Livelihoods and Food Security Trust Fund

Water Resource Assessment of the Dry Zone of Myanmar

Final Report for Component 1

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Acronyms

EC	Electrical Conductivity
ESCAP	Economic and Social Commission for Asia and the Pacific
FSWG	Food Security Working Group
GDC	Groundwater Development Consultants
GRDC	Global Runoff Data Centre
ICOLD	International Commission on Large Dams
INGO	International Non-Governmental Organization
JICA	Japan International Cooperation Agency
LIFT	Livelihoods and Food Security Trust Fund
MDGs	Millennium Development Goals
MIMU	Myanmar Information Management Unit
MOAI	Ministry of Agriculture and Irrigation
RWS	Rural Water Supply
TDS	Total Dissolved Solids
WRUD	Water Resources Utilization Department

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Summary

The report is one of a series of three reports developed as part of an IWMI-led project investigating water resources and livelihoods in the Dry Zone of Myanmar. The overall objective of the project was to assess the water resources of the region and evaluate key issues associated with water availability, access and management, as an input to the formulation of a LIFT Dry Zone program.

In the Dry Zone of Myanmar, variability in water resources and insufficient capacity to manage that variability lies behind much of the prevailing poverty and food insecurity. Access to safe and reliable water, not just for agriculture (including livestock), but also for domestic use, is widely acknowledged to be a key constraint to livelihoods and peoples' wellbeing. Flooding is also an important factor negatively effecting livelihoods and economic development. This report describes a water resource assessment, conducted to provide information on water resources and describe the context in which decisions about water resources have to be made. Rainfall and available flow data were analysed and knowledge on surface water and groundwater resources, as well as irrigation, were reviewed.

Key findings from the water resources assessment include:

- A statistically significant reduction in rainfall amounts in June in recent years, combined with the very high variability in the onset date of the wet season, is likely to impede agricultural production by increasing the risk of drought at the beginning of the rainfed crop cycle. This vulnerability is particularly high in the central part of the Dry Zone including the townships of Natmauk, Kyaukpadaung, Meiktila, Kyaukpadaung, Chauk, Nyaung-U, Taungtha and Mahlaing.
- No statistically significant trends in: i) dry season rainfall; ii) onset and retreat of the wet season; iii) length of the longest wet season dry spell. Observed trends from 1966 to 2002 most likely reflect natural variability which is high and a major constraint to agriculture.
- There is considerable uncertainty in the area actually irrigated, with very different estimates from different studies. Based on an analysis of Google Earth images, the current study derived an estimate of actual dry season irrigation in 2011/12 of 256,578 ha. This includes both formal and informal irrigation.
- Current irrigation is primarily supplementary to extend the wet season growing period or protect wet season crops, rather than full dry season irrigation.
- Total surface water storage in, and close to, the Dry Zone is estimated to be approximately 8,780 Mm^3 (i.e. 7,760 Mm^3 in 60 large reservoirs and 1,020 Mm^3 in close to 2,000 small reservoirs).
- Estimated volumes of water used in irrigation (ca. 7,540 Mm^3y^{-1}) are very small compared to runoff (<3% of the total flow of the Irrawaddy). Currently, availability of surface water (from rivers and storage) is less limiting than access, due to costs of pumping and sparse infrastructure in areas remote from the major rivers.
- Current irrigation efficiency is very low with less than 5% of water abstracted actually transpired by crops. There is significant scope for improving irrigation efficiency and crop water productivity.
- In relation to groundwater, the current study does not support the view of great abundance, but rather suggests a more moderate resource (ca. 4,777 Mm^3y^{-1}): equivalent to approximately 50% of the current surface water storage and <2% of the total surface water resource. Water quality issues associated with salinity and arsenic are evident in some areas.
- Whilst extremely important for the Dry Zone, groundwater must be planned and developed carefully to ensure utilization over the long term. Nevertheless, it is estimated that annual groundwater recharge is sufficient to irrigate a further 110,000 ha to 300,000 ha of land.

Key recommendations are:

- *Strengthen strategic water resource planning*: A comprehensive analysis of the water sector (i.e. both surface and groundwater) and the development of a coherent development strategy to guide water resources investment in the future are urgently required to avoid piecemeal development with limited impact and high risk of unsustainable practices. This should include detailed reviews of irrigation efficiency and water and energy productivity in existing formal irrigation schemes to determine opportunities for improved operation.

- *Improve water-related data management*: There is an urgent need to establish an effective water-related data management system that comprises contemporary monitoring networks supported by appropriate data collection protocols and modern easily accessible databases and analyses tools. Although such a system should be nation-wide, a scoping study undertaken for the Dry Zone would be a useful initial step in developing such a system.
- *Invest in small-scale water harvesting and storage:* The construction of small reservoirs (tanks) that harvest water from a small catchment, while generally not sufficient for full dry season irrigation, can provide water for supplementary irrigation in the wet season (i.e. to bridge dry spells) and to prolong crop growth into the start of the summer dry season. Such reservoirs can make a substantial contribution to safeguarding wet season yields. To ensure sustainability, upstream watershed management (i.e. measures that reduce flood runoff and sediment transport) must be undertaken in conjunction with the construction/rehabilitation of embankments.
- *Invest in soil and water conservation:* Simple measures that enhance infiltration and water retention in the soil profile can stabilize and increase crop yields. Such techniques are likely to be most effective: i) around the periphery of the Dry Zone (i.e. in those townships where rainfall is generally greater and broadly sufficient to enable a non-irrigated wet season crop in most years); and ii) lowland areas that, in many years, already achieve a summer crop based on residual moisture. Such practices might also be beneficial in irrigation schemes where water *per se* is not limiting but the electricity costs of pumping make water conservation desirable.
- *Conduct a groundwater assessment*: Currently, groundwater is being widely promoted as a solution to water resource issues in the Dry Zone. However, comprehensive data about the locations, depths, extent and quality of suitable aquifers to develop has not been adequately compiled. Hence, the risks of unsustainable development are high. There is an urgent need to complete and update past surveys and provide detailed hydrogeological and hydrochemical maps using modern techniques of remote sensing and GIS where applicable. In particular further work is needed to determine the extent and prevalence of arsenic.
- *Develop groundwater appropriately*: Subject to the caveat above, this study confirms that in broad terms further opportunities for groundwater development exist and groundwater can beneficially supplement surface water development. For example, many of the formal irrigation schemes contain large areas that are currently not irrigable due to shortfalls in infrastructure development or energy supplies. In such cases, farmers are, on their own initiative, turning to shallow groundwater, using “private” wells powered by small motorized pumps. In this way, significant volumes of drainage created by the irrigation schemes can be recycled and used productively. Such examples of conjunctive development should be promoted - either as public or private initiatives - in places where it is practicable and can be achieved sustainably.

These recommendations were based primarily on the biophysical factors described within this report. They were complemented by the findings of a community level survey (Senaratna Sellamuttu et al. 2013). Based upon experience from elsewhere in the world they have been further elaborated in the studies final report (Johnston et al. 2013).

1. Introduction

This report relates to the challenge of managing water for inclusive and sustainable growth in the Dry Zone of Myanmar. Home to a population of approximately 14.5 million people (34% of the population of Myanmar), the Dry Zone is the most water stressed region of the country. Approximately 43% of households in the region live in poverty and it is one of the most food insecure areas in the country (JICA, 2010; WFP, 2011).

Against this background, LIFT is developing a program for the Dry Zone that will be implemented from 2013 to 2016. As water related concerns are known to have a strong bearing on food insecurity and low incomes in the Dry Zone, LIFT decided to undertake a rapid review of access to and management of water resources. This review implemented by IWMI will, in conjunction with the findings from other studies, contribute to the formulation of the LIFT program. The IWMI study was conducted to identify:

- key issues with regards to water availability, access and management
- existing activities being undertaken to address these issues
- priority actions (i.e. targeted interventions) to improve access and management of water

This report is one of three derived from the IWMI review. It comprises a water resource assessment of the Dry Zone. The other components of the study comprised:

- a community level survey to evaluate issues of water availability, access and management for local communities in villages in the Dry Zone as well as an evaluation of institutional arrangements in relation to farming strategies and water management practices (Senaratna Sellamuttu et al. 2013);
- an evaluation of current investments and how successful they have been in improving livelihoods and food security, as well as a review of lessons learned from other IWMI studies on agricultural water management solutions, in regions similar to the Dry Zone (Johnston et al. 2013).

In the past, an assessment of water resources (ESCAP, 1995) and more recently an agricultural water resources study (MOAI, 2003) have been conducted for the whole of Myanmar. Both address issues of water in the region but the study reported here is believed to be the first that focused solely on the Dry Zone. The objective of the assessment was to better understand the current state of the Dry Zone water resources, to gauge the impact of past and present water management practices and, through analyses of available data, to help facilitate future water resource planning. It presents data and information on the extent and magnitude, as well as patterns of usage of the Dry Zone water resources.

The water resource assessment comprised consultations and a desk study undertaken by IWMI in partnership with the National Engineering and Planning Services (NEPS). In Myanmar water resource development and management is dispersed across many government departments (Baw, 2011). Consequently, consultations were undertaken and data obtained from a number of national and regional government agencies, including:

- the Irrigation Department (Ministry of Agriculture and Irrigation - MOAI), which manages diversion irrigation schemes and flood defences;
- the Water Resources Utilization Department (MOAI) which manages pumped irrigation and rural water supply;
- the Department of Rural Development (Ministry of Border Affairs) which manages rural water resources;
- the Department of Human Settlement (Ministry of Construction) which is responsible for domestic water supply.

At the outset of the study an inception workshop was undertaken to identify key water resource problems and management issues in the Dry Zone. Held on 4-5 February 2013 a total of 40 people participated, representing key partners and stakeholders working in the Dry Zone, including NGOs, members of the Food Security Working Group (FSWG) and relevant government agencies. This confirmed that in the Dry Zone, variability in water resources and insufficient capacity to manage that variability lies behind much of the prevailing poverty and food insecurity. Water scarcity, not just for agriculture but also for domestic use, was identified as a key constraint to livelihoods and peoples' wellbeing. Flooding was also identified as a major hindrance. The workshop also highlighted that many interventions have been undertaken in the past with the government investing in major water storage and irrigation infrastructure and, a large number of NGOs working on a range of smaller-scale interventions. However, past development has generally occurred in a piecemeal fashion, largely through local initiatives, some of which have been successful and some of which have not. It is likely that the lack of integrated planning is one contributor to sub-optimal investments.

The desk study included analyses to add to the information gained from consultations and the inception workshop. Hydro-meteorological data (including available rainfall, evapotranspiration and river flow) and data on existing and planned water utilization and infrastructure development (including dams/irrigation schemes) as well as groundwater availability and use were collected. Some data were obtained from publically available regional and global datasets (e.g. rainfall data from the Aphrodite database and river flow data from the Global Runoff Data Centre). Data from global observation platforms were also used where appropriate (e.g. Google Earth Images and MODIS evaporation data). Other data were obtained from the Irrigation Department, the Water Resources Utilization Department as well as the Department of Meteorology and Hydrology. Because much of the data are not consolidated centrally in Myanmar this necessitated many visits to regional offices and responsible agencies. Analyses were further complicated by the fact that the way data are reported varies between regions and between agencies. As a result the depth of analysis and information presented in this assessment is limited not only by the data that could be collected during the relatively short duration of the project, but, in some instances, also by inadequacies in data interpretation. However, recognizing these constraints the assessment has, to the extent possible, determined:

- water resources (surface and groundwater) availability and use
- patterns, trends and variability in water quantity at different spatial and temporal scales
- statistics on water flows and water stores at key locations

A final project workshop was held on 28 June 2013, at which the preliminary study findings were presented to a range of stakeholders from the Government, Civil Society and donors. The findings and recommendations in an earlier version of this report were modified based on useful feedback obtained at this meeting.

The methods used to analyse the data are described in the relevant sections below. Chapter 2 provides an overview of the Dry Zone. Chapter 3 presents the results of analyses of spatial patterns in rainfall characteristics, as well as temporal trends in the historic data. Chapter 4 and 5 present a summary of surface water resources and groundwater resources respectively. Chapter 6 provides conclusions and recommendations.

2. Overview of the Dry Zone

2.1 Geographic setting

The Dry Zone is part of the central plain of Myanmar, sandwiched by the mountainous zone on the west, and the highlands on the east. It spreads across three divisions (formerly regions)—Sagaing (Sagaing, Shwebo and Monywa districts), Mandalay (Kyaukse, Myingyan, Meikhtila, Yamethin and Nyang-U districts) and Magwe (Pakokku, Magwe, Minbu and Thayet districts). The Dry Zone is mostly flat, with the Irrawaddy flowing through it from north to south (Figure 2.1). A range of hills (Bago Hills) runs parallel to the river in the southern part of the Dry Zone, gaining altitude towards the north and ending in southeast Mandalay. Fertile alluvial soil is found mostly along the banks of the Irrawaddy, with Sagaing Division having the largest area under alluvial soil, and Magwe Division the lowest (LIFT, 2011). The Bago hills are composed of sandstone, with less fertile sandy soil.

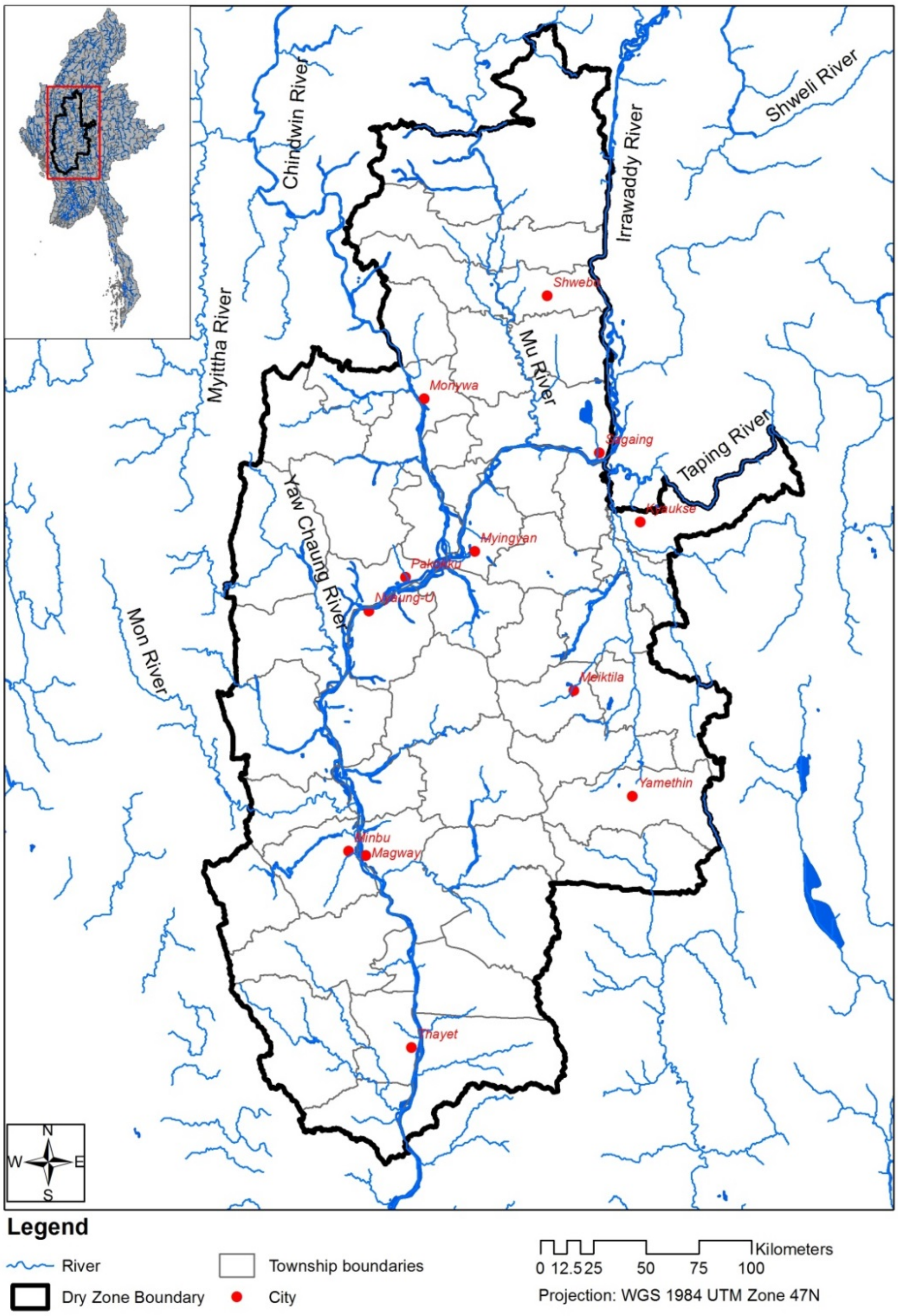


Figure 2.1: Map of the Dry Zone (boundary/townships as defined by MIMU: Map ID: MIMU983V01, March 2013)

2.2 Climate

The climate of the Dry Zone can be divided into two periods—the wet season and the dry season. The wet season coincides with the southwest monsoon and lasts from May to October. The dry season is divided into “winter” (November to February) and “summer” (March to April). Mean annual rainfall in the Dry Zone is lower than in the rest of the country, ranging from 500 to 1000 mm (LIFT, 2011). The Dry Zone also typically experiences a brief dry spell during the wet season in June/July. Figure 2.2 illustrates mean monthly rainfall and potential evapotranspiration, at Pakokku, close to the centre of the Dry Zone.

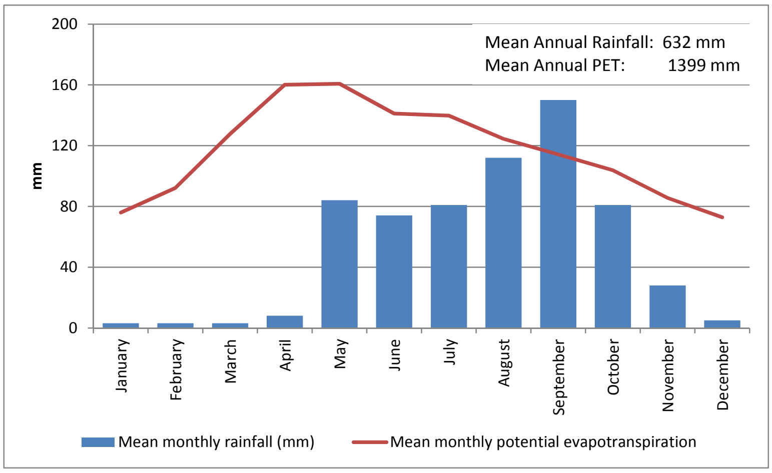


Figure 2.2: Mean monthly rainfall and potential evapotranspiration (mm) at Pakokku (source: FAO LocClim database)

Rainfall is typically associated with heterogeneity across space and time. Studies indicate that this variation is localized and largely not evident at higher levels of aggregation (JICA, 2010; LIFT, 2011; WFP, 2011; QSEM, 2012). Variation in quantity of rainfall occurs across space, with districts such as Shwebo, Meikhtila and Minbu receiving more rainfall than their neighbouring districts. This heterogeneity is more apparent at the township level. For example, for each year between 2001 and 2005 in Pakokku district, Pauk township received twice the amount of rain as Yesagyo township (JICA, 2010). Considerable temporal variation is also apparent at the township level. For instance, in Shwebo district, Kanbulu township received 1,244 mm of rain in 2004 but only 711 mm in 2005 (JICA, 2010). The starting date of the rainy season, typically in May, also varies from year to year. For example, Magwe district received around 240 mm in May 2000, but only 80-90 mm in May 2001.

2.3 Constraints to livelihoods and socioeconomic development

In the absence of irrigation, farming and crop yields are very sensitive to climatic variations. Casual labour is the most important income source in Mandalay and Magwe, followed by small-scale farming, while small-scale farming is the most important income source in Sagaing (QSEM, 2012). Both sources of income are affected by rainfall variability. The ability to grow a second crop largely depends on the timing of the monsoon (QSEM, 2011). Variability in the starting date of the monsoon and the quantity of rainfall has implications for crop yields. Insufficient rainfall results in fall in demand for casual labour, additionally impacting livelihood opportunities for the landless. Vagaries in the monsoon also impact secondary income activities such as jaggery production.

Seasonal migration is an important coping strategy, with earnings derived from migration, supporting consumption and improving livelihoods (QSEM, 2011; 2012). Pawning and selling of assets also forms an important coping strategy. Livestock is particularly important in this context. About 77% of the country’s goats and sheep are located in the Dry Zone, serving as a quick means of cash when needed. Expenditure-reducing strategies such as reduction in food intake and educational expenses are also employed.

Access to piped water for domestic use in the Dry Zone is low. Seasonal water scarcity affects water availability for domestic use in many households (Table 2.1). For example, a study of 630 households revealed that only 4% had piped water, with approximately 25% not having access to an improved water supply. As a result 38%

of households were at medium risk and 3% of households at high risk of drinking contaminated water (WFP, 2011). In this study, 19% reported sufficient water only in the wet and winter seasons and 5% report sufficient water only in the wet season (WFP, 2011).

Table 2.1: Salient facts (derived from a survey of 630 households) relating to household agriculture and domestic water supply in the Dry Zone (adapted from WFP, 2011).

Agriculture		**Domestic water**	
Access to agricultural land	61%	Access to improved water supply	73%
Average land holding (ha)	2.1	Piped	4%
Below Subsistence (<0.8ha)	22%	Borehole with pump	37%
Subsistence (0.8-1.2 ha)	14%	Protected well/protected source	32%
Above subsistence (>1.2 ha)	65%	Unprotected sources	26%
Access to Irrigation	28%	Other	2%
Owned	91%	Water available all year	77%
Rented in kind	8%	Water available during wet season and winter	19%
Rented in cash	7%	Water only available during wet season	5%
Other access	4%		

2.4 Agriculture and food security in the Dry Zone

A study conducted by UNDP in 2004, and updated by JICA in 2008 calculated two measures of poverty:

- a traditional poverty line (consumption expenditure per adult equivalent); and
- a food poverty line (the caloric requirement per adult equivalent per year).

As of 2008, 45% of the population of Mandalay, 27% of the population of Sagaing, and 44% of the population of Magwe were below the traditional poverty line. With respect to food poverty, 13% of the population of Mandalay, 8% of the population of Sagaing, and 14% of the population of Magwe were identified as food-poor. More recently, a study in 2011 of 630 households in Magwe and Mandalay revealed that about 17% of households were severely food insecure, and 24% moderately food insecure (WFP, 2011). Households with poor access to land and markets and those relying on casual labour were the most likely to be food insecure. Farming households were more likely to be food secure. However, in 2010, the food security of 41% of farming households was adversely affected by dry spells (WFP, 2011). Figure 2.3 illustrates the main factors affecting food security in the Dry Zone.

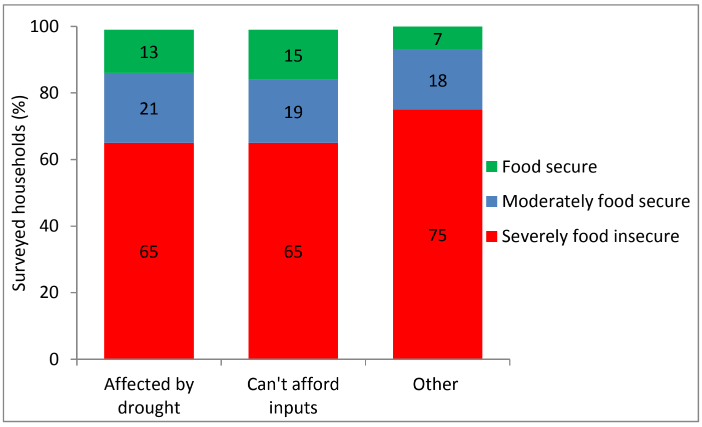


Figure 2.3: Factors adversely affecting food security in the Dry Zone (adapted from WFP, 2011).

Cropping is the main livelihood activity. About 22% of the annual paddy production of Myanmar is generated within the Dry Zone, with Shwebo district (Sagaing Division) having the highest per capita rice production in the Dry Zone (JICA, 2010). Magwe and Mandalay Divisions are classified as rice deficit regions, relying on rice transported from the Irrawaddy Delta and Shwebo respectively. Oil seeds are an important crop, with the Dry Zone accounting for 89% of Myanmar's sesame production, 69% of Myanmar's groundnut production, and 70% of the country's sunflower production. Pulses, largely for export to India, are also grown in the Dry Zone, accounting for 92% of the pigeon pea production, 97% of the chickpea production, and 52% of the green gram production of the country. Pigeon pea and chickpea production has steadily grown over time, partly due to the introduction of varieties with a shorter growing season. With the exception of onions, few vegetables are grown in the area. Cotton is a major crop, with 95% of the cotton produced in Myanmar originating in the Dry Zone.

The distribution of crop type and the number of crops per year varies across different parts of the Dry Zone, and depends on the type of land (e.g. high land, flatland, wetland etc.) and soil, the amount of rainfall, and access to irrigation. For example, in Kyaukpadaung township in Mandalay division, farmers without access to irrigation may grow a monsoon crop of sesame or green gram between April and July, followed by a short-season of late groundnut between October and February (CIAT, 2010). In Nyaung-U township, farmers with access to wetlands and/or access to irrigation usually grow monsoon paddy, followed by a post-monsoon crop of chickpeas or groundnut (LIFT, 2012). In Pakokku township, in areas with access to irrigation, groundnut is grown by almost all farmers, and rotated with green gram (LIFT, 2012). Examples of Dry Zone cropping calendars are shown in Figure 2.4.

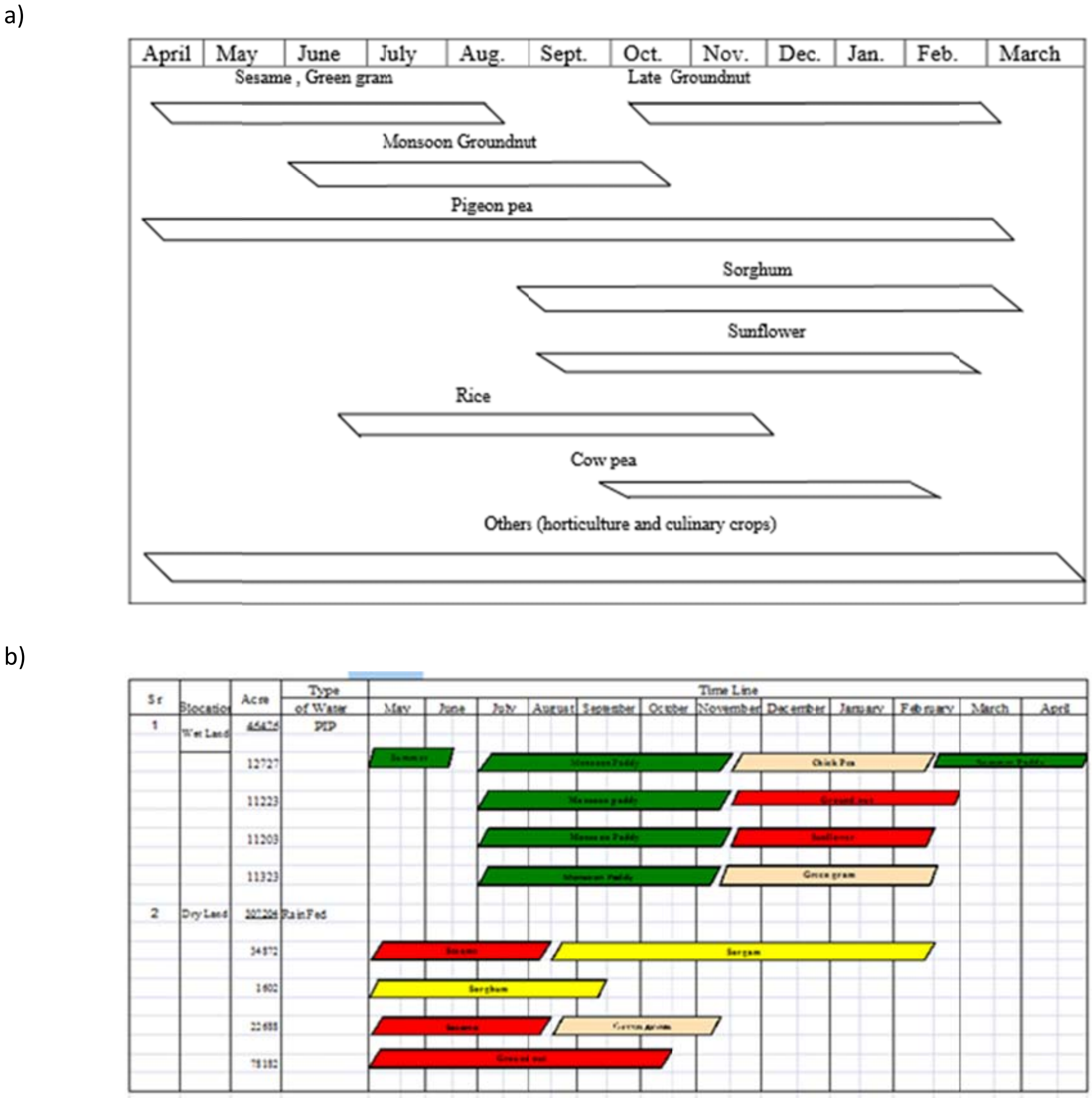


Figure 2.4: Typical Dry Zone cropping calendars: a) Kyaukpadaung Sub-District, Mandalay Division (source: Thein, 2009); b) irrigated and non-irrigated crops in Lat Pan Che Baw Pumped irrigation project, Nyaung U district (source: LIFT, 2012)

2.5 Experience with irrigation

Irrigation in the Dry Zone began in Shwebo district under the reign of Anawratha in the 11th century, who constructed a series of weirs and tanks to provide water for paddy rice. Under the British, some of the weirs created by the Burmese kings were replaced with permanent concrete diversions. However, the diversion weirs were functional only when the feeder streams were in full flow, thus enabling irrigation of only one crop a year. Between independence and 1962, irrigation weirs and tanks were added. Pumped irrigation schemes were initiated in 1962. Some of these pump from groundwater, but the majority of irrigation schemes financed by the government are surface water schemes. In Myanmar, gravity schemes are the responsibility of the Irrigation Department and pumped schemes, whether from rivers or from groundwater, fall under the remit of the Water Resources Utilization Department (WRUD). The "greening" of the Dry Zone has been a priority for the MOAI in recent years (MOAI, 2004). Though they tend to be a lot smaller in size there are also private and community irrigation schemes.

In addition to access to land, irrigation has been shown to be a significant contributor to increased food security in the Dry Zone (Figure 2.5). The WFP survey in 2011 indicated that only 28% of Dry Zone households had access to irrigation (Table 2.1). However, though it is not stated, this survey may have been biased because it is possible that villages included were purposively selected to be those not served by the formal irrigation schemes.

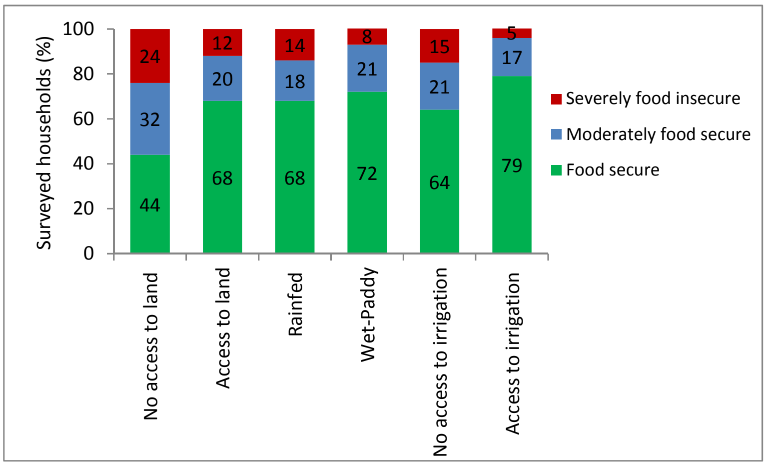


Figure 2.5: Food security status in relation to access to land and access to irrigation (adapted from WFP, 2011)

Reported problems with irrigation projects in the Dry Zone include inappropriate design that prevents adjustment of water supply according to variations in demand over seasons, incomplete tertiary canals and on-farm networks, unlined canals with high seepage, inappropriate crop choice (paddy) and irrigation method (basin) for soil-type, and lack of maintenance and monitoring (LIFT, 2011). Improved engineering, technical and extension support, changes to crop selection, and an increase in farmer involvement have been proposed as approaches to improve the performance of pumped irrigation projects.

3. Analysis of rainfall data

The Dry Zone is characterized by erratic rainfall. Both streamflow and food production are highly susceptible to rainfall variability. It is anticipated that climate change, in conjunction with increased population, may aggravate the imbalance between water demand and supply. However, currently, there is little understanding of how rainfall is spatially distributed within the Dry Zone and how rainfall patterns have changed or are changing over time.

Against this background, insights into the spatial rainfall pattern and historical rainfall trends are necessary for both agricultural and water development planning. However, detection of changes in time series of highly variable meteorological data is not straightforward, particularly in areas like the Dry Zone where rainfall generating mechanisms are complex and uncertain, and historic records are scarce.

Few studies have investigated rainfall patterns and trends in the Dry Zone. Throughout Myanmar it is reported that since the 1970s, the onset of the southwest monsoon has been increasingly delayed (i.e. later in the year) whilst simultaneously its withdrawal has been increasingly advanced (i.e. earlier in the year). Consequently, during the period 1988-2000, the average duration of the southwest monsoon was three weeks shorter in northern Myanmar and one week shorter in other parts of the country, when compared to the total period 1951-2000. Superimposed on the trend of shortening monsoon, the duration of rainfall events is reported to be decreasing and their intensity increasing in the Dry Zone (Lwin, 2002). However, it seems that to date no rigorous statistical analysis of past rainfall trends has been conducted in Myanmar.

The analyses described in this chapter were conducted to:

- characterize spatial variations in the main rainfall features of the Dry Zone;
- determine if these features have changed over time at specific locations, where long records are available.

3.1 Materials and Method

3.1.1 Data

In terms of accuracy, spatio-temporal coverage and resolution, the “Aphrodite” database is one of the best gridded rainfall databases for Southeast Asia (Yatagai et al., 2012). Unlike other gridded rainfall databases, Aphrodite includes algorithms which allow correction for topographic influences in data-scarce areas. In addition, the dataset includes metadata which enables the number of stations that were used to derive values of each grid cell to be verified. This information is particularly useful when investigating temporal trends. Selecting a period when a consistent network of gauging stations has been used avoids the possibility of artificial trends being created by using a network that varies over time. The grid has a spatial resolution of 0.25°×0.25° and covers the period 1951-2007.

Data files are available at http://www.chikyu.ac.jp/precip/. In this study the database APHRO_MA_V1101, which covers the whole of monsoonal Asia with a daily time step, was used. The domain restricted to the Dry Zone (Latitudes 18°-24° North; longitudes 93°-97° East) was extracted. Original binary files were converted into ASCII files, which were then restructured to become readable in a Visual Basic program used for trend investigations in several previous studies (e.g. Lacombe et al. 2012a, b). The trend analyses were conducted for the period 1966-2002. This period was selected because it corresponds to the highest density of actual rainfall records used to derive the interpolated/extrapolated data grid.

For purposes of comparison, records of annual rainfall depth obtained from 16 meteorological stations located in the Dry Zone were obtained. These data series generally extend from the early 1950s until 2009/2010. Since rainfall depths are originally reported in inches in Myanmar, these data were converted to mm by multiplying by 25.4.

3.1.2 Definition of rainfall variables

Rainfall variables capturing climate features that have an impact on agriculture and livelihoods were defined. These variables include: annual, seasonal and monthly rainfall depths, dates of the onset and retreat of the wet season, duration of the wet season, date and duration of the longest droughts occurring during the wet season. Coefficients of inter-annual variation were determined for all of these variables. The variables corresponding to the onset and retreat of the wet season and to the longest drought occurring during the wet season were defined as suggested by Lacombe et al. (2012a), though modified slightly to adjust to local climate features. Hence, the wet season onset was defined as the first day of the first 10-day period of the year that satisfies two conditions: i) the cumulative rainfall depth of this 10-day period exceeds 25.4 mm (i.e. a threshold defined by the Department of Meteorology and Hydrology, Myanmar; Aung and Thoung, 1985); and ii) at least two of the next three 10-day periods satisfy this condition. Due to the extreme temporal variability of precipitation, the 10-day precipitation depths were first smoothed by a 3-time-step moving average. The wet season retreat was defined by symmetrical conditions, starting from the end of the calendar year and moving backwards through 10-day periods. The duration of the longest drought occurring during the wet season was defined as the number of consecutive 'dry' days, with precipitation <2mmd^{-1}, during the wet season. These events are particularly harmful for farmers who grow rainfed crops as they can drastically reduce crop yields.

3.1.3 Production of rainfall maps

The annual values of each variable defined in section 3.1.2 were averaged for each cell of the studied domain, over the period 1966-2002, and were mapped (Figures 3.1 to 3.4).

3.1.4 Temporal trends in rainfall

The Mann-Kendall test (Mann 1945, Kendall 1975) was used to investigate trends in time series. This is the most frequently used trend detection test applied to hydro-meteorological time series. It is a non-parametric test which is robust because it does not require the data to follow any particular statistical distribution, and it has low sensitivity to outliers. However, like most trend detection tests, the Mann-Kendall test requires the data to be independent, since positive and negative auto-correlations induce overestimated and under-estimated significances of trend, respectively (Cox and Stuart 1955). In most cases, as indicated by the presence of multi-year wet and dry periods, climate time series are auto-correlated (Hurst 1951). To address this issue, an effective pre-whitening methodology was used. This consists of simultaneously estimating the slope trend and the autocorrelation coefficient using the ordinary least-square method and then correcting the bias in the correlation coefficient (Hamed 2009).

The trend tests were applied to rainfall values from 4 cells of the grid, selected because they correspond to the location of the rain gauges used to derive interpolated rainfall values in the studied area. The corresponding grid cells were identified using the metadata of the Aphrodite database. These locations correspond to the city of Shwebo, Mandalay, Yamethin and Magwe. An accurate comparison of the statistical significances at individual stations and over the region would require the statistical distribution of the test statistic to be derived by a re-sampling methodology (Lacombe et al. 2012b). However, using the original Mann-Kendall test in this study (relying on the fact that the statistical distribution converges to a normal law) induces only minor bias because the power of the re-sampling based and the original Mann-Kendall tests are similar (Yue and Pilon, 2004). Trend tests were also applied to the annual rainfall records derived from the 16 rain gauges.

3.2 Results

3.2.1 Spatial variability

Figure 3.1 displays the dates of the beginning and end of wet season and the duration of the wet season. The onset and retreat of the wet season happens later and earlier in the center of the Dry Zone, respectively, making it shorter in this area. Figure 3.2 depicts mean annual and seasonal rainfall depths within the Dry Zone. Peripheral areas of the Dry Zone are wetter than the center (between latitudes 20° and 22° and longitudes 94° and 95°) which receives, on average, less than 500mm rainfall in wet season and less than 600mmy^{-1}. The wettest areas of the Dry Zone receive up to 1,000mmy^{-1}. Surprisingly, the dry season is wetter in the center of the Dry Zone which displays the lowest annual rainfall depths. This paradox is due to the fact that the wet season (as defined in this study) is shorter in the center of the Dry Zone. Consequently, more light rainfall events occur during the dry season, most likely close to the onset and retreat of the wet season. This means that rainfall amount in the Dry Zone cannot be used by crops in rainfed areas as the rainfall pattern comprises many light rainfall events separated by long dry periods, preventing any agricultural benefit. Figure 3.3 shows that the date of the wet season onset is much more variable between years (i.e. less predictable) than the wet season retreat. This causes major challenges for farmers who don't have access to supplementary irrigation and rely on rainfall exclusively. In addition to the erratic behavior of the onset of the wet season in the center of the Dry Zone, Figure 3.4 shows that wet season dry spells are particularly long in the center of the Dry Zone. The longest dry periods generally occur in late July or early August. These observations confirm that there is a pronounced spatial variability of rainfall within the Dry Zone and that, for agriculture, the central Dry Zone is the harshest area.

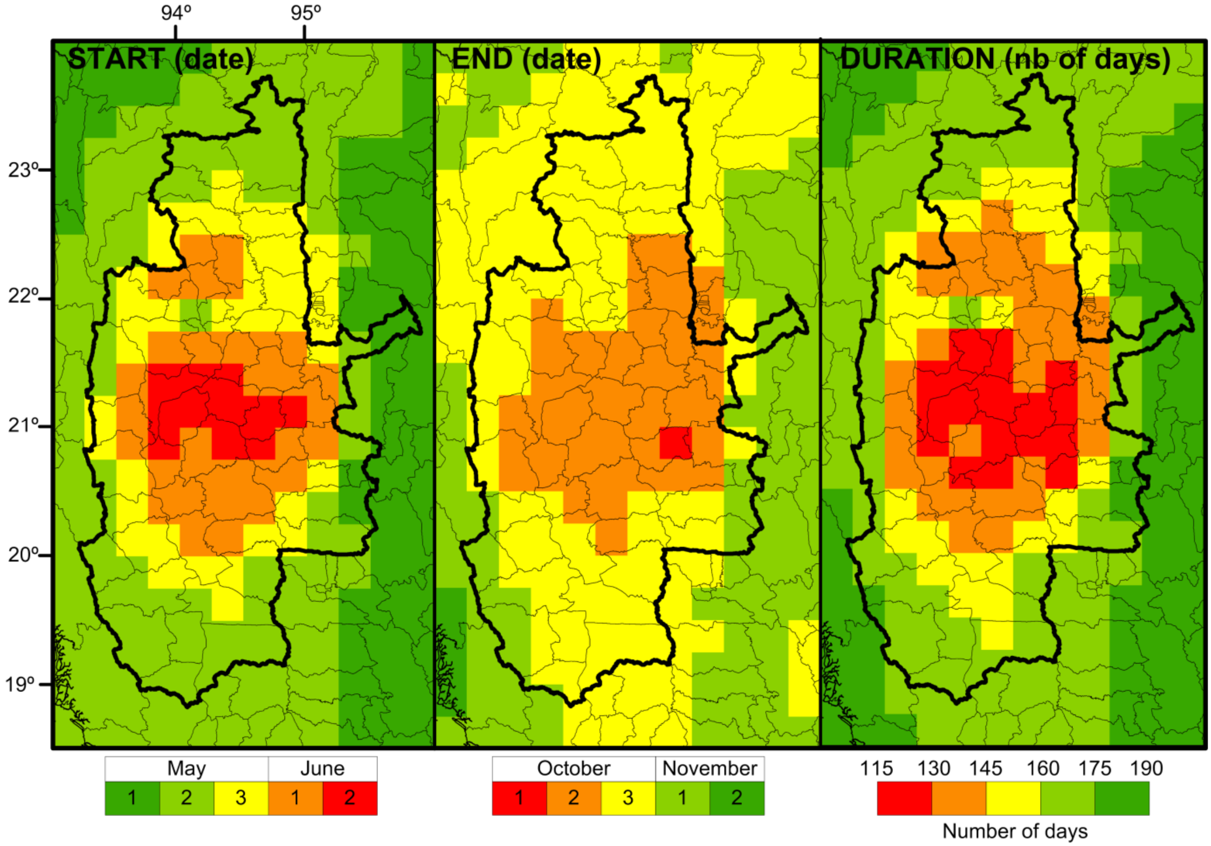


Figure 3.1: Occurrence and duration of the wet season in the Dry Zone (Dates are expressed as 1st, 2nd and 3rd 10-day period of the month)

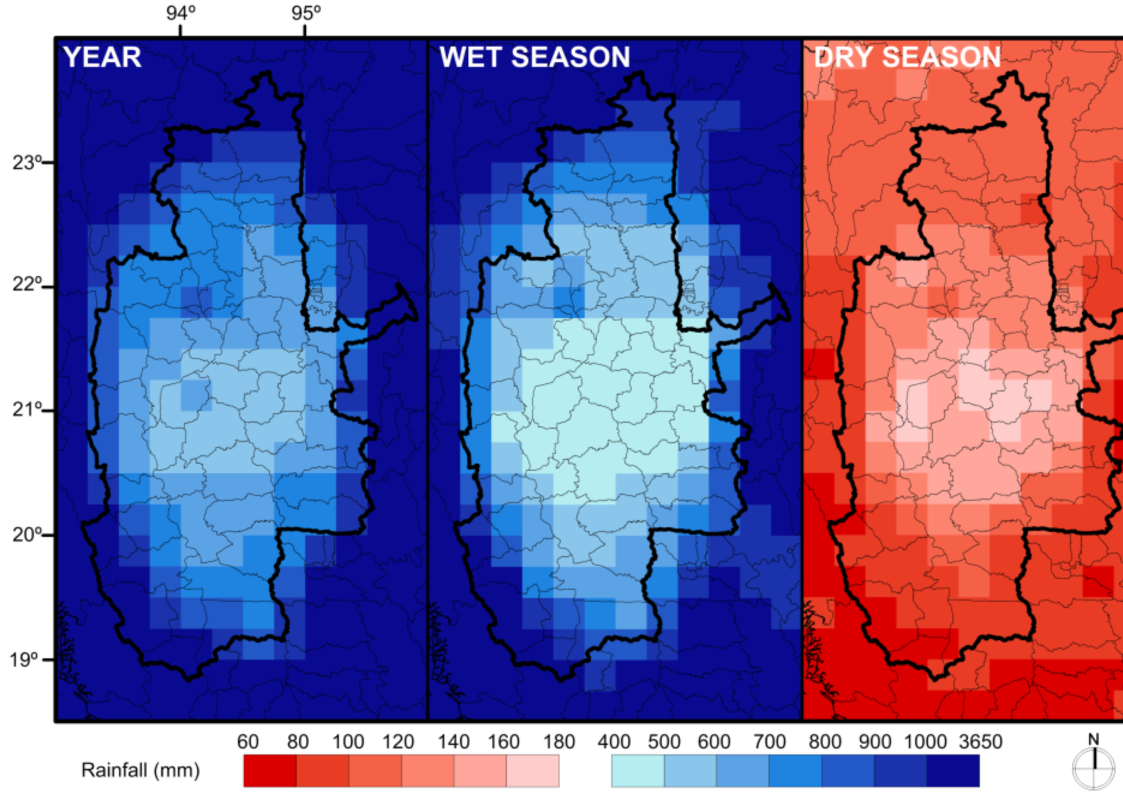


Figure 3.2: Spatial distribution of seasonal rainfall in the Dry Zone

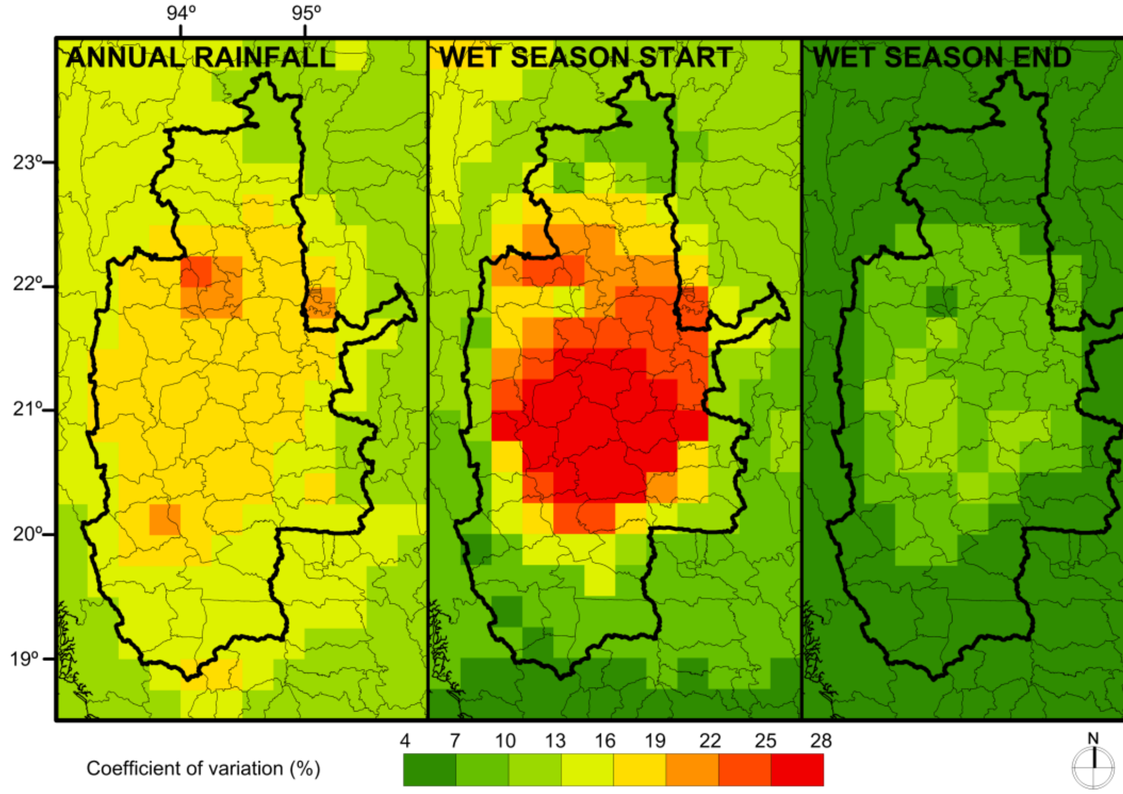


Figure 3.3: Inter-annual variability of annual rainfall (left panel), date of wet season onset (middle panel) and date of wet season retreat (right panel).

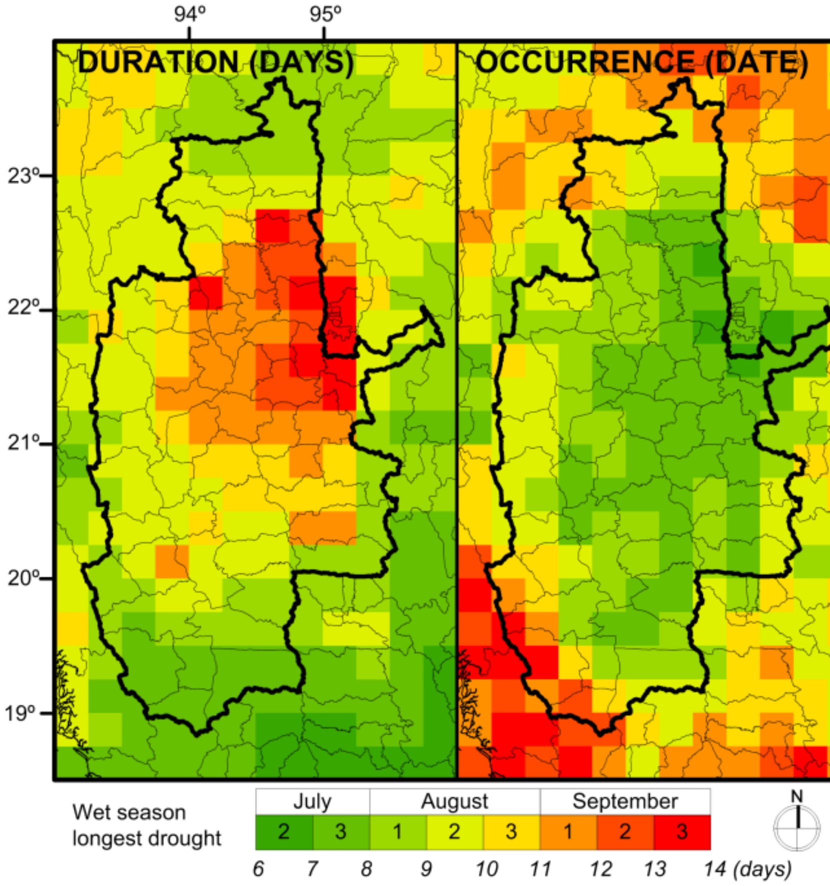


Figure 3.4: Duration (left panel) and occurrence (right panel) of the longest rainless period recorded during the wet season (Dates are expressed as 1st, 2nd and 3rd 10-day period of the month)

3.2.2 Temporal variability

Figure 3.5 displays mean monthly rainfall, trend slope, and statistical significances for monthly rainfall depths at the four locations selected. The seasonal distribution of rainfall is bimodal at the four locations, with a first peak in May or June and a second one in August or September. The occurrence of the reduced rainfall between the two peaks corresponds to the occurrence of the longest dry spell displayed in Figure 3.4. The results indicate a statistically significant (statistical significance >90%) decline in June rainfall in the northern part of the Dry Zone (i.e. Shwebo and Mandalay). This decrease is equivalent to a decline of about 50mm of rainfall between 1966 and 2002 (i.e. equivalent to about 50% of mean June rainfall). Figure 3.5 shows that there is a statistically significant increase in March rainfall at the 4 locations (statistical significance >90%) but trend slopes remain moderate ($<0.1 mmy^{-1}$), and because rainfall at this time of year is very low, there is not a large absolute change.

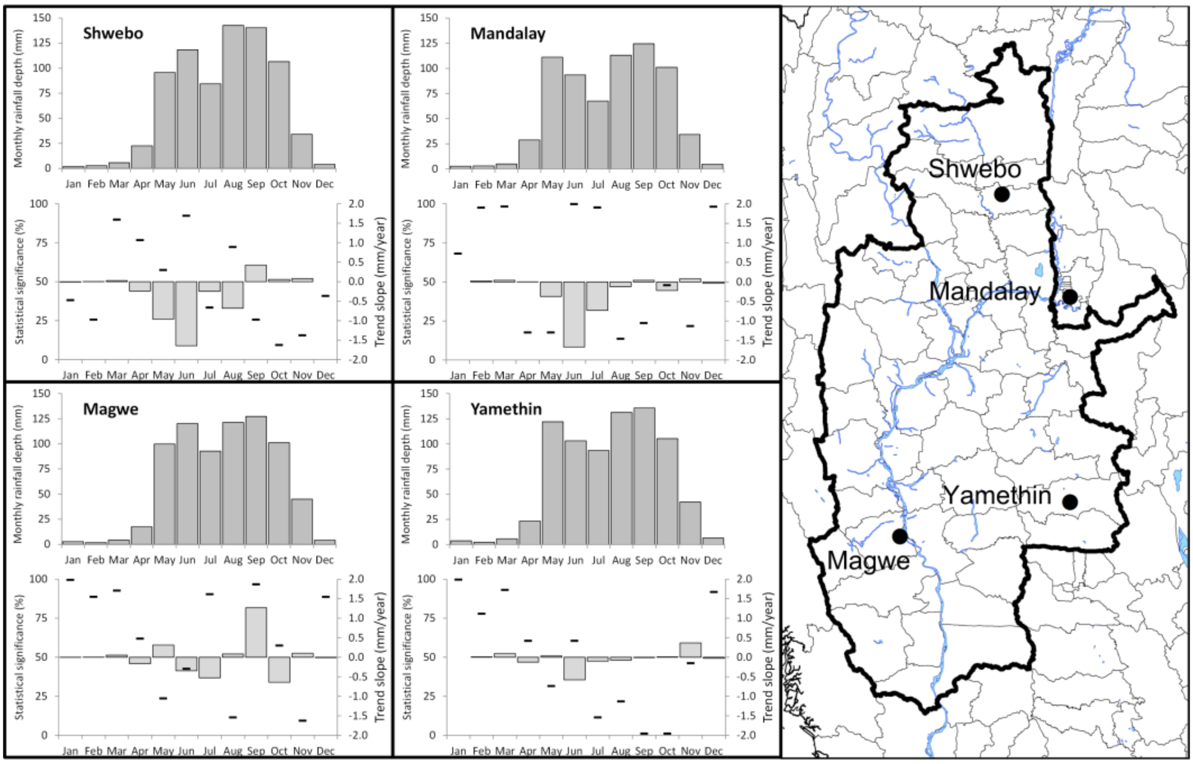


Figure 3.5: Mean monthly rainfall pattern at four main rainfall gauging stations and associated trend slope (grey bars) and statistical significance (dashes) computed over the period 1966-2002

Figure 3.6 displays annual time series of seasonal rainfall depths and dates of the wet season onset and retreat, and associated temporal trends. The results indicate a statistically significant decrease in wet season rainfall in the northern stations (i.e. Shwebo and Mandalay). This is consistent with the decrease in June rainfall observed at the same stations (Figure 3.5). No significant trends are observed for the dry season. This is consistent with the fact that significant trends for dry season months involve very small rainfall amounts (e.g. January, February and March cf. Figure 3.5). Despite a high inter-annual variability in the dates of wet season onset and retreat (Figure 3.3), no trend was observed over the long-term. This result apparently contradicts the findings of Lwin (2002). Possible causes for such discrepancy are numerous but most likely related to the spatio-temporal variability of rainfall and the methodology. Lwin (2002) may have used different stations and investigated changes over different periods and furthermore may not have accounted for auto-correlation. No significant trends were observed in the length of the longest wet season drought at any station (not displayed).

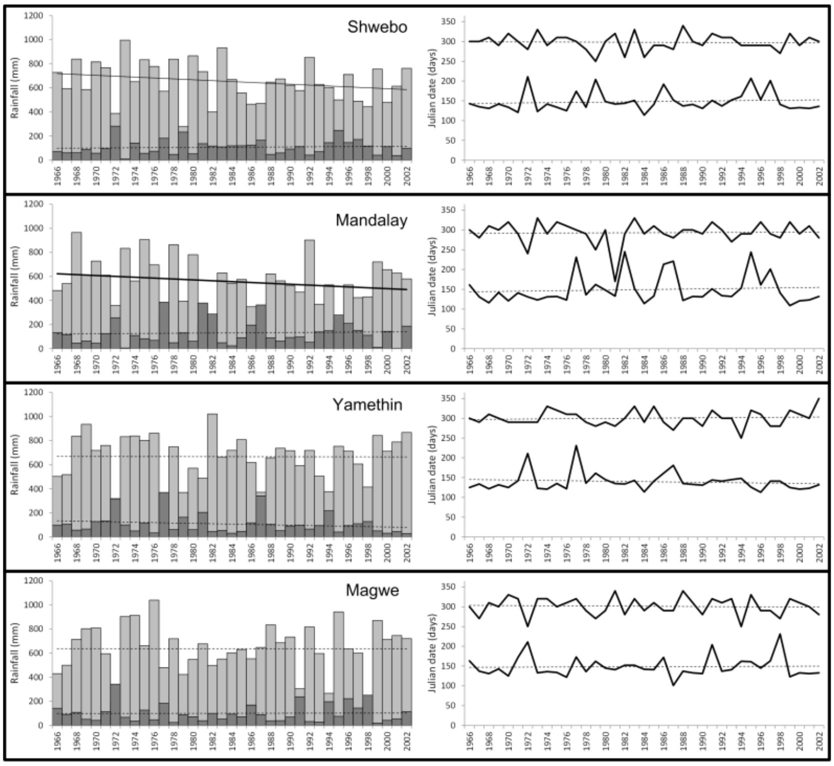


Figure 3.6: Left panel: annual time series of seasonal rainfall depth (light grey bars = wet season. dark grey bars = dry season). Right panel: annual time series of wet season occurrence (bottom curve = wet season onset. top curve = wet season retreat). Dotted line= insignificant trend. Solid line = 90% significant trend. Bold solid curve = 99% significant trend

3.2.3 Comparison with rain gauge data

Annual rainfall time series derived from both the rain gauges and the Aphrodite database were compared at four locations: Shwebo, Mandalay, Yamethin and Magwe. (Figure 3.7; Table 3.1). In general, annual rainfall depths observed at individual stations are greater than those derived from the Aphrodite database. This difference varies from 5% at Magwe to 18% at Mandalay. It is possible that these differences are partially an artefact of the conversion from inches to mm. However, the R values presented in Table 3.1 indicate that discrepancies between the two time series at each of the four locations are not only consequence of a scaling coefficient, since in this case R would be close to 1. Other possible reasons for the discrepancy include the spatial variability of rainfall (Aphrodite time series correspond to grid cells not point locations), the interpolation methods to generate the Aphrodite gridded data and any errors in the rain gauge time series. These cannot be assessed without access to metadata information.

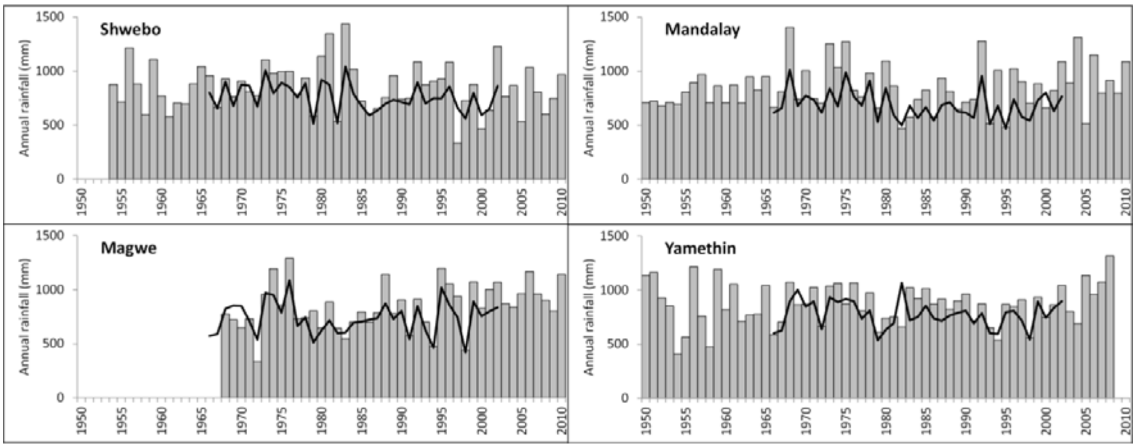


Figure 3.7: Comparison of annual rainfall derived from Aphrodite data base (black curve) with individual rain gauge records (grey bars), at four locations

Table 3.1: Multi-year averages and trend significance in annual rainfall at four individual stations over the reference period 1966-2002 and the full available record depicted in Figure 3.7.

		Magwe			Shwebo			Mandalay			Yamethin		
		APH*	RG*	R*	APH	RG	R	APH	RG	R	APH	RG	R
Rainfall average	1966-2002	738	773	85%	759	864	84%	689	843	83%	774	847	67%
	Full record		843			848			843			867	
P-value of trend+	1966-2002	0.25	0.10		-0.07	-0.24		-0.13	-0.25		-0.24	-0.24	
	Full record		0.01			-0.30			0.16			0.45	

*APH: Aphrodite data; RG: rain gauge data; R: correlation coefficient

+ The P-value provides information on the statistical significance of the trend. The greater the statistical significance the closer the P-value is to zero. A negative P-value corresponds to a negative trend and a positive P-value to a positive trend.

Comparing the annual rain gauge data, averaged over the period 1966-2002 and over the full available record, indicates that there is not much difference for Shwebo (1.8%), Mandalay (0.0%) and Yamethin (2.4%). However, at Magwe, the period 1966-2002 is clearly drier (9.1% less rainfall) than over the full record. Over the period 1966-2002, the rain gauge and Aphrodite data indicate the same direction in trends (i.e. p-values have the same sign) at all four locations: a rising trend at Magwe and declining trends at Shwebo, Mandalay and Yamethin. The rain gauge data indicates greater statistical significance than the Aphrodite data at Magwe, and vice-versa at Shwebo and Mandalay. At Yamethin the statistical significance in the trend is the same for both datasets. Over the period 1966-2002, the only significant trend at the 90% confidence level is positive and at Magwe. Over the full record, trends in the rain gauge time series are more significant at Magwe and Mandalay and less significant at Shwebo and Yamethin. Only the Magwe trend is highly significant (statistical significance =99%) over the full length of record.

3.3 Main findings

In this study, both the number of available rain gauges (16) and the length of available record (37 years) were limited. Therefore, results of the present analysis should be interpreted with caution. The time period is too short to attempt to attribute the observed trends to any specific cause. For example, the decrease in wet season rainfall observed in the northern part of the Dry Zone could reflect a natural multi-decadal cycle, rather than a long-term and unidirectional change induced by anthropogenic activities. The comparison of results derived from the Aphrodite data with the longer time series of annual rainfall from rain gauges (i.e. extending until 2010), does not show any regional consistency. This suggests that observed trends from 1966 to 2002 mostly likely reflect the natural variability.

According to the analyses conducted, the major change that occurred in recent decades is a significant reduction in rainfall amounts in June. Combined with the very high variability in the onset date of the wet season, this change is likely to be impeding agricultural production by increasing the risk of early drought at the beginning of the rainfed crop cycle. This vulnerability is particularly high in the central part of the Dry Zone including the townships of Natmauk, Kyaukpadaung, Meiktila, Kyaukpadaung, Chauk, Nyaung-U, Taungtha and Mahlaing. Another important result, depicted in Figure 3.1 and Figure 3.2, is the relatively short wet season in these same townships.

No statistically significant trends were found in: i) dry season rainfall; ii) onset and retreat of the wet season; iii) length of the longest wet season dry spell. However, the results do confirm that both relatively low rainfall and rainfall variability are key constraints to rainfed farming, particularly in the centre of the Dry Zone. Lack of predictability both in the amount and timing of rainfall makes rain-fed farming extremely difficult.

4. Surface water resources

4.1 River Flows

Surface water in the Dry Zone is dominated by the Irrawaddy River and its tributaries. The Irrawaddy River, which originates in the north of Myanmar in Kachin state, flows through the Dry Zone, from the north-east to the south. In the north it effectively forms the eastern boundary of the Dry Zone, before flowing west-south-west from Mandalay and then resuming its southerly flow at Bagan. The Chindwin a major tributary enters the Dry Zone to the north of Monywa and flows south to its confluence with the Irrawaddy to the north-west of Pakokku, almost in the centre of the Dry Zone (Figure 2.1). There are several other large tributaries, including the Mu, Shweli and Myitnge. Some of these rivers flow all year but many are seasonal (Table 4.1).

Table 4.1: Summary characteristics of the main Irrawaddy tributaries in the Dry Zone (from ESCAP, 1995)

Name	Catchment Area (km^2)	Average annual flow at confluence (Mm^3)	Annual runoff (mm)+
Chindwin	115,300	153,786	1,334
Mytinge	29,630	24,000??	810
Shweli	29,630	24,000??	810
Mon	5,993	2,800	467
Yaw	6,669	2,300	345
Tapaing	3,429	7,213	1,303
Mu	18,840	7,200	382
Myittha (flows into Chindwin)	24,030	19,000	791

+ Runoff values are based on flow and catchment area data published in ESCAP 1995. However, in some basins (e.g. Chindwin and Tapiang in particular) runoff appears to be exceptionally high. This suggests that estimated flows should be treated with caution.

These rivers provide water for irrigation and in some places for floodplain recession agriculture. There are opportunities for gravity diversions but some of the river courses are deeply incised into the landscape so that water for irrigation has to be derived by pumping.

Throughout the wet season water levels are measured at key locations to provide flood warning alerts (Figure 4.1). However, few measurements are made in the dry season and rating equations are scarce. Consequently, very few of the data are converted to river flows and so are of little value for assessment of water resources. Some average monthly river flow estimates were obtained from the Irrigation Department for different locations on the Chindwin and Irrawaddy Rivers. However, daily flow data were only available from the Global Runoff Data Centre (GRDC) for two locations, the Chindwin at Hkamti (located to the north of the Dry Zone) and the Irrawaddy at Sagaing (located upstream of the confluence of the Irrawaddy and Chindwin).

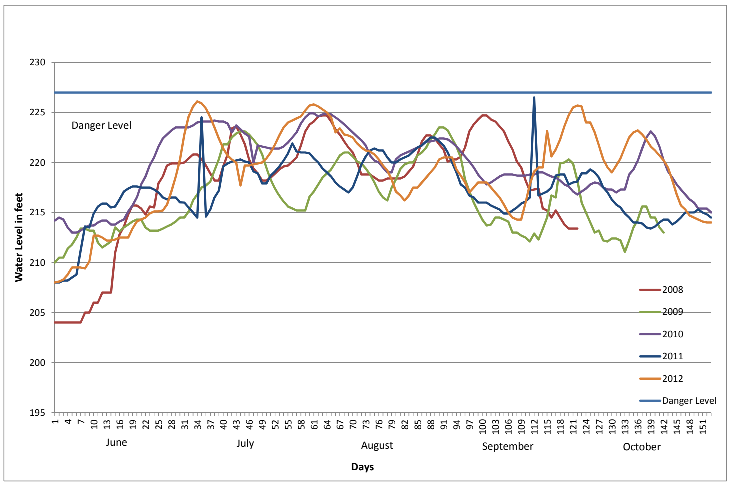
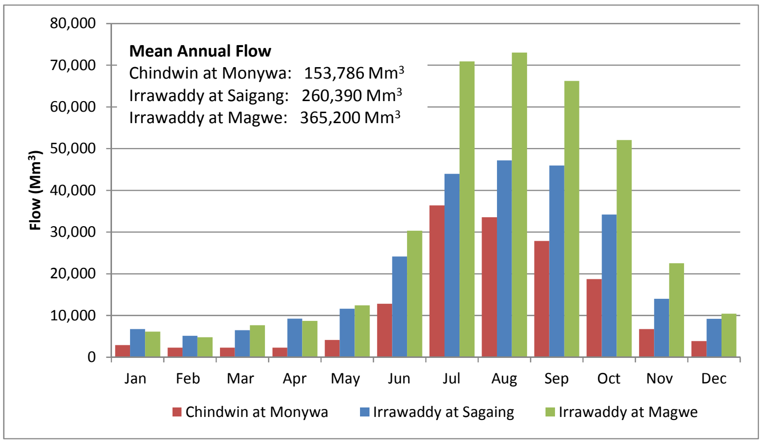


Figure 4.1: Wet season water levels measured in the Irrawaddy River at Mandalay (2008-2012) (Source: Irrigation Department)

Figure 4.2 presents the mean monthly flow for the Chindwin at Monywa and the Irrawaddy at Saigang (i.e. upstream of the confluence with the Chindwin) and at Magwe (i.e. downstream of the confluence with the Chindwin). It illustrates the considerable seasonal variation on both rivers: on average 83% of the flow of the Irrawaddy at Saigang and 86% of the flow of the Chindwin at Monywa occurs during the wet season (i.e. May to October).



	Chindwin at Monywa	Irrawaddy at Sagaing	Irrawaddy at Magwe
Jan	2,893	6,766	6,163
Feb	2,263	5,136	4,806
Mar	2,253	6,477	7,652
Apr	2,268	9,234	8,696
May	4,122	11,614	12,433
Jun	12,836	24,141	30,329
Jul	36,407	43,945	70,897
Aug	33,542	47,192	73,008
Sep	27,841	45,968	66,236
Oct	18,754	34,223	52,033
Nov	6,778	14,019	22,532
Dec	3,830	9,213	10,414
Total	153,786	257,928	365,200

Figure 4.2: Mean monthly flow (Mm^3) of the Chindwin at Monywa and the Irrawaddy at Sagaing and Magwe (derived from data provided by Department of Irrigation)

Figure 4.3 and Figure 4.4 present the hydrographs and flow duration curves of daily flow for the Chindwin at Hkamti and the Irrawaddy at Sagaing, respectively. Both have been derived from the GRDC daily data for the 10 year period 1978 to 1988. The hydrographs again illustrate the considerable seasonal variability but also the inter-annual variability in river flows. The flow duration curves show the relationship between any given discharge and the percentage of time that flow is equalled or exceeded at the location of interest (Shaw, 1984): the steeper the curve the more variable the flow.

Figure 4.5 shows the flood frequency curves for both gauging stations. Again these were derived from the 10 years of daily GRDC flow data. Flood frequency analysis entails the estimation of the peak discharge that is likely to be equalled or exceeded on average once in a specified period, T years. This is the T-year event and the peak, QT is said to have a return period or recurrence interval of T years. Deriving flood frequency curves involves fitting a statistical distribution to the series of annual maximum flows, ranked by the magnitude of flow. In this study, instantaneous maximum discharges were not available and so the maximum mean daily discharges were used. A number of probability distributions have been investigated for application to maximum flood series. In this case the extreme value-1 (EV-1) distribution, fitted using the method of moments, assuming stationarity in the mean and variance of the time series, was used. Although only 10 years of data were available, the flood frequency curve was extrapolated to T = 100 years. The results indicate the high magnitude of flood flows that occur on both rivers, but particularly the larger Irrawaddy River.

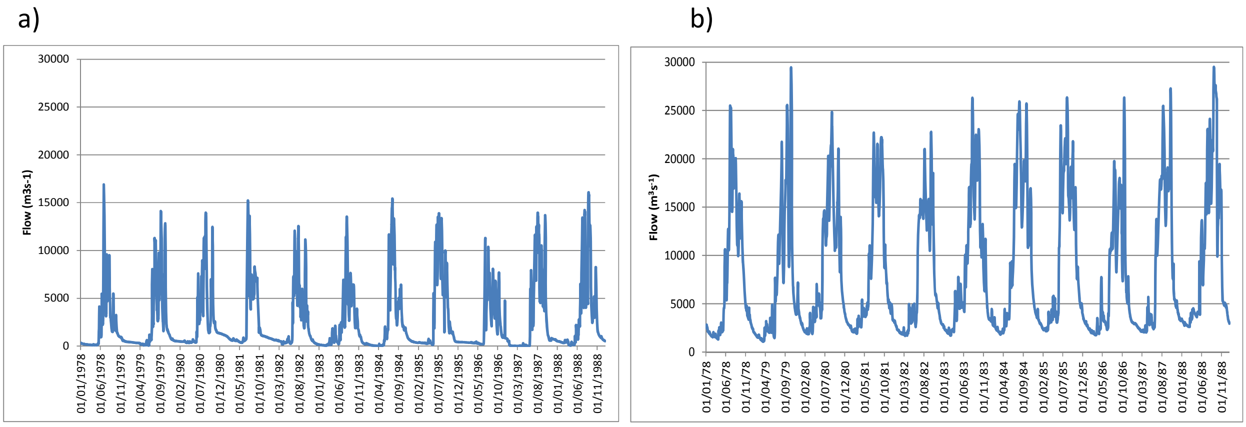
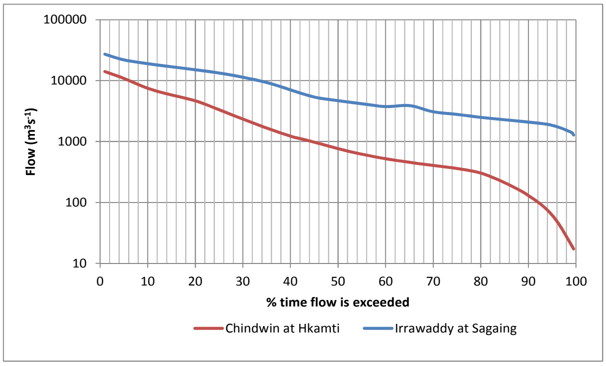


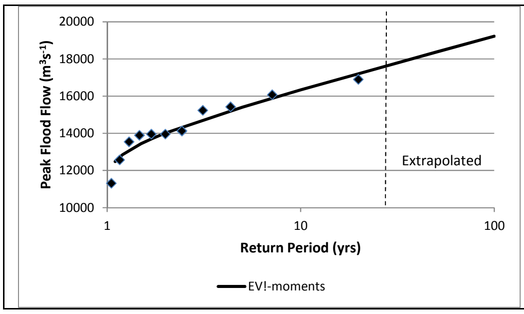
Figure 4.3: Time series of daily flow of: a) the Chindwin at Hkamti and b) the Irrawaddy at Sagaing



Percentile	Flow (m^{3}s^{-1}) Chindwin at Hkamti	Irrawaddy at Sagaing
99	20	1,417
95	62	1,846
90	130	2,086
75	360	2,788
50	764	4,689
25	3,326	13,350
10	7,479	18,974
5	10,873	21,891
1	14,082	27,106

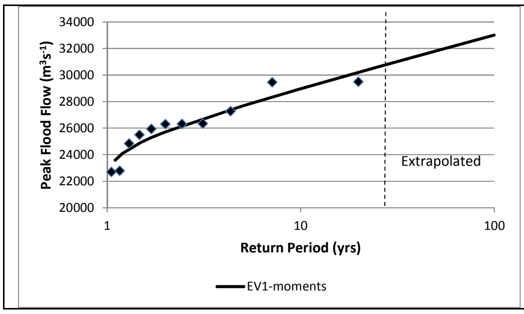
Figure 4.4: Flow duration curves for the Chindwin at Hkamti and the Irrawaddy at Sagaing

a)



Return period (yrs)	Flood Magnitude (m^{3}s^{-1})
1.1	12,478
2	14,007
5	15,404
10	16,329
25	17,497
50	18,365
100	19,225

b)



Return period (yrs)	Flood Magnitude (m^{3}s^{-1})
1.1	23,585
2	24,929
5	25,722
10	28,966
25	30,599
50	31,810
100	33,012

Figure 4.5: Flood frequency curves for: a) the Chindwin at Hkamti and b) the Irrawaddy at Sagaing

4.2 Runoff and storage

In the agricultural water resources study of Myanmar, estimates of runoff from different districts were made (MOAI, 2003). These were developed from “standardized” rainfall-runoff relationships of the sort shown in Figure 4.6. In addition to annual curves, similar curves have been developed for the wet and dry season. These curves are believed to be used in the design of small-scale storage (i.e. small reservoirs and tanks) and provide the only estimates of local runoff (Table 4.2). Exactly how the curves were derived is not clearly explained, but it seems that they are observed river flows converted to runoff “yield” by dividing by the area of the hydrological catchment contributing to the flow at that point. Within the catchments runoff “isolines” (i.e. lines of the same runoff) were then delineated. Finally, district boundaries were demarcated and runoff coefficients assumed depending on the location of the district in relation to the isolines. This makes only limited allowance for spatial variation in runoff within a hydrological catchment and consequently the results should be treated with caution. Nevertheless, they are the only estimates of runoff that are currently available.

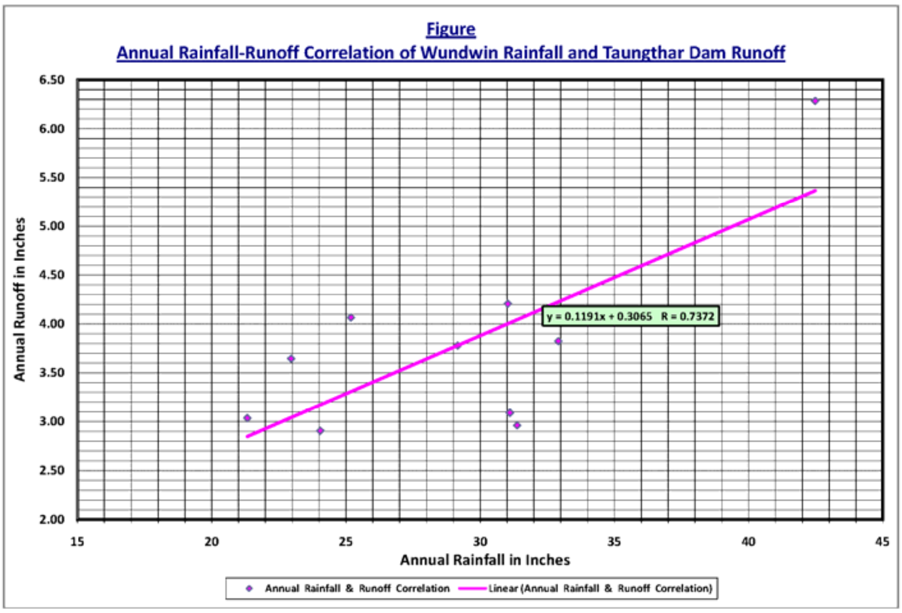


Figure 4.6: Example of rainfall-runoff relationship (source: MOAI)

In the Dry Zone, a large number of small reservoirs, ponds and tanks have been constructed by the Irrigation Department. These comprise small earth embankments as well as cavities excavated in the ground to store water. Some provide water only for domestic use, but others are also used for small-scale irrigation, and livestock drinking. In recent years, NGOs such as ActionAid, ADRA and Proximity have been working to construct and rehabilitate many of these structures. The exact location of many are not recorded but regional offices of DOAI have estimates of the number and the total irrigable area associated with the small reservoirs/ponds in each township (Figure 4.7).

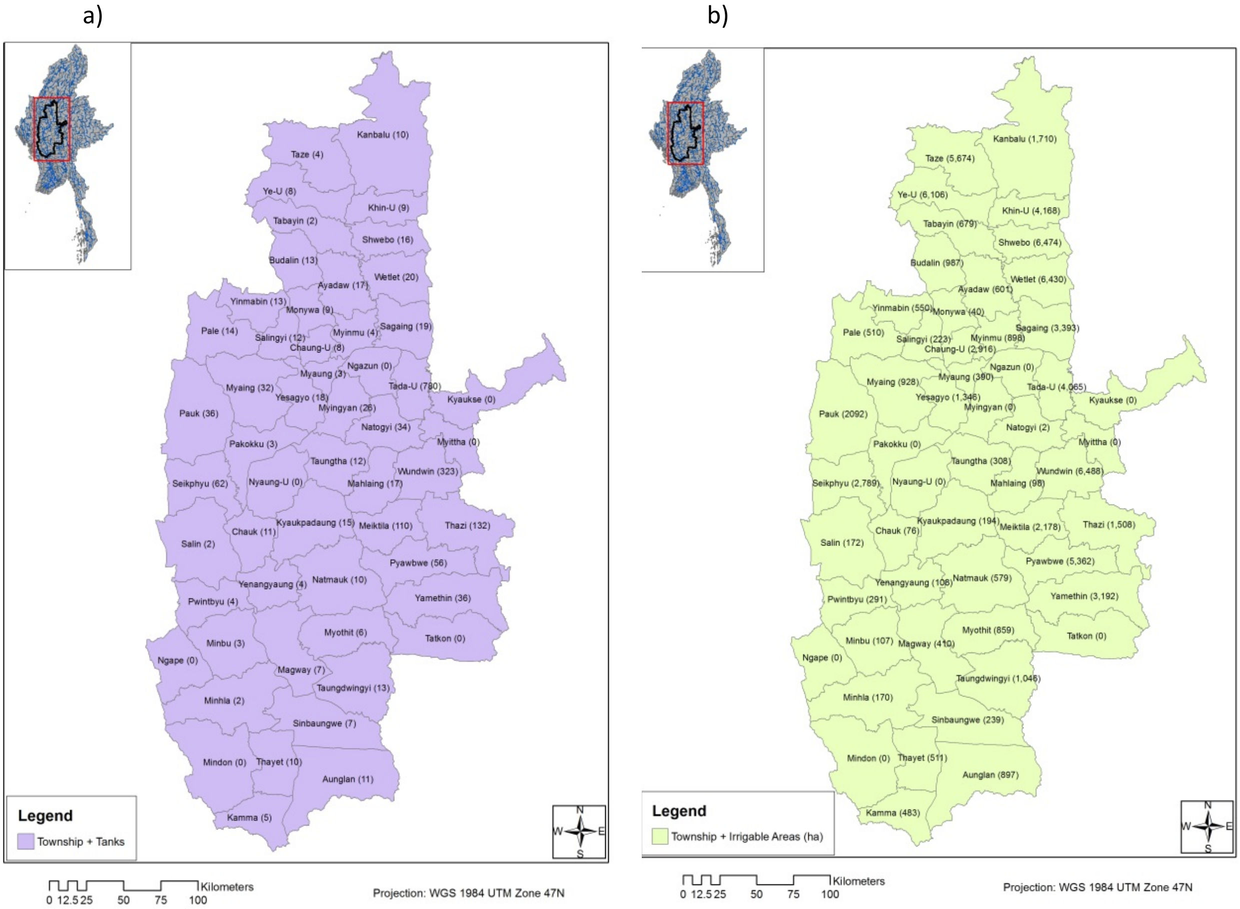


Figure 4.7: a) The number of small reservoirs and tanks in each of the townships of the Dry Zone; b) The irrigable area downstream of small reservoirs and tanks in the Dry Zone (source Regional offices of DOAI).

Table 4.2 presents a summary of the runoff and the cumulative small storage (individual reservoirs and tanks up to 1 Mm^3) in the districts of the Dry Zone. Individual large reservoirs (> 1 Mm^3)[1] located both in and close to the Dry Zone are presented in Table 4.3 and Figure 4.8. Total storage capacity is estimated to be approximately 8,780 Mm^3 (i.e. 7,760 Mm^3 in 60 large reservoirs and 1,020 Mm^3 in close to 2,000 small reservoirs).

Table 4.2: Estimated runoff/small reservoir storage in each district of Dry Zone (adapted from MOAI, 2003)

Division	District	Area (km^2)	Runoff (Mm^3)			Number of small reservoirs+	Storage (Mm^3) (excluding large reservoirs)	Storage as a % of runoff
			Dry Season	Wet Season	Total			
Sagaing	Shwebo	14,877	1,126	3,522	4,648	73	25	0.5
	Sagaing	2,484	177	532	710	26	6	0.9
	Monywa	10,041	956	7,174	8,130	92	91	1.1
Magwe	Pakokku	8,327	198	1,537	1,735	151	33	1.9
	Magwe	9,630	459	4,130	4,588	51	193	4.2
	Minbu	9,314	887	5,544	6,432	9	5	0.1
	Thayet	11,971	855	5,701	6,557	35	2	0.0
Mandalay	Kyauk Se	4,157	247	693	940	780	16	1.7
	Meiktila	5,789	276	965	1,241	582	261	21.0
	Myingyan	6,415	153	620	773	87	213	27.6
	Nyaung U	1,484	35	176	212	-	11	5.4
	Yamethin	10,878	518	2,613	3,131	92	165	5.3
				Total	**39,097**	**1,978**	**1,021**	

+ Data obtained from regional office of MOAI

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[1] The standard definition of a large reservoir is >3 Mm^3 (ICOLD, 2003). However, since data exist 1 Mm^3 was selected for this study.

Table 4.3: Large (>1 Mm^3) reservoir storage located in, and in the vicinity of, the Dry Zone

Region	District	Dam	Location		Storage capacity (Mm^3)
			Latitude (N)	Longitude (E)	
Sagaing	Shwebo	Thaphanseik	23°18'37.01"	95°20'27.28"	3,552
		Kyibinalk	23°5'28.78"	95°39'56.04"	54
		Koebin	22°40'1.62"	95°42'27.46"	12
		Paygyi	23°0'49.11"	95°38'14.99"	12
		Linpan	23°08'48.43"	95°31'26.95"	1
	Sagaing	Letpan	-	-	6
	Monywa	North Yama modulating dam	-	-	152
		North Yama	-	-	17
		Nwekhwe	-	-	4
		Ngwetha	-	-	19
		Salingyi	-	-	6
		Phaunggada	-	-	8
		Tharzi	-	-	8
		Htanzaloke	-	-	3
		Ayadaw	-	-	8
		Myothit	-	-	9
		Hlaingchaung	-	-	7
		South Yama	-	-	2
Magwe	Pakokku	Sabae	21°17'33.31"	94°48'22.39"	2
		In Beck	21°24'48.76"	94°46'55.52"	1
		Lapana	21°45'35.90"	94°54'58.29"	2
		Twin Ma	21°26'09.21"	94°47'23.40"	2
		Kyet Mauk	21°42'02.29"	94°49'20.57'	1
		Myaing Chaung	21°36'55.99"	94°48'58.23"	5
		Thi Ri Nanda	21°34'27.44"	94°52'31.90"	2
		Thit Kyi Taw	21°31'19.45"	94°52'39.27"	1
		Mye Khe Taung	21°33'10.41"	95°09'16.99"	4
		Khin Mon	21°36'08.36"	95°07'54.04"	3
		Gwe Cho	21°29'43.29"	95°09'58.48"	2
		Sin Chaung	21°31'31.59"	95°09'12.79"	4
		Nga Chin	21°05'05.73"	94°29'05.94"	1
		Wun Chaung	20°59'10.89"	94°24'33.90"	2
		Wun Yu	21°00'31.21"	94°26'15.96"	4
		Tagun	21°00'53.25"	94°32'06.47"	1
		Taung Khin Yan	22°06'02.39"	94°01'36.46"	14
	Magwe	Kyauk taga	20°42'10.18"	95°28'05.22"	51
		Lay Daing Zin	20°26'44.27"	95°09'24.36"	6
		Na Ga	20°23'41.77"	95°10'03.51"	8
		Kin Mun Daung	19°54'32.49"	95°41'36.16"	13
		Kwan Daw Gyi	20°00'59.09"	95°33'06.85'	2
		Ban Gon	19°51'07.06"	95°43'06.95"	9
		Nga Min	20°02'07.99"	95°39'04.28"	10
		Yan Pe	19°47'21.84'	95°31'04.13"	43
		San Chuang	20°10'05.48"	95°35'04.53"	38
		Sad Dan	20°06'53.23"	95°36'06.97"	31
		Palin	20°17'29.11"	95°31.74'98"	15
		Boke Chaung	20°11'04.93"	95°19'24.22'	2
		Nat Mouk	20°24'31.55"	95°28'54.77"	16
		Pin	20°36'52.30"	95°26'16.83"	1
	Minbu	Mon chaung	20°28'46.98"	94°15'51.37"	832
		Aing ma	20°07'12.06"	94°37'03.49"	1,067
		Man chaung	20°05'32.12"	94°52'27.77"	148
		Sa lin	19°52'05.65"	94°22'08.93"	164
		Yin Shay	19°57'22.36"	94°34'39.49"	3
		Tat Tu	20°33'52.42"	94°30'39.17"	2
	Thayet	Byat kyi	19°18'52.25"	95°31'36.97"	90
		Bade	19°12'18.19"	95°38'14.78"	41
		Maday	19°02'00.85"	94°52'02.16"	67
		Pwe Tha	19°07'17.02"	95°14'42.86"	2
Mandalay[+]	Kyauk Se	Kinda	21°09'36.81"	96°19'15.01"	1,078
	Meiktila				-
	Myingyan	Kyatmauktaung	20°48'23.71"	95°15'0.99"	90
	Nyaung U				-
	Yamethin				-

[+] Note: It is not clear if there are very few dams in the Mandalay region or simply no data on those that do exist.

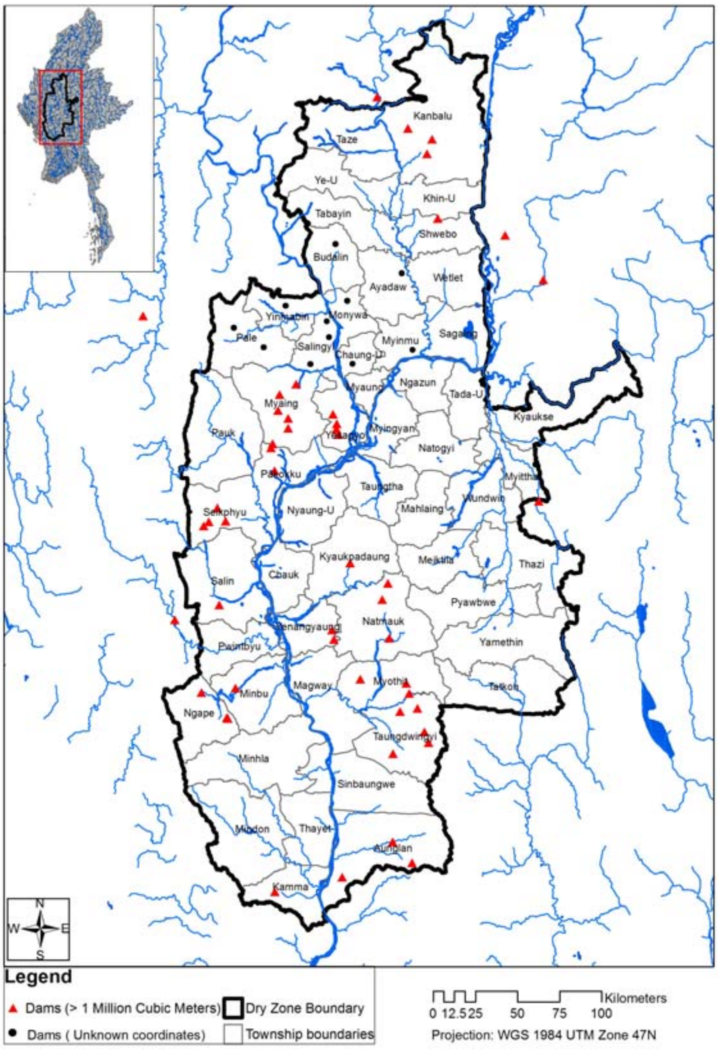

Figure 4.8: Map showing the location of large reservoirs (>1 Mm^3) in the Dry Zone. Those reservoirs for which coordinates were not provided are shown within the township in which they are located but the exact position is unknown.

4.3 Irrigation

4.3.1 Area

It is widely acknowledged that the scarcity and variability of rainfall in the Dry Zone make irrigation essential to safeguard crops. Since 1988, the government of Myanmar has made considerable efforts to increase water utilization in agriculture. Nationally a total of 233 dams and weirs have been constructed, 327 pumping stations have been built and 8,032 tube wells installed (FAO, 2011). A considerable proportion of this investment has been in the Dry Zone. For instance the Thapamzeik Dam was constructed in 1996 on the Mu River to enable increased dry season irrigation in the Shwebo irrigation scheme and a number of pumped irrigation projects have been initiated on the major rivers, the Irrawaddy, Chindwin and Mu (LIFT, 2012).

It is estimated that there is a total of approximately 350,000 ha of formal command area in the Dry Zone. A small proportion of this is supplied by groundwater (see below) but the majority is gravity-diversion and pumped surface water schemes. There is great uncertainty over the extent of informal irrigation and the actual area irrigated at any given time. There are some estimates that the area of informal irrigation maybe as great as formal irrigation (ESCAP, 1995) but it is unclear, how this was determined and if it is indeed the case.

In the current study, simple visual inspection of Google Earth images was undertaken to estimate the actual irrigated area, whether formal or informal, during the dry season of November 2011 to April 2012. The results were compared with the command area reported by the MOAI (MOAI, 2012) as well as FAO and JICA derived estimates (FAO, 2011; JICA, 2010). Google Earth images were taken during the dry season between 29/11/11 and 8/04/12. During this period there was very limited cloud cover across the Dry Zone. Weirs, pumping stations and irrigation canals could be seen on the Google Earth images and provide an indication of formal irrigation sites. Areas actually irrigated were generally distinguishable from non-irrigated dry fields by their colour (green in the case of the former and brown in the case of the latter). Areas of trees were generally distinguishable from fields. However, river bank recession agriculture and any areas of cropland growing on residual moisture were in-distinguishable from irrigation and so were included in the analysis.

Irrigated areas were marked and drawn on the Google Earth images and saved in a KML file. The KML file of pumping stations, weirs and polygons of irrigated areas were converted to shape files in ArcGIS10 and re-projected using the correct coordinate system. This calculation was projected into UTM Zone 47N, WGS84 (Figure 4.9). The area of irrigation was calculated using “Calculate Geometry” in ArcGIS and intersected with township boundaries in order to provide an estimate of the total irrigated area within each township (Appendix A).

Using this method the total delineated area was 256,578 ha. This compares to the Irrigation Departments estimate of 344,257 ha of command area, the JICA estimate of 386,110 ha, and the FAOs estimate of total irrigated area of 685,246 ha (Table 4.4). The difference between the values is attributable to a range of factors:

- The Irrigation Department estimate is believed to be the total command, or irrigable, area (i.e. the maximum weirs/pumps/canals can supply water to when there is sufficient water and schemes are operating at full capacity). Some of the schemes will only be fully functional during the wet season, with smaller areas irrigated during the dry season. Hence, it is not surprising that the delineated area derived in this study, which is specifically for the summer season is smaller than the Irrigation Department estimate.
- The JICA estimate is believed to comprise the formal irrigable area and the informal irrigated area.
- The fact that the area delineated in this study may also include some informal irrigation and non-irrigated crops growing on residual moisture, explains why, at the township level, the area delineated is not consistently smaller, but in some townships significantly exceeds, the irrigable area estimated by the Irrigation Department (Appendix A).
- The area estimated by FAO (approximately double the Irrigation Department estimate) is believed to incorporate multiple cropped areas (i.e. where there are two or three crops in a year the area will be counted two or three times, respectively).

Table 4.4: Estimates of irrigated area (by district) in the Dry Zone

Division	District	Estimated irrigated area (ha)			
		Irrigation Department*	**FAO+**	**JICA**	**Delineated in this project‡**
Sagaing	Shwebo	53,825	274,964	192,124	92,281
	Sagaing	1,417	15,418	7,187	31,140
	Monywa	23,668	23,348	19,467	8,281
Division Total		78,909	313,730	218,778	131,702
Magwe	Pakokku	13,569	5,969	793	12,298
	Magwe	35,561	36,360	20,358	10,955
	Minbu	71,640	74,668	55,053	43,458
	Thayet	12,570	3,571	20	5,745
Division Total		133,340	120,568	76,224	72,456
Mandalay	Kyauk Se	85,655	95,594	46,237	6,065
	Meiktila	5,775	71,216	34,854	10,317
	Myingyan	15,500	10,346	6,016	29,825
	Nyaung U	81	41	-	6,212
	Yamethin	24,996	72,751	-	-
Division Total		132,007	250,948	91,107	52,420
Overall total		**344,257**	**685,246**	**382,110**	**256,578**

* Command area, derived from Irrigation Department booklet (MOAI, 2012)
+ May include multiple cropping (e.g. two crops per year = double the area)
‡ Includes areas of non-formal irrigation and crops growing on residual moisture

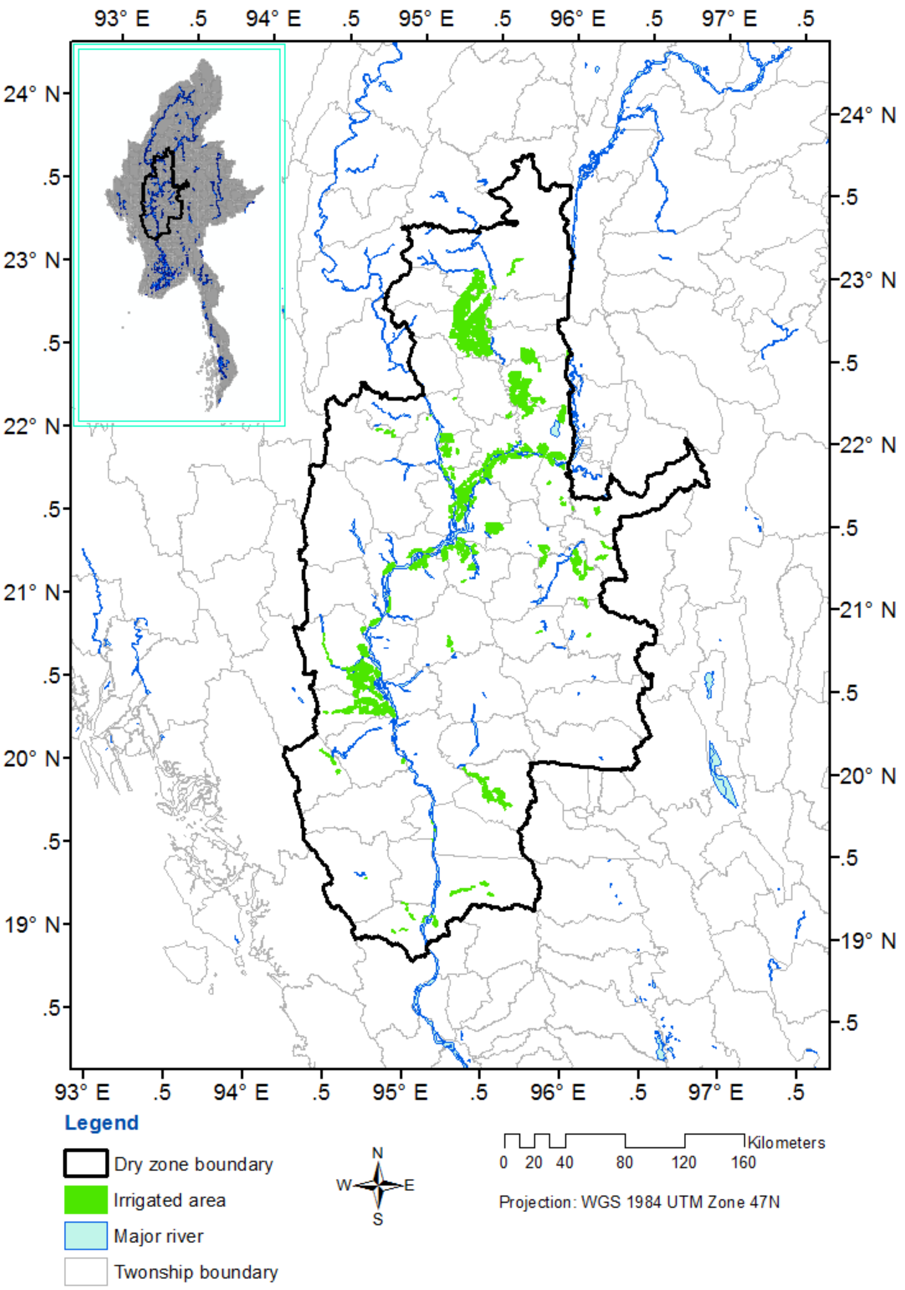

Figure 4.9: Estimated dry season irrigated area for 2011/2012, derived from analyses of Google Earth images

4.3.2 Water Use

To obtain an estimate of irrigation water requirements in the Dry Zone, actual evapotranspiration from irrigated systems was estimated and compared to rainfed areas using the MODIS 16 global evapotranspiration product (Mu et al. 2011). This is a land surface evapotranspiration product that represents all transpiration by vegetation and evaporation from canopy and soil surfaces. Evapotranspiration is computed globally for a 1x1 km grid, using MODIS land cover, FPAR/LAI data and global surface meteorology from the GMAO (http://modis.gsfc.nasa.gov/data/dataprod/dataproducts.php?MOD_NUMBER=16).

To allow for spatial variability, approximately 20km x 20km zones were selected from the north, south and close to the centre of the Dry Zone. Within each zone, irrigated areas and nearby rainfed areas were identified from the delineated Google Earth images. Within each zone, 5 points that had been identified as irrigated and 5 points that were identified as rainfed agriculture were selected (Figure 4.10). Each location, representing a

1km grid-square, was converted into a shape file to enable it to be overlain with MODIS 16 evapotranspiration data, which are in the form of raster data.

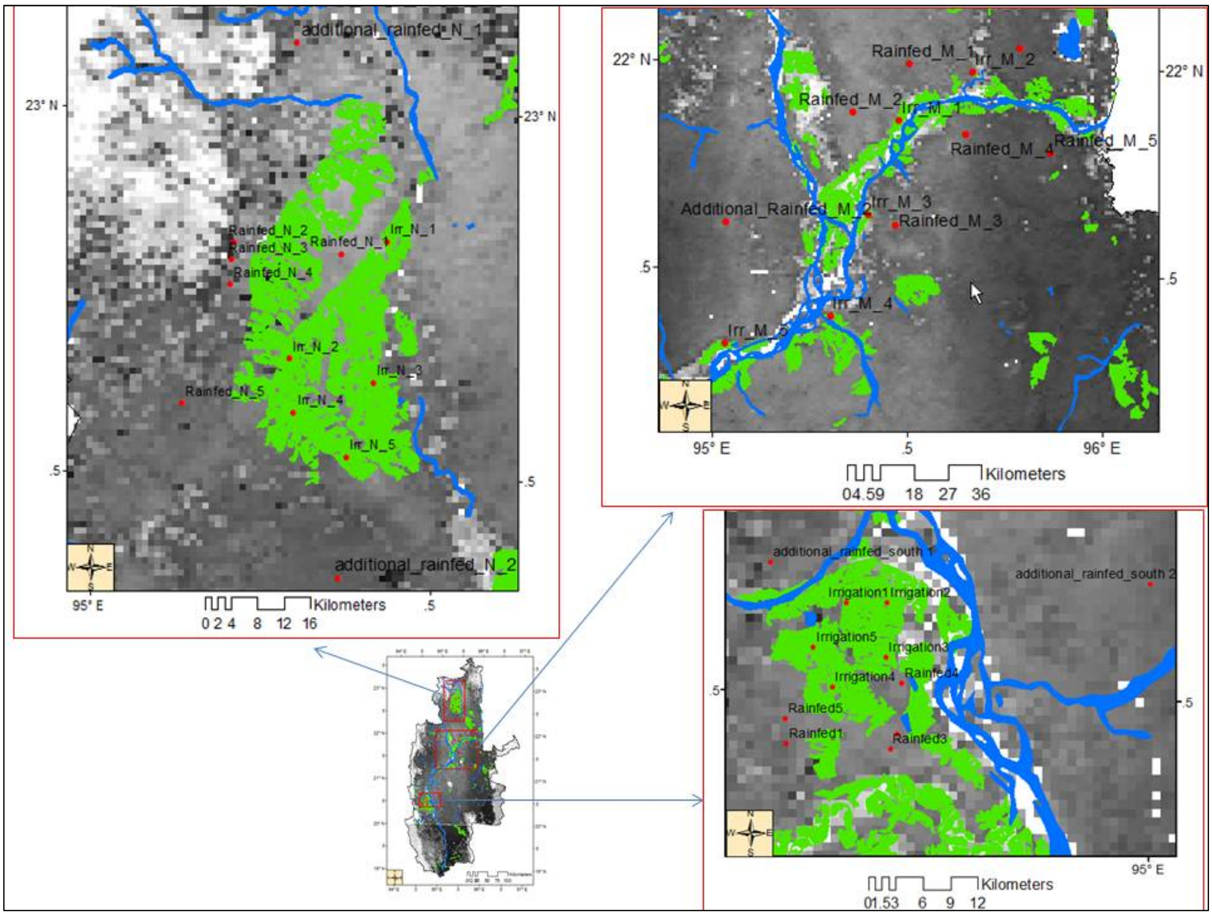

Figure 4.10: Zones and points selected for analyses of rainfed and irrigated evapotranspiration data

The global evapotranspiration data were rescaled and downloaded using MODIS_Tools. The average monthly actual evapotranspiration data (mmd^{-1}) were imported from the satellite “tile” that covered the Dry Zone and projected into the appropriate coordinate system. The monthly values of actual evapotranspiration were then extracted from the raster file, for the years 2011 and 2102 and imported into excel spread sheet to enable comparison and further analyses.

Figure 4.11 presents graphs of actual evapotranspiration in the rainfed and irrigated areas in conjunction with the potential evapotranspiration (derived from the FAO LocClim database) in each of the three zones, for the years 2011 and 2012. The data indicate where, and when, the evapotranspiration of irrigated areas is enhanced (i.e. greater than that of rainfed areas), as a consequence of the application of water. For example, in zone 1, there is much greater evapotranspiration from the irrigated areas in the period September to November 2012. Key results from the graphs are:

- In zones 1 and 3 (i.e. the north and south of the Dry Zone), during the height of wet season (i.e. June to August), irrigated and rainfed areas have evapotranspiration rates that are approximately the same and close to potential rates, in both years. If anything evapotranspiration rates from the rainfed areas appear to be higher than the irrigated areas. This suggests that irrigation did not provide any significant benefit to wet season crops in 2011 and 2012, presumably because in these areas the rainfall volume was sufficient, and sufficiently well distributed, to enable crop growth.
- By contrast in zone 2 (i.e. the centre of the Dry Zone), rates of evapotranspiration of the irrigated areas departs from those of the rainfed area in June and remain above the rainfed evapotranspiration rates throughout July and August, in both years. This highlights the important role of irrigation in supporting wet season crop growth in the central region of the Dry Zone.

- In zones 1 and 2 (i.e. the north and the centre of the Dry Zone), evapotranspiration rates in irrigated areas exceed those in rainfed areas in September to November, with no overlap of the error bars. This indicates that crops are being irrigated in these months and confirms the contribution of irrigation to dry season crop growth. The very pronounced peak in irrigated evapotranspiration rates in October 2012 in zone 1, suggests a period of fallow, followed by an irrigated "summer" crop.
- In zone 3 (i.e. the south of the Dry Zone), in September to November 2011 actual evapotranspiration is marginally higher in the irrigated areas than in the rainfed areas, indicating a possible irrigated crop. However, for the same months in 2012 the rainfed and irrigated rates are almost identical suggesting that there was no irrigation that year.
- In the period December to April actual evapotranspiration of both rainfed and irrigated areas are, significantly below potential evapotranspiration and almost identical in all three zones, in both years. This suggests that there was negligible irrigation during these months.

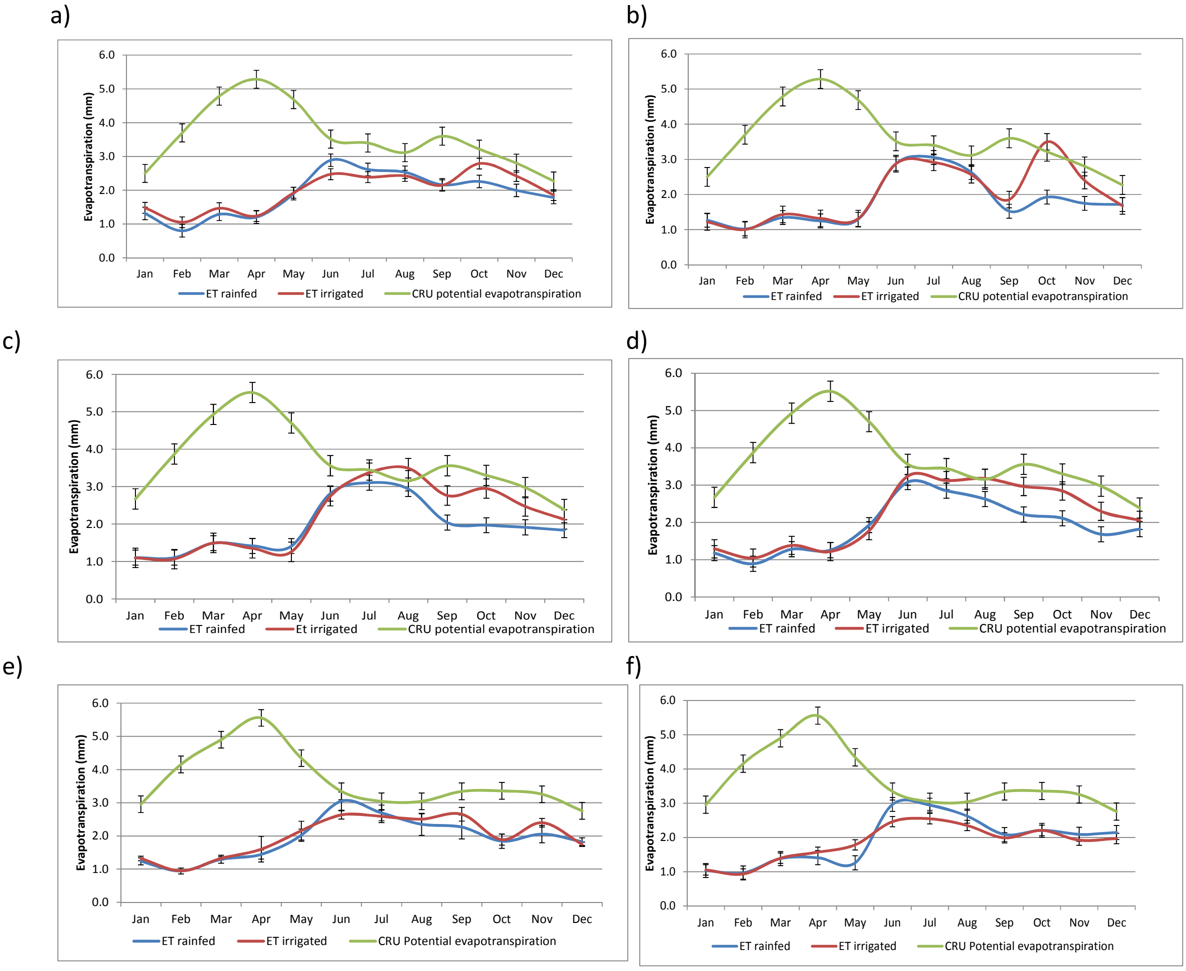

Figure 4.11: Average monthly actual evapotranspiration rates (mmd^{-1}) in rainfed and irrigated locations, compared to the potential evapotranspiration rates for: a) zone 1 (2011); b) zone 1 (2012); c) zone 2 (2011); d) zone 2 (2012); e) zone 3 (2011) and f) zone 3 (2012). Error bars correspond to standard deviation between the five cells used to compute ET in each zone and year.

Analyses of the evapotranspiration data indicates that over the years 2011 and 2012, irrigation enabled, between 22 mm and 106 mm of additional evapotranspiration (i.e. water supplied in excess of rainfall and actually transpired by the crops), depending on location. Table 4.5 presents an estimate of the volume water that equates to the maximum (i.e. 106 mm), depending on whether the actual irrigated area was as estimated in this study or the official Irrigation Department figure. In either case, the volumes are small compared to the volumes estimated in other studies (e.g. MOAI, 2003) and much smaller than the estimated average annual water used in irrigation in the Saigaing and Magwe Districts over the years 2008 to 2012 (Table 4.6). However, they reflect "beneficial" volumes (i.e. volumes of water that would have been effective in meeting crop water requirements, over and above those met by rainfall). Other studies have indicated much greater volumes are required because they assume that all crop water requirements have to be met using irrigation water (i.e. making no allowance for rainfall). The volumes indicated are also small compared to annual runoff and existing storage in the Dry Zone (see above).

The Irrigation Department figures in Table 4.6 are believed to reflect volumes of water diverted to irrigation schemes, with no allowance for transmission losses (i.e. water lost through seepage from canals) and return flows (i.e. water returned to the river as drainage). The data indicate that, even allowing for some diversions in the Mandalay Division, all irrigation water diversions equate to less than about 3% of the mean annual flow of the Irrawaddy at Magwe (Figure 4.2). Furthermore, although both sets of data are relatively crude, with possible significant errors, comparison of the numbers in Tables 4.5 and Tables 4.6 suggests that, at best, only about 5% of the water diverted for irrigation is effective in contributing to crop transpiration. This suggests that there is much scope for improving the efficiency of irrigation schemes in the Dry Zone.

Table 4.5: Estimate of irrigation water transpired by crops over and above water provided by rainfall

Area (ha)	**Irrigation Water transpired**	
	Mm	**Mm^3**
256,578	106	272
344,257	106	365

Table 4.6: Department of Irrigation estimate of water volumes used in irrigation in the Dry Zone Districts of Saigaing and Magwe (source: DOAI regional offices)

Division[+]	**District**	**Used Irrigation Water (Mm^3)**
Sagaing	Shwebo	3,347
	Sagaing	1
	Monywa	79
Division Total		3,427
Magwe	Pakokku	N/A
	Magwe	307
	Minbu	3,643
	Thayet	158
Division Total		4,109
Overall Total		7,536

[+] Note: Data were not available for Mandalay Division and Pakokku District in Magwe.

5. Groundwater Resources

5.1 Regional Geology and Hydrogeology

The regional geology of the Dry Zone is described in detail in geological reviews (Stokes, 1988; Pramumijoyo et al. 2010) from which much of what follows is drawn. Significantly more is known about the geology than the hydrogeology of the region owing to the abundance of oil, gas and mineral resources. Despite groundwater resource development spanning at least the past four decades, there exists little in the way of published information on the hydrogeology and groundwater resources. Unpublished works by Groundwater Development Consultants (GDC) (1984) and Drury (1986) are the most significant and are also heavily drawn upon here.

Of the four major geological regions of Myanmar, the Dry Zone is constrained almost exclusively within Central Lowland regions, a vast alluvial plain intermittently outcropped by mountain ranges and hills running in north-south direction. The Central Lowland is differentiated from the adjacent Shan Highland to the east and the Western Fold Belt and Rakhine Coastal Belt regions to the west by north-south oriented faults along the boundaries, including the largest and most active Sagaing Fault.

The Central Lowlands emerged as a result of uplifting of the neighbouring Shan Plateau and Western Mountains during the late Cretaceous and early Tertiary period, with the central trough subsiding and becoming gradually infilled by sediments which may attain a thickness of 20 km or more (Thein, 1973). Whilst the Lowlands extends as far south as the Andaman coast, largely derived by marine processes, the northern central portion 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 Central Lowlands, also known as the Central Cainozoic (Tertiary) Belt, may be considered a large basin divided into two unequal parts; 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 masl). In geological terms, the Central Basin may be subdivided into 6 main sub-basins: Putao, Hukawng, Upper Chindwin, Central, South Irrawaddy, Sittang and Salween basins.

The generalized geology that illustrates the distribution of the major aquifer groups in the Dry Zone is presented in Figure 5.1. The major geological (and hydrogeological) units are the Eocene, Pegu, Irrawaddy and Alluvial groups (Chibber, 1934).

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

Pegu strata outcrop over large parts of the Dry Zone (20%) and have been well-characterized due to their oil-bearing properties. The Pegu group consists of well stratified sandstones and blue or grey clays/shales, the former often calcareous and well cemented. The sediments show considerable faces changes from north to south and fossil wood occurs in some northern successions. The Padaung and Pyawbwe clay formations represent marine transgressions during the Miocene and Pliocene which extended as far north as latitude 22°N. Relatively little is currently known about the groundwater potential of the Pegu group but it is thought to be low, although in some areas boreholes have achieved low-level supplies. The Pegu group is usually considered to be of low potential with exceptions in highly folded and faulted areas. However, specific units such as the Kyaukkok formation amongst others comprise massive fine-grained sandstones and can be reasonable aquifers. In the Magwe-Minbu area Pegu group wells can attain depths of 165 m and yields up to 540 m^3d^{-1}.

The Irrawaddy group strata outcrop most extensively over the Dry Zone (38%). The unit is comprised of massive loosely cemented sand and sandstone beds, containing abundant ferruginous, calcareous and siliceous concretions and silicified fragments of fossil wood. In the Central Basin, the Irrawaddy sands are continental, often bluish, both well and poorly sorted, with a large proportion of quartz pebbles. They also include brown and red earth beds, clays and siltstones, pebble beds, gravels and conglomerates. The only distinguishing feature between the Irrawaddy and the alluvial groups is a distinctive colour change from yellowish brown downwards to bluish grey which is widespread in the sediments and a useful diagnostic test. Irrawaddy deposits, being mainly clastically-derived and loosely cemented, contain many highly permeable zones. Aquifers occur as sand and gravel layers in the alluvial sequence. Irrawaddy group aquifers are normally comprised of poorly consolidated sands, semi-confined to confined in nature. The aquifer is observed at depth of up to 350 m in Magwe Division. It is far shallower in Sagaing Division where maximum depths are only 120 m. In the Magwe-Minbu area for example, depths of up to 144 m and airlift yields ranging from 360 to 1,600m^3d^{-1} are recorded (Drury, 1986).

Across 29% of the Dry Zone the alluvial deposits lie unconformably on the Irrawaddy and Pegu outcrops. In some areas these are alluvial plateau gravels which pass laterally into red earth beds (clayey sands) representing old laterite soils. These 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 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 consist of gravels, sands, silts and clays and generally contain good aquifers except where very fine, as in some deltaic areas. Many shallow dug wells used for domestic supplies draw upon the alluvial aquifers. Shallow tube wells drilled in alluvial flats normally intersect unconsolidated through to semi-confined sand and gravel aquifers up to 40 m deep in the alluvial areas in Magwe District. The tube wells drilled along the river terraces and flats in Pakokku District attain a maximum depth in excess of 52 m and in Monywa districts over 70 m. In the Chindwin River valley alluvial aquifer, well yields vary from 270 to 4,700 m^3d^{-1} and depths can be up to 90 m (Drury, 1986).

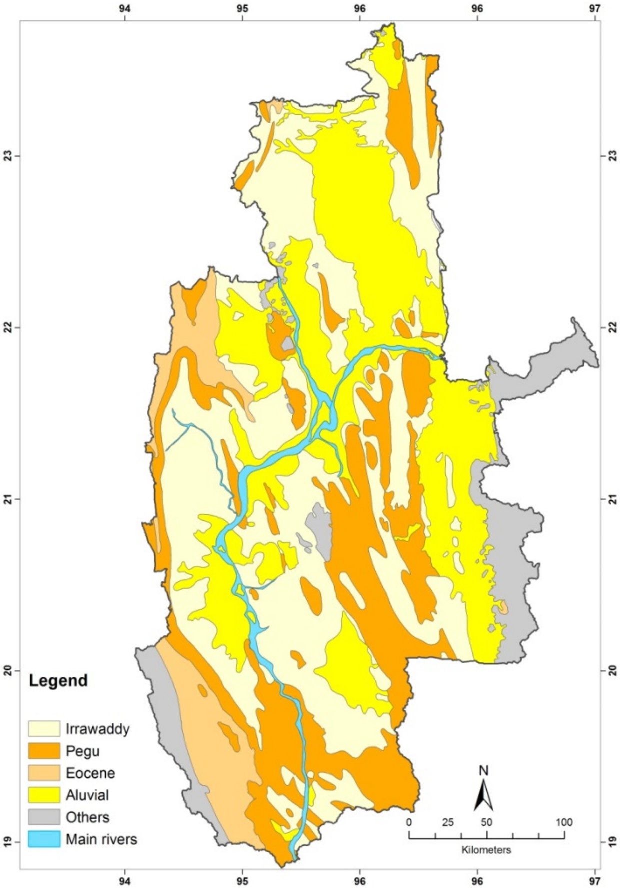

Figure 5.1: Geology of the Dry Zone (Source: Adapted from FAO Digital Agricultural Atlas – Union of Myanmar, http://dwms.fao.org/atlases/myanmar/overview_en.htm)

Springs, large and small, hot and cold, fresh and saline occur across the Dry Zone on the slopes at various levels and in other areas that are structurally controlled. Hot water springs occur at Kyaukpadaung and elsewhere around the Mount Popa complex. Halin features hot saline springs (Drury, 1986). Depths of the static water level can vary from 300 m or more to above the ground surface (artesian). Areas such Yinmabin Township, Ayadaw, Shwebo, amongst others, feature artesian groundwater that is used productively.

Groundwater largely occurs throughout the Dry Zone although useful supplies of suitable quality and cost of access cannot be found everywhere, particularly in areas underlain by aquifers of the Pegu group rocks (Table 5.1). The Irrawaddy and Alluvial groups constitute the most important aquifers. Figure 5.2 provides a cross-section from Monywa and Chaung U Townships to illustrate the alternating sequences of clays and sands/gravels associated with Alluvial and underlying Irrawaddy sediments.

Table 5.1: Summary of the major aquifer units in the Dry Zone

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

Source: Adapted from Ministry of Agriculture and Irrigation, (2003)

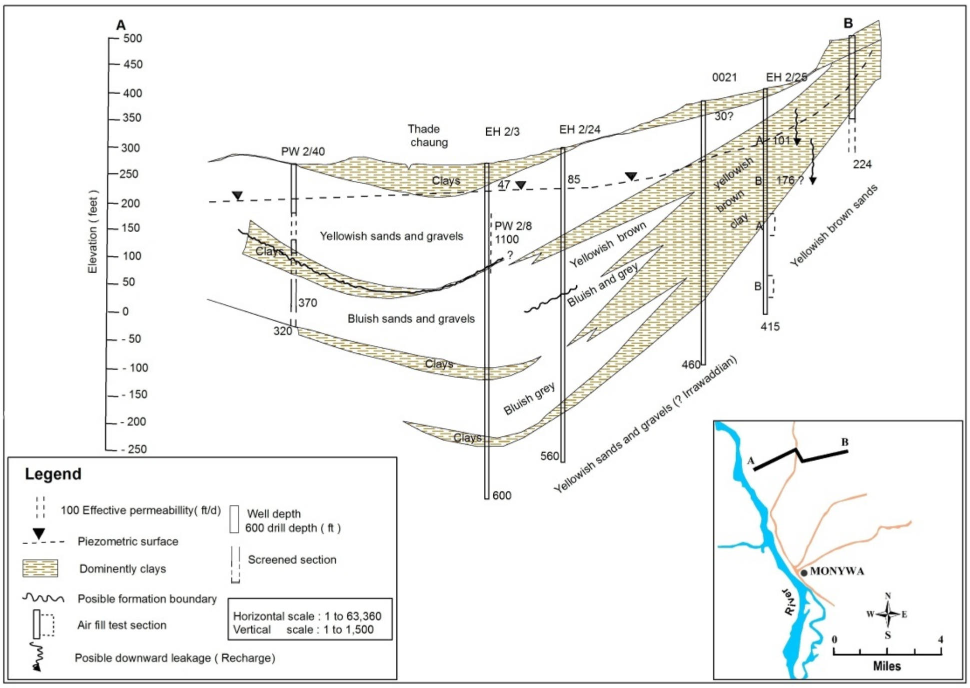

Figure 5.2: Hydrogeological cross-section illustrating the sequence of strata in the in the Monywa to Chaung U area. (Source: Modified from GDC (1984)).

5.2 Water Quality

In cases where the quantity of groundwater supplies can be adequately met, the quality is universally the most important determinant of suitability for use. Although data are limited, groundwater quality would appear to be fit for general purposes over large parts of the Dry Zone. Still, indirect evidence can be gauged by the extent of groundwater use for domestic supplies and irrigation development (section 5.4). It has been suggested that groundwater in the Dry Zone may be generally characterized as of low to moderate salinity (typically 1000-2000 µScm^{-1}) and mainly of a sodium bicarbonate type (ESCAP, 1995).

Whilst groundwater is available in varying quantities throughout the Dry Zone, spatial variability in water quality can constrain utilization. In some areas groundwater may be of brackish or saline quality due to natural processes. This may be due either to enrichment of rainwater by evapotranspiration concentrating the salt naturally present, or else due to salts trapped within the formations of marine origin that have not been leached by flushing since deposition (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 the case of some deep oil exploration wells the salinity 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 lead to rising water tables that may bring salts to the root zone or soil surface. Poor quality groundwater can directly reduce crop yields and indirectly damage soil infiltration and structure.

The four major aquifer groups across the Dry Zone vary considerably in the quantity and quality of groundwater according to their depositional environments and lithology and mineralogy. Groundwater quality for the Alluvial and Irrawaddy aquifers is more suitable for both irrigation and domestic water use. Groundwater from the Pegu and Eocene aquifers is in some cases suitable for general purposes.

Data presented by Drury (1986) reveals the variations that occur with depth, as well as different hydrogeological formations. Generalizations are difficult to make about any particular formation or area since the mechanisms that control water quality are often highly complex. The highly variable salinity of groundwater for the Monywa irrigation scheme (400 to 2000 mgl^{-1} TDS) which is drawn from the Alluvium and Irrawaddy aquifers contrasts against the much more consistent quality drawn from the 99 Ponds irrigation scheme (260 to 510 mgl^{-1} TDS) targeting Irrawaddy aquifers (Table 5.2). At the time of the Monywa project implementation, poor water quality rendered at least 8 new tube wells non-utilizable, thereby adding to the costs substantially (World Bank, 1994). INGOs such as ADRA consider salinity as being problematic for tube well development in parts of the Dry Zone.

Table 5.2: Groundwater quality sampling results at Monywa and 99 Ponds Irrigation Sites

	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})**	**$SO4^{2-}$ (mgl^{-1})**	**$HCO3^-$ (mgl^{-1})**
Monywa (N=126)											
Min.	430	670	6.07	40	2.4	26.45	5.76	0.5	103	51.84	62
Max.	2000	3150	8.45	1580	25	177.8	64.92	4	516	295.8	284
Mean	938	1452	7.55	146	7.1	68.1	23.8	1.6	226	158.5	122
99 Ponds (N=94)											
Min.	260	400	6.37	19	1.5	19.23	9.6	0.5	33	28.8	40
Max.	510	790	8.35	51	4.5	93.78	1824	4	97	6004	104
Mean	367	566	7.61	31	2.5	46	49.7	2	54	115	67

Source: WRUD data (unpublished)

Trace minerals present in the host rock may also cause water quality deterioration associated with constituents such as iron, manganese and arsenic. Iron is widely present in most rocks and has been routinely picked up in ground waters at concentrations of up to 4 mgl^{-1} at Monywa and Yinmarbin (Table 5.2). High levels of iron create largely aesthetic concerns around staining of precipitates rather than being an issue to human or animal health. Manganese usually is co-associated with iron and the issues are similar.

Arsenic, on the other hand presents a potentially major threat to public health. A number of studies report levels of arsenic in Myanmar at levels that exceed drinking water guidelines. However, in all cases they refer solely to the Irrawaddy Delta region. It has been reported that in the Delta an area of around 3,000 km^2 is affected and about 3.4 million people are at risk (World Bank, 2005). Given that arsenic is 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 arsenic levels are acceptably low within the alluvial aquifers within the Dry Zone. Data from WRUD based on a summary of three technical reports covering the periods 1952-90, 2005-11 and 2012-13 suggests that around 80% of 30,000 samples from Sagaing, Mandalay and Magwe have arsenic concentrations less than the WHO drinking water guideline value of 10 µgl^{-1} (Mr. Kyi Htut Win, WRUD, pers. comm.). The reports also indicate that around 81,000 people in Mandalay and 28,000 in Sagaing are exposed to concentrations in excess of 10 µgl^{-1}. The exposure for the higher concentration of 50 µgl^{-1} (i.e. an earlier WHO guideline) is around 12,000 people for the two regions combined. Further support is provided from model predictions for South East Asia that suggest some low level of risk of arsenic exceeding a threshold concentration of 10 µgl^{-1} in the Dry Zone (Winkel et al. 2008).

Exposure pathways 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 under oxygen-poor conditions and absorbed by rice roots along with plant nutrients. This is exacerbated when arsenic-laden groundwater is used for irrigation (Zhu et al., 2008).

Point-scale or localized contamination from microbial pathogens is prevalent in the shallow phreatic aquifers as a result of pollution from contaminated surface water runoff or nearby latrines, septic tanks and animal wastes. Many of the shallow aquifers (<10m deep) are of generally poor quality and are used only for washing, while deeper tube wells (>30m) are more acceptable for drinking. Industrial pollution from copper mining activities centred 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.

5.3 Groundwater Resources

District level figures on rates of groundwater recharge suggest 4,777 Mm^{3}y^{-1} of annually replenishable resource (Table 5.3). In terms of areal equivalents, they translate to values of around 30 to 90 mm of recharge per year. This does not support the view of great abundance, but rather a moderate resource (i.e. <2% of the total surface water resource and ca. 50% of the total surface water storage) which must be planned and developed carefully to ensure utilization over the long term. Recharge is critically important determinant of sustainable groundwater management since the amount of groundwater abstracted from an aquifer for human purposes over the long term should be less than that which is recharged.

Table 5.3: District-level ground water recharge estimates (2000/01)

Division	**District**	**Area**	**Groundwater recharge**	
		(km^2)	**(Mm^{3}y^{-1})**	**(mmy^{-1})**
Sagaing	Monywa	10041	583.8	58.1
	Shwebo	14877	1090.3	73.3
	Sagaing	2484	128.6	51.8
Magwe	Magwe	9630	594.4	61.7
	Thayet	11971	341.0	28.5
	Minbu	9314	266.1	28.6
	Pakokku	8327	771.3	92.6
Mandalay	Kyauk Se	4157	128.8	31.0
	Meiktila	5789	187.8	32.4
	Yamethin	10878	387.5	35.6
	Myingyan	6415	245.1	38.2
	Nyaung U	1484	52.3	35.3
District Total		95365	4777.0	-

Source: Adapted from MOAI, (2003)

5.4 Groundwater Use

Lack of reliable water has long been identified as the dominant constraint to increasing livelihoods and wellbeing in the Dry Zone. Groundwater is being increasingly looked upon as being complimentary to surface water supplies, particularly since the demand for water from the Dry Zone population has steadily increased. In the absence of a reliable and economically attractive source of surface water, groundwater is generally considered to be the best alternative for domestic, agriculture and industrial supplies.

Across all of the Districts of the Dry Zone groundwater plays an important role in supplying the needs for domestic, agricultural and industrial use (Table 5.4). The estimated total withdrawn in 2000/01 across the three Divisions was 763 Mm^3y^{-1}. Figures on sector-wise usage can differ widely according to different estimates. Division-wise data from Table 5.4 suggest a range of 0 to 63% of total use is abstracted for agriculture. Corresponding figures for domestic supplies range from 35 to 100% and for industrial supplies 0 to 18% (MOAI, 2003). Naing, (2005) reports that as much as 90% of total groundwater use can be for irrigation but this is not apparent from the data reported in Table 5.4.

Table 5.4: Sectors-wise groundwater utilization (2000/01)

Division	District	Industry	Agriculture	Domestic	Sector Total
		Mm^3y^{-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
Magwe	Magwe	0.8	5.8	97.7	104.2
	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	Kyauk Se	1.1	6.0	40.3	47.4
	Meiktila	0.5	2.0	55.2	57.7
	Yamethin	0.0	5.7	84.9	90.7
	Myingyan	0.6	5.2	63.8	69.5
	Nyaung U	0.0	0.0	14.1	14.1
Dry Zone Total		13.7	112.9	635.9	762.5

Source: Adapted from MOAI, (2003)

5.4.1 Domestic Supplies

The natural filtering function of underground formations and protection from potentially contaminating activities at or near the ground surface makes groundwater from deep tube wells a highly attractive source of domestic supplies. Factors such as water-borne diseases and malnutrition are thought to be attributable for the under-5 year child mortality of 38 per 1000 live births (2008 data) on average across the Dry Zone (JICA, 2010). The use of communal ponds, dug wells and locally harvested rainwater are still a relatively important source of water supply within Dry Zone villages. Household level survey data from across the Dry Zone reveals that approximately 26% use water from unprotected sources, mainly open water ponds, streams or unprotected wells; 37% have access to a borehole with pump; 32% use other protected sources such as protected wells and 4% have access to piped water (WFP, 2011). Substantial gains have been made in the development of safe water supplies since the mid-1980s when only around 20% of village domestic supplies were derived from tube wells (Drury, 1986).

Village ponds often dry-out early in the dry season and villagers will then revert to subsurface supplies that are more perennial in nature but may be quite remotely situated. Cases have been reported where family members in the village must travel several kilometres to fetch water, which may also need to be purchased. This incurs high opportunity costs in terms of reduced access to education in the case of children or reduced time for daily wage earning for adults.

Large efforts have gone into improving rural water supplies over several decades. Up until the year 1990 the rural water supply from 11,000 tube wells amounted to an estimated 530,000 m^3d^{-1} with the production increasing two-fold compared with the early 1960's (Minyt, 1991). By the year 2000, WRUD had installed over 13,000 tube wells in the three Dry Zone Divisions, benefitting 6.4 million people (Table 5.5). As the table clearly demonstrates, rural water supply programs are dominated by groundwater development, with corresponding beneficiaries from various surface water supplies benefiting only an additional 0.3 million people.

Table 5.5: Division-wise rural water supply facilities and beneficiaries

	Well Numbers			**Total No. of Beneficiaries (M)**
	Sagaing	**Magwe**	**Mandalay**	
Ground water [1]	4576	4454	4266	6.417
Other sources [2]	NA	NA	NA	0.303

[1] deep tube wells and 'sludge' wells
[2] includes supplies from river pumping, dam withdrawals and piped water reticulation
Source: adapted from WRUD, (2002)

There are thought to be thousands of drilled wells constructed in the past that have become dysfunctional because access to materials and other resources were constrained the approaches to planning and construction in the past were inadequate. Since those projects did not include technology transfer and most importantly, there was no training of local engineers to address these issues.

Some positive signs are emerging. A number of INGOs and international aid agencies including JICA, Bridge Asia Japan (BAJ), ADRA, Proximity, ActionAid and others have long been operating throughout the Dry Zone. BAJ has been operating from Kyaukpadaung Township since the beginning of the last decade and has drilled wells covering 10 nearby townships at a rate of 10 wells per year. They have rehabilitated a larger number of wells. In and around these areas, groundwater bearing layers may be as deep as 150 m and wells depths can be over 200 m, and cost as much as US$ 40,000 (JICA, 2010).

The high cost of wells in these townships can drive communities to seek alternative lower cost supplies. JICA (2010) give the example of Mingan village, where villagers opted for the construction of a primary school with roof rainwater collection facility instead of a deep tube well. The NGO 'Proximity' have developed cheap plastic foot pumps (so called 'baby elephant') that are a fraction of the price of conventional treadle pumps (US$ 13) and selling thousands of these units replacing more laborious manual methods. These operate for water tables of less than 8 m, although pressure pump models are available which can lift from greater depths.

5.4.2 Industrial Supplies

The industrial sector consumes about 0.3% of the total annual groundwater recharge rate and contributes to about 10% of the country's gross domestic product (MOAI, 2003). Across the nation, groundwater supplies 22% of water, which is similar to that within the Dry Zone Divisions (Table 5.6). Large water consuming industries such as sugar mills, paper mills and cement factories normally depend on surface water whereas most of the other industries rely on groundwater.

Table 5.6: Industrial surface and groundwater use 2000/01

Division	**Groundwater**	**Surface water**	**Total**
	Mm^3y^{-1}		
Sagaing	2.2	3.7	5.8
Magwe	10.3	34.0	44.4
Mandalay	6.1	31.6	37.7
Remainder	29.5	104.0	133.5
Total	48.1	173.3	221.4

Source: Adapted from MOAI, (2003)

5.4.3 Irrigation Supplies

The widespread use of groundwater for irrigation in Myanmar started only in the 1980s although small-scale operations are known to have been in place since the 1940s (UNESCAP, 1995). Prior to the 1980s groundwater development was restricted to private sector development 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. Whilst there has been growth in the numbers of shallow wells in recent decades, to more fully exploit the groundwater irrigation potential the development of deep tube wells has been necessary.

Irrigation water drawn from aquifers is seen to be of obvious benefit to Dry Zone farmers located in areas remote from major rivers and dams, especially when adaptation strategies are sought to climate variability and poor productivity under rainfed conditions. Because of the many problems associated with conventional irrigation from surface water (e.g. large water level fluctuations in major rivers creating problems for pump lift schemes), groundwater reserves are being increasingly viewed as an important alternative. Whilst irrigation is expanding along the major rivers, villages remote from the river floodplains can only rely on smaller, more distributed sources such as deep or phreatic 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 hectares, or equivalent to around 5% of the total. Of the countries of the Greater Mekong Subregion this is second only to Thailand. Owing to the seasonally arid climate and the difficulty or lack of availability of surface water sources, much of this development would be associated with the Dry Zone, although groundwater irrigation is also known to be practiced in the Bago, Yangon, Irrawaddy and Kachin Divisions (MOAI, 2003).

Although comprising only a small amount of the total irrigation development, the rate of change in groundwater irrigation over the 14-year period from 1988 to 2002 shows that groundwater expansion exceeds other sources, increasing at an average rate of 2.9% per annum compared with 1.2% for alternatives (Table 5.7).

Available figures from about a decade ago suggest the tube well numbers amounted to over 33,000 for the country as whole, with 60% of those wells found in the three Dry Zone Divisions (Table 5.8). Corresponding water utilization from those same regions was 215 Mm^3y^{-1}. Estimates for the most recent 10 year period are not available, but continued increases are anticipated on the basis of the estimated increases in well numbers during the past decade (Sellamuttu el al. 2013). Projections of the data presented in Tables 5.7 also support this premise.

Table 5.7: Country-level changes in irrigated area by source

Source	**Irrigated area (Mha)**				**Increase overall (%)**
	1988-99	**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

[1] classes include dams/weirs, village ponds, rivers, windmills, others

Source: MOAI (2003)

Table 5.8: Division-level groundwater abstraction for irrigation in 2000/01

Division/State	**Tubewell No's**	**Groundwater abstraction (Mm^3)**		
		Wet season	**Dry season**	**Total**
Sagaing	8271	56.40	61.93	118.33
99-ponds	442	11.45	32.71	44.16
Monywa	141	11.02	16.99	28.01
Magwe	4154	3.53	12.52	16.05
Mandalay	10989	7.88	16.33	24.21
Remainder	13238	4.31	330.59	334.90
Total	33081	91.06	458.55	549.60

Source: MOAI (2003)

A strong tradition of irrigation from groundwater did not really exist until the World Bank conducted reconnaissance studies across the Dry Zone and pilot trials at Monywa District, Sagaing Division in the late 1970s through to the early 1980s. The success of this project led to scaling up at the site and triggered development elsewhere (Niaz, 1985). The pace of development has increased since the 1980s as a result of large projects established by the government along with smaller undertakings by individuals. The project appears to have played a significant role in expanding the irrigation sector through crop diversification and socio-economic development, as detailed below.

5.5 Groundwater Sustainability

5.5.1 Undeveloped Potential

There is widespread view that the groundwater reserves available for exploitation in the Dry Zone are vast, particularly on the plains, and largely untouched (e.g. ESCAP, 1995). Utilization has mostly been limited to domestic water supply and to the irrigation of vegetables and other high value crops from hand-dug wells and tube wells in more recent times.

The utilization of groundwater resources relative to annual replenishment ranges from 5% in Monywa district through to 55% at Sagaing District, with a district-average of 23% (Table 5.9). The most intensively used areas cluster around the central west of the DZ in Mandalay and southern Sagaing Divisions (Figure 5.3). These areas coincide with moderate potential, with areas of higher and lower use potential situated in districts to the north, west and southwest.

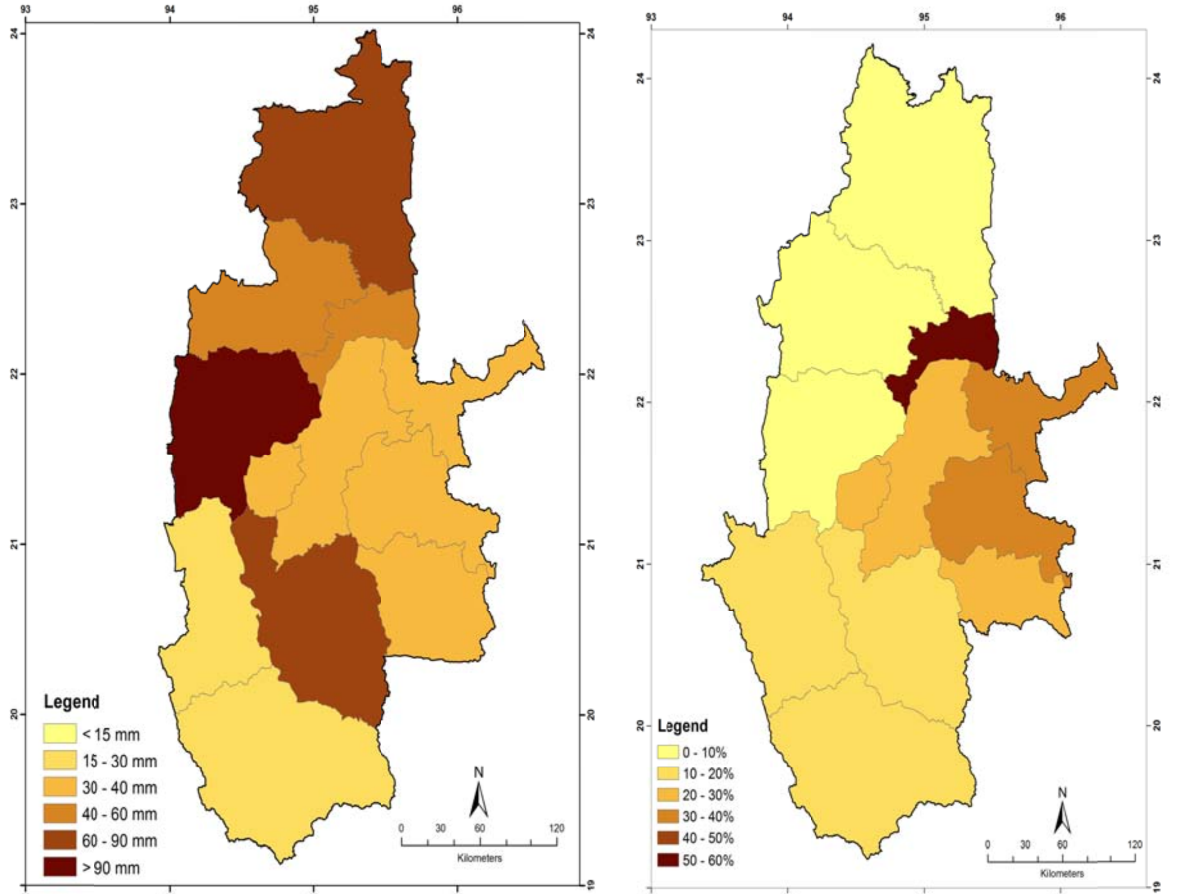

Figure 5.3: Groundwater potential in mmy^{-1} (left) and groundwater utilization, expressed as a percentage of annual recharge in 2000/01 (right)

Overall, there is clear evidence of an undeveloped potential from which substantial additional area could be irrigated from renewable fresh groundwater resources. Using the framework applied by Pavelic et al. (2012) to a number of Sub-Saharan Africa countries, whereby 50% of the annual recharge would be retained for the environmental services, it is estimated that a further 110,000 to 330,000 hectares of land could be irrigated, depending on the water demand associated with the crops selected and climatic conditions (Table 5.9). All except one of the twelve Dry Zone districts has potential for expansion. For the intermediate case of 1000 mmy^{-1} water demand, this potentially represents a 64% increase in the total area under irrigation as defined in section 4.3. It is important to also note there are areas where the groundwater will not be appropriate to develop due to poor quality, or depth to access, particularly for the Pegu and Eocene group aquifers. It must also be recognized that the undeveloped potential is based upon water use figures from around a decade ago, and that future growth in the non-agricultural sectors most also be considered, therefore suggesting that these possible areas of new irrigation represent an upper limit.

Table 5.9: Groundwater utilization as a percentage of annual recharge (2000/01) and potential area of new irrigation expansion from groundwater

Division	District	Groundwater Utilization [1]	Potential New Groundwater Irrigation Area [2] (ha)		
		(%)	500 mmy^{-1}	1000 mmy^{-1}	1500 mmy^{-1}
Sagaing	Monywa	4.82	52752	26376	17584
	Shwebo	8.66	90146	45073	30049
	Sagaing	54.92	0	0	0
Magwe	Magwe	17.53	38600	19300	12867
	Thayet	13.78	24702	12351	8234
	Minbu	19.23	16376	8188	5459
	Pakokku	9.84	61951	30975	20650
Mandalay	Kyauk Se	36.82	3395	1698	1132
	Meiktila	30.71	7245	3623	2415
	Yamethin	23.41	20607	10304	6869
	Myingyan	28.36	10608	5304	3536
	Nyaung U	26.92	2414	1207	805
	District Total	-	328797	164398	109599

Source: [1] adapted from MOAI, (2003)
[2] using figures in previous column supplemented by recharge values (Table 5.3) and assuming annual irrigation water demands of 500, 1000 and 1500 mmy^{-1}

5.5.2 Sustainability Issues

With new opportunities to develop groundwater resources to support livelihood enhancing activities in the Dry Zone comes increased onus to ensure that the degrees of understanding and management of the groundwater resources are improved. Unrestricted groundwater use could result in classic overexploitation symptoms of reduced availability, water quality deterioration and land subsidence. Preservation of groundwater is also necessary due to the natural connectivity to surface water and hence the need to protect natural flow regimes, groundwater-dependent biodiversity and cultural heritage.

A rudimentary tube well inventory system has been put in place by WRUD but a formal monitoring network has yet to be established across the Dry Zone. In the interim, some strategic monitoring has been undertaken in areas with high groundwater demand. One example is the Ywatha-Aungban aquifer where WRUD has studied differences 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, over a period of 10 years (i.e. 1999 to 2009) (Table 5.10). In the first two cases, where the same wells are have been monitored on both occasions the results show consistent declines of 7 to 20% from the initial rate. In the latter two cases, the numbers of wells have increased by factors of 2-4 and it is difficult to make level comparisons, although the results suggest a net increase, perhaps as a result of more strategic targeting of wells in high productivity zones.

Development of artesian wells will lead to flow rate declines 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 numerical or analytical modeling is needed to reveal the longer term trends and identify suitable management responses. There is also anecdotal evidence from INGO's that owing to the poor distribution system a lot of artesian groundwater is being wasted (ActionAid, pers. comm.).

The buffering capacity of groundwater to climate change and climate variability is typically higher than that of surface waters drawn from rivers and ponds, and comparable to that of large surface reservoirs. However, groundwater is not exempt from drought and in 2009 a drought resulted in water table declines by almost 1m below normal conditions. This resulted in the death of large numbers of date palms (ActionAid, pers. comm). Examples such as this emphasize the importance of information and decision support tools for effective management of groundwater resources.

Table 5.10: 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 periods**
		Total Flowing Artesian Wells	**Discharge (m^3s^{-1})**	**Total Flowing Artesian Wells**	**Discharge (m^3s^{-1})**	
Irrigation Wells	99 Ponds (WRUD)	449	0.604	449	0.566	-1.32
	Test Well (WRUD)	10	0.034	10	0.028	-0.20
	Private (Farmer)	205	0.453	752	0.713	+9.17
Total		664	1.090	1211	1.340	+8.75
Domestic wells		85	0.085	187	0.115	+1.06

Source: WRUD Sagaing 2009 Annual Report

6 Conclusions and Recommendations

Myanmar's agricultural development is central to both broad-based national growth and poverty reduction. In the Dry Zone water variability is perhaps the greatest constraint to a vibrant agricultural sector. Insufficient storage capacity and irrigation infrastructure in appropriate locations, as well as poor management of the existing infrastructure, means that both land-owning and landless farmers are exposed to climatic variability, with all the associated risks that entails. Seasonal scarcity is also the key factor limiting many peoples' access to water for domestic uses during the dry season. During the wet season flooding is frequently a problem. Peoples' livelihoods and wellbeing are adversely affected by their inability to manage water variability.

Improving water availability and access, as well as water management, in the region would reduce risk, stabilize agricultural productivity, increase the resilience of households, improve food security and, contribute to poverty reduction. From a development perspective, the primary challenge is to strengthen water security for vulnerable populations. To achieve this, the requirement is to ensure that the entire population of the Dry Zone has, in order of priority:

- improved dry season water supplies sufficient (as a minimum) for domestic uses and livestock
- sufficient water to enable irrigation during the wet season (i.e. to overcome short dry spells)
- protection against flooding
- sufficient water to enable irrigation during the dry season

This study indicates that availability of surface water (from rivers and storage) is less limiting than access, due to costs of pumping, and sparse infrastructure in areas remote from the major rivers. Furthermore, in relation to groundwater the current study does not support the view of great abundance, but rather suggests a more moderate resource which must be planned and developed carefully to ensure utilization over the long term.

Much current irrigation is supplementary in nature, to extend the wet season growing period or to protect wet season crops. Actual volumes utilized by crops are small compared to runoff, storage and volumes abstracted. There is significant scope for improvement in both irrigation efficiency and expansion of irrigation. Achieving water security, in the order outlined above, requires progressively increased investment in both the hydraulic and the institutional infrastructure needed to store, convey and manage water effectively. This needs to be carefully planned and managed in order to avoid wasted investments and sub-optimal outcomes.

Recommendations

Strengthen strategic water resource planning
Although some studies have been carried out, little systematic work has been published on the water resources of Myanmar or specifically the Dry Zone. There is no lead agency for water resource planning and management. Consequently, current water resources development in the Dry Zone is largely *ad-hoc*, conducted by different government agencies and NGOs, with little or no consideration of what has gone before, what others are doing and what might be done next.

There is an urgent need for a comprehensive analysis of the water sector (i.e. both surface and groundwater) and the development of a coherent development strategy to guide water resources investment in the future. Such a development strategy would comprise a useful component of a larger Irrawaddy Basin Master Plan. Without this guidance future investment will occur, as in the past, in a largely unplanned fashion with, at best, limited impact and increased risk of unsustainable practices. Detailed studies to ascertain irrigation efficiency and water and energy productivity in existing formal irrigation schemes (both gravity and pumped) and to determine opportunities for improved operation, would provide useful information to support the development of such a strategy.

Improve water-related data management
A major hindrance to the current (and previous) studies has been the lack of easily accessible data. Many data are dispersed across government departments and often held at division and district level. Some information is only available at individual scheme level and some simply cannot be obtained. Much monitoring, particularly of groundwater, has been limited and opportunistic, rather than strategic and inclusive. There is an urgent

need to establish an effective water-related data management system, comprising contemporary monitoring networks underpinned by appropriate data collection protocols and modern easily accessible databases and analyses tools. The development of such a system, encompassing both surface water and groundwater, must be a government owned process and should be a nation-wide endeavour. However, a scoping study undertaken in the Dry Zone would be a useful first step in development. Properly designed, such a system would greatly facilitate water resources planning in the Dry Zone (and elsewhere) and would easily justify both the financial and human resources required to establish and maintain it.

Invest in small-scale water harvesting and storage

Investment in rainwater harvesting and storage structures is needed to enable supplementary irrigation during the earliest stages of the crop cycle. Rooftop rainwater harvesting is unlikely to be sufficient for more than domestic use, but the construction of small reservoirs that harvest water from a small catchment, while generally not sufficient for full dry season irrigation, could provide enough water for supplementary irrigation in the wet season (i.e. bridging dry spells) and at the start of the summer dry season. Such reservoirs could make a substantial contribution to safeguarding wet season yields. The Irrigation Department is well placed to provide technical assistance in the placement and construction of reservoirs.

Currently, a local NGO, Proximity, is promoting the construction and rehabilitation of earth embankments in the Dry Zone. However, the primary focus is supply of domestic and livestock water, not irrigation. Past attempts at small reservoirs and tanks have had limited success due to problems of siltation and collapse of the embankments. The large number of reservoirs requiring rehabilitation in the Dry Zone is testament to the significant erosion problems. Consequently, greater consideration needs to be given to sustainability and upstream watershed management (i.e. measures that reduce flood runoff and sediment transport), in conjunction with the construction/rehabilitation of embankments, is essential.

Invest in soil and water conservation

Consideration should be given to more widespread implementation of soil and water conservation approaches. These are techniques that enhance infiltration and water retention in the soil profile with the objective of stabilizing and increasing crop yields by increasing the effectiveness of rainfall. Examples vary from place to place but the most promising include deep tillage, reduced tillage, zero tillage, mulching and various types of planting basin. It may also include the use of different (low water requirement) crops. Such techniques are likely to be most effective:

- around the periphery of the Dry Zone, in those townships where rainfall is generally greater and broadly sufficient to enable a non-irrigated wet season crop in most years; and
- lowland areas that, in many years, already achieve a summer crop based on residual moisture.

Such practices might also be beneficial in irrigation schemes where water *per se* is not limiting but the electricity costs of pumping make water conservation desirable.

Conduct a groundwater assessment

Groundwater resources have a very important role to play in the Dry Zone. There is widespread evidence of the positive contribution that groundwater makes to addressing water scarcity and livelihood related issues. In the current study, the assessment of groundwater resources was based on limited data drawn from synthesis studies, government agencies and a small number of hydrogeological investigations. Reliable and comprehensive data about the locations, depths, extent and quality of suitable aquifers to develop is not currently available. Limited information can be translated into lost investment arising from failed or poorly performing wells. Within the Dry Zone this possibility is increased by the high degree of complexity in the hydrogeological system in some areas (e.g. Pakokku). It is essential that major data gaps are resolved to better understand the nature, extent and dynamics of the resource. This should include adequate appraisals of groundwater recharge, groundwater use, sustainable yield of aquifers, and water quality and pollution. In particular, further work is needed to define the areas, aquifers and depths of arsenic prevalence so that preventative measures can be taken.

A clear indication of the resource potential and suitable areas for development is not available because detailed hydrogeological and hydrochemical maps have not been published. Work performed almost three decades ago completed 11 map sheets of the hydrogeology of the Dry Zone to draft final stage (Drury, 1986).

Currently, this represents the best available information and if completed would provide useful indicators for regional planning. Preliminary work by Min Oo and Thein, (2013) in Nyaung-U Township, combining Remote Sensing and GIS methods to determine development hotspots is a significant addition to this work but needs to be extended to cover the entire Dry Zone.

Develop groundwater appropriately

Despite data limitations this study has shown that, in broad terms, further opportunities for groundwater development exist and this could beneficially complement surface water resources development by addressing shortfalls that occur spatially (i.e. to infill areas where alternatives are not available or are too costly) or temporally (i.e. as a supplement when surface water is depleted). This study estimates that, 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 the Dry Zone. However, this is dependent on water quality and depth of access and assumes that there are no major shifts in future patterns of demand. Whilst significant opportunities potentially exist in some areas, there are also emerging issues associated with naturally high levels of salinity, arsenic, and overexploitation in some areas. These clearly indicate that groundwater development has limits and that to ensure sustainability development needs to be properly managed.

Evidence from the field reveals that farmers are, on their own initiative, turning to ground water, typically via tube wells drilled to shallow or moderate depths and powered mostly by small motorized pumps. They are emerging not only in rainfed areas, but also within irrigation command areas. Many of the formal irrigation schemes, sourced by either surface water or groundwater, contain large areas that are not irrigable due to shortfalls in infrastructure development or energy supplies and in these tail-end areas private wells are emerging to meet the supply shortfalls. Since significant volumes of deep drainage flows generated by the schemes may be picked up and recycled by the tail-end farmers, such examples of conjunctive development should be encouraged – either as public or private initiatives – in places where it is practicable and can be achieved sustainably. This is an opportunistic approach to maximize benefits within irrigation schemes, where constraints limit surface water irrigation.

Based on findings presented in the component 2 report (Senaratna Sellamuttu et al. 2013), in conjunction with relevant international experience, the component 3 report rationalises and elaborates these recommendations (Johnston et al. 2013).

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Appendix A: Estimates of irrigated area by township and district

Division	District	Township	Township area (km^2)	Village	Project Name	Opening date	MOAI: Irrigated/Flood protected area (ha)			This study delineated irrigated area (ha)		FAO estimated irrigated area (ha)
							Scheme	Township	District	Township	District	District
Magwe	Magwe	Magwe	1,770					-	35,561	-	10,955	36,360
		Yenangyaung	1,028	Ngagar	Ngagar	27.7.02	405	405		1,313		
		Chauk	1,003		Salaypakhannge	17.3.91	2,185	2,185		263		
		Taungdwingyi	1,973	Kanthar	Kinpuntaung	29.3.90	2,024	8,499		9,379		
				Taikpwe	Bangone	18.1.97	809					
				Ngamin	Ngamin	18.7.99	1,619					
				Wetkathay	Yanpe	28.2.01	4,047					
		Myothit	1,596	Yepyauge	Boatchaung	19.3.92	202	8,891		-		
				Htanaung-Kwin	Saddan	18.4.98	4,047					
				Myaypyin-thar	Sunchaung	24.6.01	3,833					
				Palinbyargyi	Palinn	16.7.01	809					
		Natmauk	2,314	Lattpankone	Natmauk(weir)	14.1.95	202	15,581		-		
				Gwetaukkone	Natmauk	20.10.95	14,569					
				Kyauktagar	Kyauktagar	30.11.04	809					
	Minbu	Minbu	1,668					-	71,640	559	43,458	74,668
		Pwinbyu	1,205		Kyiohn-kyiwa	30.3.12	38,850	38,850		16,990		
		Ngaphe	1,323	Kyaung Kone	Mann Caung	19.10.98	19,233	19,435		1,617		
				Padan	Yinshae	29.9.09	202					
		Salin	2,323	Shwetwintuu	Salin	15.8.01	13,355	13,355		24,294		
	Thayet	Thayet	1,206					-	12,570	128	5,745	3,571
		Minhla	2,383					-		-		
		Mindon	2,559					-		32		
		Kamma	1,149	Kyoupin	Maday	2007-08	1,319	1,319		1,421		
		Aunglan	2,683		Duyinkabo	17.3.91	4,209	11,251		4,055		
				Pwethar	Pwethar	26.3.92	405					
				Daundaung	Bwetkyi	30.9.03	4,047					
				Natmaut	Ba De	24.1.05	2,590					
		Sinbaungwe	2,061							109		
	Pakokku	Pakokku	1,317	Magwe	Inn bart	26.11.06	61	61	13,569	5,093	12,298	5,969
		Yesagyo	993		Sinchaung	17.2.94	405	405		5,968		
		Myaing	2,042	Thatketan	Myaing Chaung	15.6.92	405	11,480		-		
				Kanpyar	South Yamar	23.1.00	1,833					
				Kyatmauk	Kyatmauk and Lete	14.8.00	486					
				Daung Oo	Thirinandar	21.10.04	182					
				Thiyitaw	Thitkyitaw	21.10.04	8,094					
				Twinma	Twinma	26.11.06	130					
				Minkan	Minkan	30.7.08	200					
				Kyaukskuk	Kyaukskuk	29.8.08	150					
		Paukkhaung	2,464	Theegyauk	Theegyauk(weir)	16.3.91	506	1,232		-		
				Yepyar	Yew Caung-2(weir)	30.4.91	726					
		Seikphyu	1,528	Thubye	Tagon	30.9.08	150	391		1,237		

				Ngachin	Ngachin	24.1.09	101					
				Kanzonma	Wonyu	28.2.10	140					
Mandalay	Kyaukse	Kyaukse	1,874	Kanzwe	Kinda	20.3.90	81,547	83,226	85,655	1,252	6,065	96,594
				Taungtaw	Myogyi (weir)	29.8.09	1,679					
		Myittha	892	Thittatkone	Thittatkone(weir)	25.7.00	2,024	2,024		2,125		
		Tada-U	938	Kyautten	Chaungmanat	27.1.04	405	405		2,688		
	Myingyan	Myingyan	988	Kuywar	Sunlun	4.1.94	1,012	4,776	15,500	5,158	29,825	10,346
				Kan Chaw	South Pinle	6.4.94	931					
					Myingyan	9.3.96	1,619					
				Yewin	North Pinle	13.4.96	1,214					
		Taungtha	1,352	Kyauktalone	Kyauktolone	27.3.93	809	6,677		10,785		
				Thamatku	Sintewa(Thamatku)	18.9.96	1,538					
				Tharpaung	Sunkan	31.3.97	1,903					
				Natkan	Taungtha	18.7.97	809					
				Thanateai	Wehlaung	13.7.98	809					
				Zeepinkan	Kyauktalone (supplementary)	18.9.01	809					
		Natogyi	1,256					-		4,586		
		Kyaukpadaung	1,960	Monkan	Pinn Chaung	31.8.98	2,024	2,024		1,208		
				Pinte	Taung Yay	27.7.04						
		Ngazun	962	Myothar	Myothar	24.10.00	607	2,023		8,089		
				Plaungkataw	Plaungkataw	21.8.02	809					
				Natthartaw	Natthartaw		607					
	Nyaung-U	Nyaung-U	1,464	Tuyintaung	Myakan	30.8.96	81	81	81	6,212	6,212	41
	Yamethin	Yamethin	2,152	Inndine	Leptyuu(detention dam)	17.3.96	2,509	2,691	24,996	-	-	72,751
				Yeboat	Yeboatchaung	17.3.96	182					
		Pyawbwe	1,649	Thaphanchaung	Thaphanchaung	15.9.90	486	7,043		-		
				Latthekyoe	Chaung Gauk(weir)	28.8.94	1,416					
				Latthekyoe	Chaung Gauk	9.9.95	4,654					
				Maede	Natkar	1.7.12	486					
		Tatkon	1,929	Kyaukse	Kinthar	29.1.94	809	15,262		-		
					Sinthe(weir)	14.9.99	13,112					
				MyoHla	Myola		1,341					
	Meiktila	Meiktila	1,229					-	5,775	152	10,317	71,216
		Mahlaing	1,123	Nyantkan	Ponemakyi	23.9.00	202	3,494		-		
					Khinn Thar	21.9.02	202					
				Beesat Kone	Thin Pone	31.8.03	3,090					
		Thazi	2,042	Kywekya	Thattaw	5.1.95	1,012	1,012		374		
		Wundwin	1,395	Taungnyo	Thapyayyoe	9.7.99	1,269	1,269		9,791		
Sagaing	Sagaing	Sagaing	1,267	Palae	Hlaing Chaung	31.12.06	405	405	1,417	16,669	31,140	15,418
		Myinmu	773	Tawchaung Oo	Latpan	21.12.03	1,012	1,012		3,622		
		Myaung	414					-		10,849		
	Shwebo	Shwebo	1,059					-	53,825	4,821	92,281	274,964
		Khin-U	1,046					-		1,216		
		Wetlet	1,319					-		22,475		

		Kanbalu	4,071	Ngapyawtine	Kyeepinakk	25.12.01	3,238	4,856		1,797		
				Paykyi	Paykyi	27.10.06	809					
				Mezali	Lin Pan	26.7.09	809					
		Ye-U	1,402	Depeyinn	Rehabilitation project of Ye-U canal	17.3.94	48,969	48,969		20,477		
		Debayin	1,382					-		32,650		
		Taze	1,857					-		8,844		
	Monywa	Monywa	674	Chaung Oo	Groundwater irrigation project1	15.3.92	9,282	10,738	23,668	2,519	8,281	23,348
				Tharsi	Tharsi	22.8.95	607					
				Kyaukkartaung	Htanzaloke	14.7.96	809					
				Khatakan	Bawditathaung	31.12.09	40					
		Budalin	1,076	Myothit	Myothit	27.9.04	1,012	1,012		-		
		Ayadaw	1,245	Ka Myint	A Ya Daw Dam	2005-06	405	405		317		
		Chaung-U	495	Nwekhway	Nwekhway	27.3.93	506	506		4,295		
		Yinmabin	952		Ywatharya (9)	25.3.96	4,007	8,863		219		
				Chinpyit	Northyamar	24.1.98	4,856					
		Salingyi	695	Ngwe Thar	Ngwe Thar	24.4.04	1,214	2,064		122		
				Salingyi	Salingyi	27.9.04	243					
				Ma Kyi Tan	Phoung Ka Dar Dam	28.8.05	607					
		Pale	1,593	Aima	Northyamar supplementary tank	28.11.07		81		810		
				Mezali Gone	Kandaunt	15.11.09	81					
							Total		**344,257**		**256,578**	**256,578.3**