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IWMI Research Report

164

Integrated Assessment of Groundwater Use for Improving Livelihoods in the Dry Zone of Myanmar

Paul Pavelic, Sonali Senaratna Sellamuttu, Robyn Johnston, Matthew McCartney, Touleelor Sotoukee, Soumya Balasubramanya, Diana Suhardiman, Guillaume Lacombe, Somphasith Douangsavanh, Olivier Joffre, Khin Latt, Aung Kyaw Zan, Kyaw Thein, Aye Myint, Cho Cho and Ye Thaung Htut

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Front cover photograph shows groundwater irrigation at Tanpinkan village, Taungtha township, Myanmar (*photo*: Matthew McCartney, IWMI).

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Contents

Summary

Improved access to water is widely acknowledged as being vital for livelihood enhancement and the general well-being of around 10 million people in the Dry Zone (DZ) of central Myanmar; most of these people depend on agriculture for their livelihoods. Expanding the use of groundwater on a sustainable basis is, therefore, of great importance for socioeconomic development in DZ. Groundwater already serves a vital role in providing water for domestic use, livestock watering, irrigation and industrial purposes. In spite of this, very little is known and reported about the groundwater resource and the socioeconomic implications of its use in DZ. This study has attempted to address this gap through a literature review, data gathering and field research.

The study has revealed that groundwater is ubiquitous across DZ, particularly in the unconsolidated sedimentary aquifers that extend over much of this area. However, the magnitude of the replenishable resource is relatively modest (around 50 mm y^{-1} or less than 10% of rainfall), and its use is constrained by naturally elevated levels of salinity and arsenic in some places. Opportunities for accessing groundwater are generally good, and development of the resource has steadily increased over time across all water-use sectors. There still appears to be good prospects for expanding groundwater use for irrigation, with a view to increasing agricultural production by 110,000 to 330,000 hectares (ha) in almost all the districts of DZ.

Farmers use four main methods to access groundwater for irrigation, with the private investment in small pumps being the most widespread. Small-scale irrigation with groundwater involves an increasing number of farmers. This leads to improved food security and livelihoods for farmers, as well as providing flow-on effects for the landless farmers. However, when considering farmer-driven development at the local level, the pump installation costs, along with high operation and maintenance costs, are major impediments. A lack of information to support successful siting of wells, particularly where the hydrogeologic environment is complex, adds to the risk and cost involved. Provision of affordable mechanical technologies for drilling wells and support with credit facilities to purchase small-capacity motorized pumps for irrigation could improve food security and livelihoods in DZ, where there is potential to expand groundwater use.

Replenishable groundwater resources of DZ are likely to be less than previously thought and sustainable development requires proper management. More rigorous assessments are needed to develop databases and tools that can indicate where groundwater interventions are most appropriate. Draft hydrogeological maps are available, and these should be completed to inform future well siting and management. The challenge for sustainable groundwater management is to find the right balance between increasing development of the resource for enhanced irrigation, and also protecting its existing beneficial use for communities in DZ and the environment.

Integrated Assessment of Groundwater Use for Improving Livelihoods in the Dry Zone of Myanmar

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Introduction

The Dry Zone (DZ) of Myanmar extends over more than 75,000 km^2 of the central part of the country, covers 54 townships within three regions and has a total population of about 10.1 million people (Figure 1; http://www.themimu.info). Falling within a large rain shadow between the Shan Highland to the east and the western mountains to the west, DZ is the most water-stressed part of the country. The climate is semi-arid with mean annual rainfall ranging from around 500 to 1,000 mm per annum. DZ is highly food-insecure with approximately 43% of households living under conditions of poverty (JICA 2010; WFP 2011). The high mortality rate of children under 5 years old (38 per 1,000 live births) is attributed to waterborne diseases and malnutrition (JICA 2010).

The economy of DZ, and Myanmar as a whole, is largely agrarian-based with the agriculture sector being the most important for livelihood generation in the rural areas. Boosting livelihoods through the provision of improved water supplies and sanitation, along with farming strategies that enhance agricultural productivity and other rural livelihood practices (e.g., animal husbandry and fisheries), are major policy goals for the government (ADB 2012).

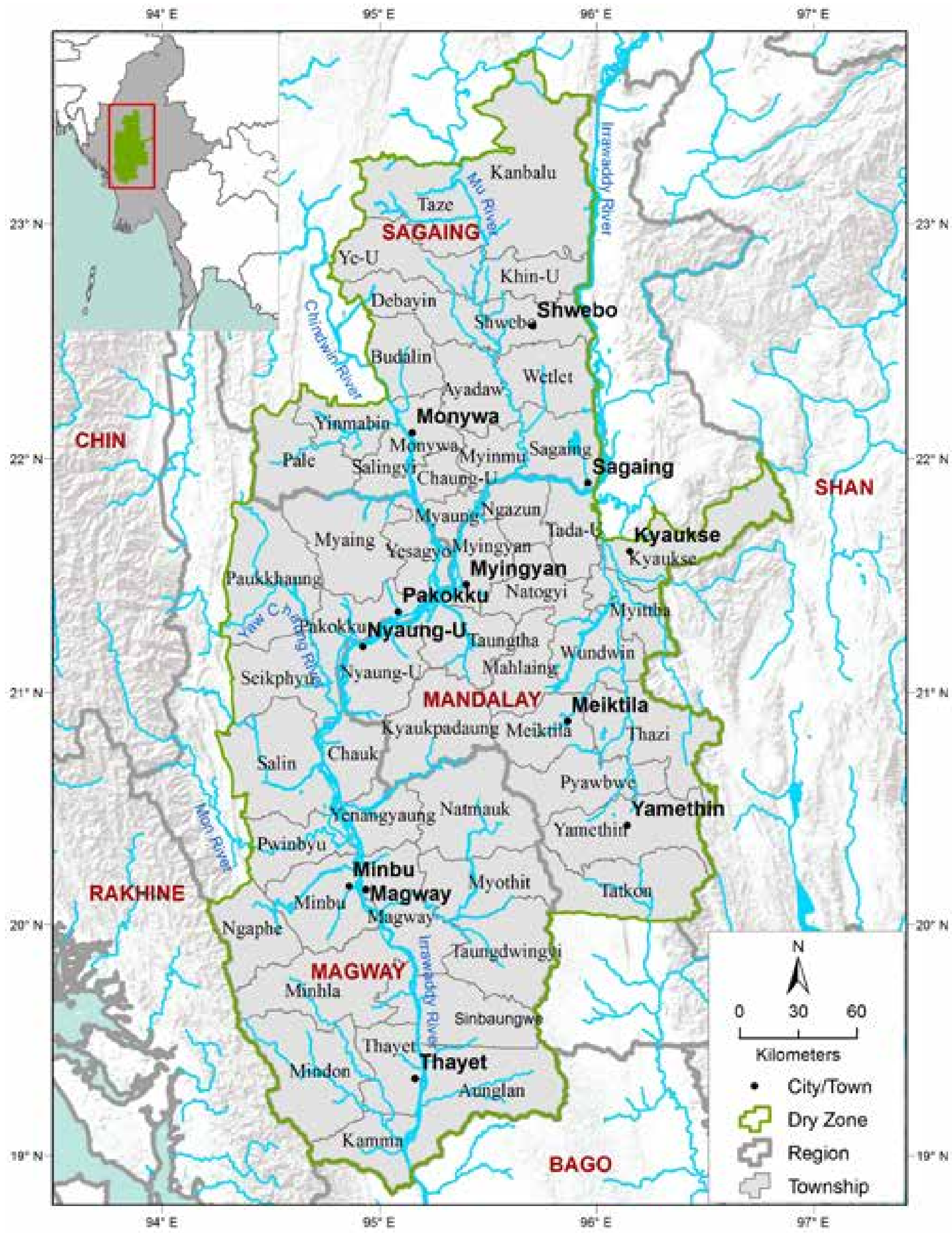
Relatively high levels of water scarcity and climate variability are major defining characteristics of DZ, which have a strong bearing on poverty, food insecurity and economic growth (ADB 2012; McCartney et al. 2013). At the same time, DZ is intersected by major rivers, such as the Irrawaddy, Chindwin and Mu, which create potential opportunities to establish large-scale formal irrigation systems nearby. In the vast tracts of land in between the river valleys, groundwater may be highly appealing for the provision of year-round water supplies across water-use sectors. The capacity of groundwater to mitigate some climate-related shocks and climate variability, often to a higher degree than surface water, could make it a particularly attractive water source. Despite its potential, there are few published accounts of the availability of groundwater resources and use or related management issues in DZ.

The specific objectives of this study are as follows:

- Characterize the physical availability of groundwater and identify barriers for its use.
- Define typologies for agricultural groundwater use and present a number of examples using case studies.
- Explain the economic costs and benefits, along with the opportunities and constraints, for smallholder farmers using groundwater for irrigation.
- Estimate the sustainable use of the groundwater resource.

This report is part of a broader study conducted by the International Water Management Institute (IWMI), in collaboration with the National Engineering and Planning Services (NEPS), and Myanmar Marketing Research and Development (MMRD) Research Services, under the '*Sustainable* *management of water to improve food security and livelihoods in the Dry Zone of Myanmar*' project (McCartney et al. 2013; Senaratna Sellamuttu et al. 2013; Johnston et al. 2013).

FIGURE 1. Regions and townships of the Dry Zone of Myanmar.



Methods of Analysis

Groundwater Resources Assessment

A groundwater resources assessment was carried out using information gathered from synthesis studies, government agencies, and a small number of hydrogeological investigations and case studies. The assessment draws heavily upon unpublished work by GDC (1984) and Drury (1986). Information on the utilization of groundwater relied largely on the *Agriculture sector review project* from December 2003 (MOAI 2003). Groundwater and related information was collected by members of the study team from government agencies in the Mandalay, Magway and Sagaing regions. Data was collected on borehole characteristics, water levels, water quality and groundwater pumping. However, the analyses were constrained by differences in the approach, amount and quality of data provided between regions and agencies. As a result, the depth of the analysis and information presented in this assessment is limited, particularly for the post-2003 period. However, it is probably the best available information to date.

A four-day study tour of DZ was conducted in the dry season over the period January 28-31, 2013. The tour was part of the water resources study reported by McCartney et al. (2013), and visits were made to a number of sites where groundwater irrigation is practiced (see Appendix A).

Consultation workshops were held in Yangon, Myanmar, at the inception and conclusion of the broader project, with about 40 participants representing key partners and stakeholders. Breakaway sessions dedicated to discussing groundwater issues with government officials, local and international nongovernmental organizations (NGOs), and other civil society groups provided useful information and guidance for this study.

The undeveloped potential for using groundwater for irrigation across DZ was derived from a groundwater balance-based methodology using data on recharge and use of the resource from secondary sources (Pavelic et al. 2013). Groundwater potential is based on recharge values on the supply side and sector-wise use on the demand side. Fifty-percent of groundwater recharge is allocated for ecosystem services to maintain environmental objectives and meet future growth in demand for the resource. This pragmatic approach is commensurate with the existing state of knowledge and development, and identifies the uncommitted, usable groundwater reserves.

Socioeconomic Assessment

A semi-structured questionnaire was developed to derive a better understanding of the nature of groundwater irrigation technologies, and the socioeconomic factors that affect household incomes and the food security status of smallholder farmers across DZ. The questionnaire was administered to a small, purposive sample of well owners (i.e., seven farmers from six villages), in parallel with the community-level survey conducted in a sample of 24 villages (as reported by Senaratna Sellamuttu et al. [2013]). The seven farmers interviewed were all males who considered themselves as the head of the household. The villages were distributed across the six townships (Nyaung-U, Kyaukpadaung, Minbu, Taungdwingyi, Sagaing and Taze) across the three regions (Mandalay, Sagaing and Magway). All the villages are situated in an alluvial geological setting, which is one of the most prospective environments for groundwater development (as indicated below).

In quantitative terms, the upfront investment required, and revenue earned for the crops produced and sold in the market were identified and disaggregated by season. The single-year production cycle covered the winter of 2011 through to the monsoon of 2012. Qualitative information was also sought to address other points of interest, such as the major constraints facing the farmers surveyed. Levels of self-consumption of produce by the farming households themselves were not directly examined, and thus the revenue is considered to represent potential upper limits rather than actual values. Also, the value of production from rainfed systems was not taken into account. The limited sample size, while too low to provide statistically defensible data, is considered as being sufficient to gain a basic understanding of the general opportunities and constraints associated with groundwater use in DZ. In addition to the questionnaire that was completed through the 72 focus group discussions conducted under the community-level survey, information was also collected on community perspectives on the availability, access and use of groundwater in the study area, as well as the constraints and opportunities they faced.

Groundwater Resources

Regional Geology and Hydrogeology

DZ is situated almost exclusively within the lowland region bounded by north-south-oriented faults along its boundaries, including the largest and most active Sagaing Fault (Stokes 1988; Pramumijoyo et al. 2010). DZ emerged as a result of the uplifting of the neighboring regions during the late Cretaceous and early Tertiary periods, with the central trough subsiding and progressively filled with sediments which may attain a thickness of 20 km or more (Thein 1973). The lowland portion of DZ is characterized by upper terrestrial deposits and marine deposits at depth. Tectonic activity in the late Tertiary period resulted in folding and thrusting, including the formation of the Pegu Yoma hills.

Nowadays, the lowland region may be considered as a large basin divided into two unequal halves; the larger Irrawaddy Valley and the smaller Sittang Valley, separated by the complex folded range of the Pegu Yoma which is structurally connected to a line of extinct volcanoes with small crater lakes and eroded cones, including the highest dormant volcano, Mount Popa (1,518 m).

The generalized geology that illustrates the distribution of the major aquifer groups in DZ is presented in Figure 2. In this area, the four major geological (and hydrogeological) units are the Eocene, Pegu, Irrawaddy and Alluvial groups (Chhibber 1934).

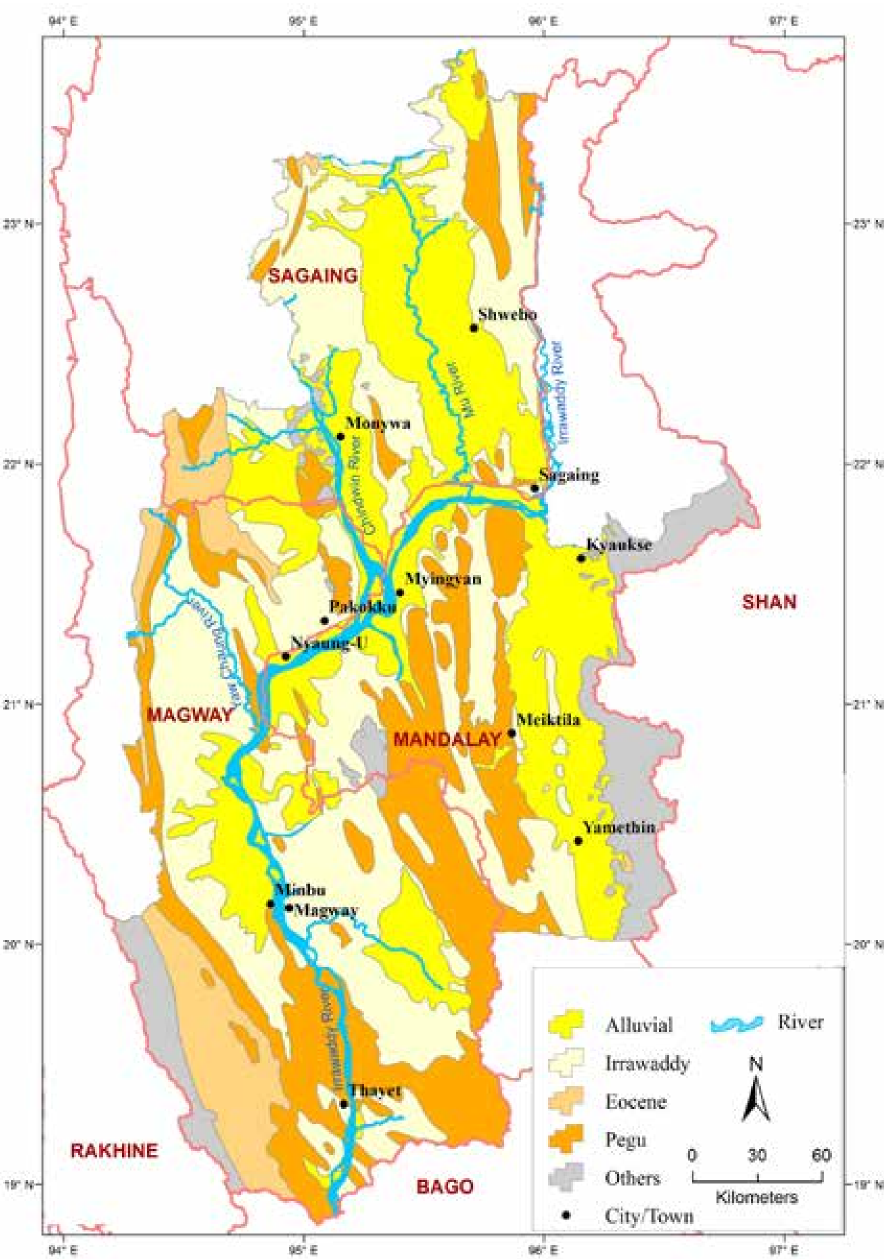
Across DZ, the Eocene sandstones, shales and clays outcrop mainly along the foothills of the western mountains (7% of DZ). Many of the sub-units of the Eocene are of low permeability or are aquicludes, but some sandstone and conglomerate units may have the potential for groundwater development and is yet to be explored.

Pegu strata outcrop over large parts of DZ (20%) and are characterized by their oil-bearing properties. The Pegu group consists of well-stratified sandstones and blue or grey clays/shales, of which the former is often calcareous and well cemented. Relatively little is currently known about the groundwater potential of the Pegu group, but it is thought to be low, except in highly folded and faulted areas where wells have provided low-level supplies in some areas. However, specific units, such as the Kyaukkok formation (amongst others), comprise massive, fine-grained sandstones and can be reasonable aquifers. In the Magway-Minbu area, Pegu group wells can attain depths of 165 m and yields of up to 540 m^3d^{-1} (Drury 1986).

The Irrawaddy group strata outcrop most extensively over DZ (38%). The unit is comprised of massive, loosely cemented sand and sandstone beds. Irrawaddy deposits, which are mainly clastically-derived and loosely cemented, contain many highly permeable zones. Irrawaddy group aquifers are usually comprised of poorly consolidated sand and gravel layers, and are semi-confined to confined in nature. The aquifer is observed at a depth of up to 350 m in the Magway region and is far shallower in the Sagaing region, where maximum depths are only 120 m. In the Magway-Minbu area, for example, depths of up to 144 m and well yields derived by 'airlift' range from 360 to 1,600 m^3 d^{-1} (Drury 1986).

Alluvial deposits overlie the Irrawaddy and Pegu outcrops, and extend across 29% of DZ. In some areas, these are alluvial plateau gravels which pass laterally into red earth beds (clayey sands) representing old laterite soils. These lateritic deposits are usually found at high elevations some distance from present river courses. The older alluvium occurs mainly in basins formed along old river courses, whereas

FIGURE 2. Geology of the Dry Zone.



Source: Adapted from the Food and Agriculture Organization of the United Nations (FAO) Digital Agricultural Atlas - Union of Myanmar (http://dwms.fao.org/atlases/myanmar/overview_en.htm).

the younger alluvium is found in significant amounts in the valleys of the main rivers, such as the Irrawaddy, Chindwin and Mu. The Alluvial deposits comprise gravels, sands, silts and clays. They generally make good aquifers, except where they are very fine-grained. The major distinguishing feature between the overlying Alluvial group and the Irrawaddy group is a distinctive change in color from yellowish brown downwards to bluish grey which is widespread in the sediments. Many shallow dug wells used for domestic supplies draw upon the alluvial aquifers. Shallow tube wells drilled in alluvial flats normally intersect unconsolidated to semi-confined sand and gravel aquifers up to 40 m deep in the alluvial areas in Magway District. The tube wells drilled along the river terraces and flats in Pakokku District can attain a maximum depth in excess of 52 m and over 70 m in Monywa District. In the Chindwin River Valley, the yields from Alluvial aquifer wells vary from 270 to 4,700 m^3 d^{-1} and depths can be up to 90 m (Drury 1986).

Springs feature across DZ, driven by structural controls, and may be large or small, hot or cold, and fresh or saline. For example, hot water springs are found at Kyaukpadaung and hot saline springs are found elsewhere, such as at the Mount Popa complex and Halin (Drury 1986). Depths of the static water level can vary from 300 m or more below the ground to levels at or above the ground surface (artesian). Areas such as Yinmabin, Ayadaw and Shwebo, amongst others, make productive use of artesian groundwater from the Irrawaddy and other aquifers.

Groundwater occurs throughout DZ. However, groundwater of a suitable quality and that which is accessible at a reasonable cost cannot be found everywhere, e.g., in areas underlain by aquifers of the Pegu group rocks (Table 1). The Irrawaddy and Alluvial groups are the most important aquifers due to their ability to provide good yields and water of a high quality. Figure 3 shows a hydrogeological cross-section from Monywa to Chaung-U townships to illustrate the alternating sequences of clays and sands/gravels associated with Alluvial and underlying Irrawaddy sediments.

Groundwater Availability

In general, groundwater availability may be considered to comprise two interconnected storage components: (i) the intrinsic part that represents the bulk, longer-term storage within the aquifer; and (ii) a more dynamic part that is derived from annual replenishment due to rainfall. While the replenishable component is usually much smaller than the intrinsic storage, it is also the part that is utilizable on a sustainable basis. The value of the intrinsic storage is that it provides buffering against supply deficits that are the result of high variability in annual recharge.

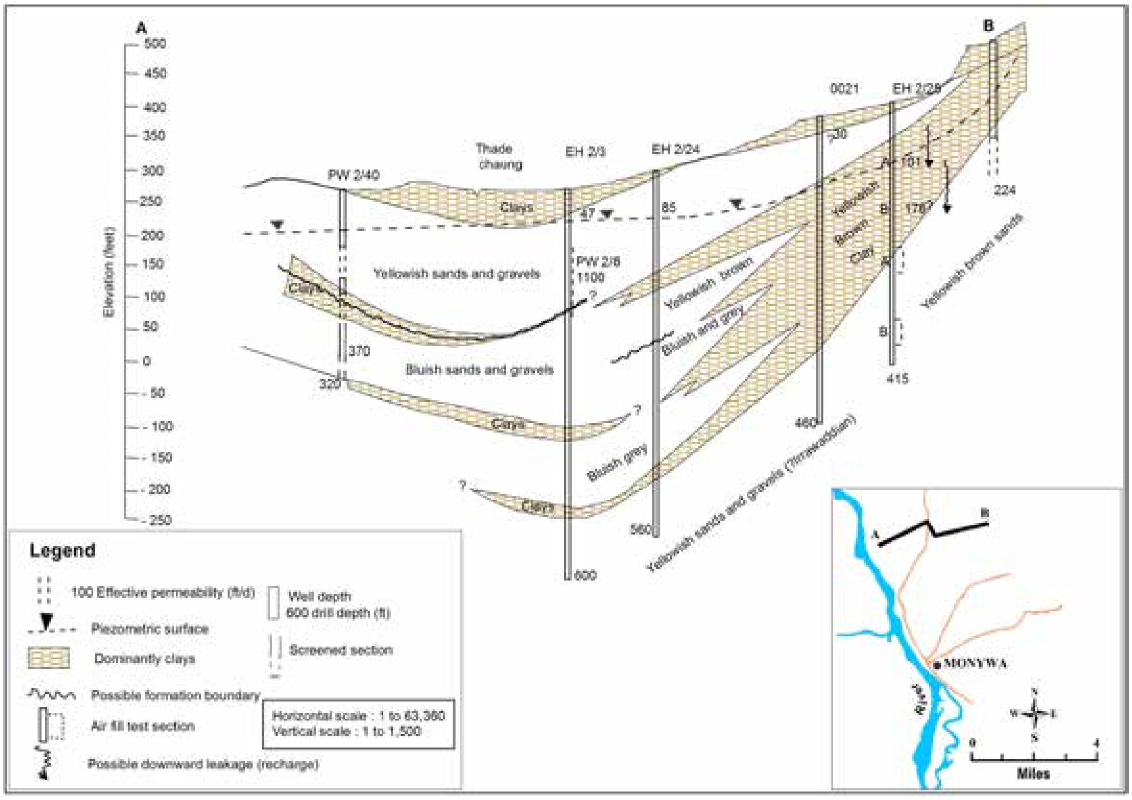
There is a widespread view that groundwater reserves of DZ are very large. For example, ESCAP (1995) estimated a groundwater potential of 150 km^3 y^{-1} for the Upper Irrawaddy and Chindwin river basins. However, district-level estimates of groundwater recharge (Table 2) suggest an annually replenishable amount of 4,777 Mm^3 y^{-1} (i.e., 4.8 km^3 y^{-1}) (MOAI 2003).

TABLE 1. Summary of the major aquifer units in the Dry Zone.

Aquifer units	Lithology	Occurrence	Quality
Alluvial	Sands, silts and gravels	Near major river courses and tributaries	Usually fresh
Irrawaddy	Mainly sands and sandstones, with gravels, grits and sandstones	Common throughout most of DZ	Usually fresh with high iron content
Pegu	Marine sandstones, shales and siltstones	Western and central parts of DZ	Mostly brackish or saline
Eocene	Sandstones, shales and clays	Mainly along the foothills of the western mountains	Unknown

Source: Adapted from MOAI 2003.

FIGURE 3. Hydrogeological cross-section illustrating the sequence of strata in the Monywa to Chaung-U area.



Source: Modified from GDC 1984.
Notes: 1 foot (ft) = 0.3048000 meters (m); 1 mile = 1.60934 kilometers; d = day.

TABLE 2. District-level groundwater recharge estimates (2000-2001).

Region	District	Area	Groundwater recharge	
		(km^2)	($Mm^3\ y^{-1}$)	($mm\ y^{-1}$)
Sagaing	Monywa	10,041	583.8	58.1
	Shwebo	14,877	1,090.3	73.3
	Sagaing	2,484	128.6	51.8
Magway	Magway	9,630	594.4	61.7
	Thayet	11,971	341.0	28.5
	Minbu	9,314	266.1	28.6
	Pakokku	8,327	771.3	92.6
Mandalay	Kyaukse	4,157	128.8	31.0
	Meiktila	5,789	187.8	32.4
	Yamethin	10,878	387.5	35.6
	Myingyan	6,415	245.1	38.2
	Nyaung-U	1,484	52.3	35.3
	District total	95,367	4,777.0	50.1

Source: Adapted from MOAI 2003.

In equivalent areal terms, this translates to a modest, but not unrealistic, average value of around 50 mm of groundwater recharge per year. This is less than 10% of the average rainfall across DZ. The range in the values shown across the districts is typical of the recharge fluxes found in countries such as China, Mongolia, Cyprus and Israel (Scanlon et al. 2006). Even under the most optimistic assumption that all this water may be available for consumptive uses (which neglects discharges to surface water in the dry season), these estimates do not support the view that there is a great abundance of groundwater. Rather, it suggests that it is a moderate resource which must be planned and developed carefully to ensure sustainable utilization over the long term. It should also be noted that the method used to determine these estimates is not clearly stated in MOAI (2003), and suggests that some degree of caution should be taken when considering these values.

Water Quality

Groundwater quality would appear to be fit for general purposes over large parts of DZ. Although data on water quality is limited, indirect evidence of groundwater use can be gauged by the extent of the resource used for domestic supplies and irrigation development (described later in this report). Groundwater in DZ is generally of low to moderate salinity (typically 1,000-2,000 μScm^{-1}), and mainly of a sodium bicarbonate type (ESCAP 1995).

While groundwater is available in varying quantities throughout DZ, spatial variations in water quality can seriously constrain utilization. In some areas, groundwater may be of brackish or saline quality due to natural processes. This may be due to either (i) evapotranspiration concentrating the salts naturally present in the water, or (ii) salts trapped within geological formations of marine origin (e.g., Eocene marine shales and sandstones). This is also apparent in areas that are underlain by aquifers from the Pegu group. Elevated salinity in such cases may constrain use across all sectors. In some deep oil exploration wells, salinity levels may exceed that of seawater (Drury 1986). Salinity may be induced by human activities such as large-scale irrigation developments that lead to enhanced seepage, which in turn leads to rising water tables that bring salts to the root zone or soil surface. Poor quality groundwater can directly reduce crop yields, and indirectly degrade the soil structure and impede infiltration.

The four major aquifer groups across DZ (Table 1) vary considerably in the quantity and quality of groundwater they provide, and depend on their depositional environments, lithology and mineralogy. The quality of groundwater from the Alluvial and Irrawaddy aquifers is more suitable for irrigation and domestic use. In some instances, groundwater from the Pegu and Eocene aquifers is suitable for general purposes.

Data presented by Drury (1986) reveals the variations in aquifer characteristics that occur with depth as well as the different hydrogeological formations. It is difficult to make generalizations about any particular formation or area because the mechanisms that control water quality are complex. The highly variable salinity of groundwater in the Monywa irrigation scheme (400 to 2,000 mg l^{-1} total dissolved solids [TDS]), which is drawn from the Alluvial and Irrawaddy aquifers, is in contrast to the more consistent quality of water in the 99 Ponds irrigation scheme (260 to 510 mg l^{-1} TDS), which is drawn from the Irrawaddy aquifers (Table 3). During the commissioning of the Monywa project, poor water quality rendered at least 8 new tube wells unusable, adding significantly to the setup cost (World Bank 1994). Salinity can be problematic for tube well development in parts of DZ (Adventist Development and Relief Agency [ADRA] pers. comm. February 4, 2013).

Trace minerals present in the host rock may also cause deterioration of water quality associated with iron, manganese and arsenic. Iron is widely present in most rocks and has been routinely picked up in groundwater at concentrations of up to 4 mg l^{-1} at Monywa and Yinmarbin (Table 3). High levels of iron create aesthetic concerns around the staining

TABLE 3. Results from the groundwater quality sampling at Monywa and 99 Ponds irrigation schemes.

	TDS (mgl^{-1})	EC (μScm^{-1})	pH	Na^+ (mgl^{-1})	K^+ (mgl^{-1})	Ca^{2+} (mgl^{-1})	Mg^{2+} (mgl^{-1})	Fe^{2+} (mgl^{-1})	Cl^- (mgl^{-1})	SO_4^{2-} (mgl^{-1})	HCO_3^- (mgl^{-1})
Monywa (N=126)											
Minimum	430	670	6.07	40	2.4	26.45	5.76	0.5	103	51.84	62
Maximum	2,000	3,150	8.45	1,580	25	177.8	64.92	4	516	295.8	284
Mean	938	1,452	7.55	146	7.1	68.1	23.8	1.6	226	158.5	122
99 Ponds (N=94)											
Minimum	260	400	6.37	19	1.5	19.23	9.6	0.5	33	28.8	40
Maximum	510	790	8.35	51	4.5	93.78	1,824	4	97	6,004	104
Mean	367	566	7.61	31	2.5	46	49.7	2	54	115	67

Source: Unpublished data from the Water Resources Utilization Department (WRUD).

Notes: EC - electrical conductivity; pH – acidity; Na^+ - sodium ion; K^+ - potassium ion; Ca^{2+} - calcium ion; Mg^{2+} - magnesium ion; Fe^{2+} - iron (II) ion; Cl^- - chloride ion; SO_4^{2-} - sulfate ion; HCO_3^- - bicarbonate ion.

of precipitates, but is not a major issue for human or animal health. Manganese is usually associated with iron and the impacts are similar to iron.

Point-scale or localized contamination of water from microbial pathogens is prevalent in the shallow aquifers, due to the pollution from contaminated surface water runoff, latrines, septic tanks and animal waste. Many of the shallow aquifers (< 10 m deep) produce water that is of a poor quality which is only used for washing, while the water from deeper tube wells (> 30 m) is generally more acceptable for drinking purposes. Industrial pollution from copper mining activities centered around the town of Monywa, which began in the early 1980s, has reportedly led to contamination of the soils and groundwater in the area around the mine.

Arsenic

Arsenic derived from contaminated groundwater presents a potentially major threat to public health, because it is highly toxic to humans (World Bank 2005; Rahman et al. 2009). Chronic arsenic poisoning (arsenicosis) results from the consumption of water with high levels of arsenic over extended periods of time. The health effects are dependent on the susceptibility, dose and period of exposure. Today, tens of millions of people, mainly in developing countries, are affected by levels of arsenic in drinking water that exceed the drinking water guideline value of 10 $\mu g\ l^{-1}$ (parts per billion) of the World Health Organization (WHO). In some developing countries, the earlier WHO guideline value of 50 $\mu g\ l^{-1}$ has been maintained and such water is still considered as being suitable for drinking purposes. Exposure pathways for arsenic through agricultural activities include rice grains and straw, as rice is typically grown under flooded conditions where inorganic forms of arsenic are released from iron oxides in the soil under oxygen-poor conditions and absorbed by rice roots along with plant nutrients. This is exacerbated, if arsenic-laden groundwater is used for irrigation (Zhu et al. 2008).

Elevated concentrations of arsenic were first revealed during national-scale surveys (which included DZ) conducted by WRUD and the Department of Development Affairs with support from some international NGOs. This sparked follow-up efforts to better understand the prevalence of arsenic and activities related to arsenic mitigation (Jakariya and Deeble 2008).

Given that arsenic is derived geogenically from the major alluvial and deltaic basins, and is most prevalent in aquifers composed of recent Holocene (Quaternary) sediments that are organic-rich, there is a need to ensure that levels are acceptably low within the alluvial aquifers in DZ. Data provided by WRUD covering the periods 1952-1990, 2005-2011 and 2012-2013 are presented in Table 4. The data suggest that approximately 80% of around 30,000 samples from Sagaing, Mandalay and Magway regions have arsenic concentrations less than the WHO drinking water guideline value of 10 µg l^{-1}, and only 1-2% of the samples exceed 50 µg l^{-1}. Table 5 shows a small degree of exceedance (< 5%) of the 50 µg l^{-1} threshold across the townships tested, but a much higher exceedance (5-40%) of the 10 µg l^{-1} level. From this data supported by population statistics, it is estimated that around 81,000 people in Mandalay and 28,000 in Sagaing are exposed to arsenic concentrations in excess of 10 µg l^{-1}. Model predictions by Winkel et al. (2008) suggest a generally low level of risk of arsenic exceeding a threshold of 10 µg l^{-1} in DZ. The findings by Winkel et al. (2008) appear to be supported by the observed data.

TABLE 4. Frequency of samples detected with three levels of arsenic in groundwater at the regional level.

Region	Total samples		Concentration < 10 µg l^{-1}		Concentration 10-50 µg l^{-1}		Concentration > 50 µg l^{-1}	
	N[1]	%	N[1]	%	N[1]	%	N[1]	%
Sagaing	8,807	100	6,992	79.4	1,619	18.4	196	2.2
Mandalay	21,560	100	17,430	80.8	3,827	17.8	303	1.4
Magway	529	100	426	80.5	96	18.1	7	1.3

Source: Unpublished data from WRUD.

Note: [1]N - number of samples tested.

TABLE 5. Frequency of samples detected with two levels of arsenic in groundwater at the township level.

Region	Township	Total samples tested	Concentration > 10 µg l^{-1}		Concentration > 50 µg l^{-1}	
			N	%	N	%
Sagaing	Chaung-U	500	34	6.8		
	Monywa	221				
	Shwebo	556	30	5.4	1	0.2
	Wetlet	563	91	16.2		
	Sagaing	1,809	264	14.6	9	0.5
	Myinmu	1,781	323	18.1	41	2.3
	Myaung	3,181	877	27.6	145	4.6
Mandalay	Kyaukse	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	40.0	20	4.0
	Leway	2,782	809	29.1	63	2.3
	Sintgaing	4,650	765	16.5	82	1.8
	Myittha	6,061	933	15.4	37	0.6
	Tada-U	2,824	452	16.0	12	0.4
Magway	Yesagyo	522	96	18.4	7	1.3

Source: Unpublished data from WRUD.

Groundwater Use

Groundwater has played an important role across all the districts of DZ for many years, by supplying water for domestic, agricultural and industrial uses (Table 6). The estimated total amount of groundwater withdrawn during the period 2000-2001 across the three study regions was 763 $Mm^3\ y^{-1}$. Estimates of sector-wise usage differ widely. District-wise data from MOAI (2003) (Table 6) reported that between 0 and 63% of total groundwater use is for agriculture. Corresponding figures for domestic and industrial use range from 35 to 100% and 0 to 18%, respectively (MOAI 2003). Naing (2005) reported that as much as 90% of the total groundwater pumped can be used for irrigation, but this is not apparent from the data of MOAI (2003) shown in Table 6.

Domestic Supplies

The natural filtering function of underground formations and protection from potentially contaminating activities (at or near the ground surface) mean that groundwater from deep tube wells, if properly located, designed and maintained, are free of waterborne pathogens and provide a relatively safe supply of water for domestic use from a public health perspective. This, combined with the relatively low cost of establishing tube wells, fitted with either hand or motorized pumps, has apparently led to high levels of groundwater use in DZ and, more broadly, across the country.

Household-level survey data from across DZ reveals that 26% of those sampled use water from an unprotected source, mainly open water ponds, streams or unprotected wells; 37% have access to a tube well with a pump; 32% use other protected sources such as protected wells; and 4% have access to piped water from surface water sources (WFP 2011). Communal ponds, dug wells and locally harvested rainwater are still relatively important sources of water within villages in DZ. Substantial gains have been made in the development of safe water supplies since the mid-1980s, when only around 20% of village domestic supplies in DZ were derived from tube wells (Drury 1986).

TABLE 6. Sector-wise groundwater utilization (2000-2001).

Region	District	Industry	Agriculture	Domestic	Total
		$Mm^3\ y^{-1}$			
Sagaing	Monywa	0.0	0.0	39.7	39.7
	Shwebo	0.3	33.1	61.0	94.4
	Sagaing	0.9	44.8	24.9	70.6
Magway	Magway	0.8	5.8	97.7	104.3
	Thayet	0.0	1.3	45.7	47.0
	Minbu	9.1	2.0	40.1	51.2
	Pakokku	0.5	7.0	68.4	75.9
Mandalay	Kyaukse	1.1	6.0	40.3	47.4
	Meiktila	0.5	2.0	55.2	57.7
	Yamethin	0.0	5.7	84.9	90.6
	Myingyan	0.6	5.2	63.8	69.6
	Nyaung-U	0.0	0.0	14.1	14.1
DZ Total		13.8	112.9	635.8	762.5

Source: Adapted from MOAI 2003.

As some villages do not have access to groundwater, ponds are used but they often dry out in the early stages of the dry season and villagers will revert to subsurface supplies that may be situated more remotely. Cases have been reported where family members in the village have to travel several kilometers to fetch water, which may also need to be purchased. In such circumstances, water collection can be a very time-consuming activity that limits women, in particular, from engaging in other livelihood activities.

Large efforts have gone into improving rural water supplies over several decades. Up to 1990, the rural water supply from 11,000 tube wells amounted to an estimated 530,000 m^3 d^{-1}, with a twofold increase in the production compared to the early 1960s (Myint 1991). By 2000, WRUD had installed over 13,000 tube wells for domestic use in the three study regions of DZ, which benefitted 6.4 million people (Table 7). The beneficiaries from other surface water supplies were only 0.3 million people, which highlights the importance of groundwater development for rural water supply programs.

It seems that thousands of wells have been drilled in the past which have become dysfunctional because access to materials and other resources were constrained, or planning, construction and maintenance were inadequate. Those projects did not include technology transfer and, most importantly, there was no training of local engineers to address these issues (JICA and DDA 2007).

Some positive signs have begun to emerge in recent years. A number of international NGOs and aid agencies, including Japan International Cooperation Agency (JICA), Bridge Asia Japan (BAJ), ADRA, Proximity, ActionAid and others, are operating throughout DZ. BAJ has been operating from Kyaukpadaung township since around 2006, and has drilled wells for rural water supplies covering 10 nearby townships at a rate of 10 wells per year and has also rehabilitated a larger number of wells. In and around these areas, well depths can be over 200 m and cost as much as USD 40,000 or more (JICA 2010). The high cost of wells in these townships can drive communities to seek alternative low-cost water supplies. For example, JICA (2010) cited Mingan village, where villagers opted for the construction of a primary school with a rooftop rainwater harvesting facility instead of a deep tube well. The NGO Proximity has developed cheap, plastic foot pumps (referred to as 'baby elephants') which, at USD 13, are a fraction of the price of conventional treadle pumps. It has sold thousands of these units, replacing more laborious manual methods of accessing groundwater. These pumps operate for water tables that are less than 8 m deep, but there are pressure pump models which can lift water from greater depths.

TABLE 7. Region-wise rural water supply facilities and beneficiaries.

	Number of wells			Total number of beneficiaries (millions)
	Sagaing	Magway	Mandalay	
Groundwater[1]	4,576	4,454	4,266	6.42
Other sources[2]	-	-	-	0.30

Source: Data from WRUD.

Notes:

[1] Deep tube wells and 'sludge' wells.

[2] Includes supplies from river pumping, withdrawals from dams and water from reticulation pipes.

Industrial Supplies

On a national level, the industrial sector utilizes about 0.3% of the total annual groundwater recharge rate and contributes to about 10% of the country's gross domestic product (GDP) (MOAI 2003). On average, groundwater supplies 22% of the total industrial water use in the country, which is similar to that within the DZ regions (Table 8). Large water-intensive industries, such as sugar mills, paper mills and cement factories, normally depend on surface water whereas smaller industries rely on groundwater.

Irrigation

Irrigation water drawn from aquifers is an obvious benefit for farmers in DZ who are located in remote areas away from major rivers and dams, mainly as adaptation strategies to climate variability and poor productivity under rainfed conditions. As such, access to irrigation has a vital role to play in reducing food insecurity and poverty (WFP 2011). Because of the difficulties associated with conventional irrigation from surface water (e.g., limited geographic coverage and extreme water level fluctuations creating problems with lifting water), groundwater reserves are increasingly being viewed as an important alternative. While surface water irrigation is expanding along the major rivers, villages located away from the river floodplains can only rely on smaller, more distributed sources of water such as deep or surficial groundwater and seasonal village ponds.

Country-level data reported from a global inventory of census statistics (Siebert et al. 2010) indicate the present extent of groundwater irrigation in Myanmar to be about 100,000 ha or equivalent to approximately 5% of the total irrigated area. This is second only to Thailand in terms of the countries in the Greater Mekong Subregion (GMS). Owing to the highly seasonal climate and the lack of availability of surface water sources, much of this development is thought to be in DZ, although groundwater irrigation is also practiced in the Bago, Yangon, Irrawaddy and Kachin regions (MOAI 2003).

In Myanmar, the mainstream use of groundwater for irrigation only started as recently as the 1980s, although small-scale operations are known to have been in place since the 1940s (ESCAP 1995). Prior to the 1980s, groundwater development was restricted to small farmers of limited areas with shallow water tables, which could be utilized either manually or with simple pump sets from dug wells or shallow tube wells. While there has been an increase in the numbers of shallow wells in recent decades, the development of deep tube wells (> 30 m deep) has also been necessary to fully exploit the potential of groundwater irrigation.

A strong tradition of irrigation using groundwater did not really exist until the World Bank conducted reconnaissance studies across

TABLE 8. Surface water and groundwater use by industries in the period 2000-2001.

Region	Groundwater	Surface water	Total
		$Mm^3\ y^{-1}$	
Sagaing	2.2	3.7	5.8
Magway	10.3	34.0	44.4
Mandalay	6.1	31.6	37.7
Others	29.5	104.0	133.5
Total	48.1	173.3	221.4

Source: Adapted from MOAI 2003.

DZ and implemented pilot trials at Monywa District, Sagaing region, in the late 1970s through to the early 1980s (see Appendix A). The success of this pilot project led to scaling up at the Monywa site and triggered groundwater development elsewhere (Niaz 1985). The pace of groundwater development has increased since the 1980s as a result of the government establishing large projects to support small-scale farmers along with smaller undertakings by individuals.

Typologies of Agricultural Use of Groundwater

Farmers across DZ access groundwater through a range of modalities. These modes can be characterized on the basis of many number of attributes that include the type of well, method used to lift the groundwater, scale of operation, depth of groundwater utilized, source of funds, types of institutions present and degree of operational risk (Villholth 2013). Our study tour of DZ in late February 2013 suggested four major typologies as presented in Table 9.

Type 1 represents the larger-scale 'formal' irrigation schemes that are implemented by WRUD, usually with funding or support from international donors. There are only a handful of known examples of such schemes in Myanmar, including the Monywa Groundwater Irrigation Project in Monywa District and the 99 Pond Yinmarbin Artesian Zone Project in Yinmarbin township. Type 1 projects typically draw water from deep tube wells, rely on a dedicated multi-phase power supply for large electric pumps (except where naturally 'free-flowing' artesian conditions prevail, such as for Yinmarbin), and support command areas fed by a lined and unlined distribution network of canals. Crops are generally grown year-round with paddy most common in the wet season and higher-value crops in the dry season.

Type 2 systems access groundwater from shallow dug wells or tube wells that are typically less than 30 m deep, and require much lower upfront and ongoing capital investments than type 1. Being mostly financed and managed by the farmers themselves at a household level, they are 'informal' in nature. Lifting is performed by small-scale motorized pumps (< 12 horsepower [hp]) that operate effectively when the water level in the well is less than about 6-8 m from the ground surface. Production systems do not differ substantially from those of the larger-scale systems and usually involves irrigation of small areas of high-value crops, such as vegetables, to support local markets or for export to regional markets, such as the neighboring states in China. Type 2 interventions are found in rainfed areas as well as within the tail end reaches of surface water irrigation command areas.

TABLE 9. Modes of groundwater development for irrigated agriculture in the Dry Zone.

Typology	TYPE 1 Deep tube wells[1]	TYPE 2 Shallow tube wells and dug wells - permanent	TYPE 3 Seasonal riverbeds	TYPE 4 Shallow infrastructure (reuse of seepage)
Characteristics	Formal irrigation	Informal	Informal	Informal
	Larger scale	Small-scale	Small-scale	Small-scale
	Donor or government funding	Private or NGO funding	Private funding	Private funding
	Large electric pumps[2]	Farmer-managed	Farmer-managed	Farmer-managed
	Collective-driven	Un-subsidized	Manual lifting	Seasonal
	Market-oriented	Low risk	Un-subsidized	Un-subsidized
	Highly subsidized		Opportunistic	Opportunistic
	Low risk		High risk	Moderate risk

Notes: [1] Somewhat arbitrarily, the deep wells are typically drilled wells greater than 30 m in depth.
[2] Except for artesian subsurface conditions.

Type 3 systems are established on alluvial riverbeds when water levels recede during the pre-monsoon season. Rudimentary wells or pits are constructed and extraction methods such as ropes and buckets, or human- or animal-operated mechanical pumps, or occasionally motorized pump sets are used. Most irrigators lack effective means of production as they generally do not possess treadle or motor pumps. Being seasonal in nature, these systems must be rebuilt annually and can be highly risky in a floodplain setting where heavy losses may be incurred due to storms or early breaks in the season. This typology is analogous to the irrigation systems in place in the Upper East Region of Ghana, where groundwater is accessed in inland low-lying areas, such as floodplains and valley bottoms, to grow vegetables (Namara et al. 2011).

Type 4 is an opportunistic form of groundwater use where, during the dry season, water is drawn from the open pools present in surface irrigation canals via small, motorized pumps. While these pools reflect the local groundwater table, the origins are largely infiltrated canal water and subsurface return flows from nearby fields. In the wet season, the same infrastructure is used to draw surface water from the canals; from the farmer's perspective, this form of water access can be regarded as being functionally equivalent to surface water use.

Small-scale irrigation by pumping from groundwater as is the case in types 2 to 4 does not require costly infrastructure, and gives farmers direct control over water access which may be lacking in centralized irrigation systems. Appendix A provides examples of the typologies, drawing mostly upon information provided by farmers and local officials in the field, supplemented by relevant literature where available. As yet, there are no figures on the irrigated land area or the number of farmers involved in the different types of irrigation.

Temporal Trends in Groundwater Use

The rate of change in the utilization of groundwater for irrigation over the 14-year period (1988-2002) shows that groundwater expansion exceeds other sources, increasing at an average rate of 2.9% per annum in irrigated areas compared with 1.2% for other alternative sources (Table 10). Available figures from 2001-2002 suggest that the number of tube wells used for irrigation was over 33,000 for the entire country, with 70% of those found in the three DZ regions (Sagaing, Magway and Mandalay) (Table 11). Corresponding groundwater utilization in those same regions was 231 Mm^3 y^{-1}.

Official statistics for the most recent decade are not available, but sustained increases in the number of wells for all purposes are known to have occurred on the basis of the results

TABLE 10. Country-level changes in irrigated area by source.

Source	Irrigated area (Mha)				Overall increase (%)
	1988-1989	1999-2000	2000-2001	2001-2002	
Well/borehole	0.066	0.081	0.089	0.093	41
Others[1]	1.625	1.76	1.821	1.903	17
Total	1.691	1.841	1.910	1.996	18

Source: MOAI 2003.

Notes: [1] Classes include dams/weirs, village ponds, rivers and others.

Mha – Million hectares.

TABLE 11. Regional-level groundwater abstraction for irrigation in 2000-2001.

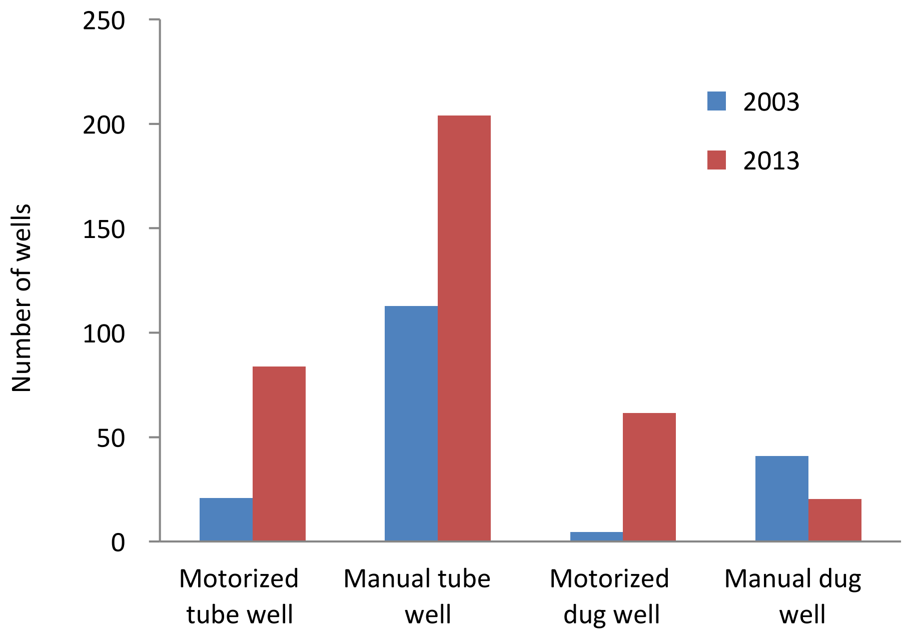
Region	Number of tube wells	Groundwater abstraction ($Mm^3 y^{-1}$)		
		Wet season	Dry season	Total
Sagaing	8,271	56.40	61.93	118.33
99 Ponds	442	11.45	32.71	44.16
Monywa	141	11.02	16.99	28.01
Magway	4,154	3.53	12.52	16.05
Mandalay	10,989	7.88	16.33	24.21
Total of the three regions	23,997	90.28	140.48	230.76[1]
Remainder	9,084	0.78	318.07	318.84
Total	33,081	91.06	458.55	549.60

Source: MOAI 2003.

Note: [1] Total abstraction is greater than that given in Table 6, presumably because it extends beyond DZ in covering all districts in the three regions.

of the community survey, with the sole exception of the number of dug wells (that rely on manual lifting) (Figure 4) which has decreased. The general increase in the number of wells is not uniform across the villages, with some villages observing significant increases while others revealing no change or even a decrease. For villages characterized by high levels of irrigation, large increases in the use of tube wells was found. However, in villages practicing supplementary irrigation, the increase in the number of tube wells was associated with a decrease in the use of dug wells.

FIGURE 4. Changes in the average number of private wells per village from a sample of 24 villages in the Dry Zone between 2003 and 2013.



Source: Senaratna Sellamuttu et al. 2013.

Socioeconomic Opportunities and Constraints

This section is based on information drawn from interviews conducted with seven farmers who use groundwater for irrigation. Although only a small sample of farmers were interviewed (Table 12), which may not be fully representative of the hydrogeological condition across DZ, their experiences are useful in illustrating some of the opportunities and constraints faced by smallholders using groundwater. A summary of the key findings are given below with more detailed farmer-level information provided in Appendix B.

TABLE 12. Summary of the characteristics of the well-owner farmers surveyed.

Sample size	7
Townships covered	Taungdwingyi, Minbu, Taze, Sagaing
Surface geology	Alluvial
Land type irrigated	Paddy and non-paddy lands
Well type	Mostly tube wells
Age of well	2-16 years
Depth of well	3-61 m
Depth to groundwater	1-9 m
Water quality	Good
Farm size	0.2-15 ha
Total irrigated area	0.2-15 ha
Number of crops per year	1-2
Months of cropping per year	3-9
Days of pumping per year	6-127

Financial Costs and Benefits

The investment costs needed by the seven farmers to construct the well, and purchase the water pumps and distribution pipe varies from USD 110 to USD 1,360 (Table 13). This large cost variation reflects the range of conditions encountered, configurations of well type and depth, and pumping capacity. On average, this investment is allocated as follows: drilling (31%), motor pump (49%) and provision of water pipe (20%). Not surprisingly, the drilling costs, which account for almost one-third of the setup cost, are well correlated with the total drilled depth (R^2 = 0.65). Of the three components, drilling costs are mostly variable due to the diverse range of hydrogeological conditions

TABLE 13. Farmer-wise costs to setup groundwater infrastructure (includes drilling, pump and pipe costs).

Tube well costs (USD)[1] (N=6)	110-1,360
Dug well costs (USD)[1] (N=1)	160

Notes: [1] Based on an assumed exchange rate of USD 1 = MMK 1,000.

and the associated modes of installation. Savings in pump purchase costs would represent the single biggest opportunity to bring down the total investment cost. Higher upfront costs for good quality pumps may need to be traded-off against higher maintenance and opportunity costs for poor quality pumps. Motor pumps are an expensive investment for farmers, but are highly valued for their efficiency in lifting water. In six of the seven cases, the groundwater infrastructure was funded by the well owner, either through savings or family loans. In the remaining case, the infrastructure was supported through a government subsidy.

Farm incomes and agricultural expenditure were highly variable, even for farmers growing the same crop (Table 14). In the wet season, potential revenues range from USD -295/ha^{-1} to USD +585/ha for rice (not all farmers grow rice in the wet season; Appendix B). In the dry season, potential revenues were consistently positive and range from a low of USD 22/ha^{-1} for chickpea to USD 257/ha^{-1} for wheat in the winter, and USD 1,967/ha^{-1} for ridge gourd in the summer. This suggests that irrigation is most profitable for those who can diversify into high-value cash crops. Net annual potential revenues range from USD -362 to +577 for the seven farmers surveyed in 2011-2012. The significance of the various input costs are ordered as follows: additional labor (44%), pumping (24%), fertilizer (21%), and pesticides and herbicides (11%).

The highest reported seasonal income came from the betel leaf irrigated using a dug well. Deeper tube wells are least prone to seasonal drying out and can thus provide more reliable supplies. The high variability in profitability, and particularly the losses incurred in the wet season by some farmers growing paddy, can be attributed to the very dry year in 2012. A late start to monsoonal rains and the high water demand of the crop necessitated significantly more supplemental pumping than anticipated.

Estimates of the payback time on original investment suggest that from less than 1 year to 17 years is required by farmers, if maintenance costs are accounted for (Appendix B). These periods neglect the interest rate component that would need to be factored in, if funds were sourced from lending institutions. In three of the cases, negative rates of net revenue precluded the calculation of a payback time.

TABLE 14. Season-wise potential revenue that can be earned by farmers.

	Wet-season crop[2]	Winter crop[2]	Summer crop[2]
Crop types	Rice, groundnut, betel leaf	Chickpea, wheat	Ridge gourd
Crop area (ha)	0.8 - 2.8	0.6 - 6	0.2
Crop yield (basket ha^{-1})	62 - 222	30 - 49	11,100[3]
Selling price (USD basket^{-1})[1]	3 - 8	14 - 15	0.1[3]
Total input cost (USD)[1]	185 - 599	139 - 1,366	26
Gross revenue (USD)[1]	200 - 1,120	180 - 280	450
Net revenue (USD)[1]	-362 - +577	127 - 156	398
Normalized net revenue (USD ha^{-1})	-295 - +585	22 - 257	1,967

Notes:

[1] Based on an assumed exchange rate of USD 1 = MMK 1,000.

[2] Since the cropping calendar varies, the season referred to is indicative (specific details are given in Appendix B, Table B2).

[3] Refers to the number of fruits rather than USD per basket.

Challenges and Constraints

The single greatest challenge reported by the farmers owning wells concerning their groundwater irrigation systems was the high fuel costs for diesel pumps in most cases, especially during the dry spells when groundwater levels were depressed and a greater lift was needed to access water (four of the seven cases). In some instances, this limited the area that could be irrigated. Sharing of wells and pumps offers a practical way of reducing the financial burden of establishing groundwater infrastructure. Water sharing would appear to be commonly practiced, as in almost all cases there were reports of well owners providing water to anywhere from two to thirty other farmers. The net annual income generated from this practice has not been taken into account in the analysis.

Mechanical problems with pumps or associated costs were either perceived as a problem (one case) or reported but not considered problematic (one case). Interestingly, access to capital to purchase inputs, maintain equipment or for system improvements was not reported to be a major issue. Only one case reported not having any issues.

Irrigated cropping, even with motorized pumps, is still a labor-intensive practice, with the cost of additional labor typically representing the highest, single input cost. The survey results point to reasonably strong linkages and inter-dependencies between the land-owning groundwater irrigators and the landless. In most cases, the landless play an important role in terms of casual labor, except for limited cases where there was no requirement for casual labor. The tasks of those employed included the laying out of the pipes in the fields, running the pump, checking crop water needs and general supervision. In less than half of the cases, casual labor was used during well construction, where laborers were hired for a short one-off period. Those employed as casual laborers have additional indirect benefits through assured access to their domestic water supplies.

Groundwater Management

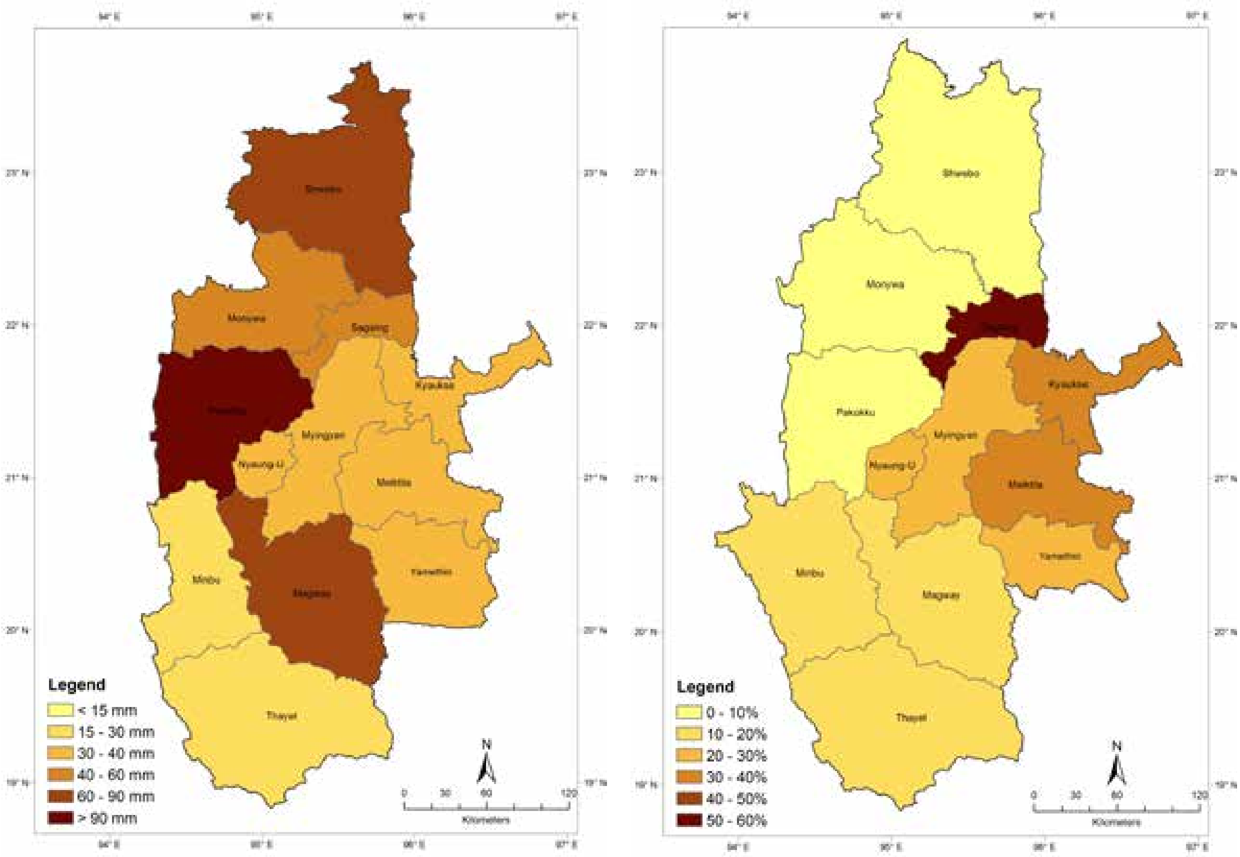
Undeveloped Potential

There appears to be a view that the groundwater reserves available for exploitation in DZ are vast, particularly on the plains, which are largely untouched (e.g., ESCAP 1995). It is also felt that groundwater utilization, in more recent times, has mostly been limited to domestic water supply, and to the irrigation of vegetables and other high-value crops with water from hand-dug wells and tube wells. This study indicates that utilization of groundwater resources relative to annual replenishment is estimated to range from 5% in Monywa District to 55% in Sagaing District, with a district average of 23% (Table 15). The most intensively used areas cluster around the central west of DZ in Mandalay and southern Sagaing regions (Figure 5). These areas coincide with moderate development potential, with areas of higher and lower potential situated in districts to the north, west and southwest.

Overall, there is clear evidence of an undeveloped potential from which substantial additional area could be irrigated from renewable fresh groundwater resources. It is estimated that a further 110,000 to 330,000 ha of land could be irrigated, depending on the irrigation water demand associated with the crops selected and the estimated average groundwater recharge (Table 15). Except for one, there is potential for expansion in all the twelve districts of DZ. It is important to note that there are areas where the groundwater will not be appropriate for use due to poor quality, depth or access to pumps, particularly for the Pegu and Eocene group aquifers.

FIGURE 5. (a) Groundwater potential (mm y^{-1}); and (b) groundwater utilization, expressed as a percentage of annual recharge in 2000-2001.

(a) (b)



Source: created using data from MOAI 2003.

TABLE 15. Groundwater utilization as a percentage of annual recharge (2000-2001), and potential area of new irrigation expansion from groundwater.

Region	District	Groundwater utilization (%)	Potential new groundwater irrigation area[1] (ha)		
			500 mm y^{-1}	1,000 mm y^{-1}	1,500 mm y^{-1}
Sagaing	Monywa	4.82	52,752	26,376	17,584
	Shwebo	8.66	90,146	45,073	30,049
	Sagaing	54.92	0	0	0
Magway	Magway	17.53	38,600	19,300	12,867
	Thayet	13.78	24,702	12,351	8,234
	Minbu	19.23	16,376	8,188	5,459
	Pakokku	9.84	61,951	30,975	20,650
Mandalay	Kyaukse	36.82	3,395	1,698	1,132
	Meiktila	30.71	7,245	3,623	2,415
	Yamethin	23.41	20,607	10,304	6,869
	Myingyan	28.36	10,608	5,304	3,536
	Nyaung-U	26.92	2,414	1,207	805
	District Total	-	328,796	164,399	109,600

Source: Adapted from MOAI 2003.

Note: [1] Using figures in the previous column supplemented by recharge values (Table 2) and assuming annual irrigation water demands of 500, 1,000 and 1,500 mm y^{-1}.

It must also be recognized that the undeveloped potential is based on water use figures from around a decade ago, and future growth in the non-agriculture sectors must also be considered. This suggests that areas of new irrigation (given above) may represent an upper limit. Most of DZ, except for the Bago Hills and surrounding areas, is quite flat and agricultural land use is intensive, and thus water represents more of a constraint than the availability or use of land.

Sustainability Issues

With the new opportunities to develop groundwater resources to support livelihood-enhancing activities in DZ comes the increased responsibility to ensure that the degree of understanding and managing groundwater resources is improved. Unrestricted groundwater use could result in classic over-exploitation symptoms of reduced availability, water quality deterioration and land subsidence. Natural connectivity to surface water means that it is also important to preserve groundwater to protect natural baseflow regimes, groundwater-dependent biodiversity and cultural heritage. The areas where increased groundwater exploitation would be most detrimental to such regimes remain largely speculative at this stage.

WRUD has implemented a rudimentary tube well inventory system, but a formal monitoring network has yet to be established across DZ. In the interim period, some strategic monitoring has been undertaken in areas with high groundwater demand. One such example is the Ywatha-Aungban aquifer, where WRUD had studied the 10-year difference in the rate of artesian discharge by comparing the total discharge of four sets of wells: WRUD artesian wells, WRUD test wells, farmers' wells and domestic wells in 1999 and 2009 (Table 16). For the WRUD wells, the same wells were monitored on both occasions and the results show consistent decreases of 6 to 17% relative to the initial rate. As 2009 was a drought year, this may represent an anomaly rather than a long-term trend. For farmers' and domestic wells, the number of wells monitored increased by factors of around two to four and it is not possible to make direct comparisons, although the results suggest higher flows in wells measured in 2009, perhaps as a result of more strategic targeting of wells in high productivity zones.

Development of artesian wells will lead to a decline in flow rates due to the steady release of pressure from the aquifer and is not in itself an indicator of unsustainable practices. Analysis of sustainable well yields through mathematical modeling is needed to reveal the

TABLE 16. Comparison of the discharge and well status of the Ywatha-Aungban aquifer in 1999 and again in 2009.

	Well type	1999		2009		Difference in discharge over the 10-year period (%)
		Total flowing artesian wells	Discharge $m^3 d^{-1}$	Total flowing artesian wells	Discharge $m^3 d^{-1}$	
Irrigation wells	99 Ponds (WRUD)	449	52,161	449	48,932	-6.2
	Test well (WRUD)	10	2,936	10	2,447	-16.7
	Private (farmer)	205	39,145	752	61,581	+57.3
	Total	664	94,242	1,211	112,960	+22.7
Domestic wells		85	7,340	187	9,933	+35.3

Source: Data from WRUD.

long-term trends and identify suitable management responses. There is also anecdotal evidence from international NGOs that a lot of artesian groundwater is being inefficiently utilized due to the poor distribution systems (ActionAid pers. comm. February 4, 2013).

The capacity of groundwater to buffer the impacts of climate change and climate variability is typically higher than that of surface water drawn from rivers and ponds, and comparable to that of large surface reservoirs. At the same time, groundwater is not exempt from the effects of drought and discharge via evapotranspiration, as in the situation in 2009 where a drought resulted in a decline in the water table by almost 1 meter below normal conditions and the death of a large number of date palms (ActionAid pers. comm. February 4, 2013). Such examples highlight the importance of information and other decision support tools for effective management of groundwater resources.

Conclusions and Recommendations

Access to water is widely acknowledged as being a key constraint for livelihood enhancement and general well-being of the rural population of the Dry Zone in central Myanmar. Sustainable use of groundwater has tremendous potential for addressing water scarcity issues by providing safe and reliable water supplies for multiple purposes, including domestic use, livestock, irrigation and industry.

Groundwater is ubiquitous across DZ, but the local opportunities for accessing it vary depending on specific hydrogeological conditions and socioeconomic factors. In general terms, farmers are, on their own initiative and with little or no external support, turning to groundwater, typically via tube wells drilled to shallow or moderate depths and powered mostly by small motorized pumps or, to a lesser extent, treadle pumps. Such interventions are emerging not only in rainfed areas, where expected, but also within irrigation command areas. Formal irrigation schemes, drawing on either surface water or groundwater, invariably contain areas that are not irrigable due to limited infrastructure development or energy supplies, and private wells are emerging in these tail-end areas. Significant volumes of deep drainage flows generated by the schemes can be collected and recycled by the tail-end farmers, serving to 'close the water cycle' from a water accounting perspective and 'fill the gaps' from an upstream-downstream perspective. Potential risks of salt accumulation in the soils and aquifers would need to be monitored.

Farmers use four different modalities to gain access to groundwater resources, ranging from simple excavations in dry riverbeds and drawing out water using a bucket to government-operated large-scale groundwater irrigation schemes in a limited number of potential areas from a hydrogeological perspective. The most widespread method is private investment in small pumps by individual farmers. It is possibly this modality that offers the most widespread and significant opportunities for further developing the resource.

Small-scale irrigation through the use of groundwater involves an increasing number of small farmers. It contributes to improved food security, and is a viable recourse against climate variability and climate change. It can be an important means for farmers to improve their livelihoods, particularly during the dry season. This is most effective when high-value crops are grown (sometimes in addition to staple food crops such as rice), and household cash flows are sufficient to cover the basic input costs. Job opportunities for landless workers in irrigation emerge in around 70% of the cases. When considering irrigation expansion, the implications on these sectors must also be taken into account. Provision for domestic needs, including drinking water (for people and livestock), must be given the highest priority, and any plans to expand irrigation development should not compromise current or future access to these essential supplies. The environmental services provided by groundwater also need to be safeguarded by dedicated provisioning of the resource for this purpose.

The high cost of installation, operation and maintenance, and replacement of pumps are major impediments to the adoption of groundwater use, given the limited financial capacity of most farmers in DZ. The farmers themselves appear to possess the technical know-how to support farmer-managed groundwater irrigation. However, access to credit facilities are needed to enable farmers to cover drilling costs and to purchase small-capacity motorized pumps. The total investment cost to establish groundwater irrigation infrastructure is highly conditional upon the local conditions and can vary by an order of magnitude. Lack of information to support successful well siting in complex hydrogeologic environments generally adds to the risks and costs, and better knowledge of the hydrogeological conditions is essential to enable effective planning, especially at the local level, to maximize investments. Under optimal conditions, the payback times on initial investments can be as short as a year.

Groundwater development has steadily increased over time. However, in broad terms, there would still appear to be significant undeveloped potential for expanding groundwater use for agriculture. The development of groundwater could beneficially complement surface water resources development to address shortfalls spatially (i.e., to supply areas where alternatives are not available or expensive) or temporally (i.e., as a supplement when surface water is unavailable).

The average groundwater recharge for DZ is estimated to be around 50 mm per year, a figure which does not support the view of great abundance. Still, this study estimates that, recognizing the caveats described earlier and depending on which crops are grown, the replenishable resource may be sufficient to irrigate an additional 110,000 to 330,000 ha of land in DZ. While significant opportunities exist in many (but not all) areas, there are also potential issues associated with naturally high levels of salinity and arsenic, and over-exploitation from large projects or agglomeration of many smallholder farmers. This clearly indicates that groundwater development has limits and has to be properly managed, if it is to be sustainable.

This assessment of groundwater resources was based on limited data drawn from synthesis studies, government agency data and a small number of hydrogeological investigations. While this has been sufficient to reveal, in broad terms, that further opportunities for groundwater development exist, reliable and comprehensive data about the locations, depths, extent and quality of suitable aquifers that can be developed are not yet available. More rigorous assessments are needed to identify areas of DZ where groundwater interventions are most appropriate, with follow-up work focussed on the priority townships and villages.

Limited information can translate, for example, into poor investments due to the unacceptable risk of constructing expensive wells, those that perform poorly or those that produce low-quality water. This is exacerbated by the complexity of the hydrogeological system in some areas (e.g., Pakokku). This can mean large variations in groundwater potential, both in terms of water quantity and quality, over small distances, not covered in the relatively simple potential analysis carried out in this study.

Detailed hydrogeological and hydro-chemical maps that can be used by practitioners to provide a clear indication of the potential of the resource and suitable areas for development have not been published. Work carried out almost three decades ago by Drury (1986), virtually completed but never published, comprises 11 map sheets on the hydrogeology of DZ at approximate district scale and represents the best available information known. If finalized and updated, this would provide useful indicators for regional planning purposes. Preliminary work carried out by Min Oo and Thein (2013) in Nyaung-U township, which used a combination of remote sensing and geographic information system (GIS) methods to determine development hot spots, would appear to be a significant contribution. However, this work needs to be verified and potentially extended to cover the entire DZ. Further, monitoring to date has been limited and opportunistic rather than strategic and inclusive. To underpin long-term management needs, a regional groundwater monitoring network should be established and operated across DZ, supported by a centralized database that can contribute effectively towards strengthened groundwater management.

The way forward must entail acting upon the major data gaps to better understand the nature, extent and dynamics of the resource that include adequate appraisals of groundwater recharge and use, sustainable yield of aquifers, water quality and pollution. Further work on arsenic may be needed to more clearly define the areas, aquifers and depths of its prevalence. Better understanding of the socioeconomic factors that enable or constrain groundwater development and use would help inform policies that promote use of the resource to enhance agrarian economies and alleviate poverty.

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Appendix A. Case Studies of Groundwater Irrigation Typologies.

Monywa Groundwater Irrigation Project (Type 1)

The Monywa groundwater irrigation project was funded by the United Nations Development Programme (UNDP) and International Development Association (IDA), and built upon pilot studies supported by the World Bank from 1983-1992 in Monywa, Chaung-U and Budalin townships of Sagaing region. The main aim of the project was to increase crop production and farm incomes by expanding the irrigated area from 810 ha in the early 1980s to about 8,100 ha at project completion through the development of groundwater resources. Another aim of the project was to strengthen the capability and inter-agency coordination of the institutions involved (World Bank 1994).

The project area was selected from a large area encompassing five regions on the basis of rainfall, agricultural production, groundwater conditions, water demand, soil type, flood risk and accessibility (World Bank 1983). Since 1995, the project has been managed by WRUD with local pump operations being delegated to farmers who have been given relevant training. Major maintenance and repairs are handled by WRUD.

According to Mr. U Tin Maung, Hydrogeologist, WRUD, the scheme currently comprises 141 deep tube wells, and the corresponding power supply infrastructure, pumping, water distribution and drainage systems are fully functional and irrigate an area of 6,360 ha (or around 45 ha per well, on average) (Figure A1). The scheme is partitioned according to energy transfer as four electric circles (or rings), where each ring is served by a specific transformer that services the transmission lines for a particular ring.

The total cost of the project was estimated to be USD 21 million. A large proportion of this was spent on investments in transmission lines, substation transformers and load dispatching between the main grids. Cost recovery was largely achieved by an indirect agricultural tax through procurement of 'controlled' crops, such as cotton, wheat and mung beans, at below the export or import prices. Since groundwater development has a low capital investment per unit area overall, but relatively high operation and maintenance (O&M) costs, the key economic issue is how to ensure that there are sufficient funds available to sustain the project work. Water charges have been introduced to cover the O&M costs associated with power, routine maintenance and repairs (World Bank 1994). Nowadays, farmers across the scheme pay a fee for irrigation water of MMK 6,000 per acre[1] for wet paddy, MMK 9,000 per acre for dry paddy and MMK 3,000 per acre for other crops during all the seasons through a Water User Group (WUG). Production from the scheme in terms of total area planted is 28% of wet season paddy, 1% of summer paddy and 71% of non-paddy crops over the period from 1995 to 2013 (WRUD, Monywa, unpublished data).

Local representatives from WRUD quote the cost of a single tube well to be MMK 5 million. The cost of the turbine pump and electrical control system is MMK 15 million. Cost of the distribution system is MMK 30 million. Electrical consumption from the turbine pump is 18.5 kW h^{-1} to supply 2,400 m^3 d^{-1}. The system is designed for pumping around 14 hours per day, but pumps can currently be operated for longer to meet water demands. Regular power shortages and poor reliability due to overloads on the grid system create significant problems with delivery across the command areas.

The irrigation well visited on electric circle 4 (no. 4/1) commands an area of 30 ha, although around 25 ha is effectively under command (type 2 irrigation supplies the remaining command) (Figure A2). The system is comprised of a 46-m deep well with 10-inch casing with a screen over two productive

[1] 1 acre = 0.404686 hectares; 1 hectare = 2.47105 acres.

intervals, and a pump delivering water to a main channel running along the upstream boundary which drains into 13 laterals that are traversed by 8 minor canals; and the 13 x 8 grid arrangement supports 104 individual plots.

The target aquifers are at depths of around 12-18 m and 37-40 m. The well yield is around 2,400 $m^3\ d^{-1}$. An aquifer pump test was first conducted to assess the long-term yield and estimate the size of the command area. The double cropping system comprises of paddy for the wet season crop followed by wheat, chickpea or onion for the second crop. The estimated crop water demand is 1,200 mm for paddy and 600 mm for other crops.

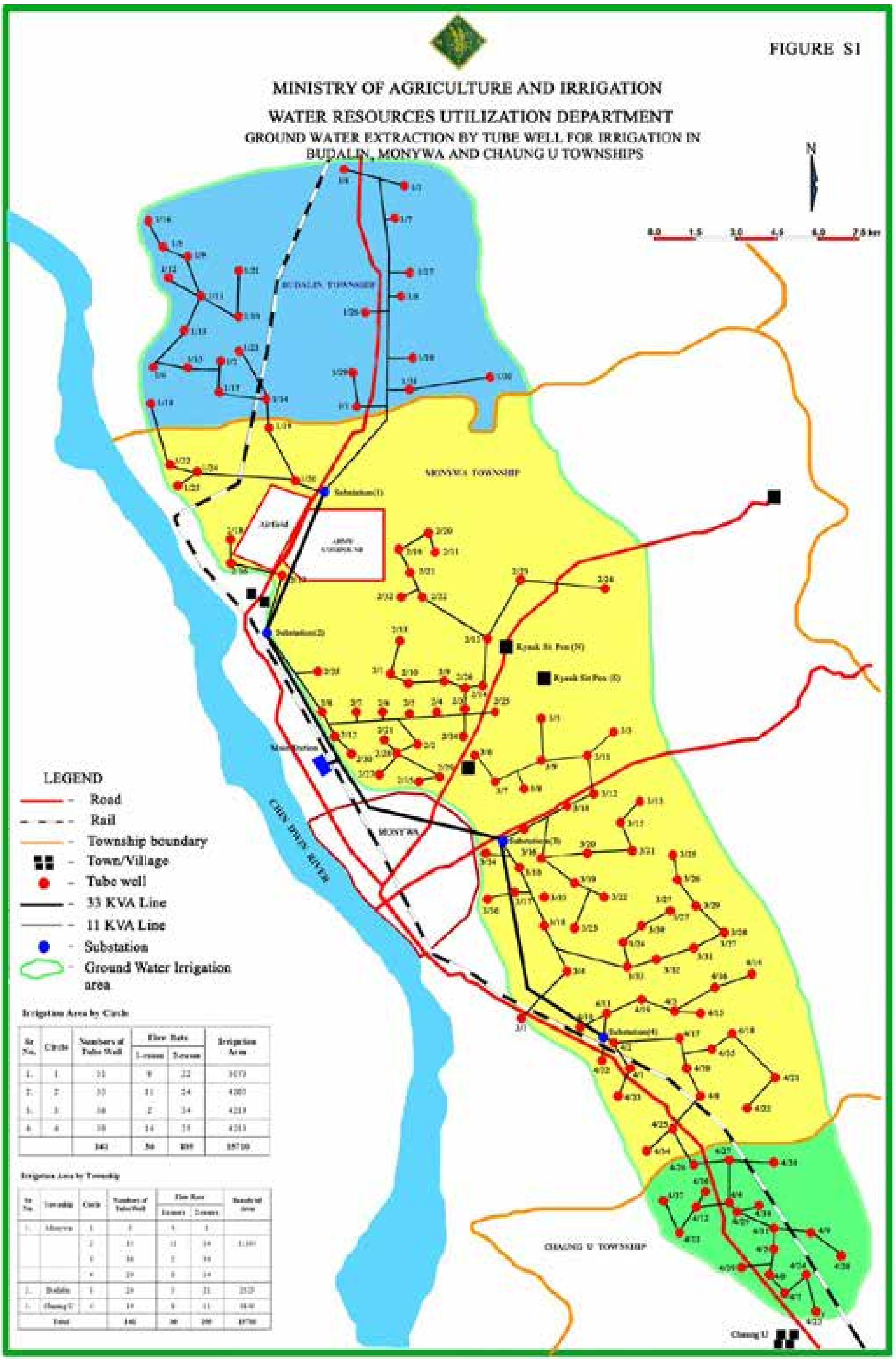
The aquifers targeted include an upper layer at 12-18 m of unconsolidated brown/yellow sands (Alluvial formation) overlying a lower layer of unconsolidated 'blue sands' of the Irrawaddy group at 37-40 m. Both aquifers are under pressure. A superficial low-productivity aquifer is also present, but is not targeted for commercial operations. The detailed project report by WRUD (2005) indicated that the quality of the pumped water at the time of construction was fresh (120 $\mu S\ cm^{-1}$) – other irrigation wells are more brackish at around 800 to 2,400 $\mu S\ cm^{-1}$. When classified for irrigation, the groundwater is of a moderate salinity hazard and a low sodium hazard, but is generally considered to be suitable for irrigation. However, the high salinity of water necessitated the provision of drainage works under the project.

All the farmers who use the scheme are smallholders with landholdings ranging from less than 0.5 acres or less to less than 2 acres. Irrigation plans are developed through a committee comprising of the farmers, WUG and government representatives taking into account the projected water and energy availability. At the tail-end of the command area visited, two private wells were in operation to provide for shortfalls in local supply.

At the inception of the project, 157 wells were constructed, and 16 wells (10%) have been abandoned over time because the formation in these areas was unstable and extraction of fine sediments caused the screen to collapse. Since implementation, around 15 Italian manufactured turbine pumps have been replaced with Indian submersible pumps.

Sustainability concerns were considered in the design of the scheme and, while accurate estimates of water balance for the project area are not available, crude estimates of sustainable well-field operating capacity of 0.0017 $m^3\ m^{-2}\ d^{-1}$ was derived from hydrogeological investigations, which included vertical recharge and the lateral discharge of groundwater to the Chindwin River situated around 3 km to the downstream. Monitoring of the level of water from 16 wells suggested no deterioration, although the duration of monitoring was limited to only 2 years (GDC 1984). Inspection of one irrigation well suggested no major signs of over-exploitation, with the water levels in the shallow private wells that tap only the upper aquifer visible at the soil surface while the pump was active. Water level monitoring of the scheme had taken place in the past, but this has since been abandoned following breakdown of the equipment. Operational performance is gauged independently. WRUD would value the revival of the monitoring system for long-term planning that could address concerns about climate change and advanced warning about land subsidence.

FIGURE A1. Current layout of irrigation wells for the Monywa groundwater irrigation scheme covering Monywa, Chaung-U and Budalin townships.



Source: MOAI.

FIGURE A2. Pump house for a community irrigation well 4/1 (the stilling tank before distribution is evident to the left of the image).

Photo: Paul Pavelic.

Tail-end Farmers at Monywa (Type 2)

Type 2 operations can co-exist within a type 1 system as in the case of Monywa, where private farmers operate shallow tube wells at the tail-end of the system. These wells have limited water availability owing largely to constraints in power supply and pumping duration that are not able to serve the needs of all the farmers within the command area.

Farmers' tube wells are smaller in diameter and shallower than the community irrigation wells. They typically feature a smaller 3-inch casing and are screened over the interval from 12-18 m, which taps only the upper brown/yellow sand layer aquifer (Figure A3). A 7.5 hp motorized pump supplies about 98 m^3 d^{-1}. The cost of a well is estimated to be MMK 100,000 and so is the cost of the pump. Fuel cost was reportedly MMK 5,000. Urea was being applied at the time of the visit.

FIGURE A3. Monywa scheme tail-end farmer providing water from his well to the lateral canal.

Photo: Paul Pavelic.

Water Trading and Co-investment at Nyaungkhan Village (Type 2)

Large portions within many of the large surface water irrigation project command boundaries are considered ‘uncontrollable’, in the sense that the existing lift irrigation system cannot deliver water to those parts of the landscape. In these areas, farmers are making investments in utilizing groundwater, sometimes in an innovative manner. In the Seik Nyaung Pump Irrigation project, we visited Mr. Aye Thaung, a farmer from Nyaungkhan village, Taungtha township, who created viable informal irrigation through an entrepreneurial arrangement with three other farmers situated on nearby lands. The well was constructed and paid for by another member of the village in 2007. The pump was purchased by Mr. Aye Thaung. Two other farmers use the groundwater irrigation system to water their fields. This water trading and investment sharing initiative can be self-started, is free from formal agreements, and is based on mutual consent and willingness to participate. The owner of the well has 0.6 ha under irrigation at this site and two other farmers have 0.4 ha of land, each bringing the total land area under the command of the irrigation well to 1.8 ha. They pay a fee of MMK 4,000 per day to the pump owner to use the well. This does not include the cost of the diesel. The pump owner presumably shares this revenue with the well owner.

The irrigation well is 30 m deep and was drilled using manual percussion methods (Figure A4). It cost MMK 400,000 at the time. The 18-hp diesel pump used was purchased 4 years ago for MMK 450,000. The cost of a gallon of diesel was MMK 3,500.

Family labor is used on the land owned by Mr. Aye Thaung. He has 0.4 ha of onions and grows corn on the plot fringe. The total input cost for this crop was MMK 500,000, which covers the costs of fertilizer (inorganic fertilizer and cow dung are applied), pesticides and fuel. He will irrigate according to the water requirements of the plant, as fuel is expensive. The crop has to be watered seven times over the life cycle of the crop, and each watering takes 11 hours. Eleven liters of fuel are used in the process. The discharge rate of the pump is 540 $m^3 d^{-1}$.

Water quality is slightly brackish and the sodium content is sufficiently high to create slaking of fine textured soil on the surface, which creates some problems with soil aeration and requires seasonal rotation to allow for the natural soil remediation process. In the monsoon season, tobacco is grown. Whist onions fetch a higher price than tobacco, in recent times the price of onions has become more unstable than tobacco. Like many farmers, he has limited savings and cannot wait for a favorable selling price. Mr. Aye Thaung owns 22.8 ha of land in total, including 0.8 ha for paddy within the command area, which he irrigates with surface water.

FIGURE A4. Pumping into the distribution channel of the farmer who owns the pump set.

Photo: Paul Pavelic.

New Private Well Owner at Tanpinkan Village, Taungtha Township (Type 2)

Mr. Shwe Myaing, a 40 year old father of two and head of his household, constructed a new well 4 months before our visit, after years of toiling with rainfed agriculture on this land. He recently received a family inheritance which he invested in improving water management on his farm.

The deep well, necessary because of his upland location, is an open, large diameter well of 5 m and tube well of 55 m. It irrigates a field of 0.5 ha (Figure A5). The limestone layer evident at the surface is only present in the top few meters. The most productive layer is the ‘brown sands’ found at depth. This is the first crop (onions), with land preparation requiring 1 month and the crop being 1 month old. The soils are calcareous sand with low fertility. The total cost of the groundwater infrastructure is MMK 1.1 million. Mechanical drilling of the well cost MMK 300,000. The down-hole pump costs MMK 350,000. The large diesel engine was purchased second hand and also cost MMK 350,000, which included the cost of repairs. Land preparation cost was MMK 100,000.

Cow dung and urea are applied. The expected yield from this harvest is 3,000 *viss* (where 1 *viss* = 1.63 kg). The selling price at present is MMK 300-400 per *viss*.

At this upland site, he produced sesame as well as some mung bean under rainfed conditions. When there was sufficient rainfall, he was able to harvest 10 baskets at most, but often the crop failed. When asked why he grew onions like the majority of farmers rather than producing watermelon for export and achieving higher returns on the Chinese market, he cited lack of experience and high risk as the main constraints.

Like most farmers in the region, Mr. Shwe Myaing sells his produce at the nearby markets or through brokers that visit the village. While being clearly aware of the latest prices for each type of produce, which can be used to maximize their bargaining position, such farmers are still vulnerable and receive a lower price. However, more powerful farmers that can transport their produce directly to the larger markets in the cities receive higher prices for their produce.

FIGURE A5. The newly constructed deep well which pumps water that is manually spread across the first crop of onions.

Photo: Paul Pavelic.

Recession Farming on the Riverbed of the Sin Te Wa River (Type 3)

Recession farming on the dry riverbed of the Sin Te Wa River is practiced during the pre-monsoon season each year. Prior to the start of the dry season, the village committee distributes the available land and each farmer receives an allocation of 0.2 ha. Temporary holes are dug in the sand to a depth of a few tens of centimeters which are sufficiently wide to provide direct access to water and allow farmers to fill containers, and the sand walls of the hole are supported by bamboo reinforcing (Figure A6). Wells are quickly constructed within a few hours and are dug in a grid to minimize the energy expended in water distribution. The water table is close to the surface and the irrigator typically uses dual watering cans to spread water on a few square meters of crop per application. A few farmers use small motorized pumps. The crop water demand in this tree-less environment is high and the soil water storage capacity is low, which makes frequent irrigation a necessity. Irrigation commences early in the morning when the climate is cool and little activity is observed by the middle of the day. The dominant crop is onions for the local market, although the cultivation of groundnuts can also be observed in the fringe areas where the water table is sufficiently high. The quality of water would appear to be good as onions have poor tolerance to salinity. White precipitates evident on the surface of the drainage canals would appear to be urea, which is washed away from the plots and re-deposited in concentrated form.

The farming practice is highly risky. If the monsoon season begins earlier than normal (e.g., in April or before) then the crop will be destroyed and the farmers will lose everything. In the most recent decade or so, this has occurred in about one year in three.

Mr. Shwe Myaing, the type 2 farmer described above, was practicing type 3 irrigation until recently, but is now in a financial position to be able to invest in groundwater pumping infrastructure for dry-season irrigation of his upland site. He selected this option mainly because of the assured harvest.

FIGURE A6. Onions are cultivated along the riverbed of the Sin Te Wa River during the dry season, with a regular grid of seasonal dug wells.

Photo: Paul Pavelic.

Appendix B. Farmer-level Information.

Profiles of Farmers Surveyed

The farmers surveyed were tube well owners except for a single farmer who owned a dug well (Table B1). The wells, constructed between 2 and 16 years prior to the survey (conducted in 2013), were almost entirely self-funded and only one of the owners received a government subsidy to establish the groundwater irrigation infrastructure. The depth of the wells ranged from 2.7 m to 61 m with an average of 26 m. The depth to standing water level (SWL) in the wells ranged from 0.8 m to 9.1 m with an average of 4.8 m during the wet season, and from 1.4 m to 9.1 m with an average of 5.8 m in the summer. Pumping rates varied from 93 m^3 d^{-1} to 409 m^3 d^{-1}. All sites are situated in an alluvial geological setting, which is one of the most prospective environments for groundwater development (McCartney et al. 2013).

Motorized pumps were used in each case with no reported instances of using manual lift methods. Pumps predominantly use diesel fuel with capacities ranging from 3 to 18 hp. The pumps were manufactured in either Japan or China, according to the company names reported during the survey.

The quality of the groundwater was described as being ‘good’ in all cases with no impacts on plant health or soil structure, with aesthetic water quality issues evident in a limited number of cases. In more than half of the cases, the pumped water served multiple purposes, including domestic and livestock, either regularly or on a supplemental basis.

Landholdings vary in size from 0.2 to 15 ha with a mean of 3.6 ha. Four of the seven farmers would be considered ‘landed’ (i.e., owning greater than 2 ha) and the remaining three ‘marginal’ (i.e., owning less than 2 ha) (Table B2). The average area under irrigation is 3.2 ha (or 89% of the total land area). Most of the areas in the sample practiced rainfed agriculture. Thus, the farmers access groundwater for supplementing rainfall in the wet season and in the dry season to grow a second or third crop during the year (Tables B3-B5). The moderate size of landholdings support the view that the more affluent farmers endowed with land can afford to pursue groundwater irrigation. According to the average days of pumping, the pumps are used most heavily and in all the cases during the wet season, whereas they are used in 86% of the cases in the winter and only 43% in the summer. The reduction in the use of pumps over the course of the dry season reflects the diminished water availability and demand. Rice is most commonly grown in the wet season whereas it is chickpea in the winter (Table B2). It is not uncommon for farmers using tube wells with year-round access to water to stop cultivating around April, possibly due to a combination of the high temperatures and the need for a break before the main wet-season cropping.

TABLE B1. Characteristics of the farmers that owned wells as identified from the surveys.

No.	Village	Township	Owner[1]	Well location	Surface geology	Land type[2]	Well type	Year built	Total depth (m) (m)	Screen depth range	Depth to SWL[3] (m)	Depth to SWL[4] (m)	Water quality	Pumping rate (m^3/day)
1	Ma Hti San Pya	Taungdwingyi	U Thein Aung	N 19° 59.29 E 95° 28.67	Alluvial	*Le*	Tube well	1997	18.3	11.0-17.7	3.0	3.7	Good	327
2	Kyauk Tan	Minbu	U Min Min Oo	N 20° 09.844 E 094° 48.894	Alluvial (near Pegu)	*Ya*	Dug well	2011	2.7	1.2-1.8	0.8	1.4	Good	136
3	Kone Thar	Minbu	U Myint Wai	N 20° 08.931 E 094° 51.906	Alluvial	*Le, Ya*	Tube well	2008	16.8	13.7-16.8	6.1	6.7	Good	409
4	Bay Yinn	Taze	U Htay Maung	N 23° 05.804 E 095° 24.805	Alluvial	*Le, Ya*	Tube well	1998	16.2	11.6-16.2	5.5	6.1	Good	409
5	Kan Du Ma	Taze	U Aye Ko	N 22° 56.585 E 095° 14.007	Alluvial (near Irrawaddy)	*Le*	Tube well	2009	27.4	24.4-27.4	1.5	4.6	Good	300
6	De Pa Yin Kwal	Sagaing	U Kyaw Zaw	N 22° 03.299 E 095° 40.339	Alluvial	*Ya*	Tube well	2000	36.6	27.4-36.6	9.1	9.1	Good	93
7	De Pa Yin Kwal	Sagaing	U Zaw Naing Soe	N 22° 03.323 E 095° 40.549	Alluvial	*Ya*	Tube well	1997	61.0	21.3-61.0	7.6	9.1	Good	109

Notes: [1] Head of household in each case.
[2] *Le* = paddy land; *Ya* = non-paddy land.
[3] SWL as measured during the wet season.
[4] SWL as measured during the summer.

TABLE B2. Farming systems of the farmers that owned wells.

No.	Total farm size (ha)	Total irrigated area (ha)	Number of crops per year	Wet-season crop	Winter crop	Summer crop	Months of cropping per year	Days of wet-season pumping per year	Days of winter pumping per year	Days of summer pumping per year
1	3.2	1.6	1	Rice (June-October)	-	-	5	6	0	0
2	0.2	0.2	1	-	-	Ridge gourd (November -March)	5	70	12	45
3	2.8	1.2	2	Rice (July-October)	Chickpea (October -January)	-	7	7	9	9
4	1.0	1.0	2	Rice (July-December)	Chickpea (December-March)	-	9	24	8	0
5	1.0	1.0	1	Betel leaf (September-November)	-	-	3	8	8	12
6	15.0	15.0	2	Groundnut (July-October)	Chickpea (November -March)	-	9	30	15	0
7	2.2	2.2	1	Rice (August-December)	Wheat (November-March)	-	8	6	16	0

TABLE B3. Farmer-wise costs to setup groundwater infrastructure.

No.	Well type	Year built	Total depth (m)	Drilling cost (USD)	Pump cost (USD)	Pipe cost (USD)	Total setup cost (USD)
1	Tube well	1997	18.3	80	460	118	658
2	Dug well	2011	2.7	5	130	20	155
3	Tube well	2008	16.8	300	250	600	1,150
4	Tube well	1998	16.2	61	37	14	112
5	Tube well	2009	27.4	465	444	85	994
6	Tube well	2000	36.6	318	600	250	1,168
7	Tube well	1997	61.0	500	800	55	1,355

TABLE B4. Season-wise potential yield and revenue that can be achieved by farmers.

No.	Crop type	Crop area (ha)	Crop yield (baskets/ ha)	Selling price (USD/ basket)	Labor cost per crop (USD)	Fertilizer cost per crop (USD)	Pesticide cost per crop (USD)	Herbicide cost per crop (USD)	Pumping cost per crop (USD)	Total input cost (USD)	Gross revenue per crop (USD)	Net revenue per crop (USD)	Normalized net potential revenue per crop (USD/ha)
Wet-season crop													
1	Rice	1.6	173	3	226	136	0	0	210	572	210	-362	-224
2	-	-	-	-	-	-	-	-	-	-	-	-	-
3	Rice	2.8	198	3	490	0	0	0	101	591	240	-351	-124
4	Rice	1.0	148	5	184	145	0	0	270	599	300	-299	-295
5	Betel leaf	1.0	1,384 *viss*/ha	2 per *viss*	70	0	438	0	35	543	1,120	578	570
6	Groundnut	0.8	62	8	64	100	0	0	14	178	200	22	27
7	Rice	0.6	222	6	83	66	0	0	36	185	540	356	585
Winter crop													
1	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-
3	Chickpea	1.6	30	15	160	0	0	0	0	160	180	140	86
4	Chickpea	1.0	32	14	0	0	49	0	90	139	182	127	125
5	-	-	-	-	-	-	-	-	-	-	-		
6	Chickpea	6.1	37	15	750	300	0	0	315	1,365	225	134	22
7	Wheat	0.6	49	14	105	33	0	0	48	186	280	156	257
Summer crop													
1	-	-	-	-	-	-	-	-	-	-	-	-	-
2	Ridge gourd	0.2	4,500[1]	0.1[2]	8	14	0	0	5	26	450	398	1,967
3	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-	-

Notes: [1] Per number of baskets.
[2] USD per number of fruits.

TABLE B5. Net annual returns achieved by farmers in relation to investment and maintenance costs.

No.	Total setup cost (USD)	Total net potential revenue (USD/year)	Number of years required to achieve return on initial investment[1]	Number of years required to achieve return on initial investment, including maintenance costs[1]
1	658	-362	NA	NA
2	155	398	0.4	0.4
3	1,150	-211	NA	NA
4	112	-172	NA	NA
5	994	578	1.7	1.7
6	1,168	156	7.5	17.1
7	1,355	512	2.6	6.6

Note: [1] NA – not applicable, where the revenue was negative.

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