SOBA 2A: GROUNDWATER RESOURCES

AYEYARWADY STATE OF THE BASIN ASSESSMENT (SOBA)

Status: FINAL
Last updated: December 2017

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Disclaimer
"The Ayeyarwady State of the Basin Assessment (SOBA) study is conducted within the political boundary of Myanmar, where more than 93% of the Basin is situated."

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ACKNOWLEDGEMENTS

Report citation:

Viossanges, M. Johnston, R, Drury, L. 2017. *Groundwater Resources of the Ayeyarwady Basin*. Ayeyarwady State of the Basin Assessment (SOBA) Report 2a. National Water Resources Committee (NWRC), Myanmar.

We gratefully acknowledge the support provided by the Groundwater Division of the Irrigation Water Utilization Management Department (IWUMD) in organising workshops and field visits, and providing data, technical input, and guidance. The DG, U Tin Maung Aye Htoo, DDGs of Groundwater Division U Htay Lwin and U Than Zaw, and national consultants U Myint Thein and U Thein Soe provided very valuable inputs on technical issues and identifying and accessing data sources and relevant experts.

LIST OF ABBREVIATIONS

ΔS	change in aquifer storage
µg/L	microgram per litre
µS.cm^{-1}	micro Siemens per centimetre at 25°C
AAZ	Ayadaw Artesian Zone
abs.	abstractions
AIRBM	Ayeyarwady Integrated River Basin Management
As-	arsenic
C	degrees Celsius
C-14	radiocarbon (carbon-14) dating
Ca2+	calcium
CaCO32-	calcium carbonate Cl$^-$ chloride
cm	centimetre
DRD	Department of Rural Development
DTW	deep tubewell
DW	dugwell
FAO	Food and Agriculture Organization
Fm	formation
GDC	Groundwater Development Consultants
GIP	Groundwater Irrigation Project
GW	groundwater
GW-ecosystem	Groundwater ecosystem
GWSWI	Groundwater-Surface Water Interactions
GWZ	groundwater zone
ha	hectare
HCO3-	bicarbonate
HEZ	Hydro-Ecological Zone
IWMI	International Water Management Institute
IWUMD	Irrigation Water Utilization Management Department
IZ	Industrial Zone
JICA	Japan International Cooperation Agency
KBA	Key Biodiversity Area
km	kilometre
km^2	square kilometre
km^3	cubic kilometre
L	litre
L day^{-1}	litre per day
L s^{-1}	litre per second
m	metre
m AMSL	metre above mean sea level
m day^{-1}	metre per day
m^{2}day^{-1}	square metre per day
m^{3}day^{-1}	cubic metre per day
MGIP	Monywa Groundwater Irrigation Project
mgL^{-1}	milligram per litre
M ha	million ha
MIMU	Myanmar Information Management Unit

ML day^{-1}	million litre per day
mm	millimetre
Mm^3	million cubic metre
Mm^3 yr^{-1}	million cubic metre per year
MOAI	Ministry of Agriculture and Irrigation
MOALI	Ministry of Agriculture, Livestock and Irrigation
MOI	Ministry of Industry
MONRE	Ministry of Natural Resources and Environmental Conservation
NGO	Non-government Organisation
N-S	north-south
NWRC	National Water Resources Committee
pers. com.	personal communication
R/R	recharge/rainfall ratio
SOBA	State of the Basin Assessment
sy	specific yield
TDS	total dissolved solids
TU	Tritium Units
TW	tubewell
TWS	Town Water Supply
UNICEF	United Nations Children's Fund
VWS	Village Water Supply
WCS	World Conservation Society
WHO	World Health Organisation
WISDM	Water Information System for Data Management
WRUD	Water Resources Utilization Department
WS	water supply

GLOSSARY

From Dury, 2017

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.

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.

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.

ARTIFICIAL RECHARGE - Recharge at a rate greater than natural, resulting from deliberate actions of man.

BASE FLOW - That part of stream discharge that is not attributable to direct runoff from precipitation and is generally derived from groundwater storage.

BEDROCK - A general term for the rock, usually solid, that underlies soil or other unconsolidated material.

COLLUVIAL - Unconsolidated material at the bottom of a cliff or slope.

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.

DEPRESSURISATION - Causing appreciable drop in pressure in an aquitard by an artificial means of groundwater removal.

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 - A 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.

FLOW LINES - Lines indicating the direction followed by groundwater towards points of discharge.

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 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.

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.

HYDROGEOLOGIC - Those factors that deal with subsurface waters and related geologic aspects of surface waters.

INFILTRATION - Infiltration is the movement of water through the ground surface into small voids in either the saturated or unsaturated zone.

INTERMITTENT (EPHEMERAL) STREAM/LAKE - A channel in which water sometimes flows or a lake sometimes containing water.

MONITORING - Systematic testing of the environment to record changes over time caused by impacts such as landfills.

PERMEABILITY - The permeability of a rock or soil measures of the ease with which fluids can flow through it.

PRODUCTION TUBEWELL - A small diameter hole from which groundwater is extracted. Usually 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.

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.

RUNOFF - That part of precipitation flowing to surface streams.

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 (mgL^{-1}). The significance of salinity depends on the nature as well as the amount of the dissolved solids. See also SPECIFIC CONDUCTANCE.

SALT WATER 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.

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.

SPECIFIC CONDUCTANCE - A determination of total dissolved solids (TDS) can be made by measuring the electrical conductance of a groundwater sample. Specific conductance defines the conductance of a cubic centimetre of water of a standard temperature of 25° C, measure in micro Siemens/cm ($\mu S.cm^{-1}$).

SPECIFIC YIELD - Specific yield is 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.

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.

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.

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.

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.

WELL - A generic term defined as a hole dug, drilled or bored into the earth to obtain water. See also DUGWELL and TUBEWELL.

YIELD - Yield of a tubewell can refer either to the capacity of the hole or to the amount of water withdrawn.

EXECUTIVE SUMMARY

This report presents a synthesis of existing knowledge on groundwater resources and use within the Ayeyarwady Basin. It draws on a range of published and unpublished reports, workshops and interviews with key local experts, analysis of data held by the Groundwater Division, and compilation of other data sources, supplemented with field verification visits. To simplify description of groundwater systems, we have defined nine zones within the Ayeyarwady Basin with similar characteristics in terms of aquifers and groundwater resources. These are based on the Ayeyarwady Basin Hydro-Ecological Zones, sub-divided to reflect dominant geology, hydrogeological flow boundaries and aquifers. For each of these zones, information is presented on regional geology, main aquifers, storage and recharge, groundwater quality and use, and the role of groundwater in maintaining key ecosystems.

Based on the issues and assets identified in each groundwater zone, we have identified four indicator domains for describing and managing groundwater in the Ayeyarwady Basin: quantity (recharge and storage); quality (natural and anthropogenic contamination); abstraction (domestic, industrial, and agricultural use); and ecosystem-support functions. A mix of quantitative and semi-quantitative indicators are presented to describe the status and dynamics of the groundwater resource in the Ayeyarwady Basin.

The study confirms the existence of a sizable renewable groundwater resource within the Ayeyarwady Basin, estimated at approximately 27 cubic kilometres per year, based on recharge. Current extraction is of the order of 7 - 15% of the renewable resource, with largest use in the Dry Zone. This is well within the bounds of sustainable use, and suggests that there could be important opportunities to expand exploitation of groundwater, within the constraints of local conditions and variability. Uncertainty around estimates of agricultural use is high, but it seems that the total volume of groundwater withdrawn for irrigation now approaches or surpasses the volume for domestic supply. Groundwater discharge contributes significantly to dry season flows both in the intermittent chaungs of the Dry Zone, and the Ayeyarwady mainstream. We estimate that at Magway, groundwater contributes approximately 20% of dry season flows.

Water quality constrains groundwater use over large areas of the Ayeyarwady Basin. High levels of arsenic are a risk in the recent (Holocene) Alluvial aquifers, though the problem seems limited to the sediments of the Ayeyarwady mainstream and does not affect the Chindwin and Mu systems. Salinity is mostly associated with aquifers of the marine Pegu Group sedimentary rocks and with intrusion of seawater in the delta.

The study highlights the lack of any legislative or regulatory framework for groundwater management, and the paucity of basic data on groundwater status and use. In the context of growing interest and demand for groundwater in Myanmar, establishing a monitoring network and registering and testing water quality in new wells are essential prerequisites to support sustainable management and planning of groundwater use.

1 INTRODUCTION

Groundwater is a vital resource for Myanmar. Nationally, more than half of all households use groundwater for drinking and domestic supplies; in rural areas, particularly in the Dry Zone, the proportion using groundwater often exceeds 80% (Myanmar Census, 2014). Industries rely heavily on groundwater from private wells, due to lack of reliable public supply. Official statistics indicate that groundwater supplies approximately 7% of Myanmar's formal irrigation, but these do not account for widespread private pumping. Groundwater is the fastest growing irrigation sector with increasing uptake of tubewell (TW) pumping by individual farmers, and investment by the Ministry of Agriculture, Irrigation and Livestock (MOALI) in pumped and artesian systems. Access to groundwater can provide new opportunities and reduce risk for both rural and urban communities. Groundwater can often fill gaps in supply from surface supplies and rainwater, and conjunctive management and use of groundwater and surface water can improve the security of supply and reduce the impacts and costs of providing water.

The Ayeyarwady Basin is known to host substantial groundwater (Food and Agriculture Organization [FAO], 2016; Pavelic et al., 2015), but there is considerable uncertainty around the extent of the renewable resource, links between surface and groundwater, and limits to sustainable extraction. This report reviews the current state of knowledge on groundwater in the Ayeyarwady Basin, to contribute to sustainable use of groundwater as part of integrated water resource management in the Ayeyarwady Basin.

The study was conducted in close collaboration with the Groundwater Division (GWD) of the Irrigation and Water Utilization Management Department (IWUMD) of the Ministry of Agriculture, Irrigation and Livestock. The sections on the Dry Zone and many of the insights regarding hydrogeology in Myanmar come directly from *Hydrogeology of the Dry Zone – Central Myanmar* (Drury, 2017), a major study published jointly by AWP and Ayeyarwady Integrated River Basin Management (AIRBM), based on an update and revision of joint work by Dr Drury and GWD (then the Rural Water Supply Division) begun in the 1980s.

1.1 Purpose and Structure of the Report

This report was prepared for the State of the Basin Assessment (SOBA) for the AIRBM project. It presents a synthesis of existing knowledge on groundwater resources and use within the Ayeyarwady Basin. The core objectives of the SOBA groundwater assessment were to:

- Review and summarise the current understanding of the significance and role of groundwater in the context of overall basin water resources, to underpin an integrated approach to water management. This requires a quantitative assessment aspect of: groundwater (resource and recharge dynamics) and quality; aquifer characteristics; connectivity and interaction with surface resources; current and potential use patterns; and constraints to use, pressures, and threats.
- Define a set of dynamic indicators that can be used to track the status and sustainability of groundwater resources and use and, within the constraints of current data availability, report on current status and trends.
- Identify key data requirements for future planning and management, and conceptualise a strategic approach to monitoring sustainability of groundwater use and resources. This component is covered in a separate report (*Terms of Reference for Groundwater Monitoring*).

2 APPROACH AND METHODS

The study aims to present the best available information and understanding of the groundwater systems of the Ayeyarwady Basin (Section 3). It draws on a range of published and unpublished reports, workshops, and interviews with key local experts, analysis of data held by the Groundwater Division, and the compilation of other data sources, supplemented with field verification visits.

Based on analysis of this information, we have defined a set of key indicators to describe the status of groundwater resources in the Ayeyarwady Basin and, where possible, trends in resource condition (Section 4).

2.1 Local Consultations and Field Visits

Two workshops were hosted jointly by the International Water Management Institute (IWMI) and IWUMD in Nay Pyi Taw:

1. A preliminary workshop in November 2016 introduced the AIRBM SOBA project and gathered information about which agencies and individuals hold relevant data and knowledge to support the study.

2. A technical workshop was held from 14 to 15 June, to gain feedback on Dr Drury's revision of the report on the hydrogeology of the Dry Zone and to work through water balance calculations for the Dry Zone regions with local experts.

Field visits, hosted by GWD, were made to the following areas to visit irrigation and water supply groundwater systems, facilitate discussions with local experts, and access records held by state, regional, and township authorities:

- Dry Zone — Monywa/Pale - (November 2016, January 2017, May to June 2017);
- Ayeyarwady Delta — Hinthada, Pathein, Maubin, and Bogale (30 June to 3 July 2017);
- Myittha River Valley (Western Hills) - Kalewa and Katha (5 to 8 June 2017); and
- Shan State — Naypyitaw, Taunggyi, Lawksawk, and Pinthaya (29 and 30 July 2017).

Consultations were held with groundwater experts at the national and local level, including meetings with the following:

- GWD, IWUMD at MOALI in Naypyitaw;
- The Department of Rural Development (DRD), MOALI in Naypyitaw;
- The Parliamentary Committee, Naypyitaw;
- The Department of Geological Survey, Ministry of Natural Resources and Environmental Conservation (MONRE), Naypyitaw;
- The Department of Environment, MONRE, Naypyitaw;
- Yangon University, Department of Geology;
- The Yangon City Development Committee;
- The Mandalay City Development Committee;
- Sagaing Region (Monywa and Kalay);
- IWUMD local staff and township authorities at Mandalay, Thazi, Pyawbye, Yamethin, Magwe, Minbu, Yenangyaung, Taungdwingyi, Kyaukpadaung, Nyaung Oo, Pakokku, Yinmabin, Monywa, Shwebo, Sagaing, Myingyan, Ayeyarwady Region (Pathein, Hinthada): IWUMD local staff, and township authority at Pathein; and
- Shan state (Taunggyi) — IWUMD local staff.

A full list of people consulted during the study is in Annex 1.

2.2 Data Sources

Digital spatial datasets describing context are available from public domain sources, and are included in the Water Information System for Data Management (WISDM) database. These include the following:

- Climate data, including evapotranspiration and rainfall remote sensing products — World Climate Atlas (www.iwmi.cgiar.org/resources/world-water-and-climate-atlas); Climate Hazards Group InfraRed Precipitation with Station data (http://chg.geog.ucsb.edu/data/chirps/);
- DEM and surface water networks (HydroSHEDS — http://www.hydrosheds.org/);
- Land use/land cover mapping (IWMI, 2016; UNEP, 2000); and
- Population distribution and density (Gaughan et al., 2013).

National reports and maps (included in WISDM) include:

- A 1:2,250,000 geological map of Myanmar (Myanmar Geosciences Society, 2014);
- A soil map (Ministry of Agriculture and Irrigation, Land Use Division, 2002);
- Map of major aquifer units of Myanmar (Water Resources Utilization Department [WRUD]);
- An initial groundwater potential map (per district) and its associated report (Irrigation Department and Water Resources Utilization Department, 2003); and
- Myanmar's 2014 Census, for data on household water sources.

Hydrogeological data (well logs and water quality analyses, including a large database on arsenic occurrence) are held by IWUMD. Some data were made available for analysis. The full datasets can be accessed through IWUMD. The quality and completeness of the data varies greatly between different areas. Data on artesian flow, hot water, irrigation projects, water quality (salinity, arsenic, fluoride, and hardness), and areas of high-yield/low-salinity have been mapped for the Dry Zone, but data availability outside the Dry Zone is very limited.

City and town development committees have data on their individual municipal water supplies, to varying degrees. Mandalay City Development Committee has good quality, reliable data. Universities obtain their data mainly from IWUMD. Some Non-government Organizations (NGOs) and International Non-government Organisations have their own databases on locations of wells drilled in rural development programs, but records are often destroyed after a few years.

A comprehensive bibliography of more than 550 reports, theses, journal articles, and presentations relevant to groundwater in Myanmar was compiled, covering geological studies as well as hydrogeology. The majority of these relate to the Dry Zone or national studies. There are few reports available on the groundwater in the Upper Ayeyarwady or Chindwin Basins. In the delta, a number of detailed studies have been conducted in the Yangon Region, but information in other areas is limited. The bibliography is available in the WISDM Knowledge Base, and a summary is in Annex 2.

There is a lack of groundwater monitoring throughout the basin, including in the Dry Zone. Very few organisations carry out pump-out tests to obtain hydrogeological aquifer characteristics. There are no groundwater laws or regulations that require developers or users to monitor and manage the groundwater resource. Government agencies and NGOs are not obliged to record hydrogeological data. Drillers, local government, and farmer organizations have provided some information on water table behaviour and overall hydrogeological trends through IWUMD staff and local experts.

Information on groundwater use is sparse, though the 2014 Census has data on number of households using groundwater for domestic and agricultural supplies. MOALI has some data on irrigation extractions by formal schemes. No reliable source of data on pumping by the private sector or individual farmers has been identified. GWD has compiled data from some (but not all) townships, on the number of tubewells, dugwells (DW), rainfall collection points, and the volumes pumped for their town water supply.

2.3 Groundwater Zones

To simplify description of groundwater systems, we have defined zones within the Ayeyarwady Basin with similar characteristics in terms of aquifers and groundwater resources. These are based on the Ayeyarwady Basin Hydro-Ecological Zones (HEZs), sub-divided to reflect dominant geology and aquifers. Figure 2.3-a shows the groundwater zones (GWZs), and Table 2.3-a gives a short description of each. Within the Dry Zone, Drury (2017) used smaller sub-sections of the GWZs based on local sub-basins, as seen hereafter in figure 2.3.

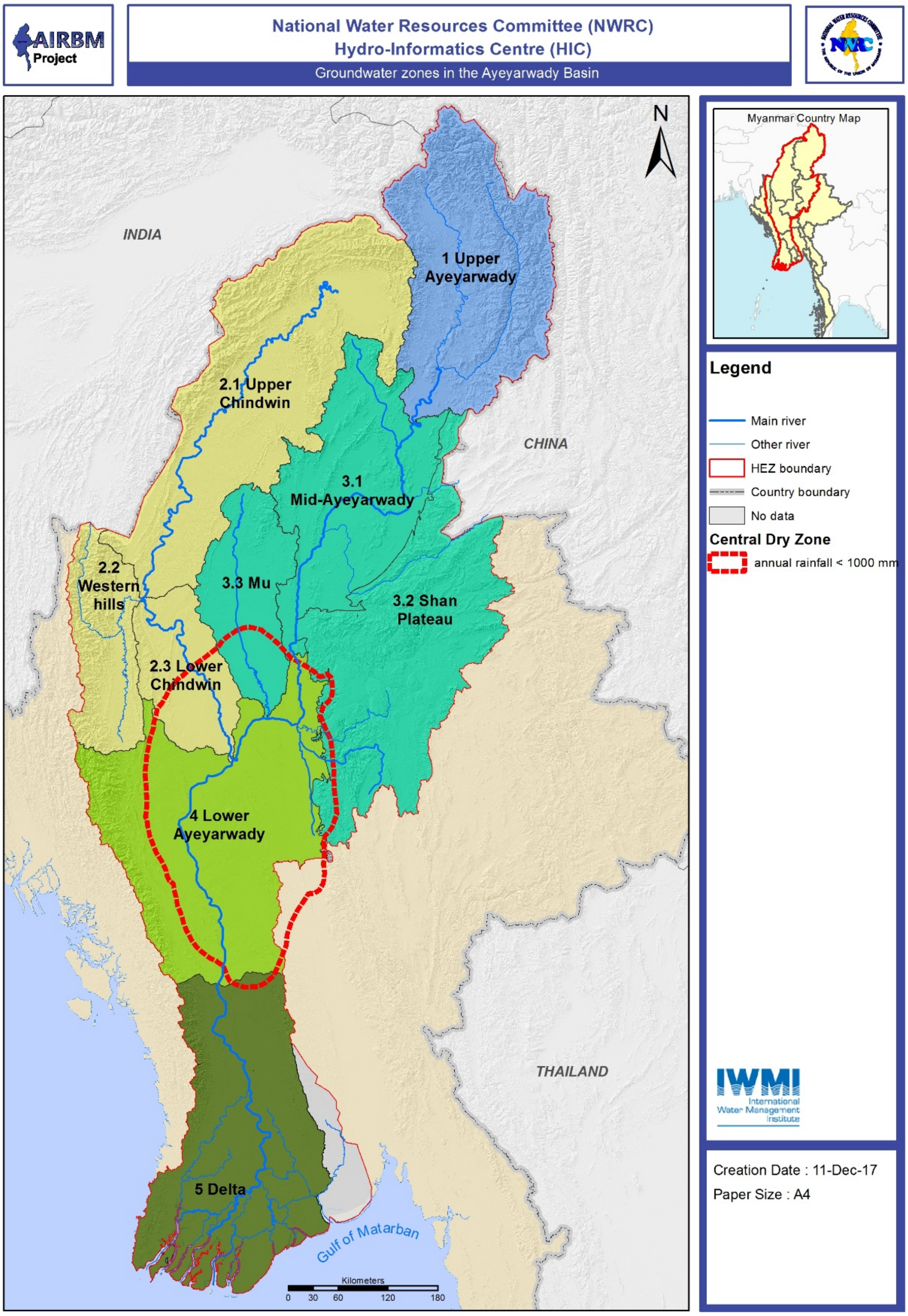

Figure 3.2.1-a - GWZs of the Ayeyarwady Basin: *See descriptions in Table 1 below. Inset map: groundwater sub-basins and study areas described in Drury (2017).*

Table 3.2.1-a – Groundwater regions of the Ayeyarwady Basin

HEZ	Groundwater Region	Geology	Main aquifers	Drury, 2017*
HEZ 1	1. - Upper Ayeyarwady	Dominantly Precambrian, Palaeozoic and Mesozoic metamorphics, and Mesozoic granites. Small alluvial floodplains.	Dominantly low-yielding fracture hard rocks. Alluvial aquifers in floodplains.	
HEZ 2	2.1 - Upper Chindwin	Dominantly Paleocene to Holocene sediments, including Irrawaddy Fm and Pegu Group; some metamorphics of Western Ranges.	Mostly sandstones of variable age including Miocene Pegu Group Formation (Fm) with salinity risk. Limited Alluvial aquifers and some Irrawaddy Fm.	
	2.2 - Western Ranges	Cretaceous flysch units in Western Ranges; Paleocene- Eocene molasse and flysch in river valleys.	Older Alluvium in river valleys.	DZ5 (Pale) and DZ6 (Budalin)
	2.3 - Lower Chindwin	Irrawaddy Fm and Younger Alluvium.	Irrawaddy Fm and Younger Alluvium.	
HEZ 3	3.1 - Middle Ayeyarwady Lowlands	Miocene to Holocene alluvial sediments.	Alluvial aquifers including Younger Alluvium, Irrawaddy Fm and Pegu Group.	
	3.2 - Shan Plateau	Ordovician to Cretaceous sediments, including large areas of Perma-Triassic Plateau Limestone Group.	Limestone aquifers, fractured hard rock aquifers.	
	3.3 - Mu	Irrawaddy Fm and Younger Alluvium with small areas of Pegu Group, Cretaceous Volcanics, and Mesozoic granites.	Irrawaddy Fm and Younger Alluvium.	DZ7 Shwebo/ Monywa
HEZ 4	4 - Lower Ayeyarwady	Dominantly Miocene to Holocene alluvial sediments (includes area of HEZ 3 around Mandalay).	Pegu Group, Irrawaddy Fm, and Younger Alluvium.	DZ1, DZ2, DZ3, DZ4, DZ9, part of DZ10, DZ11
HEZ 5	5 - Delta	Recent alluvial deposits.	Younger Alluvium with underlying Irrawaddy.	

This column indicates the zones used in Drury (2017).

2.4 Estimating Groundwater Parameters

AQUIFER EXTENT

The extent of major aquifer groups within each GWZ zone was calculated by associating each outcropping geological unit from the 2014 map to an aquifer group. Thus, in some cases, areas can be underestimated; for example, recent alluviums overlay the older Irrawaddy Fm. It still provides a useful way to quickly describe a GWZ through the relative spatial importance of aquifer groups.

AQUIFER STORAGE

Storage describes the quantity of groundwater held within aquifer systems. Storage should not be used as an indicator of the quantity of groundwater sustainably available for extraction. Instead, estimate of storage gives an indication of the importance of the aquifer, and its capacity to buffer variability in recharge. Due to the scarcity of detailed information on aquifer storage properties, broad conservative estimations were used. The areal extent of aquifers was calculated from the geological map. The thickness of aquifers was estimated based on structural geology and drilling depths, and the percentage of productive aquifer within the formation was estimated from tubewell logs when sufficient data were available. Total volume of water was then calculated, assuming a specific yield[1] varying from 0.08 in hard rock formations, up to 0.20 in mostly gravel and sands aquifers, based on global literature (Heath, 1983). Due to the assumptions made in the process, these values should be considered only as an indicator of the order of magnitude of storage, not as accurate estimates.

RECHARGE

Groundwater recharge is usually an important groundwater resource parameter as it helps to define the annual renewable portion of the storage. Understanding recharge dynamics is a prerequisite for sustainable management of the resource. There are very few studies that estimate recharge in Myanmar (Than Zaw, 2010; Bremer, 2017). Calculating recharge accurately requires intensive studies and data, which are usually not available in Myanmar. For this study, recharge was estimated for each aquifer group based on annual rainfall and a recharge/rainfall (R/R) ratio, which describes the portion of rainfall infiltrating to groundwater compared to the portion going to runoff and/or evapotranspiration. The R/R ratio was always conservatively estimated for each unit based on their generic permeability properties, literature research, and expert opinions. Due to the assumptions made in the process, these values should be considered only as an indicator of the order of magnitude of recharge, not as accurate estimates.

GROUNDWATER BALANCE

Water balance for groundwater systems was calculated for some areas of detailed study as part of *Hydrogeology of the Dry Zone – Central Myanmar* (Drury, 2017), and are included in this report. These water balance estimates focus on the groundwater components of the hydrological cycle, and provide a snapshot of the situation at a certain time. Groundwater balances were based on the assumption that there is no change in storage or water level at annual time scales, though levels may vary seasonally. Thus, the volumes of groundwater entering and leaving the system must be equal. Each groundwater system has specific components to consider, but the following equation was used as a starting point.

$$Q_{rech} + Q_{sub\text{-}in} + Q_{inf} = Q_{VWS} + Q_{TWS} + Q_{irr.gw} + Q_{bf} + Q_{sub\text{-}out}$$

where:

- Q_{rech} is the amount of groundwater recharge.
- $Q_{sub\ in/out}$ is the subsurface flow entering or exiting the area.
- Q_{inf} is the groundwater infiltration from irrigated surfaces.
- Q_{VWS} is the groundwater use for village supply.
- Q_{TWS} is the groundwater use for town water supply.
- $Q_{irr.gw}$ is the abstraction of groundwater for irrigation.
- Q_{bf} is the total contribution to the baseflow of the river draining the watershed.

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[1] Specific yield (sy) is 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.

Each parameter was estimated with the best available data, including remote sensing, reported data, expert opinion, and local knowledge. Contribution to baseflow was set as adjusting variable to allow closure of the budget and also include errors from other terms.

The following considerations were taken into account:

- It is impossible to determine the proportion of the water balance attributable to a so-called 'adjusting variable' to account for errors in water balance components, including baseflow, in particular, which was determined by closing the balance.
- In two locations (175 kilometres [km] north of Mandalay and near Magway), groundwater flow is constrained by structural geology and has no other possibility than to exit the system as baseflow, suggesting an important contribution to the water balance. This shows that at the basin or sub-basin scale it is assumed that in the 'adjusting variable' component, the contribution to baseflow may be expected to be much more significant than accumulated errors from other water balance parameters.

Thus, this 'adjusting variable,' referred to as baseflow in the water balance, incorporates cumulative error terms.

2.5 Estimating Groundwater Use

Information on groundwater extraction and use is very limited. There are no regulations mandating licensing or monitoring of wells, and information collection by government is ad hoc. No national statistics are available on extraction of groundwater for irrigation. IWUMD collects information on groundwater use at the irrigation schemes they manage, but there are no data available on private irrigation from tubewells. The Yangon and Mandalay City Development Committees, and townships using groundwater for town and village supplies, maintain some records on extraction but these data are not easily accessible, nor comprehensive.

Within specific township covered by Drury (2017), officials from GWD and township authorities estimated withdrawals in different sectors, based on local knowledge. These figures were used in calculation of water balance and are considered reliable, but are only available for some areas.

The Ministry of Agriculture and Irrigation (MOAI, 2003) compiled estimates of groundwater use in 2000 by sector (agriculture, industry, and domestic) for all districts nationally, and projected extraction by 2015, based on planned or expected growth of irrigation areas, industry, and population. These are the only nationally comprehensive figures on groundwater use that we have been able to source. Based on these figures, we calculated withdrawals in different sectors for each GWZ, using the proportion of district area within each GWZ. These estimates are considered indicative of the order of magnitude of groundwater use, and the relative withdrawals in different regions.

In Section 3 we have compiled information relevant to groundwater use and withdrawals in each major sector. While this gives a general picture of groundwater use, quantitative data was rarely available, and usually limited to a few townships or areas.

To derive indicators for groundwater use in Section 4, we used a range of surrogate measures and approximations. These are described in detail for each relevant indicator:

- Domestic and urban use — Section 4.3.1;
- Industrial use — Section 4.3.2; and
- Agricultural use — Section 4.3.3.

2.6 Estimating Groundwater-Ecosystem Support Function

Estimating the reliance of valuable ecosystems to groundwater is a difficult task. The interactions are complex, and often overlooked. As there are no primary data on these processes, proxies were used. For each GWZ, the most important ecosystems were identified and their reliance to groundwater was assessed.

Important ecosystems were identified through previous conservation studies. Key Biodiversity Areas (KBAs) of high conservation concern were identified by the World Conservation Society (WCS) in a consultation process within Myanmar (WCS, 2012). Of the 135 identified KBAs, 72 are located within the Ayeyarwady Basin, with 43 defined as 'terrestrial KBA' and 29 as 'freshwater KBA' (Figure 4.4.3-a). Each KBA was evaluated regarding its degree of reliance (low, average, or high) to groundwater for ecosystems support. This reliance was estimated based on:

- When information was available, the nature of the KBA (wetland, river, springs, caves, and forest).
- When no information was available, GIS analysis (ArcGIS and Google Earth 3D) to assess the geomorphologic features, topography, LULC, and geology.

Some of the key features used for the assessment assumed the following:

- Wetlands are usually closely linked to groundwater.
- Geology and aquifer properties will have a strong control on the level of connectivity.
- Mountain and hill ecosystems are less reliant on groundwater aside from springs systems.
- Small rivers and associated plains are more reliant on groundwater than large rivers draining larger watersheds (e.g., Ayeyarwady).

This ranking is based on preliminary desktop analysis and should be used with caution. Pending further research on the topic, it gives an initial assessment of the importance of groundwater in supporting the most important ecosystem in each GWZ.

3 HYDROGEOLOGY OF THE AYEYARWADY BASIN

Groundwater occurrence is directly related to geology, as it provides the matrix for sub-surface storage and flow. This section presents the general geological setting of the Ayeyarwady Basin; subsequent sections provide details of hydrogeology within each GWZ, as defined in Section 2.2.

3.1 Overview of the Geology of the Ayeyarwady Basin

Myanmar is located within a subduction zone where the Indian Plate meets the Himalayas. This creates specific structural and geological settings, described by Bender (1983). Tectonic structures occur east of and parallel to the subduction zone, in a series of north-south (N-S) axis arcs, creating a series of anticlines, synclines, and associated faults (Figure 3.1-a).

From west to east are found: the Outer Arc (Indo-Burma Range), the Inter-arc Trough (Western Trough), the Inner Volcanic Arc (Central Volcanic Line), and the Back-arc Basin (Eastern Trough). The Eastern Trough is located along the Sagaing Fault. The Sagaing Fault and associated Shan Fault systems act as an important separation in the geological setting of the Ayeyarwady Basin.

The Indo Burma Ranges and the Chindwin-Irrawaddy Basin together constitute the Inner Burman Tertiary Basin. The Sagaing Fault and Sino-Burma Ranges form the eastern boundary.

- The Indo-Burma Ranges are found over 1,300 km of land and continue a further 1,700 km into the Gulf of Martaban as a submarine mountain range. This zone includes the Rakhine Yoma (also known as Arakan Yoma) in the southwest and the Chin Hills further north. The highest altitude is above 3,000 m and declines towards the South. Geologically, it consists mainly of sedimentary and meta-sedimentary units. This range is part of several GWZs: the Upper Chindwin, the Western Hills, the west of the Lower Ayeyarwady and the Delta.
- The Inner Burman Tertiary Basin is in between the Indo-Burma and Sino-Burma Ranges. It is a complex basin, often subdivided into smaller sub-basins. Extensive Tertiary sediments, estimated to be up to 10,000 metres (m) thick have been uplifted, folded, faulted, and intruded by igneous rocks of the Central Volcanic Line. Uplift zones act as boundaries between sub-basins. The Inner Burman Tertiary Basin encompasses parts of several GWZs: the Lower Chindwin (2.3), the Mu-Shwebo (3.3), the Lower Ayeyarwady (4), and the Delta (5). This geological group structure and associated aquifers are described in detail in Drury (2017).
- The Sino-Burma Range area is east of the Sagaing Fault system. Tectonic activity led to an uplift of the eastern block by more than 1,000 m, resulting in the current topography. The main structure is the Shan Plateau, consisting of older meta-sedimentary rocks and thick limestone units. Further north, a heavily faulted system of metamorphic and igneous rocks forms the hills and high mountains of Kachin State, with recent alluvium found along rivers and in inter-montane valleys. The GWZs of Upper (1) and Middle (3.1) Ayeyarwady, and Shan (3.2) are found in this area.

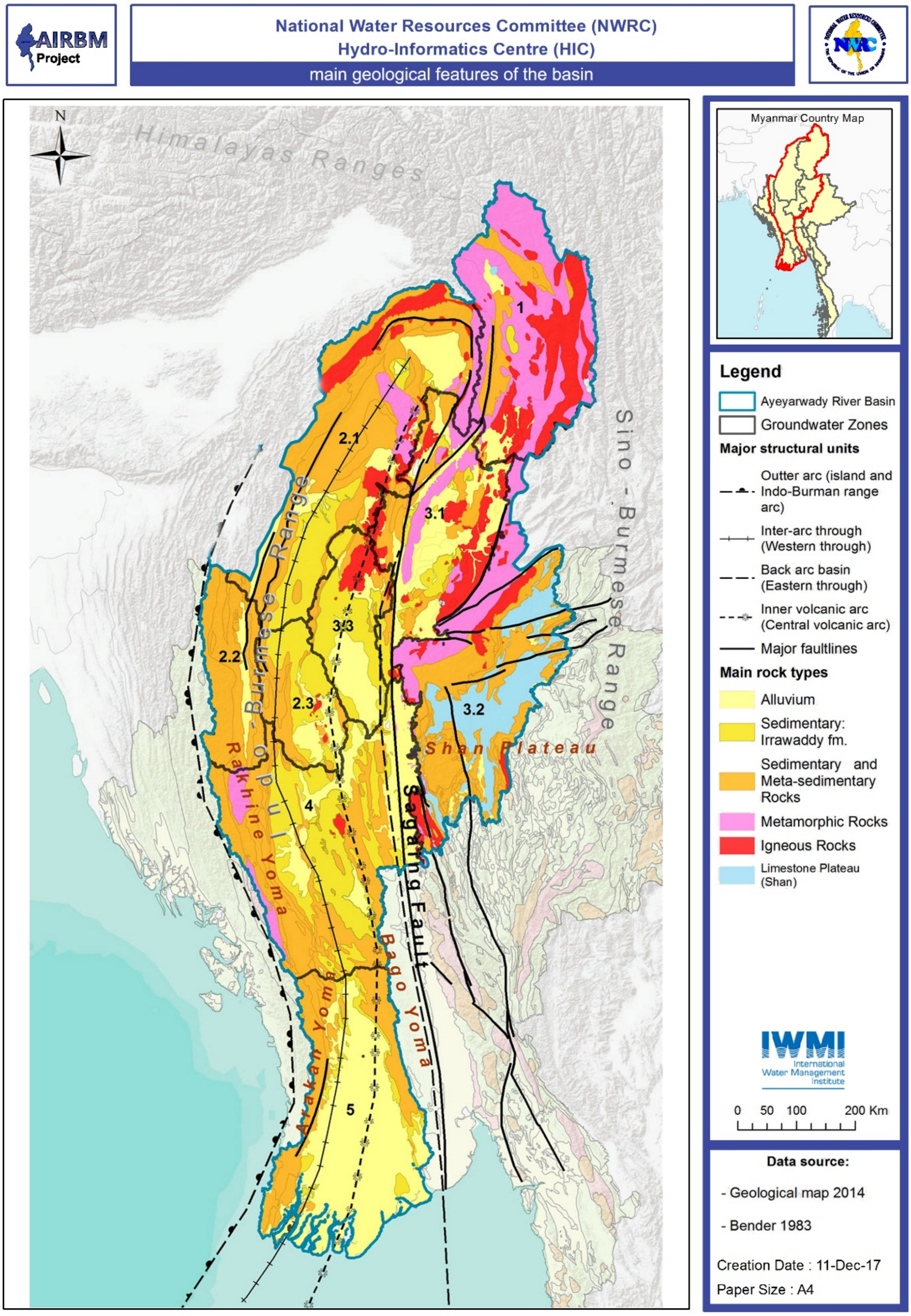

Figure 3.2.1-a - Main geological features of the Ayeyarwady Basin *(Geological map of Myanmar, 2014)*

3.2 Upper Ayeyarwady Groundwater Zone

The Upper Ayeyarwady GWZ comprises the catchment of the N'Mai and Mali Rivers, the headwaters of the Ayeyarwady. It covers 50,700 square kilometres (km^2) in the northeast Kachin State, and includes 4,500 km^2 in China, which is not considered in this report. The total population within the Upper Ayeyarwady GWZ in Myanmar is estimated at 0.41 million people, while population in this area in China is very low, with fewer than 20,000 people. Population density in this zone is one of the lowest in the country, at 6.7 inhabitants per km^2. The only urban centres are Myitkyina in the south, with a population of ~111,000, and Putao in the north, with fewer than 50,000. Small plains around the major rivers are more densely populated, remote villages are found scattered over the hills, and the northern mountains are mostly uninhabited.

Plains cover only 2,000 km^2 (or 4% of area) around Myitkyina in the south, and the small inter-montane basin near Putao in the north. Otherwise the landscape is mountainous terrain with altitude ranging from 150 m in the plains of Myitkyina, up to 5,881 m Hkakabo Razi, the highest peak in Myanmar. Due to dramatic changes in elevation, there are several climatic zones and associated land covers (Peel et al., 2007; Rubel and Kottek, 2010). From south to north, the climate ranges from humid subtropical to the subtropical highland variety (Cwb and Cwc) typical of tropical mountains with colder temperatures, and even sub-arctic and mountain tundra conditions (Dwc) in the driest parts. Total annual rainfall over the zone averages 2,070 millimetres (mm).

3.2.1 Regional Geology

Eastern Kachin State is located east of the northern extension of the Sagaing Fault. It is part of the Sino-Burman Range complex and consists mainly of metamorphosed Palaeozoic sequences (m2 and m1: Mogok series)[2] intruded by Mesozoic and Lower Tertiary granitoids (b, gr2, v1). An extensive ophiolite sequence north of Myithyina is thought to be of Jurassic age (ub). As with the Shan Plateau to the south, the uplifting of the Eastern Kachin originated from the reactivation of the Shan Fault zone and intense activity during Cretaceous and Triassic Periods (Bender, 1983). As a result, no Tertiary deposits are found east of the fault line of the Kumon Range (Figure 3.2.2-a).

More recent sedimentary and meta-sedimentary rocks are found only in the west (Figure 3.2.2-a), notably the Oligocene and Miocene rocks of the Pegu Fm (To, Tm) in the north-south trending Kumon Range, along the northern extension of Sagaing Fault. Pliocene-Quaternary deposits (Ir, Q2) are not extensive and found only as small intra-montane basins in the south near Myitkyina and in the north around Putao, with smaller-scale alluvial deposits along river channels.

3.2.2 Main aquifers

Groundwater systems are fairly limited in the Upper Ayeyarwady GWZ. Most of the groundwater potential is in Plio-Quaternary deposits in lowland plains. Aquifer systems can be divided in four groups: (i) Alluvial and unconsolidated aquifers, (ii) Sandstones, siltstones, and equivalents, (iii) Metamorphic and meta-sedimentary aquifers and (iv) Granitic aquifers. Figure 3.2.2-b shows the spatial extent of each aquifer group within the Upper Ayeyarwady GWZ.

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[2] Geological codes are from the Myanmar geological map and are included for reference.

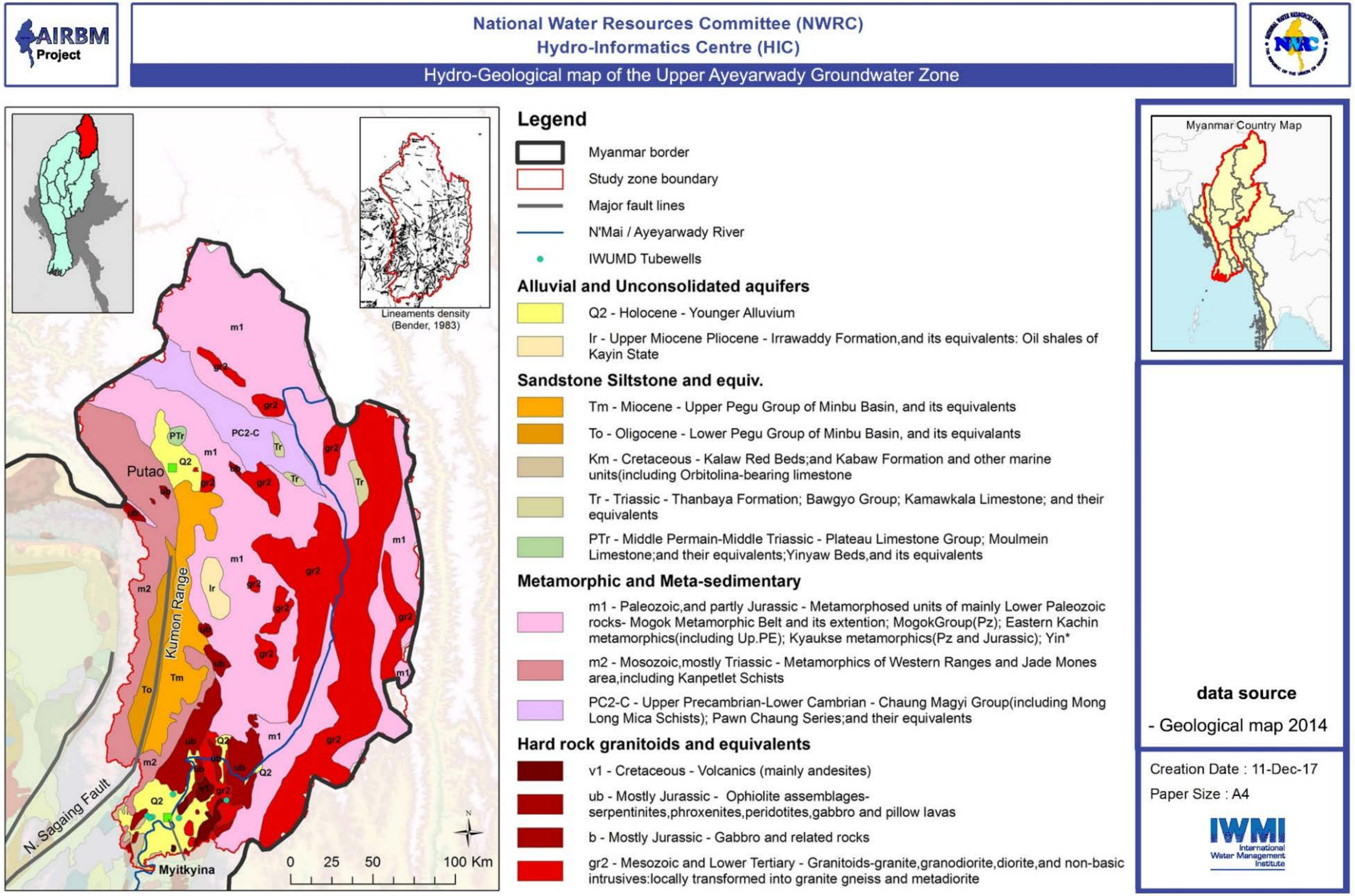

Figure 3.2.2-a - Hydro-geological map of the Upper Ayeyarwady GWZ *(Geological map of Myanmar, 2014)*

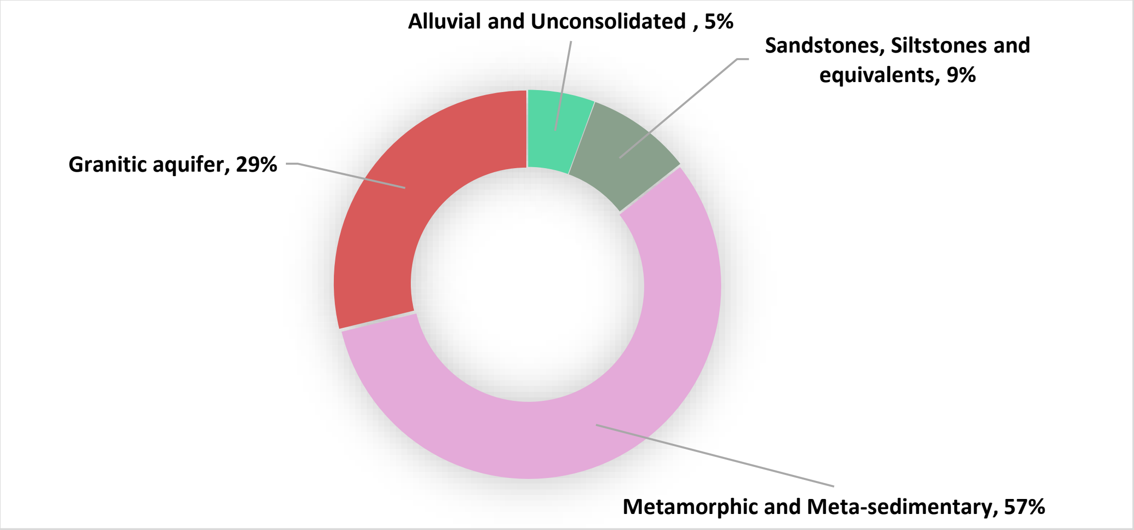

Figure 3.2.2-b - Spatial extent of each aquifer group within the Upper Ayeyarwady GWZ

ALLUVIAL AND UNCONSOLIDATED AQUIFERS

These aquifers comprise intra-montane deposits mainly from Pliocene (Irrawaddy Fm equivalents) and more recent Quaternary sand, gravel, and silt. There is very limited information on the composition and thickness of these formations. Basic data on a limited number of tubewells installed for small-scale irrigation indicates an average tubewell depth of 46 m and average yields of 2.8 litres per second (L s^{-1}) for 10.16 centimetre (cm) diameter agricultural tubewells.

Table 3.2.2-a - Examples of tubewell capacity in alluvial wells used for irrigation *(Data: IWUMD)*

Township	Village	Well diameter (cm)	Well depth*	Water level*	Estimated yield (L s^{-1})
Waingjmaw	Gawehtu	10.16	61	4.57	3.8
Waimaaw	Maingnar	10.16	61	-	1.9
Myitkyina	Mankhein	10.16	15	4.57	3.8
Myitkyina	Maungpaung	10.16	61	6.1	3.8
Myitkyina	Mawfoung	10.16	61	-	1.3
Myitkyina	Mawfoung	10.16	61	-	1.3
Myitkyina	Mawfoung	10.16	61	-	1.3
Waingjmaw	Mokelwe	10.16	18	3.05	3.8
Myitkyina	Nankwe	10.16	61	-	1.3
Waingmaw	Naungchein	10.16	61	-	1.3
Myitkyina	Naungnan	10.16	15	4.57	3.8
Myitkyina	Pamadi	10.16	61	4.57	3.8
Myitkyina	Pamadi	10.16	61	6.1	3.8
Myitkyina	Sitarpu	10.16	15	4.57	3.8
Waingjmaw	Ward 1	10.16	15	4.57	3.8

OTHER AQUIFERS

Other groups of aquifer types have significantly lower potential for groundwater. The Pegu Group sandstones and equivalent sedimentary rock formations are usually poor aquifers. These formations host limited quantities of water, often brackish or saline. The metamorphic sequences and granites are also usually poor aquifers. However, with intense folding, faulting, and weathering, a limited quantity of water may be stored in weathered and fractured layers. Such groundwater can support springs or be accessed through shallow tubewells.

3.2.3 Storage and recharge

Approximately 94% of the study area is covered by rock sequences that are considered poor to very poor aquifers. Storage and recharge were estimated for these formations, however as there is no data on these aquifers, the accuracy is expected to be low.

Tubewell logs show that the alluvial aquifers are at least 50 m deep. Assuming a total aquifer thickness of 50 m, an area of 2,559 km^2, and specific yield of 0.15, total storage is estimated at more than 25,590 million cubic metres (Mm^3) for the unconsolidated alluvial aquifer. Based on the recharge rate observed in the Dry Zone, a rainfall-recharge coefficient of 15% is assumed, and recharge is estimated at 1,156 Mm^3 for this aquifer group. It should be noted that the high values obtained for the Metamorphics are mainly due to their vast coverage, rather that aquifer productivity. The ratio of recharge to storage is approximately 5% in the alluvial aquifer.

Table 3.2.3-a – Estimate of storage and recharge properties of main aquifers in Upper Ayeyarwady GWZ

Aquifer group	Area (km^2)	Aquifer thickness (m)	Average annual rainfall (mm)	R/R ratio	Sy assumed	Storage (Mm^3)*	Recharge (Mm^3)*
Alluvial and unconsolidated aquifers	2,560	50	3,010	0.15	0.20	25,590	1,160
Sandstones, siltstone, and equivalents	4,070	20	3,090	0.08	0.08	6,510	1,010
Metamorphic and meta-sedimentary	26,140	20	2,510	0.05	0.08	41,820	3,280
Granitic aquifer	13,260	20	3,090	0.05	0.08	21,210	2,050
TOTAL	46,030					95,130	7,500

These values are broad estimates and only indicative.

3.2.4 Groundwater Quality

Naturally occurring groundwater contaminants

No naturally-occurring groundwater contaminants have been reported in this GWZ; but data is very limited.

GROUNDWATER POLLUTION

No data are available on levels of organic and industrial pollutants in groundwater in Upper Ayeyarwady GWZ. Within the urban zone of Myitkyina, seepage of urban wastes (including sewage) to shallow groundwater poses some risks. Outside Myitkyina, population pressure is very low and groundwater pollution is not likely. Intensification of agriculture in the alluvial plains around Myitkyina poses potential for contamination by agrochemicals.

Alluvial gold mining in the riverbed and surrounding deposits may also affect shallow groundwater. Mercury and cyanide, both highly toxic, are used in gold processing and although most is recovered, a proportion ends up in the environment, disposed directly into the surface water or by infiltration into the groundwater. Mercury is highly toxic, causing damage to the human nervous system at even relatively low levels of exposure. Mining operations are largely unregulated (Images Asia Environment Desk [IAED], 2004). Surface water is at greater risk than groundwater, but particular caution to past and present gold mining activities should be taken before drilling new wells close to rivers.

3.2.5 Groundwater Use

In the alluvial plains around Myitkyina and Putao, most households use groundwater for domestic supply drawing on small alluvial aquifers. In Putao, dugwells are most common (TW/DW[3] = 0.04). In Myitkyina, tubewells and dugwells are both used (TW/DW = 1.4). Elsewhere, in the uplands, most households use rivers, streams, or rainfall.

Using census data (Myanmar Information Management Unit [MIMU], 2014) on percentage of households using groundwater at township level, an assumed consumption of 135 litres (L) and population density maps (Gaughan et al., 2013), it is possible to map estimates of groundwater use from different aquifers. Total abstraction for domestic use is limited, due to both low density of population and limited groundwater availability. Prior to 2011, the WRUD (now IWUMD) drilled 672 tubewells in Kachin State to supply drinking water for 141,000 people. No additional wells have been constructed since 2011.

Table 3.2.5-a – Estimated abstraction for domestic supply by aquifer group

Aquifer group	Domestic abstraction, in million cubic metres per year ($Mm^3 yr^{-1}$)
Alluvial and unconsolidated	7.9
Sandstones, siltstone, and equivalent	1.0
Metamorphic and meta-sediment	2.7
Granitic aquifer	1.9
TOTAL	13.5

The total area of irrigation in the Upper Ayeyarwady GWZ is small (<30,000 hectares [ha] of water-managed and double cropping in IWMI landcover map). In areas close to the river, irrigation is drawn from surface water. There is some use of groundwater from alluvial aquifers in the floodplains. Since 1992, WRUD (now IWUMD) has drilled 89 tubewells in Kachin State for irrigation, serving an area of 200 ha (Thein Soe and IWUMD, 2016). Each year, budget is allocated from both state and national governments for drilling 4-inch diameter tubewells for farmers. These tubewells are fitted with diesel engines that run either a centrifugal pump (if the water table is shallow) or a small belt generator to produce enough electricity to run a submersible pump. Sets such as the combination of 1) a diesel engine, electricity production, and a submersible pump, or 2) a diesel engine and surface suction centrifugal pump, cost approximately 840,000 kyats and 300,000 kyats, respectively. An individual installation of a tubewell costs between 2 and 4 million kyats (IWUMD pers. com.).

Table 3.2.5-b summarises best available estimates of groundwater use in the Upper Ayeyarwady GWZ, based on the methods described in Section 2. Due to the uncertainties involved in estimating agricultural use, a range is given.

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[3] TW/DW is the ratio of tubewells to dugwells and springs, data by township from the Myanmar Census (2014).

Table 3.2.5-b – Range of estimates of groundwater use for Upper Ayeyarwady GWZ from different sources

	Industrial	Agricultural	Domestic	Total	Source
Estimated use 2000	0	1	26	27	MOAI, 2003
Projected use 2015	0	2	35	37	MOAI, 2003
Estimated current use range	1	Low: 1 High: 13	13	Low: 15 High: 27	This study

3.2.6 *Groundwater and Ecosystems*

There are nine Key Biodiversity Areas (KBAs) within the Upper Ayeyarwady GWZ. Most, including the Hkakborazi National Park (which contains the highest peak in Myanmar, at 5,881 m), are located in steep mountains of mostly metamorphic and igneous rocks. In this context, the groundwater-ecosystem support function is probably limited, but groundwater still plays an indirect role through buffering climate variability and supporting springs.

Two KBAs are likely to depend on groundwater to some extent. The Myitkyina to Sinbo Section of the Ayeyarwady River relies on groundwater through the baseflow of Ayeyarwady in the dry season. Given the large size of the watershed and discharge of the river, the level of reliance is estimated as moderate. The Myitkyina-Nandebad-Talawgyi area is underlain by alluvial plain, and its conservation value is unclear. In general, groundwater is not a key factor for conservation in this GWZ.

Table 3.2.6-a – KBAs in the Upper Ayeyarwady and reliance to groundwater

KBA name	Type of KBA	Priority	Area (km^2)	Groundwater (GW)-ecosystems link	GW reliance
May Hka Area	Terrestrial	High	10,090	Mountainous, possibly springs	Low
Mali Hka Area	Terrestrial	Medium	5,129	Mountainous, possibly springs	Low
Hkakaborazi NP	Terrestrial	Medium	4,313	Mountainous, possibly springs	Low
Hponkanrazi WS	Terrestrial	Medium	2,803	Mountainous, possibly springs	Low
Babulon Htan	Terrestrial	Medium	1,896	Mountainous, possibly springs	Low
Bumhpabum WS	Terrestrial	Medium	2,939	Mountainous, possibly springs	Low
Ayeyarwady River (Myitkyina to Sinbo Section)	Freshwater	High	578	Large river, limted alluvial plain	Average
Myitkyina-Nandebad-Talawgyi	Terrestrial	Data deficient	554	Alluvial plain, mostly agricultural fields	Average
Lwoilin/Ginga mountain	Terrestrial	Data deficient	548	Mountainous, possibly springs	Low

3.2.7 *Summary - Assets and Issues*

- Alluvial aquifers provide important domestic suppliesm, and small-scale cash crop irrigation opportunities supported by the state and national government.
- Locally, potential pollution of shallow aquifers from unregulated artisanal mining.

3.3 Upper Chindwin Groundwater Zone

The Upper Chindwin GWZ comprises the Chindwin catchment within Myanmar, north of the junction with the Myittha River at Kalewa, an area of 62,900 km^2. Major tributaries of the Upper Chindwin River include: the Uru River, with headwaters that contain the jade mines at Hpakant; the Tizu River, which drains from the Naga Hills; and the Myittha, which drains the Kale Valley. The zone lies mostly within Sagaing Region (Hkamti, Mawlaik, and Tamu Districts) and includes some of northern Kachin State (western Myitkyina and Mohnyin Districts). The total population of the Upper Chindwin GWZ in Myanmar is 0.70 million people.

Approximately 10,500 km^2 (14% of the catchment) lies within the Indian States of Nagaland and Manipur, in the Naga Hills. This area is home to 0.68 million people, and is not considered in this study.

The Chindwin River is the largest tributary of the Ayeyarwady River. It originates as the Tanai River in the Hukawng Valley of Kachin State, where its tributaries drain the rugged and densely forested mountain ranges of the Hukawng Valley Wildlife Sanctuary. The watercourse changes its name to Chindwin upstream of Homalin. It travels in a southwesterly direction to Kalaymyo before entering the Lower Chindwin River Valley, upstream of Twin Taung Crater Lake and Monywa Town. Commercial vessels ply the Chindwin River to Homalin. Teak, Burmese amber, and jade are extracted from the Upper Chindwin River Valley.

Annual average rainfall in the zone is 2,370 mm, varying from over 3,500 mm in the northern ranges, to less than 1,500 mm around Kalewa.

3.3.1 Regional Geology

The Upper Chindwin GWZ includes three main geological regions (Figure 3.3.1-a).

- The Western Ranges — elevated areas bordered by the Kabaw Fault and Myittha River Valley, comprise the following:
    - Palaeocene to Eocene Molasse type units (TEM), including the Paunggyi Fm and equivalents (containing coal and oil/gas);
    - Cretaceous Kalaw Red Beds (Km); and
    - Miocene Upper Pegu Group (TM), shale, mudstone, and sandstone along the course of the Chindwin River.
- The Central Chindwin River Valley includes the following:
    - The Upper Miocene to Lower Pleistocene Irrawaddy Fm (IR): semi-consolidated sand, gravel, and clay with anticlinal folds of the Pegu Group sometimes exposed; and
    - Small outcrops of Holocene Younger Alluvium (Q).
- The upper catchment areas include the following:
    - Mesozoic (mostly Triassic) Metamorphics of Western Ranges and jade mine area (m2) (including Kanpetlet Schists);
    - Granites (gr2), serpentine and gabbro ultramafic (ub) and andesites (v1); and
    - Areas of all the above geological units.

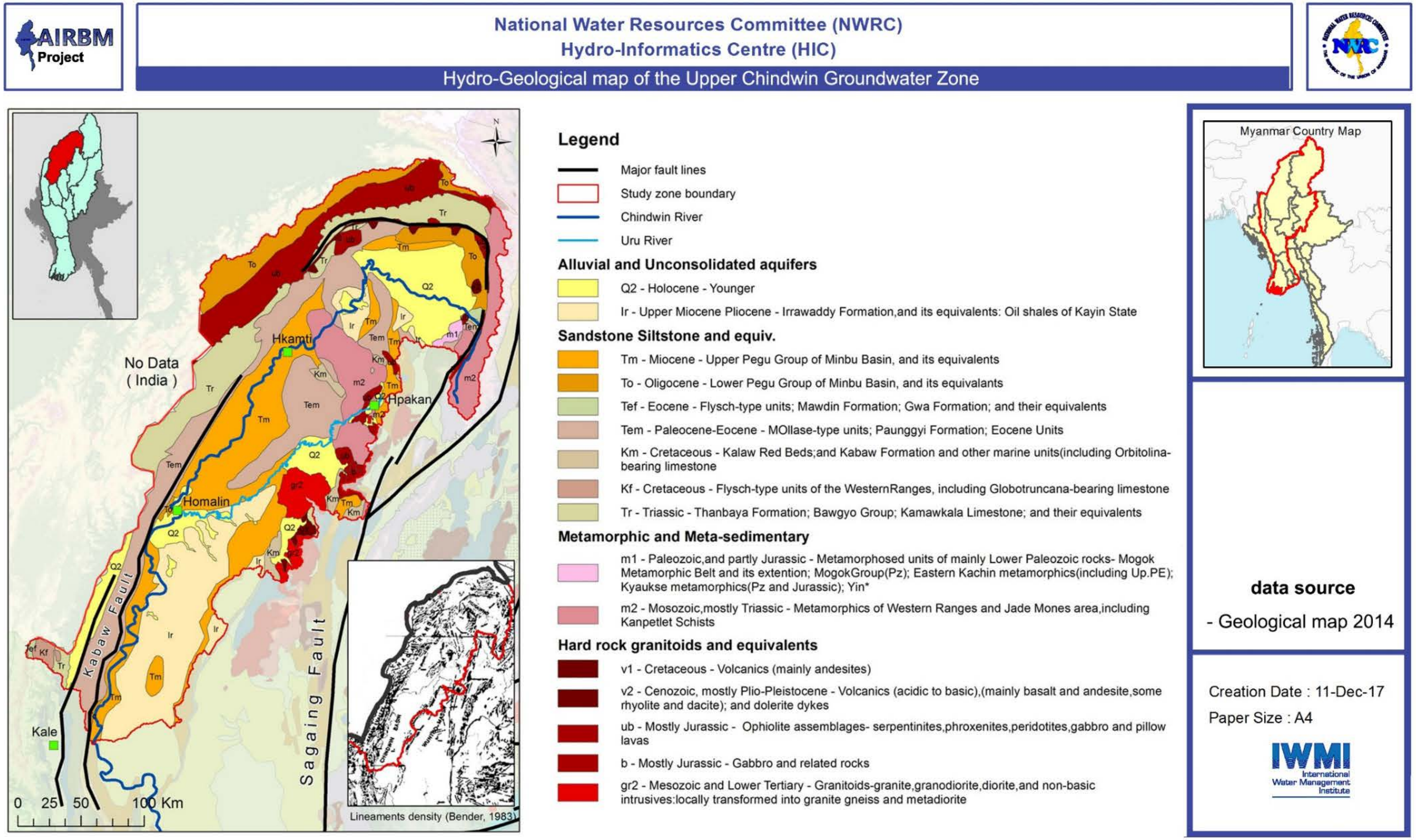

Figure 3.3.1-a – Hydro-geological map of the Upper Chindwin GWZ *(Geological map of Myanmar, 2014)*

3.3.2 *Main Aquifers*

The major low-salinity and high-yield groundwater aquifers of the Upper Chindwin River Valley are located in the Irrawaddy Fm and Alluvium. Low-yield and brackish aquifers are generally encountered in the sandstones of the Pegu Group and Eocene rocks.

The Irrawaddy Fm aquifers are mainly semi-consolidated brown and blue sand and gravel with clay aquitard bands. Groundwater yield ranges from 1 to 10 L s^{-1}, with hydraulic conductivity less than 15 metres per day (m day^{-1}).

The Alluvium consists of shallow, unconsolidated yellow brown sand and gravel. Due to the steep mountainous terrain, the alluvial flats are thin and discontinuous. There are some extensive alluvial flats on the Uru River with shallow dugwells. Depth to the water table is shallow. Groundwater yields up to 20 L s^{-1} are anticipated in tubewells close to the river. Hydraulic conductivity is likely in the order of 100 to 200 m day^{-1}. The thickness varies from 70 m at Kelewa to less than 40 m in the upper catchment.

The hydrogeology of the fractured volcanic and metamorphic rocks (schist, phyllite, granite, serpentine, gabbro, and andesites) is poorly documented. Typical groundwater yields are in the order of:

- <1 L s^{-1} at depths less than 200 m in fractured rock;
- <5 L s^{-1} in the highly fractured fault zones;
- <5 L s^{-1} at depth less than 50 m in weathered granites; and
- Negligible in the unweathered volcanic and metamorphic rocks.

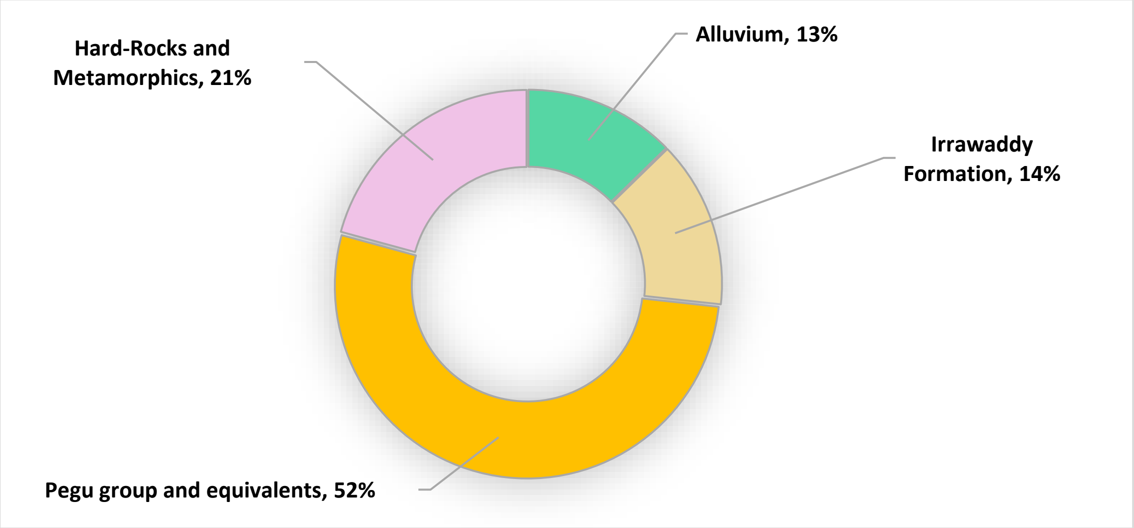

Figure 3.3.2-a – Spatial extent of major aquifer groups in the Upper Chindwin GWZ

3.3.3 *Storage and Recharge*

There is very limited understanding of the recharge, storage, and discharge processes in this part of the watershed. Broad assumptions can be used to obtain a first-pass estimate of the recharge and storage. Volumes were calculated using spatialized rainfall and aquifer extent data, with additional assumptions on aquifer thickness, storage properties, and R/R ratios (Table 3.3.3–a). These are only broad estimates and appropriate groundwater studies should be carried out to refine these values.

Table 3.3.3-a – Estimate of storage and recharge properties of main aquifer groups

Aquifer group	Area (km^2)	Aquifer thickness (m)	Rain (mm) average	R/R ratio	Sy assumed	Storage (Mm^3)*	Recharge (Mm^3)*
Irrawaddy Fm	8,850	50	2,140	0.15	0.2	88,520	2,840
Alluvium	8,020	50	3,090	0.15	0.2	80,180	3,720
Pegu Group and equivalents	33,140	50	2,760	0.05	0.08	132,550	4,580
Hard-Rocks and Metamorphics	13,100	50	3,060	0.05	0.08	52,390	2,000
	63,110				TOTAL	353,640	13,140

**These values are broad estimates and only indicative.*

3.3.4 Groundwater Quality

SALINITY

Salinity in the aquifers of the Alluvium and Irrawaddy Fm in the Upper Chindwin GWZ is consistently low, with a specific conductance below 1,000 micro Siemens per centimetre (µS.cm^{-1}). Limited areas of higher salinity may occur immediately downstream of the more saline Pegu Group outcrops. The Eocene rocks usually have low salinity.

ARSENIC

No records exist of arsenic testing in this GWZ. In the Lower Chindwin where analyses have been carried out, no instances of elevated levels of arsenic have been detected. It is thought that arsenic is generally low risk in the Chindwin Valley, and is restricted to the sediments of the Ayeyarwady mainstream.

Other naturally occurring groundwater contaminants

No reports on other naturally occurring contaminants in groundwater were found.

GROUNDWATER POLLUTION

No reports documenting groundwater pollution in the Upper Chindwin GWZ were found, but there are potential areas of risk associated with mining:

- Small-scale artisanal gold mining in the Mawlaik to Paung Pyin area may pose a threat of pollution of shallow aquifers by mercury and cyanides, as in the Upper Ayeyarwady GWZ (see section 3.1.5 above).
- Mining of jade and precious minerals between Paung Pyin to Homalin on the Uru (Oo) River involves large-scale earthmoving, with sediment discharging into the Chindwin River. This is not likely to have a direct impact on groundwater systems, although it can disturb the groundwater-surface water exchanges locally through changes in riverbed sediments.
- Coal mining and small oil operations in the Paungggyi Fm and equivalents west of Kalaymyo, and coal loading on the Myittha River, near the confluence of the Upper Chindwin River. Yellow fluorescence oil slicks have been observed in minor chaungs.

In all cases, impact on groundwater is likely limted and localized, as groundwater flow is towards the river (and potential pollution sites), rather than away.

Approximately 25% of households do not have access to safe sanitation, and there is a moderate risk of localised pollution of shallow aquifers, particularly in the river valleys where population density is highest.

3.3.5 *Groundwater Use*

The Upper Chindwin River has significantly less groundwater potential than the Myittha and Lower Chindwin River valleys. Due to the presence of abundant surface water sources and small population centres, the groundwater demand for urban and irrigation usage is small. The main towns of Homalin, Paungbyin, and Kalewa are all on the river. There are no signficant industries using groundwater.

Dependence on groundwater for domestic supply in rural areas is high, particularly in the uplands – on average, over 70% of households use wells, springs, or tubewells. Tubewells are more common in the valleys of Mawlaik and Hkamti (TW/DW = 2 - 3), but dugwells predominate in the remote uplands of Putao and Tamu (TW/DW = 0.1 - 0.2). Using census data (MIMU, 2014) on percentage of households using groundwater at township level, an assumption of 135 L per person per day and population density maps (Gaughan et al., 2013), it is possible to map estimates of groundwater use from different aquifers.

Table 3.3.5-a – Estimated domestic abstraction by aquifer group

Aquifer group	Domestic abstraction, Mm^3 yr^{-1}
Alluvium	6.4
Irrawaddy Fm	5.5
Pegu Group and equivalents	7.8
Hard-Rocks and Metamorphics	1.7
TOTAL	21.4

Small areas of intensive irrigation occur around the main towns which mostly lie along watercourses. It is not clear whether water is drawn from surface water, groundwater or both. Cropping in the valley north of Khampat Town appears to be an extension of the colluvial systems in the Myittha River Valley further south, and may also use artesian or sub-artesian wells. IWMI landcover mapping identified 47,000 ha of water-managed single cropping systems; and approximately 63,000 ha of intensive cropping systems (double cropping). IWUMD has completed more than 3,300 wells for irrigation in Sagaing Region, serving an area of 22,750 ha, but most of these are likely in the Monywa Region and the Mu Valley. In calculating likely agricultural use, we have assumed that only 10% of these wells are in the Upper Chindwin, even though the GWZ includes almost half of Sagaing Region. An estimated range for possible agricultural use is given in Table 3.3.5–b, based on methods described in Section 2.

Table 3.3.5-b – Range of estimates of groundwater use for Upper Chindwin (Mm3 yr-1)

	Industrial	Agricultural	Domestic	TOTAL	Source
Estimated use 2000	0	0	55	56	MOAI, 2003
Projected use 2015	0	365	73	438	MOAI, 2003
Estimated current use	0	Low: 5 High: 49	21	Low: 26 High: 70	This study

3.3.6 *Groundwater and Ecosystems*

The Upper Chindwin GWZ hosts 10 KBAs, and several rank as a high priority for conservation. KBAs are usually large in this GWZ, spanning often over several thousands of square kilometres. Some areas cover mostly sedimentary and meta-sedimentary forested hills and in this case the groundwater-ecosystem link is expected to be low. However, two identified KBAs of high priority are closely related to groundwater resources.

Satellite imagery (Google Earth) shows the Tanai River KBA as meandering river and associated marshes ecosystems. The alluvial aquifer, through interactions with both the marshes and the river is likely a key factor in the ecosytem functioning.

The Hukaung Valley Wildlife Sanctuary and extension is the world's largest tiger reserve. This large territory includes wetlands of importance for conservation, which are underlain by and often connected to alluvium deposits.

Table 3.3.6-a – Summary of KBAs in Upper Chindwin GWZ and reliance on groundwater

KBA name	Type of KBA	Priority	Area (km^2)	Groundwater ecosystems (GW-ecosystems) link	GW reliance
Hukaung Valley WS	Terrestrial	High	6,483	Presence on wetland Geology: Alluvial	High
Tanai River	Freshwater	High	636	Imagery shows meanders and associated marshes Geology: Alluvial	High
Hukaung Valley WS (Extension)	Terrestrial	High	11,348	Large area, mostly mountaineous	Average
Saramati Taung	Terrestrial	Medium	274	Mountainous, possibly springs	Low
Yaybawmee	Terrestrial	Data deficient	3,213	Hilly terrain, mostly sandstones	Low
Upper Chindwin (Kaunghein-Padumone)	Freshwater	High	45	Mountainous -Possibly springs	Low
Htamanthi WS	Terrestrial	High	2,542	Large area Geology: sandstones, no reported wetland	Average
Uyu River	Freshwater	Medium	844	Alluvial plain, limited mining	Average
Mahamyaing WS	Terrestrial	Medium	1,204	Hills Geology: Irawaddy	Low
Thaungdut	Terrestrial	Data deficient	325	Location unclear, inter-montane	Low

3.3.7 *Summary – Assets and Issues*

- Large recharge to alluvial aquifers.
- Alluvial aquifers provide important domestic supplies.
- Alluvial aquifers provide small-scale cash crop irrigation opportunities.
- Alluvial aquifer supports high priority KBAs.
- Potential pollution of shallow aquifers from unregulated artisanal mining.
- Potential pollution of shallow aquifers around towns in the alluvial plains from unsafe sanitation.

3.4 Western Hills Groundwater Zone

The Western Hills GWZ encompasses the catchment of the Myittha River within Myanmar, an area of 17,600 km^2. The uplands lie within Chin State, and the river valley is within the Magway and Sagaing Regions. The total population within Myanmar is 0.62 million people, with main population centres at Kalay and Kalewa. Approximately 10,600 km^2 (38% of the total catchment) lies within the Indian state of Manipur. Over 2.7 million people live within this area, mostly in the valley of the Manipur River.

The Myittha River originates in the Chin Hills and flows northwards draining the Kale Valley. A major tributary of the Myittha is the Manipur, which flow southward out of India and meets the Myittha 35 km south of Kalay. The Ne Win Za Yac Chaung also flows southwards, with the confluence east of Kalay Town. Large colluvial fans emanate from the Chin Hills. Since the surface topogaphy slopes from west to east, the watercourses flow along the eastern periphery of the valley. The Myittha River then heads east into the Chindwin River below the town of Kalewa (Figure 3.4.3-a) through a narrow fault-controlled hard rock valley.

Annual average rainfall across the zone is 1,670 mm, ranging from more than 2,600 mm in parts of the Chin Hills to less than 1,100 mm in the southern part of the zone in Magway Region.

A flood in 2015 on the alluvial plain was up to 9 m high, destroying most paddy fields by infilling with large to fine sediment (up to 2.5 m of deposition). The farmers are still recovering their paddy fields from this event.

3.4.1 *Regional Geology*

The Myittha River Valley is formed within a major horst and graben structure, with elevated mountains bordered by major fault zones to the west and east (Kabaw Fault) and a dropped valley centre (Figure 3.4.3-a). The following are the major geological features:

- Elevated western Chin Hills (Western Ranges) comprises the following:
    - Cretaceous Flysch type units, including limestone;
    - Triassic Thanbaya Fm (limestone); and
    - Jurassic serpentine and volcanics (pods).
- The central valley consists of extensive heterogeneous alluvial fluviatile sediments and colluvial fans (boulder, cobble, gravel, sand, silt, and clay):
    - The most extensive Holocene colluvial fan is sited under the west to east orientated Tahan-Kalay Town area. The thickness of colluvium is greater than 300 m near the Chin Hills to less than 30 m near the Myittha River.
    - Thick Holocene silt and clay sediments occur near the eastern river system.
- Elevated eastern mountain ranges of the Thit Chauk Reserve Forest host the following:
    - Palaeocene to Eocene Molasse type units, including the Paungggyi Fm and equivalents (containing coal and oil/gas reserves); and
    - Cretaceous Kalaw Red Beds.

3.4.2 *Main Aquifers*

Sandstones and sediments of Triassic (Kf, Km) to Eocene (Tef, Tem) age represent by far the most abundant aquifer units in the area. Recent Alluvial aquifers of various types, including colluvial fans with artesian zones, outcrop in 12% of the Western Hills GWZ (Figure 3.4.2-a).

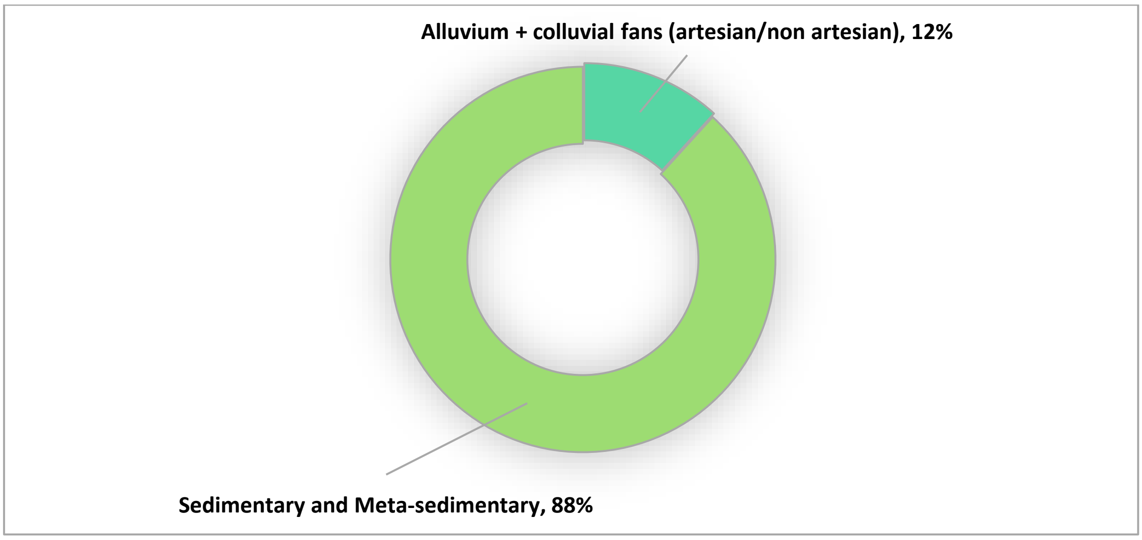

Figure 3.4.2-a - Spatial extent of major aquifer groups in the Western Hills GWZ

METASEDIMENTARY AND SEDIMENTARY AQUIFERS

The hydrogeology of the fractured hard rock aquifers along the elevated western and eastern limestone, sandstone, and volcanic mountain ranges is poorly documented. Low yields (<1.26 L s^{-1}) at depths less than 200 m are expected, except in the highly fractured fault zones where larger yields up to 5 L s^{-1} are likely.

COLLUVIAL FANS

Colluvial fans formed by erosion of the uplands form heterogeneous aquifers that are highly permeable in the west, becoming less permeable in the intertonguing alluvial sediments to the east, as silt content increases. There is a large amplitude in water level fluctuation within the colluvial fans; dry season level may be 10 m deeper than the wet season level.

There are many tubewells in the colluvial fans, which are used for domestic and irrigation purposes. Problems arise with tubewell construction due to large boulders and cobbles within the colluvial fans, which are hard to penetrate by local drilling rigs. Many drilled holes are unsuccessful before reaching the water table. To address this, a large diameter dugwell is manually constructed to the dry season water table and then a drilling rig over the dugwell extends the hole into the aquifer.

ARTESIAN AQUIFERS

There are two artesian zones within the Myittha River Valley. The most extensive artesian area is north of Tahan-Kalay Town to Letpanchaung Village,[4] a north-south distance of 10 km. This zone occurs near the base of the primary colluvial fan, where it meets the less permeable alluvium to the east. Initial groundwater flow varies from 1 to 12 L s^{-1}. Some artesian flows were reduced after the 2015 flood, presumably due to sedimentation down the open borehole or the adjacent annulus. Drill depths in the artesian aquifers are usually from 25 to 100 m, with artesian flow commencing approximately 30 m, and initial pressure head approximately +2 to +7 m. Some tubewells are equipped with small hydro-generators for household power supply.

Some irrigation tubewells have control valves, but only a few owners turn off non-required flow. Consequently, artesian flows in many tubewells are slowly decreasing. Due to pressure reduction only the tubewells in topographically low positions within a village continue to flow, with handpumps or centrifugal pumps in the higher elevated regions.

A less extensive artesian area is found to the south of Kalay to Sithar Village. Flows have reduced from approximately 5 L s^{-1} to <3 L s^{-1} since initial drilling. Sithar Village does not contain any flowing tubewells to the depth of 30 m. Attempts to go deeper have intersected large cobbles and drilling was terminated.

NON-ARTESIAN AREAS

The surface elevation of the adjoining Kalay and Tahan Township areas rises 300 m from east to west, over a distance of 10 km. No artesian aquifers are intersected even though it is sited on the centre of the major colluvial fan. Shallow dugwells in the eastern part of town are 10 to 15 m deep. The upper aquifers go dry during the dry season because of declining water levels. Due to the presence of cobbles, drilling a successful tubewell sometimes takes several attempts.

There is no reticulated water supply system in Kalay and Tahan Towns. Many household have a dugwell or tubewell; there are over 500 tubewells and 1,000 dugwells. The government is to drill two tubewells in the higher elevated wards and two in the Industrial Zone (IZ) in Kalay and Tahan towns. They will need to be

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[4] Letpanchaung artesian flows in the wet season only.

drilled to at least 180 m to penetrate the dry season potentiometric surface and intersect high yields. IWUMD is aware of the drilling difficulties likely encountered.

3.4.3 Storage and Recharge

The aquifers are annually recharged by rainfall and surface water runoff along the western Chin Hills. Annual rainfall in the area is high (>2,000 mm), and there is likely considerable recharge, particularly through the highly permeable colluvial fans. The direction of groundwater flow is towards the Myittha River and tributaries. The extent to which groundwater movement occurs between the various aquifers is controlled by the permeability of the multiple clay aquicludes, their thickness, and head differences.

High groundwater yields are available from deep, correctly designed, and constructed production tubewells within the colluvial fans. Due to the heterogeneous nature of the aquifers, yield varies between 2 and 20 L s^{-1}. There is poor potential of obtaining high-yield aquifers in the fine-grained alluvium along the eastern edge of the valley.

There are no alluvial flats in the narrow hard rock river gorge joining the Myittha River to the Upper Chindwin River. Groundwater stored in Myittha River Valley cannot be transferred to the lower drainage system, but must discharge either into the Myittha River and associated chaungs, from flowing or pumping tubewells, or from natural springs.

Very broad estimates of groundwater storage can be obtained using assumptions about aquifers properties, extent, thickness, and R/R ratios. Such estimates, given in Table 3.4.3–a, are only indicative of the order of magnitude expected for each parameter, and should be used with caution.

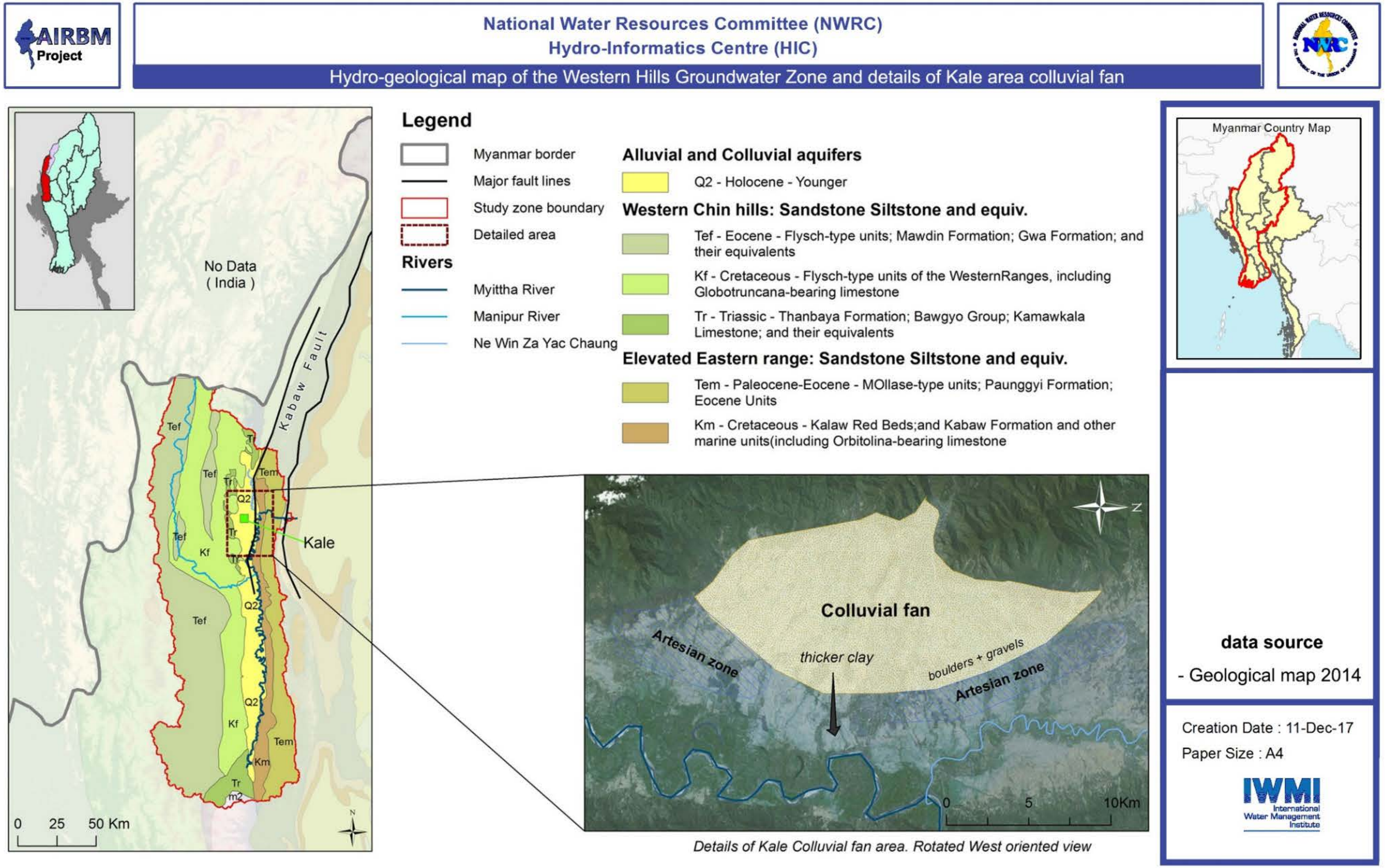

Figure 3.4.3-a - Hydro-geological map of the Western Hills GWZ and details of Kale area colluvial fan

Table 3.4.3-a – Estimates of storage and recharge parameters from aquifer groups of the Western Hills GWZ

Aquifer group	Area (km^2)	Aquifer thickness (m)	Rain (mm) average	R/R ratio	Sy assumed	Storage (Mm^3)*	Recharge (Mm^3)*
Alluvium and colluvial fans (artesian/non-artesian)	2,070	50	1,790	0.15	0.2	20,680	560
Sedimentary and meta-sedimentary	15,500	50	2,120	0.05	0.08	62,010	1,640

3.4.4 Groundwater Quality

SALINITY

Groundwater within the Myittha River Valley is consistently of low salinity and cold. Table 3.4.4–a indicates that the specific conductance within the artesian aquifers ranges from 160 to 330 $\mu S.cm^{-1}$ at 25° C. It is rare to record salinity above 500 $\mu S.cm^{-1}$ at 25°C.

AGRICHEMICAL

As agriculture intensifies in the colluvial fans, there is increasing risk for aquifer pollution from agrichemicals. To date, the use of such products is not monitored and assessing such risk is difficult.

Table 3.4.4-a – Groundwater chemistry in the Western Hills GWZ, measured on site June 2017

Village name	pH	Electrical conductivity ($\mu S.cm^{-1}$ at 25°C)	Total dissolved salts, miligrams per litre (mgL^{-1})	Temperature °C	Yield initial to recent ($L\ s^{-1}$)
Northern artesian aquifers					
Nansaw	8.5	170	130	25.6	8 - 5
Kyaung Taik	8.5	180	140	26	2 - 1.5
Pyu Daw Thar	8.4	300	220	27	6 - 1
Tharyargone	8.4	270	200	26	4 - 4*
Maunklin	8.4	200	180	26	3 - 2.5
Southern artesian aquifers					
Sithar	9.1	330	240	26	2 - 1.5
Hto Mar School	8.2	240	174	28	3 - 0.5
Thar Zi	8.4	160	121	28.5	3 - 1.5

**Equipped with turn off valve*

3.4.5 Groundwater Use

Dependence on groundwater for drinking is low (<20%) in the uplands of the Chin Hills, but very high (>70%) along the river valley, where there are large numbers of artesian tubewells in addition to non-artesian tubewells and shallow dugwells. Kalay and Tahan towns have approximately 500 tubewells and 1,000 dugwells. Using census data (MIMU, 2014) on the percentage of households using groundwater at the township level, population density maps (Gaughan et al., 2013), and an assumed use of 135 L per person per day, it is possible to map estimates of groundwater use from different aquifers (Table 3.4.5–a).

Table 3.4.5-a – Estimated domestic abstraction by aquifer group

Aquifer group	Domestic abstraction $Mm^3\ yr^{-1}$
Alluvium and colluvial fans (artesian/non-artesian)	12.5
Sedimentary and meta-sedimentary	6.3
TOTAL	18.8

Industrial use of groundwater is currently limited, but a new Industrial Zone is planned for Kalay (see Section 4) and there are plans to drill two tubewells for water supply.

The government has promoted irrigation using groundwater by installing 28 artesian tubewells in the valley; there are currently approximately 500 private tubewells. The average artesian flow is 2 L s^{-1} (>90 ML day^{-1}). The numbers of non-flowing tubewells and dugwells in the valley are not known. It is estimated that there are in the order of 10,000 tubewells and 5,000 dugwells equipped with an air compressor, centrifugal, or hand pump, but these may be mainly for domestic and village use. IWUMD is planning a 70 tubewell drilling program for 'flood affected' communities. One tubewell will supply four to six farms for rice paddy cultivation.

IWMI (2016) land cover mapping estimated ~42,500 ha of intensive cropping system (double or triple cropping) in the Myithha River valley on the colluvial fans described above, or along the river floodplain (see Figure 3.4.3-a). It is not clear what proportion is drawn from groundwater, and pumping from both groundwater and surface water sources is likely.

Table 3.4.5-b – Range of estimates of groundwater use for the Western Hills GWZ (Mm3 yr-1)

	Industrial	Agricultural	Domestic	Total	Source
Estimated use 2000	0	0	48	48	MOAI, 2003
Projected use 2015	0	133	63	195	MOAI, 2003
Estimated current use	1	Low: 33 High: 50	19	Low: 53 High: 70	This study

3.4.6 *Groundwater and Ecosystems*

Groundwater is not expected to be an important component of ecosystems in the Western Hills, as most of the GWZ is located in steep mountainous terrain, of mostly sedimentary aquifer. Aside from springs, groundwater plays an active role in supporting the dry season flow in the inter-montane valley. However, there are no important key ecosystems reported in the valley. The only KBA mentioned in this KBA is located in the hills around a peak, covers an area approximately 100 km^2, and is considered of low reliance towards groundwater.

Table 3.4.6-a – Summary of the KBA found in the Western Hills GWZ (WCS) and reliance to groundwater

KBA name	Type of KBA	Priority	Area (km^2)	GW-ecosystem link	GW reliance
Kennedy Peak	Terrestrial	Data deficient	108	Mountainous, possibly springs	Low

3.4.7 *Summary - Assets and Issues*

- Productive aquifers in the colluvial fans abutting the Chin Hills are extensively used for town and domestic supply as well as irrigation.
- There are artesian zones both north and south of Kalay.
- There are difficulties with drilling in colluvial aquifers.
- There is a decline in groundwater pressure in artesian zones due to a failure to cap flowing tubewells.

3.5 Lower Chindwin Groundwater Zone

The Lower Chindwin GWZ comprises the catchment of the Chindwin downstream of the junction with the Myittha and above the junction with the Ayeyarwady, south of Yesagyo. The total area of the GWZ is 16,600 km^2. The Lower Chindwin GWZ has a total population of 1.80 million, and includes the major city of Monywa, with a population 195,000. It lies mostly within Sagaing Region, with a small area in the south in Magway Region. Rainfall in the Lower Chindwin GWZ averages 1,140 mm, ranging from less than 700 mm in the south around Yesagyo to more than 1,500 mm in the north around Kalewa. Evaporation is very high (mean PET >1,600 mm).

In this GWZ, two significant groundwater areas have been assessed in detail as part of the *Hydrogeology of the Dry Zone – Central Myanmar* (Drury, 2017; Figure 3.4.7-a):

Monywa Sub-basin[5] **—** The alluvial plain of the Lower Chindwin is bounded to the west by the Pale Sub-basin and east by the Kyaukka Range. To the south, the flats become swampy near the confluence with the Ayeyarwady River. Ground elevation of the alluvial plains gradually rises from 65 m near Monywa to 120 m towards the base of the Kyaukka Hills (elevated 150 to 375 metres above mean sea level [m AMSL]). The main towns are Budalin, Monywa, and Chaung-U. Drainage to the NNW-SSE flowing Chindwin River is from a series of ephemeral, sinusoidal gravel-bedded streams. Drainage is mainly east-west with all intermittent chaungs becoming braided as they cross the plain. 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 800 mm. Due to the presence of shallow, low-salinity groundwater, very few villages use surface ponds for domestic water supplies. There are many surface water pumping schemes that utilise the Chindwin River for irrigation purposes. No impounding dams or diversion weirs have been built on the tributaries, except in the Pale Sub-basin, described below. The Monywa Sub-basin contains the Monywa Groundwater Irrigation Project (MGIA). Hundreds of government and thousands of private tubewells and dugwells have been constructed. Some shallow dugwells need to be progressively deepened, due to groundwater extraction for irrigation purposes from underlying aquifers.

Pale Sub-basin — This basin lies within Yinmabin and Salingyi Townships, in the Sagaing Region. Yinmabin and Pale are the main towns. 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 were intentionally designed for groundwater recharge. Channels from the two dams supply irrigation water to the western part of the sub-basin, an irrigation area of 40 x 52 km. Surface elevation on the alluvial plains gradually rises from 110 m near Yinmabin to greater than 180 m towards the base of the eastern and western hills. Pre-dam construction, the North Yama Chaung dry season baseflow was recorded at 2,400 L s^{-1} (Groundwater Development Consultants [GDC], 1984). Discharge at the end of the dry season at the exit channel was recently measured at 3,937 L s^{-1} (2017), which may include some water from the upstream dam. The Pale Sub-basin contains the 99 Ponds Groundwater Irrigation Project.

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[5] This area is denoted Lower Chindwin in Drury (2017).

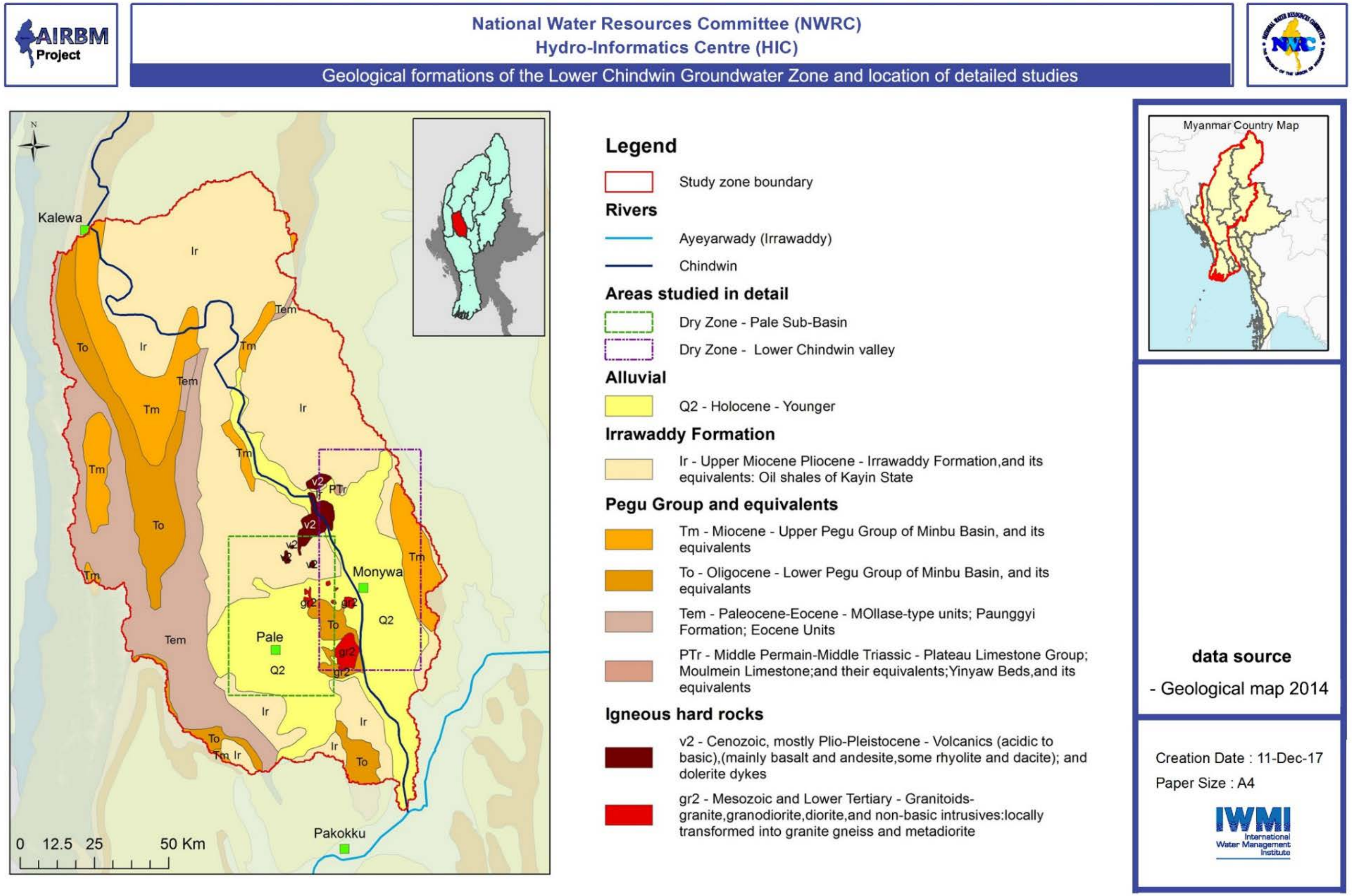


Figure 3.4.7-a – Geological formations of the Lower Chindwin GWZ and location of detailed studies

3.5.1 Regional Geology

The Lower Chindwin GWZ (Figure 3.4.7-a) includes parts of both the Western and Eastern Troughs, and is bisected by the Central Volcanic line. Sandstones of the Pegu Group (Oligocene [To] to Miocene [Tm]) and older Eocene meta-sedimentary rocks form hills in the west. These hills are mostly covered by forests and include the Alongtaw Kassapa National Park (1,600 km^2). The northern part of the GWZ is dominantly Irrawaddy Fm (Ir), loosely cemented sandstones outcropping over large areas as forested hills, east of Kalewa. In the central eastern area, north of Monywa, the Irrawaddy Fm hosts a mix of cropping with variable tree cover, with streams eroding ravines. These areas have not been studied in detail. Significant groundwater resources could be present, as favourable recharge conditions over the Irrawaddy Fm outcrops are favourable, and it represents an area where further investigation is warranted.

The southern part of the GWZ comprises the Monywa and Pale Sub-basins, and is dominated by recent Alluvium (Q2) underlain by Irrawaddy Fm. These areas have been extensively developed for groundwater irrigation.

Monywa Sub-basin is located along the Central Volcanic Line and in the southwest corner of the Shwebo-Monywa Basin of the Eastern Trough. Its main geological units are the following:

- Pegu Group outcrops in the east along the Kyaukka Range and west near Salingyi;
- Irrawaddy Fm, exposed along the alluvial boundary east and west of Budalin, and at the base of the Kyaukka Range;
- Igneous rocks, including extinct volcanic craters, copper ore volcanics, and intrusive rocks, at Powintaung and Salingyi, and basalts on Kyaukka Range; and
- Alluvium, which unconformably overlies weakly cemented sand of the Irrawaddy Fm.

Faulting and folding has strongly influenced the distribution of the various formations. The Alluvium and Irrawaddy Fm 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 Irrawaddy Fm and alluvial sediment along its axis.

Hydrogeological maps and cross-sections for Monywa Sub-basin are given in Figures 3.5.2 b and c.

Pale Sub-basin is located within the Western Trough. Its main geological units are the following:

- Eocene and Pegu Group sediments found along the western hills and near Salingyi.
- Irrawaddy Fm under the Alluvium, and exposed along the surrounding hills. It is subdivided into two important aquifer units, the upper Kokkogon and lower Ywatha/Aungban Fms.
- Alluvium, which unconformably overlies the Irrawaddy Fm in the centre of the sub-basin, filling topographic lows.

The Central Volcanic Line (granite, andesite, rhyolite, and basalt) and Pegu Group rocks crop out to the east in the ‘Salingyi Uplift’, which forms a hydrogeological divide that partly isolates this sub-basin from the Chindwin River/Monywa Basin. Groundwater resources are primarily located in the Irrawaddy Fm aquifers. Sediments of the basin are folded and faulted; these structures play an important role in groundwater movement.

Hydrogeological maps and cross-sections for Pale Sub-basin are given in Figures 3.5.2 d and e.

3.5.2 Main Aquifers

Table 3.5.2–a describes the characteristics of the main aquifers.

The major low-salinity and high-yield groundwater aquifers of the Lower Chindwin GWZ are in the Irrawaddy Fm (Ir—Kokkogon and Ywatha/Aungban Fms) and Alluvium (Q2—shallow sand and gravel). These units represent nearly the two-third of the total outcrop in the GWZ. A large percentage of the Alluvium and/or Irrawaddy Fm could be considered potential sources of high-yield and low-salinity groundwater for irrigation purposes.

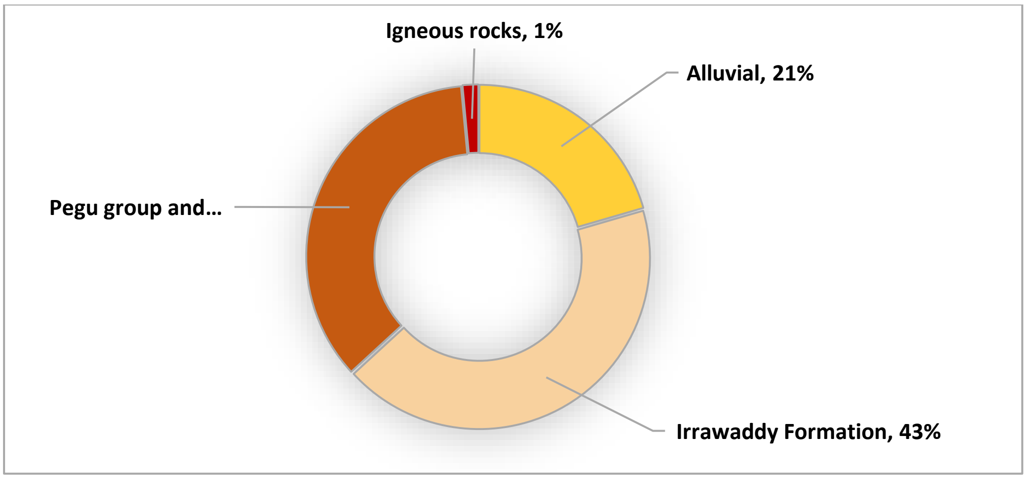


Figure 3.5.2-a – Spatial extent of major aquifer groups in the Lower Chindwin GWZ

Low-yield and brackish aquifers are encountered in the sandstones of the Pegu Group and Eocene rocks, which occupy approximately a third of the GWZ. Areas of granites and volcanics are small and very localized (Figure 3.4.7-a), and the groundwater yields are low due to the confining nature of the narrow fractures.

There are two major groundwater irrigation schemes in this GWZ: the 99 Ponds Groundwater Irrigation Project in the Pale Sub-basin (see Box 3.5.1); and MGIP in the Monywa Sub-Basin, between Budalin and Chaung U (see Box 3.5.2).

MGIP has been operational for 30 years, with 105 tubewells pumping at 50 L s^{-1} and 36 at 25 L s^{-1}. No hydrogeological monitoring has occurred since 1984. Water level decline is reported in some shallow aquifers, but no overall decline is observed. It is important that a groundwater monitoring system be installed to assess how best to manage the MGIP.

The 99 Ponds project has been operating since 1995. Initial artesian flows up to 80 L s^{-1} with maximum artesian pressure head of 15 m were recorded, but there has been a steady decline in flow and effective command area. Pre-2000, 7% of ponds quickly went dry, and were replaced under Stage 2; 24% of ponds have subsequently become dry, and 31% of ponds have significant lower flow. By 2016, the potentiometric pressure in the Ywatha/Aungban Aquifer had declined from 131 to 121 m AMSL, as a result of uncontrolled groundwater flow by both government and private irrigators. Hundreds of private artesian irrigation and domestic tubewells have been drilled. There is no control of artesian flow in non-irrigation periods, and no effective water management strategy.

Table 3.5.2-a – Summary of aquifer depth and characteristics in the Lower Chindwin GWZ

Aquifer type	Sub-basin	Specific location	Drill depth/ average (m)	SWL range (m)	Yield (L s^{-1})	Quality (μS/cm^{-1})	Hydraulic characteristics		
							Transmissivity ($m^2 day^{-1}$)	Hydraulic conductivity (m day^{-1})	Storage coefficient
Alluvium	Monywa	Monywa	15 - 70/45	3 - 18	10 - 50	500 - 2,500	200 - 15,000	18 - 44/24	8.4×10^{-3}
Irrawaddy Fm	Pale Monywa	Kokkogon Fm Ywatha/Aungban Aquifer Kyaukka	270 30 - 310 200	+ 5 - 20 + 10 - 30 5 - 10	5 - 50 18 - 100 1 - 25	600 - 1,900 <1,000 <1,500	100 - 1,700 2 - 170	1 - 65/30 30 - 260/100	5×10^{-4} 2×10^{-4}
Pegu Group	Monywa	Kyaukka	100	50	0.5 - 5	2,000 -10,000	0.5 - 70		
Eocene	Pale		280		0.5 - 5	>1,500		1 - 10	
Volcanics	Monywa	Cu Mine Area	30 - 240	2 - 30	0.5 - 4	500 - >10,000		3×10^{-4} - 7×10^{-2}	

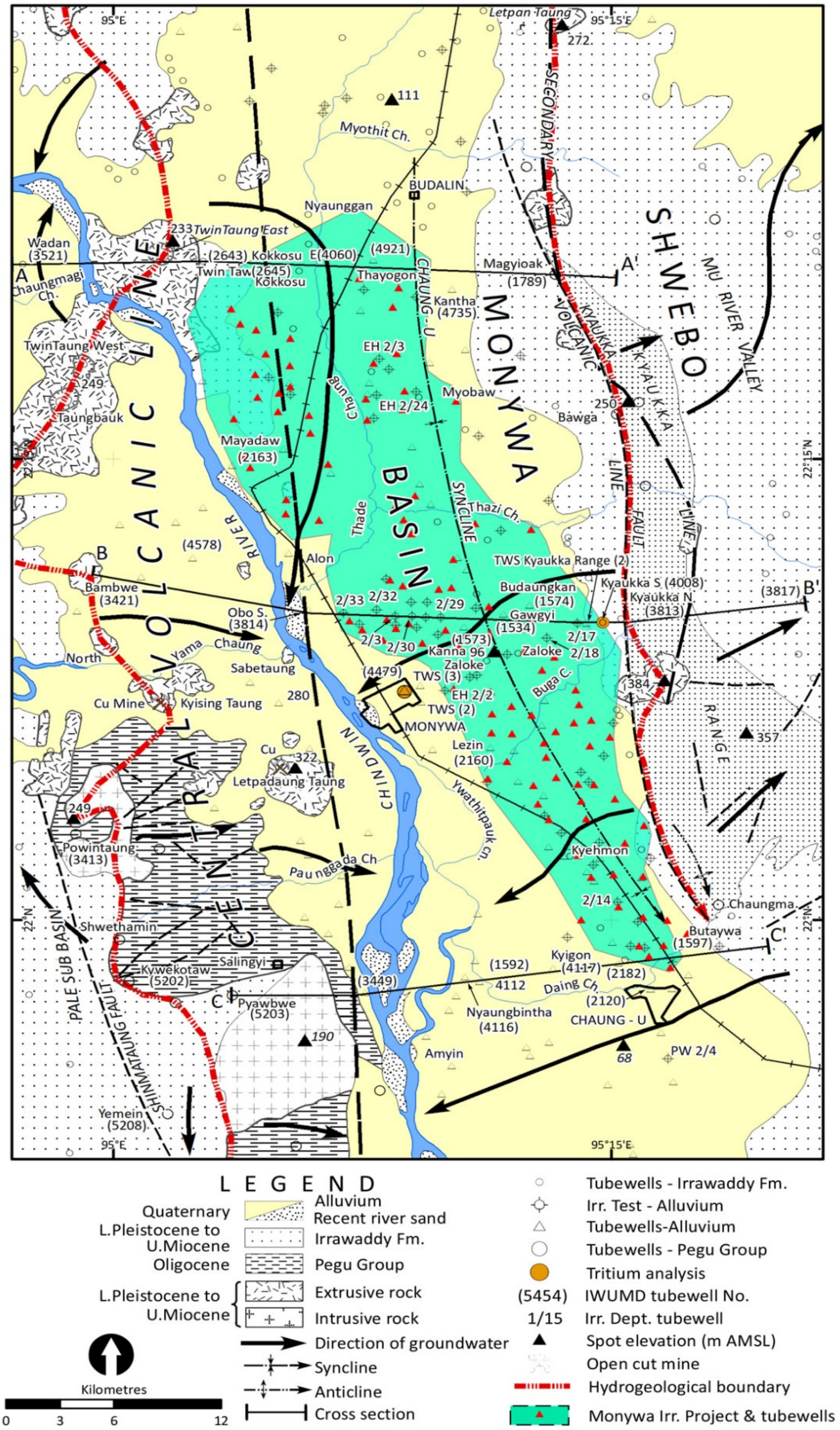
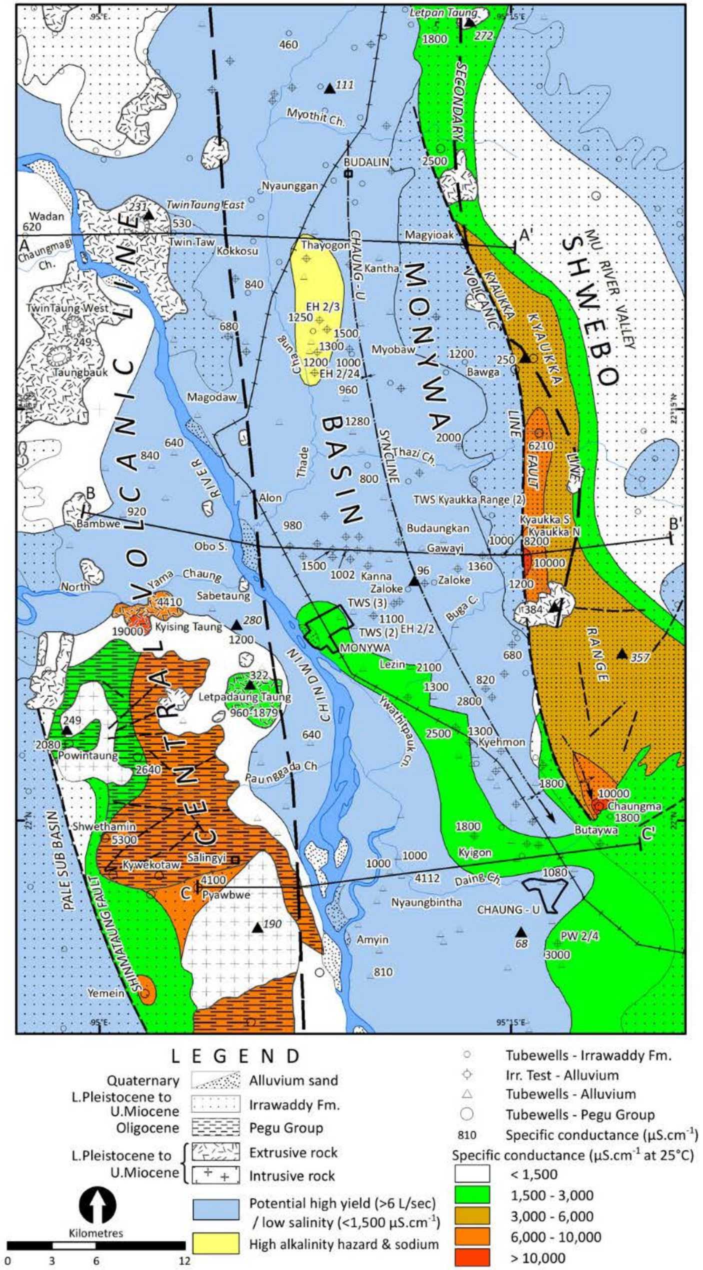


Figure 3.5.2-b – Hydrogeology of the Monywa Sub-basin (Drury, 2017)



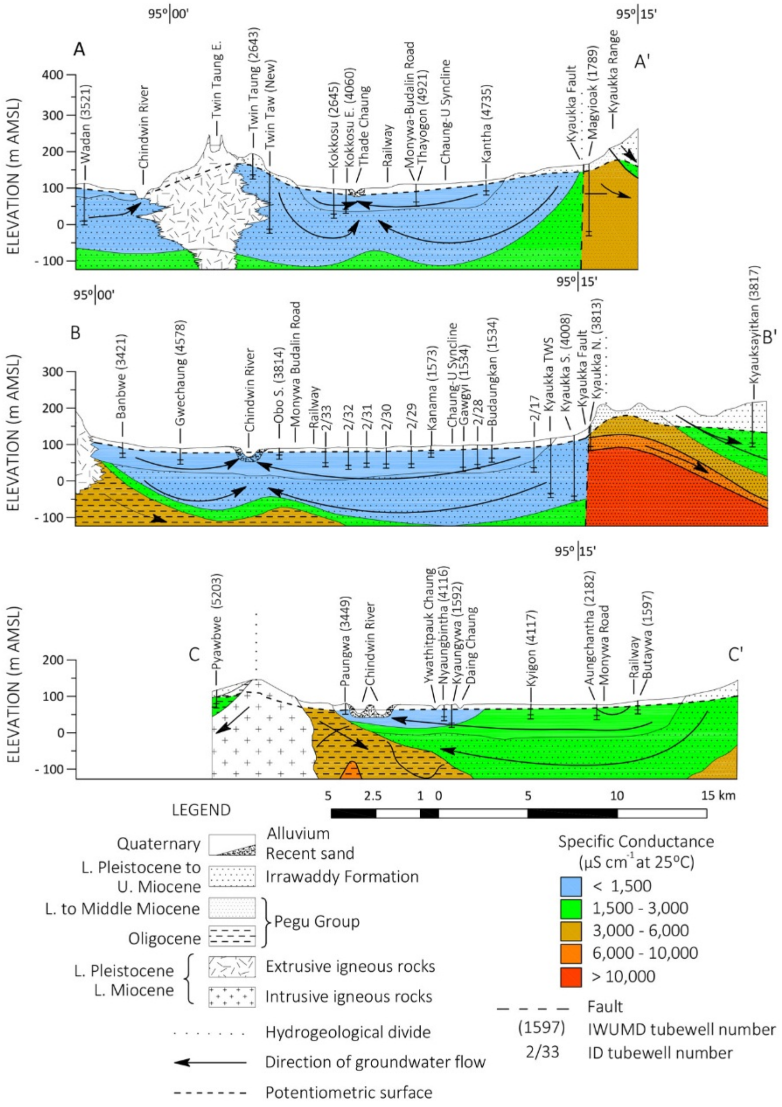


Figure 3.5.2-c - Hydro-chemistry and cross-sections of the Monywa sub-basin (Drury 2017)

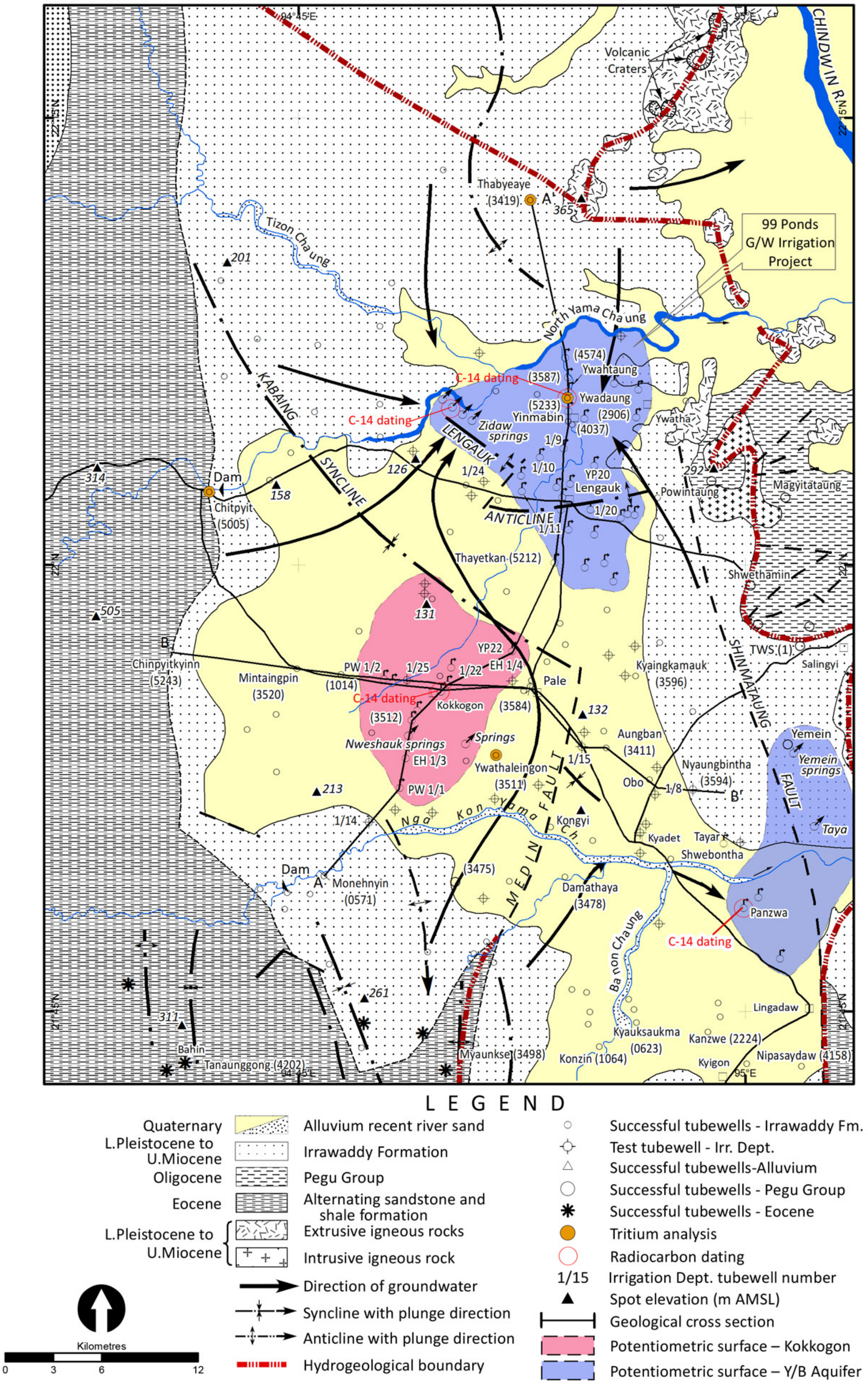
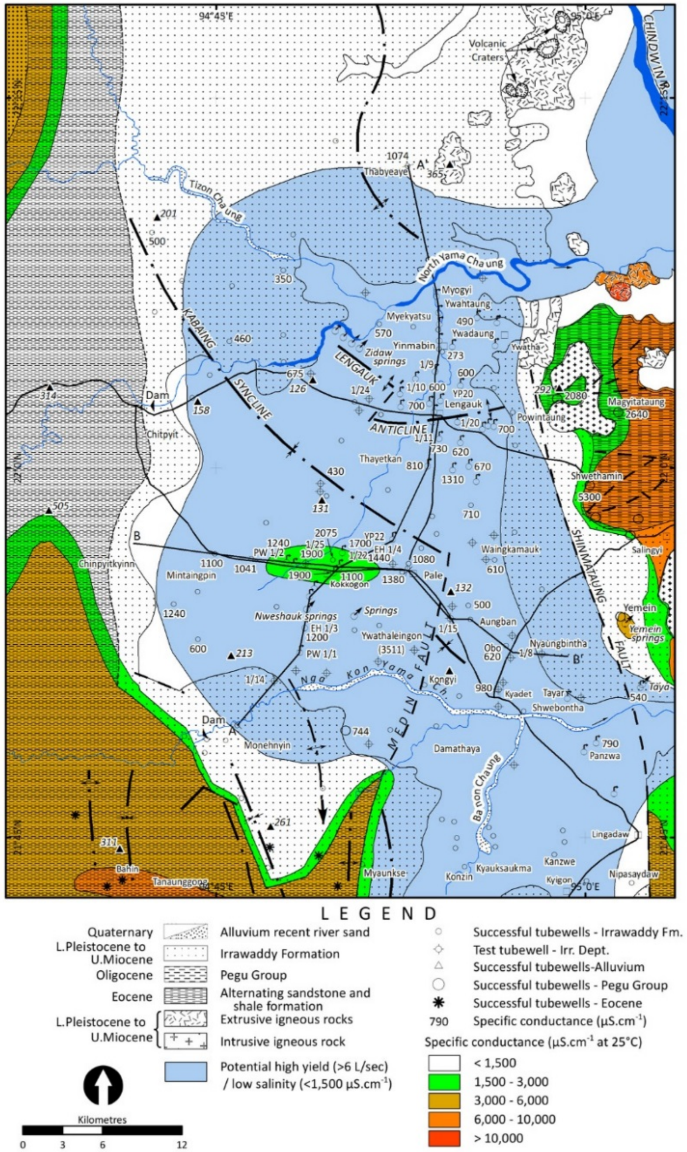


Figure 3.5.2-d – Hydrogeology of the Pale Sub-basin *(Drury, 2017)*



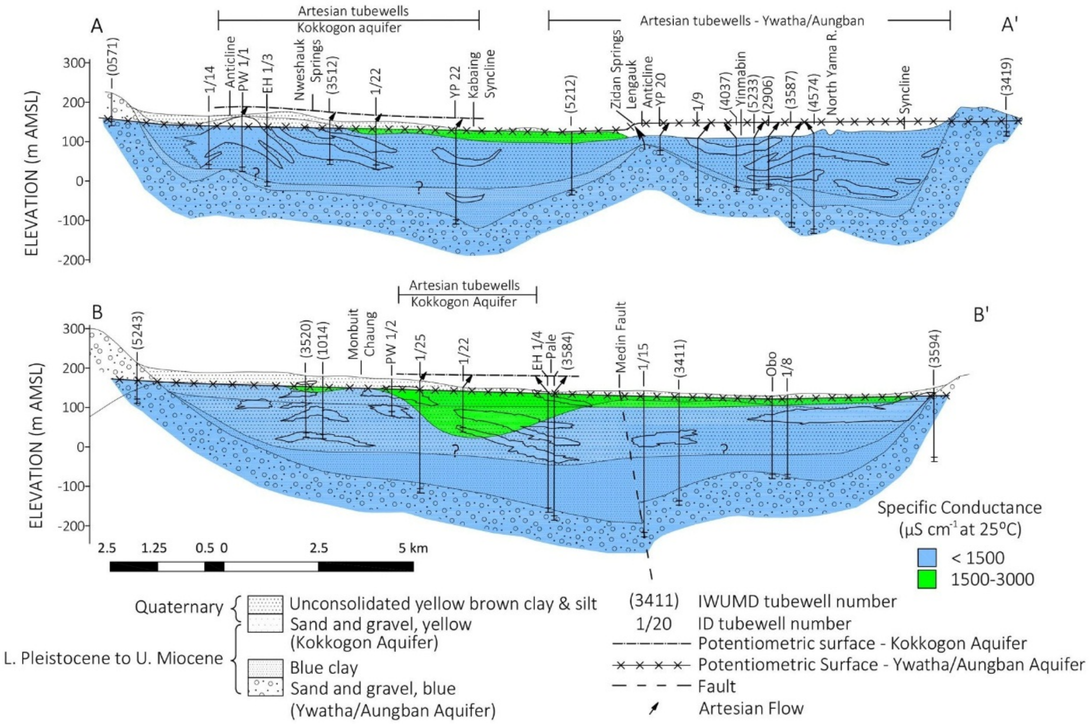


Figure 3.5.2-e – Hydro-chemistry and cross-sections of the Pale sub-basin *(Drury, 2017)*

BOX 3.5.2-a

Project: 99 Pond Groundwater Irrigation Project

Stage 1
Construction date: 1994 to 1995
Ponds: 99
Number of tubewells: 417 (each of the 99 ponds contains 3 to 5 artesian tubewells)
Irrigation command: 3,300 ha
Canals: 99 Nos.
Implementing agency: Government of Myanmar
Operator: IWUMD
Aquifer: Ywatha/Aungban Fm
Piezometric surface: Above ground 2 to 12 m
Artesian flow: 1 to 18 L s^{-1}, average 6 L s^{-1}
Stage 2
Construction date: 2000
Number of tubewells: 32
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 $Mm^3 yr^{-1}$
Hydrogeological profile:

Geology	Aquifer	Depth (m)	Lithofacies	Potential yield (L s^{-1})	Transmissivity ($m^2 day^{-1}$)	Extraction method
Holocene	Alluvium		Brown clay, sandy clay			
Lower Pleistocene	Kokkogon Fm	20 - 100	Yellow sand/gravel	1 - 10	250	Artesian/ pumping
Pliocene to Mid-Miocene	Ywatha-Aungban Fm	60 - >240	Blue gray sand/gravel	10 - 100	200 - 1,500	Artesian/ pumping

Pressure head decline: From 1996 to 2016, 2 to 10 m
Summary of Stage 2 average of 32 tubewell 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+}	Cr	SO_4^{2-}	HCO_3^-
	(mgL^{-1})	$\mu S.cm^{-1}$		(mgL^{-1})							
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

(Pavelic et al., 2015; Aung Khaing Moe, 2016; Win Tin, 2016; IWUMD)

Box 3.5.2-

Project: Monywa Groundwater Irrigation Area

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 s^{-1} + 36 @ 25 L s^{-1}) 120 DTW operational in 2016.
Potentiometric surface: Minimum of 15 m (north) and maximum of 45 m (central and south)
Operation: The system pumps 14 hours/day or longer to meet water demands.
Total groundwater extraction: 120 MCM to 53 MCM by government, 67 MCM private.
Crop demand: 1,200 mm for paddy and 600 mm for other.
Implementing agency: Funded by the United Nations Development Programme, the International Development Association, and the World Bank.
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 Fm	2 central 35 east			Clay aquitard
			>50	Blue sand	Aquifer

Aquifer:

- Hydraulic Conductivity: Alluvium — near hills (8 to 15 m day^{-1}), near Chindwin River and north (200 m day^{-1}) and south to Chaung-U (100 m day^{-1}). Irrawaddy Fm — uniform at 8 to 15 m day^{-1};
- Transmissivity: Alluvium — 1 to 15,000 m^2day^{-1}; Irrawaddy Fm — 2[6] to 170 m^2day^{-1};
- Storage coefficient: Alluvium — 0.16 to 8 x 10^{-3}; Irrawaddy Fm — 10^{-4}; and
- Groundwater yield average: 330 ML day^{-1}.

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+}	Cr	SO_4^{2-}	HCO_3^-
	(mgL^{-1})	µS.cm		(mgL^{-1})							
Monywa											
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

(IWUMD)

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[6] Maybe shallow Pegu Group

3.5.3 *Storage, Recharge and Water Balance*

A first pass estimate of recharge and storage in the GWZ as a whole is presented in Table 3.5.3–a. More detailed estimates for the productive aquifers of the Pale and Monywa Sub-basins are given in Table 3.5.3–b. 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.

Table 3.5.3-a - Estimate of storage and recharge properties of major aquifer units of the Lower Chindwin GWZ

Aquifer group	Outcropping area*	Aquifer thickness (m)	Rain (mm) average	R/R ratio	Sy assumed	Storage (Mm^3)**	Recharge (Mm^3)**
Alluvial	3,400	50	1,030	0.15	0.2	34,030	530
Irrawaddy Fm	7,080	90	1,450	0.15	0.2	188,770	1,540
Pegu Group and Sedimentary	5,870	50	1,660	0.05	0.08	23,470	490
Igneous rocks	250	50	1,060	0.05	0.08	990	10
TOTAL						247,260	2,570

**For storage, all Alluivum area was added to the Irrawaddy Fm, as Irrawaddy is underlying all Alluvium outcrops.*
***Estimates are based on assumptions and only indicative.*

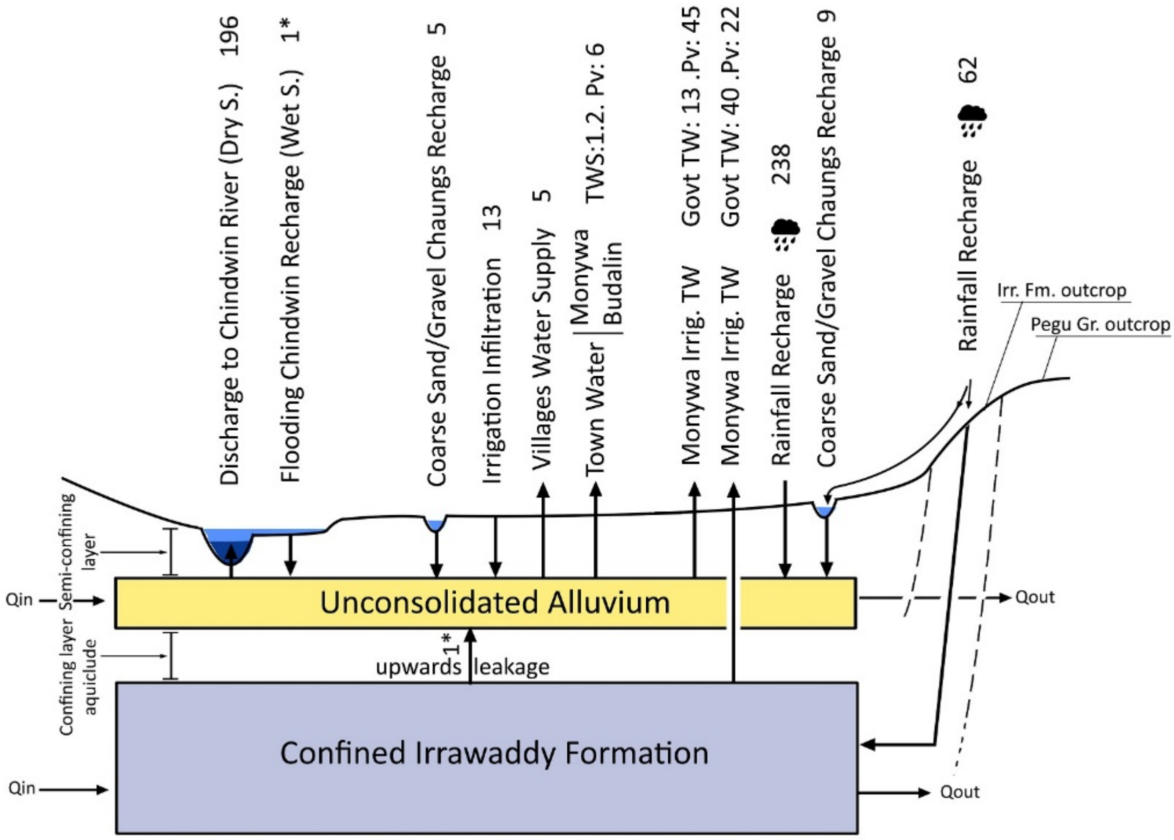
Table 3.5.3-b – Estimate of low-salinity groundwater in aquifer storage, Lower Chindwin

Location	Formation	Assumed depth (m)	Aquifer occurrence (%)		Storage (Mm^3)
Pale Sub-basin	Kokkogon Fm	150	Central to south	16	
	Ywatha/Aungban	350 - 500	Anticline/syncline	31 - 36	54,100
			Regional	21	
L. Chindwin River Valley	Alluvium	75 - 95	Regional	56 - 90	84,200
	Irrawaddy Fm	250 - 350	Regional	35 - 54	

In the Monywa Sub-basin, groundwater flow is towards the Chindwin River (Figure 3.5.2-c). The extent to which groundwater flow occurs between the Alluvium and Irrawaddy Fm aquifers is controlled by the presence of the clay layers (aquicludes). In the Pale Sub-basin, regional groundwater movement is from the recharge areas in the surrounding hills towards the centre of the basin. Groundwater discharge is mainly to Zidaw Springs (along the anticline), the North Yama River, and the artesian tubewells.

WATER BALANCE

Monywa Sub-basin — Based on estimates of vertical recharge from rainfall, irrigation, and watercourses (328 Mm^3 yr^{-1}), approximately 40% is utilised by groundwater extraction from the shallow Alluvium and deeper Irrawaddy Fm (132 Mm^3 yr^{-1}) in the Monywa sub-basin, and groundwater excess (60%) discharges to the Lower Chindwin River (196 Mm^3 yr^{-1}). The model results suggest that more groundwater could be extracted, but caution is required in respect to its impact on shallow tubewells, water quality, and environmental requirements. North of Twin Taung East could be a new development area but soil types and water quality would need detailed assessment. The MGIP has been operational for 30 years. Even though no hydrogeological monitoring has occurred since 1984 and water level declines in some shallow aquifers are reported, it appears that the groundwater irrigation system can be managed sustainably.



Units: Annual volumes in Mm^3

Figure 3.5.3-a – Water balance for main aquifers in the Monywa Sub-basin

Pale Sub-basin — The water balance model indicates a groundwater loss to the aquifer system (ΔS <0.2 Mm^3 yr^{-1}). This is supported by reduction in piezometric pressure documented by IWUMD. If the government and private artesian tubewells were closed when not required (assume 25% of time), a groundwater saving of 22.5 Mm^3 yr^{-1} would occur. Since the change in aquifer depletion has been slow (average <~0.2 Mm^3 yr^{-1} verses 96 Mm^3 yr^{-1} extraction), aquifer repressurisation could reasonably be expected with subsequent flow increase in springs, tubewells, and river discharge. Alternatively, additional groundwater development elsewhere in the basin may be possible.

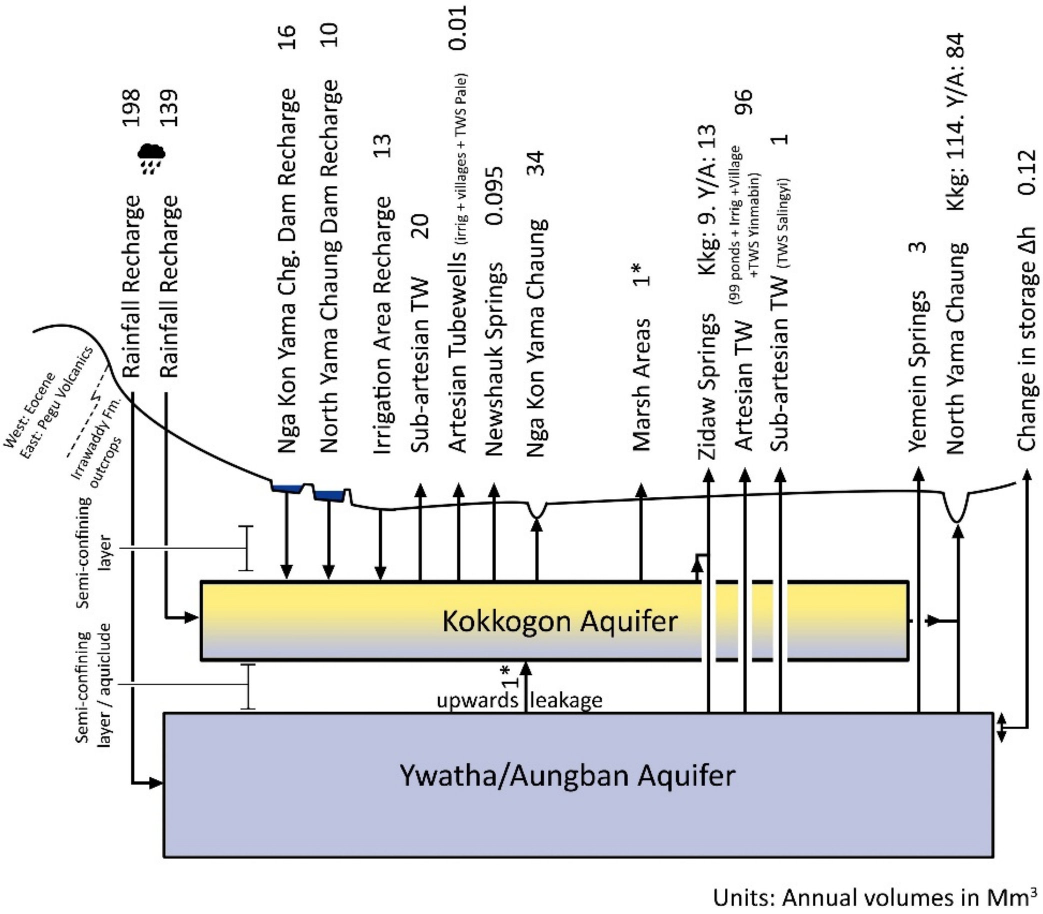


Figure 3.5.3-b – Water balance for main aquifers in the Pale Sub-Basin

GROUNDWATER DATING

Tritium analysis of groundwater from the Monywa Sub-basin indicates that modern recharge water is encountered in the shallow Ywatha/Aungban aquifer in the western hills; and along the Kyaukka Fault. The centre of the basin has older, pre-thermonuclear age groundwater.

In the Pale Sub-basin, the ages of groundwater in the highly permeable Ywatha/Aungban Aquifer range from 2,455 to 4,000 radiocarbon years, the youngest being in the Lengauk Anticline and the oldest near the sub-basin exit near Nga Kon Yama Chaung. In the centre of the basin the shallower, more clayey Kokkogon Aquifer has a groundwater date of 6,400 radiocarbon years. Table 3.5.3–c gives radiocarbon dating results for the Pale Sub-basin.

Table 3.5.3-c – Radiocarbon dating of groundwater in the Pale Sub-basin

Location	Depth (m)	Screen (m)	Formation	Sample date in 2017	Radiocarbon (carbon-14) dating (years)	Comment
Kokkogon Village	98	43 - 74	Kokkogon	12 May	6,415 ± 35	Kokkogon artesian area
Ywahtaung	159	146 - 158	Ywatha/Aungban	12 May	2,800 ± 25	99 Pond irrigation area
Zidaw Village	30	25 - 30	Ywatha/Aungban	12 May	2,455 ± 25	Western flank of anticline
Tayar Village	223	200 - 223	Ywatha/Aungban	12 May	4,000 ± 30	Southern artesian area

3.5.4 *Water Quality*

SALINITY

The aquifers of the Alluvium and Irrawaddy Fm are usually low salinity, with specific conductance below 1,500 µS.cm^{-1}. The Monywa Sub-basin has mostly Na^+:HCO_3^- type water, except immediately downstream of Pegu Group outcrops, where higher salinity Na^+:Cl^- type waters are found (1,500 to 5,000 µS.cm^{-1}). There is an extensive brackish salinity plume within the Alluvium and Irrawaddy Fm between the Monywa to Chaung-U, where the Pegu Group rocks occur at shallow depth. Waters in the Pale Sub-basin are also dominantly bicarbonate. Water from the Ywatha/Aungban Aquifer is better suited to irrigation than the Kokkogon Aquifer, with lower sodium absorption ratio (SAR)[7] and generally lower hardness (50 to 410 mgL^{-1} in Kokkogon Aquifer, 80 to 200 mgL^{-1} in Ywatha/Aungban Aquifer). Figure 3.5.2-e summarises data on the chemical composition.

Groundwaters from the copper bearing volcanics near Monywa have variable quality, and can be very saline (1,000 to 19,000 µS.cm^{-1}). Brackish to high salinity (1,500 to >10,000 µS.cm^{-1}) groundwater is found within the Pegu Group rocks (Na^+:Cl^- and Ca^{2+}:SO_4^{2}). Eocene rocks of the western hills have low salinity.

Figures 3.5.2 – c and 3.5.2 – e show the spatial variation in groundwater salinity in the Monywa and Pale sub-basins. Figure 3.5.4-a shows the variability in chemical composition of groundwaters in the two basins.

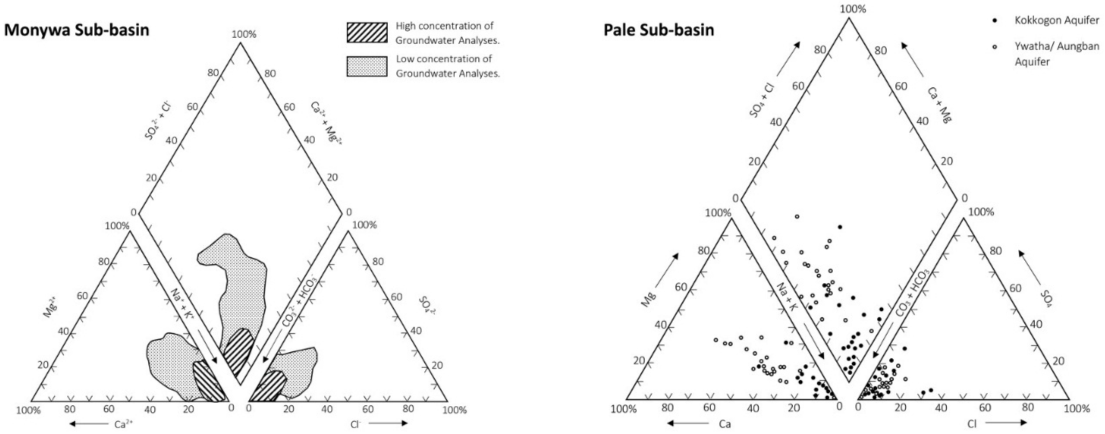


Figure 3.5.4-a - Piper-Palmer diagram for Alluvium and Irrawaddy Fm Aquifers

ARSENIC

Elevated levels of arsenic are not found in aquifers of the Chindwin River system, but only in the aquifers along the Ayeyarwady mainstream. No instances of arsenic levels above the World Health Organization (WHO) standard of 10 micrograms per litre (µg/L) were found in 221 samples from the Chindwin system around Monywa. Of the 500 samples taken in the Chaung-U Township, at the junction with the Ayeyarwady, 34 samples (6.8%) had arsenic above 10 µg/L (WRUD and United Nations Children's Fund [UNICEF], 2005).

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[7] The Sodium adsorption ratio (SAR) is an irrigation water quality parameter determined from the concentrations of the main alkaline and earth alkaline cations present.

GROUNDWATER POLLUTION

Like most large towns, Monywa generates municipal and industrial wastes, including the following:

- Fifty-two tons of solid waste (paper, organic waste, glass, plastic, textile, metal, and ash) daily;
- One million litres of septic waste per year, collectively generated by more than 20,000 septic tanks;
- Metal contamination (sodium, potassium, iron, zinc, copper, and cobalt), acids and alkalines, oils, solvents, food wastes, and paints generated by 588 industries; and
- Agricultural wastes (animal effluent and agrochemicals), which are stored and distributed (Ma Theingi Oo, 2006).

Large agricultural areas grow watermelon for the Chinese market, and 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. No chemical analysis of such contamination has been undertaken.

Monywa Copper Project — Like other copper projects close to alluvial deposits, there is potential soil and groundwater contamination centered under the heap leach pad, other mineral processing and rock dump areas, and waste water facilities. The local villagers use the old slurry and waste rock dumps to process copper. It is likely that there will be contamination to shallow aquifers downgradient of these small-scale village copper extraction areas. No water quality reports on the mining operation have been made available for review.

3.5.5 Groundwater Use

Approximately 77% of households in Lower Chindwin GWZ rely on groundwater for drinking water (Myanmar Census 2014). Tubewells are more common, but dugwells are still widely used (TW/DW ~2.6). Using census data (MIMU, 2014) on the percentage of households using groundwater at the township level, an assumed use of 135 L per person per day and population density maps (Gaughan et al., 2013), it is possible to map estimates of groundwater use from different aquifers.

Table 3.5.5-a – Estimated extraction for domestic use from aquifers in Lower Chindwin GWZ (Mm3 yr-1)

Aquifer group	Domestic abstraction Mm^3 yr^{-1}
Alluvial	37.6
Irrawaddy Fm	19.2
Pegu Group and Sedimentary	9.5
Igneous rocks	1.4
TOTAL	**67**

Groundwater is extensively used for irrigation, both in formal irrigation schemes and from small-scale farmer managed pumping. Hundreds of government and thousands of private tubewells and dugwells have been constructed in the Lower Chindwin. Some dugwells need to be progressively deepened, due to groundwater extraction for irrigation purposes from underlying aquifers (particularly in the vicinity of the MGIP).

The MGIP (see Box 3.5.2), initially constructed in 1982, now provides irrigation for 6,100 ha (2016) from 141 deep tubewells, 120 of which were operational in 2016. Total annual extraction is in the order of 53 Mm^3 from government wells, with a further estimated 67 Mm^3 from private tubewells. Initial monitoring for 2 years after construction (GDC, 1984) indicated no deterioration in water level, quality or yield; monitoring then ceased for 33 years and has only recently recommenced (April 2017). It is important that water level and groundwater extraction monitoring continues to assess the impact of the MGIP on the hydrogeological regime.

The 99 Pond Groundwater Irrigation Project was constructed in 1994 and upgraded in 2000, and now provides irrigation for 3,300 ha from 107 ponds. Estimated annual extraction is 44.7 Mm^3 from the formal scheme (2017), with a further 43.4 Mm^3 from private tubewells. Due to lack of flow control, there has been a steady decline in potentiometric pressure from 131 to 121 m AMSL, and a significant reduction of effective command area. Details are given in Box 3.5.1.

Total abstraction for agriculture is estimated at 236 Mm^3 annually within the Monywa and Pale Sub-basins. This provides a lower bound for abstraction for the GWZ. Currently, groundwater use outside these areas is limited.

MOAI estimated industrial use in Monywa in 2000 at 2 million litres per day (ML day^{-1}), projected to rise to 4 ML day^{-1} by 2015. Industries are mainly agro-processing, including production of cotton, flour, noodles, and edible oils.

Table 3.5.5-b – Range of estimates of groundwater use for Lower Chindwin GWZ (Mm3 yr-1)

	Industrial	Agricultural	Domestic	TOTAL	Source
Estimated use 2000	1	104	74	179	MOAI, 2003
Projected use 2015	2	119	186	307	MOAI, 2003
Pale and Monywa sub-basins only		236	13	249	This study
Estimated current use	3	Low: 236 High: 250	68	Low: 307 High: 321	This study

3.5.6 *Groundwater and Ecosystems*

Only two zones identified as important for conservation have been identified within the Lower Chindwin GWZ. The Alaungdaw Kathapa National Park is located on the thickly forested hills composed of Paelocene to Miocene sedimentary rocks including the Pegu Group Fm. In this hilly context and without reported wetland in the area, the link is considered low. Some groundwater influence on the Twintaung KBA is likely to occur through springs within the Cenozoic Volcanic aquifer of the Mount Popa area. Given the deficiency of data, the degree of reliance is considered moderate.

Table 3.5.6-a – Summary of the KBAs found in the Lower Chindwin and associated reliance on groundwater

KBA name	Type of KBA	Priority	Area (km^2)	GW-ecosystems link	GW reliance
Twintaung	Freshwater	Data deficient	8	Ravines in volcanic plain, springs?	Average
Alaungdaw Kathapa NP	Terrestrial	Medium	1433	Mountainous, possibly springs	Low

3.5.7 *Summary – Assets and Issues*

- A large percentage of the Alluvium and/or Irrawaddy Fm is potential source of high-yield and low-salinity groundwater for irrigation purposes.
    - Potential for expansion in Twin Taung East and some areas of Pale Basin.
    - Approximately 40% of recharge in Lower Chindwin GWZ is currently extracted.
- Potential resources in the Irrawaddy Fm in north of GWZ (currently not exploited).
- Pale sub-basin is fully developed, with a small net annual loss from the system and resulting loss of pressure. This could potentially be corrected by improved management.
- There is a high dependence for drinking and domestic supplies.
- Artesian irrigation systems at 99 Ponds and Monywa Groundwater Irrigation Projects (GIPs).
    - Sustainable extraction at MGIP.
    - Depletion at 99 Ponds could be reversed through proper management.
- Risk of pollution from the Monywa copper mine and small-scale village copper extractors.
- Arsenic occurrence in Ayeyarwady floodplain (Chaung U).

3.6 Middle Ayeyarwady Groundwater Zone

The Middle Ayeyarwady GWZ is located within the larger Middle Ayeyarwady HEZ. It comprises the lowlands of the middle reaches of the Ayeyarwady, between Myitkyina and Chaung Gyi, with a total area of 38,100 km^2. The total population in the GWZ is 1.42 million. The population density is low, at 29.6 inhabitants per km^2, with higher densities found along the Ayeyarwady River and in the intra-montane valleys. The largest town is Bhamo, with a population of approximately 52,000.

This area is bordered on the east and west by hills along major fault zones. In the east, the area is bounded by the Shan Fault complex, with metamorphic rocks of the Mogok Belt forming the foothills of the Shan Plateau. In the west, the Katha-Gangaw Range extends in a N-S axis, along the Sagaing Fault. Within this range are two parallel, long, narrow intra-montane alluvial valleys: one containing Indawgyi Lake, the other Hopin - Mohnyin.

South of Myitkyina, the Ayeyarwady River cuts through a series of hills until it reaches Bhamo Town, where it widens to form an alluvial plain fed by numerous streams descending from the Shan Plateau. Following a second constriction at Naungmo, the river opens into a 30-km wide alluvial plain near Takaung, then flows in a remarkably straight channel for 90 km along the Sagaing Fault until it is diverted by the hard rocks of the Chaung Gyi volcanics, which form the southern boundary, near Chaung Gyi.

Indawgyi Lake, Myanmar's largest natural lake and an important wetland area, is located in an intra-montane valley of the Katha-Gangaw Range. It is connected to the Ayeyarwady River through the Indaw Chaung, which flows out of the north of the lake. The Hpakant Jade mining area is 30 km north of Indawgyi Lake, but the mining area is in a different watershed (cf. Section 3.8).

3.6.1 Regional geology

The geology of the area is strongly controlled by the folding and thrusting related to the Sagaing Fault and the Shan Fault complex systems. A mix of older metamorphic rocks and more recent sedimentary units of the Tertiary Basin (Irrawaddy Fm) are found. Major geological features include:

- The N-S Sagaing Fault in the west, with Miocene rocks of the Pegu Group outcropping westwards and metamorphic rocks forming a wedge-shape range extending 200 km along the fault from Myitkyina southwards.
- Mesozoic granites in the east outcrop to forms hills at the foot of the uplifted Shan Plateau, where the Mogok Belt forms high mountain ranges.

In between the two older ranges, Upper Miocene and Quaternary alluvial deposits are found, intercalated with sedimentary formations of Cretaceous (Kalaw Red Beds), granitoid and volcanic intrusions of variable age.

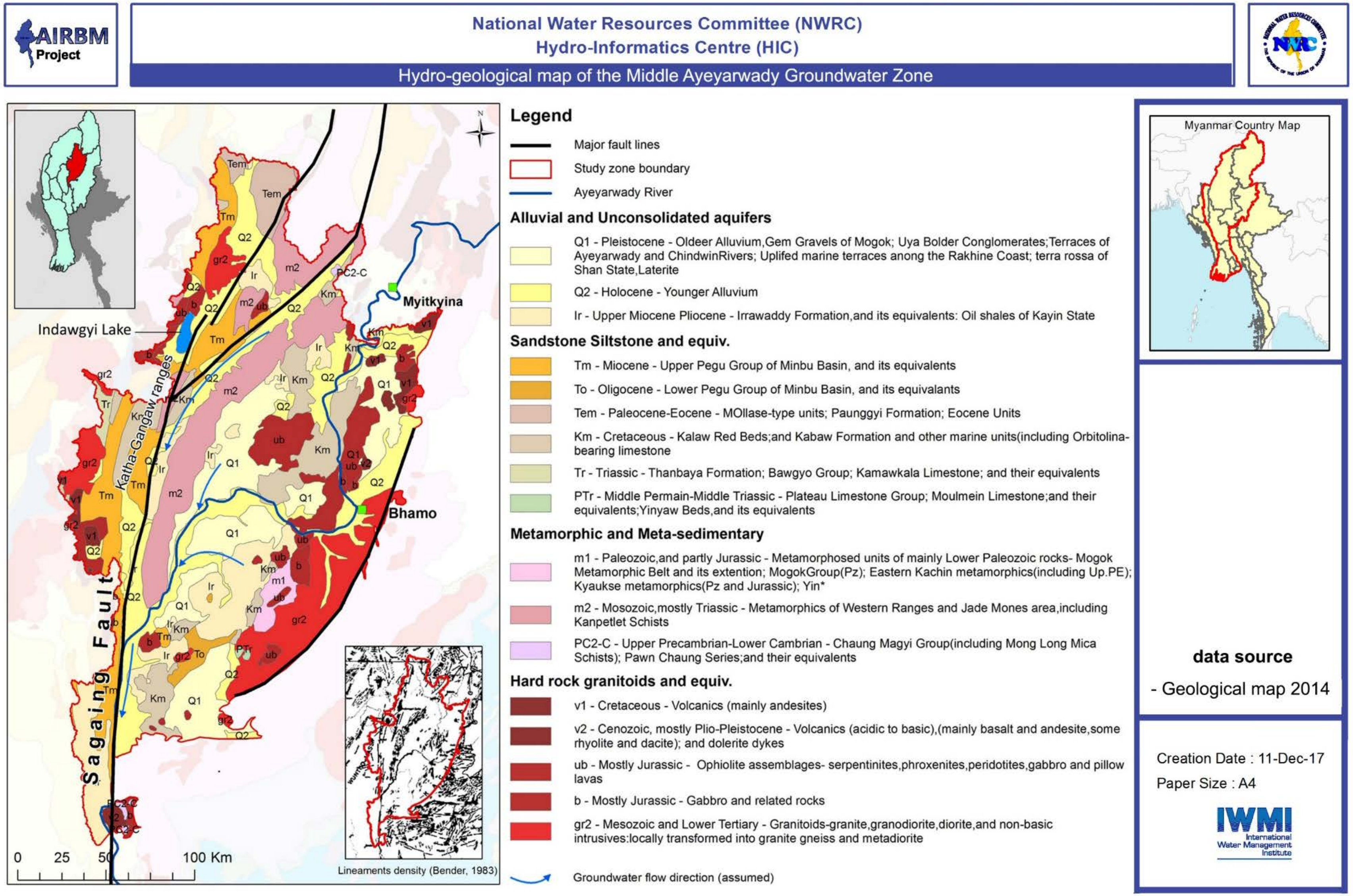


Figure 3.6.1-a – Hydro-geological map of the Middle Ayeyarwady GWZ

3.6.2 Main aquifers

The complex geology provides a wide range of groundwater systems, but there have been few hydrogeological studies carried out in the area. In general, it is assumed that groundwater will only be found in large quantities in the semi-unconsolidated aquifers of the Irrawaddy Fm (Upper Miocene) and Quaternary Alluvium. The folded and fractured hilly terrain, of mostly hard rock or metamorphic rocks is expected to have very limited groundwater storage, except in intensely weathered areas. The extent of the major aquifer groups is show in Figure 3.6.2-a.

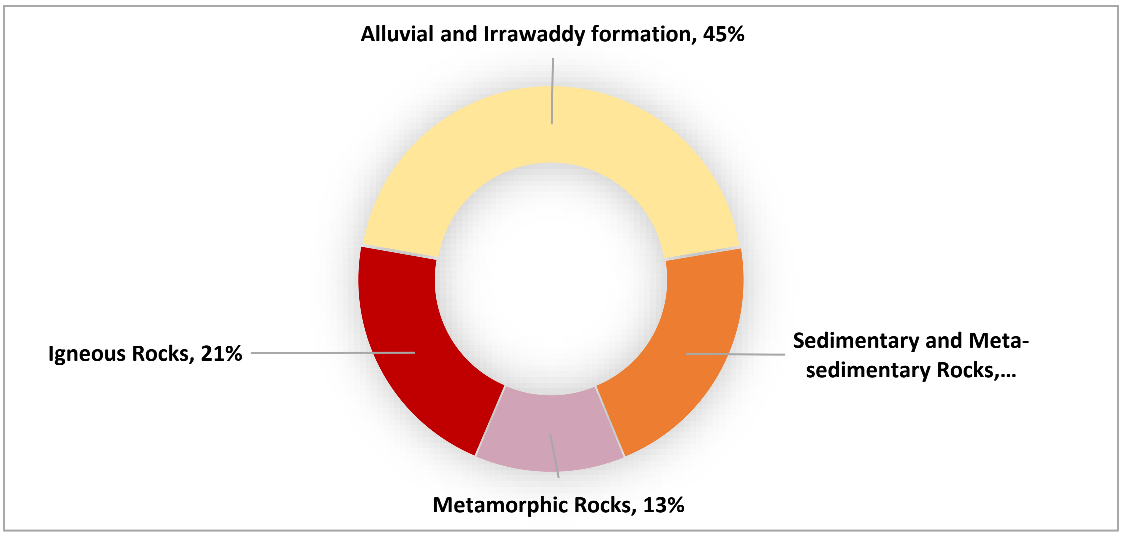


Figure 3.6.2-a – Extent of major aquifers in Middle Ayeyarwady GWZ

Alluvial aquifers are found in three major areas (see Figure 3.6.1-a):

- The intra-montane valley extending within the Katha-Gangaw Range (Figure 3.6.2-b). This aquifer is of limited width, usually less than 10 km, and is expected to receive high volumes of recharge from adjacent mountain ranges. Alluvial fan structures are expected. The boulders can be a constraint for exploiting the aquifer, although available logs do not show any evidence of such issue.
- The recent alluvium from the Ayeyarwady River and smaller streams draining from Shan State near Bhamo Town.
- The Ayeyarwady River alluvium and associated older sediments of Irrawaddy Fm in the central area and on the eastern bank of the river in the 90-km straight channel along the Sagaing Fault.

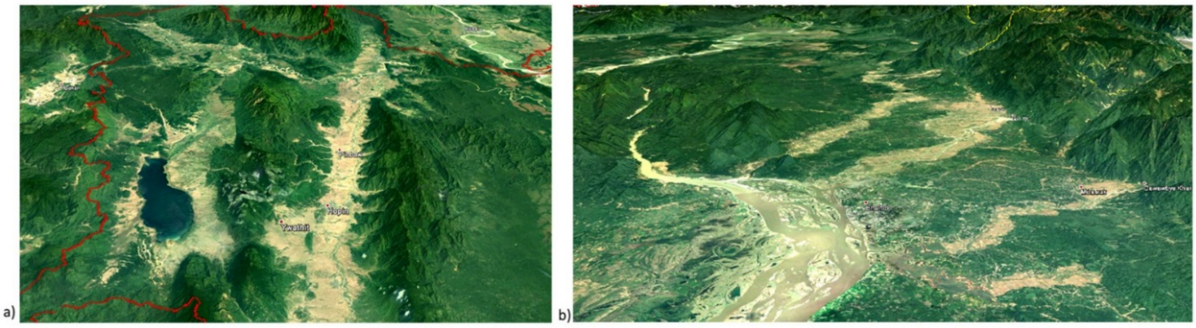


Figure 3.6.2-b – The north-west intra-montane alluvial valley and Indawgyi Lake (a; loc: 25.075, 96.537); alluvial deposits from the Ayeyarwady River and streams from Shan Plateau near Bhamo (b; loc: 24.263, 97.249). *(Google Earth imagery)*

Tubewell information for 132 holes was obtained from IWUMD, including coordinates. These data show that recent alluvium along river channels are often targeted, usually to supply small-scale irrigation. Using relatively shallow tubewells of often less than 50 m (46 m average), yields of 4.7 L s^{-1} can be expected for 10.16 cm diameter tubewells and 2.5 L s^{-1} for smaller 5 cm diameter tubewells.

GROUNDWATER FLOW

The groundwater flow has not been studied in the area, however, topography and aquifer properties can be used to broadly map the flow patterns. The general flow direction is north to south. Groundwater flow tends to follow topography and most of the year the flow is towards the rivers. In river meanders areas, both gaining and losing streams condition might occur over short distances. In the south the Sagaing Fault acts as a hydrogeological boundary. West of the fault, Miocene Pegu Group rocks outcropping as hills have low transmissivity and act as a barrier to groundwater movement. Flow is also constrained in the south by the metamorphic units of the Mogok Belt and Chaung Gyi Volcanics; it is estimated that all groundwater from the alluvial aquifer drains to the Ayeyarwady River.

3.6.3 *Storage and Recharge*

The quantity of groundwater stored within the aquifer units and the annual recharge rate can be estimated using broad assumptions. Alluvial and other unconsolidated materials cover 45% of the area (17,000 km^2). For the alluvial aquifer and Irrawaddy Fm, considering a total thickness of 50 m on average based on available tubewell logs and a specific yield of 15%, a total volume of 170,000 Mm^3 is estimated, demonstrating the importance of these two formations.

The groundwater recharge can be estimated, using a similar approach as in the Lower Ayeyarwady (Section 3.9.3), assuming a R/R ratio of 15%. High annual precipitation (>2,000 mm) leads to substantial recharge. The estimates in Table 3.6.3–a indicate a possible potential for groundwater in the area, but results must be treated with caution as there is no ground-based study to support these indicators.

Table 3.6.3-a – Estimate of storage and recharge properties of main aquifer groups

Aquifer group	Area km^2	Aquifer thickness (m)	Rain (mm) average	R/R ratio	Sy assumed	Storage (Mm^3)*	Recharge (Mm^3)*
Alluvial and Irrawaddy Fm	17,040	50	2,020	0.15	0.20	170,440	5,180
Sedimentary and Meta-sedimentary Rocks	8,180	20	2,290	0.08	0.08	13,100	1,500
Metamorphic Rocks	4,830	20	2,320	0.05	0.08	7,720	560
Igneous Rocks	8,170	20	2,130	0.05	0.08	13,070	870
TOTAL	38,220					204,330	8,110

**These values are broad estimates and only indicative.*

3.6.4 *Groundwater Quality*

ARSENIC

As part of a large hydrochemical investigation in 2005, five townships were selected in Kachin State for testing of arsenic in groundwater. A total of 1,598 tubewells were sampled in townships of Bhamo, Myitkyina, Mogaung, Mohnyin, and Waingmaw (located in the northern part of the study area and in the adjacent Upper Ayeyarwady GWZ), as reported by WRUD (2012). Arsenic was found in 66 samples (4.3%) in concentrations higher than the WHO limit (10 µg/L) and only 7 samples exceeded the Myanmar limit (50µg/L). This shows that although it might not be a major issue, arsenic can be found in the middle and upper reaches of the Ayeyarwady River Valley and appropriate chemical analysis should be carried out when new drillings are implemented.

NATURALLY OCCURRING GROUNDWATER CONTAMINANTS

There are no reports of other naturally-occurring groundwater contaminants in this GWZ, but data are very limited.

POLLUTION OF GROUNDWATER

Most of the areas of high population density and agricultural activity are underlain by alluvial and unconsolidated aquifers, which are particularly sensitive to pollution. The risk of pollution from agrochemicals is currently moderately low; Kachin State has one of the lowest use of chemical fertilizers in the country and only 1.6% of households reported using them (Hnin Yu Lwin et al., 2010). Pesticides use is not reported in this area. However, it is likely that use of agrochemicals will increase, as observed in neighbouring Shan State. Appropriate management measures should be taken to prevent excessive use of agricultural inputs in the alluvial plains and safeguard shallow aquifers.

There is some risk of bacterial pollution of shallow aquifers. On average, only 75% of households in this area have access to safe sanitation with much lower rates in some areas (for example, in Indaw Township).

Unregulated small-scale gold mining occurs from placer deposits in the Alluvium and unconsolidated Irrawaddy Fm, as well as in the riverbed of the Ayeyarwady River in this area. Between Myitkyina and Bhamo, 245 manual sluice and gold panning operations were identified in 2002 along the Ayeyarwady River. These operations were not observed in 2005, supposedly due to government interventions (WCS, 2002; 2007), but recent Google Earth satellite imagery from 2007 to 2014 shows several operations still extant (Figure 3.6.4-a). This land disturbance is confirmed in many areas by remote sensing (LaJeunesse Connette et al., 2016) although it is difficult to state the kind of activity occurring. Mercury is often used in separation of gold in informal operations (IAED, 2004; Osawa and Hatsukawa, 2015) and small quantities not recovered during processing can contaminate surface or groundwater systems. A study on mercury contamination near artisanal mining operations confirmed mercury in river sediments in several locations in Myanmar and in fish from Indawgyi Lake (Osawa and Hatsukawa, 2015).

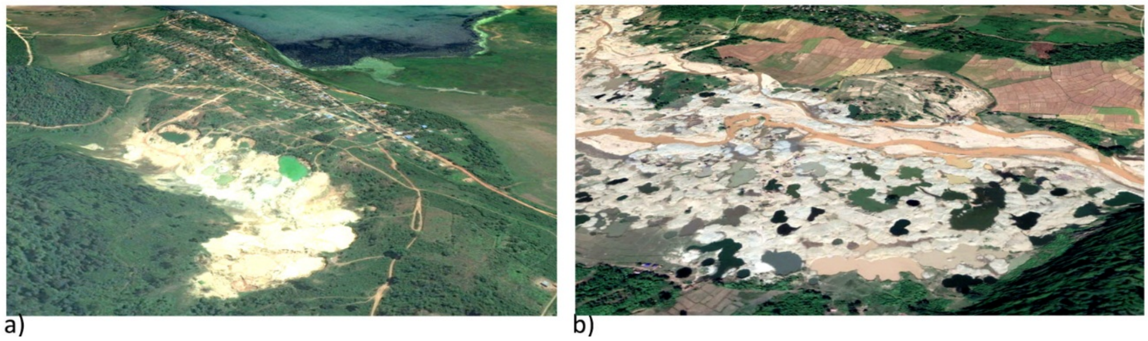


Figure 3.6.4-a – Land disturbance showing mining operations, often targeting gold deposits and using mercury in process: *Near the Indawgyi Lake (a; loc: 25.058, 96.280) and along an Ayeyarwady River tributary (b; loc: 24.147, 96.803)*

3.6.5 Groundwater Use

Approximately 75% of households in the Middle Ayeyarwardy use groundwater for domestic supply. In the areas around the Ayeyarwady mainstream, this is mostly from tubewells (TW/DW = 2 - 4), but in the intra-montane valleys, dugwells are more common (TW/DW <1). Using census data (MIMU, 2014) on percentage of households using groundwater at township level, population density maps (Gaughan et al., 2013), and assuming use of 135 L per person per day it is possible to map estimates of groundwater use from each aquifer group (Table 3.6.5–a).

Table 3.6.5-a – Estimates of groundwater abstraction from population density and 2014 Census data

Aquifer types	Domestic GW abstraction (Mm^3 yr^{-1})
Alluvial and Irrawaddy Fm	37.4
Sedimentary and Meta-sedimentary rocks	6.9
Metamorphic Rocks	3.6
Igneous Rocks	7.7
TOTAL:	56

IWMI landcover mapping indicates approximately 225,000 ha of double or triple cropping systems, which likely use irrigation. The majority of this is around Indawgyi Lake, and along the floodplains of the Ayeyarwady and major tributaries. While groundwater is likely to play some role, it is not likely a major source of irrigation. In the areas around both Myitkyina and Kachin State, national governments are investing in drilling tubewells for farmers.

No significant industrial use of groundwater is reported in the Middle Ayeyarwady GWZ.

Table 3.6.5–b gives range of estimates for groundwater use from different sources. Our estimates for agriculture are likely inflated because a proportion of the large number of wells drilled in Sagaing and Mandalay Regions are attributed to this GWZ, but are probably mostly in areas further south, in the Dry Zone.

Table 3.6.5-b – Range of estimates for groundwater use in the Middle Ayeyarwady GWZ

	Industrial	Agricultural	Domestic	TOTAL	Source
Estimated use 2000	0	4	63	67	MOAI, 2003
Projected use 2015	0	109	83	192	MOAI, 2003
Estimated current use	0	Low: 29 High: 180	56	Low: 86 High: 136	This study

3.6.6 *Groundwater and ecosystems*

Groundwater may play a significant function in supporting aquatic ecosystems in the Middle Ayeyarwady GWZ. WWF (2004) has mapped two major zones of wetlands in this region.

Indawgyi Lake and its surrounding wetlands are now classified as a ‘wetland of international importance’ under the Ramsar Convention. The site was identified by Tordoff et al. (2012) as a key biodiversity area in Asia. At Indawgyi Lake and wetlands, fluctuation in groundwater levels is known to impact on rice cultivation and is likely to similarly influence condition of wetlands around the lake (Bhandari, 2015).

WWF identified a major zone of riverine wetlands and small lakes connected to the rivers, stretching along the length of the Indaw and Ayeyarwady rivers in this GWZ, also identifed by Tordoff et al. (2012) as key biodiversity areas. Groundwater inputs to baseflow in the rivers are likely to play a role in supporting these ecosystems, particularly during the dry season. Connections between groundwater and wetlands in this area are poorly understood, and require further study.

Aside from the Indawgyi Lake and associated ecosystems, 11 other KBAs have been identified within the GWZ, including several sections of the Ayeyarwady River that are considered connected to groundwater systems through dry season flow support to a certain extent. Aerial images show that the Kamaing KBA consists of a meandering stream that flows southwards from the north-west edge of the GWZ. Quaternary alluvial deposits present in the area are most likely connected to the meanders and marshes and actively support the ecosystem functions.

3.6.7 Summary – Assets and Issues

- There are important alluvial deposits, 50 m deep and actively recharged.
- Groundwater is used for domestic and for small-scale and irrigation that is supported by the government.
- Groundwater inputs to Indawgyi Lake and riverine wetlands.
- There is a potential for mercury pollution from current and past alluvial gold mining operations.

Table 3.6.7-a – Summary of the KBAs found in the Middle Ayeyarwady (WCS) and associated reliance on groundwater

KBA name	Type of KBA	Priority	Area (km^2)	GW-ecosystems link	GW reliance
Kamaing	Terrestrial	High	588	Meanders and Q2 Alluvial plain	High
Indawgyi grassland and Indaw Chaung wetland	Freshwater	Medium	258	Mountainous, possibly springs	Low
Indawgyi WS	Terrestrial	High	737	Alluvial plain and wetland around lake	High
Upper Mogaung Chaung Basin	Terrestrial	High	188	Average, small Alluvial plain	Average
Pidaung WS	Terrestrial	Medium	150	Mountainous, possibly springs	Low
Nam Sam Chaung (Kachin State)	Terrestrial	Medium	458	Small hills	Low
Ninety-six Inns	Terrestrial	High	587	Large river (Ayeyarwady) Alluvial plain, no reported wetland	Average
Ayeyarwady River (Bhamo)	Freshwater	High	102	Large river (Ayeyarwady) Alluvial plain, no reported wetland	Average
Ayeyarwady River (Bhamo to Shwegu Section)	Freshwater	High	200	Large river (Ayeyarwady), Alluvial plain, oxbow lakes	Average
Ayeyarwady River (Moda Section)	Freshwater	High	303	Large river (Ayeyarwady) Alluvial plain, oxbow lakes	Average
Ayeyarwady River (Shwegu)	Freshwater	High	373	Large river (Ayeyarwady) Alluvial plain, no reported wetland	Average
Momeik-Mabein	Terrestrial	Medium	2,821	Mixed hills and valley, geology: Alluvial	Average
Ayeyarwady River (Singu Section)	Freshwater	High	75	Large river (Ayeyarwady) Alluvial plain	Average

3.7 Shan Plateau Groundwater Zone

Located in the Sino-Burman Mountain Ranges in the northeast of Myanmar and bordered by China, the Shan Plateau GWZ covers the part of the Shan Plateau located within the Ayeyarwady Basin. It encompasses approximately one third of Shan State (in the west and north), and includes most of the districts of Kyaukme and Pyin Oo Lwin, and parts of Taunggyi, Lashio, Bhamo, Muse, Loilen, Kyaukse, and Meiktila. The Shan Plateau GWZ extends into China 200 km north of the border town of Muse. The total GWZ area is 71,500 km^2, with 54,500 km² in Myanmar and an additional 17,000 km² (23% of total area) within China. The area within China is not considered in this report.

Main towns are located along the road towards China, including Pwin Oo Lwin, with a population of 162,000, Lashio, with 147,000, as well as Hsipaw and Muse. The overall population density is low, at 46 inhabitants per km². However, like most of Myanmar, the Shan State has seen a population increase of 36% from 1983 to 2014 (Census, 1983-2014).

The Shan Plateau is separated from the central basin both in terms of geography and geology by the Shan Boundary Fault complex (see Geology section below) running north-south to the east of Mandalay. From Mandalay City in the plain to Pyin Oo Lwin, located 40 km east and marking the start of the plateau, the altitude rises from 80 m up to 1,100 m. The maximum elevation is 3,740 m, on the Chinese side of the border. Main geomorphological features are the plateau with gently undulating hills, and mountain ranges. In between ranges, some intra-montane valleys flats have developed.

The climate is humid sub-tropical (Köppen-Geiger classification). The warmest months are April and May, while the coldest are from December to January. Due to altitude, temperature ranges widely; for example, in Lashio Town (altitude: 770 m) average daily minimum temperature can be as low as 11°C in January, with frost is observed in higher elevations, while average daily maximums can be as high as 31°C in April. Most precipitation occurs during the rainy season from May to October. Annual rainfall ranges from 1,050 mm in the foothills of the plateau near Mandalay, up to 2,454 mm in highest ranges. Average precipitation is 1,800 mm in the study area.

The main river is the Myitnge, which is also referred to as the Namtu in upper reaches. Running from NNE to SSW for 440 km, it cuts a deep gorge of a depth of up to 400 m through the plateau starting 40 km south of Hsipaw and eventually reaches the Ayeyarwady River 15 km south of Mandalay. Although perennial rivers are rare in the plateau, springs and intermittent streams are abundant.

Figure 3.6.7-a - The Mytinge River cuts a gorge through limestone plateau exposed near Goteik Bridge (loc. 22.342, 98.858) (Photo: Creative Commons — Clay Gilliland)

3.7.1 Regional Geology

The geology of the Shan State Plateau is particularly complex and under-studied, partly due to political unrest in the last 50 years. The Shan Boundary Fault zone, running North-South over more than 1,000 km, acts as a boundary between the Eastern-Burma Tertiary Basin and the continental Sino-Burma Ranges. Part of the Sino-Burma Ranges, the Shan Plateau consists of mostly Late Precambrian to Cretaceous sedimentary, metamorphic, and plutonic rocks (Bender, 1983). The fault zone originated during Mesozoic or earlier, reactivated during Cenozoic (Bender, 1983) and induced large vertical movement of more than 1,000 m in some places (U Soe Min, 2010). The intensity of folding and faulting varied in time and space between Carboniferous and Jurassic. As well as the major N-S fault lines (Sagaing, Kayaukkyan, and Pan Laung), lineaments have been mapped using Landsat imagery (Bannert and Helmcke, in Bender, 1983) and show a higher fracture density in the Northern Shan State (Figure 3.7.1-c).

Figure 3.7.1-a - View over the plateau on the southern boundary of the study: *Alluvial infill in the linter-montane valley. Taunggyi City and mountain range seen in the distance (limestone). Inle Lake is in the rainy area on right side. Location: 20.733, 96.970 (photo: Viossanges).*

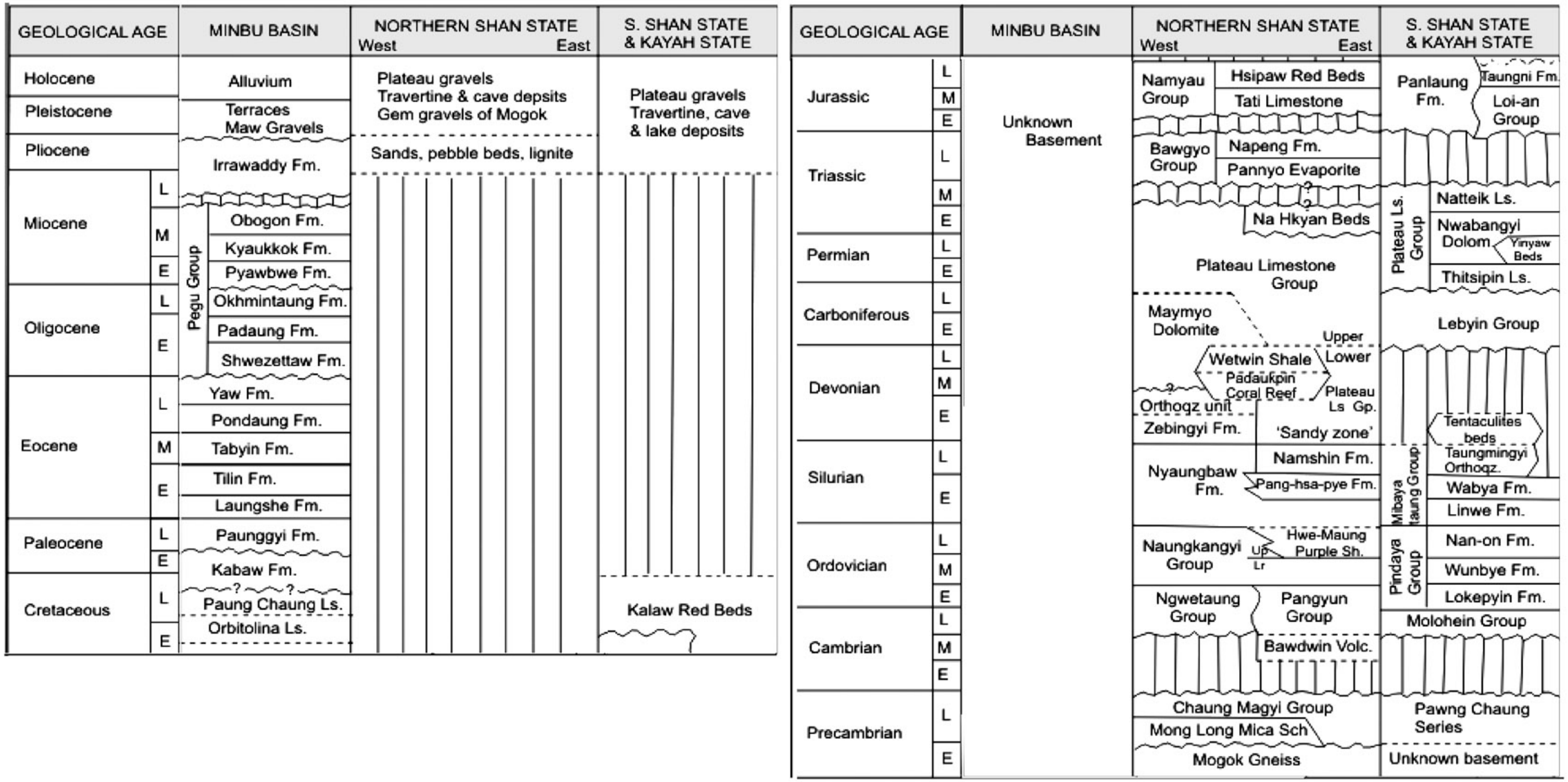
The metamorphic Mogok Belt extends on the northwest margin of the plateau from 40 km north of Mandalay, initially in S-N axis then SW-NE axis. These rocks cover up to 20% of the area and include gem-bearing formations.

Granitoid intrusions occurred at variable periods and are often related with the Shan Fault system. They are found outcropping mainly in the southern margin of the plateau.

Sedimentary formations (sandstones, mudstones, and limestones) are the most abundant rock-types, covering 69% of the area. Thickness of sedimentary formations is often several hundred up to thousands of metres. The mid-Permian to mid-Triassic group referred as Plateau Limestone covers a large extent of the plateau, between Pwin Oo Lwin and Lashio (**Figure *3.7.1-c***). Other sedimentary and meta-sedimentary rocks form mountain ranges, notably the late Pre- and Early Cambrian Chaung Magyi Group of sandstones and shales.

During the Quaternary period, alluvial deposits infilled the intra-montane basins, resulting from tectonic activity. Alluvial deposits are relatively limited in extent, to 2% of the total area.

The stratigraphy is shown in Figure 3.7.1-b and geological units in Figure 3.7.1-c.



Sratigraphic units of North-East Myanmar, modified from Bender, 1983; Maung Thein, 2000

Figure 3.7.1-b - Stratigraphic units of Northeast Myanmar: *(Modified from Bender [1983] and Maung Thein [2000])*

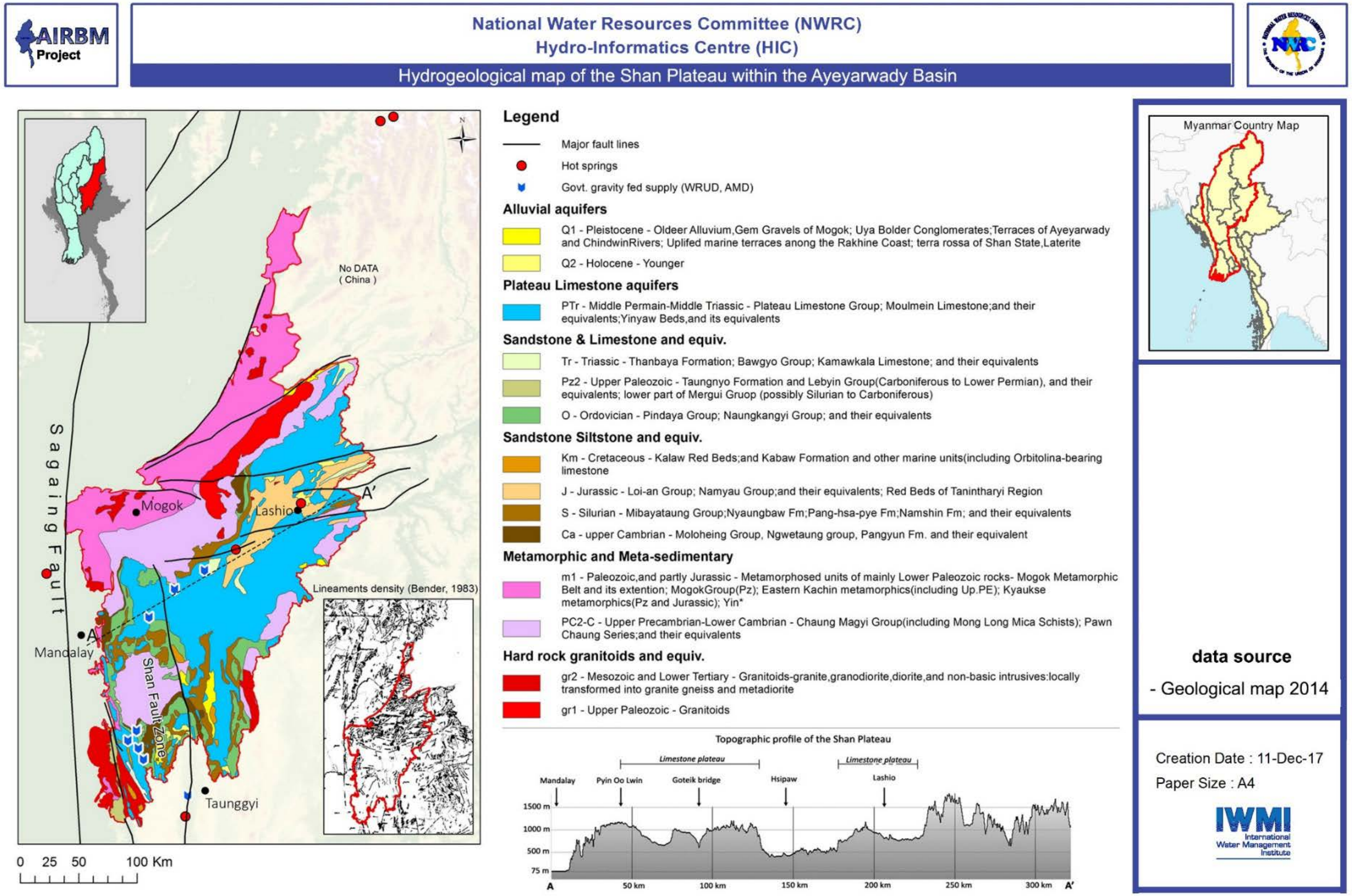


Figure 3.7.1-c – Hydrogeological map of the Shan Plateau within the Ayeyarwady Basin

3.7.2 *Main aquifers*

In terms of groundwater systems, the geological units of the Shan GWZ can be divided into six aquifer groups: (i) Alluvial aquifers, (ii) Plateau Limestone, (iii) Limestone/Sandstones, (iv) Sandstones and equivalents, (v) Metamorphic and meta-sedimentary aquifers, and (vi) Granitic aquifers. The relative areas are show in Figure 3.7.2-a.

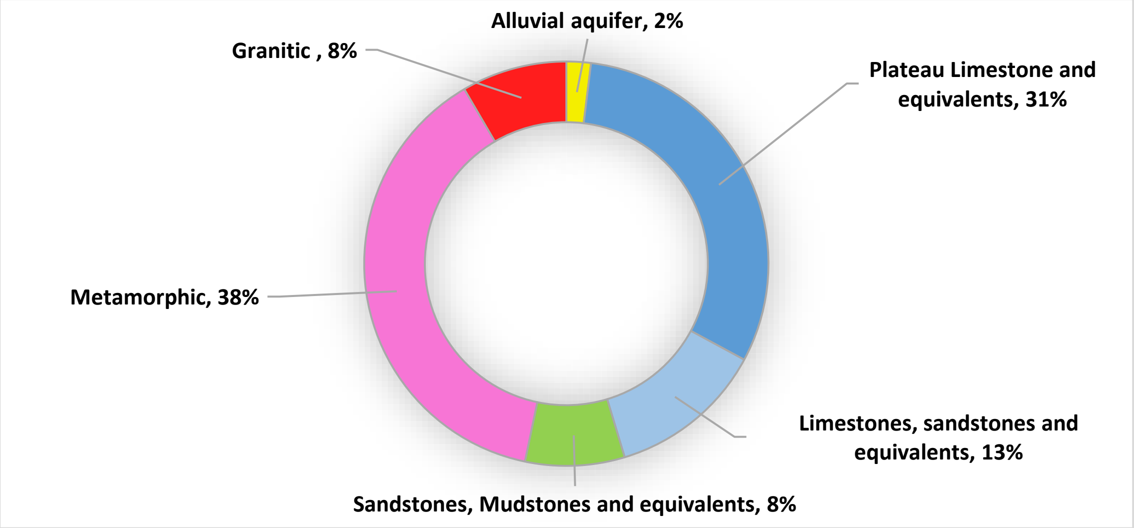


Figure 3.7.2-a - Relative areas of major aquifers in the Shan Plateau GWZ

ALLUVIAL AQUIFERS

The Alluvium is composed of Quaternary sand, silts, and gravel mostly of fluviatile origin. Mapped units cover only 2% of the area, but actual extent may be higher, as smaller alluvial deposits are often not mapped. These are found as small 'pockets' along rivers and intra-montane basins and are usually not thick (<50 m). Superficial lateritic soils overlaying meta-sedimentary and sedimentary geological units, usually at most tens of metres thick (and also often not mapped), are considered in this group.

There is very limited data on this aquifer unit in Shan State, although it is relied upon by communities for domestic supply. The Japan International Cooperation Agency (JICA, 2001) provides basic data on some tubewells in alluvial aquifer in several locations across the area (Table 3.7.2–a). Based on alluvial deposits found elsewhere in Myanmar, yields up to 6 to 12 m^3/h can be expected. Small diameter (2 to 4 inche) wells are drilled by private drillers at affordable cost.

Table 3.7.2-a – Table of alluvial wells sampled in study area (JICA, 2001)

No.	District	Township	Village/Place	Lat	Long	Elevation (mAMSL)	Aquifer	WL (m)	TOC (m)	SWL (mBGL)	Depth (mBGL)	T°C	PH	EC (µS/cm)	DO	Coliform	Note
24	Lashio	Theinni	Pesa	23.238	97.914		Alluvia]	0.5	0.5	0	3.2	24.3	6.27	9.75	5.6	1	spring
28	Kyaukme	Thipaw	u Aung (Route	22.592	97.412	550	Alluvial	0	0	0		25.8	6.38	0.399	5	100<	
29	Kyaukme	Thipaw	San Phaik	22.615	97.283	490	Alluvial			0		22.8	6.11	0.147	1.9	100<	
30	Kyaukme	Thipaw	Bowgyo	22.585	97.241	460	Alluvial	4.8	0.75	4.05	7.2	25.4	6.65	1.028	4.8	100<	
18	Lashio	Theinni	Kungkok BEPS	23.324	98.098	630	Alluvial	0.9	0.65	0.25		25.3	6.63	0.464	1.5	49	drinking
19	Lashio	Theinni	m Salad (Wel	23.352	98.215	910	Alluvial	0.9	0.6	0.3	4.45	26.8	6.93	1.139	5.9	84	drinking
21	Lashio	Theinni	Se Oo (Well 1)	23.309	98.041	665	Alluvial	1.2	0.45	0.75	3.1	27.3	5.28	0.081	6	8	
23	Lashio	Theinni	Nante	23.372	98.353	620	Alluvial	0.35	0	0.35	1.4	24	7.02	0.702	5.2	100<	
5	Muse	Naung Khan	aung Khan BEP	23.878	97.742	770	Alluvial	3.9	0.65	3.25	5.1	23.1	5.95	0.234	-	2	No.l
6	Muse	Naung Khan	Man Khan BEP	23.866	97.728	755	Alluvial	3.25	0.8	2.45	5.5	23.4	5.73	0.141	-		No.2
7	Muse	Naung Khan	Kon Sar BEPS	23.856	97.716	740	Alluvial	tap from spring				22.9	6.39	0.621	-		
8	Muse	Naung Khan	Kun Long	23.826	97.65	760	Alluvial	3.05/0.75/2.30			5.15	24.7	6.07	0.369	-		
10	Muse	Naung Khan	Ngwn In	23.821	97.667	780	Alluvial	flowing			1.9	23.1	5.12	0.081	-		
11	Muse	Muse	Nam Tee	23.813	97.658	780	Alluvial			0		23.5	5.24	0.073	-		
12	Muse	Muse	Tein Lon	23.961	97.863	765	Alluvial	2.9	0.85	2.05		23.3	6	0.271	-		
13	Muse		Pan Kham	23.968	97.869	745	Alluvial	1.63	0.7	0.93					-		
14	Muse	Kyukok	yukok (Pan Sa	24.075	98.065	850	Alluvial	public tap				21.6	6.53	0.647	6.4	23	
15	Muse		Nam Gaung	24.013	98.045	985	Alluvial	public tap				22.1	7.06	2.638	5.4	100<	
16	Muse	Kukhaing	haing TS Hosp	23.46	97.929	1335	Alluvial				115	21.1	7.29	0.881	7.8	12	DTW (No. 8025)
9	Muse	Naung Khan	Shwe Li Bridge	23.729	97.631	785	Alluvial?	public water				-25	-5.95	-0.079	-		
3	Mekhtila	Kukhaing	Man Pyein BEP	23.339	97.955	1070	Laterite	2.07	0.57	1.5	3.02	22.1	7.16	0.536	1.9	100<	
4	Mekhtila	Kukhaing	Man Naung BEP	23.396	97.941	1360	Laterite	spring				19.3	6.98	0.418	6.1	100<	
25	Lashio	Lashio	shio Hot Spri	22.99	97.777	740	Limestone	38.1		38.1	7	22.2	7.28	0.487	8.5	100<	
26	Lashio	Lashio	io Railway sta	22.971	97.732	-	Limestone			0		21.3	7.53	0.632	5.9	100<	
27	Lashio	Lashio	io Degree Col	22.955	97.739	835	Limestone	2.4		2.4	101.6	23,5	7.63	0.581	8.2	100<	Q=9.1 m3/h
31	Pyin U Lyin	Pyin U Lyin	oung Chan Tha	21.941	96.39	980	Limestone			0		23.3	7.6	3.3	4	1	Indian Mark U
1	Mekhtila	Wandwin	Kanthit	21.174	96.02	151	Alluvial	76.2	-	76.2		33.5	7.56	1.364	-	0	
2	Mekhtila	Wandwin	Kaing	21.345	96.1	97	Alluvial	4.27	-	4.3		30.4	7.85	2.04	-	0	

PLATEAU LIMESTONES

The Plateau Limestone aquifer unit represents the largest aquifer of the Shan Plateau within the Ayeyarwady Basin. With thickness up to several thousand metres, karst development and structures are often observed (Figure 3.7.2-b), including fractures, sinkholes, and caves. Although they underlie more than 30% of the area, very little is known about these units. Limestone springs have historically been used by communities for domestic supply. Interest in the resource has increased as adequate drilling technology has become available since the 2000s.

In the south of the study area, IWUMD has drilled more than 150 tubewells in southern Shan, mostly in limestone aquifers, using DTH drilling.[8] The aquifer is thick and drilling is usually to depths of 75 m to 130 m, occasionally deeper with a maximum of 250 m (800 feet). Limestone is a heterogeneous aquifer, and dry tubewells have occurred. In these cases, a second tubewell drilled in the same area was often successful. Based on IWUMD data, the failure rate is in the order of 20%. (cf. Figure 3.7.2-b and Table 3.7.2–b). Tubewell yields are mostly 1.25 to 2.5 L s^{-1}, and up to 8.3 L s^{-1} in most successful cases.

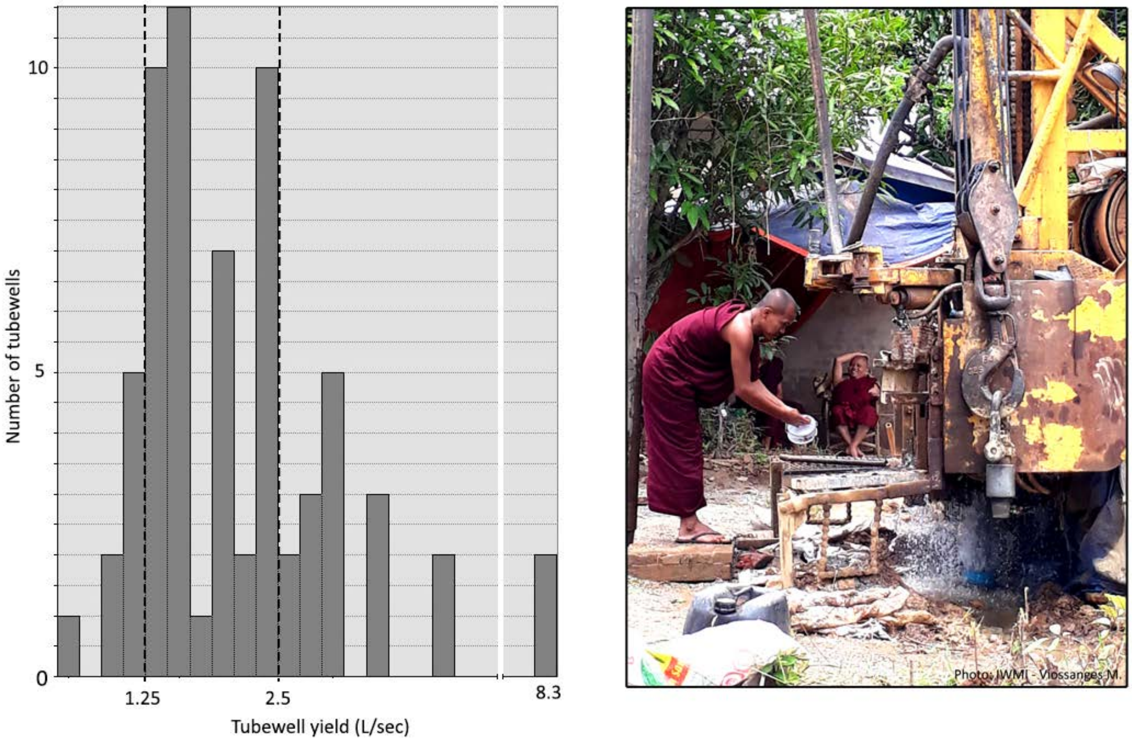


Figure 3.7.2-b – Frequency distribution of tubewell yields in limestone
Picture: a successful tubewell in limestone, with a yield estimated at 8.3 L s^{-1} (IWUMD, 2017). Location: 21.230; 96.894 (photo: Viossanges).

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[8] DTH: Down the Hole Hammer — a drilling technique adapted for drilling in hard rocks, requiring specific drilling rigs.

Table 3.7.2-b – Success rates of tubewells drilled in limestone in Shan State

Financial year	Total	Successful	Abandoned	Success rate
2014 - 2015	61	35	26	57%
2015 - 2016	45	37	8	82%
2016 - 2017	49	35	14	71%

In the Lashio City area in Northern Shan State, IWUMD (2016) reports 65 tubewells completed at 2" and 2 completed at 4". The 2" tubewells were usually completed at a depth of 60 m to 100 m and provide yields ranging from 2.25 m^3/h to 4.5 m^3/h. Groundwater discharge through springs is reported south of Lashio near a fracture zone; IWUMD recommend drilling in the same area to obtain higher yields and lower drawdown. Results of a long-term pump test indicate a transmissivity of 3 m^2day^{-1} (Table 3.7.2–c), however results in limestones are usually difficult to interpret given the heterogeneity of the aquifer.

Table 3.7.2-c – Pump test result in a limestone tubewell, Lashio Town (IWUMD)

Test (Lashio)	Duration (min)	Δh (m)	Q (cubic metres per day [m^3day^{-1}])	Method	T (m^2day^{-1})	Thickness (m)	K (m day^{-1})
Pump test	900	4.5	76	Jacob	2.4	40	0.077
Recovery	240	-	-	Jacob	4.28	40	0.107

SANDSTONE AND LIMESTONES

This aquifer group mostly constitutes limestones, with interbedded sandstones. These units are differentiated from the Plateau Limestone by their topography (often forming hills and mountain ranges) and related folding and faulting. The Ordovician (Pindaya Group) aquifers form hills with common karst development, including sinkholes and large fractures (Myanmar Institute for Integrated Development, 2015). Given the complexity of the geology in the south, it is likely that some tubewells drilled by IWUMD were occasionally located in these formations. Due to the topography, the aquifer units represent a lower potential for groundwater compared to the Plateau Limestone, but these units probably play an important role in groundwater recharge processes.

OTHER AQUIFER GROUPS

Thick sandstone deposits cover 8% of the GWZ. In most cases, they are relatively hard and possess limited water bearing capacity, although no data on these aquifers are available. Similarly, meta-sedimentary (including the Chaug Maygyi Group with sandstones with various degrees of metamorphism), metamorphic rocks, and granitoids are considered poor aquifers. However, tectonic folding and faulting have induced fracture zones that might provide local aquifers of sufficient yield for domestic supply or small-scale irrigation.

3.7.3 *Storage and Recharge*

Due to the complexity of the geology of the Shan Plateau, and the paucity of data available, storage cannot be reliably quantified for this area.

The spatial distribution of the alluvial deposits is only partially known, as laterite layers are not accounted for and any estimate using current geological map would probably underestimate the storage. Without tubewell logs or soil information, the ratio of coarse material and lower porosity material such as clay is difficult to estimate. General principles of groundwater storage in alluvial aquifers apply, and these aquifer units, with thickness of up to 50 m, are likely to host a significant amount of groundwater.

The storage of groundwater within the Shan Plateau Limestone is also expected to be high, as recharge water quickly percolates vertically and is stored in fractures and conduits. Limestone aquifers are often heterogeneous and the degree of weathering, fracture occurrence, depth, and karst features can greatly influence the total amount of groundwater stored. In the absence of information on these parameters, storage cannot be calculated without excessive uncertainty.

Indurated sandstones, metamorphic, and granitic rocks are not likely to provide significant storage.

RECHARGE

Based on other areas in Myanmar, recharge coefficients in alluvium are expected to be 10% to 15% of annual rainfall. With rainfall varying from 1,600 to 1,900 mm over the alluvial areas, recharge estimates of 160 mm up to 285 mm per annum could be expected.

In the Plateau Limestone and associated aquifers, very high recharge rates are expected, particularly in areas where intense weathering and karst features are observed. The low density of perennial rivers over the plateau also tends to point to a fast percolation of rainwater to deep aquifers. Published recharge values in other parts of the world for tropical limestones vary considerably and values of R/R ratios vary from 9 to 20% (Jones et al., 2000) up to 50 to 79% (Allocca et al., 2014). The uncertainty in estimates is thus very high.

3.7.4 Groundwater Quality

Naturally occurring groundwater contaminants

In the Shan Plateau, no naturally-occurring groundwater pollution has been reported. However, given the extreme data scarcity in the area, it is difficult to assess the current situation.

POLLUTION OF GROUNDWATER

Organic pollution might be found near villages. Particular caution should be taken in karstic environments when pollution can quickly infiltrate into the aquifer without soil filtration and degradation. Agricultural inputs, including fertilizers, herbicides, and pesticides are widely available in the Shan Plateau through a network of dealers. Cross border importation of illegal agrochemicals and poor knowledge of good practice with agrochemical use are issues to be addressed (Winrock, 2015). Traditional farming methods and the cost of inputs are still strong constraints hindering the increase of inputs, but the situation is changing rapidly.

Mining activities have occurred in the Shan States over many centuries. Major mining areas include the world renowned Mogok gem deposit and the historic Namtu-Bawdwin Mine with lead, silver, nickel, copper, and antimony (MONRE, 2017). Although activity has considerably reduced, pollution of surface water and groundwater from present and past mining activities has not been evaluated and cannot be assessed. Pollution of surface water and downstream basins are likely. As these mines are located in hard rock areas, any occurrence of groundwater contamination should be reasonably contained in the vicinity of the mining areas.

Industrial activity in the main towns of Pyin Oo Lwin, Lashio, and Mogok may pose some threat of groundwater pollution.

3.7.5 Groundwater Use

Groundwater use in the Shan Plateau is historically from springs flowing from mountain ranges and shallow wells in the alluvial aquifers in valley bottoms and along rivers. Approximately 57% of households depend on groundwater for domestic supply; in rural areas, springs and dugwells are much more common that tubewells (TW/DW = 0.1 - 0.5) but in towns such as Muse and Pyin Oo Lwin, use of tubewells is much higher (TW/DW = 2 - 12). Using census data (MIMU, 2014) on the percentage of households using groundwater at the township level and population density maps (Gaughan et al., 2013), groundwater use was mapped spatially and assigned to aquifers. The synthesis shown in Table 3.7.5–a is a rough estimate but highlights the very low abstraction of groundwater. Significant abstraction in areas of dominantly metamorphic aqufiers may be due to alluvial aquifers that are not mapped, or shallow lateritic aquifers, found for example near Mogok City. As groundwater is not easily accessible aside from springs, and population density is low in mountainous areas, abstraction rates are low. The total abstraction is only 10 Mm³, significantly less than in adjoining lowlands (Figure 3.7.5-a).

The cultural significance of groundwater has not been investigated in this assessment. Hot springs occur along the Sagaing fault (Halin) and in the Shan. They are important to local people, who use them to bathe and as local tourist attractions. We did not come across any mention of specific sacred or culturally significant springs in fieldwork or interviews with groundwater experts, although it is possible that such springs exist. In karst systems, caves are often sacred (eg. Pinthaya Cave) and it could be expected that if spring water occurs, it will be of cultural importance.

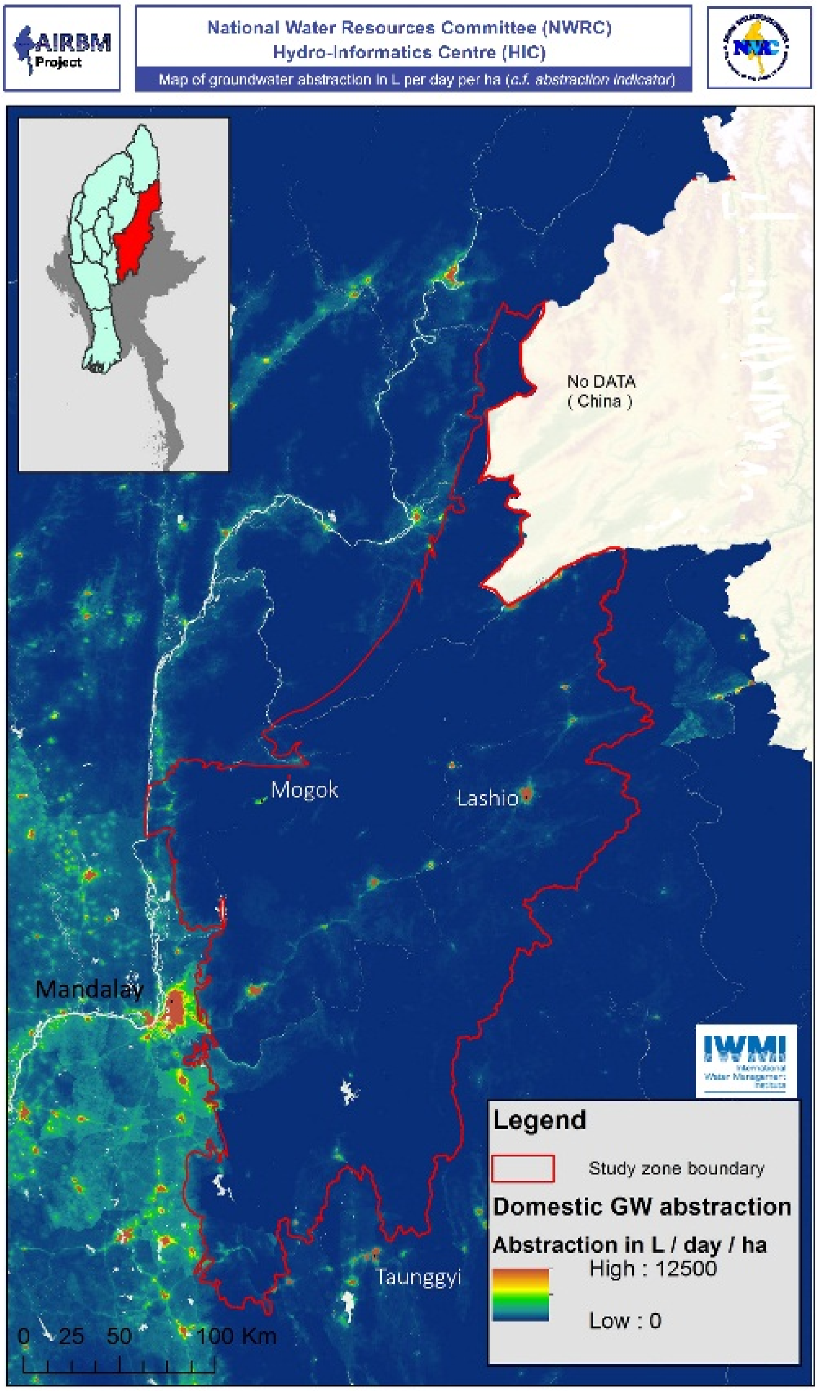

Figure 3.7.5-a - Map of groundwater abstraction in L per day per ha (100 m x 100 m resolution)

Table 3.7.5-a – Estimates of groundwater abstraction from population density and 2014 Census data

Aquifer group	Domestic abstraction ($Mm^3 yr^{-1}$)	Abstraction (mm)
Alluvial aquifer	2.8	0.63
Plateau Limestone and equivalent	17.7	0.22
Limestone/sandstone and equivalent*	7.8	0.27
Sandstones, mudstones, and equivalent	3.3	0.05
Metamorphic*	12.5	0.21
Granitic	4.4	0.18
TOTAL	**48.5**	

Springs are commonly used as a source for gravity-fed village water supply systems in remote hilly areas; a total of 73 such systems benefitting more than 156,000 people have been installed in Shan State. IWUMD plans 10 additional systems per year in the 2018 to 2021 budget; further systems are also planned by DRD. In Lashio in Northern Shan State, four springs supply water to five wards of the city (IWUMD, 2016). Since the 1950s, a total of 393 tubewells have been installed in Shan State, providing water for 163,500 people (Thein Soe and IWUMD, 2016).[9]

Private drillers operate small mud drilling tripod rigs to install small capacity tubewells (usually 2" diameter) for household supply. JICA (2001) undertook a large groundwater development project, with WRUD proposed as implementing agents. This included drilling 250 tubewells in Northern Shan State (DRD, undated). This project is now implemented through DRD; further information on status of the project was not available. IWUMD has drilled more than 160 tubewells in the limestone for community water supply either by their own funds or with donor support (Kanbawza Brighter Future Myanmar Foundation and IWUMD, 2017). These tubewells are mostly located in Southern Shan State. Targets area are villages where water resources are scarce, and communities must rely on rainwater harvesting for domestic consumption. For the 2018 to 2021 budget, IWUMD plans to drill an average of 20 deep tubewell (DTW) per year.

Figure 3.7.5-b – Plateau Limestone: *Large-scale rainwater harvesting was installed in 2007. Then in 2016 a 250 m tubewell was drilled by IWUMD, with a yield of 4.5 m^3/h. Loc: 20.876°, 96.766° (photo: Viossanges)*

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[9] These figures relate to the whole of Shan State, not only the area within the Ayeyarwady Basin.

Figure 3.7.5-c – Formal gravity-fed system: *IWUMD Collection tank up-gradient of community. Spring water is 10 km away behind the hill seen in distance. Loc: 21.327, 96.860 (photo: Viossanges).*

IWMI landcover mapping indicates approximately 180,000 ha of intensive (double or triple) cropping systems within the Shan GWZ. Most of this is in the alluvial valleys around rivers and is probably from surface water. IWUMD has constructed only 14 tubewells serving 81 ha for irrigation in Shan State (MOAI, 2014). Groundwater is used mainly for home gardening and small-scale irrigation using water saving technology (Myanmar Institute for Integrated Development, 2015).

Urban areas at Pyin Oo Lwin, Lashio, Mogok, and Muse, all with more than 100,000 people, have small-scale industries which may access groundwater. No information is available on use of groundwater for industry in the Shan Plateau.

Table 3.7.5-b – Range of estimates of groundwater use for the Shan GWZ (Mm^3 yr^{-1})

	Industrial	Agricultural	Domestic	TOTAL	Source
Estimated use 2000	1	4	112	117	MOAI, 2003
Projected use 2015	1	4	148	153	MOAI, 2003
Estimated current use	4	Low: 50 High: 100	49	Low: 103 High: 153	This study

3.7.6 Groundwater and Ecosystems

Groundwater-ecosystems links in the Shan Plateau are difficult to evaluate, due to the complex geological setting and the large size of the GWZ. Springs are numerous in the hills, where they support many rural communities and possibly high value ecosystems. Only three KBAs are located in the Shan GWZ and two are Terrestrial, with low connection to groundwater. However, the Doke-Hta River KBA is located in the center of the karstic plateau. In karst, there is usually a fast response and connection between groundwater and rivers through conduits and fractures, and water levels are closely interconnected. This KBA is considered highly reliant on groundwater.

Table 3.7.6-a – Summary of the KBAs found in the Shan Plateau (WCS) and associated reliance on groundwater

KBA name	Type of KBA	Priority	Area (km^2)	GW-ecosystems link	GW reliance
Shwe U Daung WS	Terrestrial	High	183	Mountainous, possibly springs	Low
Mehon (Doke-hta Wady River)	Freshwater	Data deficient	881	River draining the limestone plateau Quick GW, SW response	High
Panlaung Pyadalin Cave WS	Terrestrial	Data deficient	349	Mountainous, possibly springs	Low

3.7.7 *Summary – Assets and Issues*

- Deep tubewells drilled in limestone can provide all-year safe water supplies for communities otherwise exposed to drought without perennial surface water available.
- Annual recharge rates of the Plateau Limestone are expected to be high. Total storage is unknown, but possibly high.
- Springs constitute an important part of the water supply in the plateau and adequate protection should be ensured.
- Alluvial aquifers are limited in extent but support small-scale irrigation using water saving technologies.
- Drilling in limestone is expensive and requires specific drilling rigs (DTH) and qualified drillers.
- Limestones are heterogeneous aquifers sensitive to pollution. Yields are highly variable. Success rate: 80%.
- Agricultural inputs, pesticides—including illegal substances from China are widely available over the plateau. Given the sensitive nature of underlaying aquifers pollution by agro-chemicals is a risk.
- Changes in land use land-cover in springs recharge areas (mountain ranges).

3.8 Mu Groundwater Zone

The Mu GWZ comprises the catchment of the Mu River, to its junction with the Ayeyarwady near Myinmu. It includes an area of 19,500 km^2, with a population of 1.85 million, including the towns of Shwebo, Ayadaw, Myinmu, Ye-U, and Taze. The Mu GWZ lies completely within the Sagaing Region and includes most of Shwebo District and parts of Katha, Monywa, and Sagaing Districts.

The Mu River rises in the hills of the Wuntho Massif and meanders south through the valley centre to meet the Ayeyarwady River near Myinmu. The Upper Mu River drains densely forested mountains. 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. Rainfall shows a steep gradient from more than 1,800 mm annually in the north to approximately 900 mm at Shwebo and Ayadaw in the south. The mean rainfall for the GWZ of 1,280 mm is lower than the mean evaporation (1,420 mm), and the southernmost area around Wetlet falls within the definition of semi-arid (rainfall/PET <0.5).

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 km long, making it one of the largest dams in Southeast Asia, and stores 3,552 Mm^3. The dam enables year-round irrigation for up to three crops over a potential command area of half-a-million hectares, with feeder canals extending to eight townships.

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. An artesian scheme has been developed near Ayadaw. Most villages rely on groundwater for domestic purposes.

The southern Mu Valley (from Shewbo to Myinmu) was studied in detail by Drury (2017) and results from that study are presented here. Limited information is available north of the GWZ.

3.8.1 *Regional Geology*

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. In contrast to the Middle and Upper-Ayeyarwady River GWZs, the Mu GWZ is not tectonically active, and has no major fault zones.

The Upper Mu River Valley centres on the Wuntho Massif, an area of significant intrusive and extrusive volcanics. Sedimentary rocks are located south of the igneous rocks. Major geological units are (Figure 3.8.1-a) the following:

- Mesozoic to Tertiary granites (gr_2), serpentine and gabbro ultramafic (ub) and andesites (v_1);
- Cretaceous Kalaw Red Beds (Km);
- Lower to Middle Miocene Pegu Group rocks (TM);
- Lower Pleistocene to Upper Miocene basalt along the Kyaukka Range;
- Lower Pleistocene to Upper Miocene Irrawaddy Fm (Ir); and
- Small outcrops of Holocene Younger Alluvium (Q2).

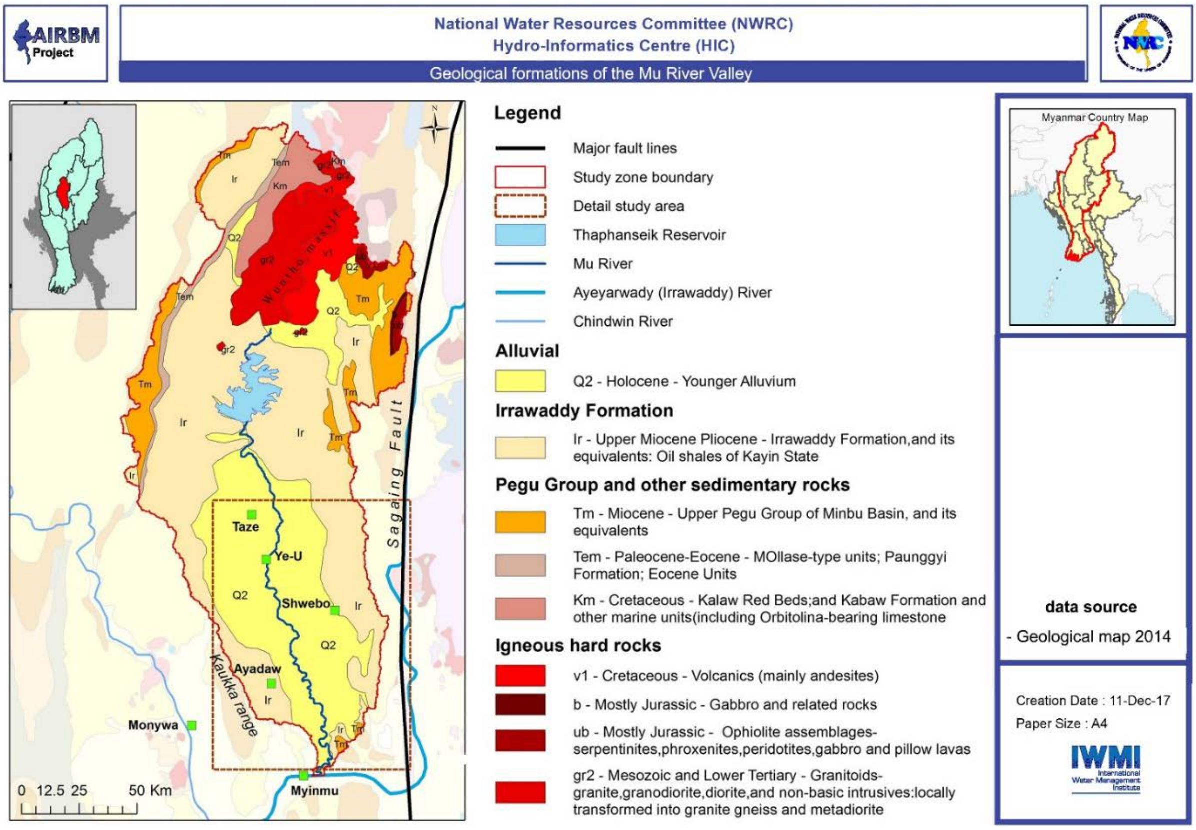


Figure 3.8.1-a – Geology of the Mu River Valley: *Inset box is area of Lower Mu Valley, described in detail based on Drury (2017).*

The Lower Mu River Valley consists dominantly of Lower Pleistocene to Upper Miocene Irrawaddy Fm and Quaternary Alluvium (gravel, sand, silt, and clay). The area is underlain by two long NNW-SSE orientated plunging synclines (Ayadaw and Shwebo synclines) separated by a slightly elevated bedrock ridge. The western hydrogeological boundary is the easterly dipping Pegu Group (Lower to Middle Miocene) and Lower Pleistocene to Upper Miocene basalt along the Kyaukka Range. The eastern boundary includes Lower Palaeozoic to Precambrian metamorphics, igneous intrusions and Eocene rocks associated with the 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. Detailed maps and cross-sections for the Lower Mu Valley are given in Figure 3.8.2-b, Figure 3.8.2-c, and Figure 3.8.2-d.

3.8.2 Main Aquifers

The major low-salinity and high-yield groundwater aquifers of the Mu GWZ are located in the following:

- Irrawaddy Fm — in the Ayadaw Syncline, the sediments consist of shallow yellow brown sand, silt, and clay overlying deep blue gray, medium- to coarse-grained sand, fine gravel, and clay. By contrast, the Shwebo Syncline consists of finer-grained sediments.

- Alluvium — in the shallow, sand, and gravel of the Mu and Ayeyarwady Rivers.

Low-yield and brackish to saline aquifers are encountered in the sandstones of the Pegu Group and Eocene rocks. The massive igneous rocks of the Wuntho Massif are expected to have limited groundwater recharge and storage except from the intensely weathered areas.

The extent of the main aquifer groups in the Mu GWZ is given in Figure 3.8.2-a. Details of aquifer depth, potentiometric surface, aquifer characteristics, and salinity are in Table 3.8.2–a (data only from the Lower Mu).

1. Tubewells in the Alluvium and Irrawaddy Fm between Taze to south of Ayadaw intersect multiple blue gray sand and gravel aquifers of the Ayadaw Syncline, at depths of 40 to 400+ m, with potential tubewell yields exceeding 50 L s^{-1}. Most high-yield aquifers are aligned along or near the synclinal axis where many aquifers are artesian. Transmissivity ranges from 13 to 1,200 m^{2}day^{-1}, with an average approximately 280 m^{2}day^{-1}. Combined aquifer thickness varies from 30 to 220 m. 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}. The Ayadaw Artesian Zone (AAZ) gives an example of the types of aquifers present. Aquifer recharge in the AAZ is in excess of 120 Mm^{3} yr^{-1} (15% of rainfall; Than Zaw, 2010).

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 m. 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^{-1}, compared to 210 m^{2}day^{-1} in the Ayadaw Syncline. Artesian aquifers at depths of 55 to 240 m occur along the full length of the syncline. Artesian flow is between 0.3 to 5 L s^{-1}, and a large percentage of the Alluvium and/or Irrawaddy Fm can be considered 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. Most high groundwater yields and low-salinity are located within the synclinal structures and close to the Ayeyarwady River.

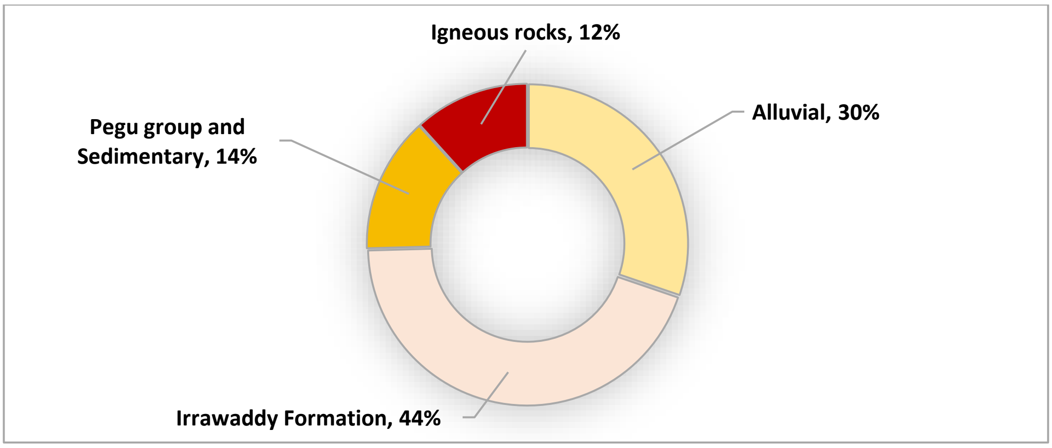


Figure 3.8.2-a – Extent of main aquifers in the Mu GWZ

Table 3.8.2-a – Generalised Summary of Aquifer Depth and Characteristics in the Mu River Valley

Aquifer type	Specific location	Drill depth (m)	SWL range (m)	Yield (L s^{-1})	Salinity (µS/cm^{-1})	Aquifer characteristics		
						Transmissivity/ av. (m^{2}day^{-1})	Hydraulic conductivity (m day^{-1})	Storage coefficient
Alluvium	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		
Irrawaddy Fm	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		0.2
	Ayadaw Syn. middle	120 - 180	+ 5 - 11	15 - 50	<1.500	20 - 280/48	15 - 100	5 x 10^{-4}
	Ayadaw Syn. deep	240 - 450	+ 15 - 10	20 - 110	<1.500	20 - 1,000/210	2 - 100	
	Shwebo Syncline	37 - 240	+ 5 - 10	1 - 25	500 - 6,000	75	50 - 200	
Pegu Group	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		

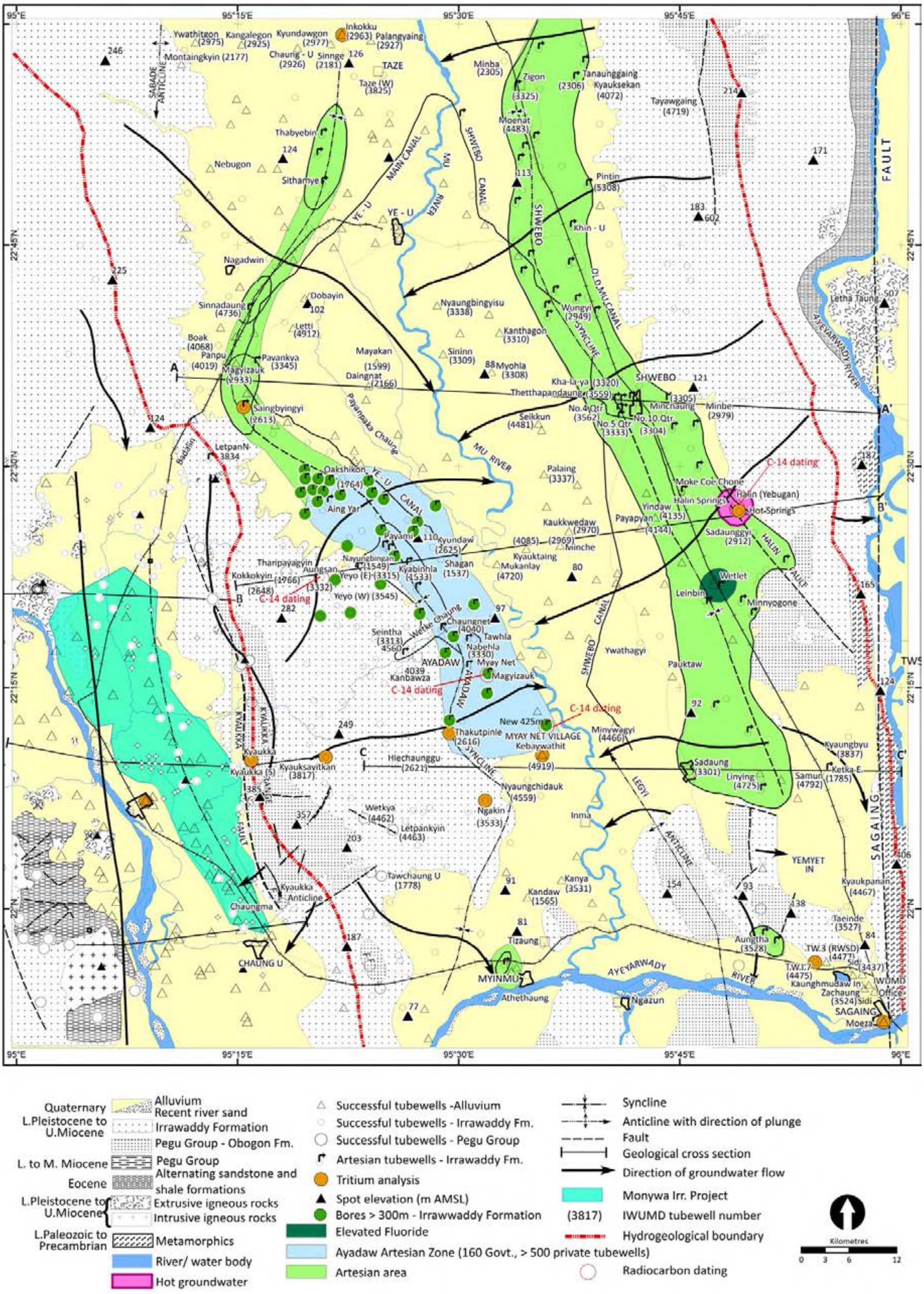


Figure 3.8.2-b - Hydrogeological map of the Lower Mu River Valley (Drury, 2017)

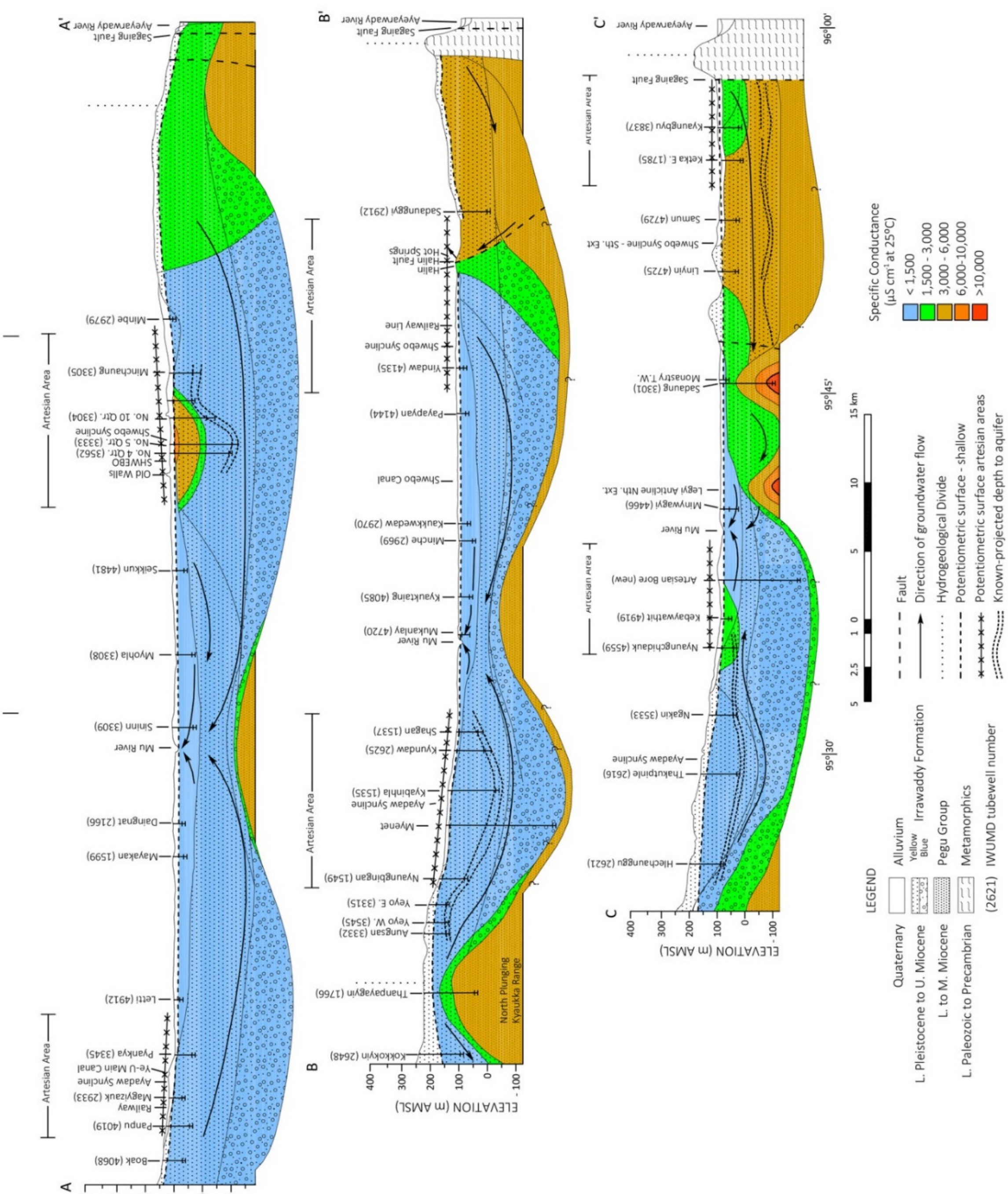


Figure 3.8.2-c – Hydrogeological cross-sections of the Lower Mu River Valley (Drury, 2017)

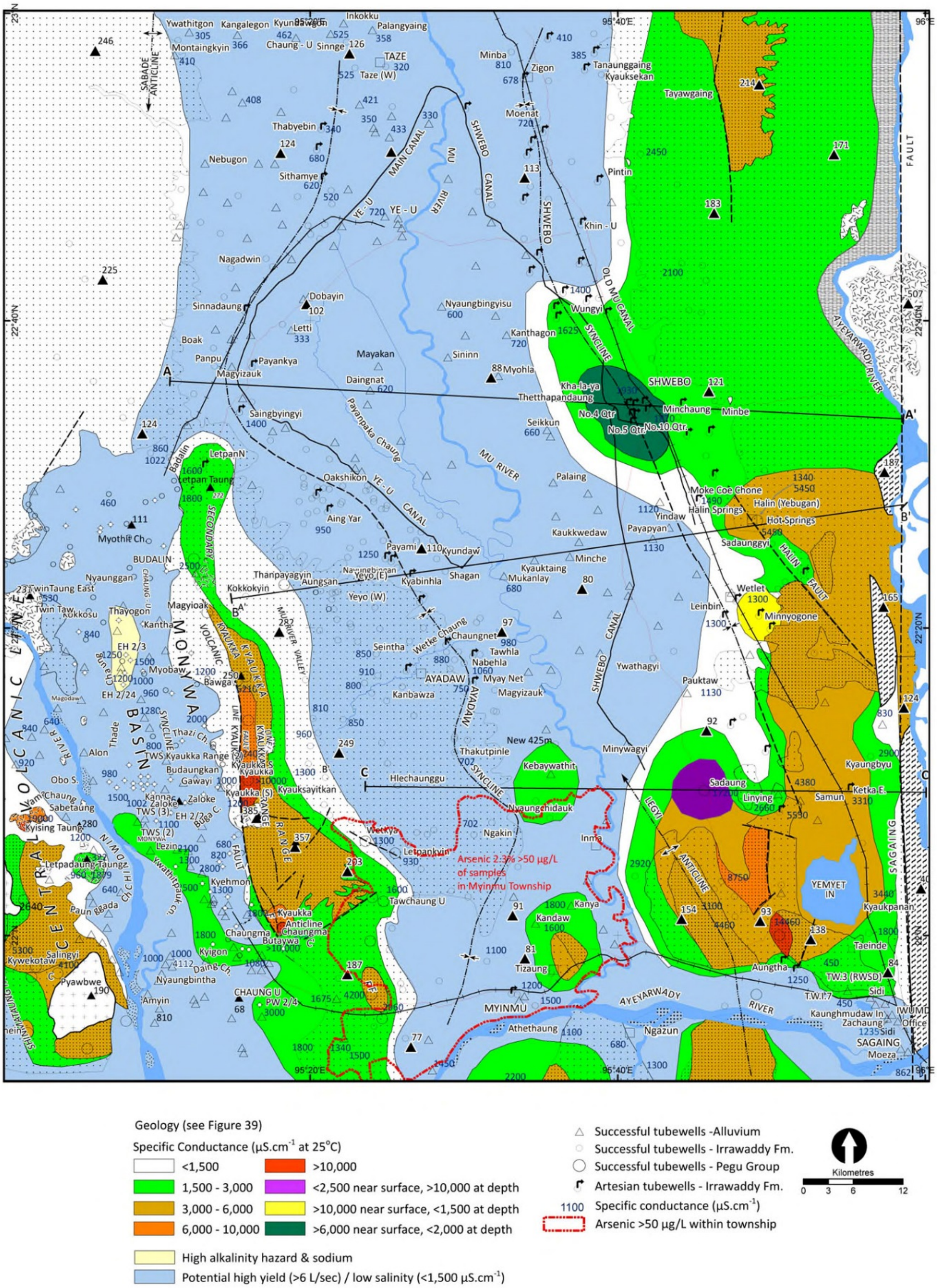


Figure 3.8.2-d – Salinity map of the Lower Mu River Valley (Drury, 2017)

Box 3.8.2

Ayadaw Artesian Zone

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 s^{-1} and average 12 L s^{-1}.

Total artesian flow: Collectively 80 MCM (40 MCM from government DTW and 40 MCM by private TW).

Potentiometric surface: Minimum of 1 m, maximum of 50 m, and average of 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 Fm
3. Confined Irrawaddy Fm

Potentiometric surface response: IWUMD has no monitoring program for this aquifer system.

Myay Net No. 1 Tubewell, Aquifer 3, 366 - 385 m deep, SWL >15 m high

Geology

Geology	**Unit**		**Aquifer condition/ depth (m)**	**Lithofacies**	**Location**	**Flow (L s^{-1})**
Holocene	Alluvial		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 Fm	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 aquifer 240 - >450	Gray/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^{-1})	15 - 100	2 - 100	Not tested
Transmissivity ($m^2 day^{-1}$)	58 -1,035, av. 680	20 - 280, av. 48	20 to 1,000, av. 210
Storage coefficient	0.2	10^{-4}	10^{-4} to 10^{-5}
Specific capacity (L s^{-1}/m)	4.5	2 - 400	Not tested

3.8.3 Storage and Recharge

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. Flow is complex, with vertical leakage between the more permeable layers as important as lateral flow towards the discharge areas. The overall gentle groundwater gradient beneath the Mu River Valley is indicative of high permeability.

Radiocarbon dating and tritium analyses have been carried out, to assist in understanding the dynamics of groundwater flow in the area. Tritium analysis of groundwater around the Ayadaw Syncline indicates a pre-thermonuclear age (older than 50 years), indicating that recharge processes are not immediate. Radiocarbon dates from three locations in the Ayadaw Syncline (Table 3.8.3–b) range from 1,350 to 9,800 years along the flow path, indicating that recharge takes place in the Irrawaddy Fm near the Kyaukka Range (Aungsan

Village) and moves 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.

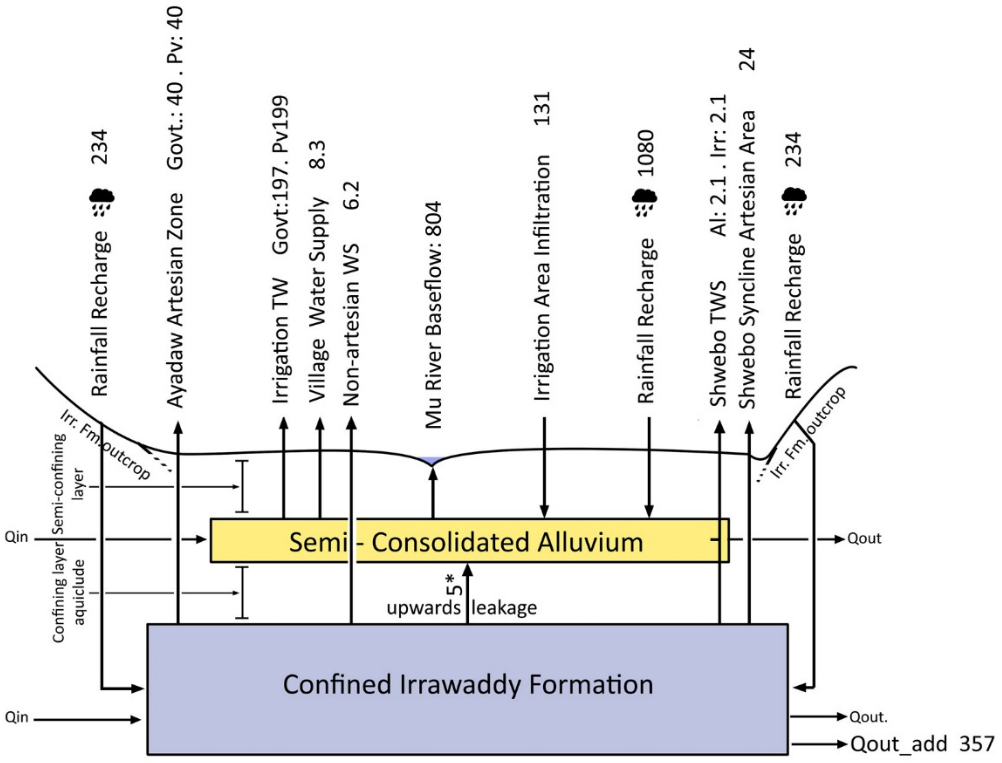
At the scale of the entire Mu GWZ, it is possible to obtain a first-pass estimate of the order of magnitude of the recharge and storage using basic assumptions (Table 3.8.3–a). These estimates are only indicative and should be used with caution.

Table 3.8.3-a – Estimates of storage and recharge for each major aquifer group of the Mu-Shwebo GWZ

Aquifer types	Area (km^2)	Aquifer thickness (m)	Rain (mm) average	R/R ratio	Sy assumed	Storage* (Mm^3)**	Recharge (Mm^3)**
Alluvial	5,880	50	1,210	0.15	0.15	26,460	1,070
Irrawaddy Fm	8,630	80	1,520	0.15	0.15	174,120	1,960
Pegu Group and Sedimentary	2,670	50	1,770	0.05	0.08	10,670	240
Igneous rocks	2,280	30	1,820	0.05	0.08	5,470	210
						216,720	3,480

*The storage of the Irrawaddy Fm calculation considered the area of Alluvium and the Irrawaddy Fm.
**These values are broad estimates and only indicative.

The Lower Mu Valley was studied in detail by Drury (2017) and more detailed estimates were made of water balance for that area. Figure 3.8.3-a shows the water balance for the Lower Mu River Valley. From rainfall and irrigation return, the vertical recharge to the shallow Alluvium is 1,211 Mm^3 yr^{-1}. Approximately 33% is utilised by groundwater extraction (404 Mm^3 yr^{-1}), and the remainder discharges into the Mu River (804 Mm^3 yr^{-1}). Similarly, for the deeper Irrawaddy Fm, 25% of rainfall water recharge is utilised by groundwater extraction, while the remainder is assumed to discharge into the Ayeyarwady River.



Units: Annual volumes in Mm^3

Figure 3.8.3-a – Water balance for main aquifers in the Lower Mu River Valley

Table 3.8.3-b – Radiocarbon dating of groundwater in the Lower Mu River Valley

Location	Depth (m)	Screen (m)	Formation	Sample date in 2017	Radiocarbon (carbon-14) dating (years)	Comment
Aungsan Village	83	75 - 82	Irrawaddy Fm	13 May	1,355 ±30	Recharge area
Myay Net No. 1	396	366 - 385	Irrawaddy Fm	13 May	9, 175 ± 40	In Ayadaw Synclinal axis
Myay Net Village	430	405 - 423	Irrawaddy Fm	13 May	9,790 ± 40	East of syncline axis
Yebugon Village Halin Hot Spring	+ 1		Pegu Group	13 May	26,120 ± 120	Intersection of Halin and Sagaing faults

3.8.4 Groundwater Quality

SALINITY

Brackish to high salinity (3,000 to >15,000 µS.cm^{-1}) groundwater is located within the Pegu Group rocks along the Kyaukka Range and south of the Halin hot springs to north of Sagaing. The dominant ions are Na^+:Cl^- and Ca^{2+}:SO_4^{2-}.

Overall low-salinity (<1,500 µS.cm^{-1}), Ca^{2+}:HCO_3^- dominant groundwater is located within aquifers of the Alluvium and Irrawaddy Fm except immediately downstream of Pegu Group outcrops, where higher salinity (usually 1,500 to 6,000 µS.cm^{-1}) Na^+:Cl^- type waters are encountered.

Figure 3.8.2-d shows the variation in groundwater salinity in the Lower Mu valley.

ARSENIC

High level of arsenic in groundwater were found in four townships within or on the periphery of the Mu River Valley (Table 3.8.4–a). The highest arsenic concentrations were in the townships of Myaung (4.6% exceeding 50 µg/L) and Myinmu (2.3%), both close to the Ayeyarwady River. Of the 5,556 samples taken in the Shwebo Township, only one sample exceeded 50 µg/L and no high values were found in Wetlet Township. It appears that high arsenic in groundwater is associated only with the Ayeyarwady River sediments. In the sediments of the townships tested within the Mu River, catchment arsenic is within acceptable limits.

Table 3.8.4-a – Arsenic in groundwater from three townships in proximity to Lower 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

(WRUD and UNICEF, 2005)

HOT GROUNDWATER

Many hot artesian tubewells exist in 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 of the hottest tubewell is 66°C (Win Khaing, 2008). Combined spring water flow is 2 L s^{-1}. 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.

OTHER NATURALLY OCCURRING GROUNDWATER CONTAMINANTS

Elevated fluoride concentration in groundwater is reported in Wetlet Township (Kyi Lwin Oo, 2014). Out of 1,114 drinking samples tested, 394 (35%)[10] exceeded 1.5 (mgL^{-1})[11] and 10 (≈1%) were above 2.5 mgL^{-1}. Most elevated samples came from dugwells and shallow tubewells. High fluoride was also identified at depths up to 130 metres in the Irrawaddy Fm. From a sampling of 702 students, 91% 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 Fm aquifer with upward leakage.

GROUNDWATER POLLUTION

Based on the 2014 census, approximately 30% of the population in the Mu GWZ do not have access to safe sanitation. There is thus some risk of the bacterial contamination of shallow groundwater, coupled with relatively high reliance on groundwater for drinking (73%). Monitoring of water quality in village supplies should be a priority, particularly if drawn from dugwells.

Availability of water from Thapanzeik Dam, other smaller reservoirs, and the Ayadaw Artesian Zone means that large areas of irrigation have been developed in the Mu Valley. IWMI (2016) landcover mapping indicates approximately 0.25 M ha of intensive cropping. Although the use of agrichemicals has not been widespread in the Dry Zone, there is anecdotal evidence that usage is increasing rapidly, with potential for seepage of chemicals to shallow groundwater.

3.8.5 Groundwater Use

As in most of the Dry Zone, reliance on groundwater for domestic supplies is high, at 73% of households overall, and up to 97% of households in Taze at 97%. Tubewells are much more common than dugwells for both drinking (TW/DW = 2 - 3) and non-drinking (TW/DW = 3 - 5) purposes, except in the northern areas (Katha District), where both are used equally. Using census data (MIMU, 2014) on the percentage of households using groundwater at the township level and population density maps (Gaughan et al., 2013), it is possible to map estimates of groundwater use per aquifer group.

Table 3.8.5-a - Estimated groundwater use by aquifer

Aquifer group	Domestic abstraction, Mm^3 yr^{-1}
Alluvial	40
Irrawady Fm	23
Pegu Group and Sedimentary	4.3
Igneous rocks	3.1
TOTAL	**70.4**

Both surface and groundwater are available in this area, and irrigated cropping is widespread. IWMI landcover mapping indicates approximately 0.32 million ha (M ha) of irrigated and water-managed (paddy) cropping—including 0.25 M ha of intensive cropping (double or triple). Surface water is provided from Thapanzeik Dam (3,500 Mm^3) and its associated network of canals, and a number of smaller reservoirs as well as the Mu River system. Artesian groundwater is exploited for irrigation around Ayadaw, with ~60 tubewells (half private, half government) providing irrigation. Details of the Ayadaw Irrigation Project are

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[10] Fluoride exceedance is 42% at Myingyan.

[11] This is the WHO guideline for drinking water and represents a safe upper limit.

given in Box. Similar artesian supplies are available in the east around Shwebo, but extraction is limited due to abundance of surface water. High-yielding aquifers are also found around Taze and Ye-U. Although these areas are well serviced by surface water from Thapanzeik, some farmers within the surface water irrigation scheme use small pumps to access shallow groundwater as it provides a more reliable, on-demand source (Pavelic et al., 2015). Upstream of Thapanzeik, irrigated cropping in the valleys draining the western ridge, and around Wuntho and Kawlin towns, all likely draw on a mix of surface and groundwater sources, as Alluvium and Irrawaddy Fm underlie these areas.

Groundwater supplies approximately 4.3 ML day^{-1} to Shwebo City, from four municipal artesian wells and a large number of private shallow and deep tubewells. MOALI reports some extraction of groundwater for industrial purposes in Shwebo Town (less than 1 ML day^{-1}). Community dugwells in villages and urban/market areas show signs of bacterial pollution.

Table 3.8.5-b - Range of estimates of groundwater use for Mu GWZ (Mm^3 yr^{-1})

	Industrial	Agricultural	Domestic	TOTAL	Source
Estimated use 2000	<1	69	82	151	MOAI, 2003
Projected use 2015	<1	207	139	346	MAI, 2003
Lower Mu only 2016		500	17	517	This study
Estimated current use	1	Low: 500 High: 550	70	Low: 571 High: 621	This study

3.8.6 *Groundwater and Ecosystems*

Artesian systems occur in the Mu GWZ on both sides of the Mu Valley. Artesian springs may support local ecosystems, although there are no reports available. The Mahanandar Kan, a freshwater lake/marsh located near Shwebo adjoins a large artesian flow area and is likely to have high reliance on groundwater. The second KBA is the Chatthin Wildlife Sanctuary, which includes a large wetland and flooded forests, sited in the Alluvium, and is also likely partially groundwater-fed in the dry season.

Table 3.8.6-a - Summary of the KBAs found in the Mu GWZ and reliance on groundwater

KBA name	Type of KBA	Priority	Area (km^2)	GW-ecosystems link	GW reliance
Chatthin WS	Terrestrial	Medium	284	One wetland near Kye-in. Geology: Alluvium	High
Mahanandar Kan	Freshwater	Low	78	Located near Artesian GWZ	High

3.8.7 *Summary – Assets and Issues*

- Ayadaw Artesian Zone provides water for irrigation
- Shwebo Artesian Zone has limited use due to availability of surface water from Thapanzeik.
- There is a high dependence on groundwater for domestic supply (including Shwebo Town supply).
- High potential for groundwater irrigation development in Alluvium and/or Irrawaddy Fm particularly the deep gravels and sand along the Ayadaw and Shwebo Syncline. 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}.
- Current use is approximately 25 to 33% of estimated recharge.
- Brackish to high salinity (3,000 to >15,000 µS.cm^{-1}) groundwater is located within the Pegu Group rocks along the Kyaukka Range and south of the Halin hot springs to north of Sagaing.
- Saline groundwater flows are used for salt production.
- Hot springs at Halin (high salinity) is used by local people
- Fluoride at Wetlet might cause health issues
- Arsenic at Myinmu constraints groundwater use
- Recharge from Thapanzeik Dam can increase the annual recharge to groudnwater

- Recharge from irrigation areas below Thapanzeik is also likely to increase groundwater recharge
- There is a potential for salinization of shallow groundwaters in irrigation area.

3.9 Lower Ayeyarwady Groundwater Zone

The Lower Ayeyarwady GWZ comprises the Ayeyarwady River floodplain and catchment from Singu (about 65 km north of Mandalay) to Kamma (about 125 km south of Magway), a total area of 64,120 km^2, incorporating both the Ayeyarwady River Corridor (below) and the adjacent higher areas of the Bago Yoma. It also includes the floodplains of the Samon River, which flows northwards from Pyabwe to join the Dokthawaddy[12] and then the Ayeyarwady near Tada-U.

The Lower Ayeyarwady GWZ covers a large part of the Central Dry Zone, and includes approximately 9.90 million of the Dry Zone's 15 million people, with major population centres at Mandalay, Sagaing, Myingyan, Nyaung-U, Meiktila, and Magway. Administratively, it encompasses most of the Magway Region (Pakokku, Magway, Minbu, and Theyet Districts), more than half of the Mandalay Region (Kyauske, Myingyan, Meiktila, Yamethin, and Nyaung Oo Districts, and the city of Mandalay) and a small area in the Sagaing Region (Sagaing District).

The Alluvium commences 65 km upstream of Mandalay, 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. The alluvial flats slope southwards, with surface elevation varying from 70 m AMSL at Mandalay to 45 m AMSL at Magway. The flats are enclosed to the east by the Shan Plateau (average height of 600 m AMSL), and west by the Chin Hills - Rakhine Yoma (2,000 to 3,000 m AMSL). The overall flat morphology of the central area is interrupted by a series of tectonically-induced, NNW-SSE orientated elongated anticlinal ridges, known as the Bago Yoma Anticlinorium (80 to 600 m AMSL), which rise sharply over the surrounding plains and break the continuity of the wide alluvial deposits. To the southeast, the subsurface hydrogeological boundary near Yamethin separates groundwater flow between the Samon Chaung (Ayeyarwady River) and Sinthe Chaung (Sittaung River). Mount Popa is an extinct volcano (1,518 m AMSL) which forms a prominent local topographic feature in the centre of the Dry Zone.

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 more than 70% 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 Lower Ayeyarwady GWZ is extremely short of water, especially during the latter part of the dry season.

Groundwater is critical to the livelihoods of communities in the Dry Zone. Most villages, towns, and cities rely on groundwater—some partially, most fully—for potable water supplies. Groundwater is also used extensively for industrial and irrigation purposes. Villagers without tubewells travel great distances to collect small quantities of water from shallow dugwells and polluted earth ponds. The water shortage causes people to suffer from waterborne and related diseases.

Tree felling to provide fuel for cooking, heating, and brick-making over the centuries has resulted in much of this area 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 areas.

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[12] The headwaters of the Dokthawaddy and it tributaries lie mainly within the Shan Plateau GWZ (see Section 3.7).

Over 90% of the annual rainfall occurs during the May to October monsoon period from south-westerly monsoons. A rain shadow in the lee of the Chin Hills and Rakhine Yoma, means rainfall is low 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. The average number of rainy days varies from 30 to 52 days per year. Rainfall occurs primarily as light showers with occasional heavy downpours. Average annual rainfall over the whole GWZ is 986 mm, considerably lower than PET at 1,378 mm (WorldClim). The potential evaporation in the GWZ exceeds average rainfall in almost every month of the year, except the very wet period from August to September. Temperatures vary seasonally and geographically. The mean minimum and maximum temperatures do not fall below 18.8°C and 28.5°C, respectively. During April, temperatures up to 43°C are not unusual, especially around Mandalay and Magway. The average relative humidity is over 65% from June through to December, and peaks approximately 75 to 85% in August to October. The humidity falls to 40 to 55% during the dry months of March and April. This area 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.

A combination of low rainfall, high potential evaporation, low humidity, consistently high temperature, sandy soil, thin soil cover, erosional landscape, saline baseflow, sparse vegetation, scarcity of shallow groundwater (in some areas), and tectonically complex geological features produce a semi-arid, barren region.

3.9.1 Regional Geology

The regional geological structures have a major impact on groundwater occurrence, direction of flow, depth to the potentiometric surface, presence of artesian flow, and water quality. With an understanding of the geological setting, the associated hydrogeological characteristics can be interpreted and groundwater yield and quality can be reasonably predicted.

The Lower Ayeyarwady GWZ is in an active tectonic region, with a complex system of faults, anticlinal folds and in multiple sub-basins. Major earthquake zones occur to the west (Western Hills of the Rakhine Yoma), and to the east (Sagaing Fault and Shan Plateau). The main tectonic areas are shown in Figure 3.9.1-a:

- Western Trough — including the Chindwin and Minbu Basins and Pale and Salin Sub-basins. A complex of Upper Cretaceous to Mid-Tertiary marine and non-marine deposits are overlain by younger (Upper Miocene to Recent) continental sediments. Oil deposits are found in the mid-Tertiary Lower Pegu Group and Eocene sediments of the Salin Sub-basin.
- Eastern Trough — including the Sittaung, Taungdwingyi, and Shwebo-Monywa Basins, and Bago Yoma. These are mainly Tertiary marine sediments with an increase in continental sediments to the north, overlain by younger continental sediments and recent alluvium and colluvium.
- Central Volcanic Line — a volcanic arc which stretches between the two troughs for more than 400 km, including volcanic complexes at Mount Popa (Kyaukpadaung), Shinmataung Range, Salingyi, and Monywa.

The Central Volcanic Line, uplifted areas, anticlinal structures, and major fault lines form hydrogeological boundaries that determine groundwater flow.

The main geological units, shown in Figure 3.9.1-b, are the following:

- Quaternary Alluvium, including piedmont sediments along the base of the Shan Plateau;
- Irrawaddy Fm (Upper Miocene to Lower Pleistocene continental sediments);
- Tertiary marine sediments of the Pegu Group and Eocene Fms; and
- Volcanics — Cenozoic volcanics of the Mount Popa Complex.

An example geological cross-section showing the relationships between units is in Figure 3.9.1-b.

Myanmar's main on-shore oilfields occur in the Middle Eocene to Middle Miocene Pegu Group sediments (especially sandstones of the Shwezetaw, Pyawbwe, and Kyaukkok Fms) of the Salin Sub-basin. The main 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 (see Figure 3.9.1-a). Table 3.9.1–a describes the major oilfields.

Table 3.9.1-a - Oilfields in the Ayeyarwady Basin

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. Up 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. Up 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. Up to 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. Up to Oct. 2015, 229 million barrels extracted	Total oil-in-state is 540 million barrels, >251 million recoverable
Chauk-Lanywar Chauk, Magway Region	1901 17 km long and 1.5 km wide	Peak — 1941 at 12,805 bpd. Up 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. Up 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. Up to Dec. 2015, 2.3 million barrels extracted	Total oil-in-state 76.7 million barrels, 20 million recoverable

A detailed geological map and cross-sections for this area are available in Drury (2017).

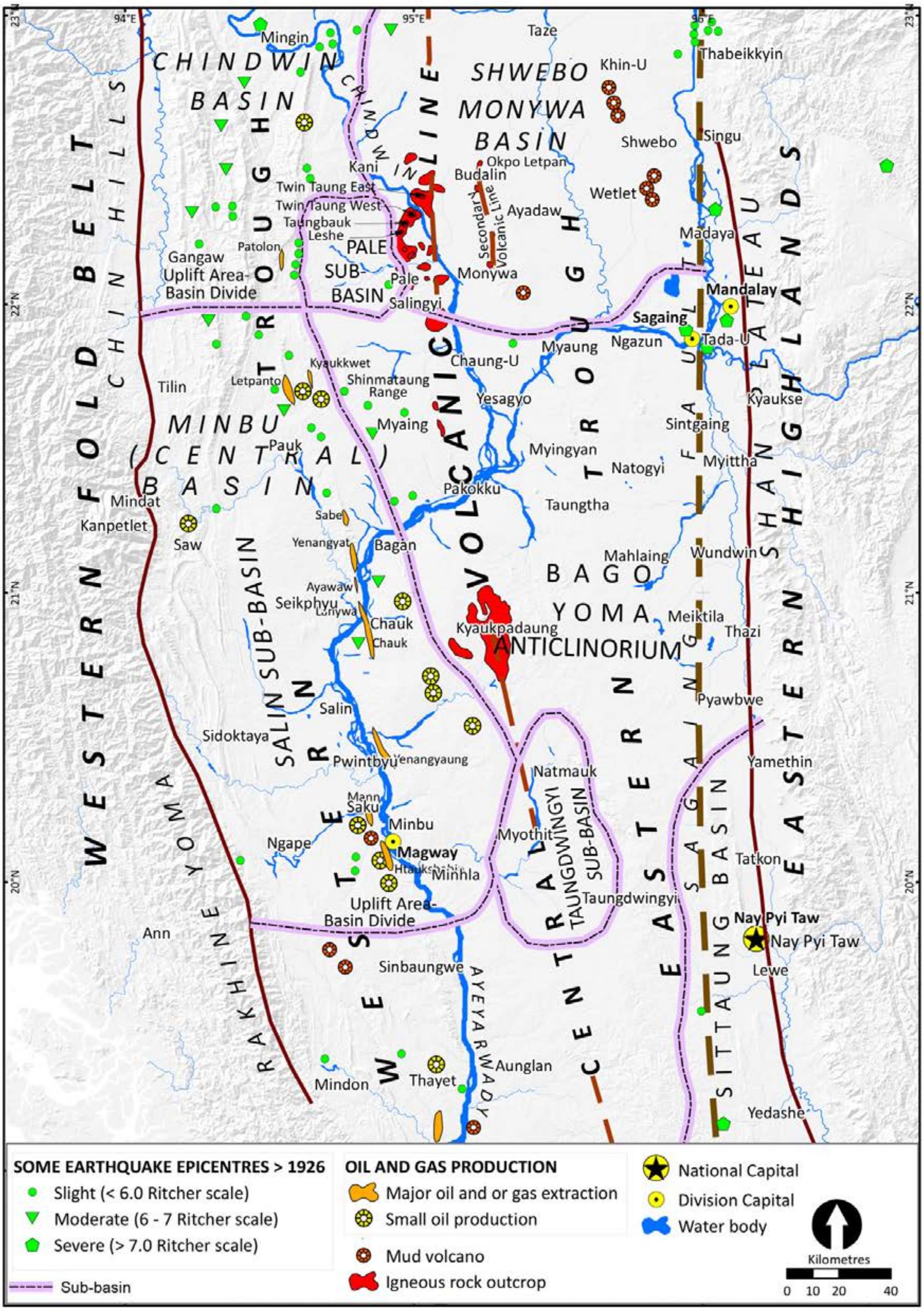

Figure 3.9.1-a – *Major tectonic features of the Dry Zone and Lower Ayeyarwady GWZ (Drury, 2017)*

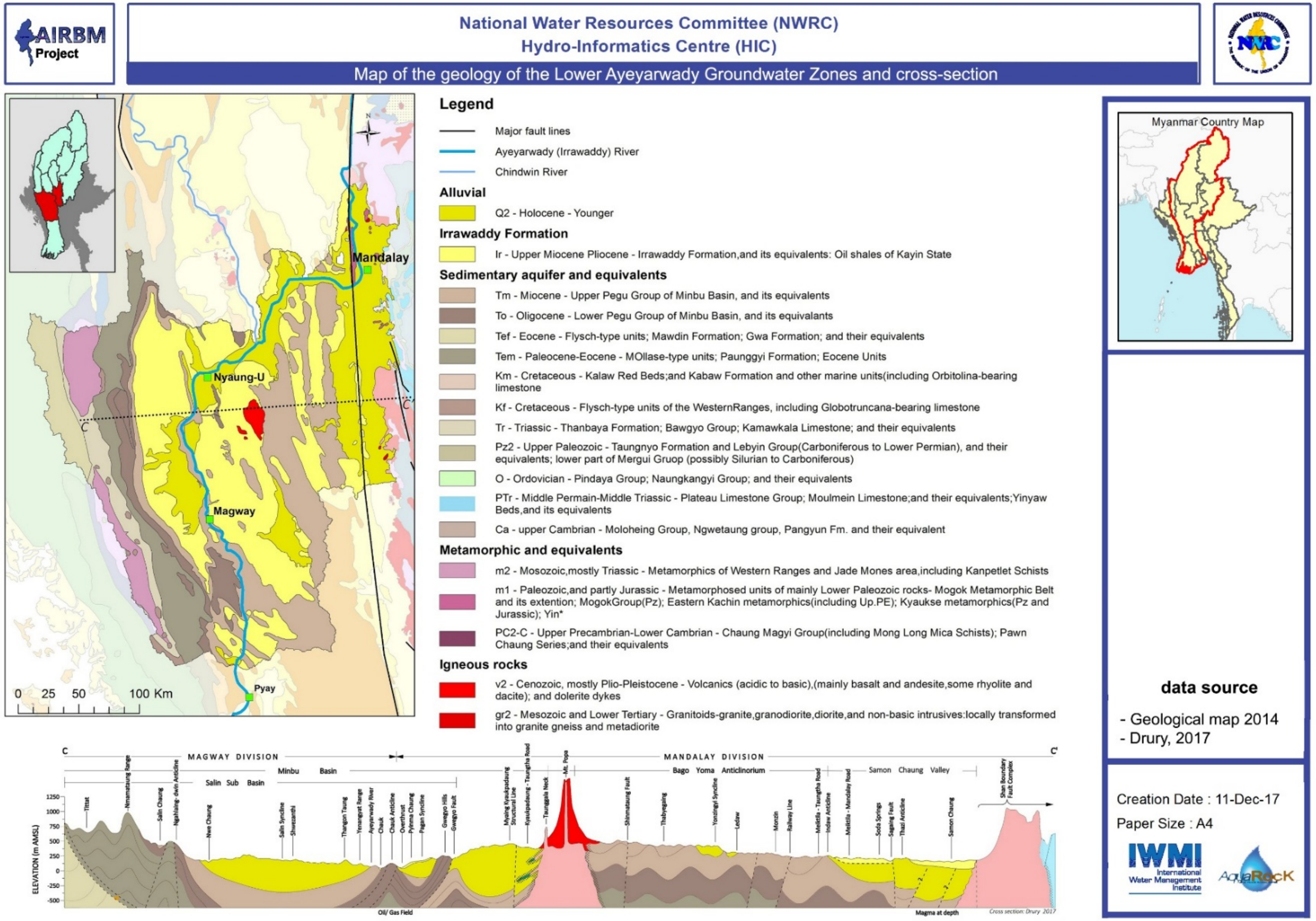

Figure 3.9.1-b – Map of the geology of the Lower Ayeyarwady GWZ and cross-section, *modified after Drury (2017)*

3.9.2 Main aquifers

The major aquifers are:

- Alluvium (Quaternary fluvial deposits along the Ayeyarwady and its tributaries) — a sequence of geologically recent, unconsolidated river and lake sediments, deposited on alluvial flats, river terraces, and piedmont plains. It varies in thickness and contains unconfined, semi-confined, and confined aquifers of variable thickness and yield in different areas. High groundwater yields are encountered in thick alluvial sediments. Where a superficial alluvial cover is present, groundwater potential in usually poor, except in the immediate vicinity of the rivers. It is usually necessary to penetrate to underlying units. Clay units of variable thickness occur, and have poor yield potential and act as aquitards. Colluvial sand, gravel, and cobble deposits along the foothills of the Western Range and Shan Plateau act as recharge zones and have high-yield, low-salinity groundwater, but have variable extent and thickness.
- Irrawaddy Fm (Upper Miocene to Lower Pleistocene continental sediments) — a thick sequence (up to 1,500 m) of continental sediments including partially cemented sands and gravels with high groundwater yield, as well as aquitard clay beds. Both confined and semi-confined aquifers occur. In some areas, deep drilling (>300 m) is required to access good quality water (for example, in Chauk — Kyaukpadaung, East of Nyaung Oo, Mandalay, Taungdwingyi Sub-basin, and along the Sagaing Fault).
- Tertiary marine sediments of the Pegu Group and Eocene Fms — contain aquifers, but groundwater is commonly brackish to saline and yield is mostly low.
- Piedmont Sediments — thick accumulation of colluvial sediments, mainly along the base of the Shan Plateau.
- Volcanics — fractured rocks of the Central Volcanic Line, may also yield good quality water locally, but are restricted in extent.

The relative areas of the main aquifer groups within the Lower Ayeyarwady GWZ are set out in Figure 3.9.2-a.

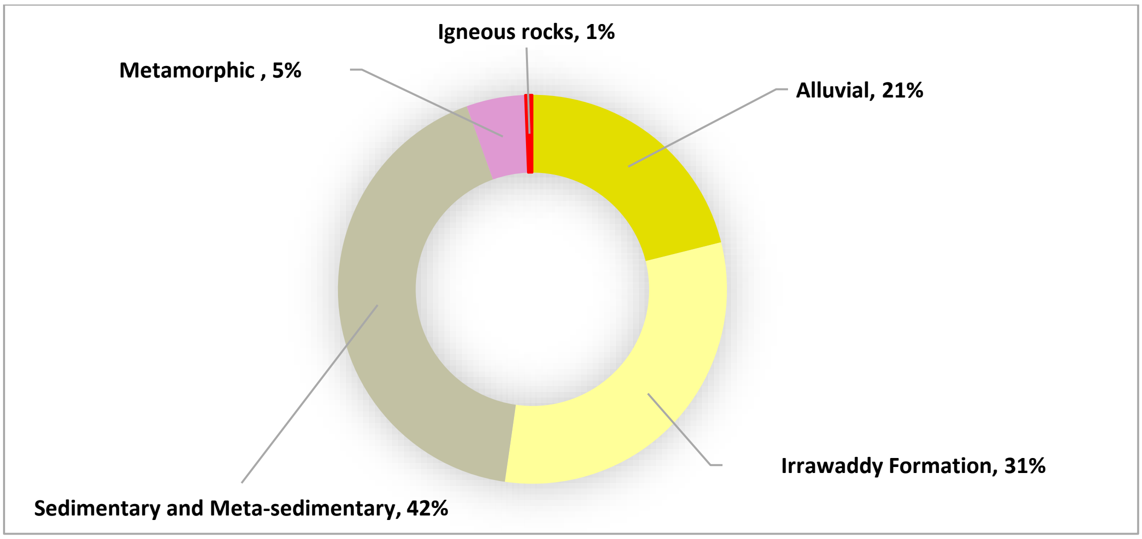

Figure 3.9.2-a - Area of main aquifer groups in Lower Ayeyarwady GWZ

The cross-section at Figure 3.9.1-b indicates the complexity of the hydrogeological regime. The characteristics of the main aquifer units are summarized in Table 3.9.2-a, and a more detailed description is given in Table 3.9.2-b.

Based on analysis of hydrogeological characteristics, it is possible to delineate areas with high likelihood of good groundwater yield (>6 L s^{-1}) and low-salinity (<1,500 µS.cm^{-1}). These areas are shown on Prospective areas include the Alluvium, the Piedmont Colluvium; and areas of the Irrawaddy Formation away from the Pegu Group (see Salinity section below). Figure 3.9.2-b is a generalised depiction and variations in yield and salinity should be expected. Some potential high yield and low salinity areas have limited width as the Ayeyarwady River cuts through the northern extension of the Bago Yoma Anticlinorium (Myinmu and Pakokku) and the Chauk and Yenangyat anticlines.

Figure 3.9.2-c shows the areas of artesian flow[13] within Lower Ayeyarwady GWZ. These occur along the base of the Shan Plateau in the Samon Chaung Valley and within the Taungdwingyi Sub-basin.

Table 3.9.2-a - Aquifer units in Lower Ayeyarwady GWZ

Formation	Area (%)	Lithology	Location	Mode of deposition	Quality/yield
Alluvium (Quaternary)	29	Sand, silty sand	Major watercourses, intermountain sub-basins	Freshwater fluviatile	Usually low-salinity, high-yield
Piedmont (Quaternary)	5	Sand, gravel, cobble	Eastern and western foothills	Freshwater colluvial	Low-salinity, moderate yield
Irrawaddy Fm (Miocene — Pleistocene)	38	Sand, sandstone, gravel, clay	Regional aquifer throughout Dry Zone	Freshwater fluviatile, deltaic	Low-salinity to brackish, moderate to high-yield
Pegu Group (Oligocene — Mid-Miocene)	20	Sandstone, fractured shale	Central and west	Marine, fluviatile and deltaic	Brackish to saline, low-yield
Eocene marine sediments	7	Sandstone, shale	Western foothills	Marine	Brackish, low-yield
Volcanics	0.6	Intrusive and extrusive	Central Volcanic Line /Secondary	Volcanic eruption or emplacement	High-yield, low-salinity, hard

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[13] An ar*tesian aquifer* is a confined *aquifer*, where water is under pressure so that the potentiometric surface is above the land surface, and water *flows* from wells without pumping.

Table 3.9.2-b – Generalised summary of aquifer characteristics throughout the Ayeyarwady River Corridor

Aquifer type	Regional location	Specific location	Depth of drilling/ average (m)	SWL range /average (m)	Yield (L s^{-1})	Quality (µS/cm^{-1})	Hydraulic characteristics		
							Transmissivity av. (m^{2}day^{-1})	Hydraulic conductivity (m day^{-1})	Storage coefficient
Alluvium	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		
	Myingyan	Sindewa Chaung	41	1 - 3	20 - 40	<1,000	400 - 1000		0^{-4} - 1.3 x 10^{-3}
		Near Ayeyarwady	90	1.5 - 24	2 - 20	<1,500	50 - 180		5 x 10^{-3}
	Mandalay	River	30	2 - 12	5 - 10	<1,000		0.89	2.4 x 10^{-3}
		TWS Aquifer 1	70	10 - 20	10 - 20	<1,000	1,900	27 - 140	1 x 10^{-3} - 5 x 10^{-5}
		TWS Aquifer 2	160	12 - 60	20 - 80	<1,000	100 - 15,000	1.3 - 220	1 x 10^{-3} - 7 x 10^{-5}
		TWS Aquifer 3	40	1 - 5	4 - 50	<1,000			
	Meiktila Tatkon	Kyauske	40 - 110	0 - 7	3 - 10	<1,500	44 - 650	112 - 124	
		Meiktila - Thazi	60	2 - 10	5 - 20	690 - 10,000			
		West of Sagaing F	>45	+ 4 - 10	2 - 10	<1,500			
		Pyawbwe	88 - 160	3 - 10	3 - 10	<1,000			
		Thein Gone Village	51	4 - 7	25	<1,000	2,800 - 4,000	150 - 200	5 x 10^{-2}
		Tatkon							
Piedmont	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}
Irrawaddy Fm	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	
		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		
	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	
	Meiktila	Wundwin	195 - 457	38 - 82	10 - 20	1,600 - 10,000	30 - 110		2 x 10^{-4}
		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 x 10^{-4}
Pegu Group	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		
	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		
Limestone	Shan Plateau	Kalaw Township	96 - 252	30 - 120	1 - 50	<1,500			

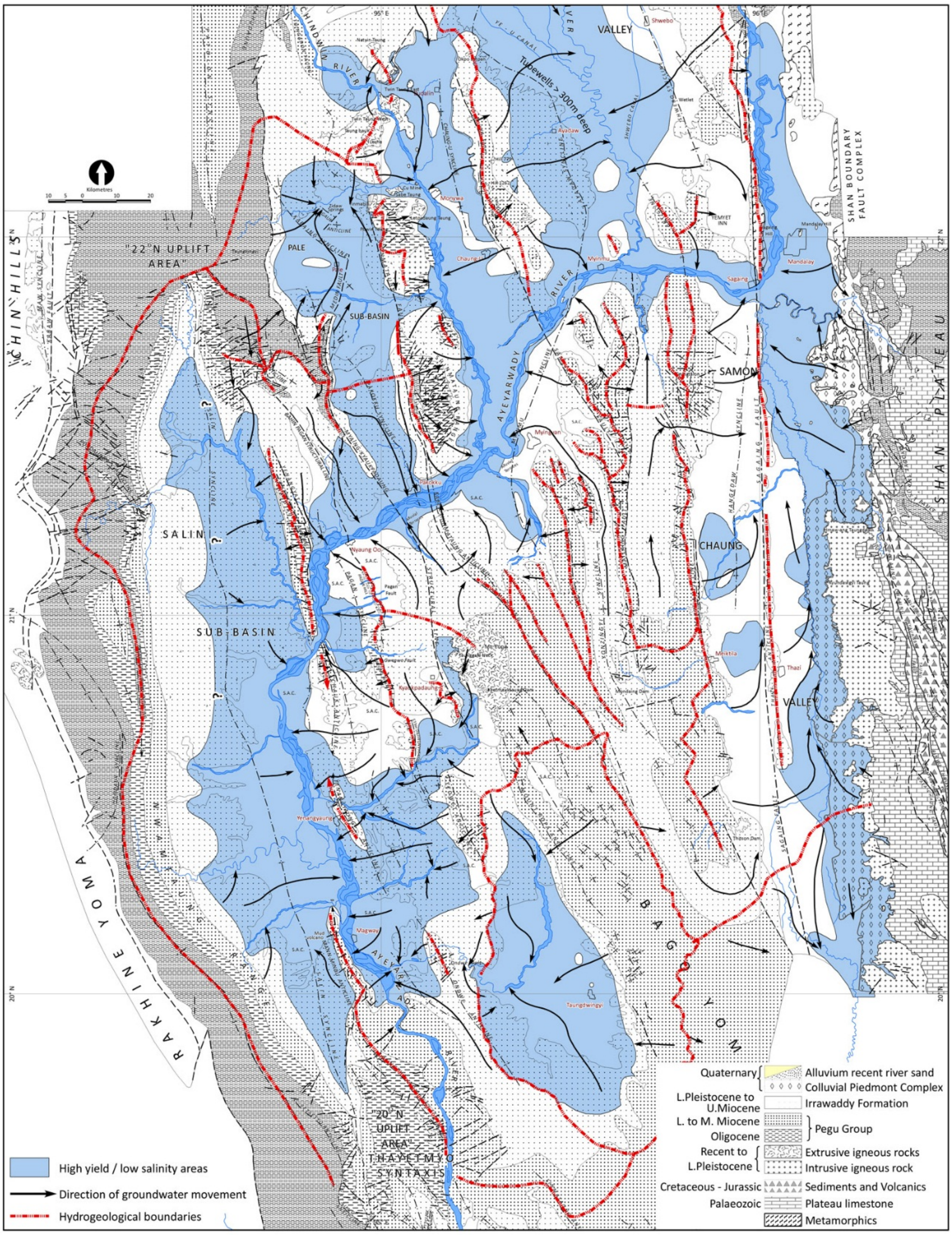

Figure 3.9.2-b – Map of likely high yield and low salinity groundwater areas in the Dry Zone, *including the Lower Ayeyarwady GWZ, the Lower Chindwin GWZ, and the lower part of the Mu GWZ (Drury, 2017)*

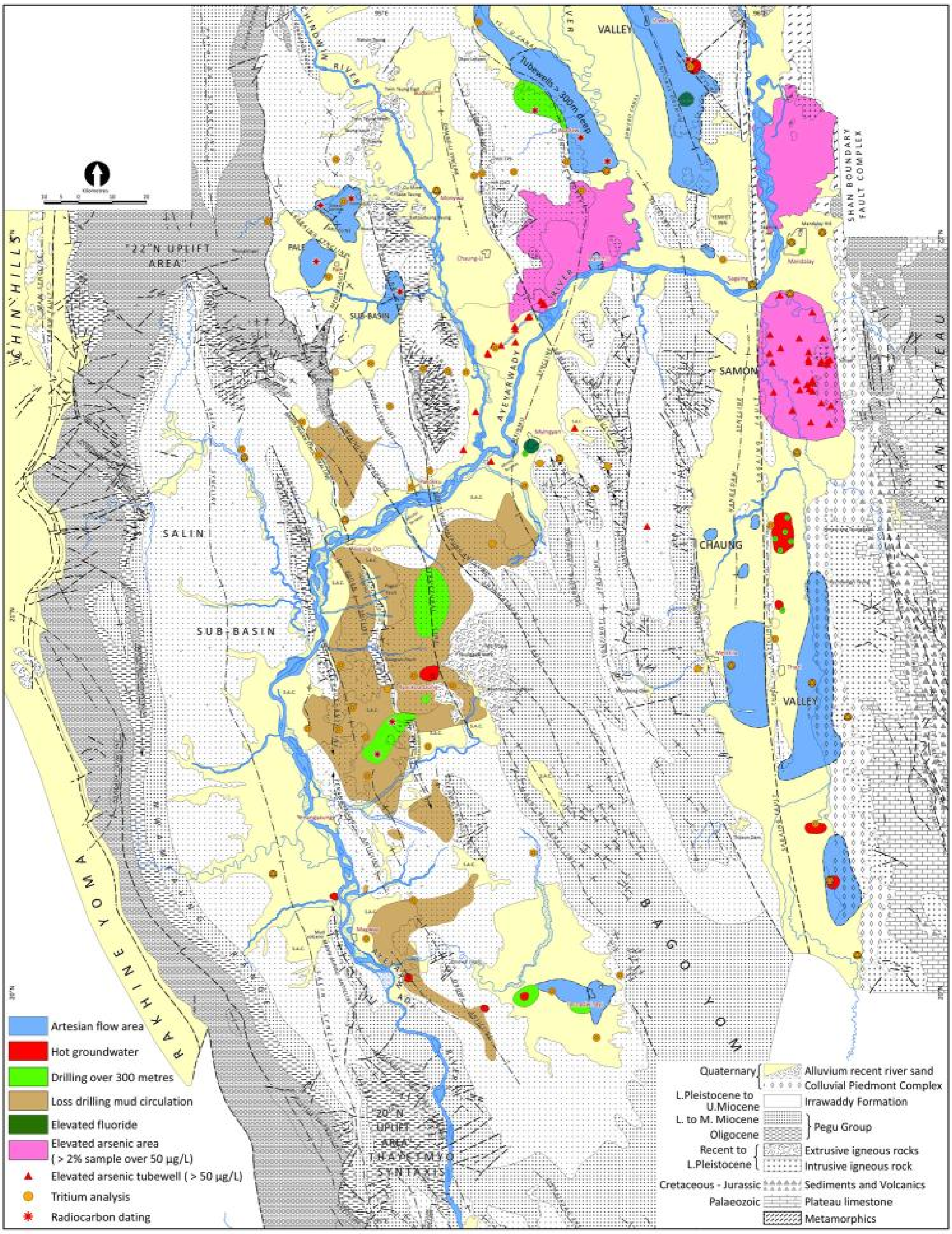

Figure 3.9.2-c – Map of artesian zones, hot water, elevated arsenic, fluoride, and deep aquifers in the Lower Ayeyarwady GWZ (Drury, 2017)

3.9.3 Storage and recharge

Throughout the Lower Ayeyarwady GWZ, the direction of groundwater flow is from the elevated aquifer recharge areas directly or indirectly towards the Ayeyarwady River. Major natural groundwater recharge areas include the following:

- Exposed areas of Alluvium;
- Elevated Piedmont Colluvial Sediment along the western edge of the Shan Plateau;
- Sandstones along the Western Fold Belt; and
- Sandy intermittent flowing chaungs.

Induced artificial groundwater recharge may occur directly where the radius of influence of pumping tubewells intersects the Ayeyarwady River and tributaries (for example, the 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.

The extent to which groundwater flow occurs between the Alluvium and Irrawaddy Fm aquifers is controlled by the vertical permeability and thickness of the clay aquicludes, and head differences.

Tritium analysis of groundwater indicates that modern recharge water is encountered in the following:

- Shallow sandy, intermittent chaungs along western hills and around Mount Popa; and
- Elevated Piedmont Colluvial Sediment along the western edge of the Shan Plateau.

Radiocarbon dating and tritium analyses were carried out, to assist in understanding the dynamics of groundwater flow in the area. Tritium analysis indicates a pre-thermonuclear age (older than 50 years) in the centre of the basin. Radiocarbon dating for the deep Irrawaddy Fm Aquifers west of Chauk gave ages of ≈ 2,565± 35 years at Gwebin and and 3,600 ± 30 years at Seinbanbin.[14] The distance between the two villages is 8 km, and aquifer depths are similar. These results indicate that groundwater moves at a very slow rate of eight metres per year, assuming radiocarbon and calendar years are equivalent.

The volume of low-salinity water available from various locations within the Lower Ayeyarwady GWZ was estimated, based on aquifer characteristics (Table 3.9.3–a). Only a small percentage of this volume can be extracted. These figures should not be quoted as the volume of water available for use. 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 require exceedance.

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[14] The ages quoted are radiocarbon ages, not calendar ages.

Table 3.9.3-a - Estimate of low salinity groundwater in aquifer storage, Lower Ayeyarwady GWZ

Location	Formation		Assumed depth (m)	Aquifer occurrence (%)		Storage (cubic kilometres [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	
				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	
	Irrawaddy 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	

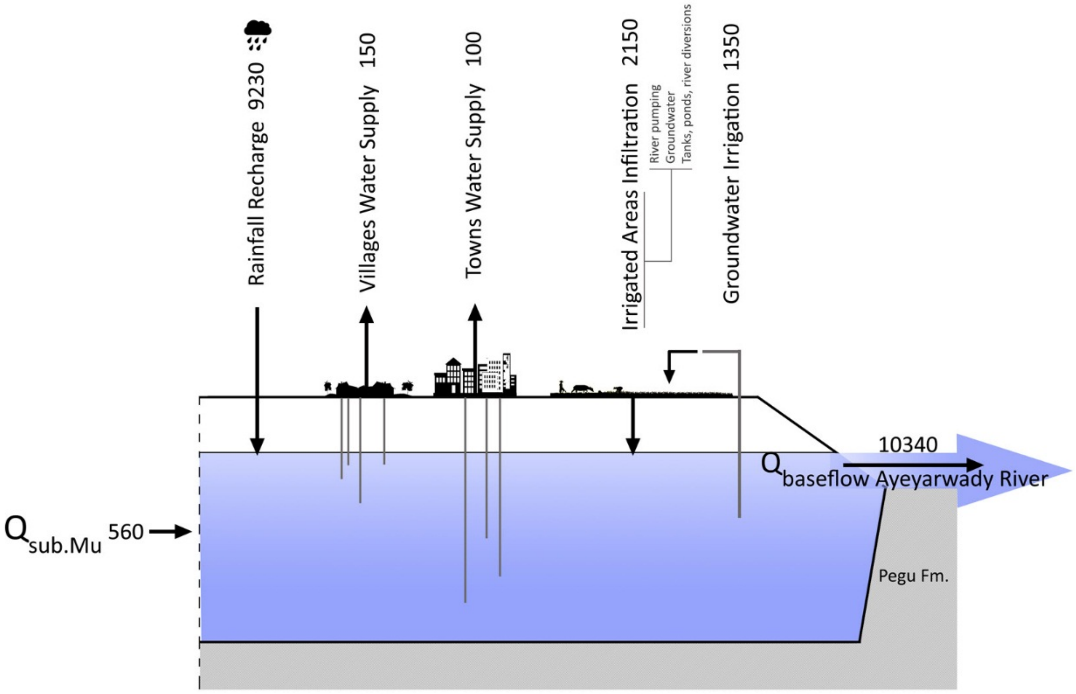
WATER BALANCE

Figure 3.9.3-a summarizes the water balance for the main aquifers of the Lower Ayeyarwady GWZ. Due to the lack of long-term monitoring of the potentiometric surface and the geological complexity, the estimate of aquifer recharge and discharge cannot be accurately known.

The 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 gauging stations so 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 this period represents 20% of the Ayeyarwady River baseflow. The water balance indicates the following:

- Groundwater extraction for on-land utilisation (1,600 Mm^3 yr^{-1}) is 14% of aquifer recharge (11,380 Mm^3 yr^{-1}).
- Discharge to the river is 10,340 Mm^3 yr^{-1}.
- Outflow to the Ayeyarwady River is approximately 1.5% of the low-salinity groundwater stored within the Alluvium, Irrawaddy Fm, and Piedmont Colluvial Sediments (750 km^3).

The water balance calculation suggests that expansion of groundwater utilisation is viable, especially close to the Ayeyarwady River. 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 basinwide water planning and management strategy. Groundwater and surface water need to be viewed as one integrated and mutually interdependent resource.



Units: Annual volumes in Mm^3

Figure 3.9.3-a - Water Balance Model for the Ayeyarwady River Corridor

3.9.4 Groundwater Quality

SALINITY

Groundwater salinity is strongly controlled by the mode of sediment deposition and geological structure of the aquifers. 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, the Shinmataung and Kyaukka ranges, the western hills, and the 20° N and 22° N Uplift areas. The specific conductance of the $Na^+:Cl^-$ or $Ca^{2+}:SO_4^{2-}$ type water is usually 1,500 to >10,000 µS.cm^{-1}. Highly saline groundwater (>60,000 µS.cm^{-1}) occurs at depth near the oilfields and in anticlinal folds.
- Saline shallow aquifers (3,000 to 10,000 µS.cm^{-1}) overlie better quality zones in deeper sediment along the Thazi Anticline.
- Highly saline aquifers (<10,000 µS.cm^{-1}) are encountered at depth within the Irrawaddy Fm along the southern periphery of the Shinmataung and Kyaukka ranges as the Pegu rocks gently plunge south.
- With increasing distance from the Pegu Group rocks, groundwater salinity in the Irrawaddy Fm or Alluvium aquifers decrease. At Myingyan and north of Sagaing, there are extensive brackish plumes.
- Low-salinity $Na^+:HCO_3^-$ type groundwater usually occurs with the Alluvium and Irrawaddy Fm aquifers.

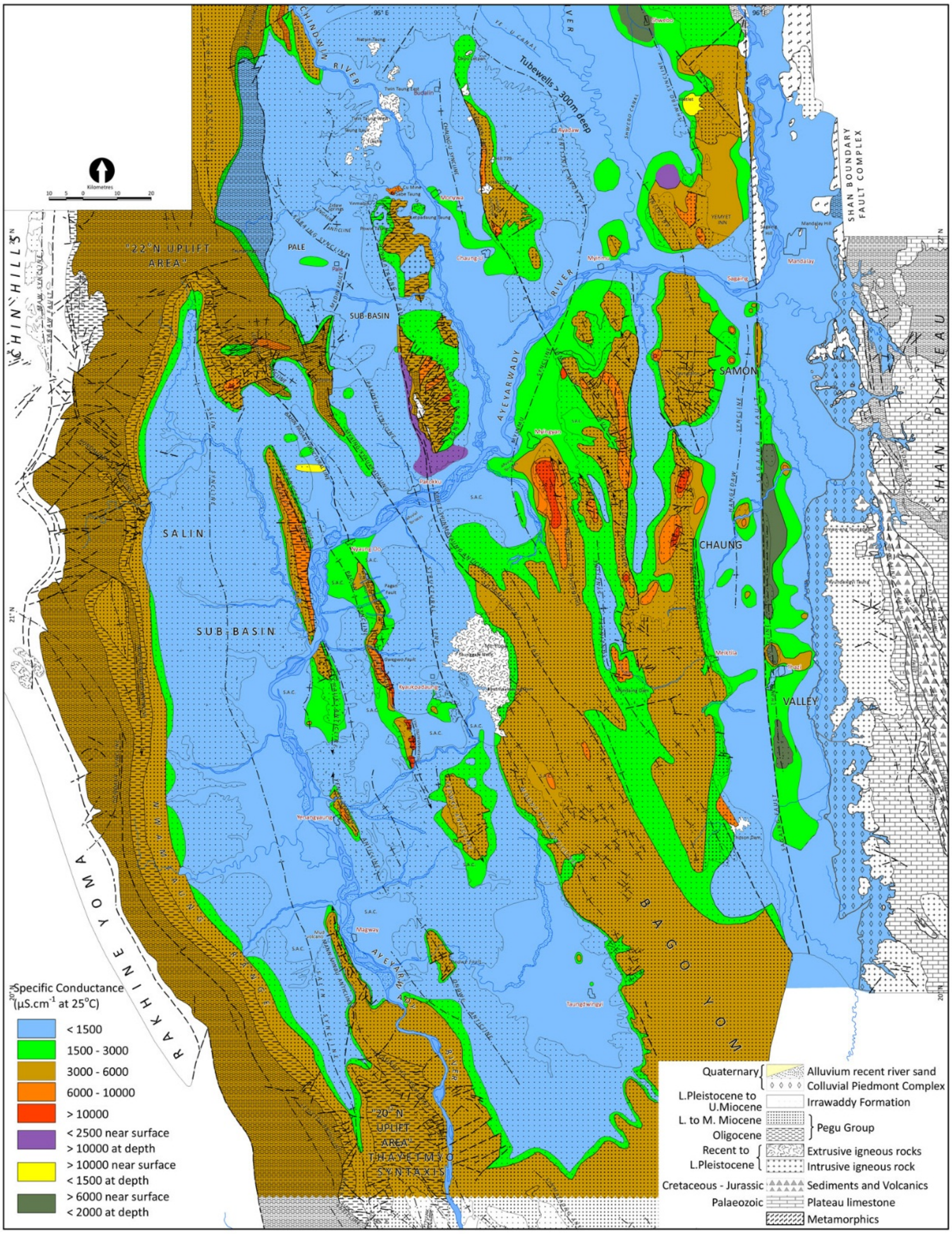


Figure 3.9.4-a – Variation in specific conductance, Ayeyarwady River Corridor (Drury, 2017)

ARSENIC

Groundwater samples were collected from 17 of the 53 townships in the Dry Zone for analysis of naturally occurring arsenic (WRUD and UNICEF, 2005; Bacquart et al., 2015). Of these, 12 townships are within the Lower Ayeyarwady GWZ (Table 3.9.4–a). WHO and Myanmar National Drinking Water Quality Standards (NDWQS) standards for arsenic in drinking water are below 10 and 50 µg/L, respectively. The results indicate the following:

- High concentrations of arsenic (>50 µg/L) occur within the Ayeyarwady River alluvial sediments (Myaung [4.6% NDWQS exceedance], Madaya [4%], Myingyan [2.8%], Myinmu [2.3%], and Yesagyo [1.3%]) and the lower Samon Chaung (Amarapura [2.4%], Leway [2.3%], Kyauske [1.9%], and Sintaung [1.8%]). Elevated arsenic is not recorded in the Mu and Chindwin river valleys.
- Elevated arsenic is known in a few shallow tubewells in the Irrawaddy Fm, in the Bago Yoma Anticlinorium near Mahlaing and Natogyi.

Comprehensive sampling for arsenic in other townships has not been undertaken, but the problem may be quite widespread. Analysis of 6 shallow tubewells at Tha Phay Thar Village (near Myingyan) showed all groundwater samples exceed the WHO Standard of 10 µg/L (Table 3.9.4–bc). Informed of this hazard, the villagers now only use one designated low arsenic tubewell within the village for drinking purposes. It seems that high arsenic is specific to the sediments of the Ayeyarwady mainstream, as elevated levels have not been found in either the Mu or Chindwin basins.

Table 3.9.4-a – Arsenic concentrations within 12 townships of the Lower Ayeyarwady GWZ

Region	Township	Total samples	Concentration >10 µg/L		Concentration >50 µg/L	
			No.	%	No.	%
Sagaing	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
	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

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

OTHER NATURALLY OCCURRING GROUNDWATER CONTAMINANTS

Testing for other contaminants in groundwater is not common. The few analyses available show that elevated levels of dissolved metals occur. For example, Table 3.9.4–b indicates the dissolved metal content in groundwater from Myingyan Town. Of the 12 samples tested, 5 exceeded WHO standards for fluoride, and 2 for uranium. In nearby Tha Phay Thar Village all 6 samples tested had high concentrations of iron and manganese, associated with high arsenic levels (Table 3.9.4–c). Other locations of high dissolved metals may occur.

Table 3.9.4-b - Dissolved metal content of groundwater from Myingyan Town

WHO	10	2,400	700	50	1,500	2,000	400	10	40	30	100	Depth
Metal	**As**	**B**	**Ba**	**Cr**	**F**	**Fe**	**Mn**	**Pb**	**Se**	**U**	**V**	
	(µg/L)											(m)
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

(Bacquart et al., 2015)

** Sample exceeded health based reference (WHO Guidelines).*

Table 3.9.4-c - Dissolved metal analyses from Tha Pyay Thar Tubewells, near Myingyan

WHO	10	2,400	700	50	1,500	2,000	400	10	40	30	100	Depth
Metal	**As**	**B**	**Ba**	**Cr**	**F**	**Fe**	**Mn**	**Pb**	**Se**	**U**	**V**	
Unit	(µg/L)											(m)
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

(Bacquart et al., 2015)

*Sample exceeded health based reference (WHO Guidelines).

HOT GROUNDWATER

Elevated groundwater temperature is found in deep aquifers along the Sagaing Fault, associated fault off-shoots, and near Mount Popa (Figure 3.9.2-c). Geophysical studies show anomalous Bouguer (gravity) highs between Wundwin and Yamethin, which indicate magma intrusions at depths, probably associated with the Sagaing Fault complex (Drury, 2017). Further north along this fault line the temperature of groundwater at Halin (Mu River Valley) is 46°C. The hottest groundwater temperatures at Wundwin, Yamethin, and Mount Popa are 42, 39 and 44.2°C respectively. Isolated random hot spots also occur within the arc.

GROUNDWATER POLLUTION

Approximately 25% of households living in this region do not have access to safe sanitation, and bacterial contamination of shallow groundwaters in the vicinity of villages is a potential threat.

Oil production in the oilfields in Magway and Minbu Districts poses a potential threat of groundwater contamination. However, analysis of four wells in the Mann oilfield at Minbu for an EIA found no evidence of contamination by oil (Environmental Resources Management [ERM], 2015).

3.9.5 Groundwater Use

Groundwater is critical to livelihoods in the Dry Zone. Communities access groundwater for both domestic and irrigation supplies through wells of different types. Shallow dugwells and tubewells with hand, air, and solar pumps are common for domestic supplies; tubewells with diesel centrifugal pumps are more common for irrigation purposes. Shallow dugwells in many areas dry out as the regional water tables drop during the dry season, and village use shifts to tubewells.

In addition to widespread private drilling, groundwater development has been carried out by national and foreign governments and NGOs. Since 2002 the DRD, through JICA funding, has conducted groundwater drilling programs in the Nyaung Oo, Kyaukpadaung, and Chauk areas. In 2014, the IWUMD constructed 100-millimetre diameter-cased tubewells in Taungtha and Mahlaing Townships as an emergency drought relief program.

IRRIGATION

The Lower Ayeyarwady GWZ includes major agricultural areas. The majority of production is rainfed (>80%), but IWMI landcover mapping identified approximately 315,000 ha of double cropping, most of which requires irrigation. The Ayeyarwady River and its tributaries are the main source of irrigation water. IWUMD (2016) list 84 large-scale river pumping stations for irrigation in the Sagaing, Mandalay, and Magway regions, serving an area of 120,000 ha, and there are a number of small gravity-fed schemes (weirs, canals, and diversions). However, water access is limited to the areas close to the river or canals, and operational problems mean that water delivery is not always reliable. Many farmers in the zone use groundwater, accessed through individually managed tubewells.

Government groundwater irrigation schemes have been constructed at four locations (Table 3.9.5–a). Details of the scheme at Meiktila-Thazi are given in Box. Small-scale irrigation also takes place from thousands of shallow, small diameter tubewells equipped with centrifugal pumps (usually diesel), with individual yields approximately 2 to 4 L s^{-1}, located mainly in the Alluvium. Artesian and sub-artesian tubewells occur in some areas, mainly in the Piedmont Complex along the base of the Shan Plateau. Deeper tubewells are used to access the Irrawaddy Fm aquifers in some areas.

Farmer-managed groundwater irrigation is common in the following areas:

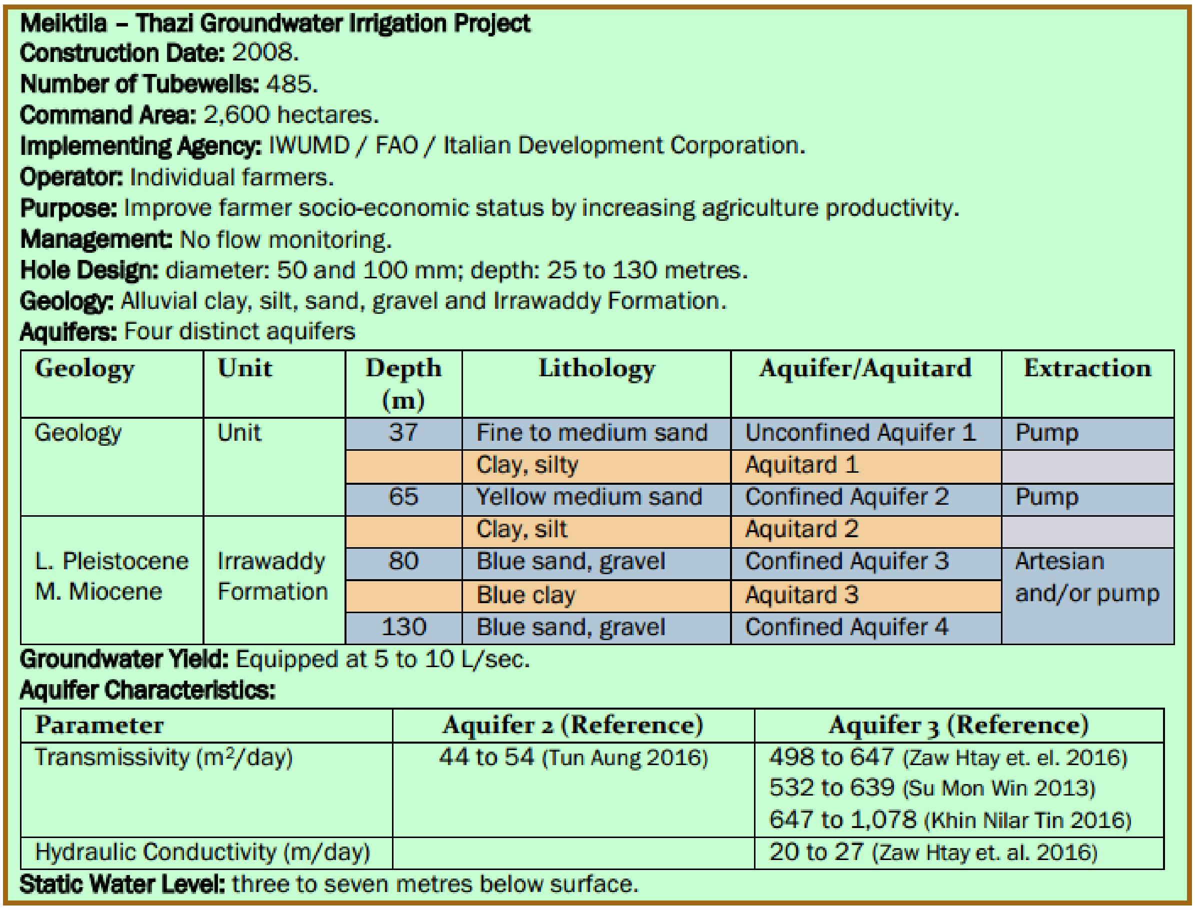
- The Ayeyarwady River Corridor, between Sagaing and Myinmu;
- The Ayeyarwady River Corridor and tributary chaungs, between Chauk and Magway;
- Thazi, west of the Sagaing Fault and near Thinbon Chaung;
- Myittha, east of the Sagaing Fault, along the Colluvial Piedmont Complex and adjacent Alluvium; and
- In sandy riverbeds of the Ayeyarwady and tributary chaungs, where recession farming takes place during the dry season, using temporary shallow dugwells and manual spreading with dual watering cans.

Table 3.9.5-a - Government groundwater irrigation projects in Lower Ayeyarwady GWZ

Name	Date	Command area	Access
Meiktila-Thazi Groundwater Irrigation Project	2008	2,600 ha	485 tubewells. Of the initial 22 artesian tubewells recorded in 2008, only one was still flowing in November 2016.
Pyawbwe-Payangazu Groundwater Irrigation Project	2009 to 2011	500 ha	100 tubewells. Initially 75 were artesian, but by 2014 only 23 were still flowing. Salinity has increased over time.
Tatkon Groundwater Irrigation Project	2014 to 2015	120 ha	10 tubewells with electro-submersible pumps.
Kyaukse-Myittha			5,016 tubewells. Regional government-financed and farmer-operated. Water table has declined 3 m since 2010.

Box 3.9.5 –a

Meiktila-Thazi Irrigation Project



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
Geology	Unit	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: 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.

DOMESTIC AND URBAN SUPPLY

More than 70% of people in the Lower Ayeyarwady rely on groundwater for drinking and domestic purposes (2014 Census). Even where surface water is readily available, issues with water quality (particularly high sediment loads in the river) and difficulty of access due to large seasonal fluctuations may mean that communities prefer to use groundwater, particularly for drinking water. Villagers without tubewells may have to travel large distances to collect small quantities of water from shallow dugwells and polluted earth ponds. The water shortage contributes to waterborne and related diseases.

Towns and cities in the Dry Zone rely on groundwater — some partially, most fully — for potable water supplies. In most towns and cities, municipal supplies are supplemented by a large number of private wells. Details of water supplies in the major towns are given in Table 3.9.5–b and Box 3.9.5 –b.

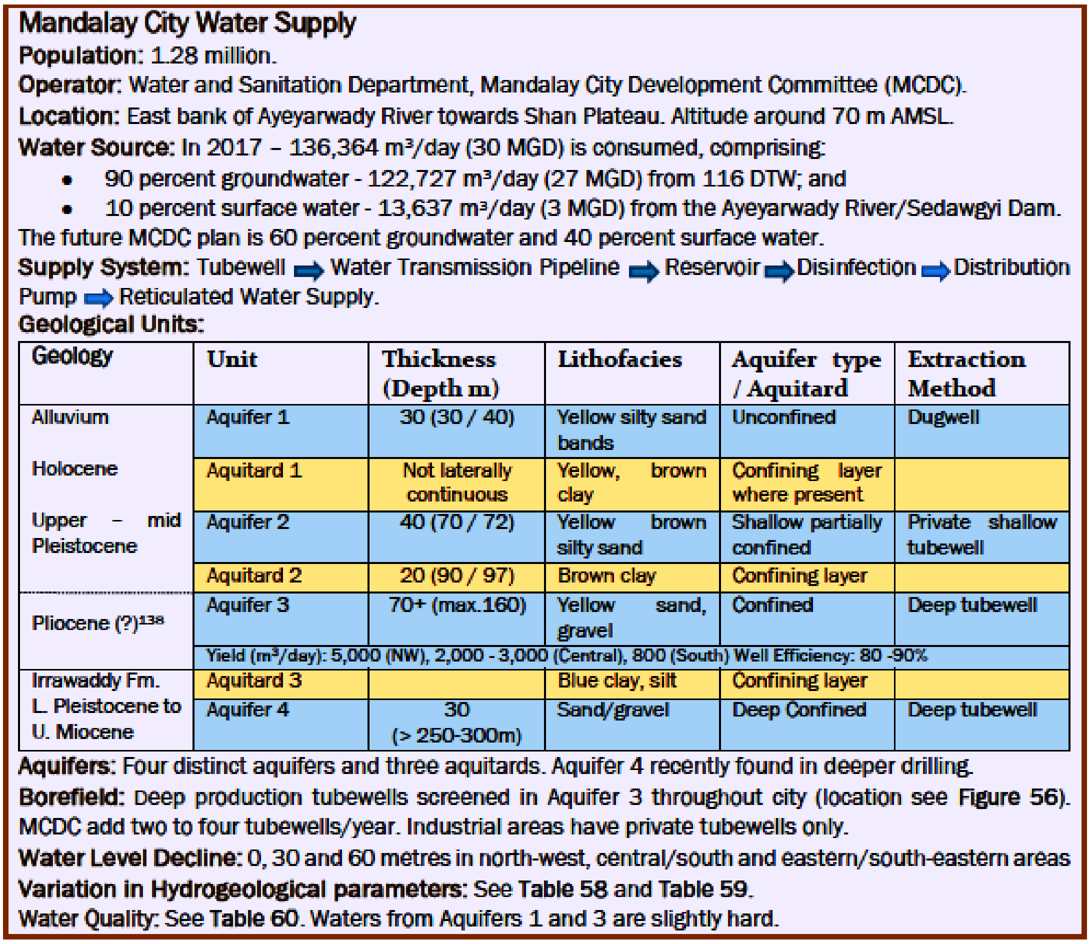
Table 3.9.5-b - Town and city water supplies using groundwater in the Lower Ayeyarwady GWZ

Town		Access	Yield
Mandalay	90% GW; remainder from river	116 DTW. More than 25,000 private wells Decline in water level in areas away from the river; careful management is required	45 Mm^3 yr^{-1} 123 ML day^{-1}
Sagaing	Groundwater, plus 11 river pumping sites	3 government tubewells, plus 1,890 tubewells and 201 dugwells	34.8 ML day^{-1}
Taungtha Town Water Supply	>100% (but mixed supply)	4 DTW, 2 x 4 m dugwells	2.7 ML day^{-1}
Myingyan	46% GW; remainder from a mix of sources	6 DTW (100 - 250 mm)	
Mahlaing	Moderate salinity 1,900 and 2,300 µS.cm^{-1}	Private tubewells at 100 - 120 m	
Natogyi	Moderate salinity 1,930 µS.cm^{-1}	16 shallow tubewells	3 L s^{-1} (4.2 ML day^{-1} if 24 hr)
Wundwin	Water quality marginal to poor	6 production tubewells to 180 m	2 L s^{-1} (1 ML day^{-1})
Thazi	Mixed GW and SW from Minhla Dam	7 DTW (~90 m) plus many private shallow tubewells	2.35 ML day^{-1}
Pyawbwe		4 DTW (~60 - 70 m)	0.7 ML day^{-1}
Yamethin		8 x 350 mm DTW (88 - 160 m) plus may private wells	1.8 ML day^{-1}

Box 3.9.5 –b –

Mandalay City Water Supply

(Drury, 2017)



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 (?)[138]	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. L. Pleistocene to U. Miocene	Aquitard 3		Blue clay, silt	Confining layer	
	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.

INDUSTRIAL

Most industries in Mandalay rely on groundwater. There are at least 1,522 private tubewells in the Industrial Zone, and total extraction for industry is likely well in excess of the 9 ML day^{-1} estimated by MOAI (2003) in 2000. Industries include agro-processing (edible oils and cotton), breweries, textile factories, sugar mills, and gem production. Industrial withdrawals also occur at Kyauske, Sagaing and Magway, estimated by MOAI (2003) at 2 to 3 ML day^{-1} for each city in 2000; and at ~1 to 1.5 ML day^{-1} in Pakokku, Meiktila, and Myingyan. Industries include cement, cotton weaving, processing of tobacco and edible oils, iron, and bronze. Industrial Zones have been established at Mandalay, Meiktila, Myingyan, Yenanchaung, and Pakokku.

Magway Region is the centre of Myanmar's onshore oilfields with production fields around Chauk, Yenanchaung, Magway, and Minbu. The majority of Myanmar's production of crude oil of 12,500 barrels a day[15] is from this region. The main oilfields are described in Table 3.9.1–a (from Drury, 2017). Production from these oilfields was historically managed by Burmah Oil Corporation, now the Myanmar Oil Corporation. A few minor oilfields are open to small-scale artisanal producers; in 2016, the government began to regulate artisanal production by issuing licences for refining activities.[16]

MOAI (2003) reports very high levels of groundwater extraction annually for industry at Minbu (25 ML day^{-1} = 9.1 Mm^3 yr^{-1}), probably mostly related to oil extraction, though the reliability of this estimate is not known. Minbu's town water supply currently withdraws approximately 4.3 ML day^{-1} (Drury, 2017). Villages within Mann Oil Field reported the use of groundwater from deep tubewells and hand dugwells as water supply (ERM, 2015).

No current figures on industrial extraction were available for this study.

Table 3.9.5-c - Range of estimates of annual groundwater use for Lower Ayeyarwady GWZ Mm^3 yr^{-1}

	Industrial	Agricultural	Domestic	TOTAL	Source
Estimated use 2000	15	70	496	581	MOAI, 2003
Projected use 2015	17	411	660	1089	MAI, 2003
Town supplies			62		This study (table above)
Estimated current use	54	Low: 1,350 High: 1,500	340	Low: 1,744 High: 1,894	This study

3.9.6 *Groundwater and Ecosystems*

Groundwater plays an important role in supporting the dry season flow of all perennial chaungs in the Dry Zone.

A large number of KBAs are identified in the Lower Ayeyarwady GWZ but some are of small extent, and of medium priority for conservation. Reliance on groundwater is low for those located in a mountainous environment. In cases where it was not possible to wetland or other features from aerial imagery, groundwater reliance was ranked as low. Several large alluvial plains are within KBAs, where groundwater is likely to support ecosystems, particularly thorugh dry season flow contribution. This is particularly true for the Ayeyarwady River, which is classified as high priority and where groundwater contribution to baseflow has been estimated to be particularly important (cf. Section 3.9.3).

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[15] https://knoema.com/atlas/Myanmar/topics/Energy/Oil/Production-of-crude-oil

[16] https://www.mmtimes.com/business/23652-artisanal-oil-licences-to-be-issued-this-month.html

Table 3.9.6-a - Summary of the KBAs of the Lower Ayeyarwady and reliance on groundwater

KBA name	Type of KBA	Priority	Area (km²)	GW-ecosystems link	GW reliance
Irrawaddy Dolphin PA	Freshwater	High	326	Large river (Ayeyarwady) - Alluvial plain	Average
Sheinmaga Tawyagyi	Terrestrial	High	1	Large river (Ayeyarwady) - Alluvial plain	Average
Yemyet Inn	Freshwater	Medium	42	Closed to artesian flow area	High
Peleik Inn	Freshwater	Medium	37	Large river (Ayeyarwady) - Alluvial plain	Average
Taungtaman Inn	Terrestrial	Medium	7	Large river (Ayeyarwady) - Alluvial plain	Average
Taung Kan at Sedawgyi	Freshwater	Data deficient	37	No particular feature. Geology: Q2	Low
Myaleik Taung	Terrestrial	High	37	Location unclear	Average
Shinmataung	Terrestrial	Medium	24	Mountainous, possibly springs	Low
Myittha Lakes	Freshwater	Data deficient	37	No particular feature. Geology: Q2	Low
Minzontaung WS	Terrestrial	Medium	17	Mountainous, possibly springs	Low
Kyee-ni Inn	Freshwater	Data deficient	37	No particular feature. Geology: Q2	Low
Popa Mountain Park	Terrestrial	Medium	98	Mountainous, possibly springs. Geology: volcanic Mountt Popa	Low
Ayeyarwady River (Bagan Section)	Freshwater	High	342	Large river (Ayeyarwady) - Alluvial plain	Average
Pauk Area	Terrestrial	Medium	195	Hills, possibly springs Geology: Sandstone	Low
Ayeyarwady River (Sinbyugyun to Minbu)	Freshwater	High	540	Large river (Ayeyarwady) - Alluvial plain	Average
Man Chaung	Freshwater	Medium	3	Large river (Ayeyarwady) - Alluvial plain	Average
Shwesettaw WS	Terrestrial	Medium	497	Average - no features, could be GW discharge zone	Average
Mone Chaung	Freshwater	Medium	15	Average - no features, could be GW discharge zone	Average
Nat-yekan	Terrestrial	Medium	160	Mountainous, possibly springs	Low
Natmataung NP	Terrestrial	High	1,100	Mountainous, possibly springs	Low

3.9.7 *Summary – Assets and Issues*

- Very large reserves of low-salinity groundwater are available along the Ayeyarwady corridor.
- The water balance indicates that current groundwater extraction (1,600 $Mm^3 yr^{-1}$) is only 14% of aquifer recharge (11,380 $Mm^3 yr^{-1}$). Expansion of groundwater use appears viable, especially close to the Ayeyarwady River, taking into account appropriate hydrogeological locations and aquifer sustainability.
- Groundwater discharge represents 20% of the Ayeyarwady River baseflow in dry season (December to May).
- Importance of groundwater for village and urban supplies (including 90% of Mandalay's water supply).
- Small artesian systems in the piedmont fringe of the Shan Plateau require careful management.
- High concentrations of arsenic (>50 µg/L) in the aquifers of the Alluvium along the Ayeyarwady River and lower Samon Chaung, and in some shallow tubewells in the Irrawaddy Fm near Mahlaing and Natogyi.

3.10 Ayeyarwady Delta Groundwater Zone

The Delta GWZ includes the catchment and floodplain of the Ayeyarwady south of Kamma Town (about 30 km north of Pyay). This is the point where the Alluvium of the Dry Zone terminates against the 20° N Uplift Area, which effectively closes the groundwater basins of the Dry Zone to the north. This delineation of the delta differs slightly from that used in defining the HEZs, in which the delta is considered to begin where the first distributary channels emerge from the mainstream, about 50 km upstream of Hinthada.

The delta covers an area of 54,700 km^2. It is bounded by hills of the Rakhine Yoma in the west and the Pegu (Bago) Yoma in the east. Below Hinthada, a broad delta opens out, with a maze of distributary channels. As defined for the AIRBM, the delta includes Yangon City and the right bank of the Yangon River. The delta divides into three zones: the tidal coastal front (including extensive mangroves); a brackish estuarine zone; and a freshwater floodplain. These zones shift with seasons and tides, with seasonal intrusion of sea water in the dry season. Paddy rice is cultivated across much of the delta, with varying degrees of irrigation and water management. The monsoon crop is dominantly rainfed, but requires protection from saline intrusion through embankments, sluice gates, and drainage systems (Ketelsen et al., 2017). Dry season cropping draws on irrigation from canals and from groundwater.

The delta is densely settled, with a total population of 15.02 million, including about 5.2 million in Yangon City. Administratively it lies mostly within the Ayeyarwady and Yangon regions, and includes a portion of Bago Region in the east.

The climate is strongly monsoonal, with distinct wet and dry seasons. Total annual rainfall averages 2,240 mm, ranging from around one metre in the northern extent, to more than 3,000 mm in the far southwest.

Like the Dry Zone, the lower Ayeyarwady Delta is expected to have high groundwater potential area (MOALI, 2003; Aung Khaing Moe, 2016). With high population density, extensive agricultural land and increasing industrial development, it is likely that groundwater will be increasingly important in future.

3.10.1 Regional geology

The Ayeyarwady Delta is part of the Tertiary Inner Burman Basin, which runs from the Gulf of Martaban north to the Himalayas. The Inner Burman Basin formed along the eastern margin of the Indian tectonic plate as it moved northwards towards Eurasia to produce the Himalayan mountains and Tibetan Plateau. Bender (1983) describes two sub-basins in the area as Prome (Pyay) embayment continued southwards by the Irrawaddy Delta Basin, hereafter referred to as a single Ayeyarwady Delta area.

This basin is constrained in the east and west by ranges formed of pre-Upper Miocene sedimentary rocks that have undergone regionally varying tectonic deformation at various periods, with dominant structural deformations caused by tangential compression and block-faulting (Bender, 1983). In the east, flysch-type rocks form the South Rakhine Yoma range and in the west Miocene sandstones of marine origin form the Bago Yoma range, which was folded and uplifted by 900 to 1,200 m during the Plio-Pleistocene, 5.3 to 2.5 My (Wandrey, 2006).

Figure 3.10.1-a – Rice paddies in the Ayeyarwady Delta (Alluvium) and Rakhine Yoma hills (Flysch) in distance in the East: *Loc.:17.78, 95.25 (photo: Viossanges)*

The central basin increases in width from 25 km in Pyay (Prome) Region up to 150 km between Pathein and Yangon. The topography is very flat, with an altitude ranging from 35 m near Pyay, down to sea-level, 350 km south. The plain is composed of recent and Quaternary (Holocene; 2.5 My) fluviatile deposits including sands, gravels, and clays, underlain by a very important sequence of continental deposits (referred to as Irrawaddy Fm) of a thickness estimated between 2,740 m and 3,050 m (Nyi Nyi Soe, 2014; Ridd and Racey, 2015) deposited from the Pliocene and Pleistocene (5.3 to 2.5 My). At depth, unconformities are found at the base of the Pliocene Irrawaddy Fm, along with Miocene and older deposits (Bender, 1983).

The geology of the area is summarised in Figure 3.10.2-b.

3.10.2 Main aquifers

The two major aquifer systems found in the Ayeyarwady Delta are the Alluvium and Irrawaddy Fm aquifers, which together cover 93% of the Ayeyarwady Delta GWZ (Figure 3.10.2-a)

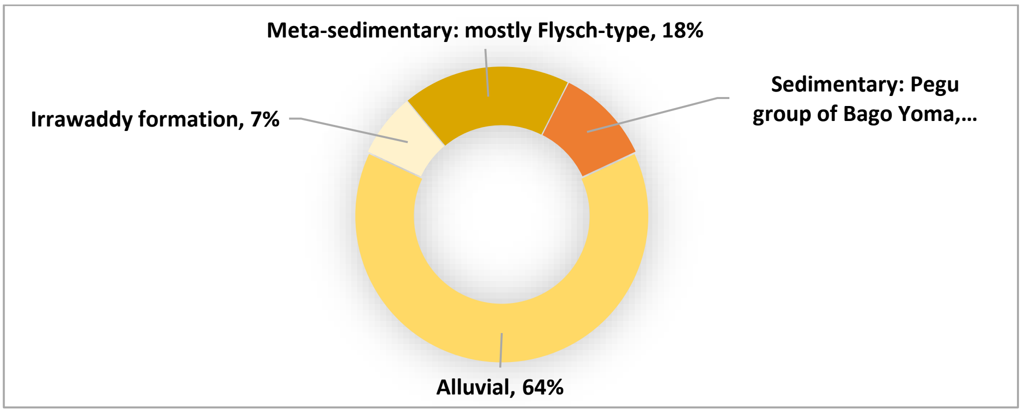

Figure 3.10.2-a – *Relative areas of main aquifers in the Delta GWZ*

The Alluvial aquifer is a sequence of geologically recent, unconsolidated sediments. It varies in thickness, and contains a number of unconfined, semi-confined, and confined aquifers of different thickness and yield in different areas. Clays are abundant in the superficial soils of the delta (Halcrow & Partners, 1983), and clay lenses are likely also found at depth. There is no clear stratigraphic delimitation between the alluvium and older Irrawaddy Fm deposits but rather a continuum. As a general rule, it can be considered that the alluvial aquifer extends to depths of 10 to 50 m below the surface (Halcrow & Partners, 1982; Htun Lin Aung, 2016). According to the limited studies available, yields of 10 cm (4”) diameter tubewells, tapping alluvium aquifers ranging from 1.8 L s^{-1} to 2.5 L s^{-1} with higher values up to 4.5 L s^{-1} are reported in the vicinity of a stream. There are no reported transmissivity values for the Alluvial aquifer in the delta, but based on the lithological description, generic values ranging in the order of 10^{-1} to 10 m^2day^{-1} could be expected (Heath, 1983). It should be noted that alluvial fans in the vicinity of the hills of Rakhine Yoma in the west and Bago Yoma in the northeast might provide higher yields due to lower clay content.

The Irrawaddy Fm is composed of sandstones, sands, and gravels of continental origin and is more or less cemented. Clay beds are present and lead to semi-confined conditions. There is not a single aquifer unit but instead a succession of sedimentary beds of variable extent and thickness. Based on data on deep tubewells drilled by IWUMD in the area, 50 m to 220 m (145 m on average) must be drilled before reaching a productive aquifer. The depth to a productive layer increases towards the Gulf of Martaban. The thickness of the Irrawaddy Fm is reported as 2,740 m to 3,050 m (Nyi Nyi Soe, 2014; Ridd and Racey, 2015), and it could be expected that huge groundwater resources are available at greater depth. Groundwater exploration has so far only drilled through 4% of the total formation thickness. Oil and gas exploration, however, has drilled at greater depths ranging from 810 m to 4,100 m (Ridd and Racey, 2015). P.H. Jones (1986, cited in MOALI, 2003 and World Bank, 1986) suggested, probably also based on oil and gas exploration bores, that important freshwater is available at a depth of 2,130 m and it is likely to flow with artesian pressure.

Data from IWUMD show that for tubewells of 10 cm diameter, yields range 2.3 L s^{-1} up to 31.5 L s^{-1}, reflecting the high heterogeneity of the Irrawaddy Fm. Average yields of 4.6 L s^{-1} demonstrate the viability of this aquifer to provide enough supply for community water supply or small-scale irrigation. Transmissivity values of the Irrawaddy Fms are only available from Masters thesis data.[17] Pump tests provide initial estimates with values ranging from T = 144 m^2day^{-1} to 5,000 m^2day^{-1} and an average value of 2,000 m^2day^{-1}, corresponding to sand and gravel aquifer types (Heath, 1983).

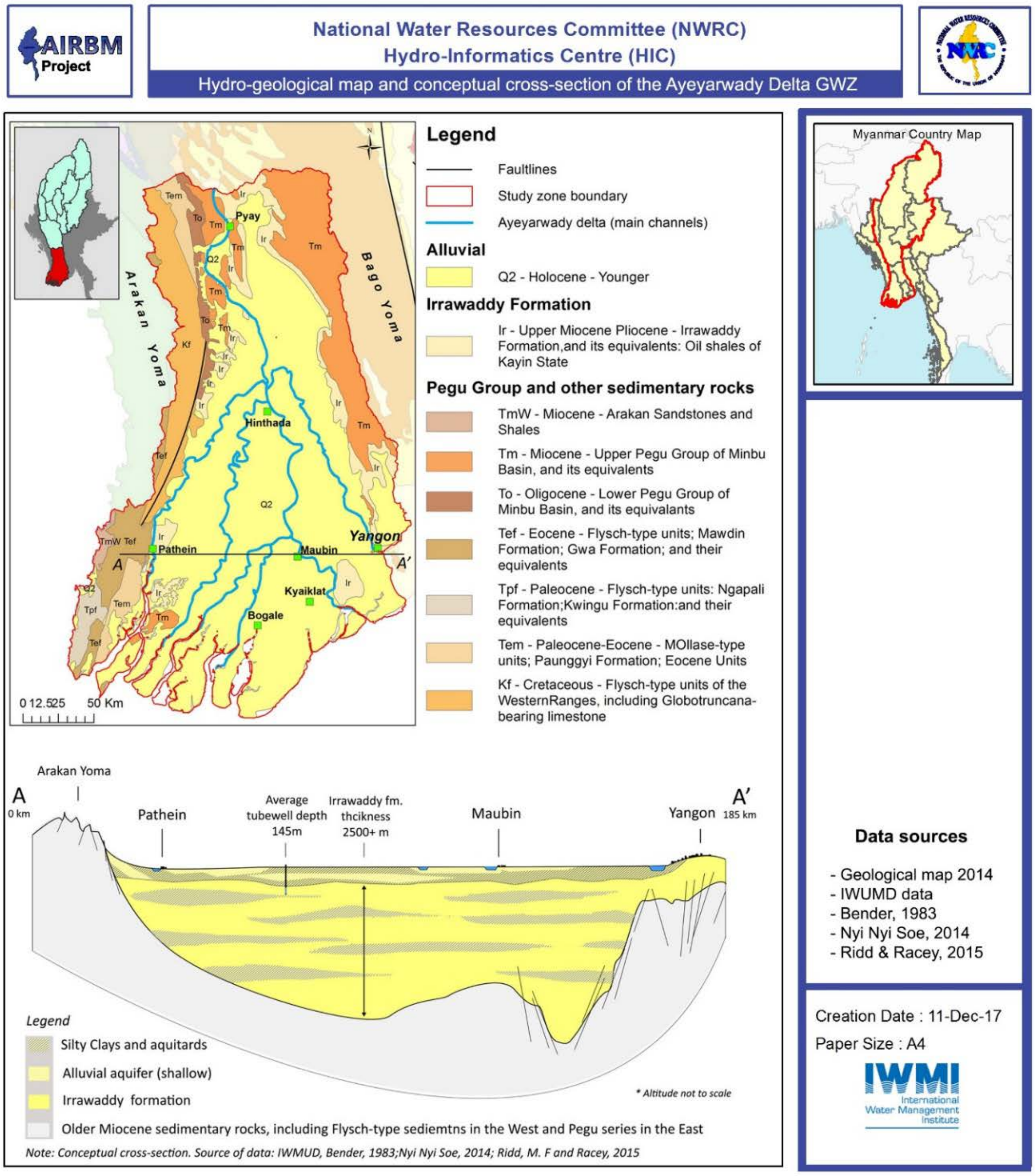

Figure 3.10.2-b – Hydro-geological map and conceptual cross-section of the Ayeyarwady Delta GWZ

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[17] See Geology Master's Theses of Hnin Ei Hlaing (2017), Win Khine Tun (2010), Thin Thiri Chaw (2013), Yie Mon Soe (2016), Htun Lin Aung (2016), Thidar Aung (2017), Tun Paing (2017), and Hnin Ei Hlaing (2017) for basic hydrogeological studies.

3.10.3 Storage and Recharge

STORAGE

Although information on stratigraphy is limited, a quick first-pass estimate of water stored in the main aquifers can be obtained by using tubewell logs to estimate the percentage of aquifer in the total formation thickness, generic values of porosity, and total area of aquifer formations. Here, two values have been estimated as the accessible resource (i.e., <220 m) and the total formation (i.e., 3,000 m).

Using a value of specific storage of $S_s=2 \times 10^{-4}\ m^{-1}$, and considering that the blue sands typical of the Irrawaddy Fm occupy 30% of the stratigraphy, volumes of 2,600 Mm^3 and 36,000 Mm^3 are estimated for the accessible and whole aquifer thickness, respectively.

These estimates give an insight into the quantity of water, but are of limited value for groundwater management. Most of this volume is either not actively recharged (making its use unsustainable) or not easily accessible (because of technical and financial constraints). Other indicators, such as recharge, should be used instead to comply with sustainable development of the resource and avoid over-exploitation.

RECHARGE

Groundwater recharge in the Ayeyarwady Delta is particularly constrained. There is no continuum between the aquifers of the Dry Zone (Lower Ayeyarwady GWZ) and the Delta GWZ, due to the Pegu Fm outcrops of the 20 N Uplift Zone, 100 km north of Pyay. As a consequence, without inflow from the north, the main recharge processes are from direct rainfall infiltration, or surface and sub-surface run off from the Rakhine Yoma and, to a lesser extent, Bago Yoma.

Direct rainfall infiltration is expected to be very limited in the plains due to the presence of clays in the soil profile, as described in the Halcrow & Partners (1983) report. This report also mentions the presence of lighter soils in the margins of the alluvial system, either where higher terraces are found in the north, where Irrawaddy Fm outcrops, or in the colluvial fans at the foothills of the Rakhine Yoma. Bender (1983) suggest outcrops of Tertiary rocks exposed in Rakhine Yoma act as a recharge area for this group located below Irrawaddy Fm. It is expected that rainfall on Rakhin Yoma and Bago Yoma will produce run-off to the alluvial plain, but also an active recharge through fractures connected to Irrawaddy Fm as sub-surface flow. Without on site estimates of the recharge, conservative R/R ratios have been applied based only on lithological descriptions. Table 3.10.3–a show a summary of estimates of all source of recharge for the major aquifer groups of the Ayeyarwady Delta GWZ.

GROUNDWATER-SURFACE WATER INTERACTIONS (GWSWI)

Interaction between surface and groundwater is not widely reported in the Ayeyarwady Delta. Halcrow & Partners (1983) mention a possible recharge equivalent to 40 mm but do not specify to which extent this value applies. Myaoka (2012) suggests there is a change in the chemistry of groundwater between seasons, related to GWSWI away from the center of the delta. However, due to the clays deposits and the relative shallow depth of river channels (often <10 m), GWSWI is expected to be limited. Both gain and loss from streams might occur over short distances depending on the substratum and flow conditions. In general, it is anticipated that in the dry season, flow direction would be from the groundwater to the river channels and in the wet season, a recharge from the river into the groundwater (at least into the alluvial system).

Table 3.10.3-a - Estimate of storage and recharge properties of main aquifer groups of the Delta GWZ

Aquifer group	Area km^2	Aquifer thickness (m)*	Rain (mm) average	R/R ratio	Sy/porosity assumed	Storage** (Mm^3)***	Recharge (Mm^3)***
Alluvial	34,550	30	2,730	0.05	0.10	103,660	4,720
Irrawaddy Fm	3,770	100	2,420	0.15	0.20	766,460	1,370

Meta-sedimentary: mostly Flysch-type of Rakhine Yoma	10,020	50	3,030	0.05	0.08	40,090	1,520
Sedimentary: Pegu Group of Bago Yoma	5,740	50	2,290	0.05	0.08	22,940	660
						933,150	8,270

*Aquifer thickness is difficult to estimate within the 2,000+ thick Ayeyarwady Fm.
**The storage of the Irrawaddy Fm calculation considered the area of Alluvium and the Irrawaddy Fm.
***These values are broad estimates and only indicative.

FLOW DIRECTION

There are currently no records of groundwater levels in the region and as a consequence, flow directions must be estimated. In sand and gravel systems such as Alluvium and the Irrawaddy Fm, groundwater flow is considered homogeneous and to normally follow topography. This suggests a north-south flow, locally modified in the vicinity of river channels where it varies seasonally. In the hills of flysch-type rocks and sandstones, groundwater is also following topography, however the direction and density of fractures might also influence groundwater flow direction.

WATER BALANCE

Based on this initial groundwater assessment, the water balance of the Ayeyarwady Delta can be expressed as

$$Q_{R.Rakhine} + Q_{R.Plain} + Q_{R.Bago} + Q_{R.Irraw} + Q_{inf} + Q_{riv} + Q_{in} = Q_{pump} + Q_{bf} + \Delta s + Q_{out},$$

where:

- $Q_{R.Rakhine}$ is the recharge as surface and sub-surface flow form the Rakhine Yoma.
- $Q_{R.Plain}$ is the recharge through direct infiltration of rainfall in the Alluvium outcrops.
- $Q_{R.Bago}$ is the recharge as surface and sub-surface flow form the Bago Yoma.
- $Q_{R.Irraw}$ is the recharge through direct infiltration of rainfall in the Irrawaddy Fm outcrops.
- Q_{inf} is the infiltration of water from seepage from irrigated area.
- Q_{riv} is the inflow of surface water into groundwater.
- Q_{in} is inflow from other major aquifers.
- Q_{pump} is the anthropic consumption of water.
- Q_{bf} is the contribiton of groundwater to baseflow of rivers.
- Δs is the change in storage.
- Q_{out} is the water that exits the system as groundwater flow into the gulf of Martaban.

This equation can be simplified with the following assumptions. There is no major inflow from the north as the aquifer is separated from the dry zone Irrawaddy Fm and $Q_{in} = 0$. Given the large amount of clays and their saturated nature (Gleysols, cf. Halcrow & Partners, 1983), it is assumed that there is negligible infiltration though the clay horizons from irrigated fields and flooded areas, and that $Q_{inf}=0$. Pending further studies, the GWSWI are considered in balance over a year and $Q_{riv} = Q_{bf}$. Finally, it is considered that there is no change in groundwater storage over the year and $\Delta s = 0$. The water balance then becomes:

$$\mathbf{Q_{R.Plain} + Q_{R.Irraw} + Q_{R.Rakhine} + Q_{R.Bago} = Q_{pump} + Q_{out}}$$

The following figure summarizes the water balance values estimated for the Ayeyarwady Delta. It is concluded from this first pass analysis that there is a large scope for increasing groundwater abstraction. However, not all the volumes presented here are either technically accessible or financialy viable.

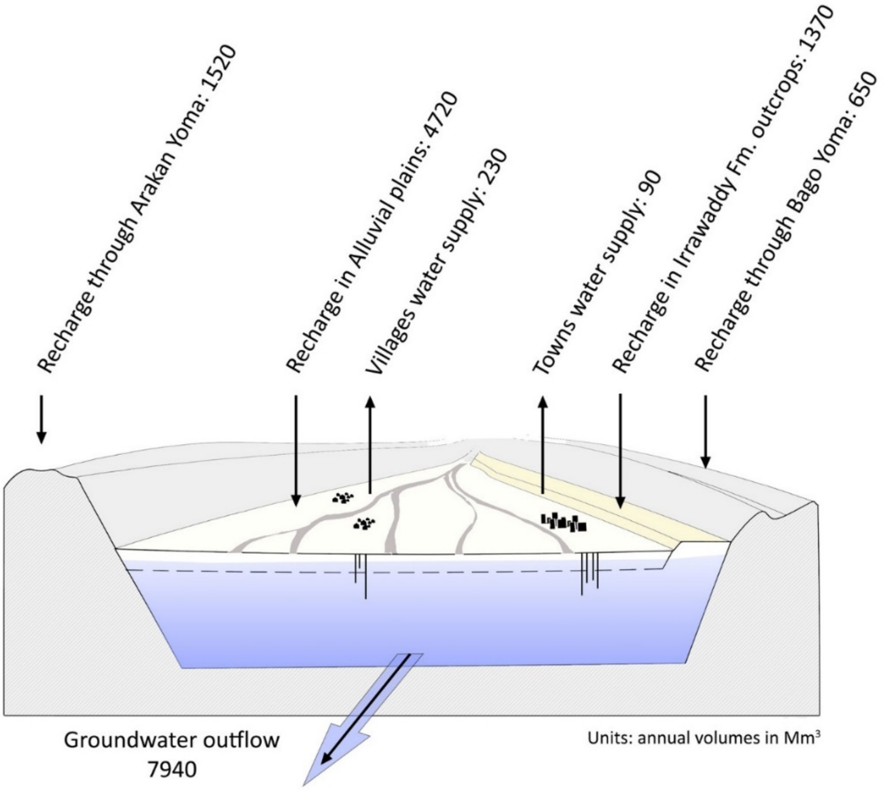


Figure 3.10.3-a – Water balance for the Delta GWZ

3.10.4 Groundwater quality

ARSENIC

As in other deltas of Southeast Asia, naturally occurring arsenic contamination of groundwater has been identified as an issue in the Ayeyarwady Delta. In 2001, Save the Children conducted a survey in 327 villages in the delta, including 1,912 relatively shallow tubewells of variable depth (all <90 m) drilled mostly in the Alluvium, and found that 45% of samples had arsenic in concentration higher than the WHO limit (10 µg/L; Tet Nat Tun, 2003)

In 2005, a large Arsenic Mitigation Project was set up as a partnership between the WHO, UNICEF, and various governmental agencies (WRUD, 2012) and included testing nearly 125,000 water points for the delta area alone. As seen in Table 3.10.4–a, in the Ayeyarwady Region, nearly 30% of samples tested are above the WHO 10 µg/L limit, but less than 10% are above Myanmar's national limit of 50 µg/L. Comparing frequency distribution of As concentrations nationally shows that a significant portion of samples fall between that national limit and the WHO limit of 10 µg/L.

(Figure 3.10.4-a). There is also a strong relation between the depth of the well and higher concentration of arsenic, as shallow tubewells drilled between 10 m to 60 m are most likely to contain high levels of As, while lower concentrations are found at greater depth. Deep aquifers may have elevated As where poorly constructed tubewells allow leakage from upper aquifers, and arsenic is especially high where old river oxbows are present (Khin Maung Lwin, 2016, pers. com.).

Winkel et al. (2008) published a predictive map using a probability analysis based on a geological map and the combination of surface parameters. It predicted a probability of exceeding the WHO limit at between 40% and 60%, over the whole delta. Based on other references in the region, the authors suggested that in the delta, arsenic is mainly concentrated in the upper Holocene Alluvium, whereas deeper aquifers are usually free of contamination.

Van Geen et al. (2014) demonstrated that the release of As into groundwater is related to the reductive dissolution of Fe oxyhydroxides, similar to the Bengal, Mekong, and Red River regions. As a consequence, the concentrations of arsenic are not expected to change rapidly, and the current practice of drilling deeper (as IWUMD practices with DTW) or changing location for contaminated wells (for local drillers) can be efficient to a certain extent. Public awareness is increasing but is still low, and more communication and continued testing is required.

Table 3.10.4-a - Arsenic level in groundwater by state/division

State/division	Tested tsp.	Nb. samples	Nb. As>10 µg/L)	% (As >10µg/L)	Sample (As >50µg/L)	% (As >50µg/L)
Ayeyarwady	17	123,962	36,178	29.18	10,161	8.2
Bago	13	82,644	35,461	42.91	7,501	9.08
Sagaing	7	8,611	1,619	18.8	196	2.28
Mandalay	9	21,257	3,827	18	303	1.43
Rakhine	1	5,232	2,189	41.84	472	9.02
Kachin	5	1,598	66	4.13	7	0.44
Shan	4	2,854	471	16.5	162	5.68
Mon	4	2,054	144	7.01	62	3.02
Mag way	1	522	96	18.39	7	1.34
Yangon	3	4,078	576	14.12	71	1.74
Taninthaii	2	1,000	14	1.4		
Total	66	253,812	80,641		18,942	
Average				19.3		4.2

Ayeyarwady Delta samples (WHO, UNESCO, and WRUD)

Nb. Samples	As max. (µg/L)	As avg. (µg/L)	Nb. As <[detect]	Nb. As >10 µg/L	Nb. As >50 µg/L
123,963	654	13.8	54%	30%	8.50%

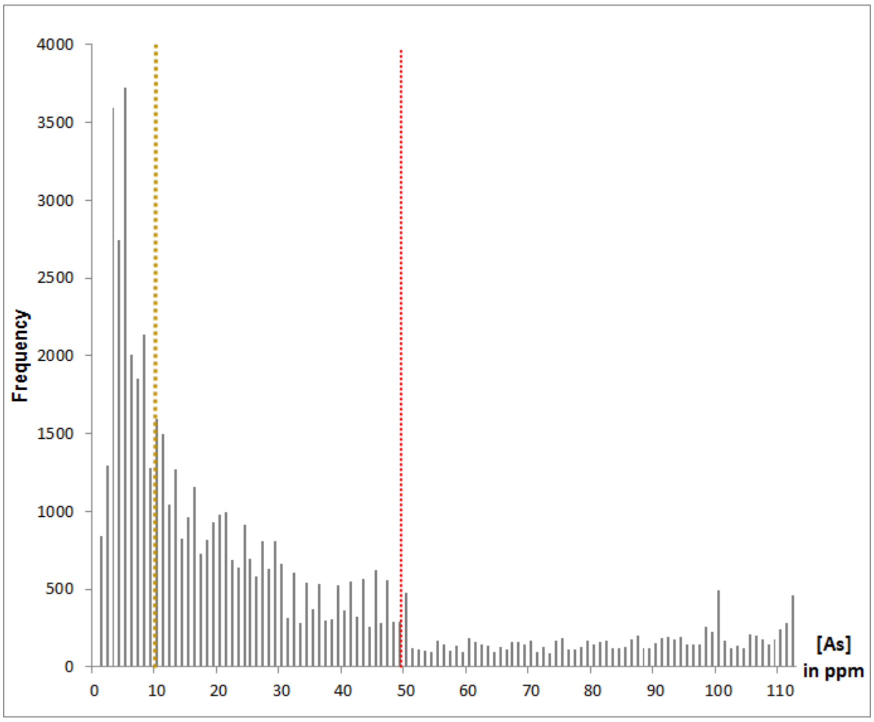


Figure 3.10.4-a – Frequency distribution of arsenic concentration in samples with As >0 (46% of samples): *Yellow and red threshold lines are WHO 10µg/L limit Myanmar limit respectively (IWUMD).*

SALINITY

Salinity caused by sea water intrusion is an important issue in the Ayeyarwady Delta and is common to several deltas in the world (Deltares, 2017). Salty and brackish water is found in the channels of the delta under tidal influence but also in the groundwater systems. Catastrophic events such as Cyclone Nargis also cause sea water to flood and then infiltrate through the soil, contaminating shallow groundwater resources.

In these cases, deep tubewells (>60 m) are likely less affected by changes related to surface water events. Recovery of such salinity induced by the surge will occur at a variable rate. With limited information and monitoring on flow conditions, direction, and rate of groundwater renewal in the delta, there is currently a limited understanding of the time frame for changes to occur.

As a consequence, wells located in the south of the delta are more affected than those in the upper area. In some locations, populations have to rely exclusively on rainwater harvesting, or shallow lenses of freshwater locally found above brackish groundwater. Data on 147 tubewells (IWUMD), shows that EC values in the delta in deep tubewells are in most cases fresh, with an average at 550 µS/cm^2. However, these values, summarized in the Figure 3.10.4-c, often only represent the deeper aquifers, targeted by IWUMD. In Pathein, salty water is frequent, and in Kyaiklat, there is no drilling as salty water is certain. Field visits measured another set of 29 locations in situ. Comparison of the salinity intrusion line between EC measured on site, field observations, and discussions with IWUMD staff in the Pathein office and local drillers, allows mapping of the best estimate of current salinity intrusion line (cf. Figure 3.10.4-c). Interestingly, although most areas are salty in the southern delta, freshwater is found at depth in some locations, near the shore, south of Bogale Town. This result is surprising, as high salinity is expected in this location. IWUMD had mixed results in the areas with deep wells (230 m) getting brackish water (EC >3500 µS), while other wells located in the same region and depth would hit freshwater at 560 µS with a screen at 215 to 220 m; a total of six tubewells were drilled, two of which were freshwater.

There is no straightforward explanation for this phenomenon. IWUMD finished a well recently with flowing water (pressure ~1 m above ground level), suggesting recharge coming from distant areas. Deep freshwater aquifers have been postulated in the past (Jones [1986], cited in MOALI). Drillers reported that in some locations they would first hit salty/brackish water (60 to 120 m) and then, below clay layers of variable thickness, fresh water.


photo: IWMI M.Viossanges

In areas with saline groundwater, rainwater harvesting provides an important part of water supply- Ayeyarwady delta

Figure 3.10.4-b – Ayeyarwady Delta, in Kyaiklat town (loc.: 16.444, 95.725): *Due to high salinity in groundwater and surface water, some communities rely nearly exclusively on rainwater harvesting.*

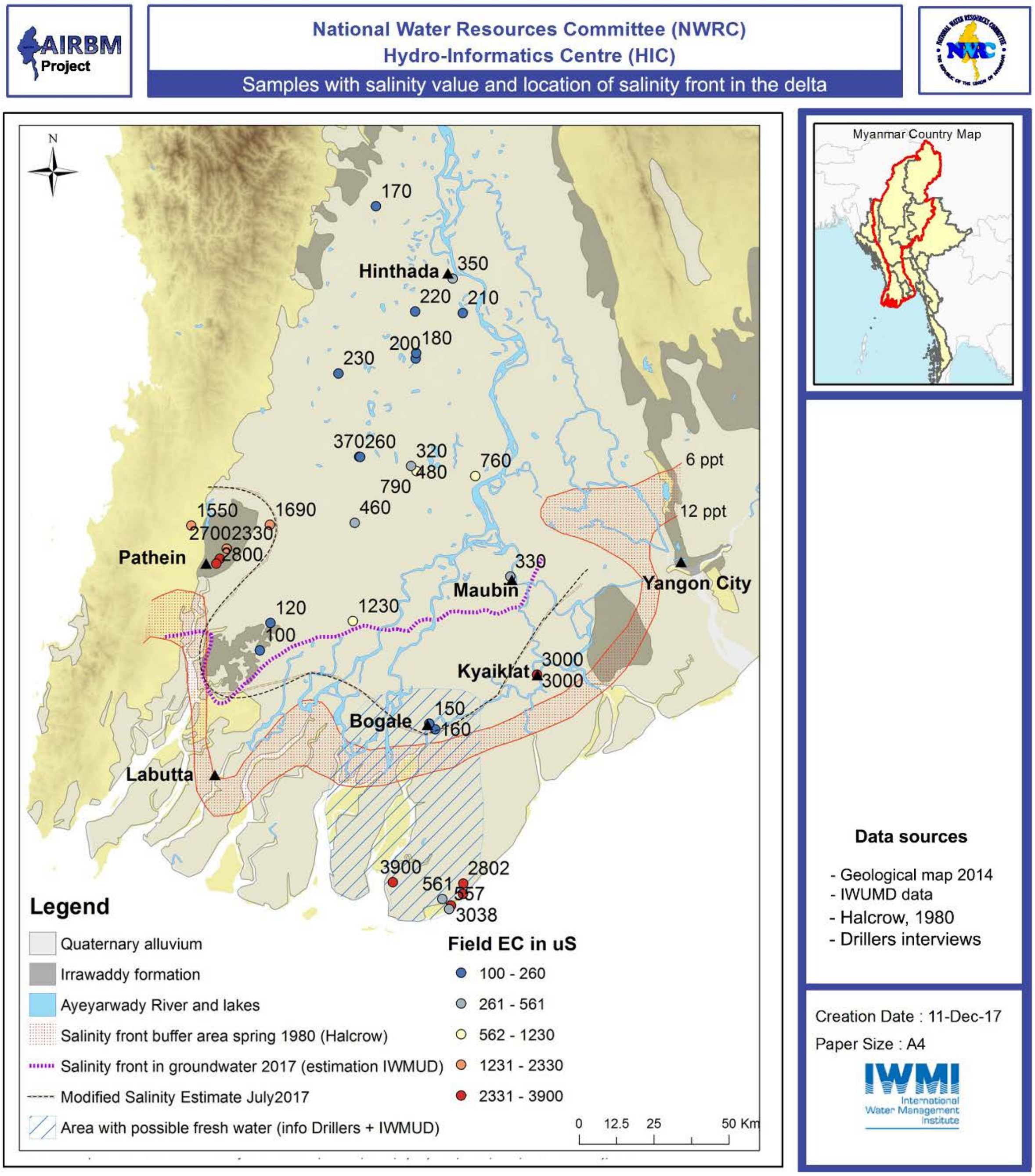


Figure 3.10.4-c – Samples with salinity value and location of salinity front in the delta

OTHER NATURALLY OCCURRING GROUNDWATER CONTAMINANTS

Elevated levels of iron in groundwater are of concern in the delta, although not considered a health issue. Fe^{2+} concentrations are found up to 3 mgL^{-1}, notably in Kyon Pyaw and Kyaunggon Townships (IWUMD). Based on IWUMD data, at least one third of the tubewells have high iron concentration. Of 144 samples, 36% were above the 1 mgL^{-1} limit of Myanmar, while 63% were above the 0.3 mgL^{-1} WHO limit.

Figure 3.10.4-d - A rusted hand-pump due to high iron in delta

POLLUTION OF SHALLOW GROUNDWATER

Pollution of shallow groundwater, mainly due to poor sanitation, is reported in the delta. Action Contre la Faim (2008) reported that 75% of population practices open-defecation, and that existing latrine are sometimes unused or not maintained. Both human and animal waste are likely to contaminate shallow groundwater, and this is of particular concern where shallow unprotected wells are used. Myanmar Census (2014) reported low levels of access to sanitation (<60%) in the southern parts of the delta.

INDUSTRY

In the delta, heavy industry is very limited away from the Yangon area. Some activities are reported outside Yangon, such as automotive equipment, textile industry and a paper mill in Sinde, Shweaung, and Thabaung, respectively (Ministry of Industry [MOI], 2017). These industries mostly use surface water as a water source. There are possibilities that contamination of groundwater resources occurs from waste produced by the processes, but there is no monitoring of waste disposal. Rice mill factories are also numerous in the delta, and can be a possible source of pollution.

photo: IWMI - M Viossanges

Figure 3.10.4-e – Rice mills activity in the Ayeyarwady Delta

In Yangon, there are up to 27 industrial areas with a wide range of activities (cf. the section on Industrial use hereafter). No reported evidence of large-scale pollution was available at the time of writing, however risks of contamination to groundwater are likely to exist.

AGRICULTURAL INPUTS

Pesticides and fertilizers are not used in large quantities in the delta region (FAO, 2002), as compared to other agricultural regions of Myanmar. Pesticide use is often related to cultivating cash crops such as watermelons, which are relatively rare in the area. Cash crops are grown near Hinthada Township but there is no information available on the current quantities and types of agricultural inputs in use. Increasing intensification of both cropping and aquaculture heightens the risk of pollution of shallow aquifers with agrochemicals and excess nutrients.

3.10.5 Groundwater use

DOMESTIC AND URBAN SUPPLIES

Communities in the delta source drinking water from rainwater harvesting, communal water ponds, and wells, particularly in the south where tidal rivers are often saline. According to the 2014 Census, 52% of households in the Delta GWZ use groundwater for drinking and domestic water supplies. This varies geographically. Groundwater use is high (more than 80%) in townships of the upper parts of the delta in Hinthada and Tharawaddy districts, and much lower (<20%) in the lower delta in townships of Pyapon and Labutta districts. Tubewells are much more common than dugwells (TW/DW ~3), except in Labutta and Myaungmya (TW/DW = 0.7 - 1.0). Using 2014 Census township level statistics on the source of domestic water supplies and population density data from Gaughan et al. (2013), we estimated the number of people using groundwater in each GWZ, and calculated total withdrawal, based on average use of 135 L day^{-1} in rural areas and 150 L day^{-1} in urban areas.

Data from the 2005 Arsenic Mitigation Program indicate that high arsenic levels are more common in shallow wells (10 to 60 m) than in deeper wells. Many ponds and shallow wells were salinized by the tidal surge accompanying Cyclone Nargis in 2008. Recovery operations emphasized provision of safe and reliable water sources from groundwater. Towns and villages in the delta use a mix of public and private sources of surface and groundwater. For example, in Labutta there is no water pipeline system: water from a lake is stored in tanks and distributed to citizens by cart. Pathein has no municipal water supply; the majority of its citizens use tubewells (JICA, and Tokyo Engineering Consultants Co., LTD., 2014). In Zalun, villages rely on river water, or dig their own wells (United Nations Development Programme Myanmar, 2014).

IWUMD reported the construction of 5,355 tubewells in the Ayeyarwady Region and 5,902 in the Yangon Region, nominally serving 3.82 million people, confirming the importance of groundwater for domestic supply in the Ayeyarwady Delta GWZ (Thein Soe and IWUMD, 2016).

The Yangon City water supply (see Box 3.10.7) uses a mix of surface water (841 ML day^{-1} from reservoirs) and groundwater from 442 DTW (90 ML day^{-1}). Based on estimates of demand, it is possible that another 475 ML day^{-1} is extracted from private wells (mainly tubewells). For example, in Yangon (West) District, which includes Yangon City, Hlaing, and Myangone, almost 40,000 households use tubewells for drinking water supply, and over 110,000 use tubewells for non-drinking supplies. This has resulted in significant aquifer stress, with drawdown of up to 60 m, intrusion of saline water into shallow aquifers, and pollution from vertical seepage from industrial and urban wastewater.

INDUSTRIAL USE

Yangon has a large and diverse industrial sector that relies heavily on groundwater. Twenty-six Industrial Zones have been established in Yangon (Figure 3.10.5-a). Major industries include grain processing, food processing, garments, toiletries, and construction materials. The large water consuming industries (including sugar mills, paper mills, and cement factories) normally depend on surface water, but many private sector industries rely on groundwater. Groundwater use is not regulated or monitored (Zin Nwe Myint, 2005). MOAI (2003) estimated groundwater withdrawal for industrial use in Yangon at 49 ML day^{-1} (14,517 acre-feet per year) in 2000, and projected that this would increase to 147 ML day^{-1} by 2015.

Heavy industry is very limited away from the Yangon area, but some activities are reported such as automotive equipment, textile industry and paper mill in Sinde, Shweaung and Thabaung respectively (MOI, 2017). These industries mostly use surface water.

Source: Ministry of Industry website

Figure 3.10.5-a – Industrial Zones in Yangon: *(MOI, 2017)*

AGRICULTURAL USE

Monsoon rice cultivation in the delta is mostly rainfed, supported by a system of polders, sluice gates, and drainage canals to allow cultivation in flood prone areas. Irrigation in the delta is mostly from surface water sources; freshwater tidal irrigation in the middle delta is used for summer paddy. Due to the availability of surface water, the use of groundwater for irrigation is not widespread. MOAI (2003) reported total extraction of less than 50 Mm^3 in 2000, with half of that in Yangon (north), presumably used for horticultural production in the peri-urban zone.

IWUMD reports the construction of 1,634 tubewells in the Ayeyarwady Region and 566 in the Yangon Region for irrigation, serving a total of 7355 ha. If fully operational (2500 gph for 4 hours per day over 120 days per season), these wells would draw ~12 Mm^3.

At this stage, we have no reliable estimates for current groundwater use for agriculture in the Delta and Yangon regions. The MOAI report projected a large increase in groundwater use for agriculture for a total of 975 Mm^3 annually, with highest growth in the middle regions of the delta around Hinthada, Tharawady, Pathein, and Maubin. While agricultural and aquacultural production in the delta has intensified significantly since 2000, it is not clear that groundwater has played a large role. Small pumps are commonly seen, but usually tap surface water sources (canals, streams, and ponds) rather than groundwater. MOAI projections for 2015 seem unwarrantedly high. The exception may be the peri-urban areas around Yangon, where groundwater is used for horticultural production.

Table 3.10.5-a - Range of estimates of groundwater use for Delta GWZ

	Industrial	Agricultural	Domestic	TOTAL	Source
Estimated use 2000	18	276	521	815	MOAI, 2003
Projected use 2015	52	975	685	1712	MOAI, 2003
Estimated current use	90	Low: 60 High: 256	317	Low: 467 High: 663	Calculated on population at village tract level and % of HH using GW (considering 135 L per person in rural and 150 in urban wards)

3.10.6 Groundwater and Ecosystems

Groundwater is expected to play an important role in supporting ecosystems in the delta due to the low-land flat topography, shallow water table, and deltaic geomorphology. In the south, close to the sea, variation in groundwater salinity is likely to impact ecosystem. Mangrove forests, considered a very high value ecosystem, are closely related to groundwater systems. A total of 12 KBAs are located in the Delta GWZ. Half are terrestrial and considered to have low reliance on groundwater. Five KBAs are located in the groundwater reliant mangrove forest and are recognized as high priority for conservation.

3.10.7 Summary – Assets and Issues

- A large resource of high-yielding, low-salinity groundwater could be available in the Irrawaddy Fm underlying the delta at depth.
- GW resources are underused.
- Deep groundwater >60 m is usually free of contamination from arsenic and anthropogenic pollution.
- Salinity intrusion affects groundwater quality in shallow aquifers in the southern delta, although there are exceptions (for example, around Bogale).
- Arsenic contamination occurs in shallow tubewells, particularly in the 10 to 60 m range; testing of all new wells is essential (continuing the work of the Arsenic Mitigation Program from 2005).
- Faecal contamination occurs, particularly in the 0 to 10 m range.

Recharge dynamics in the delta are poorly understood. If most recharge is from the Rakhine Yoma (rather than the Ayeyarwady River), the renewable resource may be much more limited than the storage volume.

Table 3.10.7-a – KBAs in the Ayeyarwady Delta and reliance on groundwater

KBA name	Type of KBA	Priority	Area (km²)	GW-ecosystems link	GW reliance
U-do	Terrestrial	Medium	5	Hills, possibly springs Geology: sandstone	Low
Hlawga Reservoir	Terrestrial	Medium	23	Reservoir possibly connected to GW. Geology: Alluvial	Low
Hlawga Park	Terrestrial	Medium	6	Reservoir possibly connected to GW. Geology: Alluvial	Low
Maletto Inn	Freshwater	Medium	386	Delta type alluvial	Average
Payagyi	Terrestrial	Medium	2	Location unclear	Low
Yelegale	Terrestrial	Medium	83	Delta type alluvial	Average
Pyindaye	Marine	High	1,323	Mangrove forest - linked to GW freshwater/sea water intrusion	High
Mainmahla Kyun WS	Marine	Medium	145	Mangrove forest - linked to GW freshwater/sea water intrusion	High

Kadonkani	Marine	Medium	647	Mangrove forest - linked to GW freshwater/sea water intrusion	High
Pyin-ah-lan	Marine	High	295	Mangrove forest - linked to GW freshwater/sea water intrusion	High
Gyobin	Terrestrial	Data deficient	161	Hills, possibly springs Geology: sandstone	Low
Khaing Thaung Island	Marine	High	14	Mangrove forest - linked to GW freshwater/sea water intrusion	High

Box 3.10.7

Yangon City Water Supply

Population: 5.21 million (2014 Census)

Operator: Yangon City Development Committee

Location: Yangon City is located at the convergence of the Yangon and Bago rivers, about 30 km from the Gulf of Martaban. The city's altitude is approximately 30 - 40 m AMSL, and it covers an area of approximately 600 km^2.

Municipal water source: 931,818 m^{3}day^{-1} (205 MGD) is consumed, comprising:

- 11% groundwater — 90,910 m^{3}day^{-1} (20 MGD) from 442 DTW; and
- 89% treated surface water — 840,908 m^{3}day^{-1} (185 MGD) from four reservoirs (Gyobyu, Phugyi, Hlawga, and Ngamoeyeik).

Assuming 270 L s^{-1} per person, the municipal water supply can supply 3.45 million people (66% of population).

Other water source: The remaining water supply of 475,000 m^3 day^{-1} comes from private groundwater (tubewells and dugwells).

Total groundwater supply: 45%

Geology	Unit	Thickness (depth m)	Lithofacies	Aquifer type /aquitard	Extraction method
Alluvium Holocene - Pleistocene	Aquifer Type 1	Multiple aquifers 20 (250)	Yellow silty sand bands	Unconfined to confined	Dugwells and deep tubewells
	Aquitard Type 1	Not laterally continuous	Yellow, brown clay	Confining layer where present	
	Aquifer yield (m^3 day^{-1}): 500 - 1,000; Well Efficiency: 70 - 85%.				
Irrawaddy Fm Lower Pleistocene to Upper Miocene	Aquifer Type 2	Multiple 30 (>250-300 m)	Brown to blue Sand/gravel	Deep Confined	Deep tubewell
	Aquitard Type 2		Blue clay, silt	Confining layer	
	Yield (m^3 day^{-1}): 400- 1,500/well efficiency: 80 - 90%				
Miocene to Oligocene Pegu Group	Poor aquifers, low yields.				

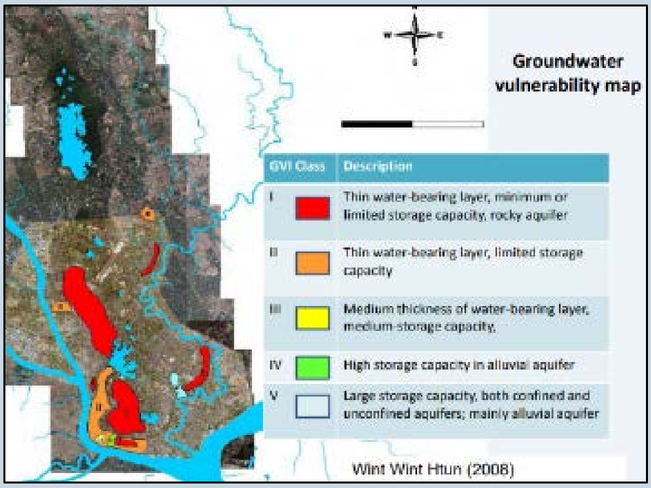
Aquifers: Aquifer and aquitard occurrences depend on location of tubewell from hard rock outcrop.

Water level decline: Up to 60 metres in areas of heavy groundwater withdrawal

Water quality:

Salt water intrusion: Due to heavy groundwater withdrawals, salt water intrusion occurs close to the Yangon and Bago rivers.

Contamination: Localised microbial pathogens occur in some shallow aquifers due to vertical seepage of contaminated surface water, septic tanks, markets, abattoirs, and industrial areas (tanneries, vegetable, and petroleum oils processing). Low-salinity groundwater occurs in deep aquifers.



Groundwater vulnerability map for Yangon (Wint Wint Htun, 2008)

4 STATUS AND TRENDS

Based on the issues and assets identified in each GWZ (summarized at the end of each section above), and analysis of the role of groundwater in the major themes identified for SOBA (Table 4.1.1–a), we have identified four indicator domains for describing and managing groundwater in the Ayeyarwady Basin:

- Quantity (recharge and storage);
- Quality (natural and anthropogenic contamination);
- Abstraction (domestic, industrial, and agricultural use); and
- Ecosystem-support functions.

In the section below, indicators are defined and described for each of these domains, within the limits of available data.

The question of groundwater management runs through all themes. Different management approaches are required to safeguard supply (e.g., protecting recharge areas, preventing pollution, and capping artesian systems) and control demand (limiting extraction, improving efficiency of use, and supplying alternatives). Management issues are discussed briefly in Section 4.5.

4.1 Groundwater Quantity

4.1.1 *Background and importance*

The size of the available resource frames the opportunities and constraints for use. Depletion of groundwater, and drawdown of water levels due to overuse has been a key risk in groundwater use and management in many areas. Ideally, the aim would be to identify and manage a 'sustainable yield': the amount of groundwater that can be extracted without the danger of aquifer depletion or other undesirable impacts (Alley and Leake, 2004). Approaching a value of 'sustainable yield' or 'sustainable abstraction rate' is challenging and beyond the scope the State of the Basin Assessment presented here. In this study however, as a first step, the quantitative status of groundwater in the Ayeyarwady Basin can be described through:

- **Storage** (total volume) — Only a small fraction of the stored volume of groundwater is realistically available, as extraction is limited by transmissivity of aquifers, as well as by the technical constraints and economic cost of drilling and pumping. Storage is difficult to estimate accurately, and change in storage even more so, and is not a suitable indicator for tracking the status of groundwater systems. However, it can be used as an indicator of the importance of aquifer systems and their capacity to buffer inter-annual climate variability.

- **Annual recharge** — Volume of water added to an aquifer, either directly from the surface, from the unsaturated zone, or discharge from overlying or underlying aquifer systems. However, in large groundwater systems there may be substantial spatial and temporal lags in recharge, and the relationship between withdrawals and recharge are neither simple nor immediate.

- **Groundwater level** — Changes in groundwater level reflect short or long-term changes in the potentiometric pressure and are an indicator of local groundwater status. In some cases, it can also indicate if there is over-exploitation of an aquifer.

Table 4.1.1-a - Planning issues and priorities

	Theme	Planning issue/priority	Indicator
Hydro-physical	Hydrology and climate regime	Change in recharge with change in rainfall/evaporation	Change in groundwater levels relative to rainfall
	Surface water resources	Recharge to/from rivers (connectivity)	Change in flow regime and/or flood extent of surface water; Groundwater level near river banks
	Groundwater resources	Water quality — naturally occurring	Arsenic
			Fluoride
			Salinity
		Water quality — pollution issues	Sewage
			Industrial pollution
			Agri-chemicals, animal waste
			Salinity (pumping induced)
		GW availability — pumped (tubewells)	GW level in wells (seasonal) Pressure decline in tubewells
			GW yield (by aquifer)
		GW availability — free flowing (springs, artesian systems)	GW flow rate (seasonal)
		Sustainable extraction limits	Volume extracted relative to storage and recharge
	Water pollution	(as above)	
	Geomorphology	Subsidence due to pumping in Delta especially in Yangon City	Coupled monitoring of groundwater and land levels
Ecological	Wetlands and floodplains	GW as baseflow	Changes in baseflow of streams
		Wetlands and flooded areas as recharge zones	Loss of wetlands
	Terrestrial resources	Impact of landuse change on recharge	Deforestation rates, groundwater levels near forested/deforested areas
Social	Food-water-energy security	GW as water source for agriculture/livestock/domestic supply	Number of households using groundwater sources/total withdrawal by HHs
	Health and well-being	GW as domestic water source	Number of households using GW as domestic water source/total withdrawals by HHs
Sector economics	Agriculture	GW for irrigation	Total area irrigated using GW Loss of irrigable land due to salinity and Sodium Absorption Ratio
			Proportion of GW irrigation from small pumps
	Mining and extractive industries	Pollution of groundwater by seepage or direct waste disposal	Groundwater chemistry (monitoring at specific sites)
	Industry	GW as primary source for water for industry	Total withdrawals for industry/proportion of industries using GW
		Pollution of GW by industrial/urban wastes	Groundwater chemistry (monitoring at specific sites)

4.1.2 *Data quantity and indicators*

Ideally, the quantitative status of groundwater resources should be monitored using regular measurements of static water level or pressure in wells as an indicator of quantity and resource depletion. Seasonal monitoring of water levels provides immediate, local information on impacts of pumping; a network of wells, monitored over time, can build understanding of the regional and long-term dynamics, particularly when combined with groundwater models. Monitoring networks should be designed taking into account the aquifer conditions and patterns of withdrawal.

Although critically needed for sustainable management, there is currently no coordinated long-term well monitoring program in Myanmar. IWUMD has made sporadic measurements at the artesian irrigation projects under their management (particularly at Pale); and both Mandalay and Yangon City Development

Councils carry out some monitoring of water levels in the respective urban areas. IWUMD is working on proposals to establish a monitoring network; in April 2017, a data logger and pressure transducer were installed in a monitoring piezometer at the IWUMD offices in Magway, Minbu, Monywa, Kyaukse, and Myingyan to observe groundwater behavior (salinity and water level) in the Irrawaddy Fm and/or Alluvium.

In the absence of well monitoring data, we have used three surrogate indicators for groundwater quantity at the scale of GWZs:

- The proportion (by area) of productive aquifers (providing significant tubewell yields);[18]
- The annual recharge of productive aquifers; and
- The total storage in productive aquifers.

Methods for estimating recharge and storage are detailed in Section 2.4.

4.1.3 Status

Based on analysis of best available information for each GWZ, reviewed in Section 3, we have estimated proportional area, total recharge, and total storage of productive aquifers (Table 4.1.3–a and Figures 4.1.1a, b, and c).

A very large volume of groundwater (>2,700 km^3) is held in storage in the aquifers underlying the Ayeyarwady Basin, mostly (77%) within the productive Alluvial and Irrawaddy aquifers. Limestone aquifers in the Shan Plateau hold an unquantified, but smaller volume. Within the productive aquifers, annual recharge represents a variable fraction of this storage. In the upland, this fraction can be more than 40%, as comparatively small aquifers and intense rainfall and recharge leads to fast recharge of the aquifers. In the larger aquifers found in the south of the basin, this fraction can be as low as 3% due to large storage, thick clay horizons, and more limited recharge.

Current evidence indicates that recharge is dominantly from direct infiltration of rainfall, particularly in the areas where Alluvium and Irrawaddy Fm outcrop in the Dry Zone plains, and in the colluvial fans around the margins of the Shan Plateau and Western Hills.

The contribution to groundwater from rivers is limited, as most groundwater flow is towards rivers. Some interaction between shallow groundwater and the river is apparent in the immediate vicinity of the river; for example, at Mandalay, aquifer recharge from the river is induced by pumping. This effect is limited to a narrow corridor around the river (approximately 0.5 km).

Dating of a limited number of groundwater samples using tritium and radio-carbon, reported in Drury (2017), has confirmed the general patterns of recharge described above. This indicates that groundwater movement through the Ayeyarwady Basin is mostly slow, with water taking thousands of years to move from recharge zones in the periphery of the basin to discharge zones along the river. The exceptions are some areas of shallow alluvium recharged by rainfall or intermittent sandy watercourses, which are young (<50 year). Such studies are essential in understanding recharge rates and patterns.2.

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[18] These productive aquifers correspond in most cases to recent alluvial deposits and older Irrawaddy Fm sediments.

Table 4.1.3-a - Summary of estimations of extent, recharge, and storage in productive aquifers in the Ayeyarwady Basin

GWZ	Aquifer group	Area (km²)	% of productive aquifers	Rain (mm) average	Storage (Mm³)	Recharge (Mm³)	Recharge (mm)
1 Upper Ayeyarwady	Alluvial and unconsolidated aquifers	2,560	6%	3,010	25,590	1,160	452
2.1 Upper Chindwin	Alluvium	8,020	13%	3,090	80,180	3,720	464
2.2 Western Hills	Alluvium and colluvial fans	2,070	12%	1,790	20,680	560	269
2.3 Lower Chindwin	Alluvial and Irrawaddy Fm	10,480	63%	1,240	222,800	2,070	186
3.1 Middle Ayeyarwady	Alluvial and Irrawaddy Fm	17,040	45%	2,020	170,440	5,180	304
3.2 Shan Plateau	Alluvial aquifer and Plateau Limestone	17,910	33%	-	-	-	-
3.3 Mu Shwebo	Alluvial and Irrawaddy Fm	14,510	74%	1,360	200,580	3,030	205
4 Lower Ayeyarwady	Alluvial and Irrawaddy Fm	33,570	52%	1,130	564,610	5,750	170
5 Delta	Alluvial and Irrawaddy Fm	38,320	71%	2,580	870,120	6,090	258

4.1.4 Trends

There are very few data available to quantify or verify trends in groundwater storage and recharge in the Ayeyarwady Basin over the last 20 years.

In general, we have assumed no change in storage in the Ayeyarwady Basin in our water balance calculations, in the absence of other data. Stored volumes are very large, and small changes in storage are difficult to detect. The exception is the Pale Sub-basin, where unregulated flow from artesian tubewells has resulted in an observed fall in flow and water levels (IWUMD data) since 1995 (see Section 3.5.2). Similar patterns of reduced flow and falling water levels are reported from other artesian systems, but no consistent data are available. These results emphasise the risks of local groundwater depletion despite the large stored volumes, and the critical importance of local management and regulation of withdrawals. In the delta, future management plans should aim at avoiding major issues related to groundwater overexploitation, such as land subsidence observed in the Mekong Delta (see Deltares et al., 2015).

While it is not possible to verify changes in recharge in the last 20 years, changes are expected in response to changes in rainfall and landcover, two major controls on recharge. In general, recharge is highest under cropped areas, lower under forests, and lowest under urban areas (Cherkauer and Ansari, 2005).

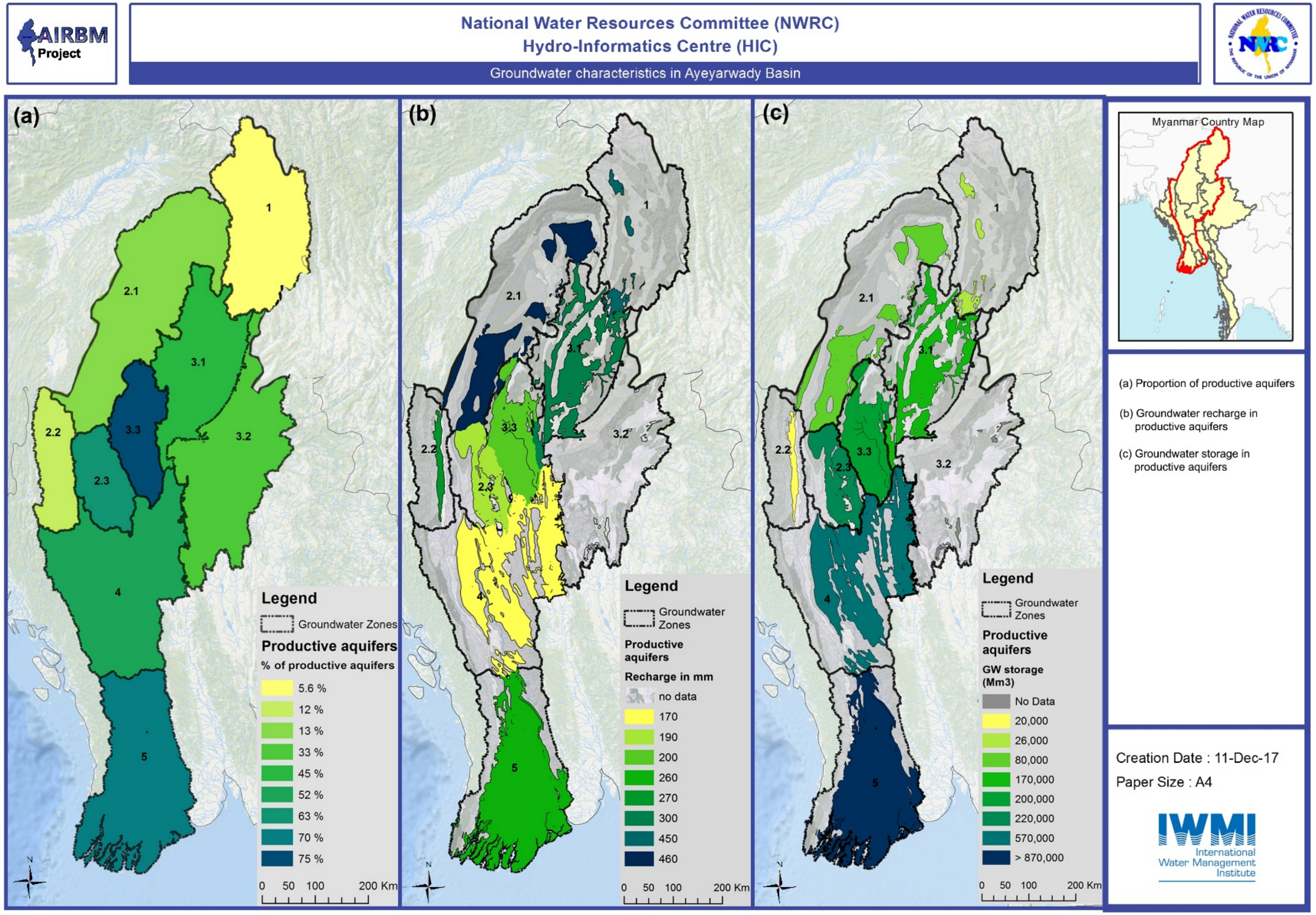

Figure 4.1.4-a – Proportion of productive aquifers *(a), groundwater recharge in productive aquifers (b), and groundwater storage in productive aquifers for each GWZ (c)*

Land cover in Myanmar has changed very significantly over the last 50 years. Forest loss and degradation has been widespread, particularly in the dry forests around the margins of the Dry Zone (Leimgruber et al., 2005). Satellite mapping of forests indicates net forest loss of 4,000 to 8,700 km^2 between 2000 and 2014 in the Ayeyarwady Basin (Hansen et al., 2015; IWMI 2016). At the same time, cropped area increased by more than 20,000 km^2 (IWMI, 2016). The impacts on total recharge are difficult to predict. Increased crop area should act to increase recharge, but loss of forest cover in sloping lands may result in increased runoff and decreased infiltration.

Impacts of climate change on recharge are similarly difficult to quantify. Horton et al. (2017) assessed climate records between 1980 and 2010 and reported a small increase in total rainfall in inland regions of Myanmar (37 mm per decade), with an increase of intensity of rainfall events. Over the same period, average temperature has increased 0.35°C per decade. Increased rainfall intensity (and the resulting lower infiltration) and higher temperature (and the resulting higher evaporation) are likely to offset any increase in precipitation.

Projections for future rainfall in Myanmar are highly uncertain, but in general mirror observed trends, with increasing temperatures and a likely increase in rainfall, particularly past 2040. It is not clear what the overall impacts will be on recharge.

4.2 Groundwater Quality

4.2.1 Background

Water quality constrains the use of groundwater as much as quantity. A range of potential contaminants can affect suitability for different uses. Arsenic, fluoride, and iron are of particular concern in domestic supplies because of their impacts on human health. Salinity affects suitability for both domestic and agricultural purposes.

Water quality issues can be divided into natural (geogenic) contaminants and man-made or induced pollution. Naturally occurring contamination may be exacerbated by human activity (for example, irrigation induced salinity). The hydrogeological studies detailed in Section 3 identified the following major contaminant issues in different areas of the Ayeyarwady Basin:

- Geogenic:
    - Salinity
    - Arsenic
    - Fluoride
    - Other trace elements (U, F, Fe, Mn)
- Man-made:
    - Faecal contamination of shallow groundwater
    - Industrial pollution (mix of contaminants)
    - Agri-chemicals (pesticides, herbicides, and fertilisers)

Groundwater quality is assessed and monitored using direct sampling of wells and chemical analysis. Because there is little correlation between the different components of water quality, results should be presented for each key parameter, indicating whether groundwater meets the standards for different uses. The proposed NDWQS (Ministry of Health, 2014) is awaiting ministerial approval. The proposed standards are presented in Table 4.2.1–a, along with WHO guidelines. With the exception of salinity and arsenic, water quality issues are mainly localized, responding either to local geological conditions (such as fluoride at Wetlett) or local human pressures (such as faecal contamination).

Table 4.2.1-a - Proposed NDWQS, WHO and Mandalay City Development Committee Standards *(from Drury, 2017)*

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.).

4.2.2 Salinity

BACKGROUND

Groundwater contains varying amounts of salts dissolved during passage through aquifers. Chemically, these salts are a mix of $Na^+ – Ca^{2+} – Mg^{2+} – K^+/Cl^- – SO_4^{2-} – HCO_3^- – CO_3^{2-}$, with a variety of trace elements including Fe, Mn, and other metals. Excessive amounts of dissolved salts affect the suitability of water for drinking and most other purposes. Saline groundwater can directly reduce crop yields, degrade soil structure, and reduce infiltration (Pavelic et al., 2015). Table 4.2.2–a presents salinity ranges (expressed as specific conductance)[19] and corresponding uses (Drury, 2017). Salinity limits groundwater use in many areas, particularly in the Dry Zone, but is a natural phenomenon and cannot be easily mitigated,[20] only avoided.

Table 4.2.2-a - Salinity ranges and corresponding uses: *(Drury, 2017)*

Specific conductance	Suitability for use
0 to 1,500 µS.cm^{-1}	Good quality — usually suitable for drinking, stock, irrigation, town water supply, and industry.
1,500 to 3,000 µS.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 µS.cm^{-1}	Inferior quality — suitable mainly for stock and washing. Avoid consumption by villagers if possible.
6,000 to 10,000 µS.cm^{-1}	Poor quality — suitable only for goats and sheep. Cattle will not tolerate >8,000 µS.cm-1.
Greater than 10,000 µS.cm^{-1}	Bad quality — unsuitable for any purpose except salt harvesting.

Salinity in groundwater occurs in the Ayeyarwady Basin in two main contexts:

- Naturally occurring (geogenic) salt held in aquifers and released to groundwater as it moves through the aquifer. In the Ayeyarwady Basin, the Pegu Group aquifers are often saline, due to the marine origin of the sediments. Salts may leach from saline aquifers into nearby freshwater aquifers, with the zone of influence varying depending on aquifer conditions and flow. Increased salinity is very common in the areas around Pegu sediments. Pumping from areas close to saline aquifers may induce increased flow of saline water towards the pumped zone. Drury (2017) has described variations in salinity in the Dry Zone in detail, and identified zones with high probability of brackish water.
- Saline intrusion of seawater in unconsolidated sediments in the delta. Shallow groundwaters in the southern areas of the Ayeyarwady Delta are frequently saline. The extent of saline intrusion in surface water varies seasonally and from year to year, depending on the interplay between river flows and tides (see Section 3.10). The extent of salinity in groundwater is less well defined, but probably mirrors surface water patterns in the main, although lenses of fresh water occur (for example, around Bogale).
- Salt water intrusion also occurs in the tidal reaches of rivers, such as by Yangon City, where nearby heavy groundwater extraction induces salt water intrusion.

Buildup of salinity in soils and shallow groundwater may also occur due to evaporation. This is most common in irrigation systems, where enhanced seepage can result in rising water tables that bring salts to the root

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[19] Specific conductance is the electrical conductance of a cubic centimetre of water of a standard temperature of 25° C, measured in µS.cm-1, and is a measure of salinity.

[20] Desalination is possible using a range of techniques including distillation and reverse osmosis. Energy demand and the costs of desalination are decreasing, but the method is generally prohibitively expensive for use in rural areas.

zone. Irrigation induced salinity is not widely reported in Myanmar, although use of marginal quality groundwater has resulted in problems in some areas (Pavelic et al., 2015).

INDICATORS AND DATA AVAILABILITY

IWUMD holds data on salinity for many thousands of wells, analysed over the last 40 to 50 years. These data are mainly in hard copy, although transfer to digital formats is underway. Drury (2017) presents a detailed analysis of available salinity data for the Dry Zone, including maps of regional patterns of salinity. Based on this work, general conclusions can be draw about likely salinity in different aquifers in other areas (see hydrogeological descriptions in Section 3). Salinity risk in the delta was mapped based on patterns of seawater intrusion in surface water, and observations of salinity in wells from IWUMD and local drillers (see Section 3.9).

STATUS

Salinity in the Ayeyarwady Basin is mainly geogenic, except in the delta where there is some intrusion of seawater into shallow groundwater. A map of the distribution of saline groundwater in the Dry Zone (from Drury, 2017) is given in Figure 4.2.2-a, overlain on likely areas of high salinity in other GWZs, based on occurrence of Pegu Group and equivalent aquifers, and on the potential risk of saline intrusion in the delta.

TRENDS

There is no evidence and little likelihood of major changes over time in patterns of geogenic salinity at a regional scale, although there are reports of localized increases in salinity as a result of pumping close to Pegu Group aquifers (Drury, 2017).

In the delta, the salinity intrusion interface is primarily controlled by Ayeyarwady River discharge. Changes in discharge as a result of climate change, increased abstraction, or infrastructure development could change the dynamics of salinity intrusion in both surface and groundwater. At this stage, no clear trend in discharge is apparent.

Increased abstraction of groundwater within the delta could result in localised increases in salinity. Htun and Oo (2015) report increased salinity in aquifers underlying Yangon City but the extent of the effect is not known.

Table 4.2.2-b - Total area at risk of saline groundwater in each GWZ

GWZ	Salinity risk total area (km^2)	Proportion of GWZ[21]
1 Upper Ayeyarwady	3,502	6%
2.1 Upper Chindwin	26,004	41%
2.2 Western Hills	2,328	14%
2.3 Lower Chindwin	7,202	37%
3.1 Middle Ayeyarwady	5,155	29%
3.2 Shan Plateau	106	-
3.3 Mu Shwebo	3,530	9%
4 Lower Ayeyarwady	30,105	48%
5 Delta	20,616	45%

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[21] Based on the area of the GWZ in Myanmar.

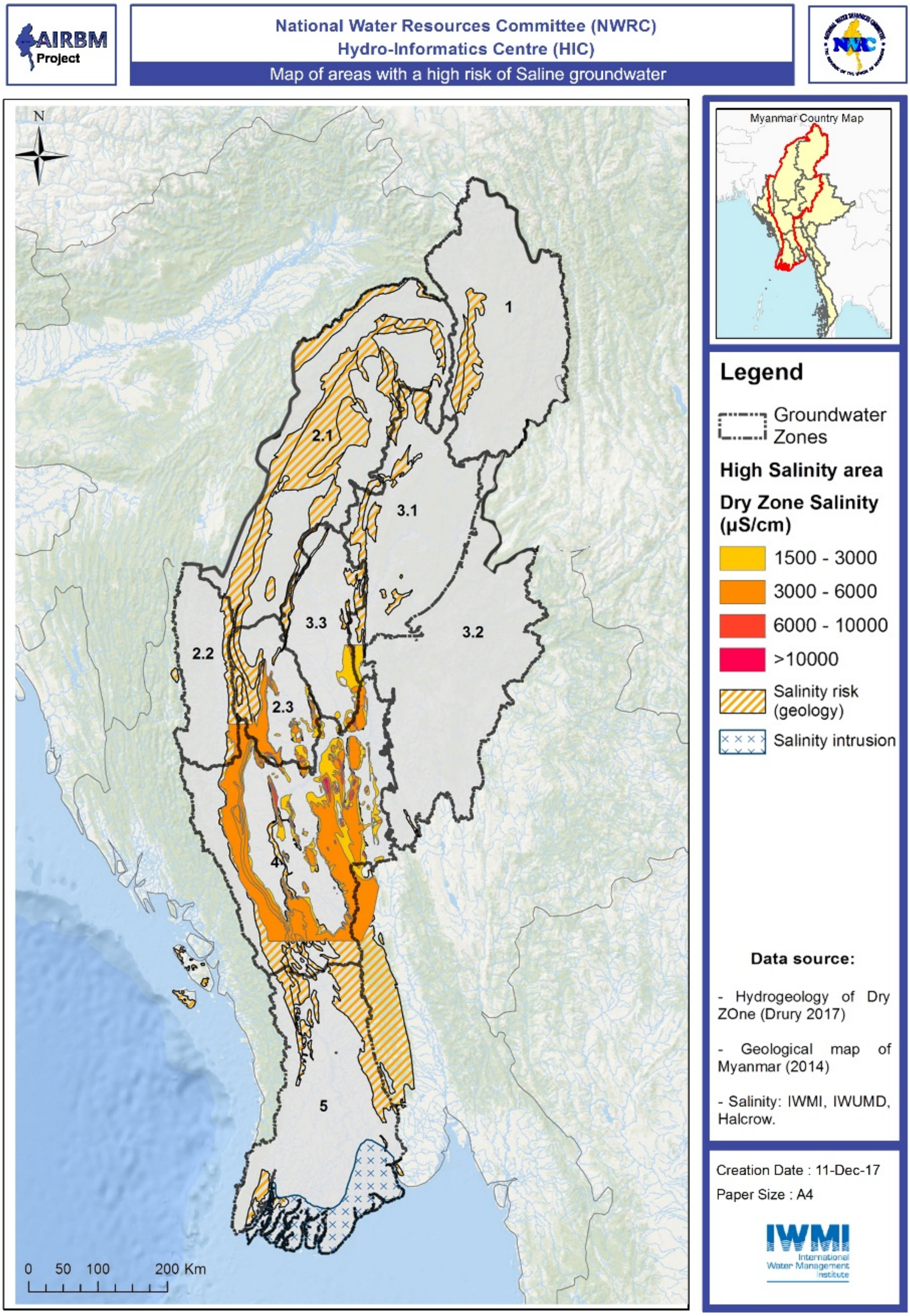

Figure 4.2.2-a – Map of areas with a high risk of Saline groundwater

4.2.3 Arsenic

BACKGROUND AND IMPORTANCE

Arsenic is one of the most common contaminants found in drinking water around the world. Arsenic is highly toxic, and even at low levels, long-term ingestion is linked to skin conditions, liver disorders, cardiovascular and kidney function issues, and often cancer.

High levels of arsenic are commonly found in groundwater from fluvial and deltaic sedimentary aquifers in major river systems in Asia, including the Mekong and Ganges. Arsenic distribution and release to groundwater is controlled by the geochemical process of oxidation and the reduction of arsenic bearing minerals. Oxidation of groundwaters due to the drilling of wells is thought to play an important role in mobilizing arsenic in groundwater. There is often a strong geological control on distribution, with concentration in particular sedimentary units (McCarly et al., 2011).

Prevention of health impacts requires testing to identify wells with unsafe levels, and public awareness programs to alert communities to the risks. Options for mitigating arsenic in groundwater include: the use of alternative water sources (e.g., rainwater harvesting), dilution of high content arsenic source water with lower arsenic water, and removal of arsenic by filtration using composite iron matrix;[22] colloidal silver (Mahlangu et al., 2012), or activated carbon with ceramic filters; reverse osmosis; or distillation (WHO, 2010).

INDICATORS AND DATA AVAILABILITY

The most commonly used indicator for arsenic is the percent of samples above the safe limit for drinking water. In Myanmar, the proposed standard in NDWQS is 50 µg/L, in line with the limit used in many other developing countries. The WHO uses an upper limit of 10 µg/L.

The Arsenic Mitigation Programme conducted in Myanmar between 2005 and 2011 analysed over 250,000 groundwater samples for arsenic in 66 townships across 11 states/divisions, with support from UNICEF and WHO. These data are held by IWUMD in a digital database; some results from the data were made available for this study. Township level data from Thein Soe and IWUMD (2016) were used to calculate an indicator for arsenic risk by township, as:

- Category A — low to moderate risk, with <10% of samples exceed drinking water standard;
- Category B — moderate risk, with 10 - 25% of samples exceed drinking water standard; and
- Category C — high risk, with >25% of samples exceed drinking water standard.

STATUS

In the Ayeyarwady Basin, high levels of arsenic are found in groundwaters from floodplain deposits of the Quaternary Alluvium of the Ayeyarwady River. Elevated levels are most commonly observed in the Ayeyarwady Delta, but also occur in other areas. Elevated arsenic is not observed in the sediments of the Chindwin and Mu Rivers, except at the confluence with the Ayeyarwady. It seems that the geological source of arsenic in sediments occurs only in the headwaters of the Ayeyarwady. Figure 4.2.3-a shows the risk category for arsenic, based on the proportion of samples exceeding the safe level for drinking water (50 µg/L) by township, for areas within the Ayeyarwady Basin where data are available. We have included mapped areas of Alluvium within the Ayeyarwady mainstream system, as these are the areas of highest risk for arsenic contamination.

Trends

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[22] https://www.koshland-science-museum.org/water/html/en/Treatment/Household-Arsenic-Filter.html

Because of the strong geogenic control, no trend in arsenic occurrence is expected over time (see Van Geen, 2014), and the current practices of drilling deeper (as IWUMD practices with DTW) or changing location for contaminated wells (for local drillers) can be effective in preventing exposure to arsenic. Testing of wells for arsenic before use is critically important, and should be mandatory for all new wells.

There is some evidence that in arid areas, irrigation induced changes in soil pH could mobilize arsenic (Podgorski et al., 2017), and on-going monitoring may be advisable in irrigated areas.

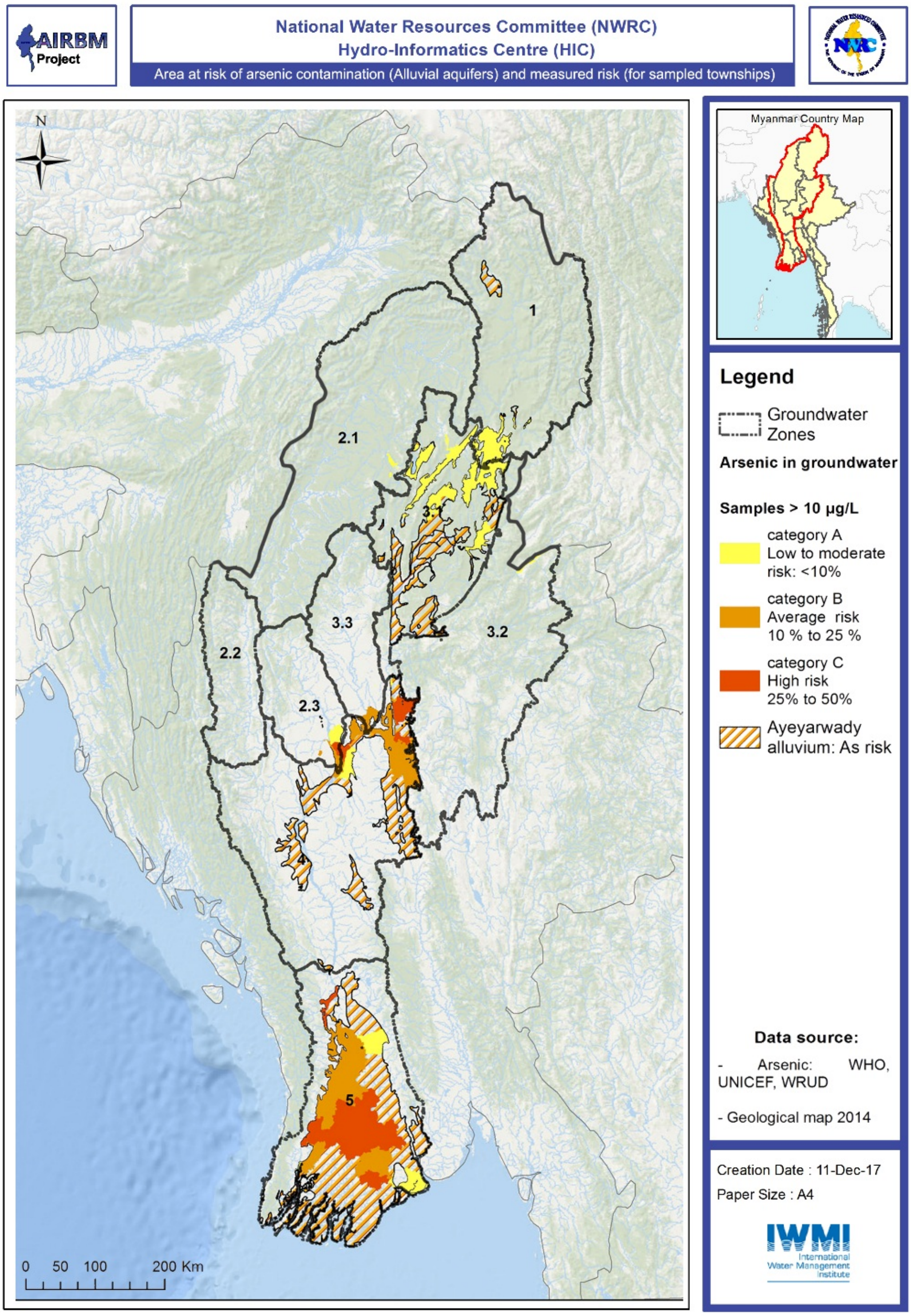

Figure 4.2.3-a – Area at risk of arsenic contamination (Alluvial aquifers) and measured risk (for sampled townships)

4.2.4 *Anthropogenic pollution of shallow groundwater*

Shallow unconfined aquifers are vulnerable to pollution by seepage of contaminated surface water into groundwater. While overlying soils and sediments can act to filter out contaminants, there is increasing evidence internationally of the degradation of shallow groundwater quality as a result of human activity. Pollution may come from point sources (such as factories and mines) or non-point sources (such as agricultural chemicals and urban runoff). The major sources of anthropogenic pollution identified in the Ayeyarwady Basin (see Section 3) are the following:

- Bacterial contamination due to inadequate sanitation in both rural and urban areas;
- Industrial and urban pollution and seepage from inappropriate disposal of industrial and urban wastes (both solid and liquid);
- Agricultural chemicals and the fertilisers, pesticides, and herbicides applied to crops, which seep through to underlying aquifers, particularly if applied in excessive amounts;
- Contamination from oil production in the oilfields of the Dry Zone; and
- Runoff and seepage from mining, which may include high levels of metals as well as chemicals used in extraction processes, such as mercury and cyanide.

In this study, we did not find sufficient data to accurately describe the status and trends of most sources of anthropogenic groundwater contamination. We have derived an indicator only for bacterial contamination from unsafe sanitation (see below).

Pollution of groundwater from agricultural chemicals is not monitored systematically in Myanmar. IWUMD's standard evaluation of groundwater for drinking purposes uses 23 parameters, including nitrate, while the evalutation for irrigation purposes includes 18 parameters, with both nitrate and phosphate. There is no routine testing for pesticides, due to the complexity and cost of the analytical procedures and the range of different chemicals used. More than 40 pesticide classes are included in the parameters identified for National Water Quality Monitoring (Aung, 2016). No indicator is proposed for agrichemical pollution in groundwater at this stage, due to lack of data. However, it is almost certain that levels of agro-chemicals, particularly pesticides, have increased substantially over the last 20 years.

Similarly, there is no systematic monitoring of industrial pollution of groundwater. This is likely an issue mainly in Mandalay and Yangon, where most industry is concentrated. Government sponsored Industrial Zones (see Figure 3.10.5-a) and larger towns such as Monywa and Pathein may also be at risk.

The Ayeyarwady Basin contains important oil and gas provinces around Magway (for example, Htankai and Mann oilfields). Current informal small-scale extraction has few safeguards, and contamination of groundwater during drilling is a risk. Analysis of four tubewells in the Mann oilfield at Minbu (ERM, 2015) found no evidence of oil in groundwater, and we have seen no data confirming groundwater contamination. However, monitoring is recommended in areas surrounding production zones.

Mining activity also poses potential threats to groundwater quality. Contamination of shallow groundwater by leachates and wastewater may occur from large-scale copper mines at Monywa and adjacent small-scale villager copper extraction. Local NGOs have raised concerns, although no data are available (Drury, 2017). Alluvial gold mining and extraction using mercury, and hard rock mining using cyanide could result in contamination of shallow groundwater, although this is more likely to affect surface water, particularly given general pattern of movement of groundwater towards rivers.

No indicator is derived here for the Ayeyarwady Basin for industrial and mining pollution in groundwater, due to lack of data and the localized nature of potential issues. As with agrichemicals, it is likely that such pollution is increasing, as the intensity of industry and mining increases as Myanmar's economy develops. Targeted monitoring programs are required around industrial and mining zones.

BACTERIAL CONTAMINATION OF SHALLOW GROUNDWATERS

Bacterial contamination of drinking-water is widespread globally, especially in low-income countries and rural areas, and affects improved sources including tubewells and dugwells (Bain et al., 2014). Bacterial pollution of shallow groundwater occurs by seepage from sewage and other wastes, such as contaminated water from markets, abattoirs, and industrial areas, such as tanneries, and food processing. Such pollution contributes to the prevalence of waterborne diseases.

INDICATORS AND DATA AVAILABILITY

There is little information available on the extent of bacterial pollution in groundwater in Myanmar. A study in Yangon (Myint et al., 2015) found high levels of coliforms in water samples, including tubewells, but it was not clear whether this was due to contamination at the source, or at the point of use. There is no comprehensive program for monitoring bacterial contamination in groundwater. Routine testing for faecal coliforms is limited, due to the complexity and cost of the analytical procedures.

In the absence of data on occurrence, we have derived an indicator for the risk of contamination, based on the number of people without access to safe sanitation, by township (Myanmar Census, 2014), and population density.

STATUS

Table 4.2.4–a and Figure 4.2.4-a show the number of people within each township without access to safe sanitation. This is an indicator of the local risk of bacterial contamination of shallow groundwater, and identifies townships where remedial measures and monitoring should be high priority.

TRENDS

It is difficult to define trends in bacterial pollution in the Ayeyarwady Basin. Gains due to increased access to improved sanitation may be offset by population growth. Pollution effects are very localized, and trends will depend on local sewage and waste management practices.

Table 4.2.4-a - Population and proportion without access to safe sanitation *(Myanmar Census, 2014)*

GWZ	Population	Population without access to safe sanitation	In %
1 Upper Ayeyarwady	449,780	101,339	23%
2.1 Upper Chindwin	1,011,522	252,644	25%
2.2 Western Hills	714,100	88,406	12%
2.3 Lower Chindwin	1,636,350	447,163	27%
3.1 Middle Ayeyarwady	1,699,441	358,251	21%
3.2 Shan Plateau	2,557,521	701,576	27%
3.3 Mu Shwebo	1,808,226	561,292	31%
4 Lower Ayeyarwady	9,165,838	2,299,486	25%
5 Delta	14,684,222	2,493,392	17%

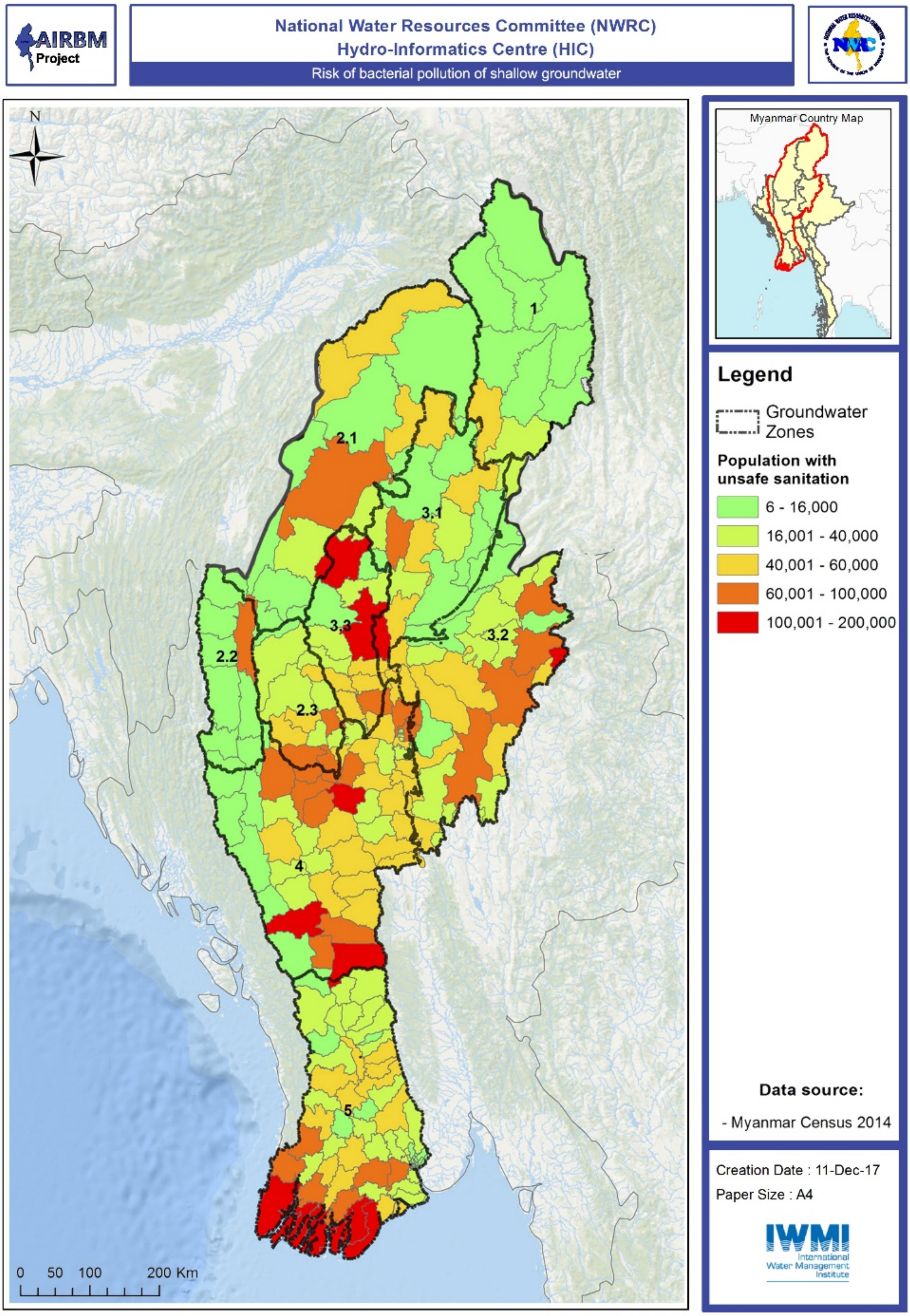

Figure 4.2.4-a – Risk of bacterial pollution of shallow groundwater, based on number of people per township without access to improved sanitation

4.3 Abstraction

Groundwater is an important component of water for human use in Myanmar, for domestic, urban, industrial, and agricultural supplies. To monitor the sustainability of groundwater use, an estimate of total withdrawals is a key indicator, but the extent of use is very difficult to quantify accurately. Groundwater use is unregulated, with no requirement to register wells or report withdrawals. Use is divided between three main sectors:

- Domestic and urban;
- Industry and mining; and
- Agriculture and irrigation.

Consistent statistics on water use in different sectors are not compiled nationally, and estimates of total water use, and the relative volumes of surface and groundwater, vary between sources. National estimates for 2000 to 2001 by MOAI (2003) are given in Table 4.2.4–a. Ministries and municipal and township authorities keep records of wells constructed within government programs and (to a lesser extent) data on extractions. The number of private wells is much higher, but not reported.

Groundwater use within each GWZ is described in more detail in the relevant sections above.

Table 4.2.4-a - Estimated water use in Myanmar in Mm^3 from 2000 to 2001 *(MOAI, 2003)*

	Industry		Domestic		Irrigation	
Surface water	174	78%	1,010	31%	25,504	93%
Groundwater	48	22%	2,245	69%	1,920	7%*
Total	**222**		**3,255**		**27,424**	

** Estimate of proportion of groundwater irrigation from IWMI (2014).*

4.3.1 *Domestic and urban use*

BACKGROUND AND IMPORTANCE

Groundwater is the primary source for domestic and drinking supplies for more than half of the population nationally. In rural and remote areas, this proportion is much higher, with almost two-thirds of the rural population drawing drinking water and village supplies from wells (Myanmar Census, 2014). Most towns and cities rely on groundwater for a substantial component of urban supply: 11% in Yangon, 90% in Mandalay, not counting private wells.

INDICATORS AND DATA AVAILABILITY

Available sources of data on domestic and urban use include the following:

- Data provided by local experts and IWUMD officials on groundwater use in specific towns (limited coverage).
- Information from Yangon and Mandalay City Development Corporations on groundwater use in urban areas.
- Numbers of wells drilled for domestic use by IWUMD. No comprehensive data were available on wells drilled by other agencies and NGOs, or private individuals.
- MOAI (2003) estimates of use in 2000 and projections for 2015 by district.
- The 2014 Myanmar Census collected township level statistics on sources of domestic water supplies (drinking and non-drinking), by household.

Since no nationally consistent data on groundwater abstraction for domestic use was available, an estimate of domestic abstraction was made based per capita use. Census data on the proportion of households per township using groundwater sources were combined with population density data from Gaughan et al. (2013) to estimate the number of people using groundwater in each GWZ. A geospatial analysis in GIS environment was used to derive the domestic abstraction per ha (at cell level), assuming a groundwater abstraction per person per day of 135 L and 150 L in rural and urban areas, respectively. A population density threshold value of 10 persons per ha was used to discriminate rural and urban areas. Resulting datasets allow mapping of intensity of abstraction and calculation of the total volumes per GWZ.

STATUS AND TRENDS

Table 4.3.1–a summarizes estimated groundwater extraction for domestic use in each GWZ. Figure 4.3.1 – a shows the proportion of households using groundwater per township, and Figure 4.3.1 – b shows the calculated spatial distribution of intensity of groundwater use, taking into account population density. Extraction of groundwater for domestic use is highest in the Lower Ayeyarwady and the Delta GWZ. The south sections of the Lower Chindwin and Mu-Shwebo GWZs are similarly high. In the western hills and the Middle Ayeyarwady, abstraction is high in alluvial inter-montane valleys and overall low in the less populated, less groundwater productive Upper Ayeyarwady and Upper Chindwin.

Groundwater use for domestic supply is determined by population (demand) and the availability and cost of groundwater relative to other sources, which is in turn linked to the availabilty of extractive technologies. The population in Myanmar is increasing steadily; the total population increased by 36% from 1983 to 2014 (Census 1983-2014). Extractive technologies have also become both more available and more affordable, with access to low-cost imported pumps, and the recent advent of small solar pumps. Groundwater extraction is thus increasing, and is likely to continue to do so. The exception may be in Yangon, where urban development plans recommend a shift away from groundwater to surface water supplies from reservoirs (JICA, 2017).

Table 4.3.1-a - Summary of estimated annual abstraction of groundwater for domestic use per GWZ

GWZ	Domestic GW abstraction* (Mm^3 yr^{-1})
1 Upper Ayeyarwady	13
2.1 Upper Chindwin	21
2.2 Western Hills	19
2.3 Lower Chindwin	68
3.1 Middle Ayeyarwady	55
3.2 Shan Plateau	49
3.3 Mu Shwebo	70
4 Lower Ayeyarwady	340
5 Delta	369
TOTAL	**1004**

**Considering 135 L per person per day in rural and 150 L per person per day in urban areas.*

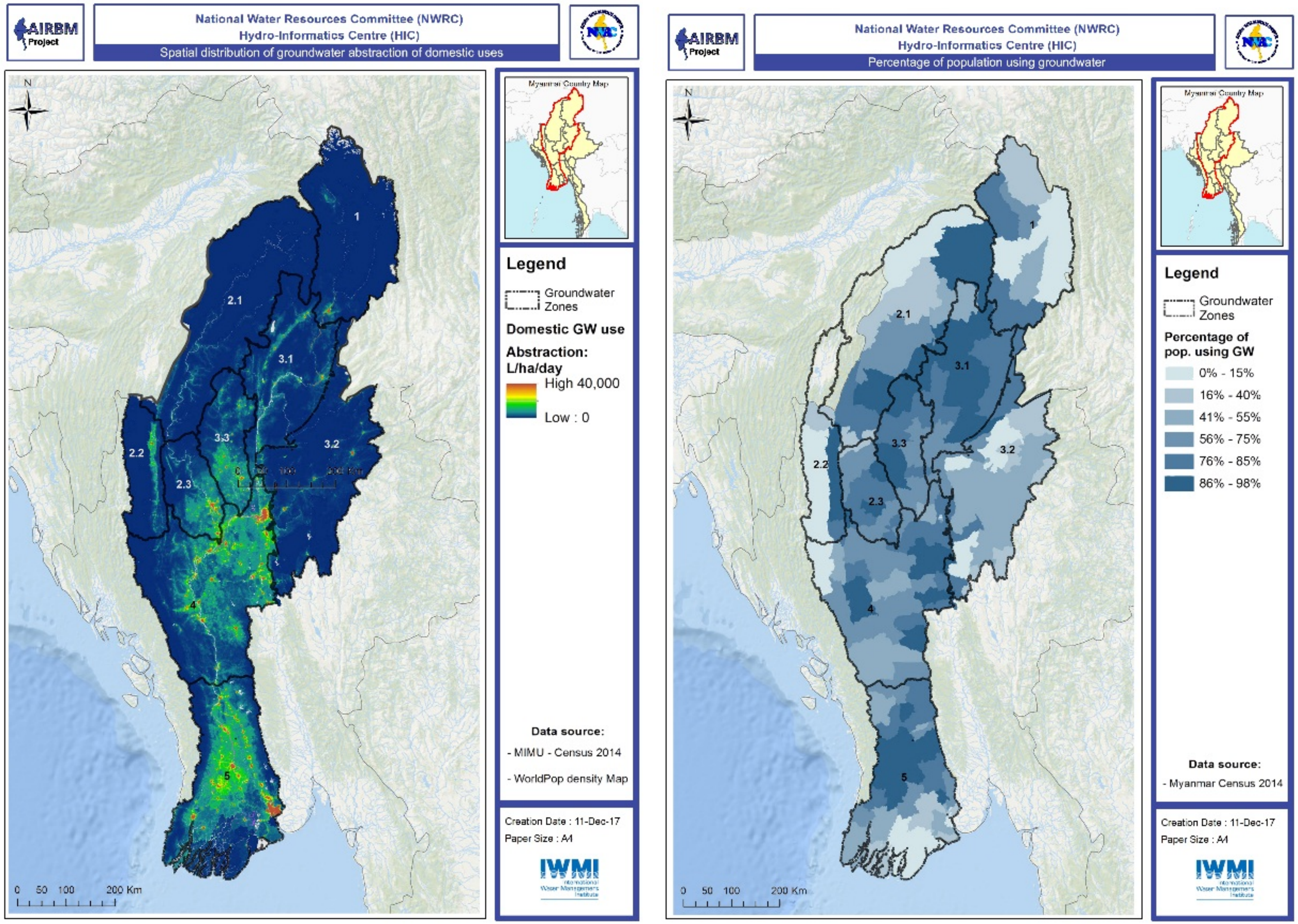

Figure 4.3.1-a – Spatial distribution of groundwater abstraction of domestic uses (a), and percentage of population using GW (b)

4.3.2 *Industrial Use*

BACKGROUND AND IMPORTANCE

Myanmar has a policy of promoting industrial development with Industrial Zones and Special Economic Zones. Within the Ayeyarwady Basin, there are currently 15 IZs (including 4 in Yangon), of different sizes. A further 2 are planned in Mandalay Region (see Figure 4.3.2-a). Sizable industries are generally restricted to the bigger towns and cities.

Although large water-using industries (such as sugar mills, paper mills, and cement factories) mainly use surface water, small industries in both cities and towns rely on private wells to secure water for production, for industries such as agro-processing (edible oils and cotton), breweries, textile factories, tanneries, electronics, etc. The main industries within each GWZ are described in the sections above.

Myanmar has large mineral resources, including precious and semi-precious metals, gems, and oil and gas. Myanmar's mining sector is effectively an artisanal industry, accounting for less than 0.1% of GDP.[23] It is likely that groundwater is used in mining operations, but no data are available. Groundwater is used in the oilfield of the Dry Zone; for example, at Yenangyaung, the Myanmar Oil Corporation operates four perforated infiltration wells for its oil production requirements (3 ML day^{-1}). Future use for mining could grow significantly as there is high potential for expansion in both oil and minerals sectors, although the NLD Government have recently announced that foreign investment in mining will not be permitted.[24] Refer to SOBA 5 for more information on industrial and mining sectors.

INDICATORS AND DATA AVAILABILITY

Insufficient data are available on the distribution of mining to assess the potential use of groundwater in the mining sector.

To estimate industrial use, we have assumed that significant industries are largely restricted to urban areas, and that the intensity of industrial development, and the volume of industrial withdrawals are likely approximately proportional to the size of the urban area. To estimate overall industrial use, we have the following information.

- Identified towns with a population of more than 50,000 (ADB data).
- Assumed that groundwater use for industry is related to size of the town, as follows, based on estimates from MOAI (2003). If the town is identified as an IZ, assumed use is doubled:
  - 50 - 100,000 — 2 ML day^{-1}
  - 100 - 200,000 — 4 ML day^{-1}
  - 200 - 500,000 — 10 ML day^{-1}
- Use for the major cities was estimated based on number of wells and known withdrawals for urbans supplies (see Section 3 above), as:
  - Mandalay — 100 ML day^{-1}
  - Yangon — 200 ML day^{-1}

STATUS AND TRENDS

Estimated total industrial use per GWZ is shown in Figure 4.3.4-a. Overall total extraction for industrial use is 153 Mm^{3} yr^{-1}. These figures are highly uncertain, but reflect relative levels of industrial use in the GWZs reasonably well.

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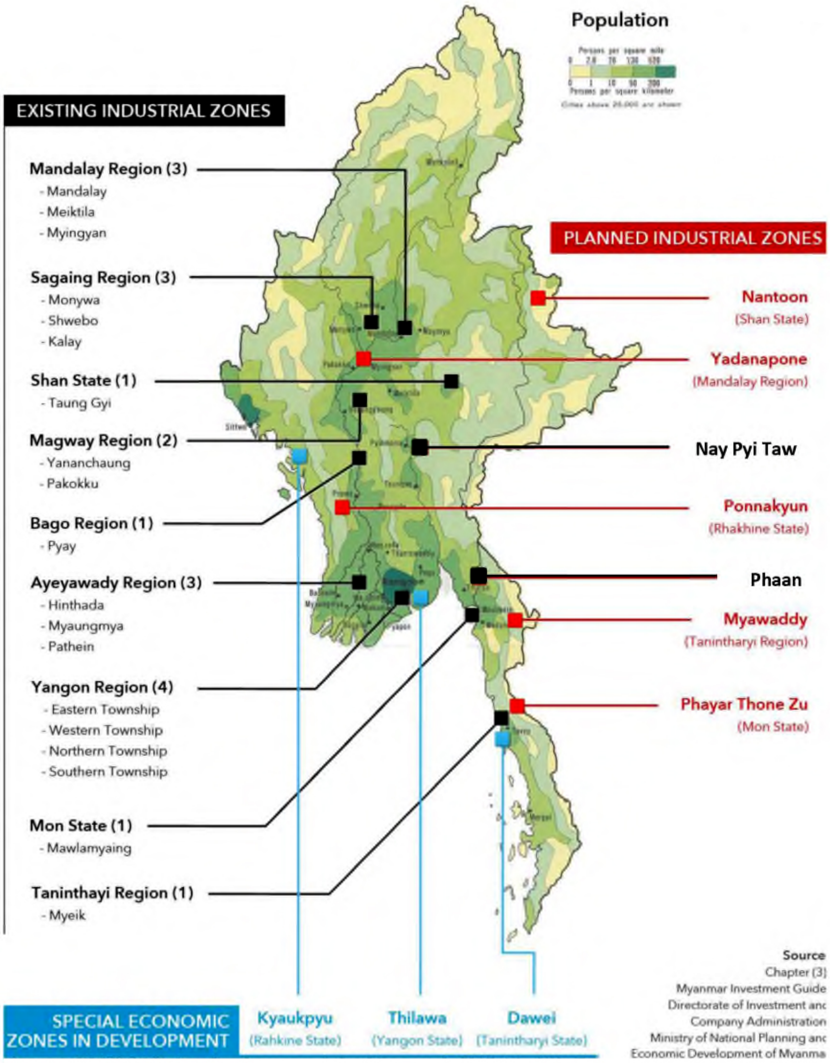
[23] https://www.ausimmbulletin.com/feature/is-myanmar-about-to-experience-an-exploration-boom/

[24] https://consult-myanmar.com/2017/03/19/no-foreign-investment-allowed-in-mining-sector-by-nld-government

As with domestic use, groundwater use for industry is likely increasing due to both growth in population and improvements in extractive technology. Development of Industrial Zones may result in decreased use of groundwater if centralized services, including water supply, are provided in the IZ.

Table 4.3.2-a- Estimated groundwater extraction for industry per GWZ

GWZ	Estimated groundwater extraction for industry, $Mm^3\ yr^{-1}$
Upper Ayeyarwady	1
Upper Chindwin	0
Western Hills	1
Lower Chindwin	3
Middle Ayeyarwady	0
Shan Plateau	4
Mu	1
Lower Ayeyarwady	54
Delta	90
TOTAL	**154**



Source
Chapter (3)
Myanmar Investment Guide
Directorate of Investment anc
Company Administration
Ministry of National Planning anc
Economic Development of Myanma

Figure 4.3.2-a – Industrial Zones and Special Economic Zones of Myanmar *(Myanmar Investment Guide)*

4.3.3 *Agricultural Use*

Myanmar is one of the few countries where current estimates of use indicate that domestic use of groundwater exceeds withdrawals for agriculture. Groundwater accounts for approximately 7% of government irrigation schemes by area (MOAI, 2014), and is the fastest growing form of irrigation. In addition to investment by IWUMD in groundwater irrigation (pumped and artesian), there is rapid growth of small-scale pumping by individual farmers (McCartney et al., 2013) due to the flexibility, reliability, and relatively low establishment costs of small-scale, farmer-managed pumping. In other parts of Asia, groundwater irrigation has boomed over the last 30 years (Mukherjee et al., 2010), and a similar revolution is possible in Myanmar. Groundwater is also important for livestock watering and home gardens, particularly in the Dry Zone. The importance of groundwater for food and water security is likely to intensify under climate change. The emergence of solar pumping is giving a further boost to groundwater use.

DATA AVAILABILITY AND INDICATORS

There are very large uncertainties in attempting to estimate groundwater use for agriculture in Myanmar. Although agricultural statistics, including information on the source of irrigation water, are collected annually by Department of Land Statistics, these data are not available in the public domain and it is not clear whether they provide comprehensive national coverage.

To estimate withdrawals of groundwater for agricultural use, we need information on either direct withdrawals (number of wells and volumes extracted), or area irrigated. IWUMD hold data on wells drilled for domestic and irrigation purposes by state; but these reflect only a small proportion of wells used for irrigation. There are currently no records collected on the number or size of privately drilled wells.

Area irrigated is similarly problematic. IWUMD collects data on areas irrigated and volume of groundwater withdrawl for the groundwater irrigation schemes that it operates, but again, no data are available on the extent of irrigation from private wells. A further complication is introduced by the use of artesian wells in several areas. Because wells are not capped, but allowed to flow freely, there is no clear relationship between volumes withdrawn and area irrigated; large volumes of water are allowed to flow with no productive use.

Our approach has been to estimate agricultural groundwater use based on a number of different sources, to put bounds around the likely range of volumes withdrawn in each GWZ. We have four sources of information:

- Local information on abstractions (abs.) from known areas of groundwater irrigation, particularly the IWUMD groundwater projects and surrounding areas. Water balance calculations in Drury (2017) summarized best available knowledge for specific sub-basins within the Dry Zone GWZs.
    - These estimates are considered the most reliable, but cover only partial areas within some GWZs. They cover the most important groundwater irrigation areas, and can be taken as a reliable lower bound for the GWZs for which they are available.
- MOAI estimates of groundwater volumes used in 2000 and projected use in 2015, by district. These estimates are known to be problematic (for example, the accompanying estimates for domestic supply appear very high).
    - Volumes are apportioned to GWZs based on area of each district in the GWZ. This is likely to cause errors, since groundwater irrigation is not evenly distributed through the districts, but clustered in specific areas.
    - The estimates are most useful as an indication of areas where government proposed to develop groundwater irrigation.
- IWUMD data on numbers of tubewells drilled for irrigation and beneficial area, by state, to 2016 (Thein Soe and IWUMD, 2016).
    - Wells are apportioned to GWZs based on area of each state in the GWZ. As above, this is likely to cause errors due to clustering of wells in particular areas. Annual withdrawals are estimated by assuming average of 2 L s^{-1} per well for 6 hours a day over 100 days (assuming only dry season irrigation). To account for private wells, we have assumed that

  private wells outnumber government wells by three to one, based on conditions in the lower Mu and Lower Chindwin. The estimates do not account for free-flowing artesian wells.
  - These estimates represent a very conservative lower bound, and are in most cases unrealistically low.
- IWMI mapping of landcover in the Ayeyarwady Basin (IWMI, 2016). A combination of Landsat and MODIS satellite imagery was used to capture seasonal greening patterns and delineate areas of single, double and triple cropping. Remote sensing methods map areas of cropping system, not actual cropped area. Mixed pixel effects meant that cropped areas are often significantly overestimated.
  - We have assumed that groundwater irrigation is primarily used to secure a second crop in the dry season, and so have used the estimated for areas of multiple cropping (double and triple cropping).
  - We have assumed that total area irrigated using groundwater within the Ayeyarwady Basin approximates the national average of 7% of total irrigation, but have apportioned this between GWZ based on knowledge of the systems in each. For example, it is very unlikely that 7% of delta irrigation is from groundwater; we have assumed 2%, with 10 - 20% in Dry Zone GWZs (see Table 4.3.4–a).
  - Total volume extracted is calculated assuming 0.8 m per year irrigation depth.
  - This approach is likely to overestimate withdrawals, except in areas with large areas of artesian flow (particularly the Lower Ayeyarwady).

STATUS AND TRENDS

Using these different approaches, we derived ranges for potential groundwater withdrawals for irrigation by GWZ, as set out in Table 4.3.3–a. The range for current total annual withdrawals for the Ayeyarwady Basin is 536 Mm^3 to 2,325 Mm^3.

Groundwater demand for irrigation in the Ayeyarwady Basin is clearly increasing. IWUMD is investing in new schemes, and the number of individually managed pumps is growing rapidly. A major constraint on expansion of groundwater pumping has been the costs involved: both investment in wells and pumps, and the on-going cost of energy, usually diesel (Pavelic et al., 2015). Solar pumping is gaining ground as a feasible, cost effective method of accessing shallow groundwater for irrigation and could accelerate the existing trend of the adoption of farmer managed groundwater pumping.

Table 4.3.3-a - Estimated groundwater withdrawals for irrigation (Mm^3)

	Estimated groundwater withdrawals for irrigation (Mm^3)				
Method	MOAI, 2000	MOAI, 2015	Drury, 2017	IWMI, 2016*	IWUMD wells (*3)**
Upper Ayeyarwady	1	2		13 (10%)	1
Upper Chindwin	0	365		49 (10%)	42
Western Hills	0	133	33	51 (15%)	5
Lower Chindwin	104	119	236	120 (25%)	15
Middle Ayeyarwady	4	109		180 (10%)	33
Shan Plateau	1	4		71 (10%)	101
Mu	69	207	500	198 (10%)	18
Lower Ayeyarwady	70	411	1,350	554 (22%)	261
Delta	61	975		256 (2%)	59
TOTAL	**310**	**2,325**	**2,119**	**1,493**	**535**

**Figures in brackets denote assumed proportion of intensive irrigation from groundwater.*

***Calculated assuming that total number of private and IWUMD ~3 times the number of IWUMD wells.*

4.3.4 *Total extraction relative to recharge*

Our starting point for discussion of sustainable use of groundwater is the general guideline that groundwater extraction should *a minima* not exceed aquifer recharge unless there are compelling social or environmental reasons to do so. By combining results from the relevant sections above, we can calculate the total annual groundwater withdrawals by GWZ as a proportion of estimated recharge. Table 4.3.4–a shows a range, including both high and low estimates for agricultural withdrawals. Figure 4.3.4-a maps the same results (including high estimates of agricultural use).

Results indicate that total groundwater extraction in the Ayeyarwady Basin is in the order of 7 – 22% of current recharge, ranging from minimal use in the upper catchment, to as much as 33% in the Lower Ayeyarwady.

Table 4.3.4-a - Comparison of total abs. and recharge

	Recharge (Mm^3)	Total abs. low (Mm^3)	Total abs. low (% of R)*	Total abs. high (Mm^3)	Total abs. high (% of R)*
Upper Ayeyarwady	1,160	15	1%	27	2%
Upper Chindwin	3,720	26	1%	70	2%
Western Hills	560	22	4%	71	13%
Lower Chindwin	2,070	307	15%	321	16%
Middle Ayeyarwady	5,180	84	2%	235	5%
Shan Plateau	*Not determined*	154	*Not determined*	124	*Not determined*
Mu	3,030	110	4%	671	22%
Lower Ayeyarwady	5,750	653	11%	1,894	33%
Delta	6,090	518	8%	715	12%
TOTAL/AVERAGE	**27,560**	**1,890**	**Avg. ~7%**	**4,128**	**Avg. ~15%**

**Abstraction as percentage of estimated recharge*

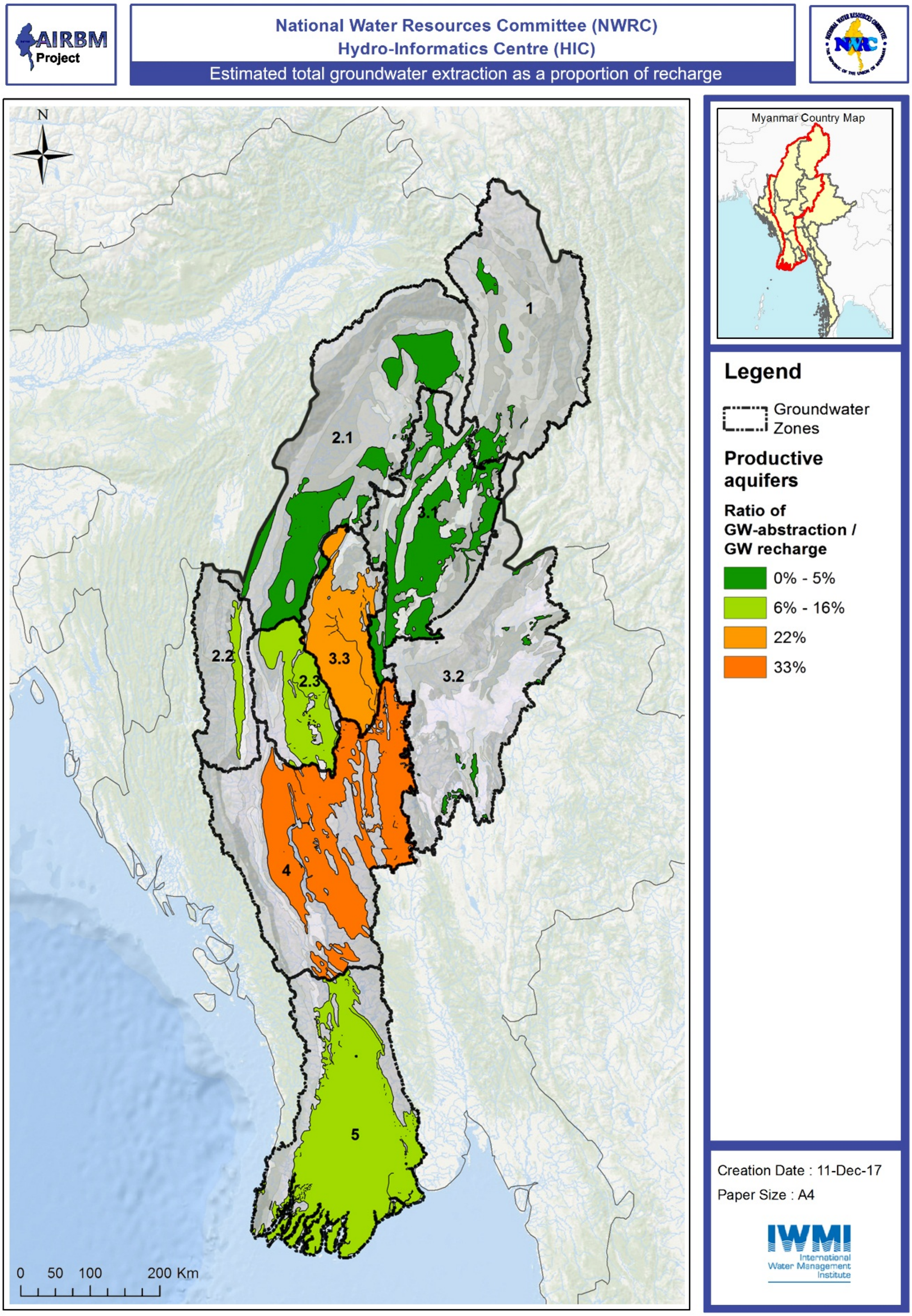


Figure 4.3.4-a – Estimated total groundwater extraction as a proportion of recharge

4.4 Ecosystems Support Functions of Groundwater

4.4.1 Background and importance

Shallow groundwater and surface water are dynamically interconnected by recharge and discharge processes. Where groundwater tables meet the surface, groundwater can play an important role in aquatic ecosystems, providing a proportion of water to support springs, marshes, and streams. The relative contribution of groundwater and surface water may vary seasonally. In a monsoonal climate such as in the Ayeyarwady Basin, baseflow in rivers during the dry season may be substantially groundwater-derived. Conversely, wetlands and streams may act as recharge zones to replenish shallow groundwater.

In the Ayeyarwady Basin, groundwater-surface water interactions (GWSWI) and groundwater dependent ecosystems occur in four main contexts:

- Contribution of groundwater to baseflow in rivers and streams, including chaungs, intermittent streams common in the Dry Zone;
- Springs;
- Wetlands, including groundwater-fed marshes and lakes; and
- Riverine wetlands.

In the Ayeyarwady Basin, groundwater flow is usually towards rivers and streams, which constitute major discharge zones, particularly in areas where groundwater flow is structurally constricted, such as the 22° N and 20° N uplift zones. At Magway, groundwater contributes approximately 50,000 Mm^3 to flow of the mainstream Ayeyarwady between December and May, representing 20% of total dry season flow. Drury (2017) reports large groundwater-derived dry season flows in chaungs with no dry season surface flow contribution, for example, at Yenangyaung (360 ML day^{-1}, excluding through flow in the underlying sand aquifer) and Yin Chuang (1700 ML day^{-1}). Larger chaungs are used for seasonal irrigation, accessing water from shallow dug-wells (Figure 4.4.1-a). As flow is sub-surface for most of the year, chaungs do not host high biodiversity.

Figure 4.4.1-a – Irrigation from shallow groundwater in chaung in the Dry Zone *(Photo: IWMI)*

Groundwater-fed springs occur in limestone/karst terrains on the Shan Plateau (for example, around Bawsaing), in volcanic aquifers, and along regional faults (Mahlaing, Sagaging, and Shinmataung Fault zones). High-yielding springs, used for village supply occur in volcanic aquifers around Mount Popa at Kyaukpadaung. Limestone springs in the Shan Plateau form small permanent ponds and lakes, and are often used for village water supply. Hot, saline springs are found along the Sagaing Fault around Halin and in the Wundwin/Yamethin area. Springs occur associated with artesian zones, for example, at Yinmabin, and in the colluvial deposits along the edge of the Shan Plateau and Western Hills.

WWF (2004) has mapped wetlands globally and delineates five main wetland types in the Ayeyarwady Basin:

- Coastal mangroves and mudflats in the Ayeyarwady Delta. These are highly productive systems with important biodiversity, under severe pressure from clearing and conversion to agricultural land (Web et al., 2005). No information is available on the extent to which these systems rely on groundwater, but it is possible that groundwater plays some role in sustaining mangroves during the dry season.
- Freshwater marshes in the Ayeyarwady Delta (beyond the saline zone); and along the river in the Middle Ayeyarwady in southern Kachin and northern Sagaing.
- Freshwater lakes and related wetlands. These vary in size from Indawgyi, Myanmar's largest natural lake (over 20 km in length), to myriad small lakes and wetlands of a few hectares, along the the Ayeyarwady and its tributaries. The lakes are flooded during the rainy season, and wetlands form as the river subsides, often sustained by groundwater discharge during the dry season. Lakes are important areas for fisheries and as breeding sites for water birds.
- River channels and associated wetlands. The network of rivers and adjacent wetlands are very important for habitat for freshwater fish, water supply, and transport. Riverine wetlands occur mainly in the floodplain zones where the gradient of the river is low, and include freshwater swamp forests in the delta and in the flooplains of the Chindwin. These ecosystems are important for a number of globally threatened species, notably for large water birds.
- Intermittent wetlands in the Dry Zone. These include riverine wetlands and chaungs, intermittently flooded forest (*indaing*-dipterocarp) at Chattin Wildlife Reserve in the upper Mu Valley, and spring-fed marshes such as those found at Yinmabin.

The degree to which specific wetlands rely on groundwater is not known, but many of the wetlands identified by WWF are linked to the river systems, and groundwater is known to play an important role in baseflow in the dry season.

4.4.2 Indicators and data availability

Given the complexity of the interactions and the data scarcity on groundwater resources, there is no direct indicator of the status of the GW-ecosystem support function. Instead, indirect proxies have been used.

In January 2012, the World Conservation Society (WCS) and more than 80 of Myanmar environment experts and stakeholders identified Key Biodiversity Areas that are of high conservation concern (WCS, 2012). Of the 135 identified KBAs, 72 are located within the Ayeyarwady Basin, with 43 defined as terrestrial KBA and 29 as Freshwater KBA. (Figure 4.4.3-a)

Each KBA has been evaluated regarding its degree of reliance (low, average, or high) to groundwater for ecosystems support. This reliance was estimated based on the following:

- When information is available, the nature of the KBA (Wetland, River, Forest, etc.).
- When information is not available, KBAs location have been analysed in GIS (ArcGIS and Google Earth 3D) to assess the geomorphologic features, topography, LULC, and geology.

Some of the key features used for the assessment assumed the following:

- Wetlands are usually closely linked to groundwater.
- Mountain and hill ecosystems are less reliant on groundwater aside from springs systems.
- Small rivers and associated plains are more reliant on groundwater than large rivers draining larger watersheds (e.g., Ayeyarwady).

Details for each GWZ are given in Section 3 above. This ranking is based on preliminary desktop analysis and should be used with caution. Pending further research on the issue, it gives an initial indicator of the importance of groundwater for ecosystem support in each GWZ.

4.4.3 Status and Trends

Table 4.4.3–a presents the number and area of KBAs in each GWZ, their conservation priority as determined by WCS, and our assessment of the overall degree of reliance on groundwater. Figure 4.4.3-a shows KBAs in each GWZ by degree of dependence on groundwater.

The Upper Chindwin, Middle Ayeyarwady, and the Delta GWZs represent the most important areas in terms of groundwater-ecosystems support function as they host KBAs which are both highly reliant on groundwater and are considered of high priority[25] for conservation. The Lower Ayeyarwady GWZ hosts 20 KBAs, and half of them have high or average groundwater reliance level, but are sometimes of small size. There are 8 KBAs in the upper Ayeyarwady, covering an area of almost 11,000 km², which are located in steep mountainous terrain mostly constituted of hard rock, and are considered to have low reliance to groundwater.

Table 4.4.3-a – Number of KBAs in each GWZ, and proportions in terms reliance and priority for conservation

GWZ	Area of KBAs km²	Number of KBAs	High priority for conservation and high GW reliance	High GW-reliance	Moderate GW-reliance	Low GW-reliance
1 Upper Ayeyarwady	7,081	8	0	0	2	6
2.1 Upper Chindwin	23	10	2	2	3	5
2.2 Western Hills	-	1	0	0	0	1
2.3 Lower Chindwin	-	2	0	0	1	1
3.1 Middle Ayeyarwady	1,074	13	2	2	8	3
3.2 Shan Plateau	596	4	0	1	0	3
3.3 Mu Shwebo	456	2	0	2	0	0
4 Lower Ayeyarwady	38	20	0	1	10	9
5 Delta	1,674	12	3	5	2	5

The conservation values of wetlands have not been fully recognized in land use planning in Myanmar, and a large percentage of wetlands and mangroves in the Ayeyarwady Basin have been lost or degraded, through clearing, drainage, and conversion to farming land.[25] This is particularly true in the delta, where the area of mangrove forest has declined from more than 2600 km² in 1978 to less than 1000 km² in 2011 (Web et al., 2014). A wetland policy is currently being drafted under the auspices of the MONRE (N. Davidson, pers. com.). The draft policy confirms the importance of groundwater for wetland ecosystems.

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[25] https://www.slideshare.net/khinayehan/wetland-conservation-in-myanmar

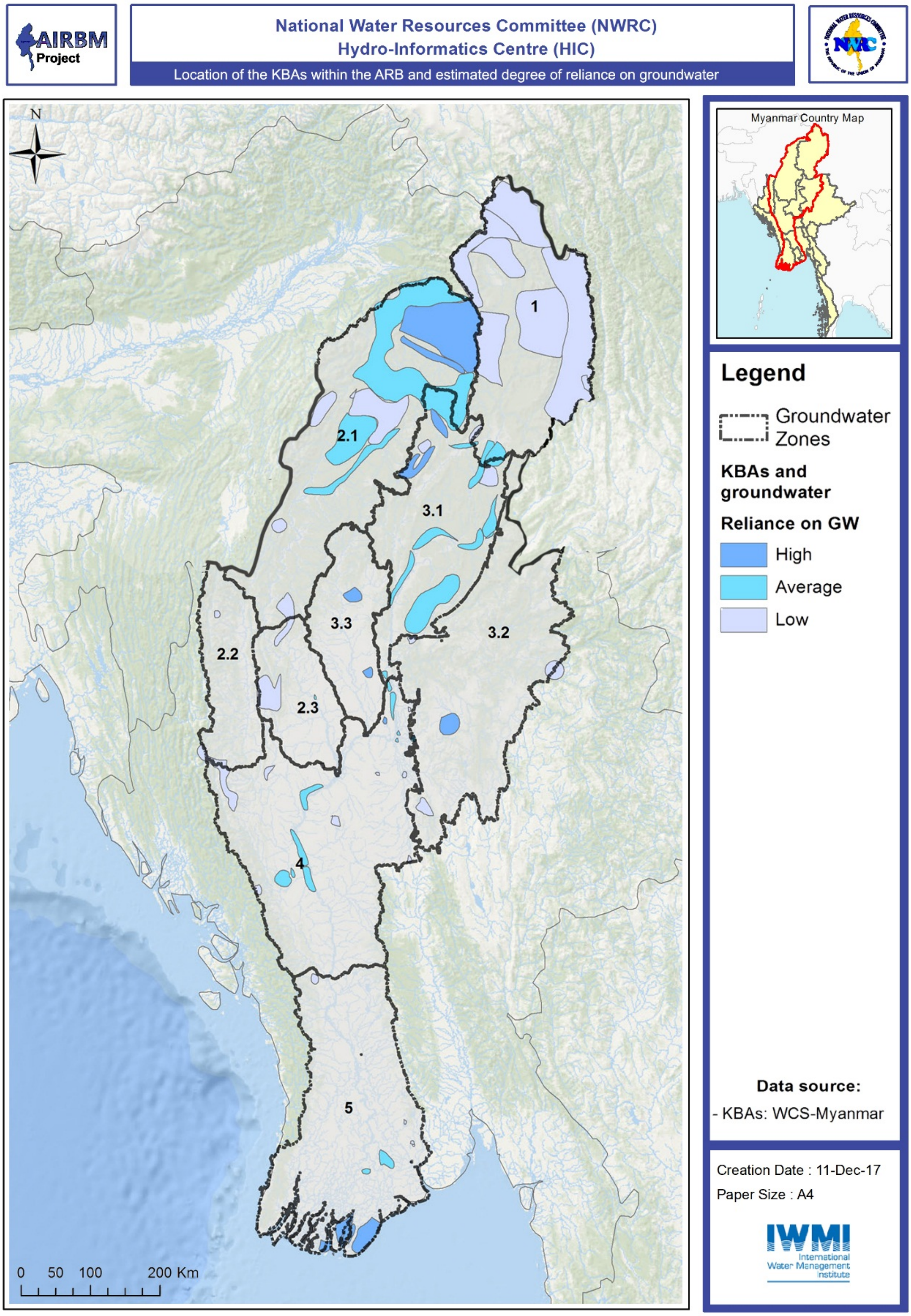


Figure 4.4.3-a – Location of the KBAs within the Ayeyarwady Basin, and estimated degree of reliance on groundwater

4.5 Indicators Synthesis Map

1 Upper Ayeyarwady GWZ

- Alluvial aquifers provide important domestic supplies and small-scale cash crop irrigation opportunities
- Locally, potential pollution of shallow aquifers from unregulated artisanal mining, unsafe sanitation around towns and agricultural inputs

2.1 Upper Chindwin GWZ

- Large recharge to alluvial aquifers, which provide important domestic supplies, small-scale cash crop irrigation opportunities, and high priority KBAs
- Potential pollution of shallow aquifers from unregulated artisanal mining and unsafe sanitation around towns.

.2.2 Western Hills GWZ

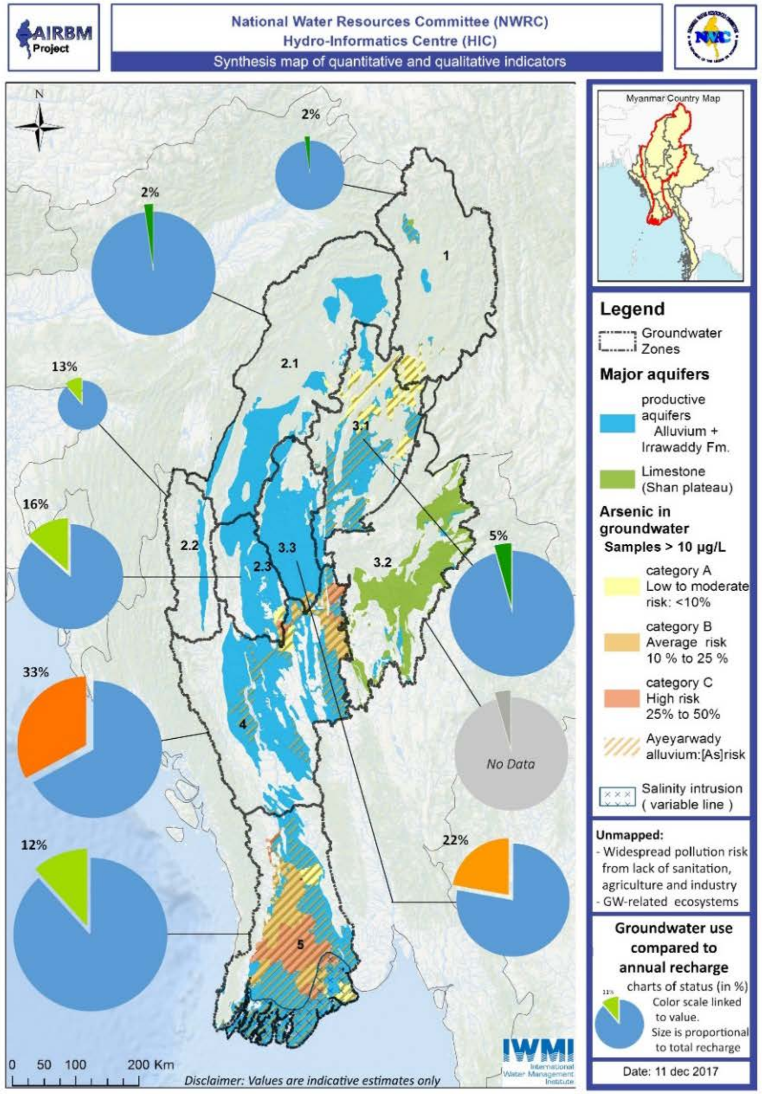
- Productive aquifers in the colluvial fans abutting the Chin Hills, extensively used for town and domestic supply as well as irrigation.
- Artesian zones north and south of Kalay
- Difficulties with drilling in colluvial aquifers due to boulders at depth.
- Decline in groundwater pressure in artesian zones due to failure to cap flowing tubewells – requires improved management.

2.3 Lower Chindwin GWZ

- Large percentage of the Alluvium and/or Irrawaddy Formation is a potential source of high-yield and low-salinity groundwater for irrigation purposes
- Pale Sub-Basin is fully developed, with a small net annual loss that could potentially be corrected by improved management (capping of flowing tubewells)
- High dependence for drinking and domestic supplies
- Artesian irrigation systems at 99 Ponds Groundwater Irrigation Project (GIP) and Monywa GIP.

5 Ayeyarwady Delta GWZ

- A very large resource of high-yielding, low-salinity groundwater could be available in the Irrawaddy Formation underlying the Delta at depth
- There is scope for much greater use of groundwater
- Salinity intrusion generally affects groundwater quality in shallow aquifers in the southern Delta and is variable seasonally and from year to year.
- Arsenic contamination occurs in shallow tubewells and testing of all new wells is essential
- Poor sanitation leads to widespread risk of faecal contamination, particularly in the 0–10 m range
- Recharge dynamics in the Delta are poorly understood – important clay deposits probably constraint the recharge from rainfall and Ayeyarwady river. The renewable resource is expected to be much more limited than the storage volume.



3.1 Mid Ayeyarwady GWZ

- Important alluvial deposits, 50 m deep and actively recharged
- Groundwater is used for domestic and small-scale irrigation
- Groundwater inputs to Indawgyi Lake and riverine wetlands
- Potential for mercury pollution from current and past alluvial gold mining operations.

3.2 Shan Plateau GWZ

- Deep tubewells drilled in limestone can provide all-year safe water supplies for communities
- Annual recharge rates of the Plateau Limestone are expected to be high – total storage is unknown, but possibly high
- Springs constitute an important part of the water supply in the plateau
- Alluvial aquifers are limited in extent but support domestic supply and in some cases small-scale irrigation using water-saving technologies
- Limestones are highly variable aquifers, sensitive to pollution, and both expensive and technically demanding to drill
- Pollution risk from unregulated use of agrichemicals.

3.3 Mu GWZ

- Ayadaw and Shwebo Artesian Zones
- High dependence on groundwater for domestic supply
- High potential for groundwater irrigation development in Alluvium and/or Irrawaddy Formation
- Current use is around 22 % of estimated recharge
- Hot saline springs at Halin
- Recharge from Thapanzeik Dam and from irrigation areas below Thapanzeik
- Potential for salinisation and agrichemical pollution of shallow groundwater underlying irrigation areas.

4 Lower Ayeyarwady GWZ

- Very large reserves of low-salinity groundwater are available along the Ayeyarwady corridor
- Water balance indicates that expansion of groundwater use appears is viable, especially close to the Ayeyarwady River. Current use at 33% of annual recharge.
- Groundwater discharge represents a significant part of Ayeyarwady River dry season baseflow
- Importance of groundwater for village and urban supplies
- Small artesian systems in the Piedmont fringe of the Shan Plateau require careful management
- High concentrations of arsenic in the aquifers of the Alluvium along the Ayeyarwady River and lower Samon Chaung, and in some shallow tubewells.

Figure 4.4.3-a – Synthesis map of quantitative and qualitative indicators

4.6 Groundwater Management and Institutions

There is no groundwater legislation or regulation specifically directed to monitoring and management of the groundwater resource. Multiple government agencies are involved in water development and management, but there is no single authority responsible for groundwater management. A list of institutions and legislation relevant to groundwater management is given in Annex 3.

Key agencies include the following:

- The Groundwater Division of IWUMD, which is responsible for provision of irrigation water to farmland and groundwater exploration.
- The DRD, which is responsible for domestic water supply and sanitation in rural areas.
- Various agencies that are responsible for urban domestic water supply, including the Ministry of Public Works, the Department of Human Settlement and Housing Development, and City and Township Development Committees.

Township authorities and General Administration Department have responsibility for infrastructure (including water supply) at the village level. Within villages, tubewells are mostly privately owned and operated, although some NGOs and development projects have installed community wells (both tubewells and dugwells).

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 (National Water Resources Committee [NWRC], 2014). 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.

Establishing a coherent groundwater monitoring and management system, tailored to the needs and issues in different contexts, is an urgent priority for Myanmar as set out in the National Water Policy (NWRC, 2014).

Different management approaches are required to safeguard supply (e.g., protecting recharge areas, preventing pollution, and capping artesian systems) and to control demand (limiting extraction). A key starting point for groundwater use and management is defining the size of the usable groundwater resource by its volume, storage, and sustainable extraction rate. This provides the basis for setting limits on extraction, which differ signficantly between different aquifers and geological contexts.

With regards to groundwater quality, a distinction must be drawn between naturally occurring groundwater contaminants (such as arsenic and fluoride) and anthropogenic pollution. Man-made pollution from industry, sewage, and agriculture can be managed and mitigated; that is, it is possible (and desirable) to remove or reduce the source of pollution. With naturally occurring contaminants, this is not possible, and users can only be protected by identifying contaminated sources and either restricting access, or treating the water before use.

Action is needed in three key areas:

1. Setting, monitoring, managing, and enforcing sustainable limits to groundwater extraction for each aquifer/region.
2. Setting, monitoring, managing, and enforcing national groundwater quality standards to ensure that water is fit for purpose.
3. Establishing a comprehensive groundwater database repository and a regional groundwater monitoring system as the basis for ongoing management and regulation.

Lack of groundwater legislation and regulation is a major hurdle. Although it is identified as a priority in the National Water Policy, establishing a suitable institutional and legislative base for groundwater management will take both time and political will.

5 CONCLUSIONS

This report summarizes the current understanding of the significance and role of groundwater in the Ayeyarwady Basin, and presents some quantitative and semi-quantitative indicators to describe the status and dynamics of the resource.

First, a caveat. The description of groundwater systems in the Dry Zone is based on a large body of data and experience of local and international hydrogeologists, and is presented with high confidence. Outside of the Dry Zone, data are scarce, and confidence is correspondingly lower. Because measurements of groundwater flow and levels are available only in limited areas, quantification of the resource at basin scale rests on assumptions and represents order of magnitude estimates. While the overall patterns and relative size of different components are likely robust, it is critically important that all estimates and indicators be seen as first-pass approximations, and used with appropriate caution.

The study confirms the existence of a sizable renewable groundwater resource within the Ayeyarwady Basin, estimated at approximately 27 km^3 per year, based on recharge. This compares, for example, with storage in irrigation reservoirs in the Dry Zone of approximately 8 km^3. Almost half of that resource is available within the lower basin (Lower Ayeyarwady and delta).

Current extraction is of the order of 7 - 15% of the renewable resource, with largest use in the Dry Zone. This seems within the bounds of sustainable use, and suggests that there are opportunities to expand exploitation of groundwater. Detailed hydrogeological investigations in the Dry Zone have identified large areas with high-yield, low-salinity groundwaters suitable for irrigation use (shown in Figure 3.9.4-a). Identification of potential areas for expansion in the delta, Shan Plateau, and the upper reaches of the Ayeyarwady Basin require similarly detailed hydrogeological mapping. In planning and implementing expansion of groundwater use it is essential that issues of aquifer sustainability (declining water levels and water quality) are taken into account, as well as broader social, economic, and environmental concerns such as ownership, community expectations, impact on dry season surface water availability and environmental demands, and the needs of future generations.

Although estimates of agricultural use have high uncertainty, it seems that volumes of groundwater withdrawn for irrigation now approach or surpass volumes for domestic supply, particularly as our estimates for domestic supply (based on the aspirational allowance of 135 L per day in rural areas) probably overestimate domestic demand. This is an important shift, and brings new management challenges to safeguard domestic supplies.

Throughout the Ayeyarwady Basin, groundwater flow direction is predominantly towards rivers and streams. Groundwater discharge contributes significantly to dry season flows both in the intermittent chaungs of the Dry Zone, and the Ayeyarwady mainstream. We estimate that at Magway, groundwater contributes approximately 20% of dry season flows. The importance of these flows both for livelihoods and for ecosystems must be taken into consideration in future planning.

A significant component of current withdrawals within the Lower Ayeyarwady, Lower Chindwin, and Mu GWZs is from artesian wells, which are allowed to flow freely year-round. Productive use from these wells may be as low as 10% of the flow (based on the assumption that a pumped well operates approximately 6 hours per day for 100 to 120 days for seasonal irrigation). Falling water levels and loss of potentiometric pressure have been observed in several of these areas since exploitation of the artesian zones began in the 1980s. Substantial savings could be made through capping and appropriate management of wells in these zone.

Estimates of groundwater storage in the Ayeyarwady Basin indicate an enormous volume, of the order of 2,000 km^3. However, current annual recharge is less than 1.5% of the volume. Radio-carbon dating indicates that much of the groundwater at depth is thousands of years old, and evolving understanding of the flow dynamics of the system suggests that this resource has accumulated over a very long period and may represent a ‘fossil’ resource, with minimal current replenishment. In addition, much of this volume may not be technically or economically accessible. While the existence of such large storage can act as a buffer, planned exploitation should work within the limits of the renewable resource until resource dynamics are more fully understood.

Water quality constrains groundwater use over large areas of the Ayeyarwady Basin. High levels of arsenic are a risk in the recent (Holocene) Alluvial aquifers, though the problem seems limited to the sediments of the Ayeyarwady mainstream and does not affect the Chindwin and Mu systems. Salinity is mostly associated with aquifers of the marine Pegu Group sediments and with intrusion of seawater in the delta. Isolated occurrence of elevated fluoride, uranium, and metals are found in specific geological contexts, but data are very scarce and the extent of contamination is not known. In general, geogenic contaminants cannot be managed, and users can only be protected by identifying contaminated sources and either restricting access, or treating the water before use.

Anthropogenic pollution of shallow groundwater from industry, sewage, mining, and agriculture is an increasing risk, although little information is available on the actual extent and severity of contamination. In contrast to naturally occurring contaminants, man-made pollution can and should be managed and mitigated. Protection of shallow aquifers is an important priority, given the high dependence on groundwater for domestic supply.

The study has highlighted two critical gaps in management of groundwater in the Ayeyarwady Basin. The first is the paucity of basic data on groundwater status and use. These data are an essential prerequisite for sustainable management. There is no systematic documentation of wells or extractions, and measurements of water levels and water quality are sporadic. Key priorities are to establish:

- a network of monitoring stations at key locations to monitor groundwater levels;
- a system to register wells, as a first step to quantifying and monitoring withdrawals;
- mandatory testing of groundwater quality in new wells; and
- a comprehensive, centralised groundwater database repository.

These data would provide the basis for setting, monitoring, managing, and enforcing sustainable limits to groundwater extraction for each aquifer/region, and national groundwater quality standards to ensure that water is fit for purpose. Recommendations for monitoring and a terms of reference for a national monitoring system are presented in a separate report (Conceptual Design for Groundwater Monitoring in the Ayeyarwady Basin).

The second is the lack of any legislative or regulatory framework for groundwater management. Establishing a suitable institutional and legislative base for groundwater management is a priority in the National Water Policy but will require both political will and community commitment to formulate and implement.

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7 ANNEXES

Annex 1: People and Organizations Interviewed

Yangon Myanmar	U Myint Thein	Principal Consultant WG&GE	Meeting with early team members
	Robyn Johnston	Country Manager IWMI	
	Phay Ko U	Program Officer	
Yangon	Prof. Dr. Khin Ni Ni Thein	Director AIRBM	Meeting with Project Management Unit members and young research professionals
	Phyu Thin Zan Kyaw	Researcher Hydromatics Centre	
	Ye Thu Aung	Researcher Hydromatics Centre	
Nay Pyi Taw WRUD Workshop	U Kyaw Win	Hydrogeologist Director (retired)	Workshop at Groundwater Division, Irrigation and Water Utilization Management Department, Ministry of Agriculture, Livestock and Irrigation
	U Myint Thein	National Water Resources Council	
	U Tin Lwin	Hydrogeologist Deputy Director (R)	
	U Zaw Htay	Hydrogeologist Deputy Director (R)	
	U Saw Than Win	Deputy Director of Groundwater Department	
	U Maung Maung	Deputy Director	
	U Than Zaw	Assistant Director	
	Daw Yu Khin	Deputy Director	
	U Thay Lwin	Director	
	U Myint Zaw	Deputy Director General AMD	
	U Moe Oo	Director (Planning)	
	U Myint Aung	Deputy Director (R) AMD	
	U Soe Myint	Deputy Director (R) AMD	
	U Soe Maung	Deputy Director (R) AMD	
	U Hla Myint Maung	Director General (R) WRUD	
	Tay Zav Mon	Sub Assistant Engineer	
	Eu Kyaw Soe	Sub Assistant Engineer	
	Kyaw Kyaw Khaing	Sub Assistant Engineer	
	Han Zaw Thaung	Sub Assistant Engineer	
	U Kyaw Nyunt	Executive Engineer	
	U Thet Naing	Assistant Director	
	U Khin Maung Htae	Assistant Director	
	Aung Khaing Mo	Assistant Director	
	Ye Win Tun	Deputy Director	
	U Myo Zaw Lwin	Assistant Director	
	Thant Zaw	Senior Sub Assistant Engineer	
	Phome Kyaw Aung	Senior Sub Engineer	
	Myo Aung	Assistant Engineer	
	Swe Tun Myit	Senior Sub Assistant Engineer	

	Kaung Htel	Senior Sub Assistant Engineer	
Yangon	Khaing Sein	President Central Executive Committee	Myanmar Geosciences Society—requesting technical data
Yangon	Mga Winn	National GIS Specialist	Meeting with Project Management Unit personnel for Letter of Introduction and plan meetings
Yangon	Le Win Khine	National Water Resources Engineer	
Yangon	Dr Khin Maung Lwin	Water Steering Committee Member	Health Department (retired)
Yangon	Khin Latt	Senior Consultant	National Engineering and Planning Services
	Cho Cho	Managing Director	
Yangon	Bijay Karmachaya	Country Programme Manager	UNHABITAT
	Dr Oddy Angelo Barrios	Project Manager	
Yangon	U Soe Maung	Driller	Discussed groundwater in Yangon
Yangon	Dr Day Wa Aung	Professor and Head	Yangon University
Yangon	Roland Lee	Chartered Financial Advisor	Roland Lee Consultancy, KL, Malaysia
Yangon	Daw Aung Aung	Staff Officer	WRUD Chemist lab
	A Mon Tu Tu	SSAE	WRUD Chemist lab
	Zin Mar Tun	SSAE	WRUD Chemist lab
	Thein Than Htay	SSAE	WRUD Chemist lab
	Kyu Kyu Myint	SSAE	WRUD Chemist lab
	Ya Mon Myo	SAE	WRUD Chemist lab
	Moe Moe Htay	SAE	WRUD Chemist lab
Nay Pyi Taw Series of workshops	U Than Zaw	Assistant Director	WRUD
	Tin Maung Aye Htoo	Deputy Director General	Irrigation and WRUD
	U Thay Lwin	Director	WRUD
Visit Takton Groundwater Irrigation area			
Review of Groundwater Data			
Nay Pyi Taw to Mandalay	U Than Zaw	Assistant Director	
	U Thant Zin	Senior Sub Assistant Engineer	
	U Antt Kyaw Soe	Senior Sub Assistant Engineer	
Mandalay	U Win San	Regional Director (Mandalay Region)	WRUD meetings in Mandalay office. Kyaukse Irrigation Area and inspected private tubewell and drilling rig developing bore.
	U Maung Naing	District Manager (Kyaukse)	
	U Ye Wint Naing	Staff Officer (Groundwater)	
Mandalay	U Tun Win	Head of Department	Mandalay City Development Corporation - Water and Sanitation Department
	U Khin Maung Thin	Assistant Director	
	Soe Maung Hla	Assistant Engineer	
Mandalay	Min Min Zaw	Assistant Director Civil Engineering	WRUD
Mandalay	Prof. Dr Than Than Nu	Professor School of Geology	Mandalay University
	Dr Myo Thant	Associate Professor	
	Dr Ali Akabarkhan	Professor	
	Dr Tin Aung Myint	Lecturer	
	Dr Kyu Kyu Man	Lecturer	
Mandalay			Visit to Shwe Hlan Bo Irrigation Area

Mya Khauk Pagoda, Mandalay			
Shwe Magin Monastry, Mandalay			
Meiktila WRUD	U Myint Ayo	Assistant Director (Meiktila District)	WRDU Meiktila
Meiktila Irr. Area	U Zaw Htay	Assistant Director (R) Hydrogeologist	
Thazi TWS	U Win Hlaing	Chairman	Thazi Township Development Committee
Meiktila, Pyawbye, Yamethin, Byawbye Irrig. Area			
Thazi TWS (again)	U Aung Kyaw Hlaing	Executive Officer	Thazi Township Development Committee
	U Aye Thu	Assistant Engineer	
	U Khin Maung Chin	Sub Assistant Engineer	
Magway	U Tin Lin	Hydrogeologist (R)	WRUD Magwe, Minbu
	U Saw Lwin	Regional Director	
Taungdwingyi Area	U Kyaw Zay Latt	Assistant Engineer	Taungdwingyi Township Development Committee
	Daw She Swe Win	Staff Officer	
	U Tin Hla	Chairman	
	U San Thein	Member	
Magway	U Sein Than Ngwe	Executive Engineer	Magway Township Development Committee
Yenangyaung	U Tun Ko Ko	Assistant Engineer	Yenangyaung Township Development Committtee
	U Ye Myint Tun	Sub Assistant Engineer	
Kyaukpadaung	U San Win Aung	Oil Merchant, Former Kyaukpadaung Township Development Committee	
Naung U	U Win Khaing	District Office Director	WRUD
Naung U	U Soe Naing	Deputy Director, Chief Hydrogeologist	DRD
Myingyan	U Aung Khaing Min	Myingyan District Director	WRUD
	U Tin Ohn	Hydrogeologist	WRUD
Myingyan	U Win Shwe	Village Leader	Tha Phay Thar
Myingyan	U Saw Than	Assistant Engineer)	Siek Nyen Pump Irrigation Project
	U Zin Wai Myint	SSAE	
	U Ye Win Aung	SAE	
Pakokku	U Myint Oo	Executive Engineer (Civil)	Pakokku WRUD
	U Aung Myint	Hydrogeologist (R)	
Pakokku	Dr Khin Maung Thant	Chairman	Pakokku Township Development Committee
	U Aung Min Khaing	Secretary	
	U Tun Tun Naing	Executive Engineer	
	U Sein Min	Member	
	U Aung Myint	Member	
	Daw Htike Htike Tun	Member	
Myaing	U Han Myint	Executive Officer	Myaing Township Development Committee
	U Aung San Oo	Assistant Engineer	
Yinmabin	U Tin Win (1)	Assistant Director (R) Moywa Division	WRUD Yinmabin, Monywa
	U Tin Win (2)	Assistant Director (R)	
	U Maung Maung Thein	Assistant Director, Yinmabin District	

	U Ngwe	Assistant Director (R)	
	U Myo Naing Go	Assistant Director, Yinmabin	
	U Win Ko Ko Tan	Staff Officer Salingyi Region	
Monywa	Dr Zaw Myint Ni	Professor of Geology Department	Monywa University
	Dr Teza Kyaw	Lecturer	
Monywa	U Than Tint	Sub Assistant Engineer	Monywa Township Development Committee
Awadaw	U Soe Naing	Staff Officer (Civil)	Ayadaw-2 Pump Irrigation Project
Shwebo	U Myint Win	Chairman	Shwebo Township Development Committee
	U Zaw Lwin	Member	
	U Phone Zaw Aung	Executive Engineer	
Mandalay	U Tin Win	Head of Department	Mandalay City Development Committee Water and Sanitation Department Pick up data from previous visit
	U Khin Maung Thin	Assistant Director	
	Soe Maung Hla	Assistant Engineer	
Mandalay	Prof. Dr Than Than Nu	Professor School of Geology	Mandalay University Pick up data from previous visit
	Dr Myo Thant	Associate Professor	
Nay Phy Taw			Weekend
Nay Pyi Taw	U Thay Lwin	Director	Obtaining missing data from WRUD
	U Than Zaw	Deputy Director	
Yangon	Khin Maung Yi	National Sanitary Consultant	World Health Organisation
Yangon	Kyaw Shwe	Advisor	Save the Children
Yangon	Theingi Soe	WASH Specialist	Water Sanitation and Hygiene, UNICEF
	Bishnu Pokhrel	Water, Sanitation and Hygiene Sp.	UNICEF
Yangon	Myo Thein	Deputy Chief Engineer	Yangon City Development Committee
	El Khaing Mon	Assistant Engineer	

Annex 2: Institutions and Legislation Relevant to Groundwater Management in Myanmar

INSTITUTIONS

Agencies	Ministry	Functions
Irrigation and Water Utilization Management Department	Agriculture, Livestock and Irrigation	Irrigation water to farmland and groundwater exploration
Rural Development		Domestic and rural water supply and sanitation
Myanmar Fishery Enterprise		Fishery works
Directorate of Water Resources & 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	Reforestation and conservation of forest
Public Works	Construction	Domestic and industrial water supply and sanitation
Human Settlement and Housing Development		Domestic water supply
Health	Health and Sport	Environmental health, water quality assessment, and control
Central Health Education Bureau		Social 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
UN Agencies, NGOs and Private Entrepreneurs	Independent Local and International donors	Domestic water supply, navigation, and fisheries

LEGISLATION

Specialist Area	Name of Legislations	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

Specialist Area	Name of Legislations	Year
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 & 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

Annex 3: Conceptual Design for Groundwater Monitoring in the Ayeyarwady Basin

CONTENTS

7.1.1 Background

The Ayeyarwady Integrated River Basin Management project aims to contribute to the development of integrated river basin management of the Ayeyarwady Basin. One important component of the Ayeyarwady Integrated River Basin Management project is the development of monitoring and information systems to support basin planning and management.

As part of the baseline assessment of groundwater resources in the Ayeyarwady Basin for the State of the Basin Assessment, the International Water Management Institute was charged with recommending a conceptual design for groundwater monitoring in the Ayeyarwady Basin. The aim is to identify major gaps for information and data to support groundwater management and to develop an initial design for a multi-year groundwater monitoring program to address those gaps.

The purpose of groundwater monitoring is to support sustainable groundwater development and use:

- monitoring groundwater quantity, to manage withdrawals to prevent over-extraction and draw-down or loss of pressure of groundwater resources, so as to protect productive use and groundwater dependent ecosystems; and
- monitoring groundwater quality, to ensure that groundwater is safe and fit for purpose, and remains so over time.

Monitoring is most beneficial if the results are useful, and used, in management and planning. Data collection and data use must be linked to and supported by relevant laws and regulations. The institutional component of a monitoring program is as important as the technical component. It is critical to identify an institutional home for monitoring, and clear chains of responsibility for delivery and use of the information collected. Allocating these roles is the responsibility of the National Water Resources Committee (NWRC).

7.1.1.1 Monitoring Groundwater Quantity

There are two complementary parts to monitoring groundwater quantity.

- **Groundwater levels** in wells are measured as a direct indicator of the status of groundwater stored in aquifers (decreasing, increasing etc.) and response to pumping and climatic patterns. The temporal frequency and spatial density of measurements depends on the hydrogeological structure and dynamics of the groundwater system. Continuous to daily measurements are used to capture variation with pumping and weather conditions; monthly to seasonal measurements will capture longer-term impacts of extraction and seasonal variability. An Ayeyarwady Basin map is available in Figure 3.1 for reference.

- **Volume of groundwater extracted** is monitored as a direct indicator of use. For individual wells, this is measured as rate and duration of pumping or flow. An estimate of extraction can be made based on the number of wells and average flow rates from a particular aquifer.

For management purposes, it is important to collect data on both, to understand the relationship between extraction and availability, which can differ very substantially in different aquifers.

7.1.1.2 Monitoring Groundwater Quality

For groundwater quality, different approaches are needed for naturally occurring (geogenic) and anthropogenic contaminants. Geogenic contaminants such as arsenic, salinity,[26] fluorine, iron, manganese, and other trace metals generally do not change significantly over time and it is not usually possible to reduce the source of pollution. Users can only be protected by identifying contaminated sources and either restricting access, or treating the water before use. The key information need is identification of potential problems by comparing the status of water quality relative to water quality standards. These data should be collected at the time of establishing the well.

Man-made pollution of shallow groundwater from industry, sewage, mining, and agriculture includes contaminants such as microbial pathogens (E. coli and others), pesticides, nitrates, pesticides, metals, hydrocarbons, and other trace organic compounds. Pollution can come from point sources (such as factories or mines) or non-point (diffuse) sources; each have different monitoring approaches and challenges. Anthropogenic contamination can be identified and potentially managed; in this case, monitoring is aimed at both warning of a potential problem, and tracking the effectiveness of mitigation efforts over time.

7.1.2 Current Status and Gaps

Availability of data relating to groundwater is reviewed in detail in the atttached report (Viossanges et al., 2017). In summary:

- Maps of groundwater resources are available for the Dry Zone (Drury, 2017) but are otherwise lacking for other parts of the Ayeyarwady Basin.
- Some measurements of groundwater levels and flow rates are available for:
    - Artesian groundwater irrigation projects managed by the Irrigation Water Utilization Management Department (IWUMD)
    - City water supply bores managed by Yangon and Mandalay City Development Committees. Mandalay is particularly well documented
    - Sporadic measurements from township bores
    - Individual NGOs involved in rural water supply may keep some records
- Data on groundwater quality:
    - A major database of approximately 250,000 wells tested for arsenic in a joint project by the Myanmar Government and UNICEF/WHO. The databased is held by IWUMD.
    - Measurements for more than 15,500 samples from different areas across the country, tested for standard water quality parameters by IWUMD laboratory (Aung, 2016).
    - Sporadic measurements for other contaminants such as fluorine and trace metals from specific areas (for example, reported in Drury, 2017).
    - The Department of Rural Development (DRD) is likely to hold data on groundwater quality as part of water supply development programmes.

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[26] Salinity is often, but not exclusively geogenic.

Most data are held in hard copy formats and are not easily accessible. Thus even though a considerable amount of data is available, it is extremely difficult to use the data to examine spatial or temporal trends.

7.1.3 Components of the Proposed Monitoring Program

Design of any monitoring program is contingent on the resources available. In the absence of information on the available budget and staffing, we have proposed a conceptual design for a monitoring program with separate components, each addressing specific issues. Each component can be implemented at a range of levels, depending on resources available, and/or can be staged over time, with implementation at pilot scale initially.

We propose a monitoring system with the following components.

In the short term (1 - 2 years):

- a centralized groundwater **database** (including data standards and formats);
- a network of **monitoring stations at key locations,** primarily to monitor groundwater levels coupled with salinity monitoring where necessary;
- a pilot program of groundwater quality measurements at designated hotspots, linked with surface water monitoring; and
- a pilot demonstration of community monitoring at selected locations.

In the longer term (3 - 5 years):

- a **system to register wells**, as a first step to quantifying and monitoring groundwater withdrawals;
- mandatory **testing of groundwater quality in new wells** (particulalry arsenic and salinity);
- expansion of community monitoring to all major groundwater use areas; and
- expansion of joint surface and groundwater monitoring of water quality.

2.

7.1.4 Groundwater Database

A centralized groundwater database compiling available groundwater information is an important precursor to basin-scale or national monitoring. Such a database could be established using a similar approach to the Water Information System for Data Management database compiled for the State of the Basin Assessment, with capacity to upload and share data online, moderated through a central organization (in the case of Water Information System for Data Management, the Hydroinformatic Center in the Ministry of Transport) which provides data management and quality control. The system should include:

- a relational database capable of storing, analyzing, and displaying spatial and time-series data
    - point data — well location and characteristics, including time-series of water level and water quality, lithology logs, bore construction logs, hydrostratigraphy logs
    - spatial data (2D and 3D) — maps of geology, stratigraphy, aquifer location and extent, flow patterns, and aquifer management areas
    - linked to climate and surface water databases
- data standards for format, content, and metadata (based on ISO standards) and agreed data exchange formats
- tools for analysis and display, including 3D GIS capacity (both ArcGIS and QGIS include 3D visualisation tools)

An example of such a database is the Australian National Groundwater Information System (www.bom.gov.au/water/groundwater/ngis) which links to open source visualisation tools in the Australian Groundwater Explorer (www.bom.gov.au/water/groundwater/explorer/index.shtml).

An appropriate agency to compile and manage a groundwater database should be identified by NWRC. IWUMD currently holds the arsenic database (with over 200,000 well locations), and the Groundwater Division of IWUMD has begun compilation of a database of well logs and is progressively digitising and uploading historical records held by the Ministry of Agriculture, Irrigation and Livestock.

7.1.5 National Network of Monitoring Wells

A network of wells instrumented to automatically monitor groundwater level and basic chemical parameters (temperature, pH, and EC) is proposed. The main purpose of this network is to monitor groundwater levels to warn of potential overuse, and to assist in understanding recharge dynamics and setting realistic limits for abstraction in each area.

We recommend that at least 10 wells should be installed in each of the 9 GWZs across the Ayeyarwady Basin (refer to Viossanges et al., 2017 for their location), with 20 to 30 wells in each of the Lower Ayeyarwady and Delta zones (reflecting higher groundwater use).

Location of the wells should be chosen to sample major aquifers in each of the GWZs described in the attached report. In most GWZs, a multiple layer aquifer system is present with upper Alluvium underlain by older Irrawaddy Fm. In this case monitoring wells for each aquifer are recommended.

The monitoring strategy will depend on local conditions, and should be designed in collaboration with local hydrogeologists in each state or region. Priority should be given to (cf. Figure 3):

- groundwater irrigation projects (GIP), particularly in artesian zones (starting with 99 Ponds and Monywa GIPs)
- aquifer zones supplying urban and township water supplies
    - Mandalay CDC already monitors groundwater levels across the urban area; these data should be included in the national database as mentioned above
    - Locations around Yangon should be chosen in consultation with Yangon CDC
- major surface water irrigation schemes (e.g., Shwebo) to monitor rising groundwater tables and salinisation
- strategically chosen wells within the Ayeyarwady floodplain in the Lower Ayeyarwady and Delta GWZs, to monitor connectivity between the river and alluvial aquifer
- a network of wells across the delta to monitor influence of seawater intrusion on groundwater
- wells within close proximity to key groundwater dependent ecosystems (e.g., Indawgyi Lake).

Minimum data collection should include water level, temperature, barometric pressure, and conductivity. Data sampling should be at a minimum once a month (for manual data collection). If budget allows, some wells should be instrumented to allow collection of more regular measurements and more parameters. Data telemetric data loggers are available, which can collect these data at pre-defined intervals and transmit them using GSM to a central data repository (see www.solinst.com or www.vanessen.com; other brands are also available).

Ideally, at least two wells in each GWZ (five in the Delta and Lower Ayeyarwady) should be equipped with automatic monitoring, sampling at hourly intervals for at least one year, to establish relationships between climate and seasonal conditions. Sampling design can then be improved for each location and aquifer, reflecting local conditions.

IWUMD installed 9 groundwater monitoring stations nationally in 2016, and are currently (from 2017 to 2018) installing a further 16 wells. Solinst Levelloggers (www.solinst.com) have been installed, which collect data on water level, temperature and conductivity. Measurements are currently made manually every 10 days. These stations could form the nucleus for an expanded basinwide or national network.

Measurements in the network of dedicated monitoring tubewells could be supplemented through regular manual measurements in existing tubewells installed by IWUMD for village or irrigation use. Liaising with local villagers 24 hours prior to visits, it could be ensured that pumps are swtiched off at least 12 hours before the field visit and manual measurement. This method is field intensive, but would provide the wide spatial coverage, which is a key point when creating goundwater level maps and understanding flow direction.

7.1.6 *Water Quality Monitoring*

Monitoring water quality is both more difficult and more expensive than monitoring water level, and a strategic approach is needed to make the most of scarce resources.

Geo-genic (natural) contaminants

The most common geo-genic contaminants (arsenic, salinity, and iron) do not generally change much over time, and can be adequately identified in one-off analysis at the time of well construction (see below). In the longer term, it would be wise to resample a random selection of wells for arsenic, particularly in areas where arsenic is common, to test this assumption. We suggest a rolling program of testing 100 wells per year in high-arsenic areas. An alternative approach is to measure arsenic levels in biological samples of hair and nails, in areas where arsenic occurs, to monitor overall exposure of local populations (Clarkson et al., 1988).

The less common geo-genic contaminants (such as fluorine, uranium, heavy metals, and hydrocarbons) mostly require expensive laboratory analysis, and routine analysis is not economically feasible. At this stage, we suggest that analysis for other geo-genic contaminants only be undertaken if the geological context indicates that problems are likely (for example, along fault zones, in volcanically active areas or petroleum provinces).

Anthropogenic contaminants

There is increasing concern in Myanmar regarding pollution of both surface and groundwater by agricultural chemicals, untreated sewage, and effluents from industry and mining. In general, the risk factors for surface and groundwater are similar, but surface waters are more susceptible to contamination and more easily flushed if the source of pollution is mitigated. We thus recommend that monitoring of groundwater quality should be included as part of a national water quality program, rather than a stand-alone program. Prioritization of sampling of groundwater analysis should be informed by occurrence of surface water quality problems, and targeted to the same areas. A possible exception to this rule may be in mining areas, where contamination of groundwater could occur independently of surface water processes. Monitoring of groundwater quality should be included as part of environmental monitoring around all major mining activities, including oil extraction.

Open defecation and disposal of untreated sewage can result in localized contamination of shallow aquifers with impacts on human health. Routine seasonal monitoring of village wells for faecal coliforms should be undertaken by village or township authorities. Simple methods for identifying the presence or absence of coliforms have been developed (for example, the H_2S method; see Sobsey and Pfaender, 2002). Although these methods are not entirely reliable, they are suitable for identifying areas of potential problems requiring follow-up analysis.

7.1.7 *Registration of Wells*

At present there is very little information available on groundwater withdrawals, and estimates are based mainly on assumptions about volumes required for various uses (see attached report). A first step towards monitoring actual use is knowing the location and purpose of wells.

In 1941, Underground Water Rules were introduced, which mandated that all tubewells sunk in Myanmar should be licenced, with submission of tubewell completion data, a lithological log, chemical and bacteriological water analyses, water level, groundwater yield, and pumping test results (Drury, 2017). These regulations have since been abandoned, and there is currently no requirement to register or license wells. Reintroduction of these regulations may be a worthwhile goal in the longer term, but would require legislation and is probably not realistic in the short term.

We suggest that a voluntary program of well registration be implemented in the short term. As a starting point, all government agencies drilling wells should register wells drilled in their programs with the central groundwater database mentioned above. At the same time, HIC (or the agency hosting the groundwater database) could work with NGOs, drilling companies, and industries or mines using large volumes of groundwater to encourage reporting of new wells. This could be implemented through:

- a simple mobile phone app to register wells (including potential payment of a small fee for each well registered);
- training programs in well location for NGOs and drilling companies working in the Dry Zone (drawing on information from Drury, 2017), and including training in reporting of wells; and
- provision of free or subsidized well testing kits, subject to the return of data to the database. Simple field kits are available to test common contaminants including arsenic, salinity, iron, and dissolved oxygen.

Minimum data for registration of wells should include:

- location with XY coordinates;
- purpose (domestic supply, irrigation, and multiple uses, etc.);
- size of tubewell;
- depth of tubewell, screening depth and water level with date;
- arsenic; and
- salinity.

Additional fields could be included to incorporate flow rate, chemical and bacteriological water analyses, tubewell completion data, lithological log, water level, groundwater yield, and pumping test results.

Analysis of new wells for arsenic and salinity should be compulsory for all wells to ensure that the water is safe for human and other uses. Most NGOs and some private drillers already routinely carry out these analyses. Compilation of the data into a central database would help to improve understanding of the distribution and occurrence of these contaminants. Since geo-genic contaminants tend not to change much over time, one-off analysis at the time of well construction is generally sufficient.

7.1.8 Community Monitoring of Water Level in Wells

The international trend towards 'citizen science' is particularly applicable in groundwater management. Groundwater pumping by individual farmers or villages is increasingly common, and is difficult to regulate due to the large numbers of people and wells involved. Educating farmers about the links between pumping and groundwater depletion is an important part of promoting sustainable use. Programs in India have successfully involved rural communities in monitoring groundwater levels to help them understand groundwater dynamics and improve local management practices. The approach can be as simple as individual farmers recording daily or weekly water level in their well for their own information, or a coordinated crowd-sourcing approach, reporting data to a central database. For example, the Monitoring Aquifer Recharge through Village Level Intervention project has developed MyWell, a simple app for mobile phones which can be used to collect and analyze data information on well water level, rainfall, and water quality parameters. MyWell displays the current groundwater level in each well, compared with historical and village level data (www.marvi.org/mywell-app). The data is used to support local management, as well as feed into state and regional level datasets.

We recommend implementing a pilot of community monitoring at one or more of the GIPs (for example, 99 Ponds or Monywa). This approach could be particularly useful in the artesian zones where drawdown is already apparent and affecting farmers' access to water. Community based monitoring could be used to raise awareness of the links between uncapped wells and loss of pressure, and to track recovery if a well-capping program is implemented.

7.1.9 Institutional Responsibility for Groundwater Monitoring

There are currently no existing laws or regulations specifically directed to the monitoring and management of the groundwater resource, although previous laws from 1930 and 1941 mandated collection of information to manage underground water supplies and prevent aquifer contamination. Existing laws give proprietary rights to groundwater through the land owner, and there is no obligation to maintain records of wells or to monitor groundwater abstraction. The National Water Policy (NWRC, 2014) recognises that establishing a coherent groundwater monitoring and management system is an urgent priority for Myanmar.

Multiple government agencies are involved in water development and management, but there is no single authority responsible for groundwater. Key agencies include:

- the Groundwater Division of IWUMD, responsible for provision of irrigation water to farmland and groundwater exploration;
- the DRD, responsible for domestic water supply and sanitation in rural areas;
- various agencies responsible for urban domestic water supply, including the Ministry of Public Works;
- the Department of Human Settlement and Housing Development; and
- City and Township Development Committees.

Only IWUMD has explicit responsibility for groundwater exploration; and as far as we know, only IWUMD maintains active datasets on groundwater occurrence, aquifer depths, and characteristics, etc. Data may also be available within the DRD. We know of no community, NGO, or private sector monitoring of groundwater in Myanmar, although both NGOs and private sector (e.g., KBZ) are actively involved in water supply programs involving groundwater.

It is the role of the NWRC to identify an appropriate agency to take responsibility for groundwater monitoring and for compilation and management of groundwater information. At this stage, IWUMD is the most obvious candidate; although, as suggested above, groundwater quality information should be managed as part of a national water quality initiative covering both surface and groundwater. An important role for NWRC will be to establish clear links between agencies with responsibility for groundwater, both for reporting of data to a central database, and for provision of information relevant to management.

National Water Resources Committee (NWRC)
Hydro-Informatics Centre (HIC)
Priority areas for groundwater monitoring

Priority areas for water level monitoring

- **Groundwater Irrigation Projects (GIPs)**
  - Thazi
  - Monywa
  - 99 ponds
  - Corridor between Sagaing and Myinmu
  - Corridor and tributary chaungs between Chauk and Magway

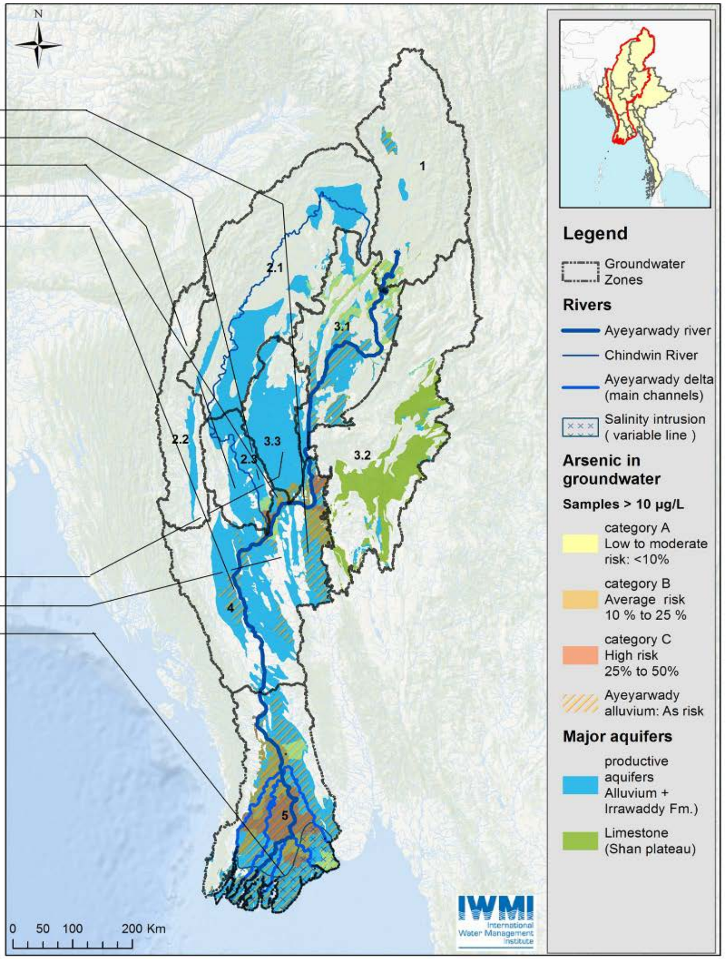
- **Large town water supply**
  - Mandalay
  - Yangon

- **GWSWi with Ayeyarwady river ssytem**
  - *locations to be defined.*

Priority areas for water level + salinity (EC)

- Shwebo surface irriagation scheme
- Areas adjacent to Pegu group in DZ
- South of Delta (important)

Ground Water Zones (GWZs):
1: Upper Ayeyarwady; 2.1: Upper Chindwin
2.2: Western Hills; 2.3: Lower Chindwin;
3.1: Mid-Ayeyarwady; 3.2 Shan Upland
3.3 Mu- Shwebo; 4: Lower Ayeyarwady; 5: Delta.
cf.: SOBA 2b Hydrogeology of ARB report for for detailed GWZs descriptions.



Disclaimer: Values are indicative estimates only. Source: *SOBA 2a report : Groundwater Resources of the Ayeyarwady River Basin*

Figure 7.1.9-a – Priority areas for monitoring of groundwater level and salinity