chaung (Sittaung River).

The Irrawaddy Formation has similar peripheral hydrogeological restrictions.

Figure 58, Plate 3a indicates that:

- elevated groundwater temperature is found along the Sagaing Fault, associated fault off-shoots and near Mount Popa. Isolated random hot spots also occur;
- artesian flows occur along synclinal structures and in areas surrounded by hills with good aquifer recharge conditions. The aquifer potentiometric head exceeds surface elevation:
- within the Mu River Valley and the Pale and Taungdwingyi sub-basins; and
- along the base of the Piedmont Colluvium Sediment adjacent to the Shan Plateau;
- based on tritium and radiocarbon dating, groundwater is:
- Modern in unconfined to semi-unconfined aquifers beneath sandy chaung recharge zones;
- ≈ 2,560 to 3,600 years in the deep Chauk Syncline aquifers;
- ≈ 2,455 to 4,000 years in the Ywatha/Aungban aquifer and 6,400 years in the shallower, clay bound Kokkogon Aquifer, both within the Pale Sub-basin; and
- ≈ 1,350 to 9,800 years in the Ayadaw Syncline and 26,120 years at Halin Springs;
- natural contamination (arsenic, fluoride, uranium) is site specific. Due to the lack of chemical analysis[132], these elements may be more widespread than documented:
- fluoride is recorded in Wetlet Township (35 % exceed the NDWQS limit of 1.5 mg/L);
- fluoride (42 % exceedance) and uranium (17 % above WHO Guidelines) in the aquifers at Myingyan;
- high concentrations of arsenic (> 50 µg/L) occurs in Alluvium within Ayeyarwady River sediments (Myaung (4.6% NDWQS exceedance), Madaya (4%), Myingyan (2.8%), Myinmu (2.3%), Yesagyo (1.3%)) and lower Samon Chaung (Amarapura (2.4%), Leway (2.3%), Kyauske (1.9%) Sintaung (1.8%)). Elevated arsenic is not recorded in the Mu and Chindwin river valleys; and

[132] Arsenic has only been tested in 17 of the 53 Dry Zone townships. Fluoride has only been tested in 2 towns

- elevated arsenic is known in a few shallow tubewells in the Irrawaddy Formation in the Bago Yoma near Mahlaing and Natogyi;

- human pollution (coliform, heavy metal) will occur in shallow aquifers around villages, towns and cities where sanitation, liquid industrial waste disposal and dugwell construction are poorly developed; and
- difficult drilling (mud circulation loss) – located in highly permeable, unsaturated, yellow sand and gravel horizons, especially in elevated terrain where the potentiometric surface and aquifers are deep and overlying synclinal structures (for example, Chauk Syncline and Myaing-Kyaukpadaung and Bahin-Pagan structural lines). Drilling in these areas sometimes exceeds 300 metres before Irrawaddy Formation aquifers are encountered. The blue grey sediment usually occurs beneath the potentiometric surface.

Figure 59, Plate 3b indicates:

- groundwater salinity within the Dry Zone is strongly controlled by the mode of sediment deposition and geological structure. Although variation in quality occurs over short distances groundwater salinity is quite predictable. The general trends are:

- brackish to saline aquifers occur in the marine rocks of the Pegu Group, especially within the Bago Yoma Anticlinorium, Shinmataung and Kyaukka ranges, the western hills and the 20º N and 22º N Uplift areas. Highly saline groundwater occurs at depth near the oil fields and in anticlinal folds;
- saline shallow aquifers overlie better quality zones in deeper sediment along the Thazi Anticline;
- highly saline aquifers are encountered at depth within the Irrawaddy Formation along the southern periphery of the Shinmataung Range as the Pegu rocks gently plunge southwards;
- with increasing distance from the Pegu Group rocks the salinity in Irrawaddy Formation or Alluvium aquifers decrease. At Myingyan and Monywa there are extensive brackish plumes; and
- low salinity aquifers usually occur with the Alluvium and Irrawaddy Formation.

Figure 60, Plate 3c indicates:

- aquifers of high groundwater yield (> 6 L/sec) and low salinity (< 1,500 $\mu S.cm^{-1}$ at 25º C), suitable for irrigation purposes, should be available from the Alluvium, Piedmont Colluvial Sediment and Irrawaddy Formation away from the Pegu Group and Eocene rocks. These areas include the Ayeyarwady, Lower Mu and Lower Chindwin river systems[133]. Due to the heterogeneity in stratigraphy and geological structure variations in yield and salinity should be expected;
- some high potential yield and low salinity areas have limited width as the Ayeyarwady River cuts through the northern extension of the Bago Yoma (Myinmu and Pakokku), the Chauk and Yenangyat anticlines and brackish plumes extending from the Nanmyingtaung, Shinmataung and Kyaukka ranges;
- due to limited alluvial width, little groundwater throughflow occurs into the Dry Zone from the Upper Chindwin and Ayeyarwady rivers upstream of Twin Taung and Letha Taung respectively. The alluvial flats of the Upper Mu River are wide and substantial groundwater may enter the downstream Alluvium;
- major natural groundwater recharge areas include:

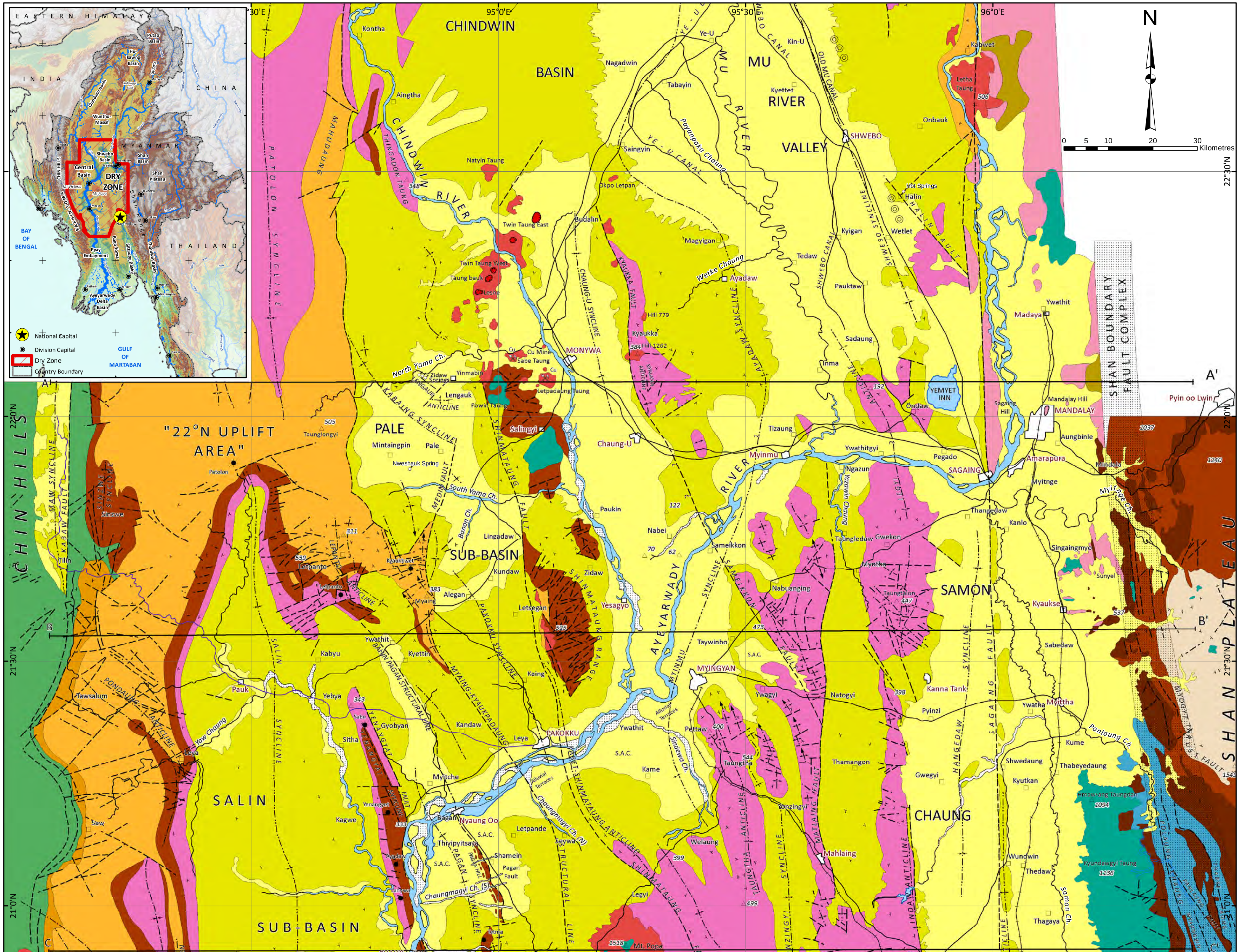
- Upper Mu River Alluvium;
- elevated Piedmont Colluvial Sediment along the western edge of the Shan Plateau;
- sandstones along the Western Fold Belt; and
- sandy intermittent flowing chaungs.

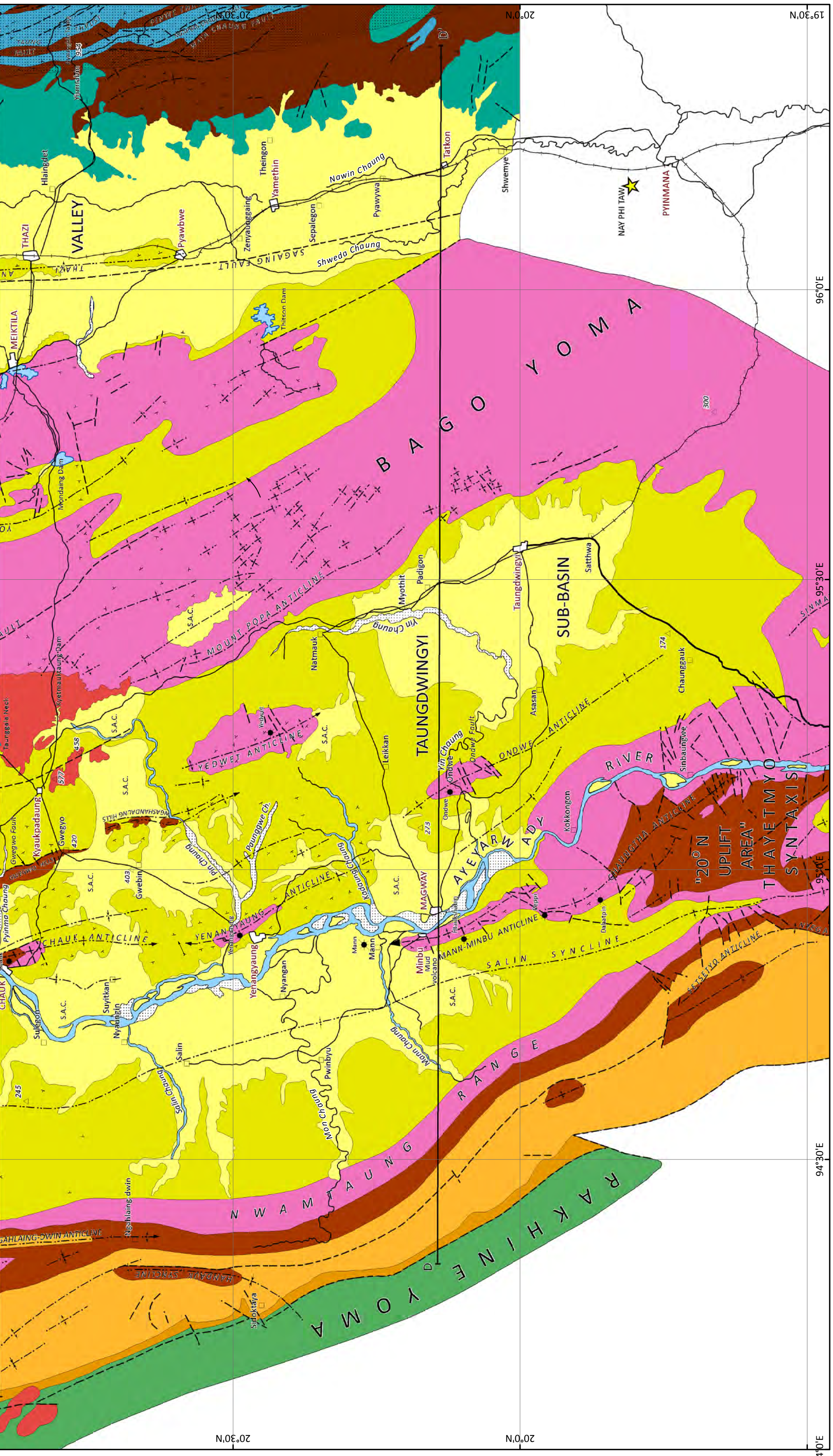
[133] Due to consideration of construction and operational costs, aquifers deeper than 250 metres with potentiometric surface more than 150 metres have been omitted;

In addition, groundwater recharge may occur indirectly where the radius of influence of pumping tubewells intersect the Ayeyarwady River and tributaries, (for example, Mandalay City Water Supply).

- Groundwater discharge occurs:
- to the downgradient watercourses;
- from evapotranspiration;
- from the large number of artesian and sub-artesian tubewells and dugwells; and
- continuously along the Ayeyarwady River before the 20° N Uplift Area.

Figure 57 Regional Geological Map of Dry Zone




BAGO YOMA
TAUNGDWINGYI SUB-BASIN
VALLEY
RAKHINE YOMA
NWAMTAUNG RANGE
AYEYARWADY RIVER
"20°N UPLIFT AREA"
THAYETMYO SYNTAXIS
MOUNT POPA ANTICLINE
YEDWET ANTICLINE
ONDWE ANTICLINE
CHAUK ANTICLINE
MANN-MINBU ANTICLINE
SALIN SYNCLINE
SAGAING FAULT
NAY PHI TAW
PYINMANA
MEIKTILA
THAZI
Pyawbwe
Yamethin
Tatkon
Taungdwingyi
MAGWAY
Minbu
Yenangyaung
CHAUK
Kyaukpadaung
Natmauk
Salin
Sidoktaya
20°0'N
20°30'N
19°30'N
96°0'E
95°30'E
95°0'E
94°30'E
94°0'E

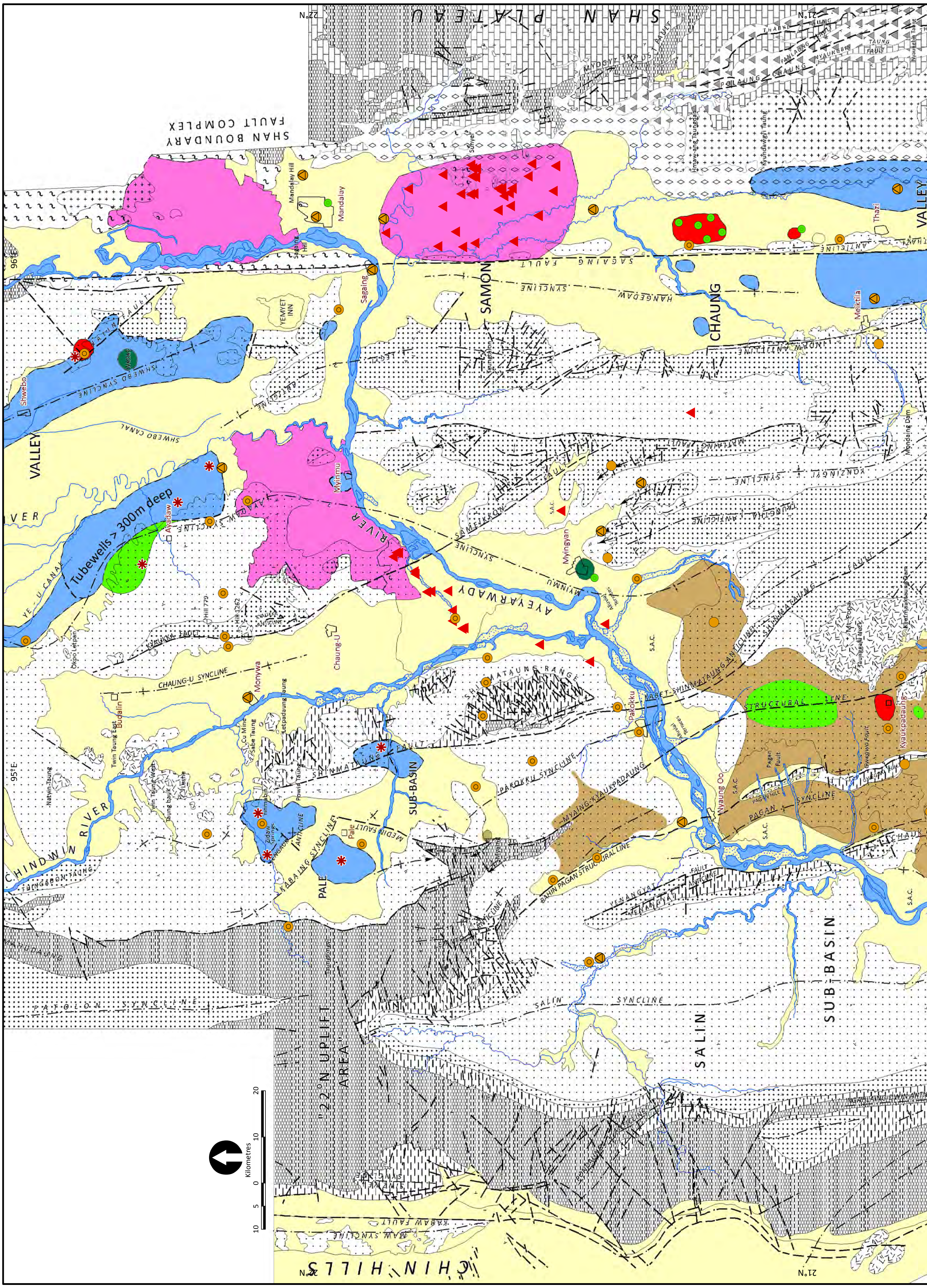
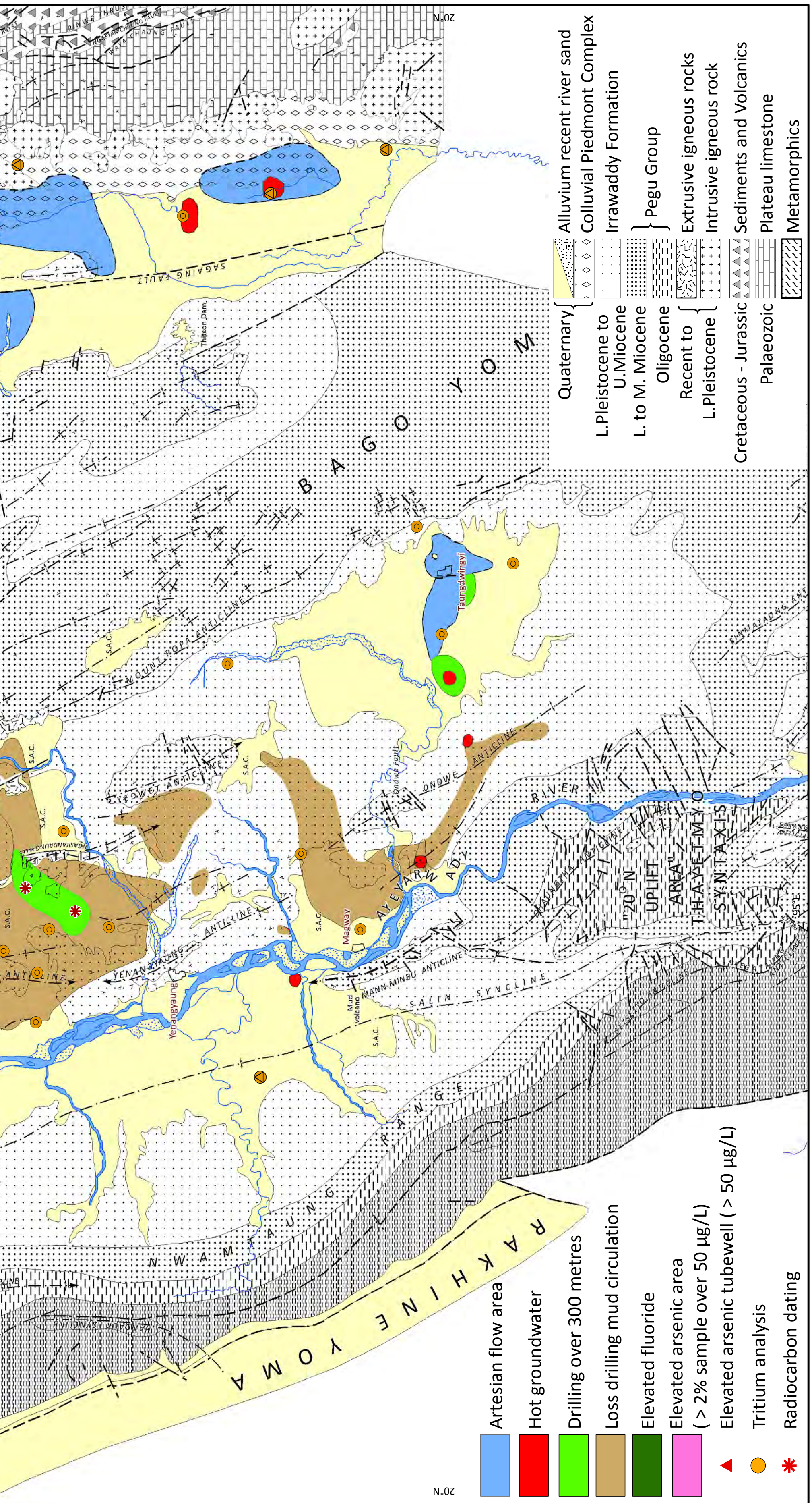


Figure 58 Regional Hydrogeological Features (Elevated Heat, Arsenic and Fluoride; Artesian Flow; Dating; and Drilling Challenges)


Quaternary
Alluvium recent river sand
Colluvial Piedmont Complex
L.Pleistocene to U.Miocene
Irrawaddy Formation
L. to M. Miocene
Oligocene
Pegu Group
Recent to L.Pleistocene
Extrusive igneous rocks
Intrusive igneous rock
Cretaceous - Jurassic
Sediments and Volcanics
Palaeozoic
Plateau limestone
Metamorphics
Artesian flow area
Hot groundwater
Drilling over 300 metres
Loss drilling mud circulation
Elevated fluoride
Elevated arsenic area
(> 2% sample over 50 µg/L)
Elevated arsenic tubewell (> 50 µg/L)
Tritium analysis
Radiocarbon dating
B A G O Y O M A
R A K H I N E Y O M A
N W A M A U N G R A N G E
SAGAING FAULT
Thitson Dam
Taungdwingyi
Magway
Yenangyaung
Mud volcano
AYEYARWADY RIVER
MANN-MINBU ANTICLINE
SALIN SYNCLINE
MOUNT POPA ANTICLINE
"20° N" UPLIFT AREA
THAYETMYO SYNTAXIS
20°N

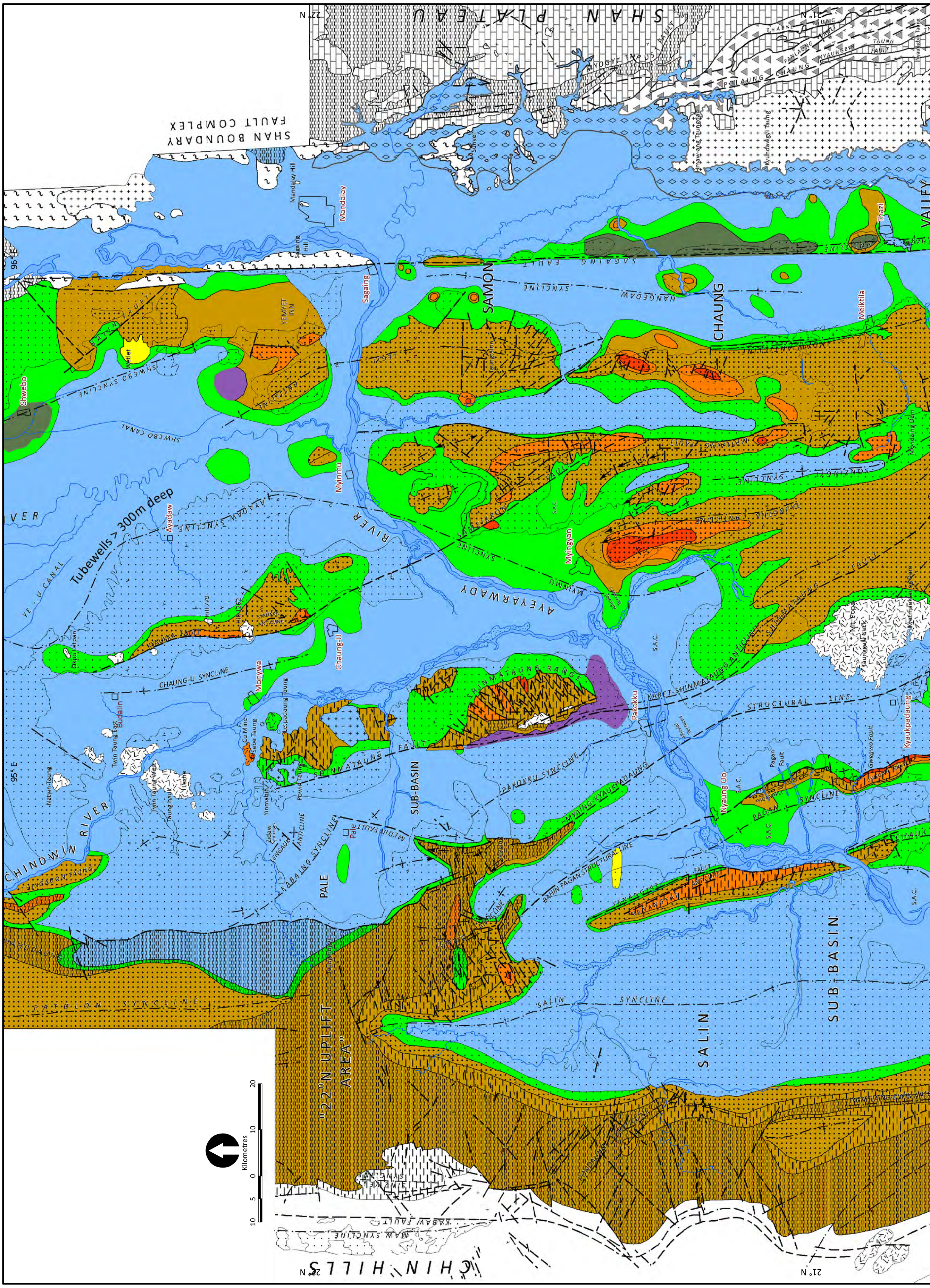
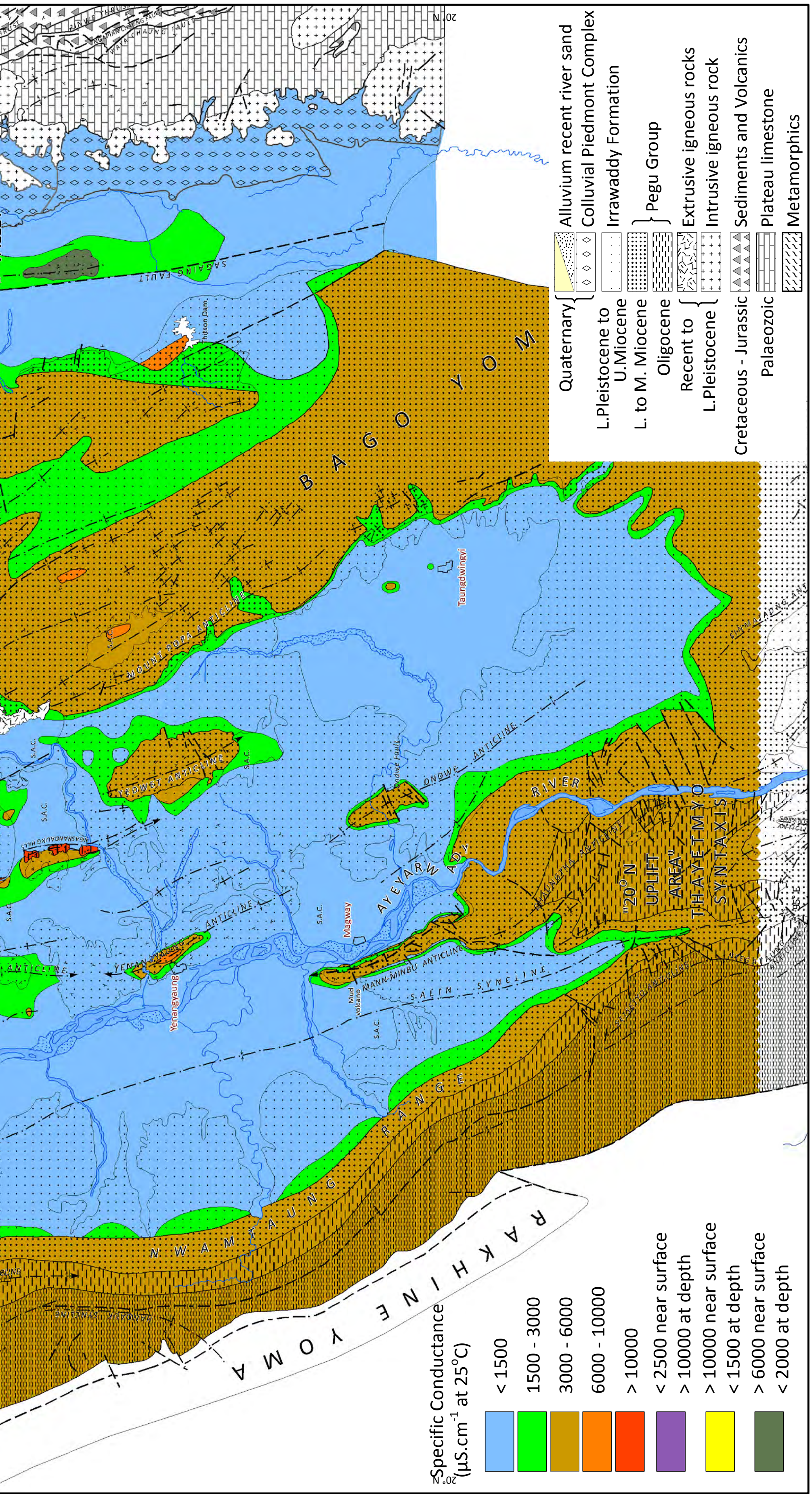


Figure 59 Regional Variation in Specific Conductance


Alluvium recent river sand
Colluvial Piedmont Complex
Irrawaddy Formation
Pegu Group
Extrusive igneous rocks
Intrusive igneous rock
Sediments and Volcanics
Plateau limestone
Metamorphics
Quaternary
L.Pleistocene to U.Miocene
L. to M. Miocene
Oligocene
Recent to L.Pleistocene
Cretaceous - Jurassic
Palaeozoic
Specific Conductance (µS.cm-1 at 25°C)
< 1500
1500 - 3000
3000 - 6000
6000 - 10000
> 10000
< 2500 near surface
> 10000 at depth
> 10000 near surface
< 1500 at depth
> 6000 near surface
< 2000 at depth
B A G O Y O M A
R A K H I N E Y O M A
N W A M T A U N G R A N G E
A Y E Y A R W A D Y R I V E R
"20° N UPLIFT AREA" THAYETMYO SYNTAXIS
SAGAING FAULT
MOUNT POPA ANTICLINE
MANN-MINBU ANTICLINE
SALIN SYNCLINE
Taungdwingyi
Magway
Yenangyaung
Mud volcano
20° N

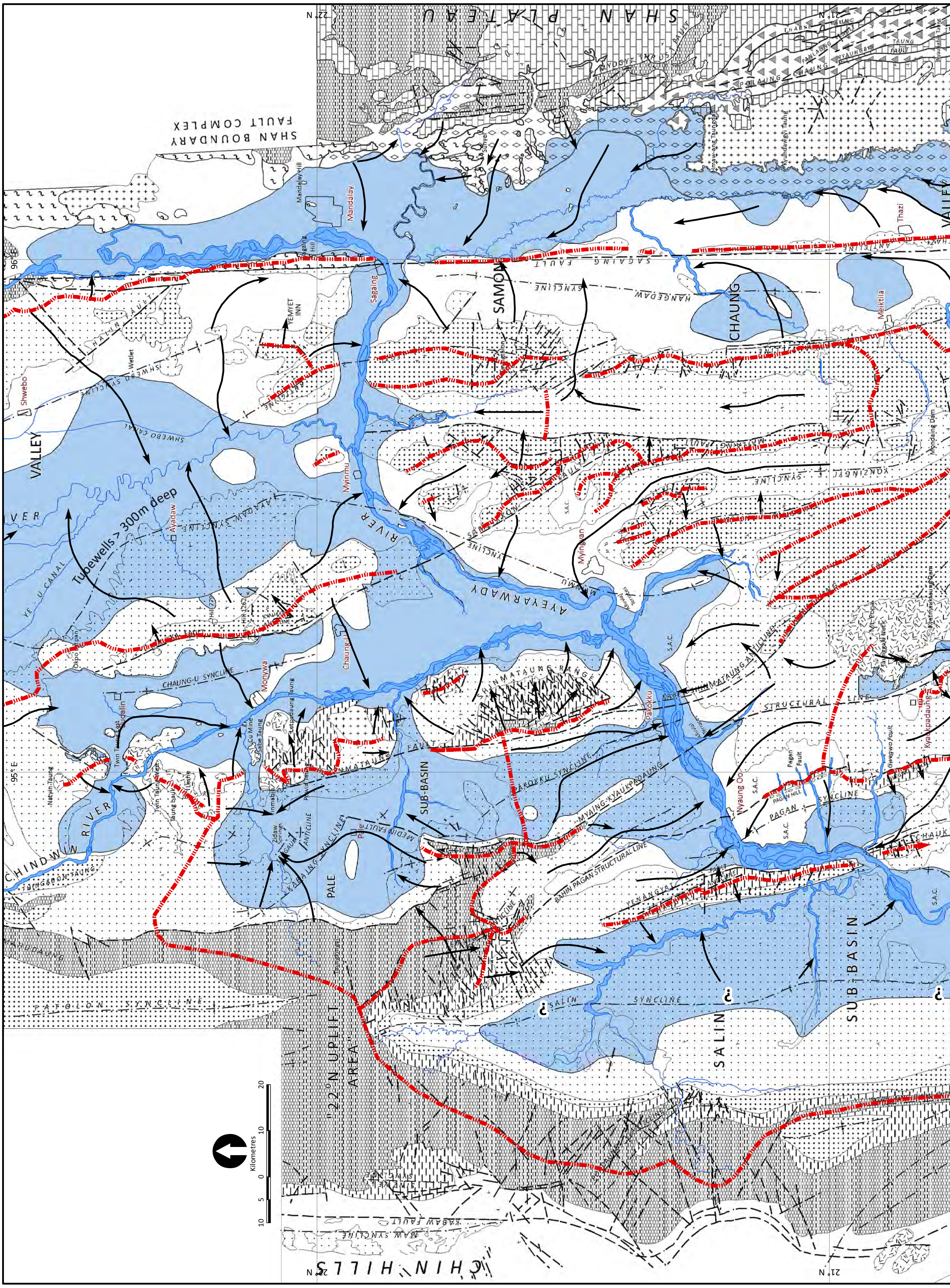

SHAN PLATEAU
SHAN BOUNDARY FAULT COMPLEX
Mandalay
Sagaing
SAGAING FAULT
SAMON
CHAUNG
Meiktila
Thazi
Shwebo
VALLEY
SHWEBO CANAL
YE-U CANAL
Tubewells > 300m deep
Ayadaw
Myinmu
Myingyan
AYEYARWADY RIVER
CHINDWIN RIVER
CHAUNG-U SYNCLINE
Monywa
Chaung-U
Pakokku
PAKOKKU SYNCLINE
Nyaung Oo
PAGAN SYNCLINE
SUB-BASIN
PALE
"22°N UPLIFT AREA"
SALIN SUB-BASIN
SALIN SYNCLINE
CHIN HILLS
Kilometres
10 5 0 10 20
22°N
21°N
96°E
95°E

Figure 60 Areas of High Groundwater Yield and Low Salinity

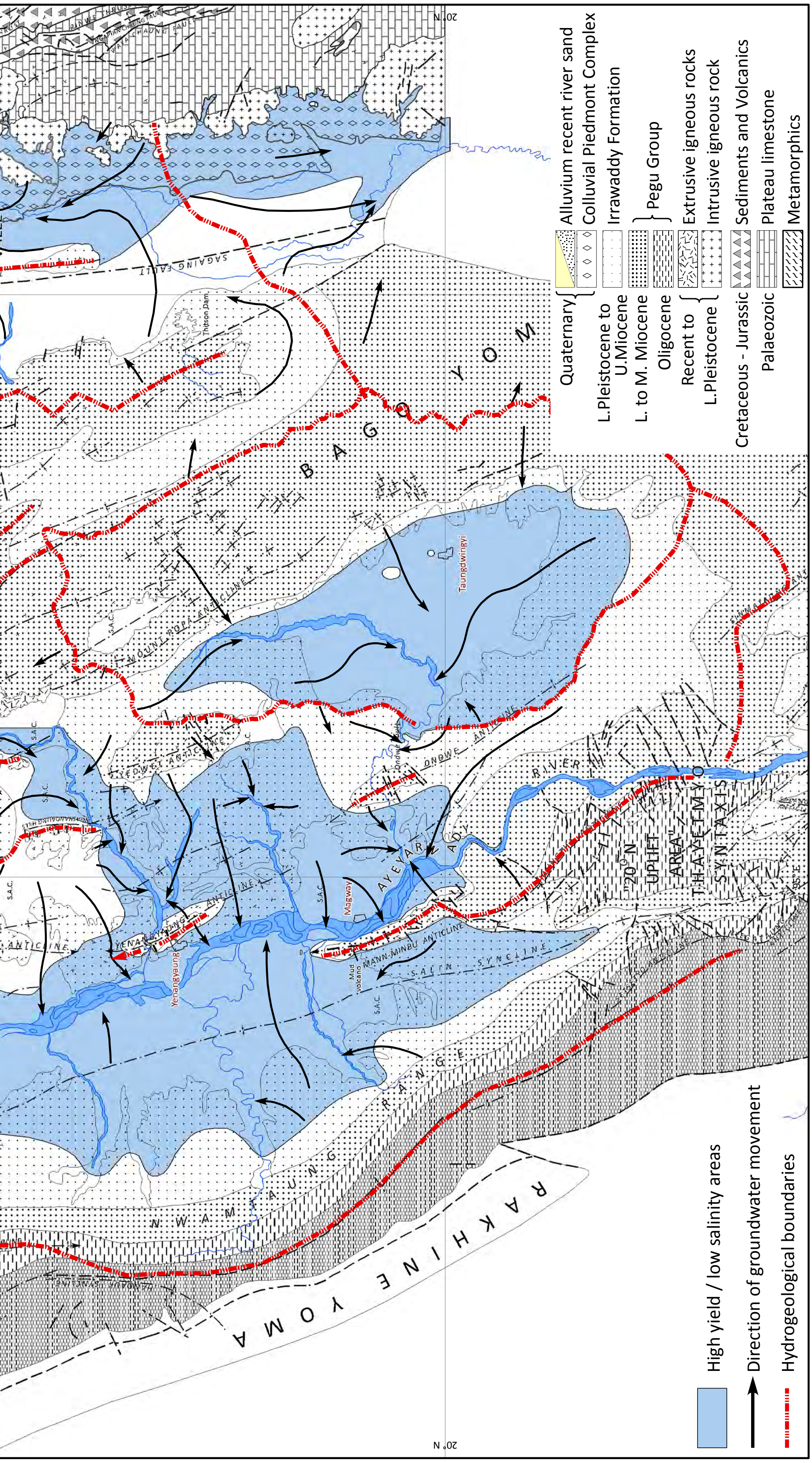

Alluvium recent river sand
Colluvial Piedmont Complex
Irrawaddy Formation
Pegu Group
Extrusive igneous rocks
Intrusive igneous rock
Sediments and Volcanics
Plateau limestone
Metamorphics
Quaternary
L.Pleistocene to U.Miocene
L. to M. Miocene
Oligocene
Recent to L.Pleistocene
Cretaceous - Jurassic
Palaeozoic
High yield / low salinity areas
Direction of groundwater movement
Hydrogeological boundaries
B A G O Y O M
R A K H I N E Y O M A
N. W A M A U N G R A N G E
SAGAING FAULT
Taungdwingyi
Magway
Yenangyaung
MOUNT POPA ANTICLINE
MANN-MINBU ANTICLINE
S A L I N SYNCLINE
AYEYARWADY RIVER
20° N
"20°N UPLIFT AREA"
THAYETMYO SYNTAXIS
Thitson Dam
20° N

Table 61 summarises aquifer occurrence and hydrogeological characteristics throughout the Dry Zone, as documented in **Chapters 6 - 16**.

Table 61 Generalised Summary of Aquifer Characteristics throughout the Dry Zone

Aquifer Type	Area (%)	Regional Location	Specific Location	Depth of Drilling/ average (m)	SWL Range / average (m)	Yield (L/sec)	Quality (µS/cm^{-1})	Hydraulic Characteristics		
								Transmissivity / av. (m^2/day)	Hydraulic conductivity (m/day)	Storage Co-efficient
		Chauk	West of River	6 – 60/30	5 – 30/15	2- 20	< 1,500	12 – 300/200		0.5 – 2 x 10^{-2}
		Magway/Minbu	West of River	20- 50	5- 10	5- 25	< 1,500	125- 2,000/300		
		Taungdwingyi	Yin Chaung	75	0- 8	5- 10	< 1,000	45- 200		
		Pakokku	Yaw Chaung	65	1- 5	2- 10	< 1,500	55- 500		
			Pakokku	72	12		< 1,500	25- 650		
		L. Chindwin River	Monywa	15 – 70/45	3- 18	10- 50	500- 2,500	200- 15,000	18 – 44 / 24	8.4 x 10^{-3}
		Lower Mu River	Central	20- 40	2- 8	5- 20	< 1,500	60- 1,000	15- 100	
			Sagaing	110	5- 10	20- 80	< 1,000	100- 3,500		
		Myingyan	Sindewa Chaung	41	1- 3	20- 40	< 1,000	400- 1000		2 x 10^{-4} - 1.3 x 10^{-3}
Alluvium	29		Near Ayeyarwady River	90	1.5- 24	2- 20	< 1,500	50- 180		5 x 10^{-3}
		Mandalay	TWS Aquifer 1	30	2- 12	5- 10	< 1,000		0.89	2.4 x 10^{-3}
			TWS Aquifer 2	70	10- 20	10- 20	< 1,000	1,900	27- 140	1 x 10^{-3} – 5 x 10^{-5}
			TWS Aquifer 3	160	12- 60	20- 80	< 1,000	100- 15,000	1.3- 220	1 x 10^{-3} – 7 x 10^{-5}
			Kyauske	40	1- 5	4- 50	< 1,000			
		Meiktila Tatkon	Meiktila- Thazi	40- 110	0- 7	3- 10	< 1,500	44- 650	112- 124	
			West of Sagaing Fault	60	2- 10	5- 20	690- 10,000			
			Pyawbwe	> 45	+ 4- 10	2- 10	< 1,500			
			Thein Gone Village	88- 160	3- 10	3- 10	< 1,000			
			Tatkon	51	4 – 7	25	< 1,000	2,800- 4,000	150- 200	5 x 10^{-2}
Piedmont	5	Mandalay	Base of Shan Plateau	90	+ 5- 20	20	< 1,500	15- 370	3 – 75	
		Meiktila	Hlaingdet	100	5 – 8	7- 10	< 1,000	60- 300	20- 60	5 x 10^{-3}
		Chauk	Chauk Syncline	300–406/330	180-313/220	8- 10	< 1,500	250		5 x 10^{-4}
		Kyaukpadaung	Kyaukpadaung Hills	0- 200	< 50	2- 10	< 1,500	10 – 700/200		5 x 10^{-4}
			Gwegyo- Khauk. Hills	150- 250	< 130	1- 10	< 1,500	10 – 700/200		5 x 10^{-4}
			Pin Chaung	< 150	< 15	1- 10	< 1,500	10 – 700/200		5 x 10^{-4}
		Yenangyaung	Yenangyaung-Yedwet	80- 240	0- 100	5- 40	< 1,000	20- 150		2 x 10^{-4}
		Magway/Minbu	Ondwe Anticline	< 250	60- 130	2- > 20	< 1.500	350		2 x 10^{-4}
			Magway	50- 100	10- 20	5- > 20	< 1,500	200 – 350 /300		2 x 10^{-4}
		Taungdwingyi	Natmauk	200	12- 120	0.5- 10	> 1,500	150		
			Southwest- shallow	100- 250	+ 5- 15	10	> 1,500	6- 75	2.5	
Irrawaddy Formation	38		Southwest – deep	100- 410	+ 10- 10	> 100	< 1,500	9- 750	21	
			South	100- 230	10- 80	1- 5	< 1,500	10- 100		
		Pakokku	Pakokku Syncline	150	0- 20	2- 20	500- 3,000	200- 600		
			SW Shinmataung	100	4- 30	3- 20	2,100-10,000	100- 450		
			The Oasis Regional	120- 220	5- 60	3- 10	< 1,500	220- 450		
		Pale Sub-basin	Kokkogon Fm	270	+ 5- 20	5- 50	600- 1,900		1 – 65 / 30	
			Ywatha/Aungban	30- 310	+ 10- 30	18- 100	< 1,000	100- 1,700	30 – 260/100	5 x 10^{-4}
		L. Chindwin River	Base Kyaukka Range	200	5- 10	1- 25	< 1,500	2- 170		2 x 10^{-4}
		Lower Mu River	West Ayadaw	90- 180	5- 20	4- 10	< 1,500	3- 20		
			Ayadaw Syncline Ye-U	250	+ 10- 12	20- 50	< 1.500	10- 150		

			Ayadaw Syn. Shallow	< 15	2- 5	5- 40	< 1.500	58- 1,035 /680	15- 100	0.2
			Ayadaw Syn. Middle	120- 180	+ 5- 11	15- 50	< 1.500	20 – 280 / 48	2- 100	5×10^{-4}
			Ayadaw Syn. Deep	240- 450	+ 15- 10	20- 110	< 1.500	20- 1,000 /210	50- 200	
			Shwebo Syncline	37- 240	+ 5- 10	1- 25	500- 6,000	75		
		Nyaung Oo	Nyaung Oo	100	10- 50	2- 12	500- 3,000	20- 140		
			Structural Line	200- 360	120- 250	2- 14	< 1,500	30- 220		
			Pagan Syncline	90	10- 30	5- 20	< 1,500-3,600	50- 250		
		Myingyan	Bago Yoma	24- 180	2- 25	1- 5	700-> 3,000			
			Myinmu Syncline	240- 285	90- 180	3- 10	> 1,500			
			Myingyan	150- 390	25- 80	2- 5	2,500- 5,000			
		Mandalay	TWS Aquifer 4	250- 300	10- 18	50	< 1,000			
			Amarapura, Ava	210- 250	3- 8	20- 100	< 1,000	200 – 600/350	40- 100	2×10^{-4}
		Meiktila	Wundwin	195- 457	38- 82	10- 20	1,600-10,000	30- 110		
			Meiktila	60- 180	+ 4- 6	1- 8	900- 10,000	500 – 1,100	20 – 27	
			Thazi	90	5- 10	3- 7	800- 2,000	20- 100		
			Yamethin	> 250	+ 6- 42	4 – 13	400- 2000	50- 200		5×10^{-4}
Pegu Group	20	Chauk	Anticlines	< 250	5- 50	0.05- 5	2,420- 7,170	1 – 13		
		Magway/Minbu	Anticlines	< 300		1- 5	> 1,500	< 50		
		Taungdwingyi	Bago Yoma	240	10- 20	0.1- 5	2,000- 9,000			
		Pakokku	Shinmataung	214	7- 28	0.5- 5	1,100-10,000	1- 65		
		Lower Chindwin	Kyaukka	100	50	0.5- 5	2,000-10,000	0.5- 70		
		Lower Mu River	Legyi Anticline	30- 204	0- 10	0.1- 3	2,000-17,200	1		
			Kyaukka Anticline	200	48- 98	0.5- 3	900- 10,600	5- 58		
		Nyaung Oo	Pagan Hills	200	10- 30	< 3	2,500- 4,400	3- 25		
		Myingyan	Bago Yoma	220	1- 38	0.1 – 5	4,000-10,000	20- 60/35		
Eocene	7	Pale Sub-basin		280		0.5 – 5	> 1,500		1 – 10	
Volcanics	1	Lower Chindwin	Cu Mine Area	30 – 240	2 – 30	0.5 – 4	500-> 10,000		$3 \times 10^{-4} – 7 \times 10^{-2}$	
Limestone		Shan Plateau	Kalaw Township	96 – 252	30 – 120	1 – 50	< 1,500			

17.2 Groundwater Availability within the Dry Zone

Radiocarbon dating indicates that groundwater has been accumulating over thousands of years into the Dry Zone aquifers. **Extreme caution should be placed on quoting values of groundwater in storage. Only a small percentage of this volume should be available for physical extraction. As a general guideline, groundwater extraction should not exceed aquifer recharge in the water balance models unless there are compelling water management, social and environmental reasons that exceedance is required.** The ARC Water Balance Model (**Section 17.2.3**) suggests that a sustainable yield is around 10,340 $Mm^3.yr^{-1}$. This is one percent of the estimated low salinity groundwater stored within the Alluvium, Irrawaddy Formation and Piedmont Colluvial Sediments in the Dry Zone.

A carefully considered groundwater management policy needs to be developed to ensure aquifer sustainability for on-coming generations.

17.2.1 Safe Yield and Sustainability

The concepts of 'safe yield' and 'sustainable yield' appear in hydrogeological literature[134].

'Safe yield' was originally considered in terms of the amount of groundwater that can be extracted without the danger of aquifer depletion or 'undesirable' impacts. It was generally considered to be equal to the volume of water that is annually recharged to the aquifer system. Over time the description of safe yield has been modified to include socio-economic impacts and concepts of optimal use. Short-term optimisation may mean depleting an aquifer in the hope that alternative water supply systems (for example, a proposed dam) may be available in the future. The definition of safe yield is thus vague and leads to misinterpretation.

Defining and measuring 'aquifer sustainability' is a major challenge and well outside the scope of current knowledge of the hydrogeology of Central Myanmar. The groundwater resource should not be viewed as a single entity as it is part of the hydrological cycle. The concept of sustainability incorporates many components which need to be included in any assessment of groundwater availability: aquifer response to recharge and discharge; groundwater quality; salt water intrusion; land subsidence; legal ownership; country legislation; community expectations; total water sources within the basin; and environmental and future demands.

To assess groundwater availability in the Dry Zone the approach has been to:

- calculate the volume of low salinity water in aquifer storage; and
- use water balance models to evaluate the input and output dynamics of the hydrogeological system and consequences of groundwater extraction.

17.2.2 Assessment of Low Salinity Groundwater in Storage

Figure 59 shows the locations of low salinity groundwater (< 1,500 $\mu S.cm^{-1}$) throughout the Dry Zone. These are confined to the Alluvium, Irrawaddy Formation and Piedmont Colluvial sediment aquifers.

Calculations on the volume of low salinity water in aquifer storage have been based on:

- lithological description from borelogs (IWUMD and DRD) to assess the percentage of aquifer thickness; and
- porosity (based on **Figure 10** and **Table 13**).

The low salinity aquifers were subdivided into 92 zones, according to their hydrogeological parameters, aquifer thickness and porosity. **Table 62** indicates the assigned aquifer depth and occurrence for individual geological units.

[134] Lee (1915), Meinzer (1923a,b), Conkling (1946), Todd (1959), Bredehoeft et. al. (1982), Bredehoeft (2002), Alley & Leake (2004)

Table 62 Assigned Aquifer Depth and Occurrence in Low Salinity Areas of the Dry Zone

Formation	Depth (m)	Percent of Aquifer in the Stratigraphic Column
Alluvium	20- 160	30 to 100
Irrawaddy Formation	250 (near boundaries) to 500 m (regional)[135]	35 to 90 in the Lower Chindwin River Valley and Mandalay 11 to 21 in the Lower Mu River Valleys and Taungdwingyi Sub-basin
Colluvium	150 - 400	12 to 80 - east of Yamethin to Hlaingdet

Allowances have been made where the Alluvium overlies the Irrawaddy Formation. Both shallow and deep aquifer systems (up to 500 metres) have been accounted for in groundwater storage calculations[136].

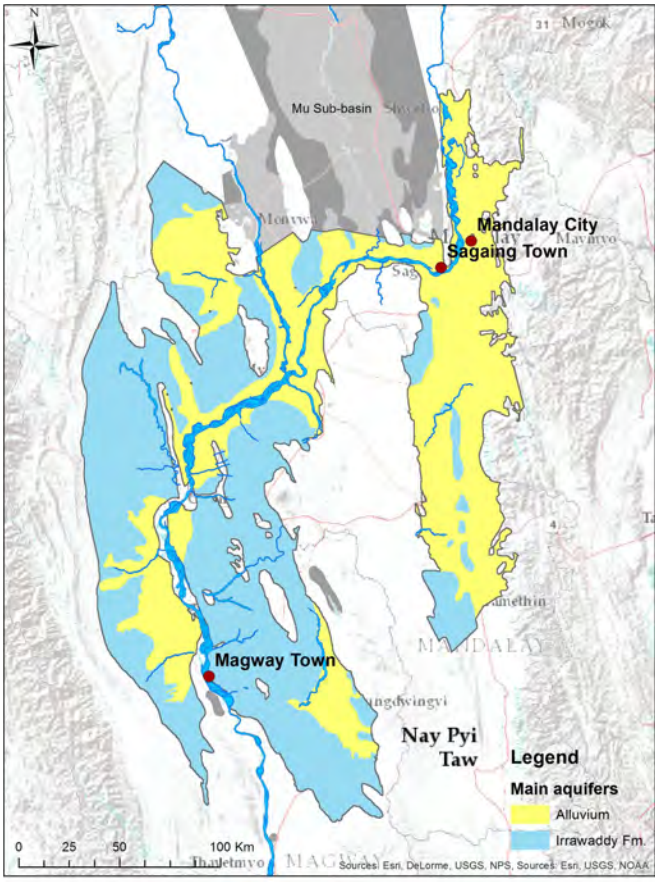
Clay, sandy clay and silt exhibit high porosity but were excluded due to their low transmitting capability.

An estimate of the volume of low salinity groundwater stored in the Dry Zone is about 950 km^3 **(Table 63)**. This volume should never be considered as the groundwater volume that can be safely extracted.

Assuming the total Dry Zone surface area is 75,700 km^2, the low salinity groundwater storage equates to 2.5 percent of the top 500 metres. Considering the area of brackish groundwater, the percentage of aquifer within the stratigraphic column and porosity, the estimate of storage is reasonable.

17.2.3 Ayeyarwady River Corridor Water Balance Model

Figure 61 Map of Irrawaddy River Corridor



Water balance models for the Pale Sub-basin, and Lower Chindwin and Lower Mu river valleys have been reported in **Chapters 10 - 12**. They indicate substantial water in storage and discharge to the watercourses. A comprehensive groundwater monitoring system needs to be installed to refine all these water balance models.

The contiguous ARC is located between Mandalay and Magway. It includes the Samon Chaung Valley and Salin and Taungdwingyi sub-basins (**Figure 61**) and outflow from the Lower Mu River (shallow alluvium and deep Irrawaddy Formation aquifers). Groundwater from the Lower Chindwin River (alluvial aquifer) is assumed to discharge into the Chindwin River upstream of the ARC.

The groundwater system is considered at equilibrium. It is assumed that there is no variation in groundwater storage over the year (ΔS=0).

The hydrogeological conditions of the sandy chaungs and Irrawaddy Formation outcrop exposure are favorable for vertical aquifer recharge.

[135] Throughout the Dry Zone the thickness of the Irrawaddy Formation is unknown. The nominated maximum depth is deeper than the current groundwater drilling of 425 metres. It is likely to extend deeper in many synclinal areas. However, a conservative approach is here considered.

[136] Consensus on aquifer depths and percent in stratigraphic column were confirmed at the June 2017 Workshop

Table 63 Estimate of Low Salinity Groundwater in Aquifer Storage in the Dry Zone

Location	Formation		Assumed Depth (m)	Aquifer Occurrence (%)		Storage (km^3)
Chauk Kyaukpadaung Yenangyaung	Pin Chaung		20		100	214.7
	Alluvium		60		49- 53	
	Irrawaddy Fm.		500	Kyaukpadaung	30	
			500	Chauk Syncline	30- 35	
			440	West of river	22	
Magway Minbu	Alluvium		60	West of river	31- 59	123.1
	Irrawaddy Fm.		440	West of river	21- 32	
			500	Magwe Town	26	
			500	Southern	23 – 40	
Taungdwingyi Sub-basin	Yin Chaung		40	Sub-basin exit	80	49.5
	Irrawaddy Fm.		300- 450	Taungdwingyi Natmauk	12- 17	
				Basin Axis	25	
				Southern Area	25- 34	
Pakokku	Alluvium		70	West Pakokku	30- 60	151.9
	Irrawaddy Fm.		430	West Pakokku	21- 33	
			500	Pakokku Syncline	23 – 30	
Pale Sub-basin	Kokkogon Fm		150	Central to south	16	54.1
	Ywatha/Aungban		350- 500	Anticline/syncline	31- 36	
				Regional	21	
L. Chindwin River Valley	Alluvium		75- 95	Regional	56- 90	84.2
	Irrawaddy Fm.		250- 350	Regional	35- 54	
Lower Mu River Valley	Irrawaddy Fm		350- 500	Ayadaw Syncline	12- 16	56.2
				Shwebo Syncline	21	
				Anticline	11- 17	
Nyaung Oo	Irrawaddy Fm		500	Shallow aquifers	30- 60	56.5
				Deep aquifers	37- 55	
Myingyan-Ngazun-Mahlaing	Alluvium		40	Sindewa Chaung	66	25.7
	Irrawaddy Fm.		500	West area	13 – 19	
			190	Yonzingyi Syn.	21	
Wundwin-Thazi-Tatkon	Alluvium	Takton	60	Shallow aquifer	31	52.0
		Myittha	40	Shallow aquifer	38	
	Piedmont		150	Base of Shan Plateau	44-80	
	Irr. Fm		400	Irrigation areas	15-25	
				West of Sagaing Fault	5-20	
Mandalay	Alluvium		40- 160	Kyaukse	38	82.2
				Mandalay	50- 98	
	Irrawaddy Fm.		500	Deep Aquifers	52- 60	
TOTAL (km^3)						**949.5**

The potentiometric surface indicates that groundwater moves from elevated recharge areas directly or indirectly (via tributaries) to the Ayeyarwady River. Groundwater contribution to surface water baseflow is expected to be high. This is especially the case considering the termination of the major aquifer systems at the 20º N Uplift Area.

Any temporary reversal in groundwater flow direction during flood events will be of short duration and of limited extent. Flooded areas have not been considered as a major recharge pathway.

For simplicity, the ARC water balance model considers the Alluvium and Irrawaddy Formation as a single entity.

The impact of evapotranspiration is considered limited due to the absence of wetlands and large phreatophytes. It has been neglected in this regional water balance.

The ARC groundwater model balance is defined as:

$$Q_{rech} + Q_{sub.Mu} + Q_{inf} = Q_{VWS} + Q_{TWS} + Q_{irr.gw} + Q_{bf}$$

- Aquifer Inputs:
- Recharge:
  - Q_{rech} - rainfall recharge is assumed to be 15 percent[137] over the total ARC area; and
  - $Q_{sub.Mu}$ - subsurface flow from the two Mu River aquifers (**Figure 42**);
- Surface Water Infiltration:
  - Q_{inf} - vertical infiltration from irrigation activity (river, dams, ponds, diversions and groundwater). Satellite imagery was used to assess land use cover from which irrigation areas and water volumes were calculated for various crop types. Cropping patterns between one and three crops/year were considered. An irrigation water return volume of 30 percent was applied to all irrigation areas within the ARC;
- Aquifer Outputs:
- Groundwater Extraction:
  - Q_{VWS} - groundwater used for village supply is a combination of artesian, sub-artesian and spring extraction based on village population and tubewell numbers (recorded and estimated), flowing/pumping times and discharge;
  - Q_{TWS} - the groundwater extracted for town water supply is based on data from IWUMD, DRD, Township Development Committees and 2014 Census population numbers;
  - $Q_{irr.gw}$ - abstraction for irrigation purposes used satellite imagery to assess land use cover. River pumping accounts for 20 percent and dam irrigation around 60 percent (IWUMD). The remaining irrigation comes from groundwater sources; and
  - Q_{bf} - total contribution of groundwater seepage directly or indirectly to the Irrawaddy River. This is the closing balance as the aquifer system terminates south of Magway and it is assumed there is no change in aquifer storage.

The water balance model for the ARC is given on **Figure 62**. Due to the lack of long-term monitoring of potentiometric surface and the geological complexity the estimate of aquifer recharge and discharge cannot be accurately known.

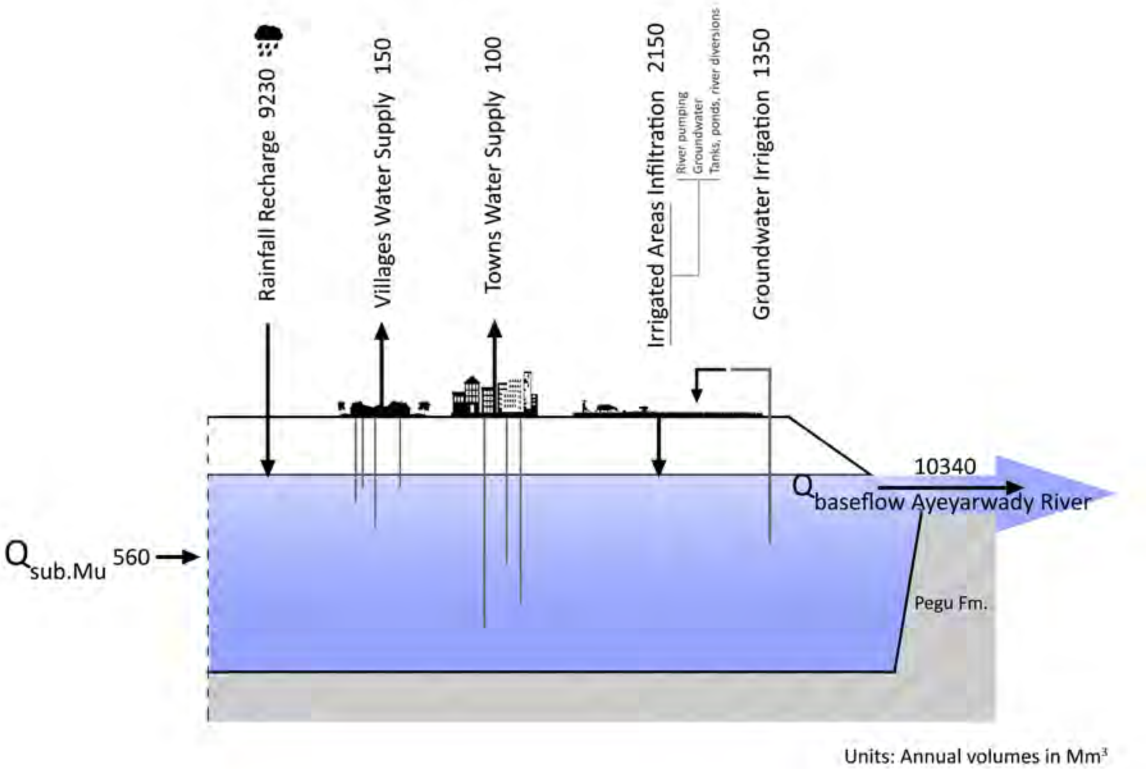
The ARC water balance indicates that 10,340 $Mm^3.yr^{-1}$ of groundwater is directly or indirectly discharged to the Ayeyarwady River. There is unreliable river flow data between river gauging stations. It is difficult to compare groundwater contribution to the surface water system. The downstream Magway gauging station indicates a Dry Season (December to May) flow of 50,000 Mm^3. Groundwater discharge to watercourses during the same period represents 20 percent of the Ayeyarwady River baseflow.

[137] GDC (1984c), ESCAP (1995), Myanmar Academy of Agriculture (2003), Than Zaw (2010), van Ramshorst (2017)

The water balance indicates that groundwater:

- extraction for on-land utilisation (1,600 $Mm^3.yr^{-1}$) is 14 percent of aquifer recharge (11,380 $Mm^3.yr^{-1}$);
- discharge to the river is 10,340 $Mm^3.yr^{-1}$; and
- outflow to the Ayeyarwady River is one percent of the low salinity groundwater stored within the Alluvium, Irrawaddy Formation and Piedmont Colluvial Sediments (950 km^3).

Figure 62 Water Balance Model for the Ayeyarwady River Corridor



The ARC Water Balance Model suggests that expansion of groundwater utilisation in the Dry Zone appears viable. However, issues of appropriate hydrogeological locations and aquifer sustainability (declining water levels, quality, salt water intrusion, subsidence, ownership, legislation, community expectations, impact on Dry Season surface water navigation, environmental demands and the needs for future generations) need to be considered in any basin wide water planning and management strategy. Groundwater and surface water need to be viewed as one integrated resource and mutually interdependent.

17.3 Dry Zone Groundwater Management

Some countries aim to achieve a balanced level of groundwater extraction so not to compromise key ecosystem functions and the future security of safe drinking water[138]. To achieve sustainable groundwater development and management it is critical to adequately monitor and professionally analyse the hydrogeological regime.

17.3.1 The Hidden Resource

Groundwater extraction in Myanmar has occurred over many centuries, yet the nature and occurrence of this subterranean resource is not fully understood. This is due to an absence of documented

[138] Groundwater is not viewed as a single, sole-source entity but as one component within a basin-wide water management system

groundwater studies, no shared reliable database, a lack of long-term monitoring and an absence of computer modelling.

For many engineers and policy makers groundwater is often the 'forgotten resource'. Despite the Dry Zone being heavily dependent on groundwater for its socio-economic survival, there is little knowledge on how to manage this vital resource to the detriment of the community and the future. This mysterious ideology is reflected in the lack of groundwater laws and regulations and no formal management authority. The importance of groundwater has been marginalised and often neglected in development strategies and projects.

After 50 years of rural water supply projects there are still many areas where unsafe drinking water is still accessed from village ponds and construction of new domestic tubewells is on-going.

With severe temperatures, lack of Dry Season rainfall and predicted Climate Change, substantial pressure will be applied to the nation's water resources. Groundwater needs to be recognised as a crucial asset and an integral part of Myanmar's long-term water planning.

17.3.2 Tools for Groundwater Management

Groundwater management is a challenge, requiring an integration of scientific knowledge, strong government support and community consultation. For sustainable development of the groundwater resources in the Dry Zone a series of actions need to be implemented. It is essential for water practitioners to have access to a reliable centralised database, legal authority, monitoring equipment and hydrogeological computer models. These should be available within the groundwater department of the primary water-related government authority.

17.3.2.1 Central Database

The IWUMD is developing an electronic hydrogeological and hydrochemical database. Initially hand-written in voluminous books with a village name as the reference location, each entry is now being laboriously georeferenced, where possible.

Many other government-archived databases have been destroyed. Government departments, city and township development committees, chemical laboratories, universities, drillers, NGOs and INGOs retain their own databases in various formats and completeness. Some NGOs supply money to private drillers for water supplies and no technical documentation is recorded.

To adequately assess the hydrogeological situation in the Dry Zone the central database should include GIS location; geological, geophysical and penetration logs; construction details; pump-out tests (transmissivity, hydraulic conductivity, storage coefficient); potentiometric surface; chemistry; proposed use; anticipated volume extracted; owner's name and licence number. The database should be available to all water practitioners.

17.3.2.2 Groundwater Legislation and Regulations

The Burma Underground Water Act of 1930 mandated collection of information to manage underground water supplies and prevent aquifer contamination, with guidelines and procedures for groundwater litigation problems, but all databases have been lost and acts and regulations abandoned. Currently there is no law or rules relating to groundwater – its extraction, monitoring, management, funding, pollution, remediation, tubewell construction, drillers licensing and regulation enforcement.

'Existing laws appear to give proprietary rights to a land owner on groundwater under his/her land, and groundwater is still perceived as an individual property and is exploited inequitably and without any

consideration to its sustainability' (Myanmar National Water Policy, February *2014).* There needs to be a balance between short-term outcomes and long-term sustainability of the water resource to benefit all members of society. Without defined laws, groundwater development and extraction is chaotic, with individuals achieving their own goals.

A set of mandatory laws and rules with strict provisions, will give government strong monitoring and management powers so all the community can benefit and the integrity and sustainability of this valuable resource maintained.

In the absence of such legislation MCDC has introduced in-proxy local regulations in relation to approval for tubewell construction; regulating groundwater extraction; and receiving hydrogeological, construction and water quality information within the city limits.

17.3.3.3 Groundwater Monitoring

Establishing a coherent groundwater monitoring and management system, tailored to the needs and issues in different hydrogeological contexts, is an urgent priority for Myanmar, as set out in the National Water Policy.

Since 2014 IWUMD has periodically measured the potentiometric pressure of the Ywatha/Aungban aquifer in one monitoring piezometer at the Pale Sub-basin. MCDC monitors selected production tubewells within Mandalay City.

In April 2017 pressure transducers and data loggers have been installed by IWUMD in five piezometers in the Dry Zone. Location, formation and purpose of monitoring are given in **Table 64**. These are downloaded monthly by local IWUMD staff and sent to the Groundwater Department, Nay Pyi Taw for analysis and archiving.

Table 64 Groundwater Monitoring in the Dry Zone

Location	Install Date	Formation	Depth (m)	Target Behaviour
Yinmabin	2004	Ywatha/Aungtha	140-150	Regional groundwater pressure
Magway	April 2017	Irrawaddy Formation	61	Magway water level / salinity
Minbu	April 2017	Irrawaddy Formation	84	Magway water level / salinity
Monywa	April 2017	Alluvium	41	Groundwater Irrigation area
Myingyan	April 2017	Irrawaddy Formation	61	Myingyan water level / salinity
Kyaukse	April 2017	Alluvium	30	Groundwater Irrigation area

Source: IWUMD (pers. comm. 2017).

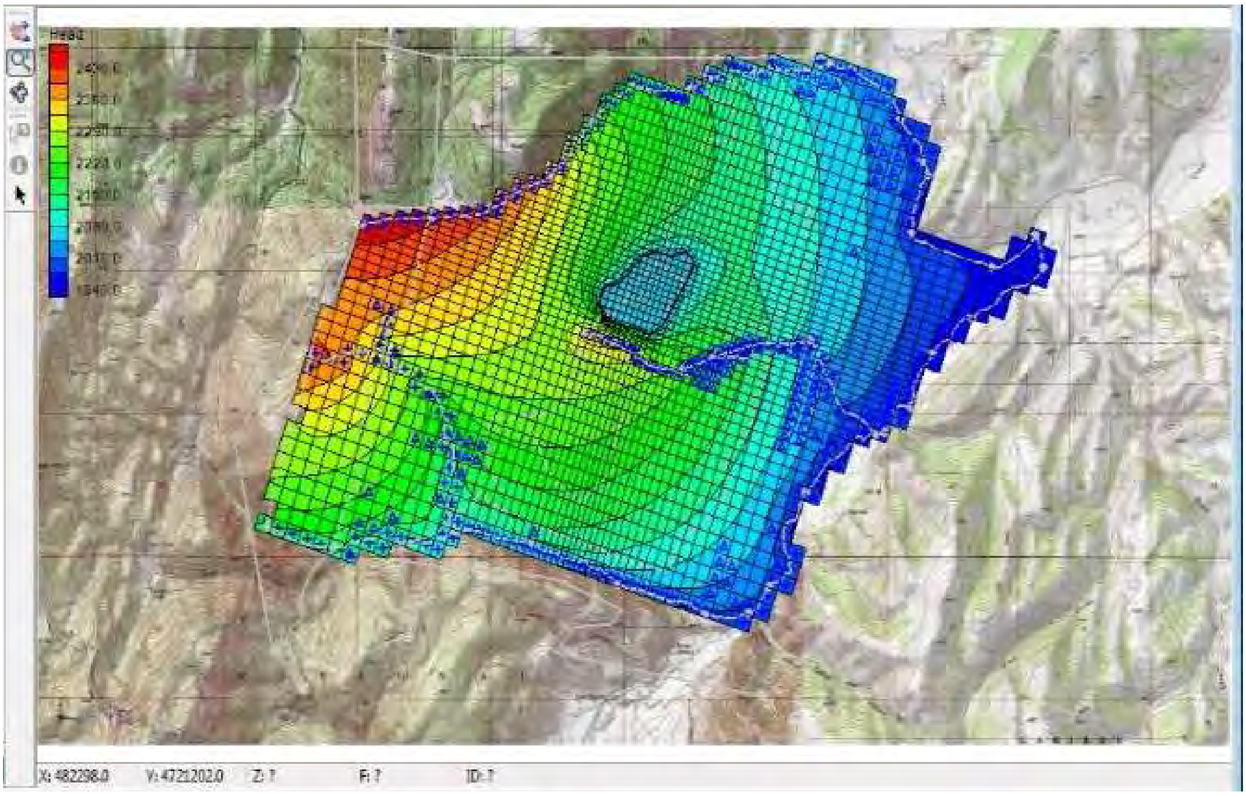
IWUMD prepared a Project Concept Paper for the national monitoring of 160 sites using pressure transducer data loggers. This proposal has been submitted to the Korea International Cooperation Agency (KOICA)[139]. This project has not proceeded.

In the Dry Zone water level and quality monitoring needs to be carried out in:

- multiple aquifers in each of the groundwater irrigation areas (Pale Sub-basin, Monywa, Ayadaw, Meiktila, Pyawbwe, Takton);
- farmer-owned shallow irrigation areas (Kyauske, Salin Sub-basin);
- areas of saline/brackish water (Myingyan);
- city and town water supplies (Kyaukpadaung, Magway, Mandalay City, Minbu, Pakokku, Thazi); and
- the Monywa Copper Mine; the oilfields; and urban market and industrial areas.

[139] IWUMD (2016)

Figure 63 Example of Groundwater Computer Output



17.3.2.4 Groundwater Modelling

Within Myanmar there is a deficiency in groundwater modelling expertise. Computer based, mathematical models are a valuable predictive management tool. They enable the simulation of local and regional aquifer systems under various operational scenarios. These models are used to represent the natural groundwater flow in various hydrogeological environments. They can predict aquifer recharge and discharge; local effects of groundwater extraction; fate of pollutants; hydrochemical changes in rural, urban or hypothetical scenarios; and impacts of Climate Change. Without such expertise, the effective management of the groundwater resource is highly restricted.

Groundwater models rely on accurate data, without which the computer-generated output is of limited value.

17.4 Rehabilitation of Artesian Aquifers

Throughout the Dry Zone there are many flowing tubewells, both within and outside designated artesian irrigation areas. Geological structures and mountain recharge areas produce high potentiometric surface in the lowlands. Artesian flows are uncontrolled and large volumes of this precious resource is wasted. In low flow areas, most tubewells have ceased flowing and pumps are now installed.

IWUMD is carrying out public consultation in the major artesian areas, but there is community resistance. For successful management of the groundwater resource the community must be educated in basic groundwater principles and the long-term consequences of inaction. Committed community leaders should have an active partnership with the government in ensuring effective monitoring, community consultation and maintenance works.

With a reduction in aquifer pressure in Pale Sub-basin tubewells, artesian conditions have reduced or ceased. Most irrigation ponds fail to effectively supply water to their entire command areas.

Remediation works have resulted in some marginal flow improvements. The crucial long-term management issue of flow control has not been addressed. This may require:

- plugging the corroded holes and replacing them with appropriately designed tubewells with corrosion-protected casing and flow control mechanisms; and
- implementing a groundwater management plan (including flow control) for the whole basin based on committed government and active community participation.

Restoration of high flow conditions to this sub-basin should result in a long-term, low cost irrigation water supply for future generations. Remediation work is expensive and a strong commitment will be required for the sustainable management of this remarkable aquifer.

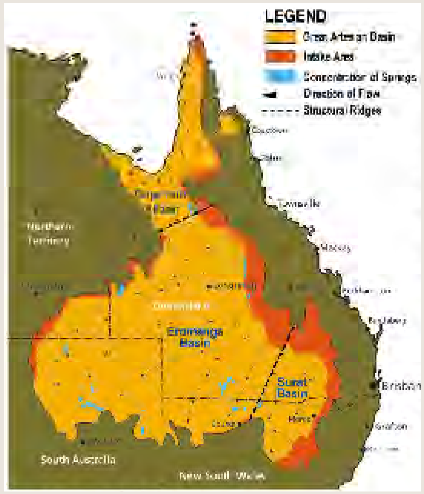
The Ayadaw Artesian Zone could be similarly considered a water management priority area.

An example of successful remediation works on a regional artesian aquifer is the Great Artesian Basin, Australia.

Project: Great Artesian Basin Sustainability Initiative (GABSI), Australia

The Great Artesian Basin (GAB) is the largest and deepest artesian basin in the world with temperature ranging from 30° C to 100° C. The depth to the sandstone aquifer is up to 3,000 metres. It underlies 23 percent of the continent.

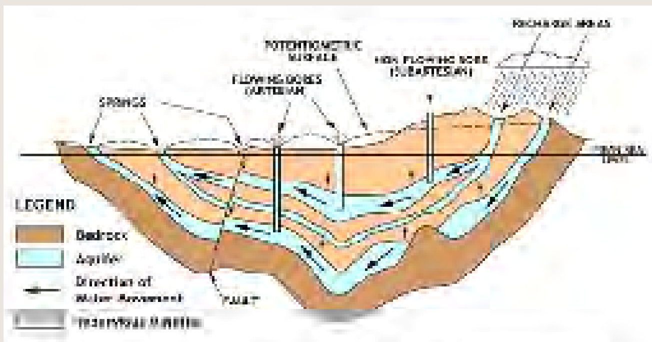
In the early 20th Century there were over 1,500 free-flowing tubewells used for stock watering and town water supplies. Total artesian discharge was 750,000 ML/ year. Uncontrolled flow and thousands of kilometres of open excavated drains led to huge water wastage (95 percent lost through evaporation and seepage). The impact of uncontrolled artesian flow on this valuable resource was largely ignored by State and Federal governments.



Artesian bore Balcaldin, Queensland (detail) c 1907, Mobsby Coll, Fryer Lib, Brisbane Source: *www.rlms.com.au*

Due to community concern in the 1950s, government regulation was introduced that all new tubewells were to be fitted with headworks to control flows. Each State commenced programs to upgrade and control tubewells and to convert drains to piped delivery systems. However, inadequate technology to deal with hot, high pressure water along with a lack of real commitment meant that by the 1990s most artesian tubewells continued to flow into open drains.

Such uncontrolled flow of water threatened the basin pressure which supported important groundwater dependent ecosystems and the continued access to low salinity water by pastoralists and inland towns. The use of open drains encouraged feral animals and weeds and contributed to other land management problems such as salinisation and erosion.



By 1999 initiatives by government and landholders were commissioned to address the uncontrolled flow of water. These programs resulted in more than 650 tubewells being controlled and 3,500 km of drains eliminated. This saved about 126,000 ML/year of water and lead to partial pressure recovery.

The Great Artesian Basin Strategic Management Plan (2000) resulted in the development of the GABSI. Over a 15-year period, the State and Australian Governments and landholders agreed to work cooperatively and to invest significant public and private funds to repair uncontrolled artesian GAB tubewells and replace the open drains with piped water reticulation systems.

Successful implementation has resulted in some remarkable outcomes – mass replacement of artesian holes, returning water back to the environment and significant recovery of artesian pressure.

Artesian bore Balcaldin, Queensland (detail) c 1907, Mobsby Coll, Fryer Lib, Brisbane. Source: *www.rlms.com.au*

Community and Government Investment:
Phase 1 (1999-2004) Australian Government A$32 million, matched by State governments and landholder contribution.

Phase 2 (2004-2009) Australian Government A$43 million, matched by the States and with landholder contribution.

Phase 3 (2009-2014) the Federal Government committed A$85 million.

Today the GAB is managed by the GAB Co-ordination Committee which overviews project-related activities between various government and community organisation. The recovery of artesian pressure protects a range of values associated with the Basin, including the ecological values of springs, long-term aquifer sustainability with social and economic benefits and the Basin's indigenous cultural values.

https://www.dnrm.qld.gov.au/.../catchments/great-artesian-basin/gabsi;
https://www.gabcc.gov.au/publications/gabsi-fact-sheet;
https://www.dnrm.qld.gov.au/__data/assets/pdf_file/0018/106029/5

17.5 Climate Change

'Climate Change' is the modification in the statistical distribution of weather patterns over an extended period. This activity may be caused by human activities, solar radiation and volcanic eruptions. The currently observed Earth warming trends is referred to as 'Global Warming'. For developing countries Climate Change will have an impact on already vulnerable populations. Higher temperatures will increase evaporation and therefore reduce surface water availability for agriculture, humans and ecosystems. Myanmar has a Draft National Climate Change Policy[140].

Due to its large storage capacity groundwater may be more capable to buffer the impact of climate variability than surface water. However, groundwater is not exempt from the effects of drought and floods. The impact of Climate Change on groundwater needs to be considered in any water management plan.

[140] Myanmar Climate Change Alliance (2017)

In the Dry Zone groundwater resources and their replenishment are controlled by long-term climate conditions. Climate Change will have impacts on enduring aquifer behaviour. Groundwater must be used and managed in a sustainable way to maintain its supply capability and quality.

Current predictions on Climate Change are given to support decision makers in setting basin-wide water management priorities. Climate Change models for Central Myanmar have been reported[141]. **Figure 64** shows a typical example of a computer predicted output for rainfall during the Wet Season from years 2016 to 2050. The ICEM models indicate:

- Rainfall:
  - Wet Season – a precipitation increase of nine to 10 percent over most of the Dry Zone, with 11 to 12 percent in the Lower Chindwin River Valley and the Pale Sub-basin; and
  - Dry Season – a 16 to 20 percent increase in rainfall south of Nyaung Oo and 21 to 30 percent in the northern part of the Dry Zone; and
- Temperature:
  - Wet Season – warming by 1.3 to 1.4° C; and
  - Dry Season – increase by 1.5 to 1.6° C.

The Climate Change prediction is for a gradual rise in rainfall and temperatures throughout the Dry Zone. It should be noted that these types of long-term predictive models have a high level of uncertainty.

Derivation of ICEM Climate Change Models

The Climate Change data was calculated based on the average of 4 models (IPCC 5th assessment)[142] in Representative Concentration Pathways (RCP) 4.5:

1. CC model (CCSM4)- developed by National Center for Atmospheric Research – United States of America
2. CN model (CNRM-CM5) – developed by Centre National de Recherches Meteorologiques / Centre European de Recherche et Formation Avancees en Calcul Scientifique – France
3. MI model (MIROC-ESM-CHEM)- Developed by Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies – Japan
4. MP model (MPI-ESM-LR) – developed by Max Planck Institute for Meteorology (MPI-M)- Germany.

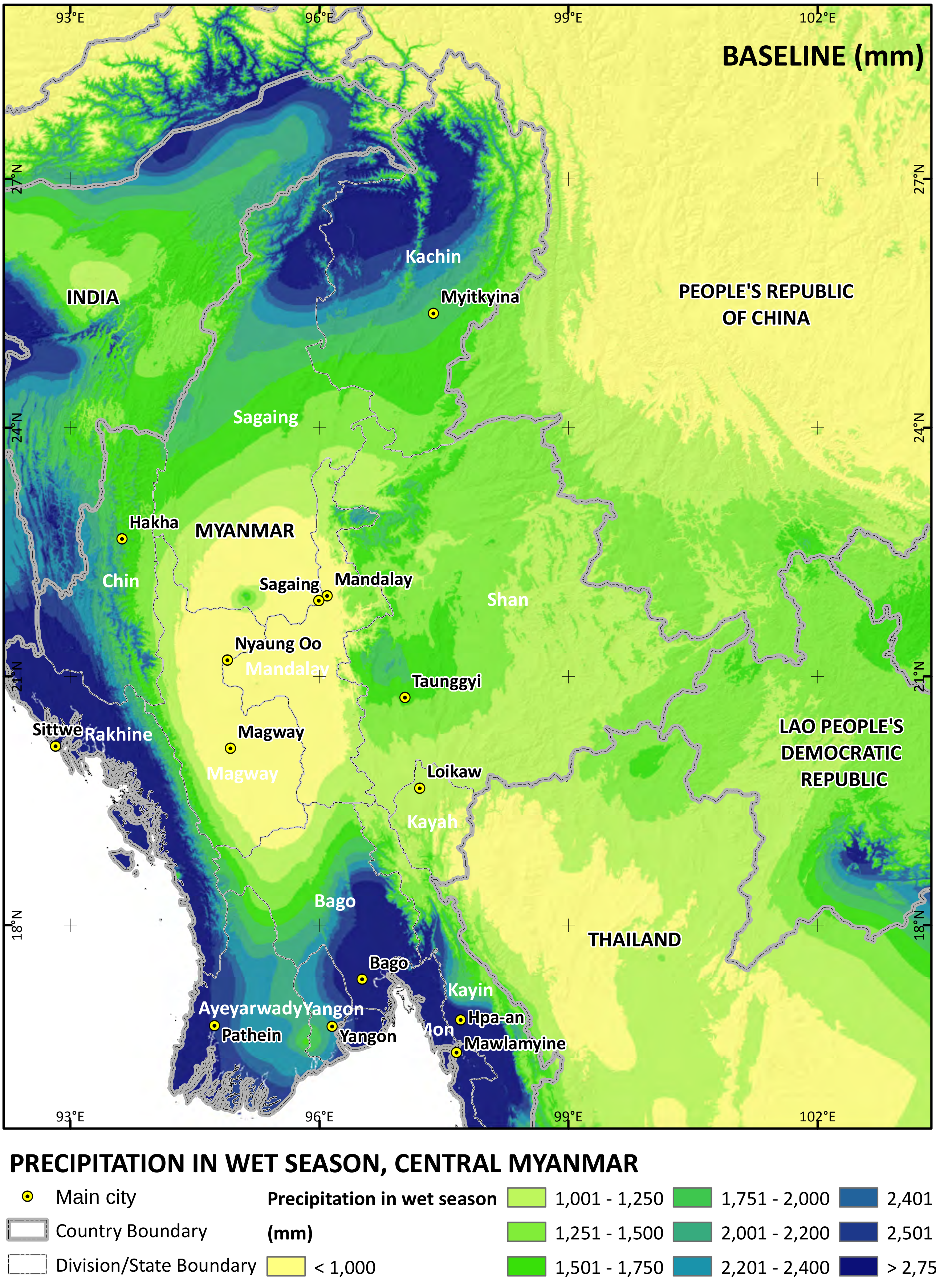
WorldClime is a set of global climate and Climate Change projection layers in gridded format with spatial resolution of one kilometre^2. The data was downscaled and calibrated (bias corrected) using WorldClim1.4

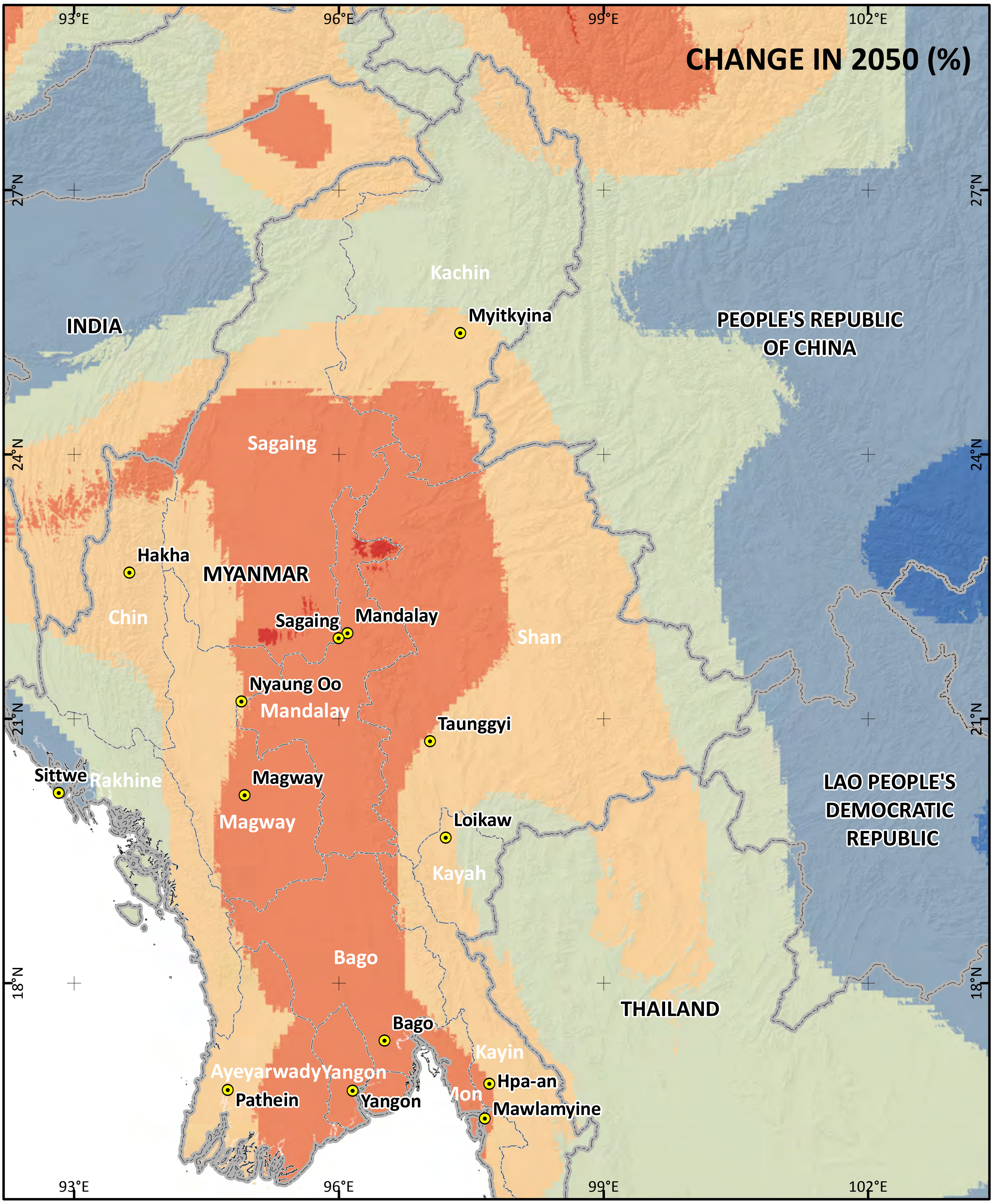
Data source: WorldClime[143] and ICEM (2017b)

Long-term predictions to temperature and rainfall patterns need to be considered in any Dry Zone groundwater management plan.

[141] ICEM (2017b)
[142] http://cmip-pcmdi.llnl.gov/cmip5/availability.html
[143] worldclim http://www.worldclim.org

Figure 64 Climate Change for Rainfall to Year 2050





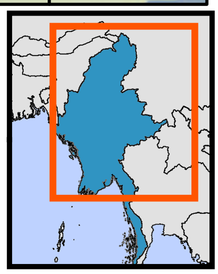
- 2,500
- 2,750
0

Change in precipitation (%)

-4 - 0	5 - 6
1 - 4	7 - 8
	9 - 10
	11 - 12

Kilometers
0 40 80 160

Data source:
Worldclim: AR5 - Wet season (May - Oct);
Boundaries are not necessarily authoritative;
ICEM GIS Database.



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APPENDIX I
Glossary of Groundwater Terms

This glossary of groundwater terms has been compiled to assist in the use of this publication. Some of the definitions given are not scientifically rigorous, but should not cause misunderstanding in common groundwater situations.

Groundwater terminology in Myanmar generally follows the traditional British nomenclature. Loman et. al. (1972) gives a terminology widely used in the USA (which is probably nearer to common international usage). In this publication, the Burmese and British usage of words such as 'artesian', 'sub-artesian', 'tubewell' and 'dugwell' have been retained.

AERATION- The process of bringing air into intimate contact with water, usually by bubbling air through the water to remove dissolved gases like carbon dioxide and hydrogen sulphide or to oxidise dissolved materials like iron compounds.

AEROBIC- The biological state of living and growing in the presence of oxygen.

AIRLIFT TEST- Removal of groundwater from an aquifer by forcing air under pressure beneath the potentiometric surface during construction or after completion of a tubewell.

ALKALINITY- Any of various soluble mineral salts found in natural water and arid soils having a pH greater than 7. In water analysis, it represents the carbonates, bicarbonates, hydroxides, and occasionally the borates, silicates, and phosphates in the water.

ALLUVIAL- Pertaining to or composed of alluvium or deposited by a stream of running water.

ALLUVIUM – Term for detrital deposits made by streams on river beds, floor plains, and alluvial fans.

ANION- A negatively charged ion that migrates to an anode, as in electrolysis.

ANION EXCHANGE- Ion exchange process in which anions in solution are exchanged for other anions from an ion exchanger.

ANTICLINE- A fold, generally convex upward, whose core contains stratigraphically older rocks.

AQUIFER- An aquifer is a body of saturated rock or soil containing a system of interconnected voids sufficient to yield significant quantities of water to tubewells, dugwells or springs.

AQUIFUGE – see "CONFINING BED"

AQUITARD- A saturated, but poorly permeable bed, formation, or group of formations that does not yield water freely to a tubewell or spring. An aquitard may transmit appreciable quantities of water to and from an aquifer when an artificial stress, such as pumping, is applied to a system.

ARENACEOUS- Composed primarily of granular material, e.g. sandstone, gravel, conglomerate.

ARGILLACEOUS- Composed predominantly of clays e.g. shale, claystone, limonite.

ARTESIAN- The term is usually applied for groundwater whose static head is above the land surface. An artesian tubewell is one from which water flows naturally at the surface. In the USA, artesian is regarded as synonymous with confined, so that an artesian tubewell is one drawing water from a confined groundwater body. The term artesian basin is used for the whole of a groundwater basin in any part of which artesian water is known to be present.

ARTIFICIAL RECHARGE - Recharge at a rate greater than natural, resulting from deliberate actions of man.

AUREOLE- A zone surrounding an igneous intrusion in which contact metamorphism of the country rock has taken place.

BASALT- Dark coloured igneous rock, commonly extrusive, composed primarily of calcic plagioclase and pyroxene.

BASE FLOW- That part of stream discharge that is not attributable to direct runoff from precipitation and is generally derived from groundwater storage.

BEDDING PLANE- Surface in a rock mass that distinguishes different sedimentation phases during formation and is parallel to the surface of deposition.

BEDROCK- A general term for the rock, usually solid, that underlies soil or other unconsolidated material.

BENTONITE- A colloidal clay, largely made up of the mineral sodium montmorillonite, a hydrated aluminium silicate.

BIOCHEMICAL OXYGEN DEMAND (BOD)- An empirical measurement in which standardised laboratory procedures are used to determine the relative oxygen requirement of a microbial population degrading organic material in a water sample. BOD test results provide an indication of organic contamination.

CAPACITY- The capacity of a tubewell is the maximum rate at which water has been, or could be, withdrawn from the hole. The capacity of a tubewell commonly decreases as the period of continuous pumping increases.

CAPILLARY FRINGE - The zone at the bottom of the vadose zone where groundwater is drawn upward by capillary force.

CARBONATE ROCK- A rock consisting chiefly of carbonate minerals, such as limestone and dolomite.

CATION- An ion having a positive charge and, in electrolytes, characteristically moving toward a negative electrode.

CATION EXCHANGE- Ion exchange process in which cations in solution are exchanged for other cations from an ion exchanger.

CLASTIC- Pertaining to a rock or sediment composed principally of broken fragments that are derived from pre-existing rocks or minerals and that have been transported some distance from their places of origin.

CLAY- A detrital mineral particle of any composition having a diameter less than 0.004 mm.

COLLUVIAL- Unconsolidated material at the bottom of a cliff or slope. It lacks stratification and is usually unsorted.

CONE OF DEPRESSION- The cone of depression measures the extent and amount of lowering of the potentiometric surface by the withdrawal of water from a tubewell or group of holes. It varies in size and shape with the rate and duration of withdrawal and the nature of the aquifer.

CONFINED GROUNDWATER- Confined groundwater is held in an aquifer at a pressure greater than atmospheric by the presence of an overlying confining bed. This bed has a distinctly lower hydraulic conductivity than the aquifer.

CONFINING BED - A confining bed is a body of less permeable material overlying or underlying an aquifer. This term is now preferred to the terms 'AQUICLUDE', 'AQUIFUGE' and 'AQUITARD'.

CONGLOMERATE- A sedimentary rock consisting of rounded or sub rounded fragments of detrital material set in a fine-grained matrix.

CONTAMINATION- The degradation of natural water quality because of man's activities. There is no implication of any specific limits, since the degree of permissible contamination depends upon the intended end use, or uses, of the water.

DARCY'S LAW- A derived equation for the flow of fluids on the assumption that the flow is laminar and that inertia can be neglected.

DEPRESSURISATION- Causing appreciable drop in pressure in an aquitard by an artificial means of groundwater removal.

DEVONIAN- A time interval in the Palaeozoic era about 410 to 360 million years ago.

DEWATERING- Part removal of water from an aquifer system more than natural recharge so that the potentiometric surface declines appreciably in the area of extraction.

DIAGENESIS- Process involving physical and chemical changes in a sediment after deposition that converts it to consolidated rock; includes compaction, cementation, recrystallization, and perhaps replacement as in the development of dolomite.

DIORITE- A dark coloured, coarse grained plutonic rock.

DISPERSION- The spreading and mixing of chemical constituents in groundwater caused by diffusion and mixing due to microscopic variations in velocities within and between pores.

DISSOLVED OXYGEN- The amount of oxygen dissolved in water or sewage, expressed in parts per million (ppm) by weight, or milligrams per litre (mg/l).

DOME- An uplift or anticlinal structure, circular or elliptical in outline in which the rocks dip gently away in all directions.

DRAINAGE- A natural or artificial gravity method of groundwater removal from an aquifer system.

DRAWDOWN- The drawdown at a point in an aquifer is the lowering of potential due to the withdrawal of water from an adjacent tubewell or dugwell.

DUGWELL – large diameter hole which is dug manually or with excavating equipment to withdraw or recharge groundwater.

ELECTRICAL (ELECTROLYTIC) CONDUCTANCE- A measure of the ease with which a current can be caused to flow through a material under the influence of an applied electric field. It is the reciprocal of resistivity and is measured in micro Siemens per cm or mill siemens per metre.

ELECTRICAL RESISTIVITY- The property of a material which resists the flow of electrical current measured per unit length through a unit cross sectional area. Normal units are ohm-metres.

EQUIPOTENTIAL CONTOURS- Lines of equal hydraulic head in an aquifer expressed as isometric contours on a map. Groundwater flow is at right angles to equipotential contour lines.

EROSION- The general process or group of processes whereby the materials of the Earth's crust are moved from one place to another by running water (including rainfall), waves and currents, glacier ice, or wind.

EVAPOTRANSPIRATION - Loss of water from a land area through transpiration of plants and evaporation from the soil.

FALLING HEAD TEST- A method to assess the permeability of an aquifer by measuring the decline rate of an artificially induced water level in an observation piezometer.

FAULT- A fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.

FERROMAGNESIUM- Containing iron and magnesium; applied to mafic minerals, esp. amphibole, pyroxene, biotite, and olivine.

FLOCCULATION- The agglomeration of finely divided suspended solids into larger, usually gelatinous, particles; the development of a "floc" after treatment with a coagulant by gentle stirring or mixing.

FLOW LINES- Lines indicating the direction followed by groundwater towards points of discharge. Flow lines are perpendicular to equipotential lines.

FRACTURES- Any breakage of a rock mass along a direction or directions not associated with cleavage or fissility.

GAMMA- High energy, short wavelength electromagnetic radiation emitted by a nucleus. It is very penetrating and can pass right through the human body.

GEOTECHNICAL- A term currently employed to cover the fields of soil mechanics, rock mechanics and engineering geology.

GRAVEL- An unconsolidated natural accumulation of rounded rock fragments of a diameter greater than 2 mm.

GROUNDWATER- Groundwater is the water in the subsurface zone; it comprises both unsaturated (vadose) zone groundwater and saturated (phreatic) zone groundwater.

GROUNDWATER BASIN – an aquifer or a group of aquifers that have large geological and hydraulic boundaries.

GROUNDWATER MODELLING - Use of mathematical functions to predict the water flow below the ground surface.

GROUNDWATER TABLE- The surface between the zone of saturation and the zone of aeration; the surface of an unconfined aquifer.

HARDNESS- A property of water causing formation of an insoluble residue when the water is used with soap. It is primarily caused by calcium and magnesium ions.

HEAD- The static head is the height above a standard reference datum of the surface of a column of water that can be supported by static pressure against the pressure of the atmosphere. The static head is the elevation of the water table above the datum. Within the zone of saturation, the static head is the sum of the elevation of the measurement point above datum and the pressure of the water at that point relative to atmospheric pressure.

HEAD LOSS- That part of head energy which is lost because of friction as water flows.

HEAVY METALS- Generally refers to the transition metals, particularly those in common industrial use such as cadmium, copper, chromium, mercury, lead, tin, and zinc. Also, frequently to the metalloids arsenic and selenium.

HEAVY MINERALS- The accessory detrital minerals of a sedimentary rock, of high specific gravity, which are separated in the laboratory from minerals of lesser specific gravity by means of liquids of high density, such as bromoform. Examples include zircon, rutile, ilmenite, monazite and tourmaline.

HETEROGENEOUS- Nonuniform in structure or composition throughout.

HOLOCENE- Recent; that period of time (an epoch) since the last ice age (120,000 years B.P) also the series of strata deposited during that epoch.

HOMOGENEOUS- Uniform in structure or composition throughout.

HYDRAULIC CHARACTERISTICS - Factors relating to the movement of water through aquifers, such as transmissivity, hydraulic conductivity (permeability) and the storage coefficient.

HYDRAULIC CONDUCTIVITY - Hydraulic conductivity is a measure of the ease with which water, in the conditions prevailing in the aquifer, can flow through rock or soil. It is measured as the flow per unit cross sectional area under unit hydraulic gradient. It depends on the intrinsic permeability of the material, the degree of saturation and on the density and viscosity of the fluid.

HYDRAULIC DIVIDE- The highest equipotential contour. Flow will proceed at right angles to the direction of the divide on both sides of the divide.

HYDRAULIC GRADIENT- The hydraulic gradient is the change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

HYDROGEOLOGIC- Those factors that deal with subsurface waters and related geologic aspects of surface waters.

HYDROGEOLOGY- The science that deals with subsurface waters and related geological aspects.

INDURATED - Rendered hard; confined in geological use to masses hardened by heat, baked, etc., as distinguished from hard or compact in natural structure. In modern usage, the term is applied to rocks hardened not only be heat, but also by pressure and cementation.

INFILTRATION- Infiltration is the movement of water through the ground surface into small voids in either the saturated or unsaturated zone.

INLIER- An area or group of rocks surrounded by rocks of younger age.

INSITU- Latin for at the site. Contrast to tasks which are performed in a different location (i.e. laboratory).

INTERFERENCE - The condition occurring when the area of influence of a tubewell comes into contact with that of a neighbouring well, as when two wells are pumping from the same aquifer or are located near each other.

INTERMITTENT (EPHEMERAL) STREAM / LAKE- A channel in which water sometimes flows or a lake sometimes containing water.

ION- An element or compound that has gained or lost an electron, so that it is no longer neutral electrically but carries a charge.

ISOTROPIC- Descriptive term for a medium whose properties are the same in all directions.

JOINTS- A fracture (see FRACTURE) in rock between the sides of which there is no observable relative movement.

LACCOLITH- A concordant igneous intrusion that has domed the overlying rocks and has a known or assumed flat floor and a postulated dike like feeder beneath its thickest point. It is roughly circular in plan, less than eight kilometres in diameter, and from a few metres to several hundred metres in thickness.

LAMINAR FLOW- Water flow in which the stream lines remain distinct and in which the flow direction at every point remains unchanged with time. It is characteristic of the movement of groundwater.

LAMINITE - A rock composed of thin, discrete layers, which may be of different lithology, or similar lithology but separated by a physical discontinuity.

LAVA- Molten rock that issues from openings in the earth's surface.

LIMESTONE- A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

LITHOLOGY- The description of rocks based on colour, mineralogic composition and grain size.

METAMORPHIC ROCKS/METAMORPHOSED- Any rock derived from preexisting rocks by mineralogical, chemical, and/or structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment, generally at depth in the Earth's crust.

MICA - A group of monoclinic minerals, frequently found in metamorphic and igneous rocks and weathered derivatives.

MICRODIORITE - A fine grained diorite.

MICROSYENITE- Plutonic rock usually containing orthoclase, microcline, or Perthite, a small amount of plagioclase, one or more mafic minerals (esp. hornblende), and a little or no quartz.

MIOCENE- An epoch of the early Tertiary period, after the Oligocene and before the Pliocene.

MONITORING- Systematic testing of the environment to record changes over time caused by impacts such as landfills.

MUDSTONE- Mudstone includes clay, silt, siltstone, claystone, shale, and argillite. It should only be used when there is doubt as to precise identification or when a deposit consists of an indefinite mixture of clay, silt, and sand particles, the proportions varying from place to place, so that a more precise term is not possible.

NORMAL FAULT - A fault in which the hanging wall appears to have moved downwards relative to the footwall. The angle of dip is usually 45°90°.

NUTRIENTS- Chemicals (nitrogen and phosphorus) essential to the growth of photosynthetic autotrophs (green plants). Excessive nutrients can cause accelerated growth which would deplete available oxygen.

OBSERVATION PIEZOMETER- A tubewell drilled in a selected location for observing parameters such as water levels and pressure changes. May also be used for groundwater sampling purposes.

OLIGOCENE- An epoch of the early Tertiary period, after the Eocene and before the Miocene.

ORDOVICIAN- The second earliest period of the Palaeozoic era.

ORTHOQUARTZITE - A clastic sedimentary rock composed of silica cemented quartz sand. The cement is commonly deposited in crystallographic continuity with the quartz of the worn grains.

OXIDATION - The combining of an element with oxygen.

PACKER TESTING- Injection testing to measure hydraulic conductivity of rock mass.

PALAEOCHANNEL- An ancient river channel infilled with alluvial material.

PERCHED GROUNDWATER- Perched groundwater is separated from the main underlying body of groundwater by an unsaturated zone. Where it is unconfined, it has a perched water table. Perched groundwater is held up by a confining bed whose hydraulic conductivity is so low that water percolating downwards through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure. Perched groundwater is a common, though not a necessary, feature of recharge areas.

PERMEABILITY- The permeability of a rock or soil is a measure of the ease with which fluids can flow through it. In physical terms, it is independent of the properties of the fluid but it is sometimes used as a synonym of hydraulic conductivity.

pH- A measure of the acidity or alkalinity of a solution, numerically the negative logarithm of the hydrogen ion activity and equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with acidity. Originally stood for the words potential of hydrogen.

PIEZOMETER- See observation piezometer.

PIEZOMETRIC SURFACE see Potentiometric Surface

PLEISTOCENE- The earlier of the two epochs comprising the Quaternary Period. Also, the PostPliocene glacial age, (120,000 to 32,000 years BC) which in the above terminology implies the glacial age is over. Also, the series of sediments deposited during this epoch.

PNEUMATIC PIEZOMETER- An observation point made of a ceramic pot emplaced in the ground and isolated from the surrounding environment through which a gas is passed to measure the change in pressure of the material being measured. It is usually used to measure depressurisation of aquitards during groundwater extraction by pumping from an associated aquifer.

POROSITY- The porosity of a rock or soil is its property of containing voids (spaces in the material not occupied by solid matter) and may be expressed quantitatively as the ratio of the volume of the voids to its total volume. With respect to the movement of water only the effective porosity, that due to interconnected voids, is significant. Many confining beds are distinguished from aquifers by their low effective porosity and/or extremely fine pore size, thus high specific retention rather than by differences in total porosity.

POTABLE- Water of suitable quality for human consumption.

POTENTIAL- The potential of groundwater is the mechanical energy per unit mass of the groundwater at a given point in space and time with respect to an arbitrary state and datum. The groundwater potential is proportional to the head.

POTENTIOMETRIC SURFACE- A potentiometric surface is an imaginary surface defined by the potentials at all points on a given plane in an aquifer. Where the hydraulic gradient perpendicular to the aquifer is much less than the hydraulic gradient along the aquifer it is reasonable to apply the concept of potentiometric surface to the aquifer as a whole. Potentiometric surface is a synonym of piezometric surface.

PRECIPITATION- Rainfall, sleet, snow etc. that reaches the earth surface.

PRODUCTION TUBEWELL- A small diameter hole from which groundwater is extracted. It usually relates to a cased and screened, adequately developed and efficient tubewell used for groundwater removal.

PUMPING TEST - A test that is conducted to determine aquifer or tubewell characteristics.

QUARTZITE- A sedimentary (or metamorphic) rock that contains crystals or grains of silicon dioxide (silica) set in a microcrystalline or amorphous silica matrix.

RADIUS OF INFLUENCE - The radial distance from the centre of a tubewell to the point where there is no lowering of the water table or potentiometric surface (the edge of its cone of depression).

RECENT- See Holocene

RECHARGE- Recharge of groundwater is the addition of water to an aquifer, either directly from the surface, from the unsaturated zone, or discharge from overlying or underlying aquifer systems.

RESIDUAL DRAWDOWN- The difference between the original static water level and the depth to water at a given instant during the recovery period.

RUNOFF - That part of precipitation flowing to surface streams.

SAFE YIELD- The aim of many investigations of groundwater resources is to estimate, quantitatively, the water available for the intended use. This estimate is often expressed as the “safe yield” or “sustained yield” of a groundwater basin. It may be defined as the maximum rate at which water can be artificially withdrawn from a groundwater basin without causing depletion or deterioration of the resources to the extent that withdrawal at that rate is no longer economically feasible. But it must be stressed that safe yield, is not a fixed figure but must vary as hydraulic, economic and technical factors change with time.

SALINITY- The total content of dissolved solids in groundwater, commonly expressed as parts of dissolved solids per million parts of solution, or milligrams of dissolved solids per litre of solution (mg/l). The significance of salinity depends on the nature as well as the amount of the dissolved solids. See also SPECIFIC CONDUCTANCE.

SALT WATER ENCROACHMENT/INTRUSION- The phenomenon occurring when a body of salt water, because of its greater density, invades a body of fresh water. It can occur either in surface or groundwater bodies. The balance between the fresh and salt water, and static situations, is expressed by GhybenHerzberg formula.

SANDSTONE- A sedimentary rock composed of abundant rounded or angular fragments of sand set in a fine-grained matrix (silt or clay) and firmly united by a cementing material.

SCREEN - A filtering device used to keep sediment from entering a water well.

SEDIMENTARY ROCKS- Rocks resulting from the consolidation of loose sediment that has accumulated in layers.

SEEPAGE- Subsurface movement of water, or emergence of subsurface flow at the ground surface.

SEMICONFINED AQUIFER- A semiconfined aquifer is one where the confining bed has sufficient permeability to allow some vertical water movement through the less permeable layer to the aquifer, thus contributing water to the aquifer system for withdrawal.

SEMIUNCONFINED AQUIFER- If the hydraulic conductivity of the sediment above the water table is so great that the vertical flow component from the vadose zone cannot be ignored, the underlying aquifer is called a semiunconfined aquifer. In general, such aquifers do not release their water instantaneously from storage and exhibit what is called delayed drainage.

SHALE- A fine grained sedimentary rock, formed by the consolidation of clay, silt or mud. It is characterised by a finely laminated structure and is sufficiently indurated so that it will not fall apart on wetting.

SHEAR ZONE- A tabular zone of rock that has been crushed and brecciated by many parallel fractures due to shear strain.

SILT- A detrital particle finer than fine sand and coarser than clay.

SILTSTONE - An indurated silt having the texture and composition of shale but lacking its fine lamination or fissility.

SILURIAN - A division of the Palaeozoic era extending from 40 to 410 million years ago

SPEARPOINT- A screening device, equipped with a point on one end, that is driven or jetted into the ground.

SPECIFIC CAPACITY- The rate of discharge of a water well per unit of drawdown, commonly expressed in gpm/ft or m^3/day/m. It varies with duration of discharge.

SPECIFIC CONDUCTANCE- A determination of total dissolved solids (TDS) can be made by measuring the electrical conductance of a groundwater sample. Specific conductance is preferred rather than its reciprocal resistance, because it increases with salt content. Specific conductance defines the conductance of a cubic centimetre of water of a standard temperature of 25° C, measure in micro Siemens/cm (µS.cm^{-1}). Specific conductance may also be expressed as decimetres/metre (dS.m-1). An increase of 1° C increases the specific conductance by about two percent.

SPECIFIC STORAGE - The amount of water that a portion of an aquifer releases from storage, per unit mass or volume of aquifer, per unit change in hydraulic head, while remaining fully saturated.

SPECIFIC YIELD- The specific yield of a rock is the volume of water yielded by gravity drainage per unit volume of previously saturated material. Definition assumes gravity drainage complete. In practice the time available for drainage is limited so calculated specific yield is significantly less than the theoretical values.

STABILISATION- Treatment technology whereby leachable contaminants are chemically altered to reduce mobilisation. See "Chemical Fixation and Solidification" which is synonymous.

STATIC WATER LEVEL- The static water level of groundwater is the water level that can be measured in a tubewell screened in an unconfined aquifer which is not being pumped. It is a measure of the head of the groundwater at the time of measurement at the depth at which the tubewell is open to the aquifer.

STORAGE COEFFICIENT - The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In a confined water body, the water derived from storage with decline in head comes from expansion of the water and compression of the aquifer. In an unconfined water body, the amount of water derived comes from gravity drainage.

STORATIVITY- see Storage Coefficient.

SUBSIDENCE- To settle down lower in the ground. The ground surface subsides over a sanitary landfill at predictable rates. The subsidence occurs in response to the degradation of the fill material.

SYNCLINE- A generally U shaped fold or structure in stratified rock, containing stratigraphically younger rocks toward the centre of curvature, unless it has been overturned.

TERTIARY- The first period of the Cainozoic era (after the Cretaceous of the Mesozoic era and before the Quaternary), thought to have covered the span of time between 65 million and 2 million years ago.

TOTAL DISSOLVED SOLIDS, TDS- Quantity of dissolved material in a sample of water, either the residue or evaporation, dried at 356oF. (180oC).

TRACE METALS- Metals present in minor amount in the earth's crust. All elements except the eight-abundant rockforming elements, (oxygen (O), silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg).

TRANSMISSIVITY- Transmissivity is the rate at which the water in an aquifer is transmitted through a unit width of aquifer under a unit hydraulic gradient. It embodies the permeability and saturated thickness of the aquifer, and the properties of the water in it. It is equal to the summation of the hydraulic conductivities across a unit width of the saturated part of the aquifer perpendicular to the flow paths.

TRANSPIRATION- The process by which water absorbed by plants, usually through the roots, is evaporated into the atmosphere from the plant surface.

TRITIUM- A radioactive isotope of hydrogen with two neutrons and one proton.

TUBEWELL- a hole which is drilled, jetted or augured to withdraw groundwater.

UNCONFINED GROUNDWATER- The upper surface of unconfined groundwater is formed either by a body of surface water or by a water table.

VADOSE ZONE - The zone containing water under pressure less than that of the atmosphere, including soil water, intermediate vadose water, and capillary water. This zone is limited above by the land surface and below by the surface of the zone of saturation, that is, the water table.

VEINS- An epigenetic mineral filling of a fault or other fracture, in tabular or sheet like form, often with associated replacement of the host rock.

WATER TABLE- The water table is that surface in an unconfined water body at which the pressure is atmospheric in tubewells which penetrate just far enough to hold standing water. When encountered in tubewells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of groundwater flow exists.

YIELD- Yield of a tubewell can refer either to the capacity of the hole or to the amount of water withdrawn.

APPENDIX II
Imperial to Metric Conversions

FLOW RATES		
gpm (US)	0.833	Imperial gpm
gpm (US)	1,440	gpd (US)
gpm (US)	0.0023	ft^3 / sec
gpm (US)	0.0630915	litres / sec
gpm (US)	5.45	m^3 / day
gpd (US)	4.38×10^{-5}	litres / sec
gpd (US)	0.00379	m^3 / day
gph	0.0011	litres/sec
ft^3 / day	6.233	Imperial gpd
ft^3 / day	0.00519	gpm (US)
ft^3 / day	1.16×10^{-5}	ft^3 / sec
ft^3 / day	3.28×10^{-4}	litres / sec
ft^3 / day	0.02832	m^3 / day
ft^3 / sec	28.32	litres / sec
ft^3 / sec	2,447	m^3 / day
litres/sec	19,020	Imperial gpd
litres/sec	15.85	gpm (US)
litres/sec	0.0353	ft^3 / sec
litres/sec	86.4	m^3 / day
m^3 / day	220.14	Imperial gpd
m^3 / day	0.1835	gpm (US)
m^3 / day	4.088×10^{-4}	ft^3 / sec
m^3 / day	0.011574	litres / sec
m^3 / day	6.94×10^{-4}	m^3 / min
m^3 / day	1.1574×10^{-5}	m^3 / sec
m^3 / sec	19.02×10^{6}	Imperial gpd
AREA		
cm^2	0.0001	m^2
cm^2	1×10^{-8}	Hectares
m^2	1×10^{4}	cm^2
m^2	1×10^{-6}	km^2
m^2	1×10^{-4}	hectares
km^2	1 x 106	m^2
km^2	100	hectares
hectares	1 x 108	cm^2
hectares	1 x 104	m^2
hectares	0.01	km^2
hectares	2.471	acres
ft^2	0.0929	m^2
ft^2	9.29×10^{-8}	km^2
ft^2	9.29×10^{-6}	hectares
mi^2	2.59	km^2
acre	0.4047	hectares

HYDRAULIC CONDUCTIVITY		
ft / day	7.48	gpd / ft^2
ft / day	0.305	m / day
gpd / ft^2	0.134	ft / day
gpd / ft^2	0.041	m / day
m / day	24.5	gpd / ft^2
m / day	3.28	ft / day
TRANSMISSIVITY		
gpd / ft	0.134	ft^2 / day
gpd / ft	0.0124	m^2 / day
ft^2 / day	7.48	gpd / ft
ft^2 / day	0.0929	m^2 / day
m^2 / day	10.76	ft^2 / day
m^2 / day	80.5	gpd / ft
VOLUME		
f^{t3}	28.317	litres
ft^3	0.02832	m^3
ft^3	2.832 x 10-11	km^3
ft^3	6.232	Imperial gal
ft^3	2.296×10^{-5}	acre feet
U.S. Gal	0.83311	Imperial gal
U.S. Gal	3.785	litres
U.S. Gal	3.785×10^{-3}	m^3
U.S. Gal	3.785×10^{-12}	km^3
Imperial gal	4.5424	litter
Imperial gal	4.54×10^{-3}	m^3
Imperial gal	4.54×10^{-12}	km^3
Imperial gal	1.200	U.S. gallon
Imperial gal	3.684×10^{-6}	acre feet
LENGTH		
mm	0.1	cm
cm	0.01	m
m	0.001	km
km	0.621	mi
In	2.54	cm
In	1.58×10^{-5}	mi
ft	0.3048	m
ft	3.05×10^{-4}	km
yd.	0.9144	m
yd.	9.14×10^{-4}	km
mi	1.6093	km
TEMPERATURE		
°F	0.375	°C

APPENDIX III
Water Chemistry Tables and Data

Table AII.I Natural Inorganic Constituents Commonly Dissolved in Water and Impact

Substance	Major Natural Sources	Effect on Water Use	Significant Concentration (mg/L)
Bicarbonate (HCO_3^-) and Carbonate ($CO_3$2-)	Products of the solution of carbonate rocks, mainly limestone ($CaCO_3$) and dolomite ($CaMgCO_3$), by water containing carbon dioxide	Control the capacity of water to neutralize strong acids. Bicarbonates of calcium and magnesium decompose in steam boilers and water heaters to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, cause carbonate hardness	150 – 200
Calcium (Ca_{2+}) and Magnesium (Mg^{2+})	Soil and rocks containing limestone, dolomite and gypsum (CaSO4). Small amounts from igneous and metamorphic rocks	Principal cause of hardness. Boiler scale and deposits in hot water heaters	25-50
Chloride (Cl^-)	Inland areas- primarily from sea water trapped in sediments at time of deposition. Coastal areas- from sea water in contact with fresh water	In large amounts, increases corrosiveness of water and, in combination with sodium, gives water a salty taste	250
Fluoride (F^-)	Both sedimentary and igneous rocks. Not widespread in occurrence	In certain concentrations, reduces tooth decay; at higher concentrations, causes mottling of tooth enamel	0.7 – 1.2
Iron (Fe^{2+}) and Manganese (Mn)	Iron present in most soils and rocks; manganese less widely distributed	Stain laundry and are objectionable in food processing, dyeing, bleaching, ice manufacturing, brewing and certain other industrial processes	Fe^{2+} 0.3 Mn 0.05
Sodium (Na^+)	Same as for Chloride. In some sedimentary rocks, a few hundred milligrams per litre may occur in fresh water because of exchange of dissolved calcium and magnesium for sodium in the aquifer materials.	See Chloride. In large concentrations, may affect persons with cardiac difficulties, hypertension and certain other medical conditions. Depending on the concentration of calcium and magnesium also present in the water, sodium may be detrimental to certain irrigated crops	70 (irrigation) 20 – 170 (health)
Sulphate (SO_4^{2}-)	Gypsum, pyrite (FeS) and other rocks containing sulphide (S) compounds	In certain concentrations, gives water a bitter taste, and at higher concentrations, has a laxative effect. In combination with calcium, forms a hard calcium sulphate scale in steam boilers	300 – 400 (taste) 600 – 1,000 (laxative)

Table AII.2 Characteristics of Water that Affect Quality

Characteristic	Principal Cause	Significance	Remarks
Hardness	Calcium and magnesium	Calcium and magnesium combine with soap to form an insoluble precipitate (curd) and thus hamper the formation of lather. Hardness also affects the suitability of water for use in the textile and paper industries and certain others, and in steam boilers and water heaters	USGS classification of hardness (mg/L as $CaCO_3$) 0– 60: Moderately hard 121– 180: Hard >180: Very hard
pH (or hydrogen ion activity)	Dissociation of water molecules and of acids and bases dissolved in water	The pH of water is a measure of its reactive characteristics. Low values of pH particularly below 4, indicate a corrosive water that will tend to dissolve metals and other substances that it contacts. High values of pH, particularly above 8.5, indicate an alkaline water that, on heating, will tend to form scale. The pH significantly affects the treatment and use of water	pH values < 7: water is acidic Value of 7: water is neutral >7: water is basic
Specific Electrical Conductance	Substances that form ions when dissolved in water	Most substances dissolved in water dissociate into ions that can conduct an electrical current. Consequently, specific electrical conductance is a valuable indicator of the amount of material dissolved in water. The larger the conductance, the more mineralised the water	Conductance values indicate the electrical conductivity, in micro Siemens cm^{-1} of water at a temperature of 25° C
Total Dissolved Solids	Mineral substances dissolved in water	Total Dissolved Solids is a measure of the total amount of minerals dissolved in water and is, therefore, a very useful parameter, in the evaluation of water quality. Water containing < 500 mg/L is preferred for domestic use and for many industrial processes	USGS classification of water based on dissolved solids (mg/L) < 1,000: Fresh 1,000–3,000: Slightly saline 3,000–10,000: Mod. saline 10,000–35,000: Very saline >35,000: Brine

Table AII.3 Examples of Chemical Analyses of Groundwater – Dry Zone (me/L)

Formation, Tubewell No. and Location	Aquifer depth below surface (m)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	Specific conductance µS cm^{-1}	Comment
ALLUVIUM EH2/19 Monywa	24-35	0.20	0.80	17.90	0.18	0.40	13.00	3.13	1.45	1,355	Irrigation, variation with depth
	35-37	0.10	1.77	13.00	0.1	0.56	12.00	2.60	1.00	1,110	
	52-58	0.60	1.48	14.40	0.11	0.12	15.00	2.60	1.00	1,074	
	67-73	0.15	0.99	12.70	0.1	0.28	9.39	0.52	3.00	1,015	
3022 Nebugan village, Salin Township	37-40	1.52	4.6	7.69	0.07	0.66	7.83	2.90	0.72	916	Village supply
Mandalay	91-101	1.60	0.64	4.16	0.04	1.47	2.52	0.96	1.97	465	City water supply
IRRAWADDY 3001 Gwebin village, Chauk Township	338-351	5.04	3.79	12.08	0.12	1.66	9.96	4.66	4.83	1.070	Deep aquifer village supply
3229 Thinbangon village, Yamethin Township	281-294	0.96	0.80	5.07	0.06	0.93	4.04	1.84	0.95	480	Deep aquifer village supply
2503 Mondaing village, Meiktila Township	63-69	1.16	0.12	6.43	0.07	-	3.08	2.48	1.12	495	Health centre, School, village supply
5214 Zibyubin village, Yinmabin Township	79-95	1.96	2.28	4.48	0.20	0.93	5.45	0.48	1.24	650	Artesian tubewell, irrigation, village supply
1535 Kyabinhla village, Ayadaw Township	168-178	1.02	1.33	6.25	0.08	0.93	3.31	1.91	2.39	1,280	Artesian tubewell, village supply
PEGU GROUP 1330 RWSD, Mektila	183-197	1.00	0.24	41.73	0.15	5.20	23.24	3.68	12.47	3,800	Industrial use
2775 Kuywa, Taungtha	49-56	12.58	11.14	73.04	0.39	6.53	20.78	9.68	41.18	12,950	Washing down children, some stock
3818 Myotha, Ngazun	98-105	29.70	41.66	55.86	0.68	6.25	27.91	42.18	51.26	17,490	Abandoned

Table AII.4 Drinking Water Standards of US Agencies and WHO (in milligrams/L)

Criterion	Recommended Desirable Limit		Max Permissible Concentration
Colour (cobalt/platinum standard	a	c	c
Odour (threshold number)	15	5	50
Residue (filterable)	3	< 2	< 3
Taste (threshold number)	500	-	-
Turbidity (units)	Inoffensive	< 2	< 3
Hardness	5	5	25
	-	300	200

Inorganic chemicals

Chemical constituents	Recommended Desirable Limit				Max Permissible Concentration			
Ammonia (NH_4)	a	b	c	d	a	b	c	d
Arsenic (As)	-	0.05	-	-	-	-	-	-
Barium (Ba)	0.01	-	-	0.01	0.05	0.05	0.05	0.05
Cadmium (Cd)	-	-	-	-	1.0	-	-	1.0
Calcium (Ca)	-	-	-	-	0.01	0.01	0.01	0.01
Chloride (Cl)	-	-	75	-	-	-	200	-
Chromium (as Cr hexavalent)	250	200	200	250	-	-	600	-
Copper (Cu)	-	-	-	-	0.05	0.05	-	0.05
Cyanide (Cn)								
Fluoride (F) *	1.00	0.05	0.05	1.0	-	-	1.5	-
Hydrogen Sulphide (H_2S)	0.01	-	-	0.01	0.2	0.05	0.05	0.2
Iron (Fe)	-	-	0.6-0.9	0.8-1.7	-	-	0.8-1.7	1.4-2.4
Lead (Pb)								
Magnesium (Mg)	-	0.05	-	-	-	-	-	-
Manganese (Mn)	0.3	0.1	0.1	0.3	1.0	-	1.0	-
Mercury (Hg)	-	-	-	-	0.05	0.1	0.1	0.05
Nitrate (as NO_3)	-	125	**	-	-	-	150	-
Oxygen dissolved	0.05	0.05	0.05	0.05	-	-	0.5	-
Selenium (Se)	-	-	-	-	-	-	0.001	0.002
Silver (Ag)	45	50	-	-	-	-	45	-
Sulphate (SO4)	-	5	-	-	-	-	-	-
Total solids	-	-	-	-	0.001	0.01	0.01	0.01
Zinc (Zn)	-	-	-	-	0.05	-	-	0.05
	250	250	200	250	-	-	400	-
	500	-	500	-	-	-	1500	-
	5	5	5	5	-	-	15	-

* Dependent on annual maximum daily air temperature. The lower the temperature, the higher the limit (e.g. 19-20˚ C, max. conc. = 2.4 mg/L; 30-34˚ C, max. conc.= 1.4.mg/L

** Not > 30 mg/L if there are 250 mg/L SO_4^{2-}; if sulphate < 250 mg/L, magnesium limit = 250 mg/L

a US Department of Health, Education & Welfare, Public Health Service (1962)

b World Health Organisation (1970), c World Health Organisation (1971), US Environmental Protection Agency (1976)

Table AII.5 Quality Classification of Water for Irrigation

Water Classification	Sodium Absorption Ratio	Sodium (%)	Specific Conductance (µS.cm^{-1} at 25°C)	Boron (mg/L)		
				Sensitive crop	Semi-tolerant crop	Tolerant crop
Excellent	< 4	< 20	< 250	< 0.33	< 0.67	< 1.0
Good	4- 10	20- 40	250- 750	0.33- 0.67	0.67- 1.33	1.0- 2.0
Permissible	10 – 18	40- 60	750- 2,000	0.67- 1.0	1.33- 2.0	2.0- 3.0
Doubtful	18- 26	60- 80	2,000- 3,000	1.0- 1.25	2.0- 2.25	3.0- 3.75
Unsuitable	> 26	> 80	> 3,000	> 1.25	> 2.5	> 3.75

Table AII.6 Relative Tolerance of Plants to Boron (listed in order of increasing tolerance)

Sensitive		Semi-tolerant		Tolerant	
Lemon	Grape	Lima bean	Barley	Carrot	Alfalfa
Grapefruit	Apple	Sweet potato	Olive	Lettuce	Mangel
Avocado	Pear	Pepper	Field pea	Cabbage	Sugar beet
Orange	Plum	Pumpkin	Radish	Turnip	Date palm
Apricot	Navy bean	Zinnia	Sweet pea	Onion	Palm
Peach	Artichoke	Oat	Tomato	Broad bean	Asparagus
Cherry	Walnut	Milo	Cotton	Gladiolus	
Persimmon	Pecan	Corn	Potato		

Table AII.7 Water Quality Requirements for Selected Industries and Processes (after US Federal Water Pollution Control Admin., 1968)

Constituent	Boiler Feedwater Pressure (kilograms per cm²)				Textile scouring, bleaching & dyeing	Chemical Pulp & Paper		Wood chemicals	Synthetic rubber	Petrol Products	Canned, Dried & Frozen Fruits & vegetables	Soft drinks bottling	Leather tanning (general finishing processes)	Hydraulic Cement Manufacture
	0-10	10-70	70-100	100-350		Un-bleached	Bleached							
Silica (SiO_2)	30	10	0.7	0.01	-	50	50	50	-	-	50	-	-	35
Manganese (Mn)	0.3	0.1	0.01	-	0.01	5	0.05	0.2	0.1	-	0.2	0.05	0.2	0.5
Aluminium (Al)	5	0.1	0.01	0.01	-	-	-	-	-	-	-	-	-	-
Calcium (Ca)	-	0	0	-	-	20	20	100	80	75	100	-	-	-
Iron (Fe)	1	0.3	0.05	0.01	0.1	1	0.1	0.3	0.1	1	0.2	0.3	0.3	25
Magnesium (Mg)	-	0	0	-	-	12	12	50	36	30	-	-	-	-
Ammonium (NH_4)	0.1	0.1	0.1	0.7	-	-	-	-	-	-	-	-	-	-
Copper (Cu)	0.5	0.05	0.05	0.01	0.01	-	-	-	-	-	-	-	-	-
Zinc (Zn)	-	0	0	-	-	-	-	-	-	-	-	-	-	-
Bicarbonate (HCO_3)	170	120	48	-	-	-	-	250	-	-	-	-	-	-
Sulphate (SO_4)	-	-	-	-	-	-	-	100	-	-	250	500	250	250
Chloride (Cl)	-	-	-	-	-	200	200	500	-	300	250	500	250	250
Fluoride (F)	-	-	-	-	-	-	-	-	-	-	1	(a)	-	-
Nitrate (NO_3)	-	-	-	-	-	-	-	5	-	-	10	-	-	-
Hardness (as $CaCO_3$)	20	0	0	0	25	100	100	900	350	350 (b)	250	-	Soft	-
pH	8-10	8.2-10	8.2-9	8.8-9.2	(c)	6-10	6-10	6.5-8	6.2-8.3	6-9	6.5-8.5	-	6-8	6.5-8.5
Alkalinity (as CO_3)	140	100	40	0	-	-	-	200	150	-	250	85	-	400
Dissolved solids (TDS)	700	500	200	0.5	100	-	-	1,000	-	1,000	500	-	-	600
Colour units	-	-	-	-	5	30	10	20	20	-	5	10	5	-
Organics CCl_4 extract	1	1	0.5	0	-	-	-	-	-	-	0.2	(d)	(e)	1
Methylene-blue active subs.	1	1	0.5	0	-	-	-	-	-	-	-	-	-	-
Chemical oxygen demand	5	5	0.5	0	-	-	-	-	-	-	-	-	-	-
Dissolved oxygen	2.5	0.007	0.007	0.007	-	-	-	-	-	-	-	-	-	-
Temperature (° C)	-	-	-	-	-	-	35	-	-	-	-	-	-	-
Suspended solids	10	5	0	0	5	10	10	30	5	10	10	-	-	500

Not to exceed US Public Health Service drinking water standards
Limit for non-carbonate hardness, 70 mg/L as $CaCO_3$
Ranges from 2.5 to 10.5, depending on process and product

Carbon chloroform extract limit 0.2 mg/L; also specified to be free from taste and odour
Carbon chloroform extract limit 0.2 mg/L

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Qualifications

- Bachelor of Science, University of New South Wales
- PhD, Hydrogeology, University of NSW
- Diploma Hydrology, University of NSW
- Certificate: Contaminated Water Treatment, USA

Key Skills and Competencies

Dr Drury has worked in government for 14 years and 35 years as an international consultant.

He has worked on major urban, village, refugee and irrigation water supplies; mining, environmental and litigation projects in 50 countries within South-east, South and Central Asia, the Pacific, Africa, Middle East, the Americas, United Kingdom and all states of Australia. Clients include private, government, bilateral agencies (AusAID), lending institutions (ADB, World Bank) and religious organisations.

Myanmar Experience

- **Groundwater and Data Management Baseline Assessment, State of Basin Assessment for the Ayeyarwady Integrated River Basin (AIRBM), Myanmar.** *Client: Myanmar Government and World Bank*
- **Hydrogeology of the Dry Zone, Central Myanmar.** *Client: Australian Water Partnership / AusAID*
- **North-west Village Water Supply, Sanitation, HIV/AIDS Project, Myanmar.** *Client: The Salvation Army, Singapore*
- **Burma Village Water Supply Project, Central Myanmar.** *Client: AusAID*
- **Mandalay City Water Supply and Sanitation Project, Central Myanmar.** *Client: Asian Development Bank*
- **Groundwater Irrigation 1 Project, Myanmar.** *Client: World Bank*
- **Mandalay City Water Supply, Central Myanmar.** *Client: Asia Development Bank*
- **Taung Zin Piped Water Supply Project, Central Myanmar.** *Client: AusAID*
- **Water Supplies for Petroleum Industry, Myanmar.** *Client: Various International Oil/Gas Companies*

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She has proof read and edited major technical project reports in Myanmar, Bangladesh, Pakistan, Saudi Arabia, Kenya and South Sudan.

PLATE 1

Regional Geological Map Areas of Dry Zone

PLATE 2

Key to Regional Geological and Hydrogeological Maps, Central Dry Zone, Myanmar

PLATE 3

Regional Hydrogeological and Hydrochemical Map of Dry Zone

Australia

water partners for development

The Australian Water Partnership is an Australian Government aid initiative bringing together public and private organisations from the Australian water sector with international development partners.

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