Estimating the Groundwater Recharge of the Chindwin and Irrawaddy Basin in Myanmar Using Remote Sensing Based Water Accounting (WA+)

Karin S. Bremer
Student number: 4086856

Supervisors:
Prof.dr. W.G,M. Bastiaanssen
Dr.ir. M.M. Rutten

Delft University of Technology, Department of Civil Engineering, Stevinweg 1, 2628CN Delft, PO-box 5048, The Netherlands

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Abstract

Sustainable land and water management in Myanmar are desired since the country is rapidly changing. An analysis of the discharge data and an estimation on the groundwater recharge are desired to obtain this. In this paper, the discharge data of seven gauge stations in the Irrawaddy river are analyzed. Also, a method is described to estimate the groundwater recharge based on the Water Accounting + framework (WA+). This is done for the Irrawaddy basin in Myanmar upstream Pyay, and the Chindwin basin, which is part of the Irrawaddy basin. The groundwater recharge estimation is made with the use of remote sensing data, no ground measurements were needed for this. The method is based on the water balance and uses precipitation data (CHIRPS), actual evaporation data (ETensv1.0.) and output from the PCRaster Global Water Balance model. On a yearly basis, it is assumed that the change in storage is zero. Therefore, the annual discharge for the Chindwin basin and at Pyay could be used to validate the remote sensing precipitation minus evaporation. For the period 2005-2010 the 6-year average groundwater recharge is estimated to be 430-500 mm/year (20-23% of the rainfall) in the Chindwin basin and 340-400 mm/year (19-22% of the rainfall) for the Irrawaddy basin upstream Pyay. Most groundwater recharge takes place in the Northern part of Myanmar, as expected considering the high rainfall there. Some simplifications were made in the groundwater recharge estimation and the calculations were made on a cell basis. This is taken into account when determining the range. The method provided in this paper can be applied everywhere with remote sensing data. However, ground truth is recommended to validate the results.

List of symbols

SYMBOL	NAME	UNITS
α	Monthly runoff ratio	-
β	Budyko Index	-
γ	Groundwater abstraction ratio	-
ϵ	Base flow ratio	-
δ	Groundwater storage ratio	-
ϕ	Dryness Index	-
E	Actual evaporation	L/T
E_{nat}	Natural evaporation	L/T
E_{incr}	Incremental evaporation	L/T
E_0	Reference evaporation	L/T
E_{prec}	Maximum evaporation constrained by precipitation	L/T
P	Precipitation	L/T
Q	Total runoff	L/T
Q_{abstr}^{GW}	Groundwater abstraction	L/T
Q_{abstr}^{SW}	Surface water abstraction	L/T
Q_{bf}	Base flow	L/T
Q_{dr}	Direct runoff	L/T
Q_{fast}	Fast runoff	L/T
$Q_{recharge}^{GW}$	Groundwater recharge	L/T
Q_{RS}	Annual discharge measured by the remote sensing P and E	L/T
Q_{sf}	Interflow	L/T
Q_{WA+}	Discharge calculated from remote sensing data and PCR-GLOBWB ratios	L/T
Q_{year}	Total annual runoff	L/T
S	Storage	L
$S_1 + S_2$	Storage unsaturated zone (storage layer 1 and 2)	L
S_3	Storage saturated zone (storage layer 3)	L
t	Time	T

Abbreviations

CGAIR-CSI	Consortium for Spatial Information, CGIAR community of geo-spatial scientists
CHIRPS	Climate Hazards group Infrared Precipitation with Stations
CSFR	CLIMATE FORECAST SYSTEM REANALYSIS
DEM	Digital Elevation Map
DMH	Department of Meteorology and Hydrology
FAO	Food and Agriculture Organization of the United Nations
GLDAS	Global Land Data Assimilation System
IHE DELFT	Institute for Water Education in partnership with UNESCO
IWMI	International Water Management Institute
LULC	Land use/Land cover
MLU	Modified Land Use
MWU	Managed Water Use
PCR-GLOBWB	PCRaster Global Water Balance model
PLU	Protected Land Use
SWAT	Soil and Water Assessment Tool
ULU	Utilised Land Use
UNESCO	United Nations Educational, Scientific and Cultural Organization
WA+	Water accounting +
WMC	Water Management Classes

Introduction

The land use in Myanmar is rapidly changing, leading to changes in water use and allocation. This includes both surface water and groundwater. Especially in the Dry Zone, a semi-arid area in the centre of Myanmar, ground water is extremely important for irrigation as well as it is a critical water resource for villages (IMWI, 2015). For sustainable use of the groundwater resources in Myanmar, an estimation of the groundwater recharge is needed.

At this moment some estimations on groundwater recharge are made for areas within the Irrawaddy basin. These are made for the Dry Zone in central Myanmar (McCartney et al., 2013) and for the Ayadaw township, which is in the Northern part of the Dry Zone along the Mu river (Than Zaw). The aim of this study is to make a groundwater recharge estimation of the Irrawaddy Basin. This includes an estimation for the spatial distribution and an estimation of the volume. By analyzing a large area, a better insight is gained in the groundwater recharge and the influence of the rainfall on it. This is useful for sustainable water management in the future.

In this study, the groundwater recharge was estimated by using the Water Accounting Plus (WA+) framework. The aim of the WA+ framework is to provide a standard and harmonized way to communicate water resources related information in a basin to users such as policy makers, water authorities, managers. This is done by several sheets, allowing a complete overview of the water resources, which is helpful for evidence based decision making. Currently, the WA+ framework is being standardized. The method described in this paper varies at two points from this standard, which are discussed in the discussion.

The input data for the WA+ framework should be based on satellite data or, if it cannot be derived from satellite data, needs to come from hydrological models that are freely available (Karimi, Bastiaanssen, & Molden, 2013; WaterAccounting+, 2016). This makes it possible to get insight in the water cycle in a river basin, regardless of the border is it crossing. WA+ is not bound to political boundaries or available ground measurements and can basically be applied everywhere, this is an advantage of the WA+ framework. Although ground measurements can be used to validate the results obtained with WA+. The term evaporation used describes the sum of the evaporation from interception, transpiration, surface evaporation and open water evaporation, as suggested by (Savenije, 2004).

With the use of precipitation and evaporation data from remote sensing and the PCRaster Global Water Balance model (PCR-GLOBWB) (van Beek, Wada, & Bierkens, 2011; Wada, Wisser, & Bierkens, 2014), estimations were made for the inflows and outflow of the groundwater reservoir, such as the groundwater recharge, groundwater abstraction and change in storage. Since WA+ is based on remote sensing data and global hydrological models that are freely available, an estimate of the groundwater recharge can be made even if there is a lack of field data or no site specific hydrological model.

Water use and evaporation are closely linked to land use/land cover (LULC). By coupling the water use and flows to the LULC, detailed information about the water use for each LULC class for a given time period is provided. This way of presenting data can give an insight in the influence of LULC changes on the water availability and water use. With the rapid changes in land use in Myanmar, having insight into the groundwater recharge contributes to the sustainable use of the water resources. WA+ uses a specific

LULC classification, which is divided into four water management classes (WMC): “Protected land use” (PLU), “utilized land use” (ULU), “modified land use” (MLU) and “managed water use” (MWU) (Karimi et al., 2013).

For this study, the period 2005-2010 was analyzed. By analyzing a period before the political and economic reforms that took place in 2011, human influence on the groundwater abstraction is small, which made it possible to only focus on the natural groundwater abstraction. In this period of time less major changes in LULC have taken place than in the years following 2011.

In the section Materials and Methods, the data used and method is described. The results of the research are provided in the results section. The final result is the 6-year average groundwater recharge for the Chindwin basin and the Irrawaddy River upstream of Pyay - called the Irrawaddy basin from now onwards. After this, the method is discussed, showing the strengths, weaknesses and a comparison with the standardized WA+ method. Also, the results of the study were compared to discharge data from gauge stations and to earlier estimates of groundwater recharge in the area. Simultaneous to this research, a groundwater recharge estimation using a SWAT model was made by Van Ramshorst (2017) for the Chindwin basin. A comparison with the results from this study and other previous groundwater recharge estimations is made in the discussion section. The discussion is followed by the conclusion.

Materials and methods

Data discharge analysis

The discharge data was provided by the Department of Meteorology and Hydrology (DMH). At seven locations the discharge was measured at gauge stations, the locations of these stations are shown in Figure 1. Sagaing has the longest data record, from 1967 to 2010, followed by Chauk which has a record from 1973-2010. Nyaung Oo has records from 2000-2010. The other four stations have records from 2000-2015. For each station, hydrographs were made and the annual, average annual flow and average monthly flow were calculated.

The data was complete for most data stations. At Sagaing the daily data of 2008 and 2009 were exactly the same as that of 2007. Comparing the data with the data of the other stations showed that most likely the daily data of 2008 and 2009 were replaced by the data of 2007. Therefore the years 2008 and 2009 were left out of the analysis. In 1997 there was a gap of 2 days in the dataset. Since most other datasets have data from 2000 onwards, this gap did not give problems for the rest of the analysis. The other station with some gaps was Myitkyina, here two daily measurements had a writing error in the discharge notation. The values of these data were linearly interpolated. The complete flow data analysis can be found in Appendix A.

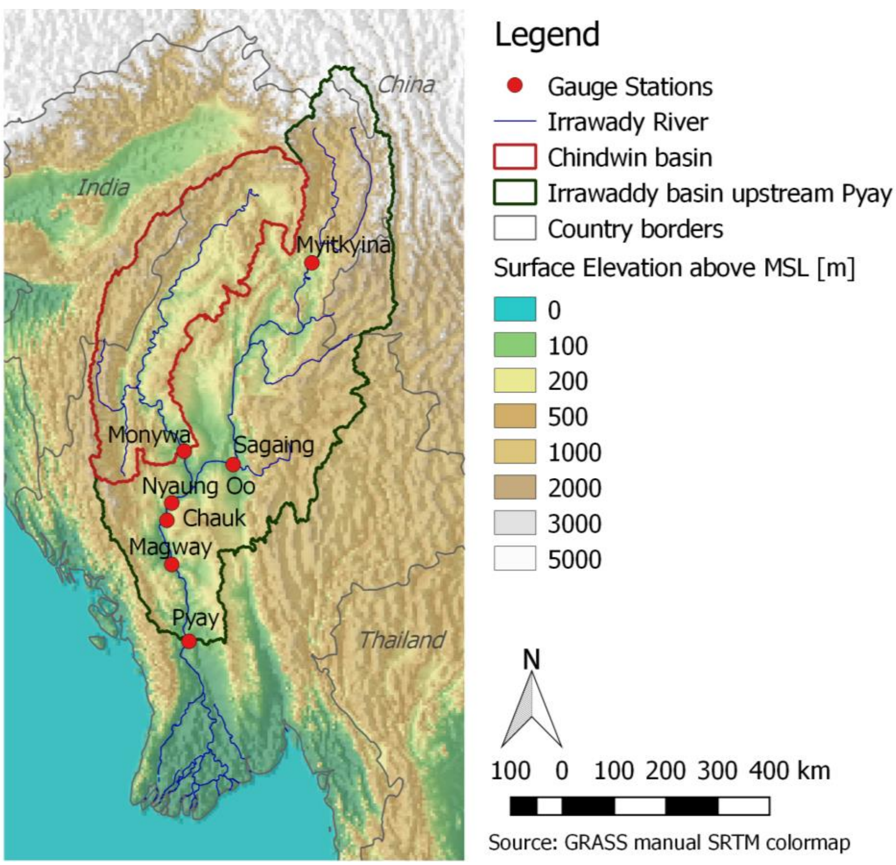

Figure 1: Map of the Irrawaddy River basin in Myanmar. The surface elevation in meters above mean sea level (MSL) is shown. The location of the seven discharge gauge stations in the Irrawaddy basin are indicated with red dots. The basins described in this report are the Irrawaddy basin upstream Pyay, indicated with a dark green outline, and the basin upstream Monywa, the Chindwin basin, with a red outline.

Data WA+

The input for the WA+ framework was given by remote sensing data for precipitation, evaporation and a LULC map. Monthly data over the period 2005-2010 was used.

For the monthly precipitation data from CHIRPS data with a 0.05° spatial resolution was used (Funk et al., 2014). The actual evaporation data used in this study is the ETensV1.0. product with a spatial resolution of 0.0025°. This product is being developed by the IHE Delft Water Accounting research group and uses MOD16, SSEBop ,SEBS, CMRSET, GLEAM and ALEXI. The ensemble product was corrected with a basin correction factor which is determined for each sub basin (Roberts-Pierel, 2016).

The reference evaporation was determined with the Penman-Monteith method (Allen, Pereira, Raes, & Smith, 1998). To calculate the reference evaporation the following data was used: humidity, air temperature, surface pressure and windspeed data from GLDAS (Matthew Rodell and Hiroko Kato Beaudoing, 2015) and downward longwave radiation flux, downward shortwave radiation flux, upward longwave radiation flux data from CSFR (Suranjana Saha et al., 2010).

The basin outlines were determined with use of the digital elevation map (DEM), obtained through the DEM hydroshed database (Lehner, 2006) and the locations of the gauge stations given by DMH as shown in Figure 1. The considered areas are the Monywa catchment, from now on called the Chindwin basin since this is almost equal, and the Irrawaddy catchment. These are shown in Figure 1.

The precipitation and evaporation data obtained with remote sensing were not sufficient to estimate the groundwater recharge. The PCRaster Global Water Balance (PCR-GLOBWB) model (version 2) (van Beek et al., 2011; Wada et al., 2014) was used to determine the missing components. This is described in detail in the methods section. PCR-GLOBWB is a leaky bucket model that gives output on raster cell basis for the period 1960-2010 on a global scale. The PCR-GLOBWB data gives the monthly average in [m/day] for the flows and a daily total value in [m] when looking at the storage. PCR-GLOBWB files used have a spatial resolution of 0.5° (30 min). PCR-GLOBWB works with a daily timescale. This should be taken into account when analyzing results that are obtained with ratios from PCR-GLOBWB.

Used for the calculations were the following output data from PCR-GLOBWB model 2:

- Monthly runoff [m/day]
- Monthly base flow [m/day]
- Storage 1 for the last day of the month [m]
- Storage 2 for the last day of the month [m]
- Storage 3 for the last day of the month [m]
- Monthly groundwater abstractions [m/day]
- Monthly surface water abstractions [m/day]

LULC input data is of key importance of the water accounting framework. International Water Management Institute (IWMI) developed a LULC map for the Irrawaddy basin (IWMI, 2016), which satisfied the WA+ requirements of land use classification. It was made by combining several inputs based on several satellite images . The spatial resolution of the LULC raster map is 30m. The different LULC classes with the contributing area in the Chindwin basin and the Irrawaddy basin upstream of Pyay can be found in Table 2. The main LULC class for the Chindwin basin is Closed Evergreen Forest (ULU3) covering 35% of the basin. This is followed by Protected Forests (PLU1), which covers 17% of the basin.

In the Irrawaddy basin, the main LULC class is also Closed Evergreen Forest (ULU3), covering 30% of the basin. The second largest LULC class for the Irrawaddy basin is the Rainfed crops – other (MLU11), covering 25% of the basin.

In Table 1 the spatial resolution of the data is given. As can be seen, the PCR data, precipitation data and the evaporation data had a finer spatial resolution than the LULC map. Since the evaporation is closely linked to the LULC, the LULC was resampled using the resampling tool in ArcMap to the same spatial resolution as the ensemble evaporation (0.0025°). Figure 2 shows the newly obtained LULC map.

Table 1: Original resolution of input data WA+

	Product	Spatial resolution
land use/land cover	land use map produced by IWMI	0.00027° (30 m)
Precipitation	CHIRPS	0.05° (5,000 m)
reference evaporation	GLDAS and CSFR	0.0025° (250 m)
actual evaporation (E ensemble)	ETensv1.0	0.0025° (250 m)
pcr-globwb raster files	PCR-GLOBWB	0.5° (50,000 m)

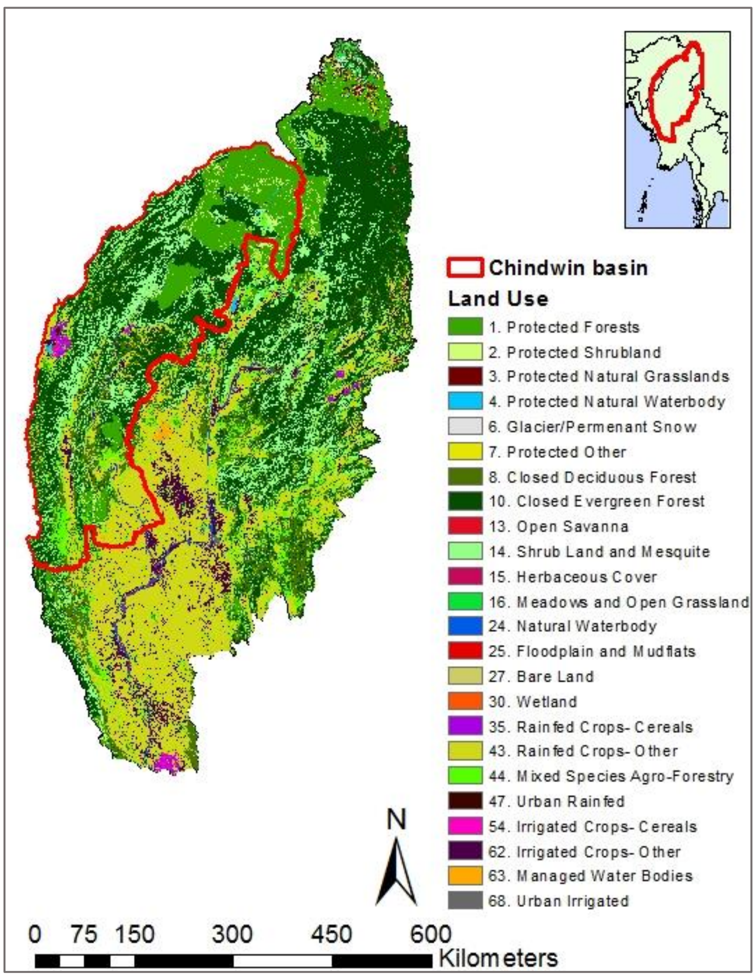

Figure 2: Land use/land cover map of the Irrawaddy basin upstream of Pyay, showing the land use/land cover classification as described by the WA+ framework. The Chindwin basin is indicated with a red outline.

Table 2: Land use/Land cover (LULC) classification table, including the area [km2] of each LULC class and the contribution of the WMC to the total area in the Chindwin basin and the Irrawaddy basin for the LULC map with 0.0025° spatial resolution.

		WATER MANAGEMENT CLASSES (WMC)	LAND USE/LAND COVER	CHINDWIN AREA (KM^2)	% TOTAL AREA	IRRAWADDY AREA (KM^2)	% TOTAL AREA
1	PLU1	Protected land use	Protected Forests	19339	17%	32335	9%
2	PLU2	Protected land use	Protected shrub land	2038	2%	3911	1%
3	PLU3	Protected land use	Protected natural grasslands	6	0%	1076	0%
4	PLU4	Protected land use	Protected natural water bodies	192	0%	347	0%
6	PLU6	Protected land use	Glaciers	0	0%	777	0%
7	PLU7	Protected land use	Protected other	5	0%	460	0%
	PLU	**TOTAL**		**21580**	**19%**	**38906**	**11%**
8	ULU1	Utilized land use	Closed deciduous forest	9699	9%	34519	10%
10	ULU3	Utilized land use	Closed evergreen forest	39128	35%	108391	30%
14	ULU7	Utilized land use	Shrub land & mesquite	16020	14%	37742	10%
15	ULU8	Utilized land use	Herbaceous cover	92	0%	1169	0%
16	ULU9	Utilized land use	Meadows & open grassland	87	0%	1323	0%
24	ULU17	Utilized land use	Natural lakes	838	1%	3536	1%
25	ULU18	Utilized land use	Flood plains & mudflats		0%	0	0%
27	ULU20	Utilized land use	Bare soil permanent	1	0%	2	0%
	ULU	**TOTAL**		**65864**	**59%**	**186682**	**52%**
35	MLU3	Modified land use	Rainfed crops – cereals	621	1%	1259	0%
43	MLU11	Modified land use	Rainfed crops - other	13445	12%	91039	25%
44	MLU12	Modified land use	Mixed species agro-forestry	7227	7%	24803	7%
47	MLU15	Modified land use	Rainfed homesteads and gardens (urban cities) - outdoor	210	0%	831	0%
	MLU	**TOTAL**		**21503**	**19%**	**117932**	**33%**
54	MWU3	Managed water use	Irrigated crops – cereals	309	0%	756	0%
62	MWU11	Managed water use	Irrigated crops – other	1589	1%	15903	4%
63	MWU12	Managed water use	Managed water bodies (reservoirs, canals, harbors, tanks)	33	0%	919	0%
68	MWU17	Managed water use	Irrigated homesteads and gardens (urban cities) - outdoor	22	0%	446	0%
	MWU	**TOTAL**		**1953**	**2%**	**18024**	**5%**
			Total area [km2]	110901		361544	

Methods

WA+ uses the water balance as a base for the calculations. The water balance is described in equation 1, and a schematization of the water balance as used in PCR-GLOBWB is shown in Figure 3. For the groundwater layer, the water balance in described in equation 2 and schematically shown in Figure 4. The precipitation and the actual evaporation were remote sensing based raster files. Therefore, the calculations were done for each cell. For this, the data has been resampled to the same spatial resolution as the actual evaporation, 0.0025˚.

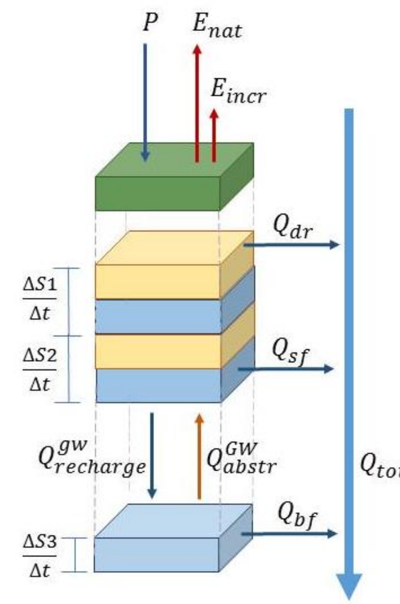

Figure 3: Schematization of the water balance as described in PCR-GLOBWB

$$\frac{\Delta S}{\Delta t} = P - E - Q \qquad (1)$$

$$\frac{\Delta S_3}{\Delta t} = Q^{GW}_{recharge} - Q^{GW}_{abstr} - Q_{bf} \qquad (2)$$

Where:

$$\frac{\Delta S}{\Delta t} = \frac{\Delta S1}{\Delta t} + \frac{\Delta S2}{\Delta t} + \frac{\Delta S3}{\Delta t} \qquad (3)$$

$$Q = Q_{fast} + Q_{bf} \qquad (4)$$

$$Q_{fast} = Q_{dr} + Q_{sf} \qquad (5)$$

Where $\frac{\Delta S}{\Delta t}$ is the change in storage over time [mm/month] in the first, second and third reservoir, as described in equation 3, P is the precipitation [mm/month], E the actual evaporation [mm/month], Q the runoff [mm/month] which consists of a fast component (Q_{dr} and Q_{sf}) and a slow component (Q_{bf}).

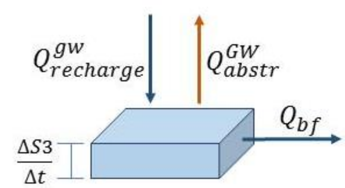

Figure 4: Schematization of the water balance for the groundwater reservoir

It was assumed that over a year $\frac{\Delta S}{\Delta t} = 0$. Which gives on a yearly basis that:

$$(P - E)_{year} = Q_{year} \qquad (6)$$

By subtracting the annual evaporation from the annual precipitation, both obtained from remote sensing data, the annual runoff was determined.

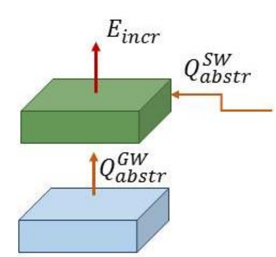

Figure 5: Water abstractions providing water for incremental evaporation

The P, E and Q_{year} were obtained from remote sensing data, however more components were needed to estimate the groundwater recharge. PCR-GLOBWB was used to determine those. Since PCR-GLOBWB uses different climate forcing than WA+ the output was not directly used, but ratios between different flows were determined, which are shown in Table 3. The monthly runoff, for example, was determined by taking the ratio between the monthly runoff and the annual runoff in PCR-GLOBWB and multiplying this with the annual flow that follows from the remote sensing based precipitation and evaporation.

Table 3: Overview of the ratios determined from PCR-GLOBWB, where Q is the monthly discharge, Q_{year} is the yearly discharge, Q_{bf} is the monthly base flow, Q_{abs}^{GW} is the monthly groundwater abstraction, Q_{abs}^{SW} is the monthly surface water abstraction, $\frac{\Delta S_3}{\Delta t}$ is the monthly change in storage of the third reservoir (groundwater reservoir, see Figure 4) and $\frac{\Delta S}{\Delta t}$ is the monthly change in total storage.

Ratio	Symbol	Formula ratio PCR-GLOBWB
monthly runoff ratio	α	$\left(\frac{Q}{Q_{year}}\right)_{WA+} = \left(\frac{Q}{Q_{year}}\right)_{PCR}$
base flow ratio	ϵ	$\left(\frac{Q_{bf}}{Q_{tot}}\right)_{WA+} = \left(\frac{Q_{bf}}{Q_{tot}}\right)_{PCR}$
groundwater abstraction ratio	γ	$\left(\frac{Q_{abstr}^{GW}}{Q_{abstr}^{GW}+Q_{abstr}^{SW}}\right)_{WA+} = \left(\frac{Q_{abstr}^{GW}}{Q_{abstr}^{GW}+Q_{abstr}^{SW}}\right)_{PCR}$
groundwater storage ratio	δ	$\left(\frac{\left(\frac{\Delta S_3}{\Delta t}\right)}{\left(\frac{\Delta S}{\Delta t}\right)}\right)_{WA+} = \left(\frac{\left(\frac{\Delta S_3}{\Delta t}\right)}{\left(\frac{\Delta S}{\Delta t}\right)}\right)_{PCR}$

The change in storage over a month is not equal to zero and could therefore not be neglected. The PCR-GLOBWB monthly runoff data was used to calculate the annual runoff in PCR-GLOBWB for each cell. With these values, the monthly runoff ratio α was determined (see Table 3). By multiplying the annual runoff with the monthly runoff ratio an estimation of the monthly runoff was made:

$$Q_{month} = Q_{year} * \alpha \qquad (7)$$

With the monthly runoff, the fast and slow runoff components could be determined. From PCR-GLOBWB the ratio of the base flow from the total flow, ϵ, was determined (Table 3). Multiplying this with the monthly discharge gave the monthly base flow. Using equation 4 gave the fast runoff component:

$$Q_{bf} = Q * \epsilon \qquad (8)$$

$$Q_{fast} = Q * (1 - \epsilon) \qquad (9)$$

Now the water balance (equation 1) could be closed for each cell, which gives $\frac{\Delta S}{\Delta t}$.

For the groundwater recharge estimation, the change in storage of the third reservoir ($\frac{\Delta S3}{\Delta t}$) was needed. With PCR-GLOBWB the groundwater storage ratio γ was obtained. From the storage at the end of each month from PCR-GLOBWB, a change in storage for a month was calculated. This was done for both the total storage (S) and the groundwater storage (S_3). With this γ could be calculated (Table 3). The change in groundwater storage was determined by multiplying the change in the total storage with γ.

$$\frac{\Delta S_3}{\Delta t} = \frac{\Delta S}{\Delta t} * \gamma \qquad (10)$$

At some points, the change in storage, $\frac{\Delta S}{\Delta t}$, from PCR-GLOBWB reached a value close to zero. This resulted in a very high groundwater storage ratio (Table 3). When the change in storage calculated with the remote sensing data value close to zero, the high ratio results in an unrealistic high change in groundwater storage.

To prevent this from happening, the outliers, which are defined as pixels that vary more than two times the standard deviation from the mean, were removed and given a value obtained by nearest neighbour interpolation. The step of removing the outliers was repeated until the standard deviation of a raster layer was below a value of 1. The values of 1118 cells (3% of the total of 39060 cells) were adjusted in this step. After this, visual inspection was used to check if all extreme outliers are removed and remaining outliers were removed if needed. In this last step, the values of another 9 cells were adjusted.

The actual evaporation can be separated in the natural evaporation and the incremental evaporation (van Eekelen et al., 2015). The natural evaporation is the evaporation of precipitation. If in a cell more water is evaporated than the precipitation in that period of time, it is incremental evaporation. This indicates water withdrawal from surface water or groundwater abstraction.

The Budyko curve was used to make the separation between the two (Gerrits, Savenije, Veling, & Pfister, 2009). To take measurement errors into account, a buffer of 10% was included, but the curve was cut off at a value of 1 since the E_{prec} cannot be higher than the precipitation.

$$\phi = \frac{E_{ref}}{P} \text{ (Dryness Index)} \tag{11}$$

$$\frac{E_{prec}}{P} = \sqrt{\phi * \tanh\left(\frac{1}{\phi}\right) * (1 - e^{-\phi})} \tag{12}$$

$$\beta = \min\left(\sqrt{\phi * \tanh\left(\frac{1}{\phi}\right) * (1 - e^{-\phi})} + 0.1\,, 1\right) \text{ (Budyko Index)} \tag{13}$$

For each month a plot was made with the values of the Dryness Index ϕ, $\frac{E}{P}$ and Budyko Index β. With the Budyko curves, the incremental and natural part of the evaporation could be distinguished. When the measured evaporation was higher than the evaporation limited by precipitation, E_{prec}, the surplus was the incremental evaporation (equation 14). The natural evaporation followed from equation 15.

$$E_{incr} = \left(\frac{E}{P} - \frac{E_{prec}}{P}\right) * P \tag{14}$$

$$E = E_{nat} + E_{incr} \qquad \text{Therefore: } E_{nat} = E - E_{incr} \tag{15}$$

The incremental evaporation can come from surface water withdrawal or groundwater abstraction, as is shown in Figure 5. An estimate for the groundwater abstraction was made by calculating the ratio groundwater abstraction over the total abstraction (Table 3). Multiplying this ratio with the incremental evaporation gave the natural groundwater abstraction:

$$Q^{GW}_{abstr,nat} = E_{incr} * \delta \tag{16}$$

The groundwater recharge estimation was made by closing the water balance for the third reservoir:

$$Q^{GW}_{recharge} = Q^{GW}_{abs} + Q_{bf} + \frac{\Delta S3}{\Delta t} \tag{20}$$

All calculations were made on a monthly basis for each cell. For each LULC classification, the average precipitation, evaporation, groundwater withdrawal and groundwater recharge were determined. Multiplying this with the area covered by that specific LULC class gave the total in [mm/year] for each land use classification. This is the final result for WA+. A summation of the groundwater recharge of the different LULC classifications was made to get the total groundwater recharge for the Chindwin and the Irrawaddy catchment, which is compared with the base flow separation and SWAT model.

Results

Flow data analysis

A clear distinguishing can be made between the wet season, July-October and the dry season. In Table 4 the annual flows and 6-year average annual flow of the seven gauge stations are shown. In the Chindwin basin, gauge station at Monywa, the average annual flow over the period 2005-2010 was 127 km^3/year. The highest annual flow was measured in 2007 (165 km^3/year) and the lowest in 2009 (102 km^3/year). At Pyay the highest flow was observed in 2007 as well (420 km^3/year), and the lowest flow in 2009 (287 km^3/year). It is observed that the base flow at Monywa decreases over the measured period. Figure 6 shows the measured river discharge at the gauge station during the dry period.

In some years, the measured discharge at a station was lower than that measured discharge at the upstream station. The downstream stations for which this is the case, have a light grey background in Table 4. This decrease in annual flow can indicate losses caused by high evaporation rates, groundwater recharge in the area between the upstream and downstream stations or measurement errors. Interestingly at Pyay, the measured discharge was for every year in the period 2005-2010 lower than the discharge measured at Magway. The more elaborate flow analysis can be found in Appendix A.

Table 4: Annual discharge and the 6-year average discharge for the different gauge stations along the Irrawaddy in [km3/year] and between brackets in [mm/year] The cells that have a light grey background indicate a lower flow than measured at the upstream stations(s).

	Myitkyina		*Sagaing*		*Monywa*		*Sagaing + Monywa*	*Nyaung Oo*		*Chauk*		*Magway*		*Pyay*	
2005	154	(3190)	148	(864)	110	(994)	258	278	(886)	286	(886)	327	(964)	304	(842)
2006	135	(2815)	198	(1156)	119	(1070)	317	315	(1002)	308	(952)	343	(1011)	333	(921)
2007	169	(3503)	258	(1506)	165	(1492)	424	391	(1244)	410	(1270)	431	(1268)	420	(1161)
2008	150	(3111)			142	(1282)		349	(1109)	358	(1108)	402	(1183)	384	(1063)
2009	126	(2612)			102	(922)		268	(853)	293	(907)	322	(947)	287	(794)
2010	161	(3352)	223	(1297)	123	(1109)	346	377	(1201)	460	(1425)	416	(1225)	391	(1082)
6-year av.	149	(3097)	207	(1206)	127	(1145)	336	330	(1049)	352	(1091)	373	(1100)	353	(977)

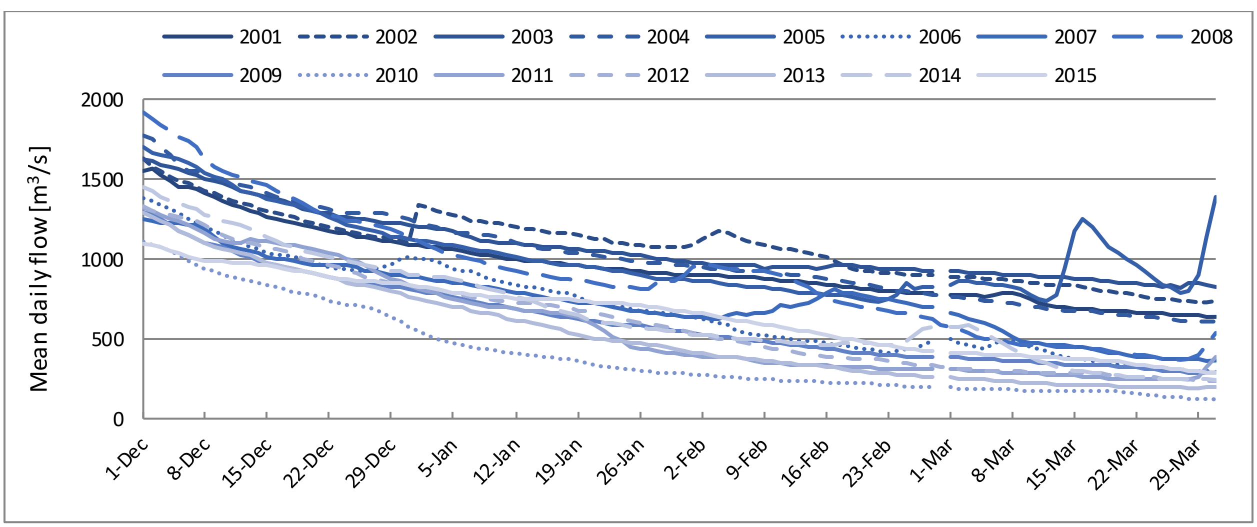

Figure 6: Discharge measured at Monywa for the dry months (December to March) for the years 2001-2015

WA+ Groundwater Recharge

Chindwin basin

The annual and 6-year average annual rainfall were calculated with the monthly rainfall data. The result of the average annual rainfall for the period 2005-2010 is shown in Figure 7a. Most rainfall was observed in the northeast area of the Chindwin basin with values around 4000 mm/year. In the south eastern part, much less rainfall was observed, around 1000 mm/year. This area is at the border of the dry zone.

Figure 7b shows the mean annual evaporation over the whole period. Most evaporation takes place in the northern part of the basin. When comparing the evaporation map, Figure 7b, and the LULC map (Figure 2) the influence of the vegetation on the evaporation is clearly visible in the south and south western part. The areas with less evaporation are the same areas where the LULC is mainly rain fed crops-other (LULC class 43).

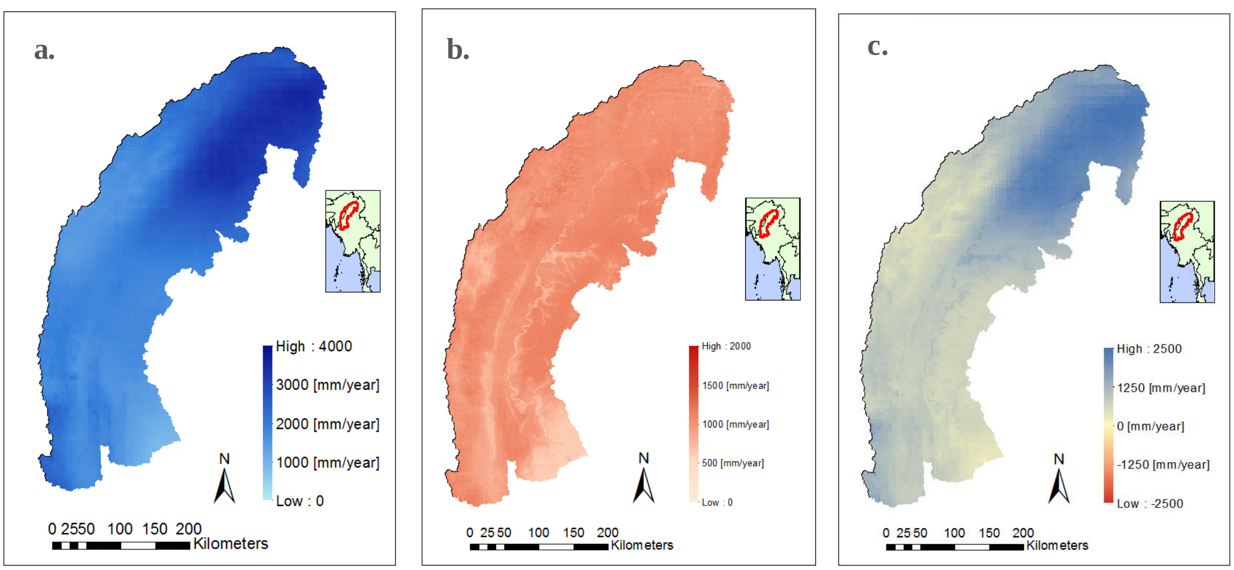

Figure 7: Average annual precipitation (a), evaporation (b) and precipitation minus evaporation (c) over the period of 2005-2010 in the Chindwin basin in Myanmar in [mm/year]

From the water balance in equation 1 and the assumption that $\frac{\Delta S}{\Delta t} = 0$ over one year, it followed that the precipitation minus the evaporation on a yearly timescale is equal to the discharge Q_{WA+}. This yearly discharge Q_{WA+} was compared to the discharge measured at the gauge station at Monywa in Table 5.

The spatial result of the mean annual precipitation minus evaporation $(P - E)$ obtained by remote sensing data for the period of 6 years is shown in Figure 7c. The $P - E$ gave the highest values in the mid-northern part of the Chindwin basin, in the valley of the mountain ranges. This was expected since this region had the highest precipitation and the evaporation was more equally distributed over the whole basin as compared to the rainfall.

By combining Figure 7a, Figure 7b, and Figure 7c with the LULC map, the average annual P, E and $P - E$ were determined for each LULC class. In WA+ the total amount in Mm^3/year for each of the LULC classes for a basin, the Chindwin basin in this case, is used. In Table 6 the P, E, E_{nat}, E_{incr} and $P-E$ for each LULC class are shown in mm/year and Mm^3/year. The Budyko curves for different LULC for each year can be found in Appendix B.

From the precipitation data and the evaporation data, it followed that 2010 is the year providing most runoff, followed by 2007. The driest year was 2006. The discharge measurements have as a result that 2007 has the highest discharge, and the driest years are 2008 and 2009. The discharge determined with WA+ was low compared to the measured discharge at the gauge station in 2006, 2007 and 2008. For most years the discharges were close to each other, with a relative error of 4 and 12 %, the only exception is 2010 with a relative error of 40%. In 2010 high precipitation was measured with remote sensing and no high evaporation, which led to high $P-E$ as can be seen in Table 5. However, in 2010 no high amount of discharge was measured at the gauge station. When looking at the 6-year average values, the discharges are very close with a relative error of 3%.

Table 5: Comparison between the annual discharge measured by remote sensing Q_{WA+} ($Q_{WA+} = P - E$) and the discharge measured in the field by a gauge station (Q_{gauge}) at Monywa in mm/year. The difference between the two is shown and the relative error of the discharge measured at the gauge station at Monywa compared to the annual discharge determined by remote sensing.

	Q_{WA+}	Q_{gauge}	$Q_{WA+} - Q_{gauge}$	$\left\lvert\frac{Q_{WA+}-Q_{gauge}}{Q_{gauge}}\right\rvert$
	[mm/year]	[mm/year]	[mm/year]	**relative error %**
2005	1035	994	41	4%
2006	968	1070	-102	10%
2007	1391	1492	-101	7%
2008	1127	1282	-155	12%
2009	1012	922	91	10%
2010	1548	1109	439	40%
6-year average	1180	1145	36	3%

Table 6: Summary of the 6-year average annual P, E and $P - E$ for each land use/land cover (LULC) class over the Chindwin basin with average values per area in mm/year and total values in Mm^3/year.

Land Use/ Land Cover Class	AREA (km2)	P (mm/yr)	P (Mm^3/yr)	E (mm/yr)	E (Mm^3/yr)	P-E (mm/yr)	P-E (Mm^3/yr)	E_{NAT} (mm/yr)	E_{NAT} (Mm^3/yr)	E_{INCR} (mm/yr)	E_{INCR} (Mm^3/yr)
protected forests	19339	2902	56132	1042	20157	1860	35975	826	15966	217	4193
protected shrubland	2038	2874	5857	1049	2139	1824	3718	833	1698	216	441
protected natural grasslands	6	2557	15	837	5	1720	10	729	4	108	1
protected natural waterbodies	192	2453	470	945	181	1508	289	771	148	175	33
glaciers	0	1831	1	793	0	1038	0	610	0	183	0
protected other	5	2997	16	860	4	2136	11	714	4	147	1
closed deciduous forest	9699	1846	17901	982	9527	863	8374	697	6759	285	2767
closed evergreen forest	39128	2171	84943	1049	41062	1121	43881	765	29949	284	11113
shrub land & mesquite	16020	2145	34367	1046	16751	1100	17616	767	12285	279	4466
herbaceous cover	92	1708	157	731	67	977	90	578	53	153	14
meadows & open grassland	87	1656	144	775	67	882	77	634	55	140	12
natural lakes	838	2092	1752	768	644	1323	1109	616	516	152	128
bare soil permanent	1	1119	1	638	0	482	0	498	0	140	0
rainfed crops – cereals	621	1528	949	786	488	742	460	661	410	125	78
rainfed crops - other	13445	1565	21043	800	10756	765	10287	610	8200	190	2557
mixed species agro-forestry	7227	1924	13907	957	6914	968	6994	698	5045	259	1869
rainfed homesteads and gardens (urban cities) – outdoor	210	1620	340	804	169	816	171	648	136	156	33
irrigated crops – cereals	309	1607	497	835	258	771	238	681	211	154	48
irrigated crops – other	1589	1816	2885	830	1319	986	1567	638	1013	192	305
managed water bodies (reservoirs, canals, harbors, tanks)	33	1508	50	688	23	820	27	527	17	161	5
irrigated homesteads and gardens (urban cities) – outdoor	22	943	21	684	15	260	6	519	11	164	4
TOTAL	**110901**		**241447**		**110546**		**130901**		**82482**		**28067**

To verify the WA+ method a comparison was made between the discharge determined with WA+ (Q_{WA+}) for the Chindwin basin and the discharge measured at the gauge station (Q_{gauge}) in Monywa. Table 5 shows that the relative error between the Q_{gauge} and Q_{WA+} for the 6-years is low. This is also visible in Figure 8, in which the cumulative discharges of Q_{gauge}, Q_{WA+} and $P - E$ are plotted.

Figure 8, shows that the variation in dry and wet season measured at the gauge station (Q_{gauge}) is larger than the discharge determined with the WA+ (Q_{WA+}). The high seasonal variation of the remote sensing data ($P - E$) is clearly visible. The trend of the cumulative discharge from WA+ is less than to that of the gauge station. For 2005 and 2006 Q_{gauge} and Q_{WA+} showed similar behaviour, but from 2007 onwards the gap between the two measurements increased until 2010. Another observation is that up to 2007 the P-E exceeds the discharge of the gauge station during the wet season. From November 2007 until June 2010 the measured discharge at the gauge station is higher than the precipitation minus evaporation measured. This would mean that more water is flowing out of the basin through the river and through evaporation than is added to the basin by the precipitation. The high amount of rainfall measured in 2010, compared with relative normal evaporation caused an increase in the $P - E$ during that year, leading to a higher discharge determined with WA+ and finally a cumulative discharge that exceeded the measured discharge at Monywa.

The hydrograph of the discharge determined with WA+ (Q_{WA+}), the measured at Monywa (Q_{gauge}) and the total precipitation minus evaporation ($P - E$) of the Chindwin basin, is shown in Figure 9. The PCR-GLOBWB ratio caused an overestimation of the discharge Q_{WA+} in the dry seasons and an underestimation of the flow in the wet season. The less extreme differences of Q_{WA+} had influence on the monthly values of the groundwater recharge and change in storage. In 2005, 2009 and 2010 the peaks were about the same magnitude. In 2010 Remote Sensing gave a higher amount of water available for runoff (P-E) than the measured runoff at the gauge station (Q_{gauge}), as can be seen in Table 5.

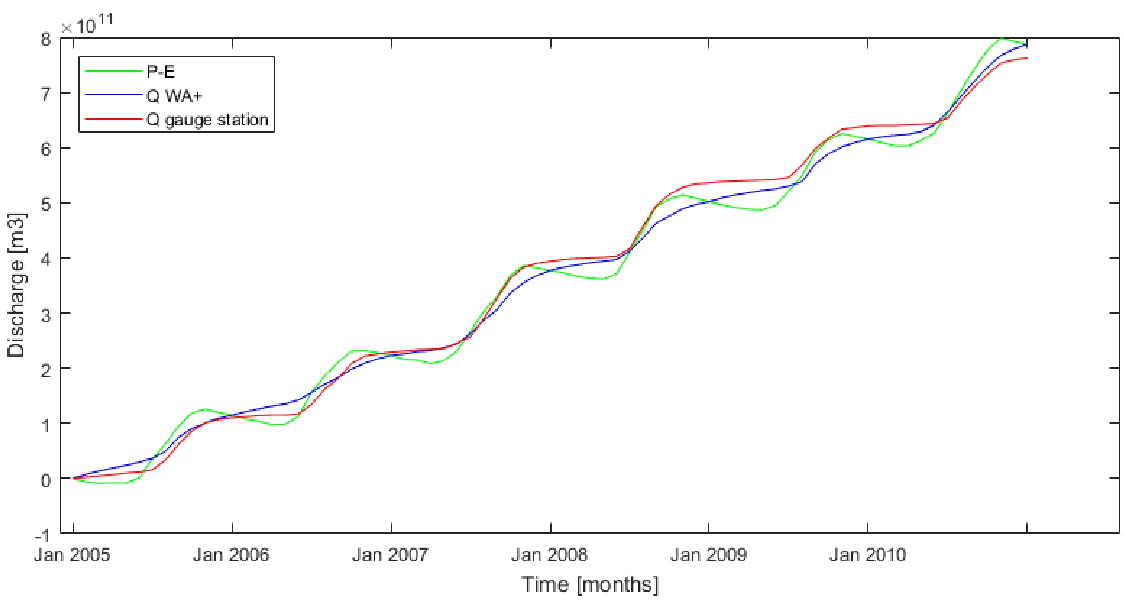

Figure 8: Cumulative discharge plot in m3 of the precipitation minus evaporation, $P - E$, the discharge determined as described in the methodology (Q_{wa+}) and the discharge at Monywa measured by the gauge station (Q_{gauge}) for the Chindwin basin.

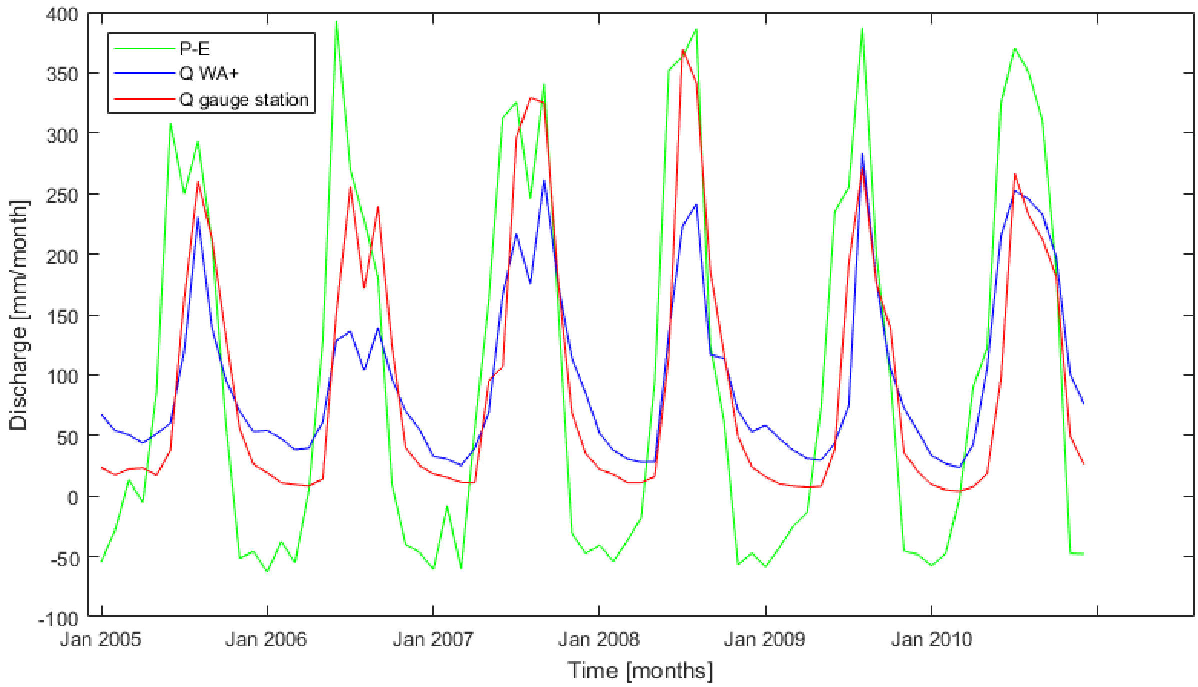

Figure 9: Hydrograph showing the precipitation minus evaporation, P-E, the discharge determined as described in the methodology (Q_{wa+}) and the discharge at Monywa measured by the gauge station (Q_{gauge}) for the Chindwin basin. All in discharges are in [mm/year] for the period 2005-2010.

The groundwater recharge estimation was obtained by closing the water balance for the third reservoir or the groundwater layer as described in the methodology, Figure 4 and equation 2. The yearly results for the groundwater recharge, change in groundwater storage, base flow for the Chindwin basin are shown in Table 7. Over the period 2005-2010, there was an average of 436 mm/year groundwater recharge. This is about 20% of the rainfall. Most groundwater recharge took place in 2010 (746 mm) and 2007 (614 mm), which were also the years with most rainfall and discharge.

Figure 8 shows the spatial distribution of the annual average groundwater recharge over the 6 years. Most recharge takes place in the northern part. This was expected when considering the regional differences in precipitation minus evaporation as shown in Figure 7c. In the south-east, the Dry Zone starts, which is a semi-arid region. The evaporation combined with less rainfall than in the north gave less $P - E$ and therefore less groundwater recharge.

In WA+ a distinction is made between the groundwater recharge for the different LULC classes, which was obtained after combining Figure 10 with the LULC map, Figure 2. The values for each LULC class are shown in Table 8. The groundwater recharge tables for the separate years for the Chindwin basin can be found in Appendix C.

Table 7: Annual precipitation (P), evaporation (E), precipitation minus evaporation ($P - E$), groundwater abstraction (Q_{abs}^{GW}), base flow (Q_{bf}), change in groundwater storage ($\frac{\Delta S_3}{\Delta t}$), the groundwater recharge ($Q_{recharge}^{GW}$) in [mm/year] and the percentage annual groundwater recharge of the annual rainfall for the Chindwin basin for each year in the period 2005-2010 and the 6-year average values.

	P (mm/year)	E (mm/year)	$P - E$ (mm/year)	Q_{abstr}^{GW} (mm/year)	Q_{bf} (mm/year)	$\frac{\Delta S_3}{\Delta t}$ (mm/year)	$Q_{recharge}^{GW}$ (mm/year)	$Q_{recharge}^{GW}$ as % of P
2005	2024	989	1035	1.9	508	-119	390	19 %
2006	1978	1010	968	2.8	389	-122	271	14 %
2007	2400	1010	1391	1.9	567	46	614	26 %
2008	2136	1010	1127	1.6	476	-115	363	17 %
2009	1993	981	1012	2.7	444	-214	233	12 %
2010	2531	982	1548	2.4	598	146	746	29 %
6-year average	2177	997	1180	2.2	497	-63	436	20 %

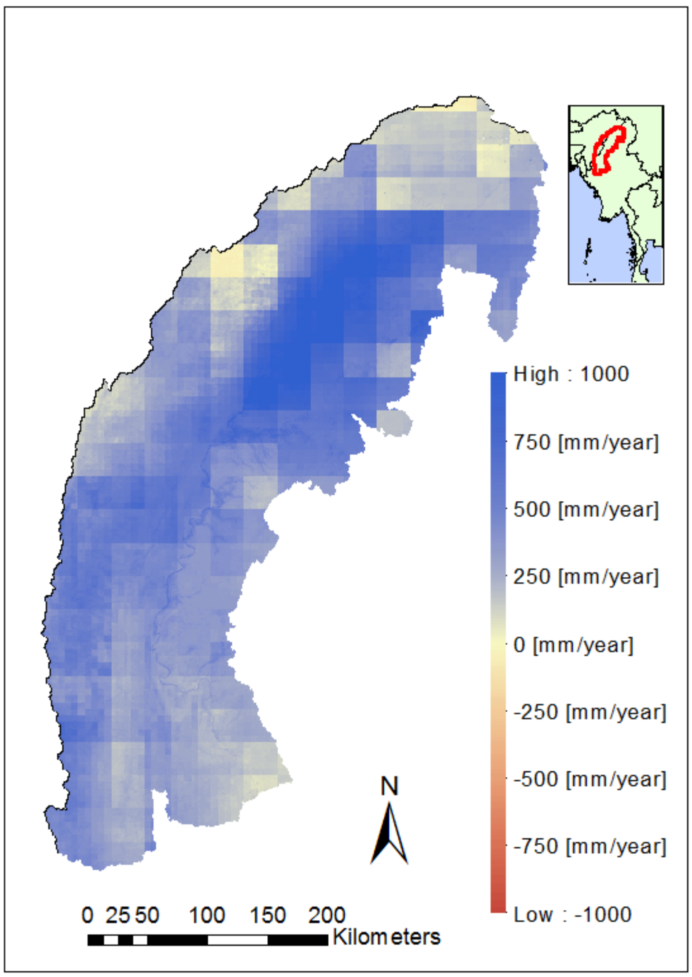

Figure 10: The 6-year average annual groundwater recharge ($Q_{recharge}^{GW}$) for the Chindwin basin, showing a high recharge in the mid northern area of the basin and lower recharge values in the North-Western border and the South East.

Table 8: Summary of the annual average groundwater abstraction (Q_{abs}^{GW}), base flow (Q_{bf}), change in groundwater storage ($\frac{\Delta S_3}{\Delta t}$), the groundwater recharge ($Q_{recharge}^{GW}$) over the period 2005-2010 across the Chindwin basin, which average values per area in mm/year and total values in Mm^3/year.

Land use/land cover class	AREA (km2)	Q_{abs}^{GW} (mm/yr)	Q_{abs}^{GW} (Mm3/yr)	Q_{bf} (mm/yr)	Q_{bf} (Mm3/yr)	$\frac{\Delta S_3}{\Delta t}$ (mm/yr)	$\frac{\Delta S_3}{\Delta t}$ (Mm3/yr)	$Q_{recharge}^{GW}$ (mm/yr)	$Q_{recharge}^{GW}$ (Mm3/yr)
protected forests	19339	0.1	2.8	606	11713	-160	-3088	446	8634
protected shrubland	2038	0.1	0.2	579	1181	-172	-351	407	829
protected natural grasslands	6	0.0	0.0	576	3	-151	-1	425	2
protected natural waterbodies	192	0.0	0.0	507	97	-124	-24	382	73
glaciers	0	0.0	0.0	517	0	25	0	542	0
protected other	5	0.0	0.0	394	2	-154	-1	241	1
closed deciduous forest	9699	2.9	28.4	412	3993	-18	-172	397	3849
closed evergreen forest	39128	2.3	90.6	519	20294	-52	-2049	469	18336
shrub land & mesquite	16020	5.8	93.7	519	8321	-35	-564	490	7850
herbaceous cover	92	0.0	0.0	449	41	3	0	452	42
meadows & open grassland	87	0.0	0.0	422	37	-55	-5	368	32
natural lakes	838	0.4	0.4	603	505	-46	-38	558	467
bare soil permanent	1	0.0	0.0	165	0	10	0	176	0
rainfed crops – cereals	621	1.9	1.2	407	253	-36	-22	373	232
rainfed crops - other	13445	1.2	16.3	340	4577	-19	-250	323	4343
mixed species agro-forestry	7227	1.7	12.6	438	3164	-47	-337	393	2840
rainfed homesteads and gardens (urban cities) – outdoor	210	0.9	0.2	397	83	-63	-13	336	70
irrigated crops – cereals	309	0.4	0.1	413	128	3	1	417	129
irrigated crops – other	1589	1.2	1.9	444	706	-44	-70	401	637
managed water bodies (reservoirs, canals, harbors, tanks)	33	0.0	0.0	327	11	-33	-1	294	10
irrigated homesteads and gardens (urban cities) – outdoor	22	0.0	0.0	79	2	35	1	114	3
TOTAL	**110901**		**248**		**55111**		**-6985**		**48381**

Irrawaddy basin

The results for the Irrawaddy basin cover only the upstream part of Pyay since the most downstream gauge station was located there. The result of the average annual rainfall and evaporation for the Irrawaddy basin over the period 2005-2010 can be seen in Figure 11a and Figure 11b respectively. The north of the Myitkyina basin and the north of the Chindwin basin had most precipitation, around 4000 mm/year. When looking at the evaporation data, a high evaporation rate is visible in the Chindwin basin and the mountain ranges. In the most Northern part, 14216 cells (0.3%) have no data. Most evaporation took place in the Chindwin basin and in the more northern and higher areas. In the dry zone, the lowest evaporation was observed.

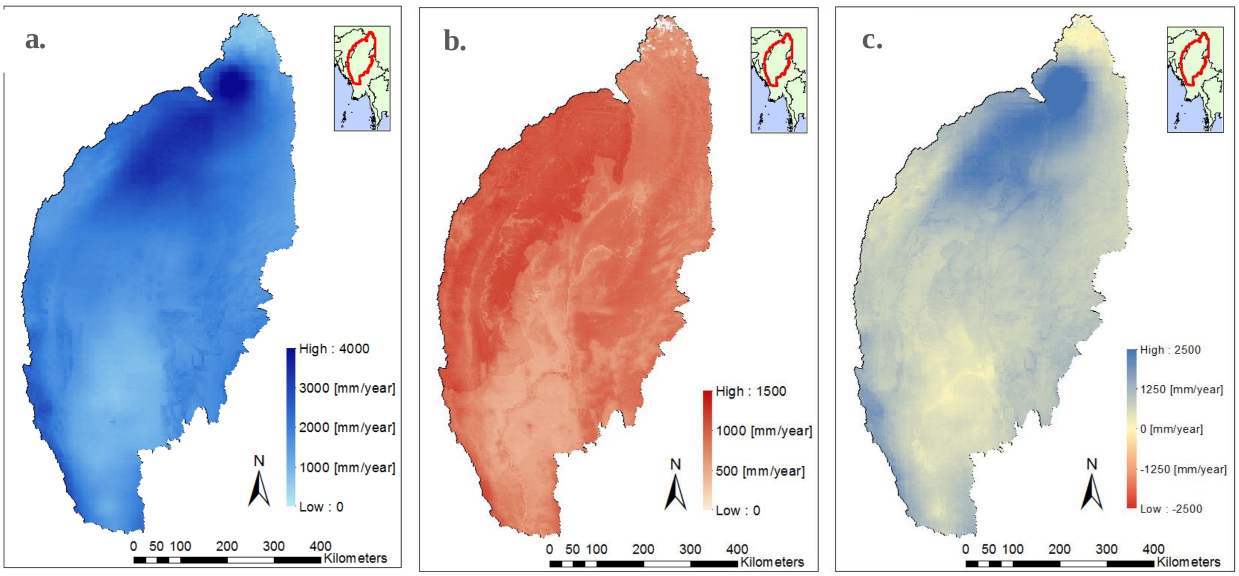

Figure 11: Average annual precipitation (a), evaporation (b) and precipitation minus evaporation (c) over the period of 2005-2010 in the Irrawaddy basin in Myanmar in [mm/year]

With the assumption that over one year $\frac{\Delta S}{\Delta t} = 0$ the annual precipitation minus annual evaporation gave the runoff determined with remote sensing. The spatial result of the 6-year average annual precipitation minus evaporation for the Irrawaddy basin is shown in Figure 11c. Most of the runoff came from the mountains in the north, the blue area in the figure. The precipitation minus evaporation in the Dry zone, especially near the river, was close to zero. Table 10 shows the 6-year average values of the P, E, E_{nat}, E_{incr} and $P - E$ for each of the LULC classes across the Irrawaddy basin.

The remote sensing based measurements were compared with the field discharge measurements in Table 9. The year with the highest discharge determined with remote sensing was 2010 (1334 mm/year), followed by 2007 (1219 mm/year). At the gauge station the highest discharge was measured in 2007 (1161 mm/year), followed by 2010 (1082 mm/year). For both measurements, the lowest discharge was in 2009 (820 mm/year for the WA+ discharge and 794 mm/year at the gauge station). When comparing both measurements it was found that in 2008 the discharge determined with remote sensing was lower than the ground measurement, with a relative error of -8%. For the other five years, the discharge measured with remote sensing (Q_{WA+}) was higher than the discharge measured by the gauge station. Of these five years, the relative error is 3-6 % with an exception for 2010. In this year the remote sensing based discharge was much more, 252 mm/year, giving a relative error of 23%.

Table 9: Comparison between the annual discharge measured by remote sensing Q_{WA+} ($Q_{WA+} = P - E$) and the discharge measured in the field by a gauge station (Q_{gauge}) at Pyay in mm/year. The difference between the two is shown and the relative error of the discharge measured at the gauge station at Pyay compared to the annual discharge determined by remote sensing.

	Q_{WA+} [mm/year]	Q_{gauge} [mm/year]	$Q_{WA+} - Q_{gauge}$ [mm/year]	$\left\lvert\frac{Q_{WA+} - Q_{gauge}}{Q_{gauge}}\right\rvert$ **relative error %**
2005	893	842	51	6%
2006	974	921	53	6%
2007	1219	1161	58	5%
2008	981	1063	-82	8%
2009	820	794	25	3%
2010	1334	1082	252	23%
6-YEAR AVERAGE	1038	977	61	6%

The groundwater recharge for the Irrawaddy basin was determined by closing the water balance. The components of the water balance of the groundwater reservoir for each year are shown in Table 11. Over the period 2005-2010, the average groundwater recharge was 346 mm/year, this is about 19% of the mean annual rainfall. Most groundwater recharge took place in 2010 (589 mm) followed by 2007 (403 mm).

The spatial distribution of the mean annual groundwater recharge is shown in Figure 12. Most of the groundwater recharge was estimated to take place in Chindwin basin and on the edges of the basin. In the top north of the Irrawaddy basin and in the dry zone least amount of groundwater recharge. The groundwater recharge map (Figure 12) and precipitation minus evaporation map (Figure 11c) show similarities, this shows the influence of the precipitation and evaporation on the groundwater recharge, although the similarities were less than when only the Chindwin basin was considered.

Table 12 gives the average values for groundwater abstraction, base flow, change in the groundwater reservoir and the groundwater recharge for each of the LULC classes. This table was obtained by combining the spatial distribution of the different components, like the groundwater recharge as shown in Figure 12, with the LULC map. The tables for the separate years for the Irrawaddy basin can be found in Appendix D.

Table 10: Summary of the 6-year average annual rainfall (P), evaporation (E) and precipitation – evaporation ($P - E$) for each land use/land cover (LULC) class over the Irrawaddy basin

land use / land cover class	AREA (km2)	P (mm/yr)	P (Mm^3/yr)	E (mm/yr)	E (Mm^3/yr)	P-E (mm/yr)	P-E (Mm^3/yr)	E_{NAT} (mm/yr)	E_{NAT} (Mm^3/yr)	E_{INCR} (mm/yr)	E_{INCR} (Mm^3/yr)
protected forests	32335	2601	84108	941	30411	1667	53892	745	24073	198	6396
protected shrubland	3911	2706	10583	963	3765	1745	6824	748	2925	215	840
protected natural grasslands	1076	1008	1084	604	650	412	443	465	500	138	149
protected natural waterbodies	347	2426	842	856	297	1570	545	697	242	159	55
glaciers	777	762	592	588	457	182	142	416	323	172	133
protected other	460	1162	534	644	296	536	246	510	234	134	62
closed deciduous forest	34519	1787	61685	855	29516	933	32192	620	21414	235	8103
closed evergreen forest	108391	2091	226653	916	99314	1177	127586	688	74523	229	24808
shrub land & mesquite	37742	2063	77878	937	35380	1126	42513	686	25873	252	9507
herbaceous cover	1169	1178	1377	638	745	588	687	506	591	131	153
meadows & open grassland	1323	973	1287	636	842	408	540	486	643	150	198
natural lakes	3536	1598	5651	624	2208	974	3443	502	1774	123	434
flood plains & mudflats	0	1747	0	705	0	1042	0	510	0	195	0
bare soil permanent	2	1010	2	528	1	512	1	431	1	97	0
rainfed crops – cereals	1259	1553	1956	729	919	824	1038	589	741	141	177
rainfed crops - other	91039	1387	126285	647	58863	741	67427	509	46342	138	12521
mixed species agro-forestry	24803	1793	44463	812	20136	983	24382	610	15124	202	5013
rainfed homesteads and gardens (urban cities) – outdoor	831	1478	1228	687	571	791	658	549	456	138	115
irrigated crops – cereals	756	1611	1219	743	562	868	657	579	438	164	124
irrigated crops – other	15903	1357	21587	654	10394	704	11194	512	8140	142	2254
managed water bodies (reservoirs, canals, harbors, tanks)	919	1408	1295	566	520	842	774	435	400	131	121
irrigated homesteads and gardens (urban cities) – outdoor	446	880	392	651	290	229	102	496	221	155	69
TOTAL	**361545**		**670704**		**296136**		**375285**		**224979**		**71232**

Table 11: Annual precipitation, evaporation, groundwater abstraction, base flow, change in groundwater storage, the groundwater recharge in [mm/year] and the percentage annual groundwater recharge of the annual rainfall. for the Irrawaddy basin for each year in the period 2005-2010 and the 6-year average values.

	P	E	$P-E$	Q^{GW}_{abstr}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$Q^{GW}_{recharge}$	$Q^{GW}_{recharge}$ as % of P
	(mm/year)	(mm/year)	(mm/year)	(mm/year)	(mm/year)	(mm/year)	(mm/year)	
2005	1697	805	893	3.2	384	-91	296	17 %
2006	1810	837	974	5.7	347	-67	286	16 %
2007	2046	828	1219	4.1	470	-71	403	20 %
2008	1811	830	981	3.4	389	-81	312	17 %
2009	1632	812	820	5.0	312	-130	187	11 %
2010	2135	802	1334	7.0	507	76	589	28 %
6-year average	1855	819	1038	4.7	402	-61	346	19 %

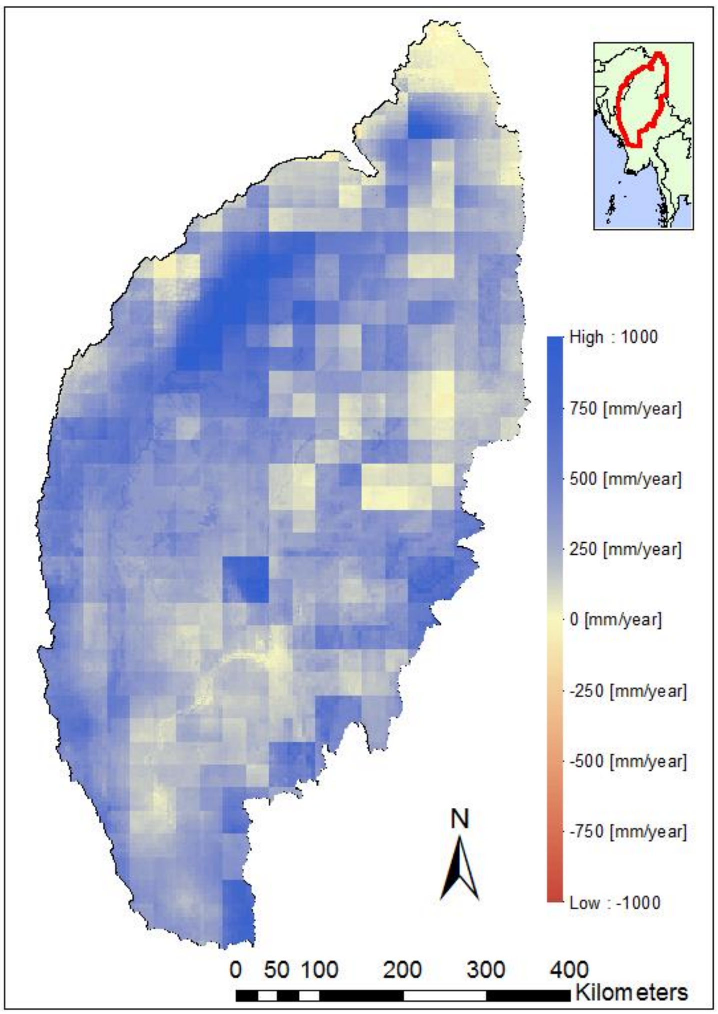

Figure 12: The 6-year average annual groundwater ($Q^{GW}_{recharge}$) recharge for the Chindwin basin in [mm/year]

Table 12: Summary of the annual average groundwater abstraction (Q^{GW}_{abs}), base flow (Q_{bf}), change in groundwater storage ($\frac{\Delta S_3}{\Delta t}$), the groundwater recharge ($Q^{GW}_{recharge}$) per land use/land cover class over the period 2005-2010 across the Irrawaddy basin. The values are given in average per area [mm/year] and total [Mm^3/year].

Land use /land cover class	AREA	Q^{GW}_{abs}	Q^{GW}_{abs}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q^{GW}_{recharge}$	$Q^{GW}_{recharge}$
	(km2)	(mm/yr)	(Mm3/yr)	(mm/yr)	(Mm3/yr)	(mm/yr)	(Mm3/yr)	(mm/yr)	(Mm3/yr)
protected forests	32335	1.1	35.4	510	16484	-136	-4397	377	12186
protected shrubland	3911	2.9	11.4	549	2146	-165	-645	387	1512
protected natural grasslands	1076	0.0	0.0	81	87	-21	-23	58	63
protected natural waterbodies	347	0.1	0.0	560	194	-90	-31	470	163
glaciers	777	0.0	0.0	42	32	-9	-7	32	25
protected other	460	0.0	0.0	113	52	-19	-9	94	43
closed deciduous forest	34519	7.7	265.9	418	14424	-65	-2227	361	12465
closed evergreen forest	108391	4.5	491.5	435	47117	-76	-8258	363	39363
shrub land & mesquite	37742	7.4	278.4	463	17458	-78	-2939	392	14798
herbaceous cover	1169	2.0	2.4	212	248	-19	-22	196	229
meadows & open grassland	1323	0.6	0.7	144	191	-22	-29	124	164
natural lakes	3536	2.4	8.6	388	1373	-46	-161	345	1220
flood plains & mudflats	0	0.0	0.0	430	0	-78	0	351	0
bare soil permanent	2	0.7	0.0	176	0	15	0	192	0
rainfed crops – cereals	1259	1.0	1.2	394	496	-41	-51	354	446
rainfed crops - other	91039	4.4	402.8	320	29093	-13	-1217	311	28279
mixed species agro-forestry	24803	6.4	157.6	415	10297	-73	-1822	348	8632
rainfed homesteads and gardens (urban cities) – outdoor	831	2.8	2.3	361	300	-47	-39	317	264
irrigated crops – cereals	756	0.2	0.1	418	316	-12	-9	406	307
irrigated crops – other	15903	3.2	50.5	290	4606	-8	-122	285	4534
managed water bodies (reservoirs, canals, harbors, tanks)	919	1.0	0.9	385	354	-17	-16	369	339
irrigated homesteads and gardens (urban cities) - outdoor	446	3.8	1.7	87	39	34	15	124	55
TOTAL	**361545**		**1712**		**145306**		**-22010**		**125088**

Discussion

From the comparison of the gauge station data and the remote sensing data, it follows that the WA+ method gave on a yearly basis a good estimation of the runoff. The average relative error for the Chindwin basin was 14% and for the Irrawaddy basin 9%. In the year 2010 Q_{WA+} and Q_{gauge} differ most, with a relative error of 40% and 23% at respectively Monywa and Pyay. It was assumed that the measured discharge at the gauge stations (Q_{gauge}) is true, no measurement errors were taken into account. However, it is likely that there are measurement errors (Di Baldassarre & Montanari, 2009). The discharges were determined with a stage-discharge relationship, although no data of the water levels at Monywa and Pyay was available. Therefore the possibility of errors in the process of determining the discharge from the water levels could not be examined.

In the review of the accuracy of remote sensing data by Karimi & Bastiaanssen (Karimi & Bastiaanssen, 2015) it is stated that satellite-based evaporation products have a relatively small error compared to the error in rainfall products since the processes to derive rainfall from satellite data is more complex. The ensemble evaporation product was not taken into account in the review, but it is assumed to have an even higher reliability. There is still a high variability in the remote sensing based evaporation determined by different methods (Prior, 2016; Simons et al., 2016). The study of Prior (2016) showed that the ensemble product gives a mid-range estimate. In this study no comparison was made between different precipitation and evaporation products and no ground data on precipitation or evaporation was used.

With the daily discharge data from the gauge station (Q_{gauge}), the precipitation minus evaporation ($P - E$) and the calculated discharge (Q_{WA+}), the influence of the PCR-ratios can be evaluated. During the dry period, the base flow ratio caused an overestimation of the Q_{WA+}. This overestimation is substantial considering the low flows measured by the gauge station. During the driest months (December – March) the flow determined by the base flow ratio (Q_{WA+}) is on average three times as high as Q_{gauge}, and in the period December 2009 – March 2010 even 4.4 times as high. One of the reasons for this can be that PCR-GLOBWB works with a daily timescale. With the high rainfall intensities in the northern part of the Chindwin basin, the runoff response is different in reality compared to when the rainfall is averaged over a day. This can lead to an underestimation of the direct runoff by PCR-GLOBWB, and with that an overestimation of the slower runoff processes and percolation. This could be the cause of the differences between the Q_{WA+} and Q_{gauge}.

The observation of the overestimation of the discharge Q_{WA+} during the dry period is important. When considering only the Q_{WA+}, this overestimation can lead to the assumption that the environmental flow in the river is maintained, while in reality, the river flow is much lower. The results of this comparison can be used to improve the determination of monthly flows and also to improve base flow ratio which are now estimated with the use of PCR-GLOBWB.

The impact of the different distribution of the annual flow among the months goes further. In the calculations, it led to a higher $\frac{\Delta S}{\Delta t}$ during the wet months and a lower $\frac{\Delta S}{\Delta t}$ during the dry months. The $\frac{\Delta S}{\Delta t}$ in this study is probably overestimated during the rainy season, leading a higher groundwater recharge estimation, and underestimated in the dry season, leading to a lower groundwater recharge estimation. In reality, it is likely that the change is storage is closer to zero on a monthly scale. For the 6-year average values, this will not have an extensive impact.

Overall, the groundwater recharge seems to be a good estimate. However, the change in the storage of the groundwater reservoir ($\frac{\Delta S_3}{\Delta t}$) was negative at Monywa and Pyay for 4 respectively 5 out of the 6 years, which means that for those years the water stored in the saturated zone has decreased, and the water stored in the unsaturated zone has increased. This is probably caused by the difference between the $\left(\frac{\Delta S}{\Delta t}\right)_{PCR}$ and those determined by the water balance, $\left(\frac{\Delta S}{\Delta t}\right)_{WA+}$. Further research about this is recommended.

As mentioned in the introduction, the method described in this paper is not exactly the same as the standard WA+ method. There are two main differences. First, in the standard WA+ method an additional supply is added, which provides part of the surface water contributing to the E_{incr} of a cell. The water balance as described in equation 1 and figure 4 is correct for the basin as a whole, not on a cell basis. Not all the water evaporated by the E_{incr} is provided by the cell itself. Therefore an additional supply, X, providing part of the surface water abstraction for E_{incr} should be taken into account for calculations on a cell basis. This supply to a cell basis is neglected in this study, which should be considered when analyzing the data on a cell basis or per LULC. Taking the extra supply into account will for some areas, lead to an increase in the $\frac{\Delta S}{\Delta t}$, meaning a higher $\frac{\Delta S_3}{\Delta t}$, which leads to an increased groundwater recharge. Most of the E_{incr} comes from abstracted surface water, therefore the impact of not taking the additional supply could be substantial on a cell basis. The current estimation of groundwater recharge is probably underestimated because of this.

The second main difference is that in the standard WA+ method the Budyko curve is calculated with a Dryness Index ϕ, that is the average over a certain period that varies per land use. For determining ϕ, the values for E_{ref} and P of the specific month is used in this study. However, for certain LULC, such as forests, a time step of 1 month is too short. It is therefore recommended to take the average E_{ref} and P over a longer period of time, e.g. 3 months, to determine the Dryness Index ϕ in future studies. The standard of WA+ uses this approach of a moving window to determine the Budyko curve. For this case, the difference in the incremental evaporation between a time step of 1 month or 3 months is small. Also, the incremental evaporation only influenced the groundwater abstraction, which was a small amount of water. In the case of the Irrawaddy basin, the chosen time step of the moving window had a small impact on the groundwater recharge estimation.

The storage layers of PCR-GLOBWB had been shifted by 0.25 degrees in the lateral direction, compared to the other PCR-GLOBWB layers. For the completeness of the result, this could be adjusted for this study. However, no significant difference in groundwater recharge on a yearly and 6-year average basis is expected, when the extent of the PCR-GLOBWB storage layers is adjusted by 0.25 degrees.

In this study, the assumption was made that $\frac{\Delta S}{\Delta t} = 0$ over a period of one year. This has an influence on the monthly discharge, $\frac{\Delta S}{\Delta t}$, $\frac{\Delta S_3}{\Delta t}$ and finally for the groundwater recharge. When the discharge of the Chindwin basin is observed in Figure 8, the assumption that $\frac{\Delta S}{\Delta t} = 0$ over a period of 6 years (2005-2010) is more realistic. In this way, not only the monthly variation in the change in storage is taken into account, but also the yearly variation.

Taking the previously mentioned points into considerations, it is likely that the groundwater recharge is underestimated. To provide a range for the groundwater recharge, the estimation can be made that no change in storage in the groundwater layer takes place over 6-years ($\frac{\Delta S_3}{\Delta t} = 0$). This provides an upper boundary of the groundwater recharge estimation. In this way, the groundwater recharge for the Chindwin basin is estimated to be 430-500 mm/year (20-23% of P) and for the Irrawaddy basin 340-400 mm/year (19-22% of P).

McCartney, et al., (2013) estimated the groundwater recharge in the dry zone to be about 4.8 km^3yr^{-1} in the year 2000-2001. This estimation was about 50 mm yr^{-1}, which is equal to about 10% of the annual rainfall in the dry zone. No specific estimation for the groundwater recharge in the Dry Zone was made in this study. The Dry Zone is an area with relatively less groundwater recharge, as can be seen in Figure 12. The Dry Zone is the southern central part of the Irrawaddy basin, with a lighter colour, so low groundwater recharge. The values found in this area are comparable to the estimations of McCartney, et al., (2013).

A study on the groundwater recharge in the area around Ayadaw town, which is part of the Mu watershed downstream of Sagaing, estimate the annual groundwater recharge for the period 2004-2007 to be 15% of annual rainfall (Than Zaw). This was based on the water balance, the annual rainfall minus the annual actual evaporation and annual direct runoff gives the groundwater recharge of that year. The result of WA+ groundwater recharge for this area is similar.

In a study by the Food and Agriculture Organization of the United Nations (FAO) the groundwater potential for the Chindwin basin was estimated to be 93 km^3 (Facon, 2004), but no estimation of the actual annual groundwater recharge is given in this study.

Recently Van Ramshorst (2017) estimated the groundwater recharge in the Chindwin basin by using a SWAT model. From this study, the groundwater recharge in the period 2005-2010 was estimated to be 685 mm/year, which equals about 30% of the mean annual rainfall. However, Van Ramshorst (2017) concluded that this is likely to be an overestimation and estimates the actual groundwater recharge to be roughly between 248-670 mm/year, which is 11-30% of the rainfall. The SWAT model gave a spatial distribution of the rainfall, evaporation and groundwater recharge. The distribution of the rainfall was similar for both studies as was expected as both used the same CHIRPS data. In SWAT the evaporation was determined with the use of climate data, land use and soil characteristics. Where for WA+ the satellite-based actual evaporation was used, determined by the surface energy balance. This resulted in a different spatial distribution for the evaporation. In SWAT the highest evaporation was found to be in the eastern side of the basin, with values of 700 mm/year and higher, and lower in the west, with lowest values in the north west of about 400-500 mm/year. In this study the evaporation data had the lowest value in the south eastern part of the basin, in the Dry Zone, of about 700 mm/year. The evaporation was even in the rest of the basin with values between 1000 and 1100 mm/year. The spatial distribution of the groundwater recharge was also different but showed some similarities. In both approaches, most groundwater recharge took place in the north eastern part of the Chindwin basin. The WA+ approach did not give much groundwater recharge in the most northern part of the Chindwin basin, where the SWAT approach gave a high groundwater recharge in that area.

A strong advantage of the WA+ framework and this study is that a rough estimation for a large region can be made in a relatively quick way, especially once it is standardized. From the comparison with the few previous studies on groundwater recharge in (parts of) the same area, it follows that the estimations made in this study are within a realistic range. Also, the spatial distribution of the groundwater recharge estimation shows a similar distribution pattern as the precipitation minus evaporation, as expected, and roughly the same pattern as was the result of the SWAT model. This shows that the method presented in this study could be used for rough estimations of groundwater recharge.

Conclusion

This paper described the groundwater sheet calculations of WA+ for the Chindwin and Irrawaddy basin in Myanmar. Myanmar is rapidly changing and developing, which has an influence on the land use and water resources. For a sustainable use of the groundwater resources, an estimation on the amount of groundwater recharge is desired. The groundwater sheet of the water accounting plus (WA+) framework was used to estimate the groundwater recharge. The remote sensing input data were precipitation, P (CHIPRS) and evaporation, E (ETensv1.0.). For components of the groundwater flows that could not be determined with remote sensing data only, the hydrological model PCR-GLOBWB was used.

As a validation of the method, the discharge determined with WA+, Q_{WA+}, which is on an annual basis equal to the $P - E$, was compared with field measurements of the discharge, Q_{gauge}, at Monywa. This showed that the discharge Q_{WA+} is underestimating the flow during the rainy season and overestimating the flow in the dry season. The overestimation of the base flow can lead to wrong estimations regarding the environmental flow of the river. Findings of this study can be used to improve the ratios used by WA+ to determine the base flow and the distribution of the discharge over a year.

The annual groundwater recharge estimated for the Chindwin basin was 430-500 mm/year, which is 20-23% of the rainfall. Most groundwater recharge takes place in the north eastern part of the basin. Least recharge took place in the north-west of the basin, high in the mountains, and in the south east of the basin, where the Dry zone starts. The annual groundwater recharge estimated for the Irrawaddy basin was 340-400 mm/year, which is 19-22 % of the rainfall. Most of the groundwater recharge in the Irrawaddy basin took place in the Chindwin basin and the most northern part of the basin, upstream of Myitkyina, and on the edges of southern half of the basin. These results were in line with results found in earlier studies for smaller areas within the Irrawaddy basin. Simultaneous to this study, an estimation of the groundwater recharge is the Chindwin basin was made with base flow separation and SWAT. The results from this study are within the range given in that study. The spatial distribution of SWAT showed some differenced to what was found with the WA+ method. However, the SWAT run was not well calibrated. Further study and a comparison with a calibrated SWAT model are recommended for a more precise comparison.

This research has shown that without the use of field measurements the groundwater recharge can be estimated within a reliable range. This is interesting for estimations of groundwater recharge in ungauged basins or basins where the (political) circumstances do not allow field measurements. Besides that, it has shown that remote sensing precipitation and evaporation for the Monywa basin can be used for reliable estimation for the annual river discharge.

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A. Analyses of discharge data stations

As a preparation for the groundwater recharge estimation the flow data of 7 gauge stations are analyzed. The data was provided by the Department of Meteorology and Hydrology of Myanmar. The location of the different stations is shown in Figure A-1. The discharge found at the different locations will be used in the different approaches described in this report.

The stations Nyaung Oo, Chauk and Sagaing have flow data until 2010. The other four stations have data until 2015. In most data sets there were no gaps or unrealistic data, with the exception of Sagaing, were the data of 2007, 2008 and 2009 were equal. For each station a hydrograph was made and the mean annual flow and the monthly average are calculated. At the end the yearly total flow of the different stations are compared for the period 2000-2015. This was done to see the changes in the discharge over space and time. When the discharge decreases more downstream, it could be that in that area the groundwater was recharged.

The discharge measurements will be analysed for each station, starting with Monywa and then from Myitkyina in downstream direction.

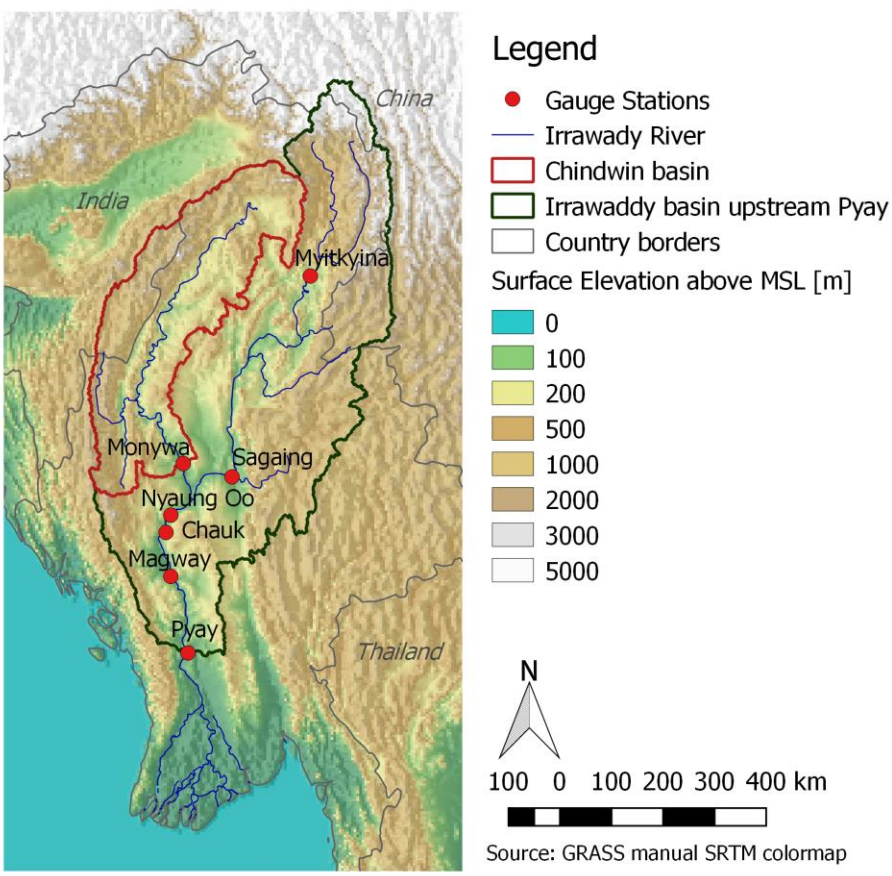


Figure A-1: Map of the Irrawaddy River basin in Myanmar. The surface elevation in meters above mean sea level (MSL) is shown. The location of the seven discharge gauge stations in the Irrawaddy basin are indicated with red dots.

Monywa

Monywa is the only gauge station at the Chindwin River, which is a major tributary of the Irrawaddy. It is located approximately 840 km upstream the Irrawaddy. The catchment contributing to the flow at this point is 120397 km^2. A complete dataset of 16 years, 2000-2015 was provided for this station. The data is presented in the hydrograph of Figure A-2.

There is a clear difference between the different seasons. The wet season occurs from July to October, as can be seen in Figure A-3. From the hydrograph an abrupt change of season can be observed. The base flow seems to decrease from 2009 to 2014; the highest peaks are over the whole period of roughly the same height. In Figure A-3 the monthly variation in discharge is shown.

The mean annual flow was 1,123 mm/year (which equals 135 km^3 and 4,284 m^3/s), with a maximum flow of 1,399 mm/year (168 km^3) in 2000 and a minimum flow of 831 mm/year (100 km^3) in 2014.

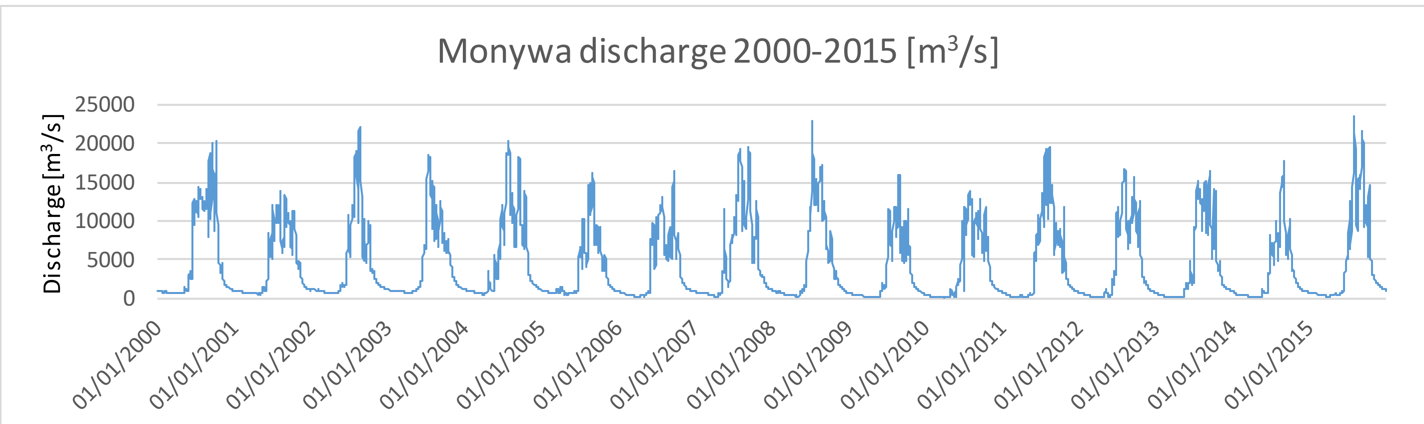
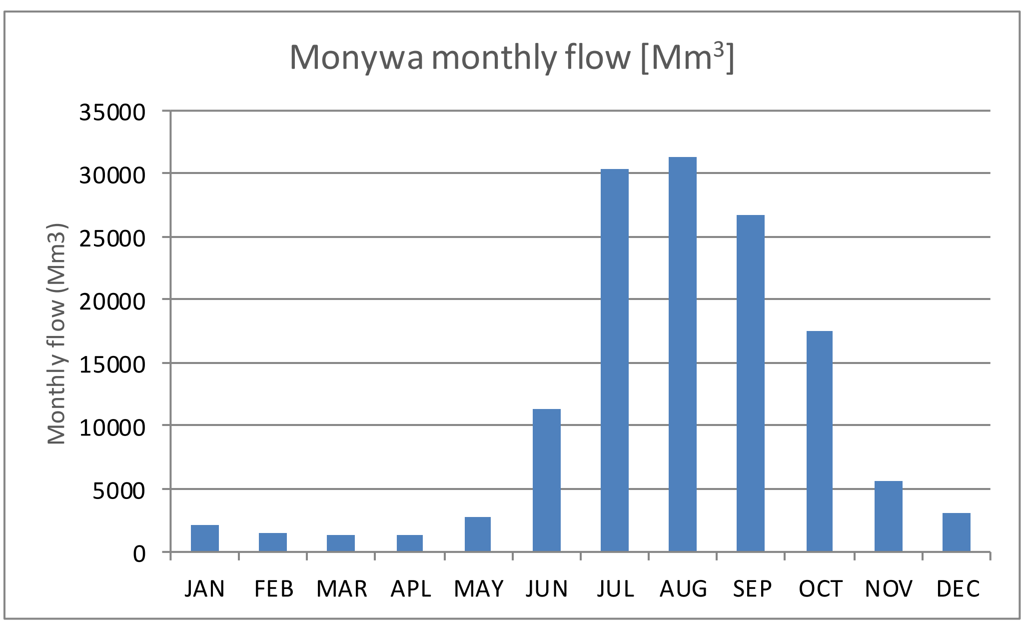


Figure A-2: Hydrograph at Monywa for the period 2000-2015



monthly flow (Mm3)	
JAN	2189
FEB	1544
MAR	1342
APR	1389
MAY	2848
JUN	11272
JUL	30393
AUG	31299
SEP	26658
OCT	17530
NOV	5586
DEC	3144
Total	**135196**

Figure A-3: Average monthly flows in the period 2000-2015 at Monywa

Myitkyina

Myitkyina is the most upstream station measuring discharge in the Irrawaddy. The distance to the sea is approximately 1440 km. The area drained by the gauge station at Myitkyina is about 53,250 km^2.

For the period 2000-2015 an almost complete dataset is provided for this station. Two measurements have an error in the discharge notation. The values of these data are interpolated. The hydrograph with the record of the discharge and a figure with the mean monthly discharges can be found in Figure A-4. The average monthly flows are shown in Figure A-5.

The catchment of Myitkyina has a clear wet and dry season, occurring in the same months as at the Chindwin sub basin. However, the observed transition between the two season is less abrupt and with more peaks. The mean annual flow was 2,734 mm/year (146 km^3; 4,613 m^3/s), with the highest flows in 2004 of 3,478 mm/year (185 km^3) and the lowest in 2011 of 2,236 mm/year (119 km^3).

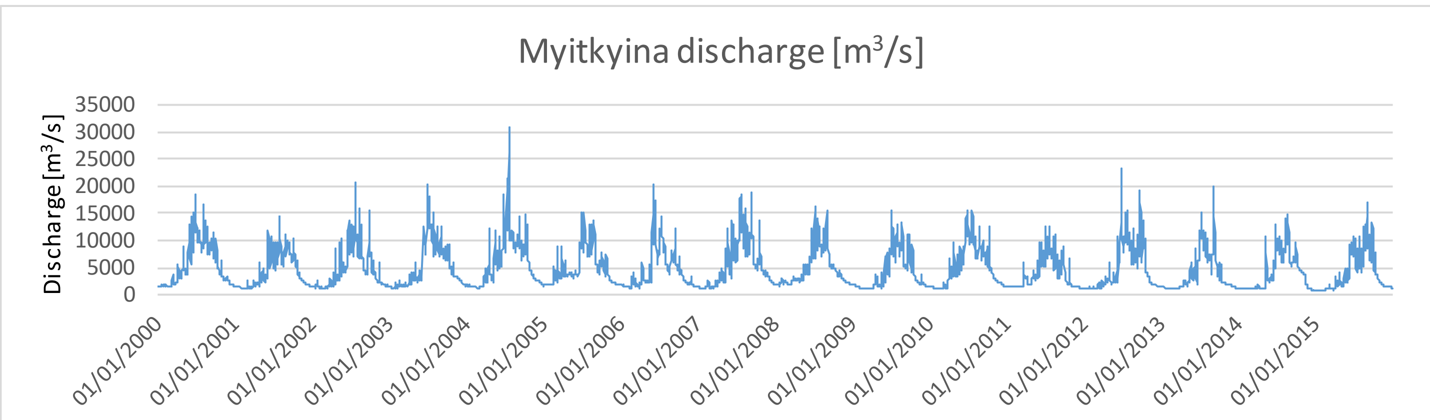
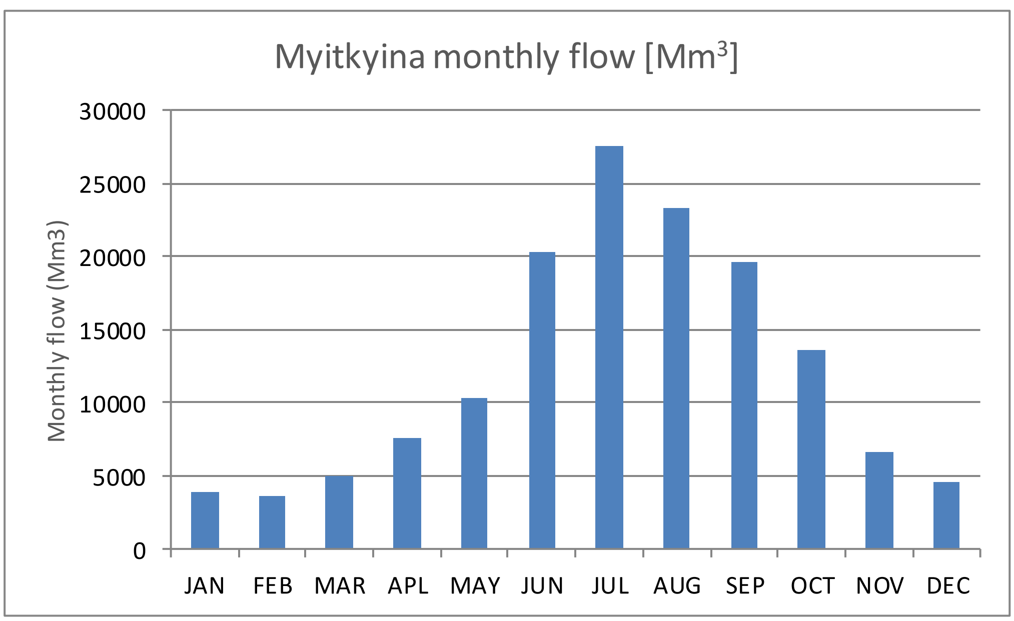


Figure A-4: Hydrograph at Myitkyina for the period 2000-2015



monthly	flow (Mm3)
JAN	3872
FEB	3596
MAR	4934
APR	7605
MAY	10288
JUN	20231
JUL	27478
AUG	23251
SEP	19571
OCT	13580
NOV	6610
DEC	4584
Total	**145600**

Figure A-5: Average monthly flows in the period 2000-2015 at Myitkyina

Sagaing

The gauge station at Sagaing is located about 880 km upstream the Irrawaddy and the catchment has an area of approximately 186,000 km^2.

From this station data is available from 1967- 2010. However, the daily data of 2008 and 2009 are exactly the same as that of 2007. Comparing the data with the data of the other stations showed that most likely the daily data of 2008 and 2009 are replaced by the data of 2007. Therefore the years 2008 and 2009 are left out of the analysis. In 1997 there is gap of 2 days the dataset. Since the other datasets we will use are from 2003 onwards, this gap will not give problems for the rest of our analysis. For the Sagaing station, two hydrographs are made, for 1967-2010 and for 2000-2010, shown in respectively Figure A-6 and Figure A-7. The average monthly flows are shown in Figure A-8.

In the hydrographs the same pattern in seasons can be seen as at Myitkyina. At Sagaing difference between the base flow and the high flows had increased, the peaks are higher and the base flow was lower, as can be seen when comparing the hydrographs and mean monthly flows of both stations. From 1999 onwards a decrease in the base flow can be observed, with the lowest base flow in 2010.

A mean annual flow of 1,396 mm/year (240 km3; 7,592 m3/s) was measured at Sagaing, with a maximum flow in 1988 of 1,700 mm/year (316 km3) and a minimum flow in 2005 of 797 mm/year (148 km3). Over the period 2000-2010 the maximum flow occurs in 2078 (1,506 mm/year; 258 km3). A table with all annual flows is shown in Table A-1. The mean annual flow was higher as in Myitkyina, which was expected since the Sagaing station is more downstream the Irrawaddy.

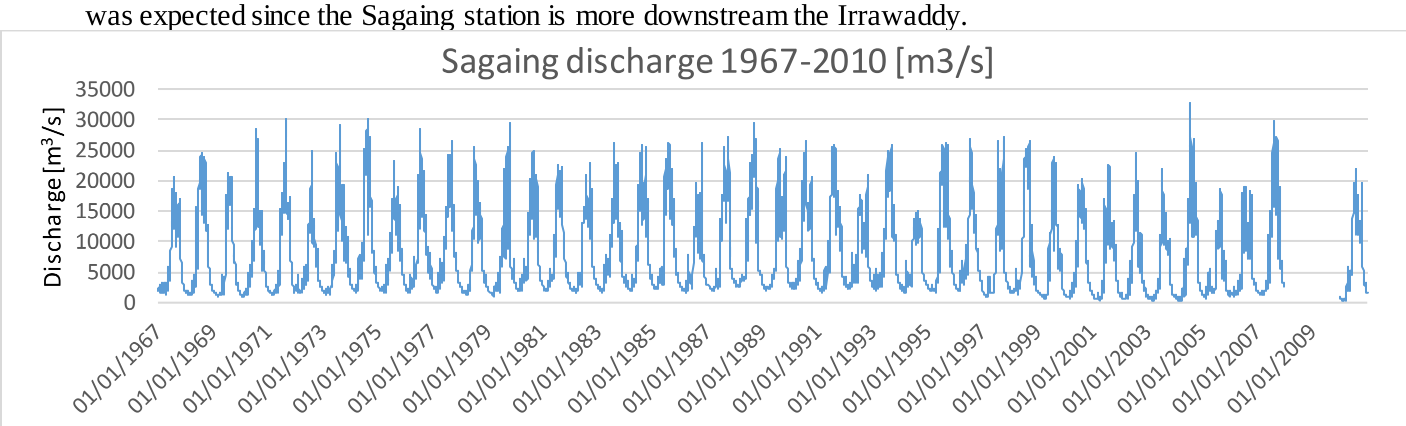


Figure A-6: Hydrograph at Sagaing for the period 1967-2010

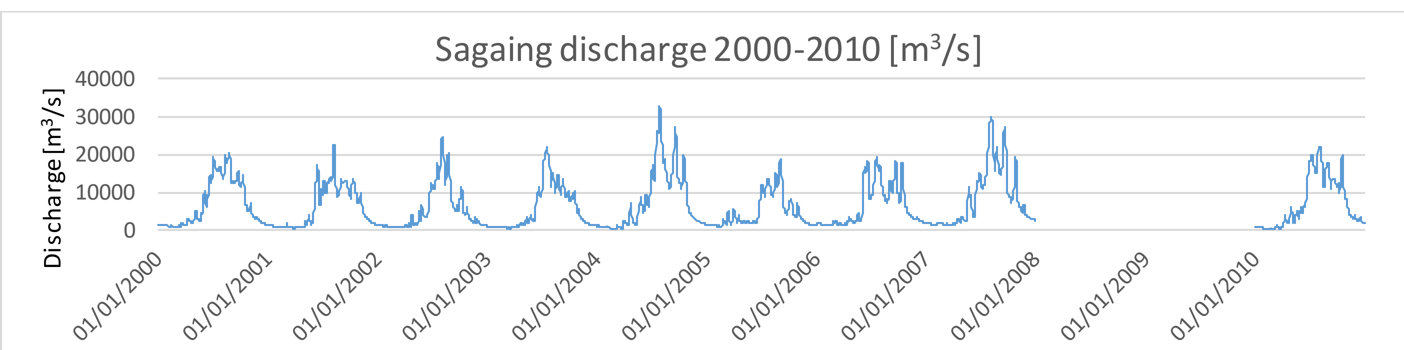
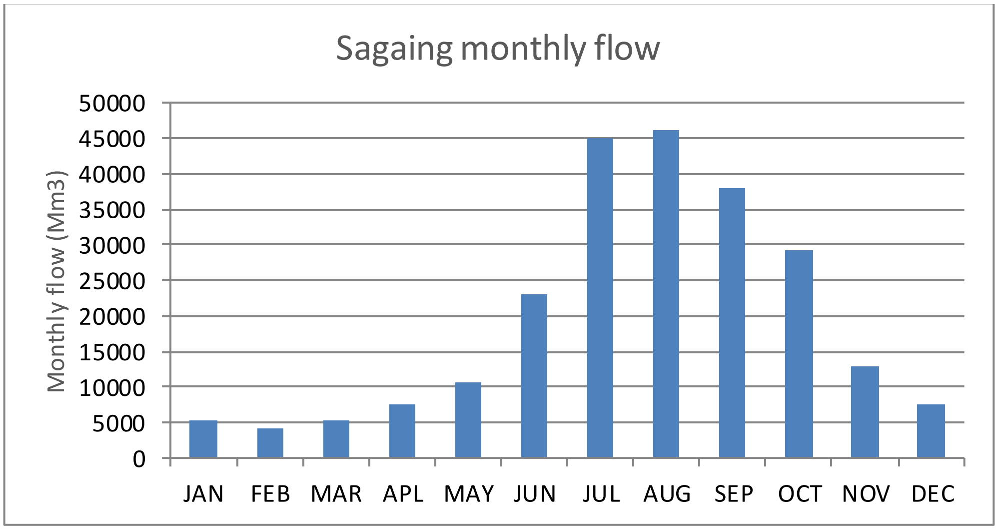


Figure A-7: Hydrograph at Sagaing for the period 2000-2010



monthly	flow (Mm3)
JAN	5476
FEB	4256
MAR	5463
APR	7643
MAY	10817
JUN	23417
JUL	46188
AUG	46868
SEP	38673
OCT	29783
NOV	13184
DEC	7810
Total	**239578**

Figure A-8: Average monthly flows in the period 1967-2010 at Sagaing

Table A-1: Annual flow and mean annual flow at Sagaing for the period 1967 - 2010

Year	Annual flow [Mm3]	Year	Annual flow [Mm3]	Year	Annual flow [Mm3]
1967	218705	1982	232663	1997	197022
1968	259713	1983	271882	1998	248778
1969	202268	1984	290414	1999	197684
1970	239126	1985	283565	2000	215885
1971	252028	1986	219523	2001	186537
1972	193108	1987	262859	2002	165108
1973	265400	1988	316241	2003	171121
1974	297917	1989	252271	2004	243177
1975	233576	1990	289113	2005	148243
1976	266693	1991	289738	2006	198353
1977	265217	1992	226272	2007	258434
1978	233924	1993	279328	2008	
1979	220740	1994	200145	2009	
1980	258107	1995	285022	2010	222690
1981	247225	1996	256443		
				Mean annual flow:	**239578**

Nyaung Oo

Nyaung Oo is the first gauge station after the confluence of the Chindwin and the Irrawaddy. It is located about 710 km upstream and has a catchment of approximately 340,400 km². Between Sagaing and Nyaung Oo the Mu River flows into the Irrawaddy.

Eleven years of complete data was provided for this station, from 2000-2015. There were no gaps or unrealistic high values in the data set. The data shows the same pattern as the other data stations: a low flow season from January - April and a high flows with peaks in July, August and September, see the hydrograph in Figure A-9 and the mean monthly flows for Nyang Oo in Figure A-10.

The mean annual flow was 994 mm/year (338 km³; 10,720 m³/s). This is lower than the mean annual flow of Sagaing and Monywa combined, which is 1018 mm/year (347 km³; 10,985 m³/s). The loss in mean annual flow was 24 mm/year (8 km³; 265 m³/s). This can be due to groundwater recharge or due to evaporation between the stations and not enough recharge. The maximum annual flow of 1,145 mm/year (390 km³) was in 2004 and the minimum in 2009 (788 mm/year; 268 km³).

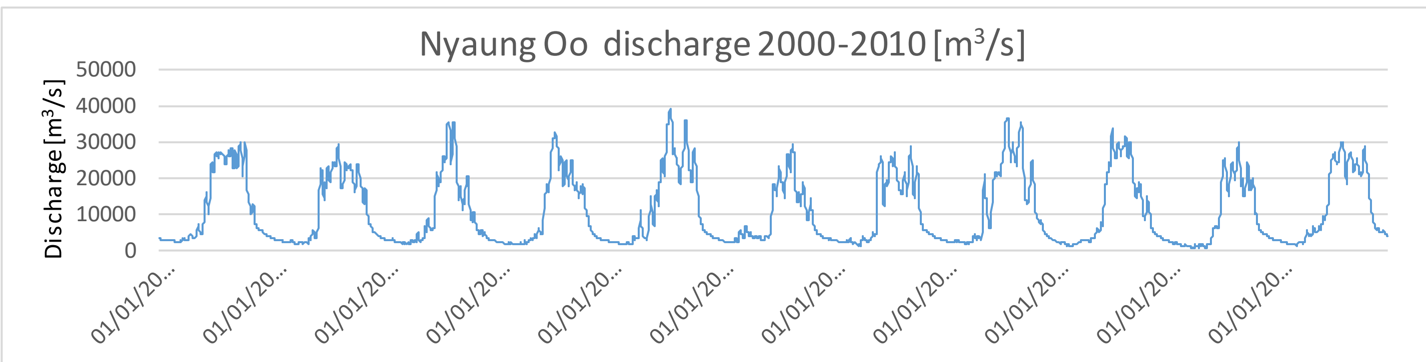
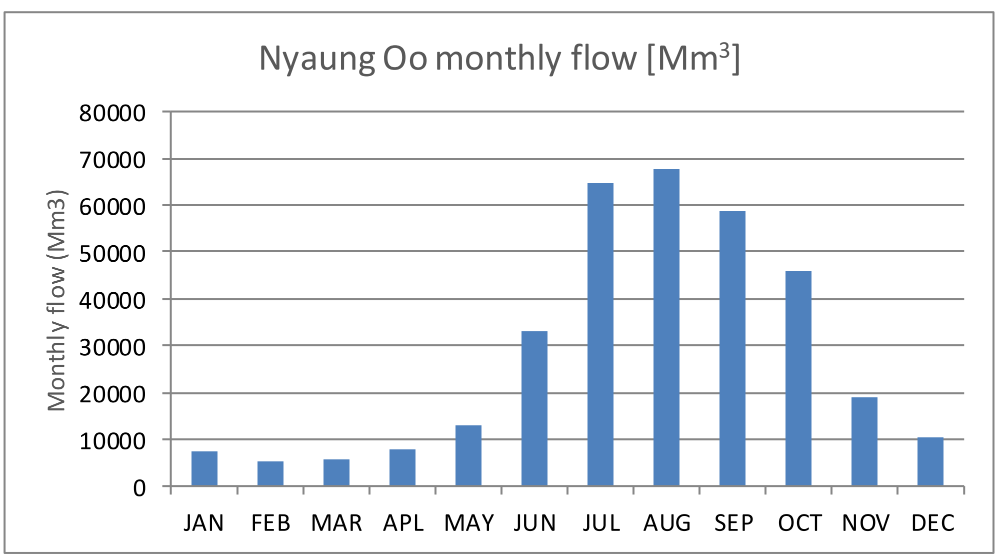


Figure A-9: Hydrograph at Nyaung Oo for the period 2000-2015



monthly flow (Mm3)	
JAN	7195
FEB	5393
MAR	5799
APR	7997
MAY	12882
JUN	32883
JUL	64794
AUG	67742
SEP	58510
OCT	45696
NOV	19019
DEC	10446
Total	**338357**

Figure A-10: Average monthly flows in the period 2000-2015 at Nyaung Oo

Chauk

Chauk is located only 40 km downstream of Nyaung Oo, with a total distance to the sea of approximately 670 km and a contributing area of nearly 350,000 km^2. Before Chauk a smaller tributary, the Yaw, flows into the Irrawaddy.

For this gauge station a complete dataset was available from 1973-2010. The distribution of the flow over the months shows a slightly more distinct difference between the wet and the dry season as Nyaung Oo, as is visible in the hydrographs of the periode 1973-2010, Figure A-12, and for the period 2000-2010, Figure A-11. The monthly average flows for the whole period with data, 1973-2010 is shown in Figure A-13.

The mean annual flow of 1967-2010 was 955 mm/year (333 km3; 10,572 m3/s). When looking at the same period of time (2000-2010) the mean annual flow at Chauk was higher than that at Nyaung Oo and was 1,002 mm/year (350 km3; 11,097 m3/s). The maximum annual flow was in 2010 with 1317 mm/year (460 km3) and the minimum flow was in 1994 with 643 mm/year (225 km3), the minimum flow over the period 2000-2010 was in 2005 with 818 mm/year (286 km3). Table A-2 shows the annual flows at Chauk.

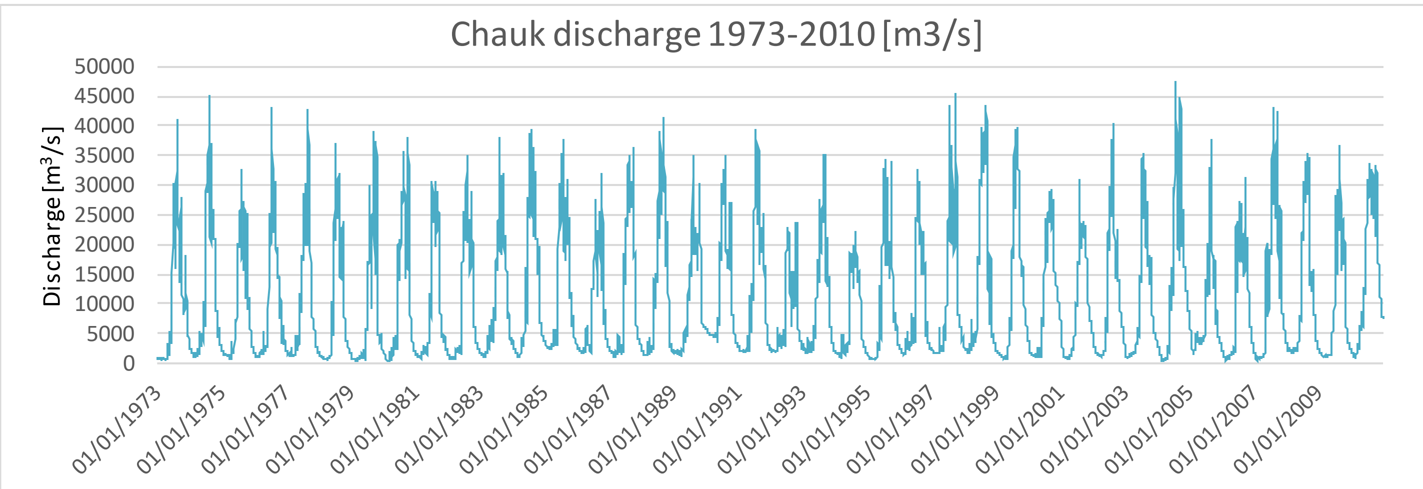


Figure A-12: Hydrograph at Chauk for the period 1973-2010

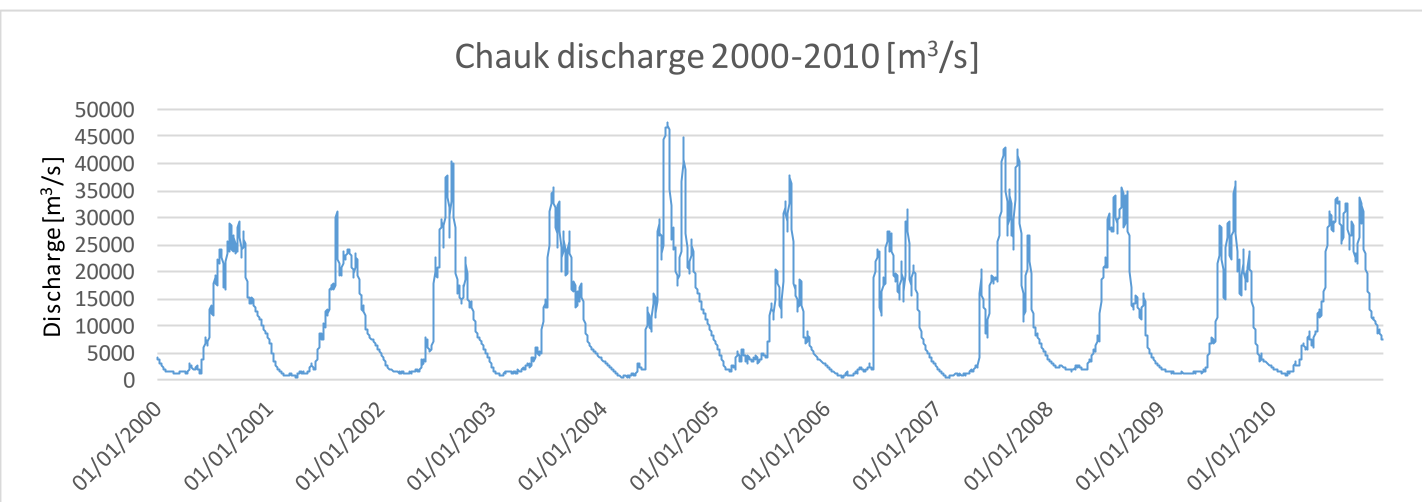


Figure A-11: Hydrograph at Chauk for the period 2000-2010

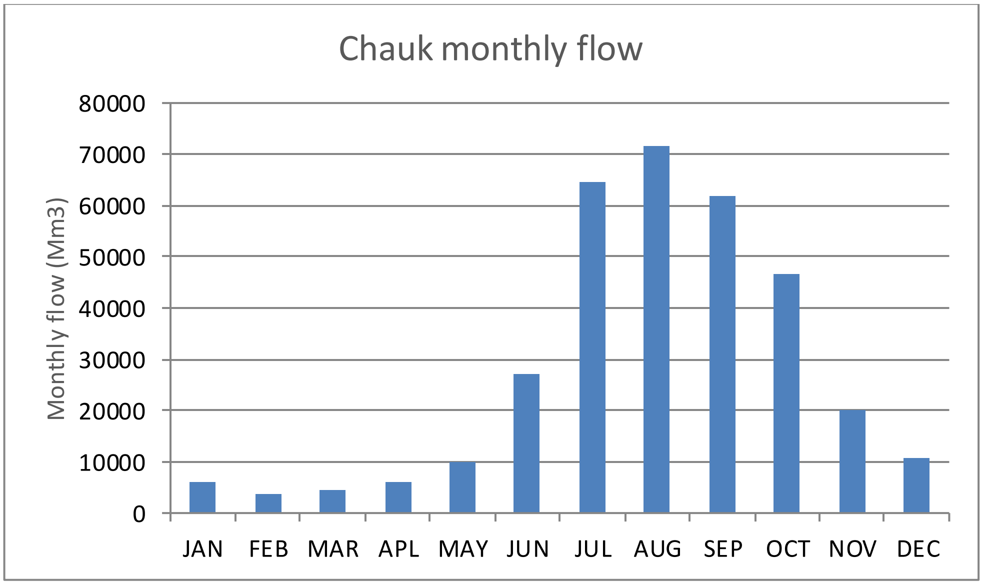


Figure A-13: Average monthly flows in the period 1973-2010 at Chauk

monthly flow (Mm3)	
JAN	6037
FEB	3723
MAR	4429
APR	6219
MAY	10138
JUN	27280
JUL	64768
AUG	71450
SEP	61774
OCT	46631
NOV	20107
DEC	10933
Total	**333489**

Table A-2: Annual flow and mean annual flow at Chauk for the period 1973-2010

Year	Annual flow [Mm3]	Year	Annual flow [Mm3]	Year	Annual flow [Mm3]
1973	320668	1986	280941	1999	358669
1974	369434	1987	349540	2000	345213
1975	297437	1988	384032	2001	295412
1976	314323	1989	324049	2002	335409
1977	314377	1990	375994	2003	322766
1978	290788	1991	381975	2004	440327
1979	266297	1992	243434	2005	286094
1980	325927	1993	319212	2006	307526
1981	281494	1994	224744	2007	410188
1982	293771	1995	325557	2008	357728
1983	337632	1996	289215	2009	293025
1984	395257	1997	362265	2010	460247
1985	386817	1998	410967		
			Mean annual flow:	**333651**	

Magway

Magway is located 570 km upstream the Irrawaddy, with a contributing area of 367,000 km². No tributaries flow into the Irrawaddy between Chauk and Magway. Since 1990 there are records of the months July, September and October at the Magway gauge station. From 1994 a daily dataset without gaps is available. For this station all flow data, including those of the peaks from 1990-1993, is made visible in Figure A-15. In Figure A-14 the same data is shown, but only for the period 2000-2015. The monthly flow determined with the data 1994-2015 is shown in Figure A-16.

The mean annual flow was 1036 mm/year (380 km3; 12,055 m3/s). The maximum annual flow was in 2004 of 1246 mm/year (457 km3) and the minimum annual flow was in 2014 of 803 mm/year (295 km3). All annual flows at Magway can be found in Table A-3.

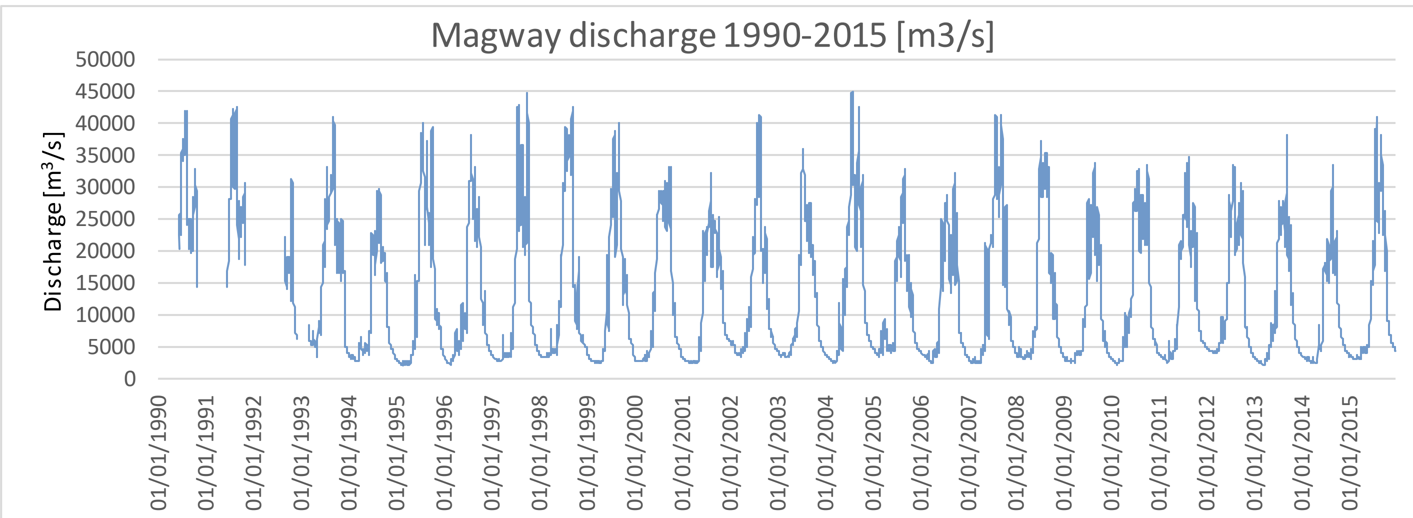


Figure A-15: Hydrograph at Magway for the period 1990-2015

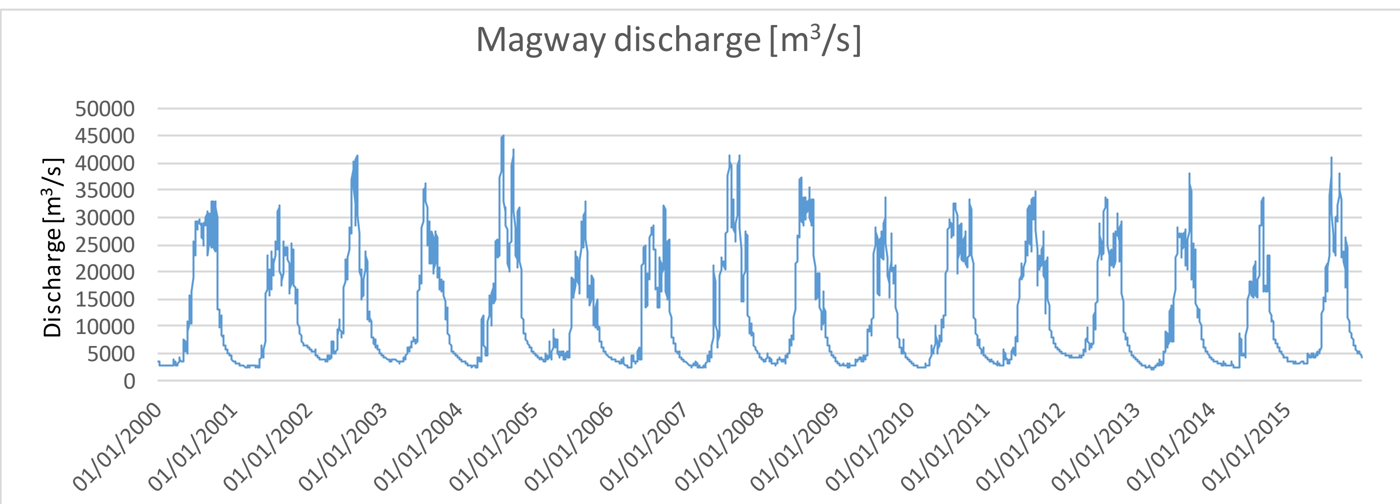
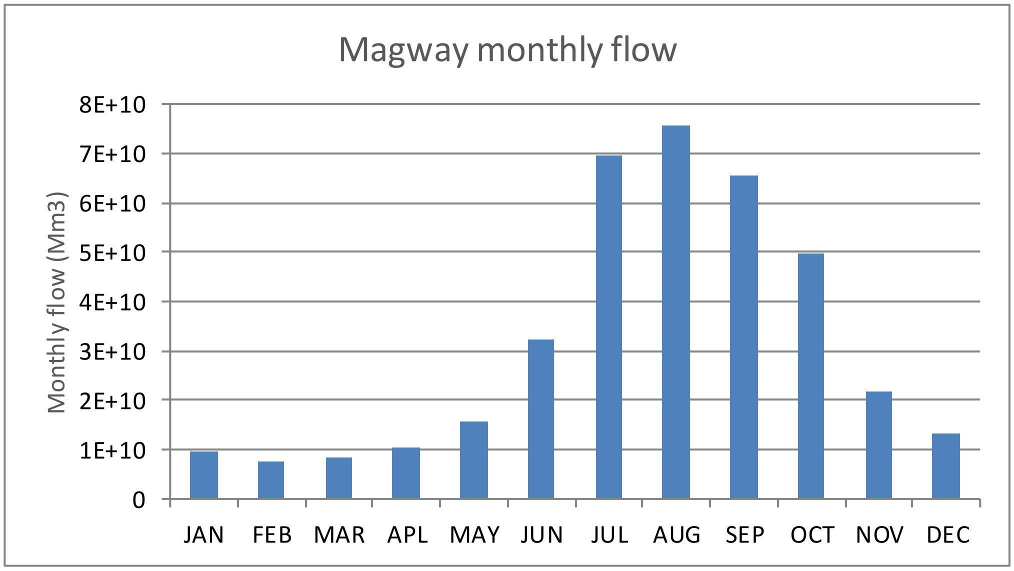


Figure A-14: Hydrograph at Magway for the period 2000-2015



monthly	flow (Mm3)
JAN	9813
FEB	7730
MAR	8536
APR	10581
MAY	15602
JUN	32258
JUL	69739
AUG	75553
SEP	65586
OCT	49801
NOV	21806
DEC	13426
Total	**380431**

Figure A-16: Average monthly flows in the period 1990-2015 at Magway

Table A-3: Annual flow and mean annual flow at Magway for the period 1994-2015

Year	Annual flow [Mm3]	Year	Annual flow [Mm3]	Year	Annual flow [Mm3]
1994	316644	2002	386005	2010	416017
1995	421280	2003	376856	2011	391133
1996	383969	2004	457358	2012	400001
1997	390565	2005	327365	2013	346326
1998	423972	2006	343312	2014	294863
1999	396971	2007	430585	2015	369172
2000	408892	2008	401599		
2001	364968	2009	321631		
			Mean annual flow:		**380431**

Pyay

The Pyay station is a pile gauge station situated in the lower river part of the Irrawaddy approximately 400 km upstream of the river mouth. It is the most downstream station analyzed and has a contributing area of 390032 km2. Sixteen years of complete data is provided for this station. From 2009 a decline in the base flow can be observed. The hydrograph at Pyay is shown in Figure A-17 and the average monthly flows are shown in Figure A-18.

The mean annual flow at Pyay was 924 mm/year (361 km^3; 11,423 m^3/s). This was less than the mean annual flow at Magway. The reasons for this can be similar as mentioned for the difference at Nyaung Oo, it can be due to groundwater recharge or increased evaporation at this area combined with not enough recharge to the river from small tributaries or groundwater. The maximum annual flow was found in 2004 (1132 mm/year; 442 km^3) and the minimum annual flow in 2014 (721 mm/year; 281 km^3).

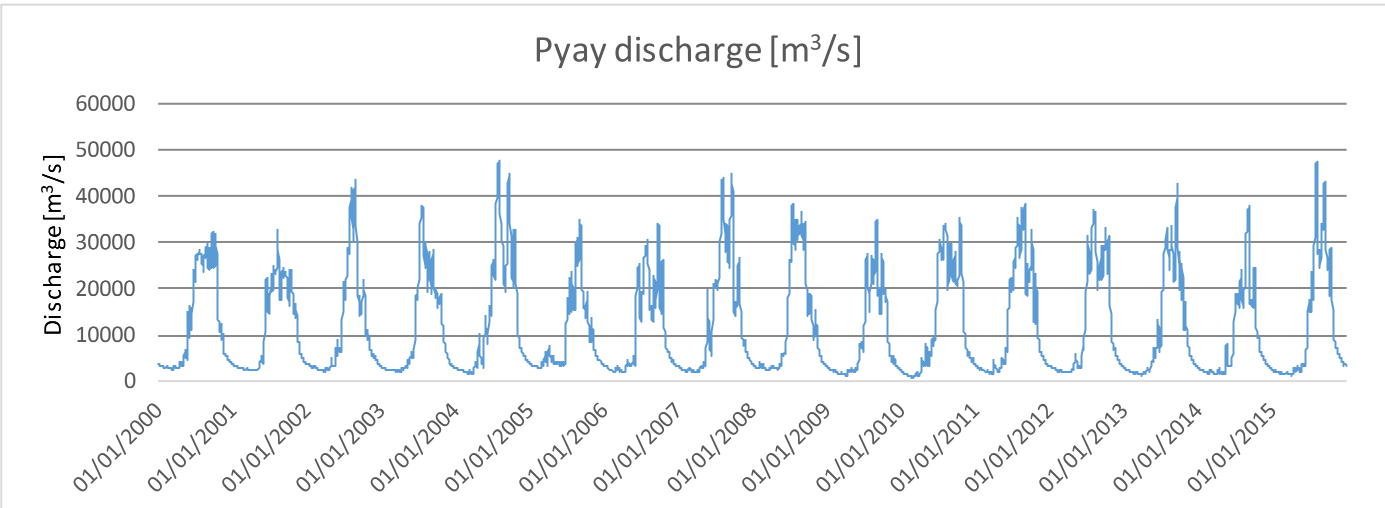
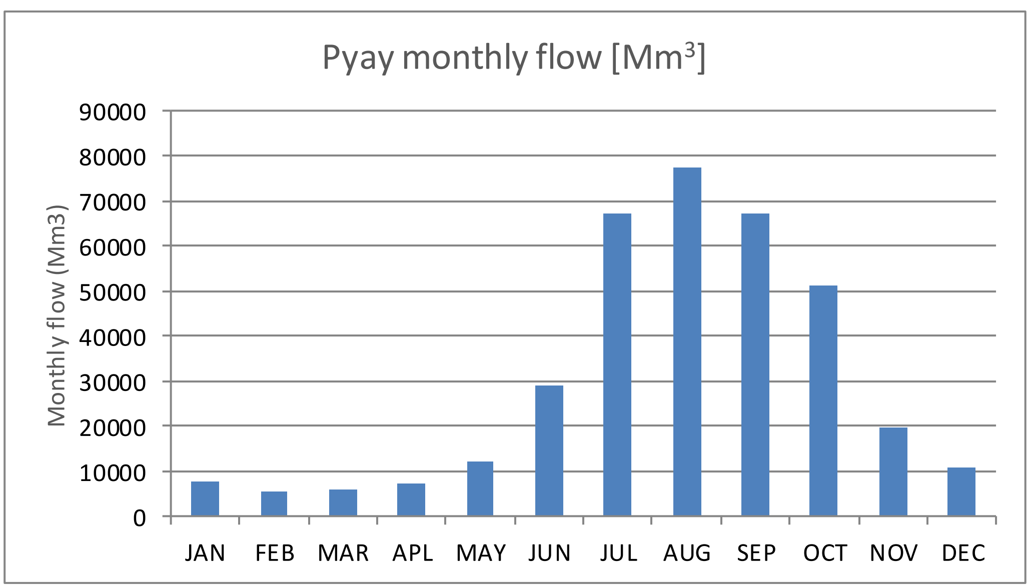


Figure A-17: Hydrograph at Pyay for the period 2000-2015



monthly flow (Mm3)	
JAN	7575
FEB	5669
MAR	5878
APR	7411
MAY	11934
JUN	28921
JUL	67055
AUG	77169
SEP	67344
OCT	50996
NOV	19811
DEC	10750
Total	**360513**

Figure A-18: Average monthly flows in the period 2000-2015 at Pyay

Comparison of yearly discharge

In the table below, Table A-4, the yearly discharge for each station is shown over the period 2000-2015. The mean annual flows are also calculated over the period 2000-2015 and not over the total available dataset for each station. The complete annual flow for the Sagaing, Chauk and Magway can be found in respectively Table A-1, Table A-2 and Table A-3. In some years the downstream station has a lower flow compared to the more upstream station, for these years the downstream station is highlighted. At Nyaung Oo and at Pyay in several years the discharge was lower than it was at the upstream station (or both stations combined in case of Nyaung Oo). The areas between those two stations can be areas where groundwater was recharged. Another reason of the lower discharge downstream can be high evaporation rates in the areas between the stations. Since we are interested in the groundwater recharge, it might be useful to have a closer look at these areas.

Table A-4: Annual flows and mean annual flows [km3/year] at all stations over the period 2000-2015; highlighted are the years where the annual flow downstream was lower than the annual flow upstream.

	Monywa	**Myitkyina**	**Sagaing**	***Sagaing+Monywa***	**Nyaung Oo**	**Chauk**	**Magway**	**Pyay**
2000	174	216	168	*384*	385	345	409	399
2001	135	187	133	*320*	343	295	365	350
2002	145	165	137	*302*	309	335	386	349
2003	162	171	143	*314*	317	323	377	349
2004	185	243	166	*409*	390	440	457	442
2005	154	148	110	*258*	278	286	327	304
2006	135	198	119	*317*	315	308	343	333
2007	169	258	165	*424*	391	410	431	420
2008	150		142		349	358	402	384
2009	126		102		268	293	322	287
2010	161	223	123	*346*	377	460	416	391
2011	119		142				391	388
2012	152		135				400	374
2013	120		131				346	348
2014	123		100				295	281
2015	121		146				369	370
Total	**146**	**201**	**135**	**192**	**338**	**350**	**377**	**361**

B. Budyko curves

This appendix contains the Budyko curves for each month for the years 2005-2010. The Dryness index is determined for 1 month and is land use independent. Each value has a color corresponding to the land use/land cover class it contains. Table A.1 shows the land use/land cover classes corresponding with the colors used in the graphs.

The high seasonal variability becomes clear from the Budyko curves. December to March is the dry period and June-October is the rainy season. It is clear that February is the month where most incremental evaporation takes place, with an actual evaporation of about 5000 times the precipitation for a few cells. In January and February most incremental evaporation takes place for the categories grass, water and other. In the other months a difference between land use categories is still visible, but not so segregated.

Table B-1:The land use/land cover classes belonging to the categories is the Budyko curves.

	% AREA			LAND USE/LAND COVER
SAVANNA	0%	-	-	-
GRASS	13%	2	PLU	Protected shrub land
		3	PLU	Protected natural grasslands
		14	ULU	Shrub land & mesquite
		15	ULU	Herbaceous cover
		16	ULU	Meadows & open grassland
OTHER	1%	6	PLU	Glaciers
		7	PLU	Protected other
		25	ULU	Flood plains & mudflats
		27	ULU	Bare soil permanent
		47	MLU	Rainfed homesteads and gardens (urbans cities) - outdoor
		68	MWU	Irrigated homesteads and gardens (urban cities) - outdoor
WATER	1%	4	PLU	Protected natural water bodies
		24	ULU	Natural lakes
		63	MWU	Managed water bodies (reservoirs, canals, harbors, tanks)
FOREST	48%	1	PLU	Protected forests
		8	ULU	Closed deciduous forest
		10	ULU	Closed evergreen forest
CROPS	37%	35	MLU	Rainfed crops – cereals
		43	MLU	Rainfed crops – other
		44	MLU	Mixed species agro-forestry
		54	MWU	Irrigated crops – cereals
		62	MWU	Irrigated crops - other

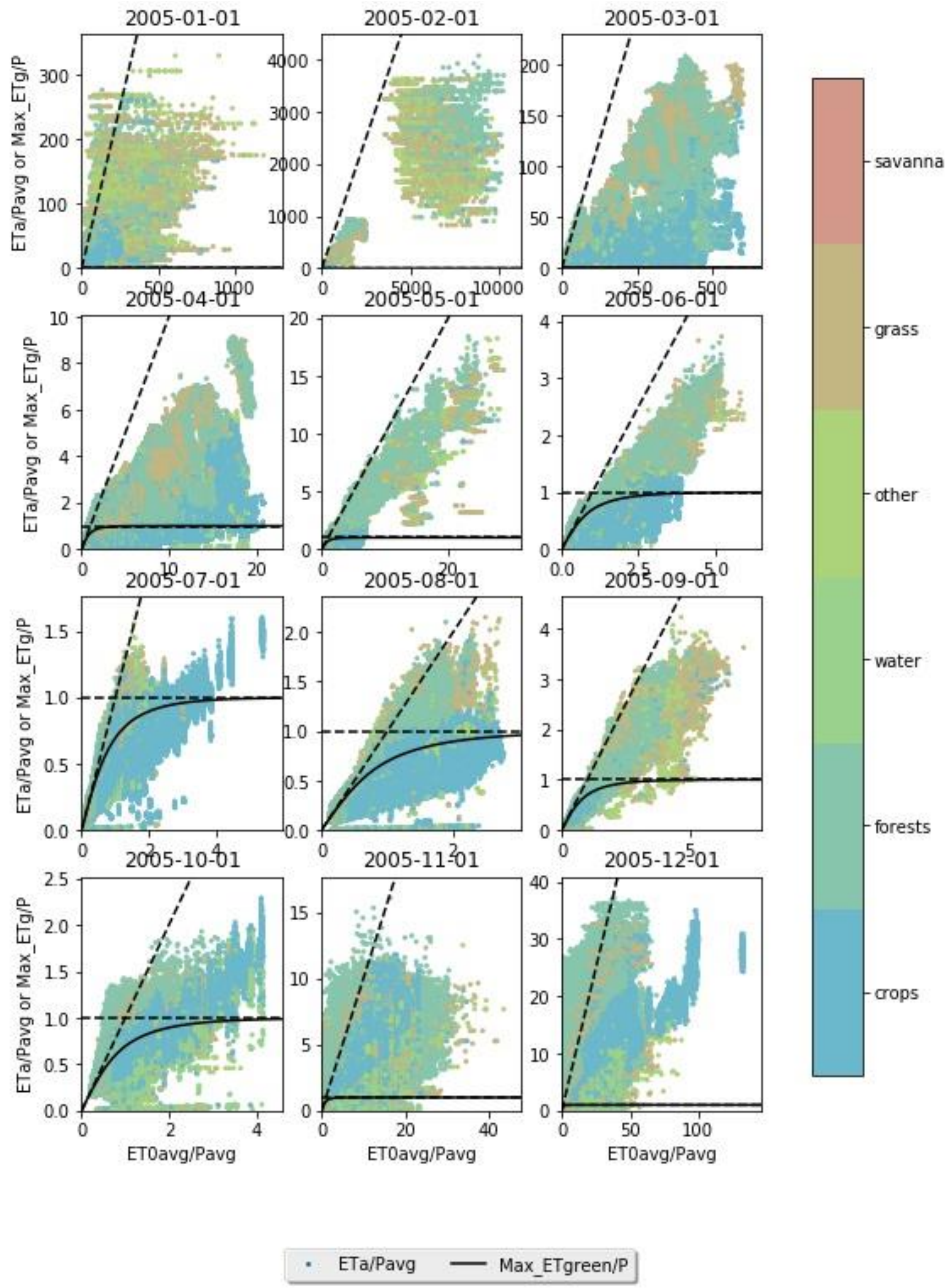


Figure B-1: Monthly Budyko curves for 2005 for the Irrawaddy basin upstream of Pyay showing different land use/land cover categories

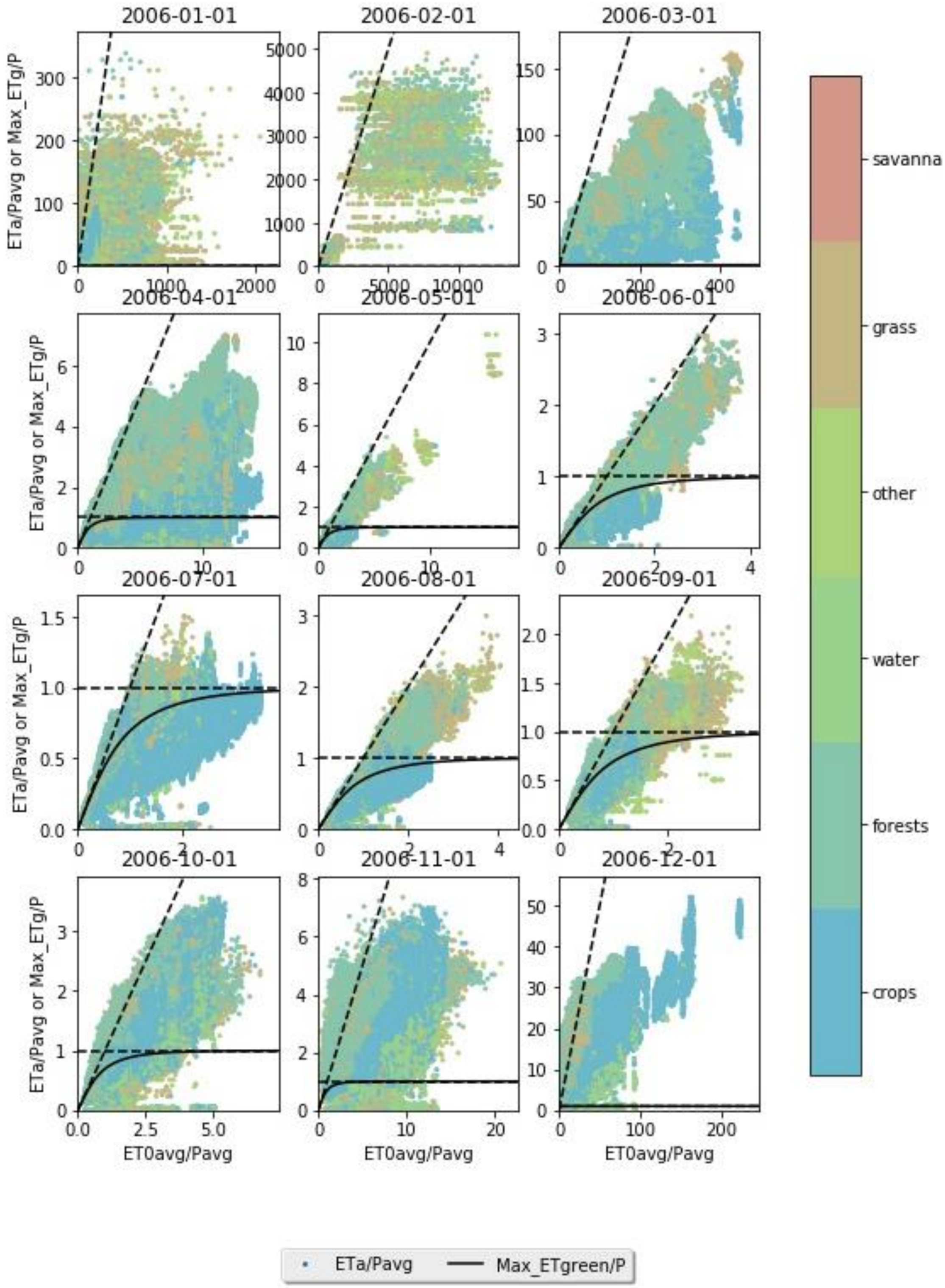


Figure B-2: Monthly Budyko curves for 2006 for the Irrawaddy basin upstream of Pyay showing different land use/land cover categories

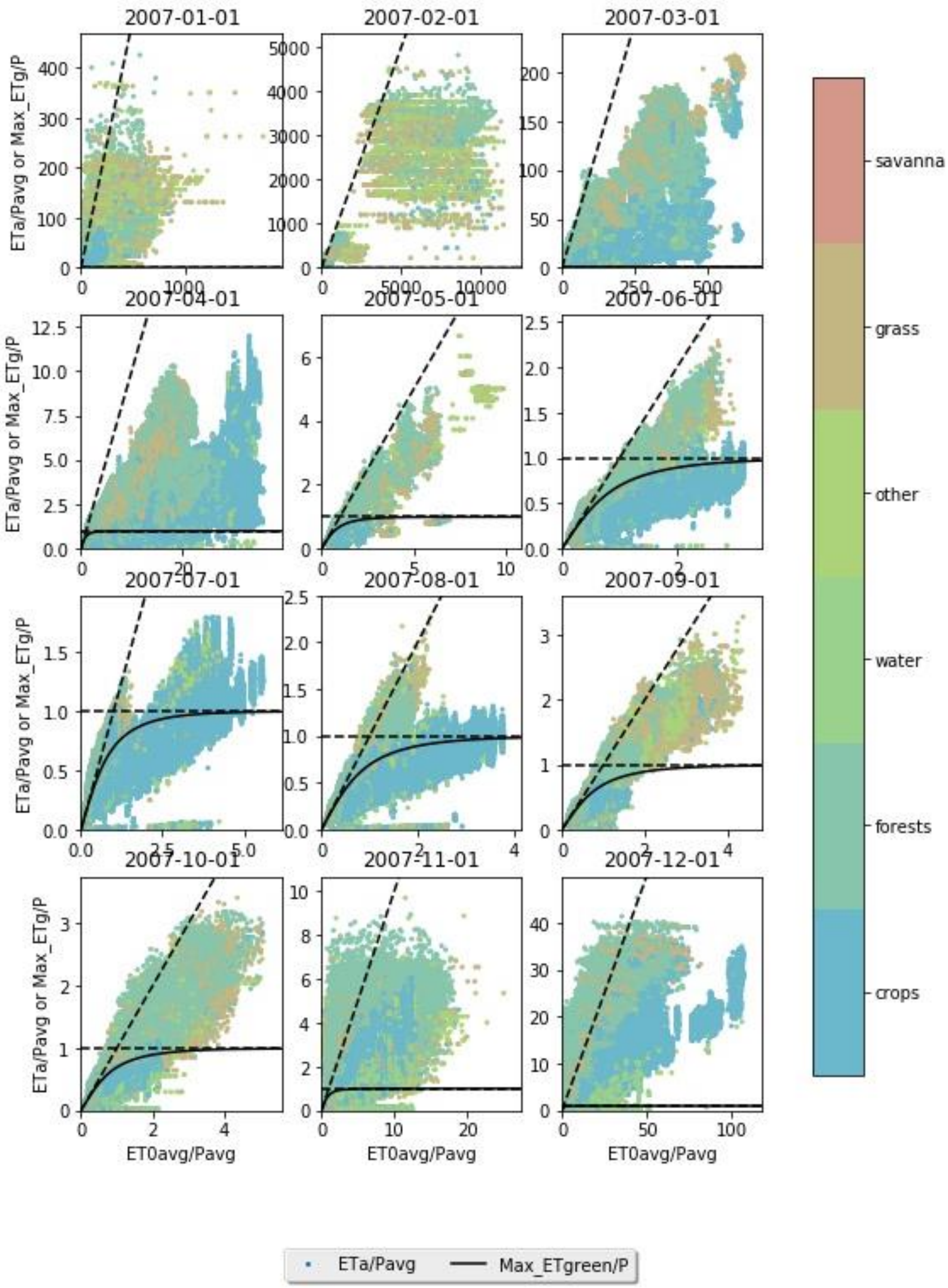


Figure B-3: Monthly Budyko curves for 2007 for the Irrawaddy basin upstream of Pyay showing different land use/land cover categories

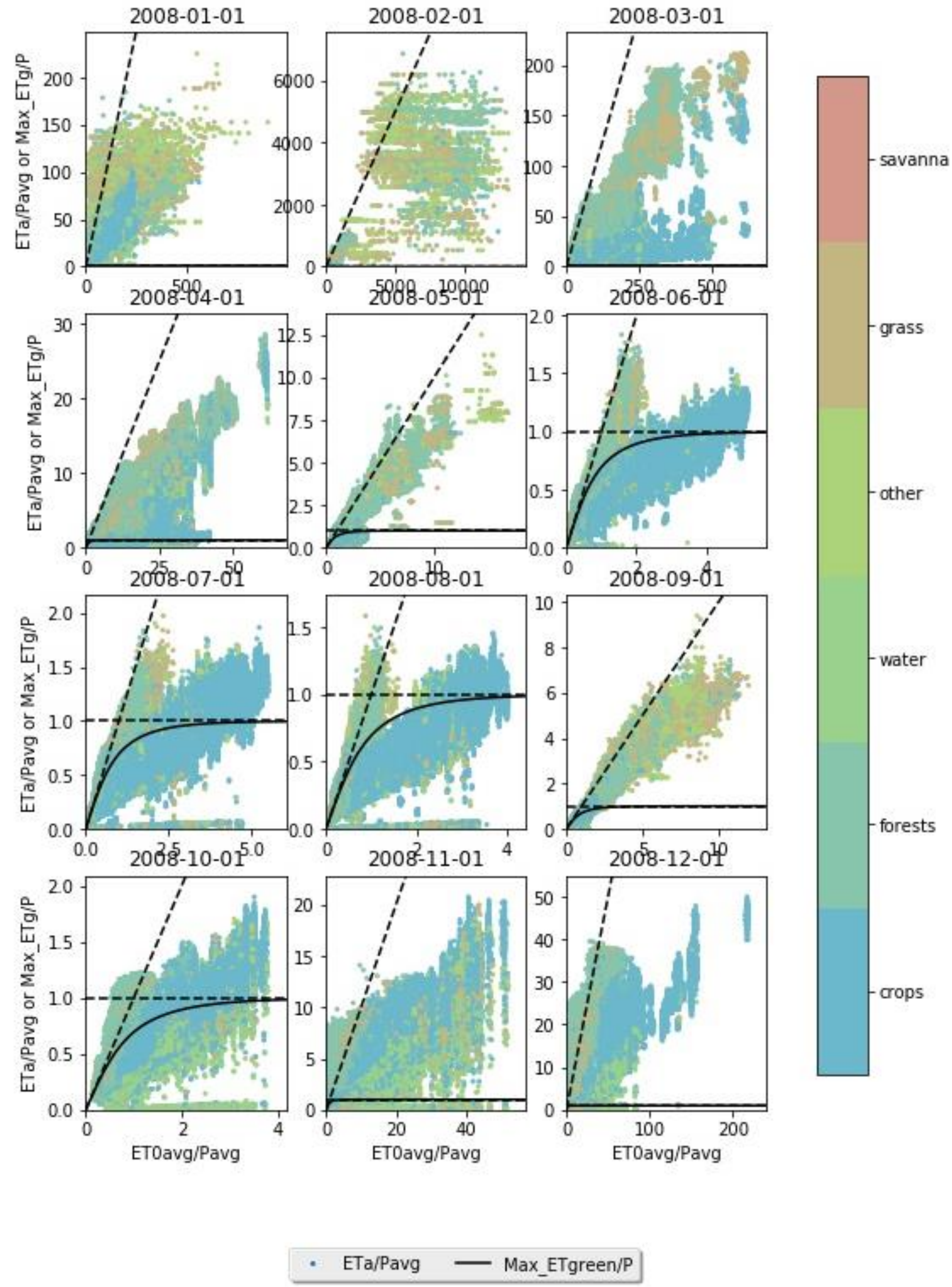


Figure B-4: Monthly Budyko curves for 2008 for the Irrawaddy basin upstream of Pyay showing different land use/land cover categories

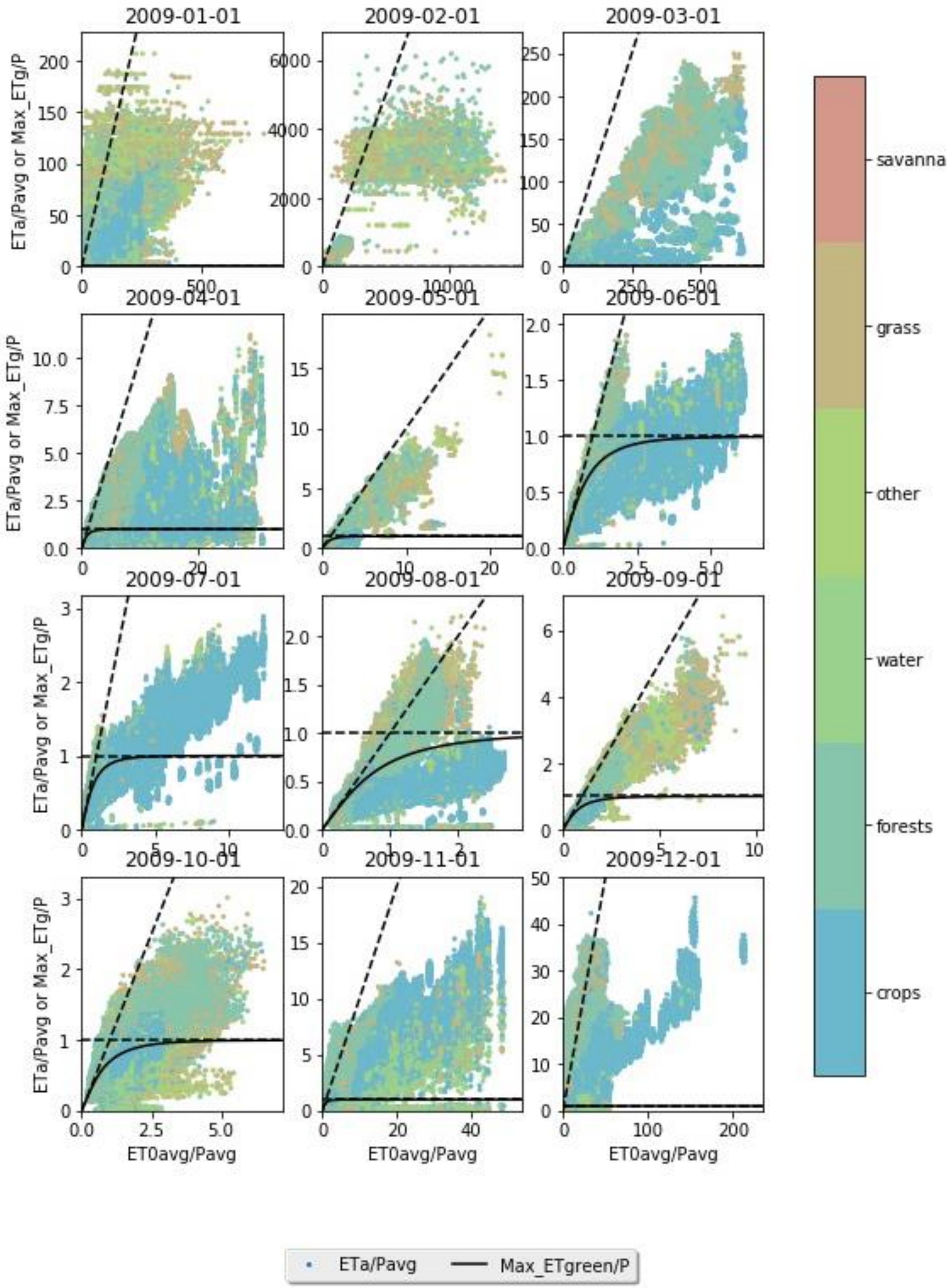


Figure B-5: Monthly Budyko curves for 2009 for the Irrawaddy basin upstream of Pyay showing different land use/land cover categories

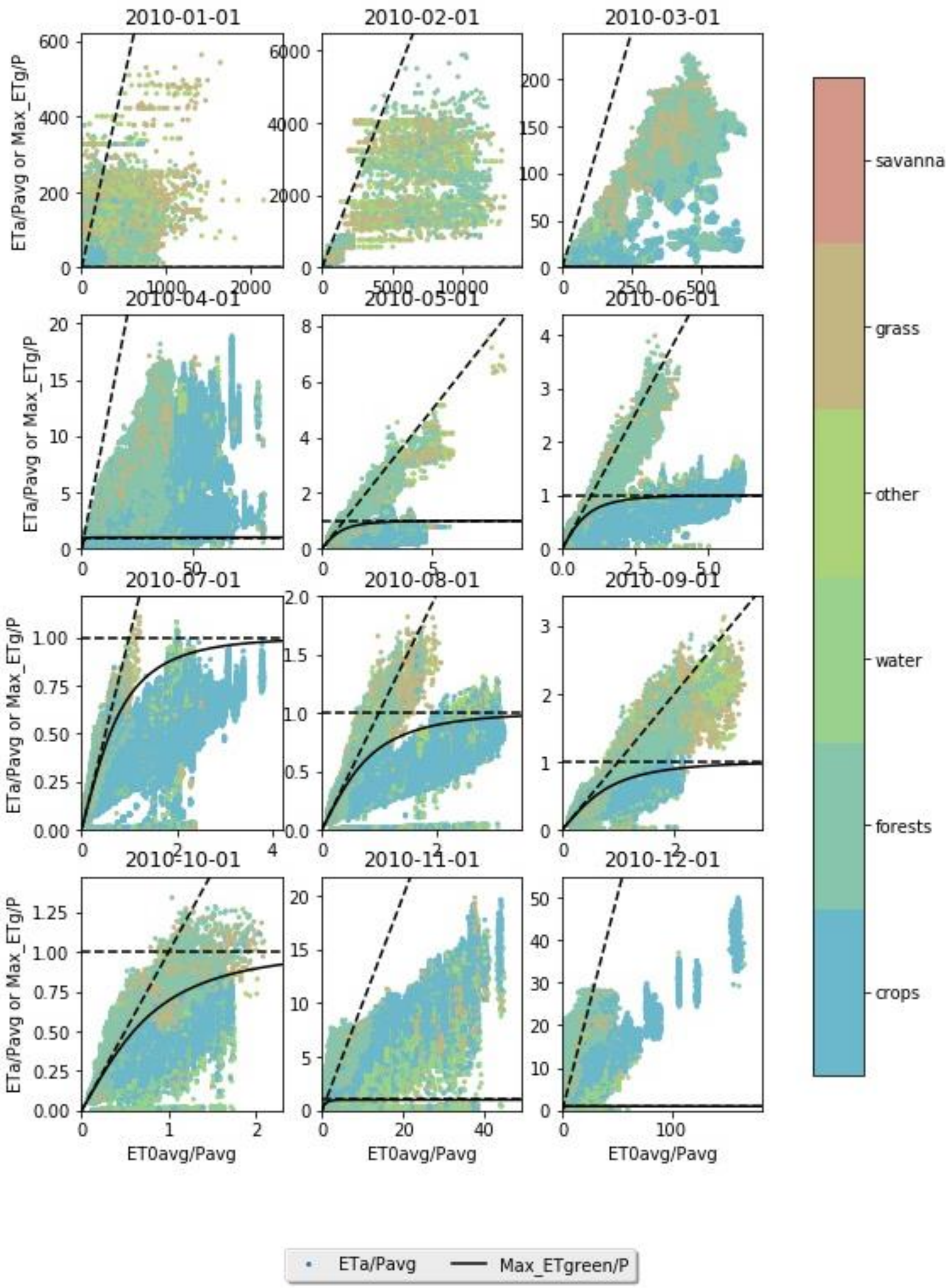


Figure B-6: Monthly Budyko curves for 2010 for the Irrawaddy basin upstream of Pyay showing different land use/land cover categories

C. Annual tables Chindwin basin

Table C-1: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Chindwin basin in 2005

2005 Chindwin	WMC	AREA	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharge}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	19339	2676	51749	1053	20362	857	16580	196	3783	1623	31387	0.0	0.0	635	12285	-256	-4957	379	7329
protected shrubland	PLU	2038	2635	5370	1057	2155	865	1763	193	393	1577	3215	0.0	0.0	601	1225	-186	-379	415	846
protected natural grasslands	PLU	6	2513	15	850	5	753	4	98	1	1663	10	0.0	0.0	668	4	-323	-2	346	2
protected natural waterbodies	PLU	192	2390	458	958	184	806	154	152	29	1432	274	0.0	0.0	596	114	-209	-40	387	74
glaciers	PLU	0	1585	1	782	0	639	0	143	0	803	0	0.0	0.0	453	0	-45	0	407	0
protected other	PLU	5	2727	14	876	5	734	4	141	1	1851	10	0.0	0.0	420	2	-334	-2	87	0
closed deciduous forest	ULU	9699	1688	16368	956	9272	696	6749	260	2523	732	7096	2.3	22.6	387	3753	-96	-933	293	2843
closed evergreen forest	ULU	39128	2041	79869	1047	40971	782	30588	265	10383	994	38898	2.1	80.2	534	20881	-102	-4000	433	16961
shrub land & mesquite	ULU	16020	2022	32393	1042	16701	786	12593	256	4107	979	15692	5.3	84.3	535	8571	-78	-1257	462	7398
herbaceous cover	ULU	92	1563	144	702	65	565	52	137	13	861	79	0.0	0.0	458	42	6	1	464	43
meadows & open grassland	ULU	87	1613	140	762	66	639	56	123	11	851	74	0.0	0.0	482	42	-82	-7	401	35
natural lakes	ULU	838	1924	1612	754	632	624	522	131	110	1169	980	0.3	0.3	624	523	-88	-73	537	450
bare soil permanent	ULU	1	951	1	579	0	443	0	137	0	371	0	0.0	0.0	160	0	21	0	181	0
rainfed crops - cereals	MLU	621	1627	1010	800	496	688	427	111	69	827	513	1.7	1.1	515	320	-63	-39	454	282
rainfed crops - other	MLU	13445	1406	18908	765	10288	593	7977	172	2311	641	8619	0.8	11.4	328	4408	-32	-431	297	3988
mixed species agro-forestry	MLU	7227	1779	12858	933	6744	700	5056	234	1689	846	6114	1.4	9.9	433	3126	-117	-846	317	2291
rainfed homesteads and gardens (urban cities) - outdoor	MLU	210	1590	334	796	167	659	138	137	29	794	167	0.4	0.1	442	93	-122	-26	321	67
irrigated crops - cereals	MWU	309	1693	524	845	261	707	219	139	43	848	262	0.4	0.1	522	161	-24	-7	499	154
irrigated crops - other	MWU	1589	1681	2671	811	1288	641	1018	170	270	871	1383	0.8	1.3	456	725	-140	-223	317	503
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	33	1279	42	641	21	502	17	140	5	638	21	0.0	0.0	276	9	11	0	287	10
irrigated homesteads and gardens (urban cities) - outdoor	MWU	22	796	17	616	14	478	11	138	3	180	4	0.0	0.0	72	2	20	0	92	2
TOTAL		**110901**	**2027**	**224497**	**990**	**109697**	**757**	**83927**	**232**	**25771**	**1037**	**114800**	**1.9**	**211**	**508**	**56287**	**-120**	**-13220**	**391**	**43279**

Table C-2: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Chindwin basin in 2006

2006 Chindwin	WMC	AREA	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharge}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	19339	2729	52775	1065	20604	834	16120	232	4485	1663	32171	0.5	8.7	391	7560	-217	-4205	174	3364
protected shrubland	PLU	2038	2697	5497	1072	2185	840	1711	233	474	1625	3312	0.3	0.6	317	646	-229	-467	88	180
protected natural grasslands	PLU	6	2332	13	823	5	708	4	116	1	1509	9	0.0	0.0	233	1	-182	-1	51	0
protected natural waterbodies	PLU	192	2225	426	954	183	747	143	207	40	1271	244	0.0	0.0	242	46	-165	-32	76	15
glaciers	PLU	0	1494	1	780	0	564	0	217	0	714	0	0.0	0.0	389	0	-62	0	327	0
protected other	PLU	5	2990	15	900	5	753	4	146	1	2090	11	0.0	0.0	190	1	-163	-1	24	0
closed deciduous forest	ULU	9699	1668	16182	990	9602	673	6527	317	3076	678	6579	3.8	36.7	344	3335	-77	-745	271	2627
closed evergreen forest	ULU	39128	1914	74888	1059	41435	745	29156	314	12280	855	33453	2.8	109.1	420	16449	-128	-4992	296	11567
shrub land & mesquite	ULU	16020	1882	30151	1058	16943	745	11936	313	5007	824	13208	7.2	115.2	412	6596	-106	-1695	313	5016
herbaceous cover	ULU	92	1597	147	734	68	568	52	166	15	863	79	0.0	0.0	415	38	-66	-6	348	32
meadows & open grassland	ULU	87	1513	132	769	67	613	53	156	14	744	65	0.0	0.0	390	34	-72	-6	318	28
natural lakes	ULU	838	1901	1593	777	651	602	504	175	147	1125	942	0.6	0.5	525	440	-188	-157	339	284
bare soil permanent	ULU	1	1278	1	661	0	524	0	137	0	618	0	0.0	0.0	211	0	-18	0	193	0
rainfed crops - cereals	MLU	621	1668	16182	990	9602	608	377	154	96	678	6579	3.8	36.7	344	3335	-77	-745	271	2627
rainfed crops - other	MLU	13445	1914	74888	1059	41435	608	8174	206	2772	855	33453	2.8	109.1	420	16449	-128	-4992	296	11567
mixed species agro-forestry	MLU	7227	1882	30151	1058	16943	682	4932	286	2069	824	13208	7.2	115.2	412	6596	-106	-1695	313	5016
rainfed homesteads and gardens (urban cities) - outdoor	MLU	210	1597	147	734	68	616	129	181	38	863	79	0.0	0.0	415	38	-66	-6	348	32
irrigated crops - cereals	MWU	309	1345	416	822	254	630	195	192	59	523	162	0.4	0.1	316	98	-48	-15	268	83
irrigated crops - other	MWU	1589	1641	2608	841	1337	619	983	222	353	800	1271	1.6	2.5	374	595	-92	-146	284	451
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	33	1543	51	718	24	547	18	171	6	825	27	0.0	0.0	343	11	38	1	380	13
irrigated homesteads and gardens (urban cities) - outdoor	MWU	22	1088	24	716	16	573	13	143	3	372	8	0.0	0.0	112	2	34	1	146	3
TOTAL		**110901**	**1980**	**219351**	**1010**	**111965**	**731**	**81032**	**279**	**30934**	**970**	**107386**	**2.8**	**313**	**390**	**43185**	**-122**	**-13488**	**270**	**30010**

Table C-3: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Chindwin basin in 2007

2007 Chindwin	WMC	AREA	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharge}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	19339	3190	61698	1042	20144	823	15915	219	4228	2149	41554	0.3	5.3	687	13290	-52	-997	636	12299
protected shrubland	PLU	2038	3180	6481	1048	2135	830	1692	217	443	2132	4346	0.2	0.4	687	1400	-92	-188	595	1213
protected natural grasslands	PLU	6	2824	16	827	5	736	4	90	1	1998	12	0.0	0.0	682	4	-209	-1	473	3
protected natural waterbodies	PLU	192	2696	517	942	180	780	149	161	31	1755	336	0.0	0.0	597	114	-122	-23	475	91
glaciers	PLU	0	1966	1	812	0	644	0	168	0	1154	0	0.0	0.0	574	0	91	0	665	0
protected other	PLU	5	3343	17	879	5	722	4	157	1	2464	13	0.0	0.0	442	2	-163	-1	279	1
closed deciduous forest	ULU	9699	2082	20197	1012	9812	759	7360	253	2452	1071	10385	2.6	25.2	502	4870	81	790	586	5685
closed evergreen forest	ULU	39128	2373	92850	1056	41306	800	31289	256	10018	1317	51544	1.9	75.6	578	22625	87	3413	667	26115
shrub land & mesquite	ULU	16020	2320	37173	1052	16856	800	12811	252	4045	1268	20316	5.1	81.5	568	9100	103	1657	677	10839
herbaceous cover	ULU	92	1905	175	759	70	629	58	129	12	1146	105	0.0	0.0	507	47	98	9	604	56
meadows & open grassland	ULU	87	1832	160	794	69	677	59	118	10	1037	90	0.0	0.0	477	42	-73	-6	404	35
natural lakes	ULU	838	2289	1918	786	659	648	543	138	116	1503	1259	0.4	0.3	655	549	120	100	775	649
bare soil permanent	ULU	1	1327	1	699	0	577	0	122	0	628	0	0.0	0.0	215	0	20	0	235	0
rainfed crops - cereals	MLU	621	1623	1008	797	495	699	434	98	61	826	513	1.0	0.6	438	272	-92	-57	347	215
rainfed crops - other	MLU	13445	1791	24076	839	11287	670	9010	169	2277	951	12789	1.0	13.0	419	5632	2	27	422	5672
mixed species agro-forestry	MLU	7227	2176	15730	985	7119	753	5445	232	1674	1191	8611	1.4	10.0	533	3852	34	246	568	4108
rainfed homesteads and gardens (urban cities) - outdoor	MLU	210	1779	373	827	173	693	145	133	28	952	200	0.7	0.2	454	95	-55	-11	400	84
irrigated crops - cereals	MWU	309	1720	532	843	261	699	434	98	61	877	271	0.2	0.1	454	141	10	3	464	144
irrigated crops - other	MWU	1589	2019	3208	853	1354	670	9010	169	2277	1167	1853	1.0	1.5	514	816	61	96	575	914
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	33	1776	59	725	24	753	5445	232	1674	1051	35	0.0	0.0	433	14	0	0	433	14
irrigated homesteads and gardens (urban cities) - outdoor	MWU	22	1115	24	760	17	693	145	133	28	355	8	0.0	0.0	106	2	-9	0	97	2
TOTAL		**110901**	**2403**	**266211**	**1010**	**111971**	**778**	**86260**	**232**	**25711**	**1393**	**154241**	**1.9**	**214**	**567**	**62868**	**45**	**5057**	**615**	**68140**

Table C-4: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Chindwin basin in 2008

2008 Chindwin	**WMC**	**AREA**	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharge}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	19339	2822	54577	1042	20146	825	15962	216	4184	1780	34431	0.1	1.4	621	12010	-215	-4153	406	7858
protected shrubland	PLU	2038	2782	5669	1051	2141	835	1703	215	438	1731	3528	0.1	0.1	602	1228	-241	-491	362	737
protected natural grasslands	PLU	6	2368	14	854	5	719	4	135	1	1514	9	0.0	0.0	550	3	-99	-1	451	3
protected natural waterbodies	PLU	192	2282	437	948	182	754	144	194	37	1334	256	0.0	0.0	484	93	-128	-25	356	68
glaciers	PLU	0	2035	1	786	0	573	0	213	0	1249	0	0.0	0.0	621	0	-16	0	605	0
protected other	PLU	5	2791	14	844	4	701	4	143	1	1947	10	0.0	0.0	376	2	-75	0	302	2
closed deciduous forest	ULU	9699	1821	17658	1005	9743	671	6506	334	3237	816	7915	2.2	21.6	394	3817	-83	-800	313	3038
closed evergreen forest	ULU	39128	2162	84585	1060	41495	747	29237	313	12258	1101	43091	1.7	65.5	490	19164	-106	-4152	385	15077
shrub land & mesquite	ULU	16020	2146	34387	1055	16909	749	11997	307	4912	1091	17479	4.2	68.0	496	7948	-106	-1692	395	6324
herbaceous cover	ULU	92	1688	155	749	69	566	52	183	17	939	86	0.0	0.0	438	40	-39	-4	399	37
meadows & open grassland	ULU	87	1524	133	795	69	619	54	176	15	729	63	0.0	0.0	337	29	-34	-3	303	26
natural lakes	ULU	838	2100	1759	780	654	607	508	173	145	1319	1105	0.4	0.3	598	501	-71	-60	527	441
bare soil permanent	ULU	1	959	1	672	0	503	0	169	0	287	0	0.0	0.0	119	0	-2	0	116	0
rainfed crops - cereals	MLU	621	1338	831	808	502	636	395	172	107	531	329	1.7	1.1	292	181	15	9	308	191
rainfed crops - other	MLU	13445	1473	19802	825	11095	597	8030	228	3065	648	8707	1.0	13.3	304	4087	-41	-549	264	3551
mixed species agro-forestry	MLU	7227	1831	13233	985	7118	680	4914	305	2204	846	6115	1.4	9.9	390	2819	-98	-708	293	2120
rainfed homesteads and gardens (urban cities) - outdoor	MLU	210	1515	318	823	173	629	132	194	41	691	145	0.8	0.2	341	72	-79	-17	263	55
irrigated crops - cereals	MWU	309	1439	445	855	264	648	200	207	64	583	180	0.3	0.1	308	95	49	15	357	110
irrigated crops - other	MWU	1589	1792	2847	852	1353	619	983	233	370	940	1493	1.0	1.5	426	676	-47	-74	380	604
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	33	1334	44	709	24	520	17	189	6	625	21	0.0	0.0	288	10	-78	-3	210	7
irrigated homesteads and gardens (urban cities) - outdoor	MWU	22	757	17	688	15	508	11	181	4	68	2	0.0	0.0	26	1	56	1	82	2
TOTAL		**110901**	**2139**	**236927**	**1010**	**111961**	**730**	**80855**	**280**	**31105**	**1129**	**124967**	**1.6**	**183**	**477**	**52776**	**-115**	**-12706**	**363**	**40252**

Table C-5: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Chindwin basin in 2009

2009 Chindwin	WMC	AREA	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharge}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	19339	2706	52324	1032	19956	811	15680	221	4277	1674	32367	0.1	1.1	583	11274	-384	-7432	199	3843
protected shrubland	PLU	2038	2681	5464	1039	2117	818	1667	221	450	1642	3347	0.0	0.0	549	1119	-398	-811	152	309
protected natural grasslands	PLU	6	2359	14	828	5	722	4	106	1	1530	9	0.0	0.0	478	3	-221	-1	257	1
protected natural waterbodies	PLU	192	2254	432	937	180	764	146	172	33	1317	252	0.0	0.0	433	83	-217	-42	216	41
glaciers	PLU	0	1635	1	757	0	580	0	178	0	878	0	0.0	0.0	423	0	-24	0	399	0
protected other	PLU	5	2758	14	838	4	693	4	145	1	1920	10	0.0	0.0	351	2	-263	-1	88	0
closed deciduous forest	ULU	9699	1638	15888	960	9307	678	6576	282	2731	679	6581	3.4	33.4	322	3120	-61	-594	264	2560
closed evergreen forest	ULU	39128	1996	78095	1038	40631	744	29101	295	11530	957	37464	2.9	114.8	469	18349	-245	-9594	227	8869
shrub land & mesquite	ULU	16020	1978	31693	1035	16575	743	11907	291	4668	944	15118	6.8	109.6	475	7602	-197	-3148	285	4563
herbaceous cover	ULU	92	1521	140	708	65	550	51	158	15	813	75	0.0	0.0	391	36	-105	-10	286	26
meadows & open grassland	ULU	87	1455	127	747	65	612	53	134	12	709	62	0.0	0.0	357	31	-110	-10	247	21
natural lakes	ULU	838	1923	1611	744	624	591	495	153	128	1179	988	0.5	0.4	561	470	-203	-170	358	300
bare soil permanent	ULU	1	1004	1	601	0	464	0	137	0	403	0	0.0	0.0	155	0	75	0	231	0
rainfed crops - cereals	MLU	621	1294	803	750	466	641	398	110	68	543	337	2.6	1.6	287	178	-134	-83	155	96
rainfed crops - other	MLU	13445	1386	18633	769	10338	588	7902	181	2435	617	8295	1.5	20.5	276	3712	-47	-638	230	3095
mixed species agro-forestry	MLU	7227	1725	12468	929	6712	679	4905	250	1807	796	5756	2.1	15.3	352	2547	-124	-897	230	1666
rainfed homesteads and gardens (urban cities) - outdoor	MLU	210	1411	296	777	163	628	132	149	31	634	133	1.1	0.2	300	63	-120	-25	181	38
irrigated crops - cereals	MWU	309	1361	421	809	250	669	207	140	43	553	171	0.5	0.1	287	89	-131	-41	156	48
irrigated crops - other	MWU	1589	1617	2569	804	1277	616	978	188	299	813	1292	1.4	2.2	376	597	-152	-242	225	358
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	33	1389	46	661	22	505	17	155	5	728	24	0.0	0.0	289	10	-68	-2	221	7
irrigated homesteads and gardens (urban cities) - outdoor	MWU	22	881	19	661	15	467	10	194	4	220	5	0.1	0.0	83	2	80	2	163	4
TOTAL		**110901**	**1996**	**221057**	**981**	**108771**	**724**	**80234**	**257**	**28538**	**1015**	**112286**	**2.7**	**300**	**445**	**49288**	**-215**	**-23739**	**233**	**25848**

Table C-6: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Chindwin basin in 2010

2010 Chindwin	**WMC**	**AREA**	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharge}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	19339	3292	63669	1020	19730	803	15533	217	4200	2272	43939	0.0	0.4	717	13860	166	3218	883	17084
protected shrubland	PLU	2038	3268	6660	1030	2099	810	1650	220	449	2238	4561	0.0	0.0	719	1466	111	227	831	1693
protected natural grasslands	PLU	6	2944	17	841	5	737	4	103	1	2104	12	0.0	0.0	845	5	127	1	973	6
protected natural waterbodies	PLU	192	2873	551	935	179	774	148	160	31	1939	371	0.0	0.0	688	132	95	18	784	150
glaciers	PLU	0	2272	1	840	0	661	0	179	0	1432	1	0.0	0.0	644	0	207	0	850	0
protected other	PLU	5	3370	17	825	4	678	4	148	1	2545	13	0.0	0.0	584	3	75	0	662	3
closed deciduous forest	ULU	9699	2177	21110	972	9423	705	6837	267	2586	1205	11687	3.2	31.2	522	5063	129	1250	654	6344
closed evergreen forest	ULU	39128	2540	99369	1036	40531	775	30325	261	10207	1504	58838	2.5	98.5	621	24295	180	7029	803	31422
shrub land & mesquite	ULU	16020	2522	40407	1031	16523	778	12466	253	4058	1491	23884	6.5	103.6	631	10108	172	2749	809	12961
herbaceous cover	ULU	92	1977	182	735	68	590	54	145	13	1242	114	0.1	0.0	483	44	126	12	609	56
meadows & open grassland	ULU	87	2001	174	781	68	647	56	133	12	1220	106	0.0	0.0	489	43	44	4	533	46
natural lakes	ULU	838	2413	2022	768	643	625	524	143	120	1645	1379	0.5	0.4	656	549	155	130	811	680
bare soil permanent	ULU	1	1198	1	614	0	475	0	139	0	584	0	0.2	0.0	132	0	-34	0	98	0
rainfed crops - cereals	MLU	621	1996	1239	800	497	693	431	107	66	1196	742	2.1	1.3	579	359	111	69	692	429
rainfed crops - other	MLU	13445	1809	24317	787	10584	603	8105	184	2479	1021	13733	1.3	17.7	390	5241	40	533	431	5792
mixed species agro-forestry	MLU	7227	2262	16351	939	6787	694	5018	245	1770	1323	9564	2.0	14.1	549	3969	100	721	651	4704
rainfed homesteads and gardens (urban cities) - outdoor	MLU	210	1981	415	806	169	665	139	141	30	1175	246	0.9	0.2	508	107	45	9	554	116
irrigated crops - cereals	MWU	309	2082	644	838	259	715	221	124	38	1243	384	0.4	0.1	594	184	163	50	757	234
irrigated crops - other	MWU	1589	2146	3409	819	1302	648	1029	172	273	1327	2108	1.3	2.0	518	824	106	168	626	994
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	33	1728	57	678	22	511	17	167	6	1050	35	0.0	0.0	336	11	-100	-3	236	8
irrigated homesteads and gardens (urban cities) - outdoor	MWU	22	1022	22	659	14	501	11	159	3	363	8	0.1	0.0	76	2	28	1	104	2
TOTAL		**110901**	**2534**	**280636**	**983**	**108910**	**745**	**82573**	**238**	**26340**	**1551**	**171726**	**2.4**	**270**	**598**	**66264**	**146**	**16185**	**747**	**82725**

D. Annual tables Irrawaddy Basin upstream of Pyay

Table D-1: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Irrawaddy basin in 2005

2005 Irrawaddy	**WMC**	**AREA**	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharge}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	32335	2377	76846	947	30635	766	24759	183	5922	1432	46303	0.8	24.6	516	16694	-221	-7133	298	9623
protected shrubland	PLU	3911	2475	9679	967	3783	774	3026	194	758	1508	5899	1.5	6.0	561	2195	-220	-862	342	1339
protected natural grasslands	PLU	1076	858	923	609	655	453	487	155	167	250	268	0.0	0.0	48	51	8	9	56	60
protected natural waterbodies	PLU	347	2252	782	859	298	722	251	137	48	1392	483	0.1	0.0	663	230	-5	-2	658	228
glaciers	PLU	777	645	501	587	456	403	313	184	143	57	44	0.0	0.0	13	10	13	10	26	20
protected other	PLU	460	987	454	650	299	498	229	152	70	342	157	0.0	0.0	72	33	8	4	80	37
closed deciduous forest	ULU	34519	1641	56651	829	28623	614	21192	215	7431	812	28032	0.9	1.1	451	568	-109	-137	343	432
closed evergreen forest	ULU	108391	1915	207550	912	98897	689	74686	223	24221	1003	108676	3.5	317.6	302	27471	-11	-963	295	26826
shrub land & mesquite	ULU	37742	1890	71322	930	35111	687	25924	243	9187	959	36213	4.3	107.9	403	9995	-111	-2742	297	7361
herbaceous cover	ULU	1169	1057	1235	622	727	487	570	134	157	440	514	1.1	1.0	350	291	-65	-54	287	238
meadows & open grassland	ULU	1323	866	1145	624	826	461	610	163	216	248	328	0.9	1.1	451	568	-109	-137	343	432
natural lakes	ULU	3536	1443	5102	608	2151	497	1759	111	392	835	2952	3.5	317.6	302	27471	-11	-963	295	26826
Flood plains & mudflats	ULU	0	1652	0	689	0	515	0	175	0	963	0	4.3	107.9	403	9995	-111	-2742	297	7361
bare soil permanent	ULU	2	869	2	490	1	394	1	96	0	379	1	1.1	1.0	350	291	-65	-54	287	238
rainfed crops - cereals	MLU	1259	1558	1963	722	910	597	752	125	157	836	1053	0.9	1.1	451	568	-109	-137	343	432
rainfed crops - other	MLU	91039	1263	114996	616	56105	492	44767	125	11338	647	58891	3.5	317.6	302	27471	-11	-963	295	26826
mixed species agro-forestry	MLU	24803	1641	40704	790	19587	605	15000	185	4587	852	21132	4.3	107.9	403	9995	-111	-2742	297	7361
rainfed homesteads and gardens (urban cities) - outdoor	MLU	831	1371	1140	666	554	540	449	126	105	705	586	1.1	1.0	350	291	-65	-54	287	238
irrigated crops - cereals	MWU	756	1619	1225	727	550	585	443	141	107	893	675	0.2	0.1	465	352	-100	-75	366	276
irrigated crops - other	MWU	15903	1238	19694	625	9935	497	7901	128	2034	614	9760	1.8	29.2	273	4346	-15	-244	260	4131
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	919	1273	1171	561	515	442	406	119	109	713	655	0.7	0.6	354	326	-21	-19	334	307
irrigated homesteads and gardens (urban cities) - outdoor	MWU	446	799	357	609	272	470	210	139	62	190	85	0.5	0.2	78	35	56	25	135	60
TOTAL			**1697**	**613440**	**805**	**290887**	**619**	**223734**	**186**	**67210**	**893**	**322709**	**3**	**1148**	**384**	**138740**	**-91**	**-33051**	**296**	**106886**

Table D-2: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Irrawaddy basin in 2006

2006 Irrawaddy	**WMC**	**AREA**	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharge}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	32335	2445	79065	961	31079	756	24456	206	6656	1487	48069	1.5	47.8	304	9832	-124	-4000	182	5886
protected shrubland	PLU	3911	2557	10002	984	3847	756	2955	228	892	1575	6159	3.6	14.1	311	1216	-133	-521	181	709
protected natural grasslands	PLU	1076	902	970	607	653	495	532	112	120	299	322	0.0	0.0	43	46	41	44	83	89
protected natural waterbodies	PLU	347	2204	765	859	298	677	235	182	63	1345	467	0.2	0.1	408	142	-292	-101	117	41
glaciers	PLU	777	687	534	591	459	440	341	151	117	105	81	0.0	0.0	21	16	19	14	39	30
protected other	PLU	460	1044	480	646	297	537	247	109	50	406	187	0.0	0.0	66	30	38	17	104	48
closed deciduous forest	ULU	34519	1803	62225	875	30196	628	21684	247	8513	928	32050	9.2	317.1	404	13961	-81	-2795	333	11484
closed evergreen forest	ULU	108391	1961	212532	927	100467	685	74210	242	26263	1036	112258	5.5	593.6	348	37750	-86	-9350	268	28997
shrub land & mesquite	ULU	37742	1927	72729	949	35826	680	25655	270	10172	978	36914	9.3	349.6	382	14422	-98	-3705	293	11067
herbaceous cover	ULU	1169	1170	1367	643	752	519	607	124	145	573	670	1.9	2.2	198	232	-9	-10	192	225
meadows & open grassland	ULU	1323	923	1221	638	844	499	660	139	184	351	464	0.4	0.6	129	171	-1	-1	130	172
natural lakes	ULU	3536	1600	5657	637	2251	509	1802	127	450	963	3406	2.5	8.7	343	1211	-77	-271	268	949
Flood plains & mudflats	ULU	0	1766	0	765	0	545	0	221	0	1001	0	0.0	0.0	404	0	52	0	456	0
bare soil permanent	ULU	2	1101	2	550	1	454	1	96	0	594	1	0.0	0.0	164	0	21	0	185	0
rainfed crops - cereals	MLU	1259	1435	1808	727	915	569	717	158	198	709	892	1.0	1.3	338	425	14	17	353	444
rainfed crops - other	MLU	91039	1467	133526	673	61294	531	48303	143	12991	793	72237	5.4	487.6	338	30766	-15	-1341	329	29913
mixed species agro-forestry	MLU	24803	1795	44517	834	20675	619	15345	215	5330	963	23885	7.8	194.1	382	9481	-82	-2026	308	7650
rainfed homesteads and gardens (urban cities) - outdoor	MLU	831	1489	1238	698	580	556	462	142	118	791	658	3.6	3.0	336	279	-33	-27	307	255
irrigated crops - cereals	MWU	756	1521	1151	752	569	569	430	183	138	770	582	0.2	0.1	380	287	73	55	453	342
irrigated crops - other	MWU	15903	1416	22527	673	10710	531	8451	142	2259	743	11818	3.4	54.7	293	4665	-8	-122	289	4599
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	919	1564	1438	581	534	447	411	134	123	983	904	1.2	1.1	476	438	-56	-51	422	388
irrigated homesteads and gardens (urban cities) - outdoor	MWU	446	1077	480	674	301	548	245	126	56	403	180	2.4	1.1	153	68	1	1	157	70
TOTAL			**1810**	**654232**	**837**	**302547**	**630**	**227749**	**207**	**74836**	**974**	**352203**	**6**	**2077**	**347**	**125441**	**-67**	**-24172**	**286**	**103357**

Table D-3: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Irrawaddy basin in 2007

2007 Irrawaddy	**WMC**	**AREA**	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharg}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	32335	2888	93370	940	30408	744	24049	197	6384	1948	62975	1.1	34.2	583	18864	-76	-2471	509	16473
protected shrubland	PLU	3911	3004	11748	961	3760	751	2936	211	824	2043	7989	2.8	10.8	637	2492	-116	-454	524	2049
protected natural grasslands	PLU	1076	1161	1249	588	632	462	497	125	134	575	618	0.0	0.0	103	111	-86	-93	17	18
protected natural waterbodies	PLU	347	2678	930	857	298	712	247	145	50	1821	632	0.0	0.0	586	204	-235	-81	352	122
glaciers	PLU	777	865	672	573	445	421	327	152	118	293	228	0.0	0.0	55	42	-60	-47	-6	-5
protected other	PLU	460	1354	622	634	291	507	233	127	58	722	332	0.0	0.0	141	65	-84	-39	56	26
closed deciduous forest	ULU	34519	1929	66590	868	29960	657	22672	211	7289	1061	36634	6.1	209.0	479	16543	-48	-1644	438	15109
closed evergreen forest	ULU	108391	2330	252510	915	99208	711	77037	205	22177	1415	153328	4.0	438.8	524	56750	-89	-9596	439	47603
shrub land & mesquite	ULU	37742	2260	85314	938	35403	712	26871	226	8533	1322	49912	6.7	253.2	529	19950	-55	-2091	480	18112
herbaceous cover	ULU	1169	1348	1576	644	753	523	611	121	141	711	831	1.3	1.5	252	294	-97	-113	157	183
meadows & open grassland	ULU	1323	1102	1457	632	836	490	649	141	187	474	627	0.3	0.4	151	199	-72	-95	80	106
natural lakes	ULU	3536	1764	6237	640	2264	530	1875	110	389	1123	3972	1.8	6.3	443	1568	-109	-384	337	1191
Flood plains & mudflats	ULU	0	1953	0	746	0	540	0	206	0	1207	0	0.0	0.0	480	0	-88	0	391	0
bare soil permanent	ULU	2	1157	2	560	1	475	1	85	0	598	1	0.0	0.0	213	0	-11	0	202	0
rainfed crops - cereals	MLU	1259	1688	2126	731	921	616	776	115	145	957	1205	0.5	0.7	448	565	-66	-83	383	483
rainfed crops - other	MLU	91039	1524	138782	669	60943	549	49980	120	10964	855	77839	3.7	337.9	371	33766	-61	-5583	313	28522
mixed species agro-forestry	MLU	24803	1952	48419	825	20465	644	15969	181	4497	1127	27961	5.0	125.1	481	11925	-77	-1901	409	10150
rainfed homesteads and gardens (urban cities) - outdoor	MLU	831	1618	1345	705	586	583	485	122	101	913	759	2.8	2.3	426	354	-100	-83	329	273
irrigated crops - cereals	MWU	756	1756	1328	741	560	605	458	135	102	1015	768	0.1	0.1	477	361	-30	-22	448	339
irrigated crops - other	MWU	15903	1489	23674	674	10717	548	8716	126	2001	815	12957	2.8	43.9	338	5370	-63	-995	278	4419
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	919	1539	1415	579	532	463	426	116	107	960	883	0.9	0.8	415	382	-49	-45	367	338
irrigated homesteads and gardens (urban cities) - outdoor	MWU	446	951	424	693	309	546	244	147	66	258	115	3.4	1.5	101	45	-48	-22	56	25
TOTAL			**2046**	**739791**	**828**	**299295**	**650**	**235057**	**178**	**64268**	**1219**	**440568**	**4**	**1466**	**470**	**169850**	**-71**	**-25841**	**403**	**145535**

Table D-4: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Irrawaddy basin in 2008

2008 Irrawaddy	**WMC**	**AREA**	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharg}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	32335	2537	82034	938	30339	738	23873	201	6484	1600	51739	0.8	24.5	530	17137	-181	-5839	351	11344
protected shrubland	PLU	3911	2624	10264	963	3767	745	2914	218	853	1661	6498	1.4	5.6	570	2230	-221	-866	350	1370
protected natural grasslands	PLU	1076	1052	1131	614	660	442	476	171	184	439	472	0.0	0.0	84	90	-41	-44	43	46
protected natural waterbodies	PLU	347	2393	831	857	298	682	237	175	61	1536	533	0.0	0.0	527	183	29	10	556	193
glaciers	PLU	777	777	604	608	472	398	309	209	163	171	133	0.0	0.0	37	29	9	7	45	35
protected other	PLU	460	1206	554	648	298	487	224	161	74	560	257	0.0	0.0	122	56	-45	-21	78	36
closed deciduous forest	ULU	34519	1750	60395	871	30074	609	21012	263	9063	878	30319	4.8	164.3	402	13861	-93	-3216	313	10811
closed evergreen forest	ULU	108391	2066	223947	920	99770	682	73899	239	25877	1146	124194	3.0	330.2	423	45878	-113	-12252	313	33963
shrub land & mesquite	ULU	37742	2089	78851	943	35609	678	25606	265	10004	1146	43243	4.9	184.1	452	17048	-124	-4668	333	12564
herbaceous cover	ULU	1169	1101	1287	648	757	495	578	153	179	455	532	0.7	0.8	174	203	-7	-8	168	196
meadows & open grassland	ULU	1323	922	1220	644	852	468	619	177	234	281	372	0.3	0.3	102	134	-2	-2	101	134
natural lakes	ULU	3536	1564	5531	631	2232	495	1750	136	481	933	3300	1.5	5.3	387	1368	-37	-130	351	1242
Flood plains & mudflats	ULU	0	1641	0	738	0	490	0	248	0	903	0	0.0	0.0	410	0	-169	0	241	0
bare soil permanent	ULU	2	904	2	552	1	428	1	124	0	352	1	0.0	0.0	140	0	2	0	142	0
rainfed crops - cereals	MLU	1259	1461	1840	751	946	575	724	176	222	710	894	0.9	1.1	343	432	-48	-60	296	372
rainfed crops - other	MLU	91039	1300	118385	666	60612	503	45788	163	14825	635	57773	4.0	363.1	297	27060	-1	-86	300	27338
mixed species agro-forestry	MLU	24803	1745	43269	830	20582	601	14912	229	5670	915	22688	4.3	106.1	394	9763	-93	-2301	305	7569
rainfed homesteads and gardens (urban cities) - outdoor	MLU	831	1412	1174	703	584	543	451	160	133	709	589	1.3	1.1	336	279	-44	-37	293	243
irrigated crops - cereals	MWU	756	1526	1154	767	580	559	423	208	157	759	574	0.1	0.1	379	287	-35	-26	344	260
irrigated crops - other	MWU	15903	1296	20615	672	10690	505	8039	167	2651	624	9924	2.3	37.2	275	4374	17	264	294	4675
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	919	1361	1251	563	517	419	385	144	132	799	734	0.8	0.7	384	353	36	33	421	387
irrigated homesteads and gardens (urban cities) - outdoor	MWU	446	734	327	660	295	477	213	183	82	73	33	0.7	0.3	35	16	80	36	115	51
TOTAL			**1811**	**654667**	**830**	**299935**	**615**	**222431**	**214**	**77528**	**981**	**354802**	**3**	**1225**	**389**	**140781**	**-81**	**-29207**	**312**	**112830**

Table D-5: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Irrawaddy basin in 2009

2009 Irrawaddy	WMC	AREA	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharg}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	32335	2397	77512	933	30157	728	23555	204	6602	1465	47357	0.9	30.4	474	15317	-339	-10964	136	4383
protected shrubland	PLU	3911	2476	9686	956	3739	734	2871	222	868	1520	5947	2.3	8.9	497	1943	-386	-1511	113	441
protected natural grasslands	PLU	1076	857	922	604	650	451	486	153	164	253	272	0.0	0.0	41	44	-41	-44	0	0
protected natural waterbodies	PLU	347	2180	757	848	294	684	238	164	57	1332	463	0.1	0.0	513	178	-158	-55	355	123
glaciers	PLU	777	609	473	589	458	397	309	192	149	20	16	0.0	0.0	7	6	-13	-10	-6	-5
protected other	PLU	460	1006	463	644	296	494	227	150	69	362	166	0.0	0.0	71	33	-51	-23	20	9
closed deciduous forest	ULU	34519	1539	53130	854	29496	611	21074	244	8422	685	23637	8.2	284.6	290	10025	-92	-3173	207	7137
closed evergreen forest	ULU	108391	1866	202209	915	99130	673	72912	242	26218	951	103103	4.5	487.8	338	36663	-171	-18563	171	18589
shrub land & mesquite	ULU	37742	1828	69006	938	35388	673	25386	265	10001	891	33619	7.1	268.3	389	14692	-180	-6803	216	8158
herbaceous cover	ULU	1169	992	1160	630	736	483	565	146	171	368	430	3.5	4.1	126	148	-9	-10	121	142
meadows & open grassland	ULU	1323	809	1071	623	824	455	602	168	222	192	253	0.8	1.0	71	94	-20	-26	53	70
natural lakes	ULU	3536	1396	4937	614	2171	485	1716	129	456	782	2765	3.5	12.3	323	1142	-87	-306	240	847
Flood plains & mudflats	ULU	0	1398	0	694	0	512	0	182	0	704	0	0.0	0.0	265	0	-170	0	95	0
bare soil permanent	ULU	2	862	2	507	1	400	1	106	0	356	1	2.3	0.0	135	0	48	0	186	0
rainfed crops - cereals	MLU	1259	1291	1626	711	896	578	728	133	168	580	730	1.3	1.6	266	335	-132	-166	136	171
rainfed crops - other	MLU	91039	1173	106756	631	57461	495	45025	137	12437	541	49295	5.1	460.6	225	20491	-16	-1446	214	19506
mixed species agro-forestry	MLU	24803	1557	38607	803	19921	598	14840	205	5081	754	18693	7.1	176.9	306	7600	-122	-3026	192	4751
rainfed homesteads and gardens (urban cities) - outdoor	MLU	831	1275	1059	671	557	533	443	138	115	604	502	3.0	2.5	281	234	-74	-61	211	175
irrigated crops - cereals	MWU	756	1322	1000	730	552	574	434	156	118	592	447	0.2	0.1	271	205	-137	-104	134	101
irrigated crops - other	MWU	15903	1149	18272	637	10124	497	7896	140	2227	512	8148	3.7	58.5	212	3374	-41	-650	175	2783
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	919	1136	1044	562	517	424	390	138	127	573	527	1.2	1.1	247	227	-8	-7	240	221
irrigated homesteads and gardens (urban cities) - outdoor	MWU	446	756	337	628	280	462	206	167	74	127	57	5.6	2.5	54	24	49	22	109	49
TOTAL			**1632**	**590027**	**812**	**293648**	**608**	**219903**	**204**	**73746**	**820**	**296429**	**5**	**1801**	**312**	**112776**	**-130**	**-46925**	**187**	**67653**

Table D-6: The precipitation, evaporation, groundwater storage and groundwater flows for each land use / land cover class in the Irrawaddy basin in 2010

2010 Irrawaddy	WMC	AREA	P	P	E	E	$Enat$	$Enat$	$Eincr$	$Eincr$	$P-E$	$P-E$	Q_{abs}^{GW}	Q_{abs}^{GW}	Q_{bf}	Q_{bf}	$\frac{\Delta S_3}{\Delta t}$	$\frac{\Delta S_3}{\Delta t}$	$Q_{recharg}^{GW}$	$Q_{recharge}^{GW}$
LAND USE		km2	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr	mm/yr	Mm3/yr
protected forests	PLU	32335	2963	95821	918	29672	725	23447	194	6270	2046	66160	1.5	49.4	644	20813	126	4077	774	25023
protected shrubland	PLU	3911	3099	12120	943	3688	727	2842	217	848	2156	8432	5.8	22.8	713	2790	88	344	807	3157
protected natural grasslands	PLU	1076	1220	1312	600	645	483	520	116	125	620	667	0.0	0.0	162	174	-12	-12	148	160
protected natural waterbodies	PLU	347	2846	988	854	296	703	244	151	52	1992	692	0.1	0.0	661	229	120	41	780	271
glaciers	PLU	777	989	768	593	460	447	347	146	113	396	307	0.0	0.0	108	84	-15	-12	91	71
protected other	PLU	460	1373	631	633	291	523	240	111	51	740	340	0.0	0.0	192	88	16	7	206	95
closed deciduous forest	ULU	34519	2060	71121	832	28719	603	20828	229	7891	1229	42407	12.8	442.8	530	18301	46	1594	589	20340
closed evergreen forest	ULU	108391	2410	261173	906	98210	684	74185	222	24038	1504	163015	7.2	785.3	571	61869	115	12437	693	75106
shrub land & mesquite	ULU	37742	2386	90045	925	34929	683	25788	242	9142	1460	55118	11.8	444.5	566	21360	108	4066	685	25871
herbaceous cover	ULU	1169	1403	1640	640	748	507	593	132	154	770	900	3.5	4.1	271	317	25	29	298	349
meadows & open grassland	ULU	1323	1214	1606	639	845	500	662	139	183	579	766	0.8	1.0	182	241	-17	-22	167	221
natural lakes	ULU	3536	1822	6443	616	2177	492	1739	124	437	1206	4266	4.6	16.2	462	1635	73	260	540	1911
Flood plains & mudflats	ULU	0	2072	0	597	0	460	0	138	0	1474	0	0.0	0.0	629	0	96	0	725	0
bare soil permanent	ULU	2	1165	2	528	1	422	1	106	0	637	1	1.8	0.0	192	0	-24	0	170	0
rainfed crops - cereals	MLU	1259	1886	2375	733	923	597	752	136	172	1153	1452	1.1	1.4	519	653	96	121	616	776
rainfed crops - other	MLU	91039	1596	145266	623	56761	485	44189	138	12572	972	88506	4.9	450.1	384	34992	23	2114	413	37557
mixed species agro-forestry	MLU	24803	2067	51262	788	19535	590	14636	198	4899	1280	31738	9.4	234.1	521	12921	43	1076	574	14231
rainfed homesteads and gardens (urban cities) - outdoor	MLU	831	1703	1415	678	564	538	447	140	116	1025	852	4.8	4.0	438	364	34	29	477	397
irrigated crops - cereals	MWU	756	1924	1455	741	561	579	438	162	123	1183	894	0.2	0.1	538	407	154	116	692	524
irrigated crops - other	MWU	15903	1556	24743	640	10186	493	7836	148	2350	915	14557	5.0	79.3	346	5503	64	1015	415	6598
managed water bodies (reservoirs, canals, harbors, tanks)	MWU	919	1577	1450	551	506	414	381	137	126	1026	943	1.4	1.3	432	397	-5	-4	429	394
irrigated homesteads and gardens (urban cities) - outdoor	MWU	446	961	429	640	286	471	210	169	76	320	143	10.0	4.4	97	43	66	29	173	77
TOTAL			**2135**	**772066**	**802**	**290004**	**609**	**220323**	**193**	**69739**	**1334**	**482158**	**7**	**2541**	**507**	**183185**	**76**	**27304**	**589**	**213128**