British
Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Malawi Hydrogeological and Water Quality Mapping: National Scale Recharge Estimation

Groundwater Directorate

Commissioned Report CR/15/061

BRITISH GEOLOGICAL SURVEY

GROUNDWATER Directorate
COMMISSIONED REPORT CR/15/061

Malawi Hydrogeological and Water Quality Mapping: National Scale Recharge Estimation

J. Scheidegger, A. Lafare, M.M. Mansour

Keywords

Groundwater, Malawi, Modelling, Recharge.

Front cover

Bibliographical reference

SCHEIDEGGER, J., LAFARE, A. MANSOUR, M.M.. 2015. Malawi National Scale Recharge Estimation. *British Geological Survey Commissioned Report*, CR/15/061. 79pp.

Keyworth, Nottingham British Geological Survey 2015

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Contents

FIGURES

TABLES

Executive Summary

A toolbox of different recharge values and a distributed recharge model have been applied to estimate the recharge values over Malawi. The toolbox is prepared within Microsoft Excel and coded using Visual Basics. The distributed recharge calculation is undertaken using the BGS ZOODRM model. The model uses gridded daily rainfall and potential evaporation data as well as gridded landuse, topography, soil, and river data to calculate recharge.

The distributed recharge model is calibrated by matching the simulated overland flows to the observed ones at selected gauging stations. However, difficulties were encountered during the calibration of the recharge model due to: (i) the resolution of the model grid being relatively coarse so that the topographical characteristics could not be fully captured, (ii) the number of runoff zones specified in the model not being enough to represent the characteristics of the study area, and (iii) there being a need to improve the representation of land cover in the model since the land cover affects the estimated recharge values.

The estimated recharge values presented in this study are highly affected by the quality of data used in the distributed recharge model. Comparing the recharge values estimated from the recharge model and averaged over the district areas to the recharge values calculated using the recharge toolbox, it was clear that the former agree with the values of at least one analytical method included in the toolbox. However, there was no consistency of agreement, i.e. the recharge values produced by the distributed model did not agree with one particular method. The sensitivity analysis results indicate that the recharge values are highly affected by the soil type parameter values specified in the model and by the definition of spatial distribution of land cover. To improve the accuracy of recharge calculations using the distributed recharge model, it is recommended that maps with a better representation of these features are included in the model. In addition, further model calibration runs are needed to improve the quality of the estimated recharge values. This can be only achieved by obtaining better field data.

1 Introduction

The British Geological Survey (BGS) was contracted by the Council for Geoscience (Pretoria, Republic of South Africa) to provide consultancy services for national hydrogeological and water quality mapping in Malawi. The contract includes three main tasks: the optimization of the groundwater monitoring network (Task 4.4), the development of analytical tools (Task 4.5), and training/capacity-building activities (Task 4.6). This report addresses some of the deliverables set out by Task 4.5: the development of analytical tools.

Task 4.5 includes the development of a modelling toolbox containing a collection of simple recharge and groundwater analytical solutions, as well as the building of a recharge model for the whole country, the undertaking of scenario runs to study potential impacts of extreme weather on the flow regime, and groundwater modelling in selected Water Resources Areas. This report only describes the development of the modelling toolbox and the development of the national scale recharge model. The other deliverables will be described in an updated version of this report.

The modelling toolbox includes 7 methods: (1) the Original Cumulated Rainfall Departure (CRD) (*Bredenkamp et al.*, 1995; *Xu and Beekman*, 2003), (2) the revised CRD (*Xu and Van Tonder*, 2001), (3) the mn CRD (*Bredenkamp et al.*, 1995; *Van Tonder and Xu*, 2000), (4) the Rainfall Infiltration Breakthrough (RIB)(*Sun et al.*, 2013; *Ahmadi et al.*, 2014), (5) the Saturated Volume Fluctuation (SVF) (*Bredenkamp et al.*, 1995; *Van Tonder and Xu*, 2000) adapted for individual boreholes, (6) the Park & Parker simple groundwater model (*Park and Parker*, 2008), and (7) the simplified Water Table Fluctuation method (WTF) (*Healy and Cook*, 2002). These methods use rainfall, groundwater levels, and abstraction data to establish a water balance from which the recharge rates can be calculated. In this exercise, the methods are applied over the administrative districts of Malawi, i.e. boreholes with acceptable length of groundwater level time series are grouped based on their locations and according to boundaries defined by the extent of the administrative districts. A single recharge value calculated from each method is then given to the relevant district and recharge maps are then produced. This provided the opportunity to compare the recharge values calculated from the different methods and later to compare these values to those calculated by the distributed recharge model.

Distributed recharge values were calculated using the BGS distributed recharge model ZOODRM (*Mansour and Hughes*, 2004).This model has been selected because it provides the possibility of using different recharge calculations spatially across the study area based on the environmental conditions of each part of the area. In addition, it has the flexibility to be easily updated with new recharge calculation methods if required. In this exercise, a variant of the FAO recharge calculation method is applied. This method includes the soil and plant characteristics but requires less parameterisation than the original FAO method. The model also includes information related to the topographical characteristics of the area, and time series of rainfall and potential evaporation data. It is run over a specified simulation period, for which the soil moisture, runoff and recharge values are calculated at every time step depending on the amount of rainfall and potential evapotranspiration at that time step. Time series of recharge values are produced at every node in the model, from which global long term average recharge values and monthly long term average recharge values are then obtained. Recharge values calculated over defined areas, in this case the administrative districts of Malawi, are compared to those calculated using the modelling toolbox described above.

Following this introduction, the second section of this report gives a brief overview of Malawi’s hydrology and hydrogeology. The third section describes the modelling toolbox and its application. The fourth section describes the application of the distributed recharge model. Finally, the last section compares the results obtained from these numerical tools and provides conclusions and recommendations for further work.

2 Malawi Overview

Malawi is a landlocked country in southern Africa which borders Zambia, Tanzania and Mozambique. Malawi has a population of 16.7 M and an area of around 118 500 km^2. The Great Rift Valley runs through Malawi from north to south. The terrain consists of distinct geographic areas, the plateau, upland, Rift Valley escarpment and Rift Valley plains. In the Rift Valley, there are several lakes, marshes and lagoons. Lake Malawi is the largest lake of Malawi, and the third largest in Africa, with a surface area of 28 760 km^2 (*Minister of Irrigation and Water Development*, 2012). Lake Malawi and the Shire River hydrological system represent the country's most important natural water resource system. African inland lakes contribute significantly to food security, livelihoods and national economies through direct exploitation of fisheries, water resources for irrigation and hydropower generation (*Kafumbata et al.*, 2014).

The major rivers are the Shire, the Bua, the Linthipe, the Songwe, the North Rukuru, the South Rukuru, the Dwangwa and the Ruo and have perennial flow, maintaining some base flow throughout the dry season. In contrast, smaller rivers show ephemeral flow (*Roche*, 2007; *Minister of Irrigation and Water Development*, 2012). Malawi has a mean annual rainfall of ~ 1100 mm, 90 % of which occurs during the rainy season from December to April. In addition to the high seasonal variability in rainfall, the annual variability in rainfall poses a large threat to the water availability. Annual recharge has previously been estimated to be 15 to 80 mm/year in weathered basement and 3 to 80 mm/year in alluvial aquifers , where recharge also occurs by seepage from the river beds (*Chipofya et al.*, 2012).

In Malawi, the main aquifers consist of weathered and crystalline basement rocks and alluvial deposits. In situ weathering of the crystalline basement has produced a layer of unconsolidated saprolite material, forming the weathered layer above the crystalline basement. The weathered basement aquifer is extensive, but low-yielding, with 1-2 l/s. Total dissolved solids are generally less than 1000 mg/l and typically around 350 mg/l (*Chavula*, 1998).

The alluvial aquifers are of fluvial and lacustrine origin and are found in the Lake Chilwa basin and along the Rift Ralley floor: Karonga Lake Shore, Salima - Nkhotakota Lake Shore, Upper Shire Valley and the Lower Shire Valley. The alluvial aquifers are high-yielding and spatially highly variable. The coarse deposits of buried river channels and littoral zones give the highest groundwater yields, with yields greater than 20 l/s. The Lake Chilwa Basin has a perched aquifer on the eastern side of the Rift Valley. The groundwater of the alluvial aquifers is more mineralised than that of the basement aquifer (*Chavula*, 1998).

In the Lower Shire Valley, the main aquifer units are weathered / fractured basement rocks, Karoo and Cretaceous sedimentary rocks, weathered basalts and unconsolidated alluvial deposits. In the alluvial deposits, the water table is usually at a depth of 3- 6 m. The aquifers are of limited lateral extent and lenticular in shape. However, there is leakage between the weathered bedrock at the valley sides and the water in the alluvium in the valley floor. Confined aquifers with upwards leakage can be found in the valley floor. Along fault zones, there are hot springs (*Monjerezi et al.*, 2012).

Robins et al. (2013) find that groundwater recharge does not meet the demands posed by abstraction on the weathered basement aquifer. Low flows due to generally low hydraulic gradients put pressure on abstraction sources which essentially pump from storage until their capture zone eventually receives episodic direct rainfall recharge. Therefore, in the short to medium term, recharge will fail to match the demand from abstractions. The authors find that the weathered basement rock aquifer is only just coping with this demand, whereas the fractured basement aquifer is slightly more resilient (*Robins et al.*, 2013).

The degradation of catchment areas due to deforestation and poor agricultural practices have resulted in soil erosion and sedimentation and siltation problems (*Roche*, 2007). *Palamuleni et al.* (2011) find that between 1989 and 2002 there was a landuse change from woodland to mostly cultivated/grazing and built up areas in the Upper Shire river catchment. This landuse change was suggested to impact on river flows in the catchment, causing shorter travel times and higher flow peaks. Higher surface runoff erodes fertile soils and increases the vulnerability to droughts. In addition, higher surface runoff is suggested to result in less groundwater infiltration and in a reduction in the base flow contribution to river flows. As the water in the Shire River is almost completely used for hydroelectric power stations, irrigation, and domestic usage, periods of drought will result in of conflicts of interest amongst its user stakeholders.

Similarly, in the Rivirivi River basin, the annual stream flow has changed and the number of zero flow days has increased between the periods of 1963-1983 and 1984-2004. Changes in stream flow are characterised by an increase in the high flows and a decrease in low flows. This change in stream flow characteristics also coincides with deforestation; faster surface runoff increases the storm flows and decreases infiltration and the base flow contribution to river flow (*Chimtengo et al.*, 2014).

Many urban areas depend on perennial rivers in which the discharge is sustained by base flow during the dry season. For example the Lilongwe River provides water for Lilongwe city and Zomba district is served by the Mulunguzi River (*Ngongondo*, 2006). Annual rainfall variations have resulted in critical water shortages. For example, the droughts of 1992 and 1994 were triggered by a reduction in rainfall of 40% and 30%, resulting in the complete drying up of the Mulunguzi reservoir in Zomba. *Ngongondo* (2006) find that the general trend in rainfall and base flow in the Mulunguzi catchment shows a decline from 1954 to 1998. However, the base flow decline is higher than the decline in of the rainfall.

The quality of the surface water resource has deteriorated due to inappropriate landuse practices, usage of heavy agrochemical and disposal of domestic and industrial waste. In contrast, the quality of groundwater is generally good. However, sporadically there are saline groundwater intrusions (*Chipofya et al.*, 2012).

In 2007, groundwater was exploited by 30 000 boreholes and 8 000 shallow wells. Generally, the groundwater quality is acceptable for drinking water (*Roche*, 2007). However, it has been estimated that 65% of the population has access to potable water; the remaining 35% access water from unprotected sources resulting in high prevalence of water born or water related diseases (*Chipofya et al.*, 2012).The World Bank states that the water resources of Malawi are considered satisfactory, but the water availability per capita is declining rapidly due to population growth, and Malawi might experience water stress after 2025 (*Roche*, 2007).

3 Numerical Modelling for National Hydrogeological and Water Quality mapping in Malawi: Analytical methods for recharge estimation

3.1 INTRODUCTION

The first task concerning the modelling part of the Consultancy Services for National Hydrogeological and Water Quality Mapping, Malawi, includes the development of a modelling toolbox made of simplified analytical solutions for the calculation of recharge. The modelling toolbox is written in Visual Basic for Applications (VBA) and implemented in an Excel spreadsheet, as described below. The implemented methods will be applied and compared to each other in an attempt to determine the potential recharge values. This exercise will also inform the development of the more complex distributed recharge calculation model.

The toolbox includes 7 methods: (1) Original Cumulated Rainfall Departure (CRD) (*Bredenkamp et al.*, 1995; *Xu and Beekman*, 2003), (2) the Revised CRD (*Xu and Van Tonder*, 2001), (3) the mn CRD (*Bredenkamp et al.*, 1995; *Van Tonder and Xu*, 2000), (4) the Rainfall Infiltration Breakthrough (RIB) (Sun et al., 2013; Ahmadi et al., 2014), (5) the Saturated Volume Fluctuation (SVF) (*Van Tonder and Xu*, 2000) adapted for individual boreholes, (6) the Park & Parker simple groundwater model *Park and Parker* (2008), (7) and the simplified Water Table Fluctuation method (WTF) recently added to replace the SVF that couldn’t be used with the current Malawi data.

The toolbox is built as an Excel 2007 spreadsheet, using (VBA) code. It contains 7 sheets: 1 for the data, 6 for the different methods. The screenshot provided in Figure 1 displays part of the VBA code written to apply the RIB method, and a part of the resulting automated sheet. The user has to prepare the data sheet (copy the available time series of rainfall, groundwater level, abstraction, etc. using the provided template) and then launch each method using the provided ActiveX control button (‘Run RIB’ in this example). Depending on the method, some parameters have to be chosen before each run (a short user manual has been written to explain the use of each method). The other parameters are automatically optimized.

The methods were first tested on UK data. The methods are then applied to the Malawi groundwater level time series at selected groundwater water boreholes. However, the implemented methods use rainfall data as well as other discharge data, such as evaporation and pumping data. The availability of time series of these data is of paramount importance for completing this task.

3.2 ANALYTICAL METHODS FOR RECHARGE ESTIMATION BASED ON THE RELATIONSHIP BETWEEN RAINFALL AND GROUNDWATER LEVEL FLUCTUATIONS

A number of methods were investigated and tested on the basis of a literature review. The main theoretical basis underlying the selected methods are described in the following.

3.2.1 The Cumulated Rainfall Departure (CRD) method

The CRD method is based on the principle that equilibrium conditions develop in an aquifer over time (*Bredenkamp et al.*, 1995) implying that, despite large annual variations in precipitation, an equilibrium is established between the average annual precipitation and the hydrological response. Similarly, the vegetation type and density have been adapted to the prevailing climate and rainfall characteristics. The *CRD* for time step *i* is calculated using the following equation:

$$CRD_i = \sum_{n=1}^{i} R_n - \kappa \sum_{n=1}^{i} R_{av} \tag{1}$$

where *R* is the rainfall amount with subscripts *i* indicating the i-th month, *av* the average, and parameter $\kappa=1+(Q_p+Q_{out})/(AR_{av})$, where Q_p [m^3/month] is abstraction in production boreholes, Q_{out} [m^3/month] is the natural outflow, *A* [m^2] the aquifer area and R_{av} is the average rainfall. K=1 indicates that pumping does not occur and κ>1 that pumping and/or natural outflow takes place. The CRD has a linear relationship with the water level fluctuation (difference between the observed water level at the i^{th} time step and the mean water level for the whole time series):

$$\Delta h_i = (r/Sy)(CRD_i) - (Q_{p\_i} + Q_{out\_i})/AS \tag{2}$$

where *r* is a percentage of the *CRD* which results in recharge from rainfall, *S* is the specific yield and *A* is the area of the catchment. The *CRD* method has for example been used for the quantification of groundwater recharge in South Africa (*Bredenkamp et al.*, 1995; *Xu and Beekman*, 2003) and in the Gaza Strip, Palestine (*Baalousha*, 2005).

3.2.2 The revised Cumulated Rainfall Departure (rCRD) method

The methodology is similar to the previous one, with a revised version of the *CRD* equation:

$$CRD_i = \sum_{n=1}^{i} R_n - \left(2 - \frac{1}{R_{av} i} \sum_{n=1}^{i} R_n\right) \sum_{n=1}^{i} R_t \tag{3}$$

This version was developed to represent a trend in the rainfall time series data (*Xu and Van Tonder*, 2001). R_t is a threshold value representing the aquifer boundary conditions and is determined during the simulation process. It may range from 0 to R_{av} with 0 indicating an aquifer that is closed and R_{av} implying that the aquifer system is open, perhaps being regulated by outflow.

$$\Delta h_i = \left(\frac{r}{S}\right)(CRD_i) - (Q_{p\_i} + Q_{out\_i})/AS \tag{4}$$

Equation 4 is used to simulate the groundwater level fluctuations, with the second term only being necessary if a pumping well is present within the study area.

3.2.3 The mn Cumulated Rainfall Departure (mnCRD) method

The mnCRD is a more complex CRD method which takes long term and short term effect of the rainfall on the groundwater level fluctuations:

$$ {}_{n}^{m}CRD_i = \frac{1}{m}\sum_{j=i-(m-1)}^{i} R_j - \kappa\frac{1}{n}\sum_{j=i-(n-1)}^{i} R_j + CRD_{i-1} \tag{5} $$

where *m* is the number of months denoting the short memory carry-over (1 month to 12 months) and *n* is the number of months for which the long-term reference rainfall is calculated (6 months to 10 years preceding a specific month). Using ${}_{n}^{m}CRD$ gives generally a higher correlation coefficient than using the long-term average rainfall over the entire period (*Bredenkamp et al.*, 1995; *Xu and Van Tonder*, 2001). The groundwater level fluctuations are reproduced using a similar method as the previously described *CRD*-based methods.

3.2.4 The Rainfall Infiltration Breakthrough (RIB) method

The *RIB* method is based on the *CRD* method and is proven to be a simple but promising tool for groundwater recharge estimation, however, the physical meaning of some of the parameters is unknown (*Sun et al.*, 2013; *Ahmadi et al.*, 2014).

The *RIB* method assumes that the arrival time of rainfall at the water table is delayed by the spreading of moisture in the unsaturated zone. The duration of the recharge event is prolonged with increasing thickness of the unsaturated zone, and the breakthrough water is not necessarily from a single rainfall event, but from a series of events. The time lag is defined as the time taken by the percolating rainfall to reach the water table and can be distinguished as (i) rapid response within hours or days of intense rainfall, generally occurring via preferential flow paths, (ii) intermediate response over months to a year or two, and (iii) slow response over several years, usually occurring as piston flow through porous matrix characterised by a low hydraulic conductivity (*Sun et al.*, 2013). Therefore, the *RIB* method uses a filter or transfer function to accommodate the delayed transfer of moisture through the unsaturated zone to the water table. The *RIB* is a lumped-parameter method and does not address parameter variations in space. It is defined as:

$$ RIB(i)_m^n = r\left(\sum_{i=m}^{n} R_i - \left(2 - \frac{\sum_{i=m}^{n} R_i}{R_{av}(n-m)}\right)\sum_{i=m}^{n} R_t\right) $$

$$ \begin{gathered} i=1,2,3,\ldots I \\ n=\mathrm{i}, i-1, i-2,\ldots N \\ m=i, i-1, i-2,\ldots M \\ M<N<I \end{gathered} \tag{6} $$

where *r* is the fraction of the *CRD* which contributes to the *RIB* (recharge percentage), R_{av} is the average rainfall over the entire rainfall time series, R_t is a threshold value (similar to R_t in the rCRD method,see Section3.2.2), *i* is the sequential number of rainfall record, *m* and *n* represent the start and the end of the period for which rainfall contributes to the breakthrough. Different time lag scenarios can be considered: the *RIB* can be a result of all previous rainfall events, rainfall from the previous *n* rainfall events, or be limited to rainfall events between *m* and *n*.

The groundwater level fluctuations are estimated using the RIB with the equation:

$$ \Delta h_i = \left(\frac{1}{S}\right)(RIB_i)_m^n - (Q_{p_i} + Q_{out_i} + Q_{oth_i})/AS \tag{7} $$

Generally, the *RIB* is a powerful tool for estimating the r/S ratio in shallow aquifers where rainfall is directly responsible for water level fluctuations.

The recharge can be estimated by using the optimised r/S ratio and an estimation of the storativity, or by calculating the difference between contiguous departures:

$$Re(i) = RIB(i)_m^n - RIB(i-1)_{m'}^{n'} - \frac{\Delta Q}{A} \tag{8}$$

The groundwater level will rise if the difference between RIBs is positive and fall if the difference is negative

3.2.5 The Saturated Volume Fluctuation method (SVF)

The Saturated Volume Fluctuation (*SVF*) or Equal Volume (E*V*) method analyses the water budget by lumping the abstraction (output) and integrating the change in aquifer storage through analysing the resultant response in the saturated volume of the aquifer over a period of time (*Bredenkamp et al.,* 1995; *Van Tonder and Xu,* 2000):

$$R + I - O - Q = S\,\Delta V/\Delta t \tag{9}$$

where R [m^3/month] is the recharge, I [m^3/month] is the inflow into the aquifer, O [m^3/month] is the outflow from the aquifer, Q [m^3/month] is the withdrawal from the aquifer, S is the specific yield and ΔV [m^3/month] is the change in saturated volume. The following simplifications are made:

- The base of the system is regarded as impervious, thus no losses or inflows via the base is considered.
- If evaporation losses are incorporated, they have to be added to Q. If not, the estimated recharge is the effective percolation to the groundwater.

A modified Hill/SVF-Hill method exist:

$$R + I - O - Q = S\,\Delta V = SAdh \tag{10}$$

Rearranging Equation 10 gives:

$$\Delta V = -\frac{Q}{S} + \frac{R}{S} \tag{11}$$

where ΔV is determined by Q, R, and S. Generally, it is not possible to differentiate between the change in R or S, unless one of the parameters is known. S can be estimated by plotting Q vs dV or R-Q vs dV, then the slope of the trend line corresponds to S. When the aquifer storativity is eliminated from the water balance equation, the average recharge can be estimated with the equal volume, or the saturated volume fluctuation method For equal volume, $\Delta V=0$ and, the recharge is equal to the abstraction, as the right hand side falls away and inflow = outflow.

In general, the *SVF* gives an integrated signal of the water-level response of an aquifer by determining the average annual recharge as well as the annual variability of recharge and by deriving S from the linear plot of *SVF* vs Q or by R-Q vs *SVF*.

The method has been implemented in the spreadsheet and tested with UK data. However, more data would be needed for Malawi, in particular data related to the outputs (abstraction, baseflow, etc.).

3.2.6 The Park and Parker simple groundwater fluctuation model

Park and Parker (2008) developed a semi-analytical model to predict water table fluctuations in response to precipitation. The water fluctuation model is based on discrete records of precipitation, such as daily or monthly precipitation data, and is solved semi analytically:

$$\hbar^{\mathrm{i}+1} = \hbar^{\mathrm{i}} \exp(k\Delta \mathrm{t_i}) + \frac{\alpha P_i(\exp(k\Delta \mathrm{t_i}) - 1)}{kn} \qquad (12)$$

$$H^{\mathrm{i}+1} = \hbar^{\mathrm{i}} + H_{\mathrm{min}}$$

where $\hbar^{\mathrm{i}}$ is the hydraulic head or discharge head at time i, P_i is precipitation, α is the proportion of recharge from precipitation, and *k* [m-1] is a rate coefficient, specified as

$$k = -\frac{Ki\,\Delta h}{n\bar{h}\,\Delta x} = \frac{I - O}{n\bar{h}\,L} \qquad (13)$$

Where K [m s^{-1}] is the hydraulic conductivity, n [-] the fillable porosity, $\bar{h} = \frac{h1+h2}{2}$ the arithmetic mean hydraulic head in the domain, $i = \frac{h1+h2}{L}$ the hydraulic gradient. Recharge, *R*, is approximated as a fixed fraction, α, of precipitation, *P*, *R*= α*P*.

This model was applied to the Hongcheon area of South Korea by *Park and Parker* (2008). The model was calibrated for H_{min}, h_0, *k* and α/n using daily water levels for one year. The model was then validated using water levels for three years. The model parameters were found to be stable over a time of three years and it was concluded that reliable predictions can be made by the model from actual or projected precipitation data following calibration for a limited time-series. The model has the following assumptions and limitations: Firstly, no external sources or sinks other than uniformly distributed recharge is considered. Therefore, if there is spatially variable recharge or if groundwater pumping occurs resulting in a significantly spatially variable hydraulic gradient, the model may not effectively predict the groundwater fluctuations. Secondly, a negligible time-lag between precipitation and water arriving to the water table is assumed. Thirdly, the model accuracy may be limited by a deep unsaturated zone or by a short calibration period. Fourthly, a uniform minimum water level is assumed.

3.2.7 The simplified Water Table Fluctuation (*WTF*) method

As the *SVF* couldn't be used with the currently available Malawi hydrological data, a simplified Water Table Fluctuation method was implemented in the spreadsheet. The fluctuations of groundwater levels over time are often used to estimate recharge (*Healy and Cook*, 2002). The *WTF* method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. The recharge is therefore calculated as:

$$R = \frac{Sy\,dh}{dt} = \frac{Sy\,\Delta h}{\Delta t} \qquad (14)$$

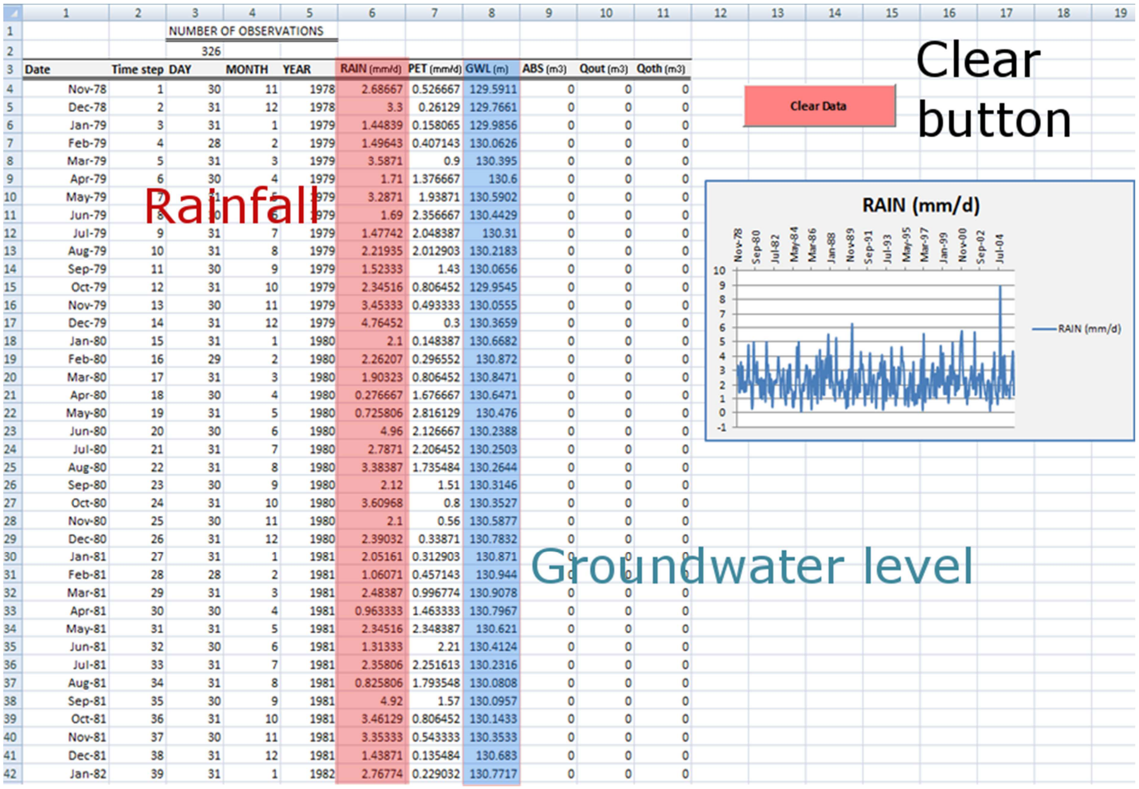
where *Sy* is the specific yield, *h* is the water table height, and *t* is the time. It is assumed that water arriving at the water table goes immediately into storage.

3.3 IMPLEMENTATION OF THE AFOREMENTIONED METHODS IN AN AUTOMATED EXCEL SPREADSHEET AND APPLICATION TO MALAWI DATA

3.3.1 Overview of the development of the analytical toolbox spreadsheet.

This section provides a brief overview of how to use the analytical toolbox spreadsheet. More details on the development of this spreadsheet and directions and advices on its use for groundwater recharge estimation can be found in Lafare (2015). The spreadsheet was initially developed using Microsoft Excel 2007 and later was successfully tested using Excel 2010 and 2013. The automation of the calculations was realised using Visual Basic for Application (VBA) code. The seven methods described in Section 3.2 were implemented.

The spreadsheet is divided into eight different worksheets. The first worksheet (also named 'Data', see Figure 1) contains the data needed for the application of the different analytical methods, i.e. the rainfall and groundwater level time series. This worksheet is the first sheet to be populated by the user with the observed data. It has a pre-defined structure as shown in Figure 1, and the data are automatically transferred from this to the other worksheets. As a good practice, the user must hit the "Clear Data" button first to clear all data that have been left from previous use of this tool. New observed data can then be copied into the emptied cells. Time series with monthly and weekly time steps have successfully been tested for use in this toolbox.



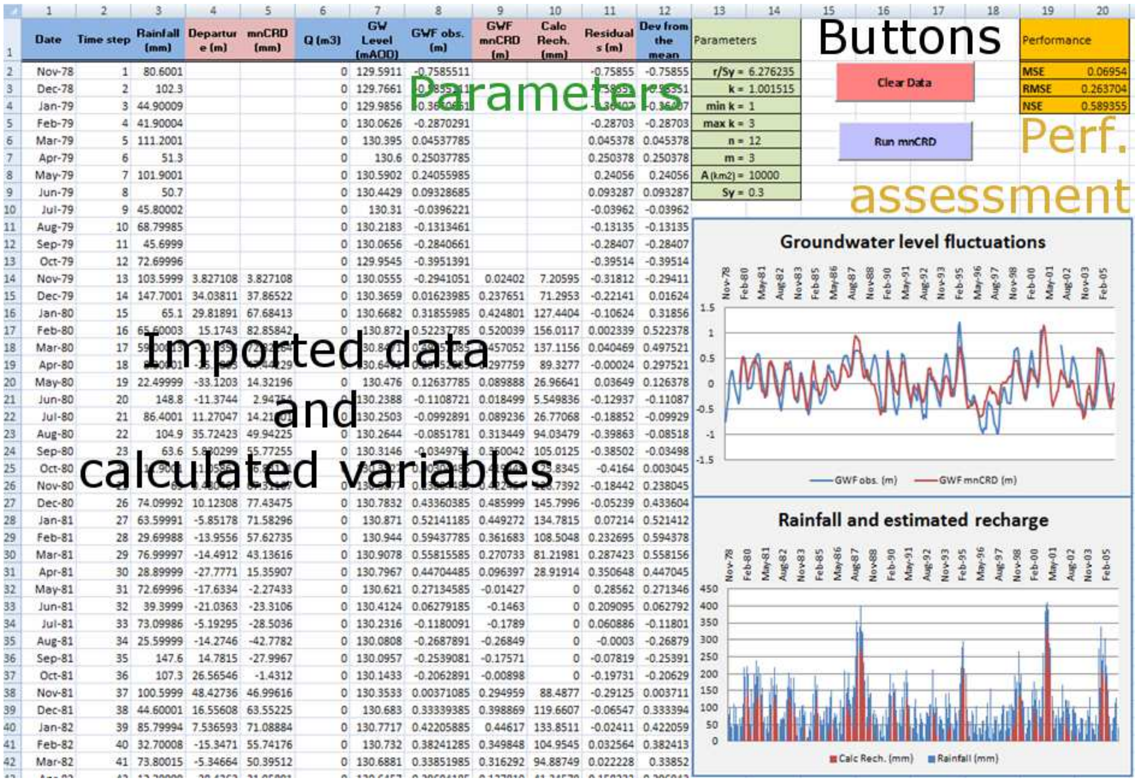
	1	2	3	4	5	6	7	8	9	10	11
1			NUMBER OF OBSERVATIONS								
2			326								
3	Date	Time step	DAY	MONTH	YEAR	RAIN (mm/d)	PET (mm/d)	GWL (m)	ABS (m3)	Qout (m3)	Qoth (m3)
4	Nov-78	1	30	11	1978	2.68667	0.526667	129.5911	0	0	0
5	Dec-78	2	31	12	1978	3.3	0.26129	129.7661	0	0	0
6	Jan-79	3	31	1	1979	1.44839	0.158065	129.9856	0	0	0
7	Feb-79	4	28	2	1979	1.49643	0.407143	130.0626	0	0	0
8	Mar-79	5	31	3	1979	3.5871	0.9	130.395	0	0	0
9	Apr-79	6	30	4	1979	1.71	1.376667	130.6	0	0	0
10	May-79	7	31	5	1979	3.2871	1.93871	130.5902	0	0	0
11	Jun-79	8	30	6	1979	1.69	2.356667	130.4429	0	0	0
12	Jul-79	9	31	7	1979	1.47742	2.048387	130.31	0	0	0
13	Aug-79	10	31	8	1979	2.21935	2.012903	130.2183	0	0	0
14	Sep-79	11	30	9	1979	1.52333	1.43	130.0656	0	0	0
15	Oct-79	12	31	10	1979	2.34516	0.806452	129.9545	0	0	0
16	Nov-79	13	30	11	1979	3.45333	0.493333	130.0555	0	0	0
17	Dec-79	14	31	12	1979	4.76452	0.3	130.3659	0	0	0
18	Jan-80	15	31	1	1980	2.1	0.148387	130.6682	0	0	0
19	Feb-80	16	29	2	1980	2.26207	0.296552	130.872	0	0	0
20	Mar-80	17	31	3	1980	1.90323	0.806452	130.8471	0	0	0
21	Apr-80	18	30	4	1980	0.276667	1.676667	130.6471	0	0	0
22	May-80	19	31	5	1980	0.725806	2.816129	130.476	0	0	0
23	Jun-80	20	30	6	1980	4.96	2.126667	130.2388	0	0	0
24	Jul-80	21	31	7	1980	2.7871	2.206452	130.2503	0	0	0
25	Aug-80	22	31	8	1980	3.38387	1.735484	130.2644	0	0	0
26	Sep-80	23	30	9	1980	2.12	1.51	130.3146	0	0	0
27	Oct-80	24	31	10	1980	3.60968	0.8	130.3527	0	0	0
28	Nov-80	25	30	11	1980	2.1	0.56	130.5877	0	0	0
29	Dec-80	26	31	12	1980	2.39032	0.33871	130.7832	0	0	0
30	Jan-81	27	31	1	1981	2.05161	0.312903	130.871	0	0	0
31	Feb-81	28	28	2	1981	1.06071	0.457143	130.944	0	0	0
32	Mar-81	29	31	3	1981	2.48387	0.996774	130.9078	0	0	0
33	Apr-81	30	30	4	1981	0.963333	1.463333	130.7967	0	0	0
34	May-81	31	31	5	1981	2.34516	2.348387	130.621	0	0	0
35	Jun-81	32	30	6	1981	1.31333	2.21	130.4124	0	0	0
36	Jul-81	33	31	7	1981	2.35806	2.251613	130.2316	0	0	0
37	Aug-81	34	31	8	1981	0.825806	1.793548	130.0808	0	0	0
38	Sep-81	35	30	9	1981	4.92	1.57	130.0957	0	0	0
39	Oct-81	36	31	10	1981	3.46129	0.806452	130.1433	0	0	0
40	Nov-81	37	30	11	1981	3.35333	0.543333	130.3533	0	0	0
41	Dec-81	38	31	12	1981	1.43871	0.135484	130.683	0	0	0
42	Jan-82	39	31	1	1982	2.76774	0.229032	130.7717	0	0	0

Figure 1 Screenshot representing the structure of the 'Data' worksheet

The seven remaining worksheets are dedicated to the different analytical methods and are all based on a similar structure (see an example in Figure 2). The 'Run' command launches the following automated process:

- Import the rainfall, groundwater level and flow data (when available) from the Data worksheet
- Calculate the observed groundwater fluctuations (GWF), and calculate the statistics required by the different methods.
- Perform mathematical calculations using the initial set of parameters.
- Assess the calculation performance (the Mean Squared Error (MSE), Root Mean Squared Error (RMSE) and Nash Sutcliffe Efficiency (NSE)) of the simulated GWF compared to the observed GWF.
- Optimise the parameters using the Microsoft Excel solver, aiming to minimize the RMSE.
- Calculate the estimated recharge using the optimised parameters and an estimation of the specific yield (Sy) if specified by the user.
- Plot the generated groundwater level time series against the observed ones, and compare the estimated recharge against the observed rainfall.

The user can test different initial sets of parameters and, after the calculation, export the produced groundwater recharge time series.



	1	2	3	4	5	6	7	8	9	10	11	12
1	Date	Time step	Rainfall (mm)	Departure (m)	mnCRD (mm)	Q (m3)	GW Level (mAOD)	GWF obs. (m)	GWF mnCRD (m)	Calc Rech. (mm)	Residuals (m)	Dev from the mean
2	Nov-78	1	80.6001			0	129.5911	-0.7585511			-0.75855	-0.75855
3	Dec-78	2	102.3			0	129.7661	[illegible]			[illegible]	-0.58551
4	Jan-79	3	44.90009			0	129.9856	[illegible]			[illegible]	-0.36407
5	Feb-79	4	41.90004			0	130.0626	-0.2870291			-0.28703	-0.28703
6	Mar-79	5	111.2001			0	130.395	0.04537785			0.045378	0.045378
7	Apr-79	6	51.3			0	130.6	0.25037785			0.250378	0.250378
8	May-79	7	101.9001			0	130.5902	0.24055985			0.24056	0.24056
9	Jun-79	8	50.7			0	130.4429	0.09328685			0.093287	0.093287
10	Jul-79	9	45.80002			0	130.31	-0.0396221			-0.03962	-0.03962
11	Aug-79	10	68.79985			0	130.2183	-0.1313461			-0.13135	-0.13135
12	Sep-79	11	45.6999			0	130.0656	-0.2840661			-0.28407	-0.28407
13	Oct-79	12	72.69996			0	129.9545	-0.3951391			-0.39514	-0.39514
14	Nov-79	13	103.5999	3.827108	3.827108	0	130.0555	-0.2941051	0.02402	7.20595	-0.31812	-0.29411
15	Dec-79	14	147.7001	34.03811	37.86522	0	130.3659	0.01623985	0.237651	71.2953	-0.22141	0.01624
16	Jan-80	15	65.1	29.81891	67.68413	0	130.6682	0.31855985	0.424801	127.4404	-0.10624	0.31856
17	Feb-80	16	65.60003	15.1743	82.85842	0	130.872	0.52237785	0.520039	156.0117	0.002339	0.522378
18	Mar-80	17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.457052	137.1156	0.040469	0.497521
19	Apr-80	18	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.297759	89.3277	-0.00024	0.297521
20	May-80	19	22.49999	-33.1203	14.32196	0	130.476	0.12637785	0.089888	26.96641	0.03649	0.126378
21	Jun-80	20	148.8	-11.3744	[illegible]	[illegible]	130.2388	-0.1108721	0.018499	5.549836	-0.12937	-0.11087
22	Jul-80	21	86.4001	11.27047	[illegible]	0	130.2503	-0.0992891	0.089236	26.77068	-0.18852	-0.09929
23	Aug-80	22	104.9	35.72423	49.94225	0	130.2644	-0.0851781	0.313449	94.03479	-0.39863	-0.08518
24	Sep-80	23	63.6	[illegible]	55.77255	0	130.3146	[illegible]	[illegible]	105.0125	-0.38502	-0.03498
25	Oct-80	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.4164	0.003045
26	Nov-80	[illegible]	[illegible]	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	[illegible]	-0.18442	0.238045
27	Dec-80	26	74.09992	10.12308	77.43475	0	130.7832	0.43360385	0.485999	145.7996	-0.05239	0.433604
28	Jan-81	27	63.59991	-5.85178	71.58296	0	130.871	0.52141185	0.449272	134.7815	0.07214	0.521412
29	Feb-81	28	29.69988	-13.9556	57.62735	0	130.944	0.59437785	0.361683	108.5048	0.232695	0.594378
30	Mar-81	29	76.99997	-14.4912	43.13616	0	130.9078	0.55815585	0.270733	81.21981	0.287423	0.558156
31	Apr-81	30	28.89999	-27.7771	15.35907	0	130.7967	0.44704485	0.096397	28.91914	0.350648	0.447045
32	May-81	31	72.69996	-17.6334	-2.27433	0	130.621	0.27134585	-0.01427	0	0.28562	0.271346
33	Jun-81	32	39.3999	-21.0363	-23.3106	0	130.4124	0.06279185	-0.1463	0	0.209095	0.062792
34	Jul-81	33	73.09986	-5.19295	-28.5036	0	130.2316	-0.1180091	-0.1789	0	0.060886	-0.11801
35	Aug-81	34	25.59999	-14.2746	-42.7782	0	130.0808	-0.2687891	-0.26849	0	-0.0003	-0.26879
36	Sep-81	35	147.6	14.7815	-27.9967	0	130.0957	-0.2539081	-0.17571	0	-0.07819	-0.25391
37	Oct-81	36	107.3	26.56546	-1.4312	0	130.1433	-0.2062891	-0.00898	0	-0.19731	-0.20629
38	Nov-81	37	100.5999	48.42736	46.99616	0	130.3533	0.00371085	0.294959	88.4877	-0.29125	0.003711
39	Dec-81	38	44.60001	16.55608	63.55225	0	130.683	0.33339385	0.398869	119.6607	-0.06547	0.333394
40	Jan-82	39	85.79994	7.536593	71.08884	0	130.7717	0.42205885	0.44617	133.8511	-0.02411	0.422059
41	Feb-82	40	32.70008	-15.3471	55.74176	0	130.732	0.38241285	0.349848	104.9545	0.032564	0.382413
42	Mar-82	41	73.80015	-5.34664	50.39512	0	130.6881	0.33851985	0.316292	94.88749	0.022228	0.33852

Parameters
r/Sy = 6.276235
k = 1.001515
min k = 1
max k = 3
n = 12
m = 3
A (km2) = 10000
Sy = 0.3

Performance	
MSE	0.06954
RMSE	0.263704
NSE	0.589355

Figure 2. Screenshot showing an example of a method worksheet (RIB method here)

3.3.2 Application of the toolbox to the Malawi groundwater level data

The spreadsheet was used to generate groundwater recharge estimations for each administrative district in Malawi. The delineation and the names of these districts are presented in Figure 3 along with the locations of the observation boreholes from which the groundwater level time series data were obtained. There are between 0 and 4 boreholes in each district (see Table 1). When no borehole is available, the groundwater level time series from the nearest observation borehole is used. When there is more than one borehole in a district, the groundwater level time series characterised by the longer time period and the higher frequency is used.

Rainfall and evaporation data were obtained as distributed grids (TRMM dataset for the rainfall (NASA (a)), MODIS dataset for the evaporation (NASA (b)) and processed with GIS methods in order to produce time series of rainfall and evaporation for each district in Malawi.

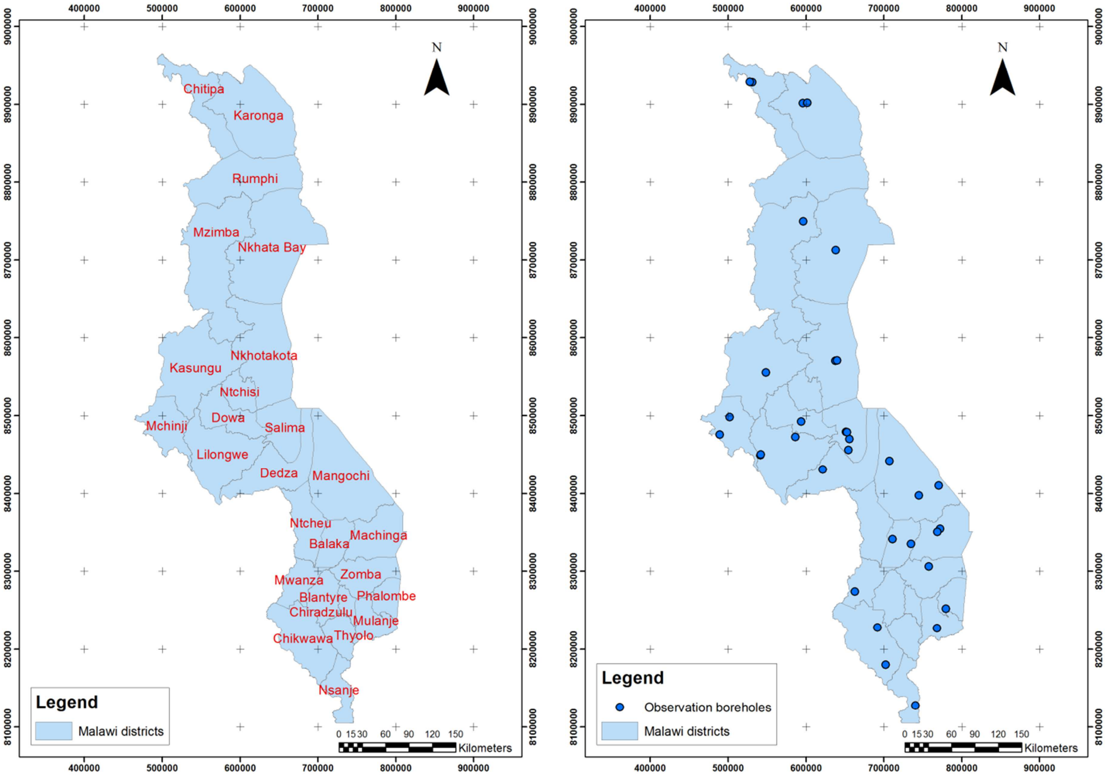


Figure 3. Administrative districts (MASDAP, http://www.masdap.mw/) and observation boreholes locations in Malawi

Table 1. Boreholes identification numbers in each district

District	**Borehole 1**	**Borehole 2**	**Borehole 3**	**Borehole 4**
Balaka	DM136	GN165		
Blantyre				
Chikwawa	DM138	GN166		
Chiradzulu				
Chitipa	GN174	GN175		
Dedza	GN176			
Dowa	GN201			
Karonga	GN168	GN169		
Kasungu	GN177			
Lilongwe	GN171	GN199	TS15	
Machinga	GN204	GN205		
Mangochi	DM134	DM135	GN203	
Mchinji	GN196	GN200		
Mulanje	DM148			
Mwanza	DM152			
Mzimba	GN167			
Nkhata Bay	GN173			
Nkhotakota	GN216			
Nsanje	DM149			
Ntcheu				
Ntchisi				
Phalombe	DM158			
Rumphi				
Salima	GN164	GN202	GN214	GN215
Thyolo				
Zomba	DM147			

Most of the analytical recharge methods implemented in the spreadsheet need an estimation of the specific yield (S_y) in order to output the recharge time series. As these data do not exist for the different boreholes, specific yield values were estimated from the literature, the borehole construction data and a simplified hydrogeological map (Figure 4). Three main aquifers are identified in Malawi, these are; the Weathered Basement (WB) aquifer, the Fractured Basement (FB) aquifer, and the Quaternary Alluvium (QA) aquifer. According to several studies available for Africa, a low specific yield (0.02-0.03) is likely for the FB, and higher for the WB (0.05-0.1) (Robins, Davies, and Farr 2013). The area covered by the three main aquifers in each district was calculated using GIS, and the information provided for some borehole in the construction data were used to determine approximate ranges of specific yield for each district.

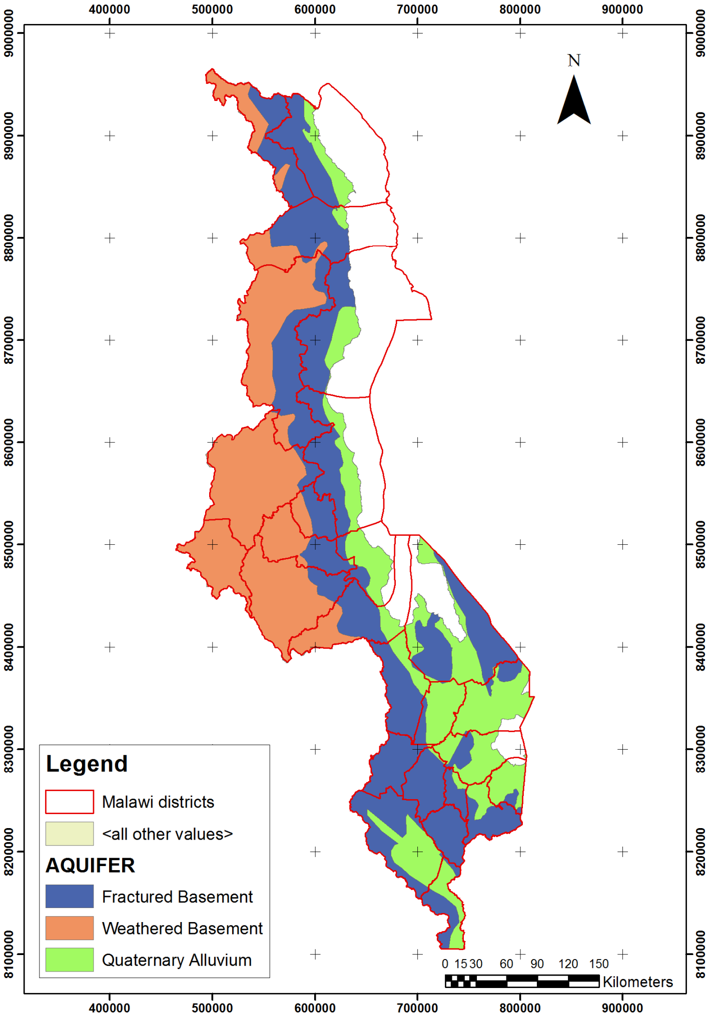


Figure 4. Simplified hydrogeological map of Malawi along with the different administrative districts (MASDAP, http://www.masdap.mw/)

The rainfall, evaporation and groundwater level time series are produced as two datasets for each district in Malawi: one with a monthly time-step and the other with a weekly time-step. The rainfall and evaporation data are produced for the period spanning from 2006 to 2014, while the groundwater level time series are only available from 2009. The period between 2006 and 2009 is, therefore, used to initiate the system. Weekly rainfall and evaporation time series were also produced because the groundwater level records are sparse for some boreholes and a higher frequency data set is needed to obtain results. These datasets were used to build two toolbox spreadsheets (weekly and monthly) for each of the 26 districts (52 spreadsheets in total).

The seven different methods were then applied; involving a variable number of trials with various initial parameters sets in order to obtain an acceptable fit between observed and calculated groundwater fluctuations, and a reasonable groundwater recharge time series. An example of a calculated time series is provided for the Balaka district in Figure 5. It can be observed that the resulting groundwater level fluctuations and recharge estimates reflect the theoretical differences between the analytical methods.

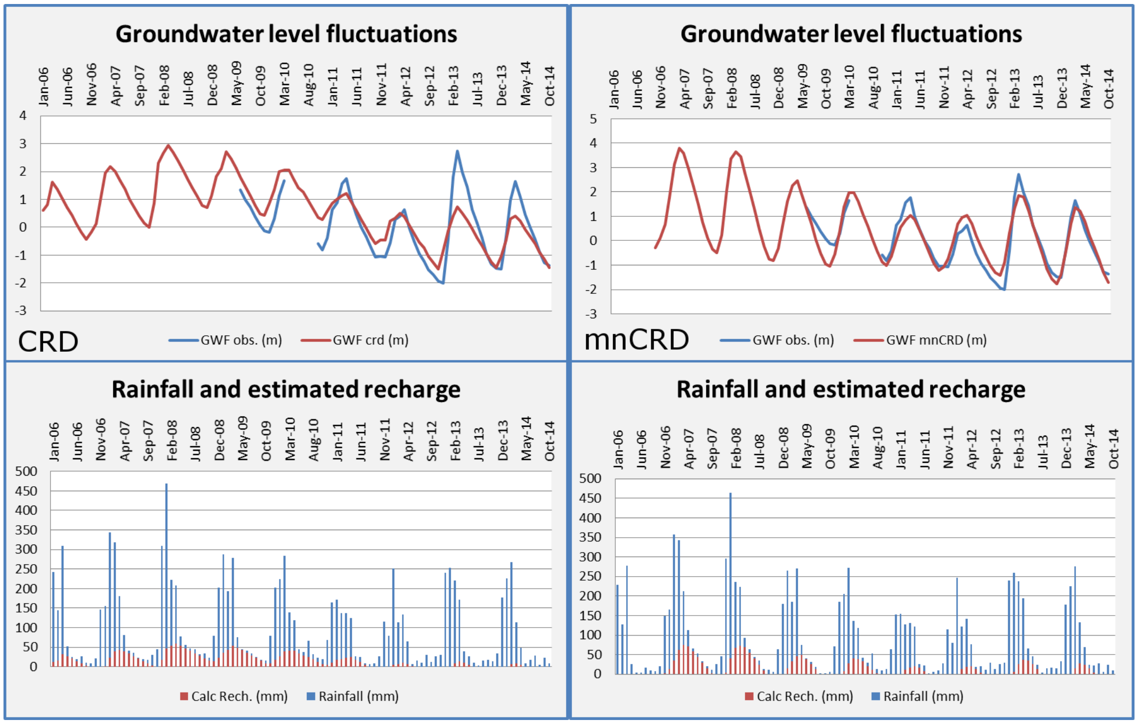


Figure 5. Example of the resulting time series for the CRD (left) and the mnCRD (right) methods (monthly time series, recharge and rainfall in mm/month) for the Balaka district

3.4 RECHARGE ESTIMATION RESULTS FOR MALAWI'S ADMINISTRATIVE DISTRICTS

After the preparation and calibration of each spreadsheet, the estimated monthly and weekly groundwater recharge time series were extracted, tabulated and finally processed to produce long term average recharge values.

Table 2 and the maps shown in Figure 6 show the long term (LTA) average recharge values estimated for each method and each district, calculated over the period from 2009 to 2014. The LTA recharge calculated over the whole of the country is approximately 120 mm/y (0.33 mm/day). The minimum LTA recharge is approximately 40 mm/y (0.11 mm/day) calculated over the Mangochi district and the maximum LTA recharge is 265 mm/y (0.73) calculated over the Machinga district. LTA recharge values calculated for each month of the year (Jan-Dec) are given in Appendix A. Tables A1 – 12 and Table 2 include the average recharge value for each method and an average value over all the methods along with the standard deviation. A colour code is added to each table, ranging from red, representing the lowest recharge value in the column, to green, representing the highest.

Table 2 shows that, in general, a reasonably good agreement can be observed between values obtained by each method for the different districts. For example Chitipa (North) and Mangochi (Middle East) consistently display low recharge values (no more than 50 mm/y). Balaka, Chikwawa and Machinga (all situated in southern Malawi) are generally characterised by higher recharge values, approaching or exceeding 200 mm/y, even if outlier lower values can be found e.g. with the Park and Parker method in the Chikwawa district. However, some methods perform poorly in certain areas. For example, for the Phalombe district (South East) the match between observed and modelled groundwater fluctuations is very poor for the CRD and the rCRD methods. Therefore, the particularly low recharge values obtained cannot be considered as reliable.

Figure 6 also shows consistency between the spatial distributions of recharge values produced by the different methods. For example, all methods show that the long term average recharge is higher in the southern half of the country than in the northern half of the country. In addition, all methods, except for the Park and Parker method, produce higher recharge estimates in the southwest region (Chikwawa district) compared to the rest of the districts in the southern part of the country.

The monthly averages display a lower consistency between the different methods. Indeed, the recharge calculations are different and therefore can lead to various time lags between the rainfall event and the recharge occurrence (from a nearly negligible time lag for the Park and Parker method to potentially important ones for the mnCRD and the RIB methods). In general, the lower recharge period occurs from August to November, and the higher recharge period from February to May.

Table 2. LTA estimated annual recharge for the period from 2009 to 2014. The colour represent, for each column, the relative value of the recharge from low (red) to high (green)

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	265.2	265.2	239.7	194.3	194.7	118.0	212.8	56.4
Blantyre	302.5	302.5	78.3	202.2	44.0	84.8	169.1	116.3
Chikwawa	409.7	409.7	194.3	367.7	70.4	136.6	264.7	149.5
Chiradzulu	201.0	201.0	86.7	80.8	87.5	92.1	124.9	59.1
Chitipa	42.5	42.5	47.6	45.0	21.5	52.4	41.9	10.7
Dedza	67.0	67.0	178.2	121.5	77.7	63.2	95.8	45.8
Dowa	72.4	72.4	76.6	76.8	35.9	107.1	73.5	22.6
Karonga	95.3	95.3	85.8	86.4	88.8	68.9	86.8	9.7
Kasungu	155.4	155.4	140.2	116.6	31.5	42.1	106.9	56.2
Lilongwe	68.9	68.9	93.8	56.6	38.5	57.8	64.1	18.3
Machinga	330.8	330.8	181.4	399.1	153.0	194.5	265.0	101.1
Mangochi	45.8	45.8	50.5	33.9	36.9	24.1	39.5	9.8
Mchinji	172.4	172.4	207.4	206.6	135.9	202.3	182.8	28.2
Mulanje	212.1	212.1	90.3	84.1	32.6	101.3	122.1	73.6
Mwanza	280.6	280.6	124.3	111.2	97.1	73.5	161.2	94.0
Mzimba	90.3	90.3	74.2	175.2	12.9	32.1	79.2	56.8
Nkhata Bay	69.8	69.8	39.7	101.8	77.9	107.1	77.7	24.5
Nkhotakota	55.4	113.8	68.7	60.5	70.0	53.0	70.2	22.4
Nsanje	64.1	64.1	70.8	141.7	48.2	47.1	72.7	35.1
Ntcheu	181.2	181.2	135.7	127.0	129.3	75.3	138.3	39.7
Ntchisi	67.8	67.8	70.8	69.1	28.8	98.9	67.2	22.4
Phalombe	8.0	15.8	65.8	73.7	60.0	98.2	74.4	16.8
Rumphi	75.5	75.5	97.7	97.9	35.4	23.9	67.7	31.3
Salima	262.0	313.7	217.2	188.6	94.8	177.5	209.0	75.3
Thyolo	299.9	299.9	100.4	183.5	91.8	94.0	178.3	100.3
Zomba	77.0	77.0	80.0	69.5	82.2	132.1	86.3	22.9

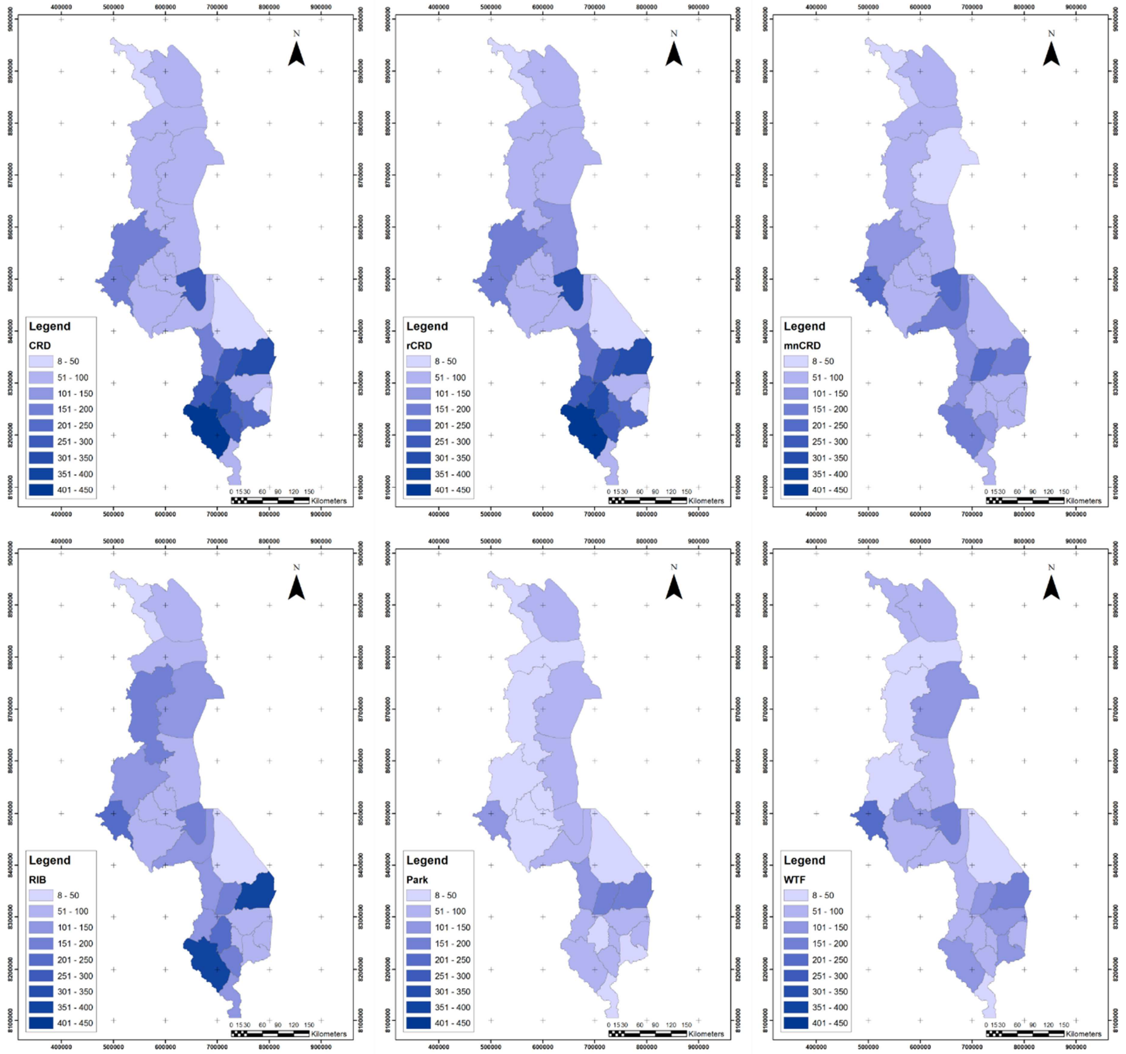


Figure 6. Average annual groundwater recharge (mm/y) for the period from 2009 to 2014. District layers, courtesy of (MASDAP, http://www.masdap.mw/)

4 Distributed recharge calculation

The distributed recharge model ZOODRM (*Mansour and Hughes*, 2004) is used to calculate the potential recharge for Malawi. ZOODRM belongs to the ZOOM suite of object oriented models (*Jackson and Spink*, 2004) developed at BGS. ZOODRM calculates distributed potential recharge values using rainfall and potential evaporation data, runoff routing derived from topography, vegetation and soil characteristics.

4.1 THE RECHARGE ALGORITHM

The recharge algorithm applied in this work is the simplified Food and Agriculture Organisation (FAO) method. The soil moisture is calculated from the maximum root depth (*Zr*), the moisture depletion factor (*dp*), and the soil field capacity (Θ_{FC}). The total available water (*TAW*) for plants to evapo-transpire is defined as a function of the maximum root depth, and the soil field capacity minus the soil moisture content at wilting point (Θ_{WP}):

$$TAW = Z_r\left(\Theta_{FC} - \Theta_{WP}\right) \tag{15}$$

The readily available water (RAW) is defined as the total available water multiplied by the depletion factor:

$$RAW = dp \times TAW \tag{16}$$

The soil storage is the difference between the total available water and the readily available water:

$$Soil\ storage = TAW - SMD \tag{17}$$

Firstly, an intermediate soil moisture deficit (*SMD’*) is calculated as a function of the soil moisture deficit at the previous time step (t-1), the potential evaporation (PE) and the rainfall (*Rf*).

$$SMD' = SMD_{t-1} + PE - Rf \tag{18}$$

The actual evapotranspiration (*AE*) will take place depending of the level of the intermediate soil moisture deficit (*SMD’*) and its relation to the calculated *TAW* and *RAW* values. The following equations give the relationship between *TAW*, *RAW*, S*MD’* and *AE*:

$$\begin{aligned} AE &= PE\left[\frac{TAW - SMD'}{TAW - RAW}\right]^{0.2} && \text{when SMD' > RAW} \\ AE &= PE && \text{when RAW < SMD' < TAW} \\ AE &= 0 && \text{when SMD' >TAW.} \end{aligned} \tag{19}$$

The soil moisture deficit at the end of the time step is then calculated from:

$$SMD = SMD' + AE - PE \tag{20}$$

If the soil moisture deficit calculated from Equation 20 is negative it means that there more rainfall water than is required for plants to evapo-transpire and to fill in the soil store. This excess water is divided into two parts using a runoff coefficient the value of which is always less than unity. The first part which is the excess water multiplied by the runoff coefficient value forms the overland flow which is routed downstream to rivers. The second part which the remainder from the excess water will percolate downward and forms the potential recharge.

4.2 MODEL APPLICATION

The area over which recharge is calculated is bound by the geographic boundaries of Malawi, excluding Lake Malawi (Figure 7). The study area was discretised using a grid with 2000 m square cells. This cell size was selected to offer acceptable accuracy for the calculation of recharge values at national scale while maintaining reasonable overall model run time. While the cell size is too large to capture small details within a cell, the level of representation of some features can be increased within the model. For example, the model allows the representation of more than one landuse type in each cell if the data are available. This is achieved by specifying a value for the percentage of landuse type at each node and repeating the calculation of recharge for each landuse type specified at the node for every time step. The calculated evapo-transpiration, runoff, soil moisture and recharge values are then scaled according to the percentage of the landuse type. The data that are required by the recharge model are: a Digital Elevation Model, a soil map, a land cover map, a rainfall time series and an evaporation time series.

4.2.1 Digital Elevation Model

The topography of the study area is defined by a Digital Elevation Model (DEM) which is obtained from the Shuttle Radar Topography Mission (SRTM) (http://srtm.csi.cgiar.org/). The topographical information is used to route any overland flow to streams. The cell size of the SRTM DEM is close to 90 m (Figure 8). Because the cell size of the recharge model is larger than the cell size of the gridded topographical map, the recharge model ZOODRM calculates an average elevation for every node in the model using the ground elevations of the DEM cells contained within the numerical node. An aspect direction is then derived for each node based on the maximum topographical gradient calculated between the node and its surrounding nodes. This is calculated along the eight directions. In addition to the naturally occurring topographical depressions, the upscaling of topographical information often introduces spurious sinks. The recharge model allows user intervention to correct the aspect directions in order to remove these false sinks.

Numerical rivers are defined in the model using GIS shape files. The recharge model calculates the total overland flow at every node representing the river for every time step. To do so, the river branches need to be defined and the river nodes need to be numbered. An application developed at BGS is used for this purpose. The river polylines are first converted into points in GIS. These points are then imported into this application where they are numbered and connected together to create the rivers. The application produces text files describing the links between the different points. These text files are processed when the numerical grid is created to produce a mathematical representation of the rivers and then the numerical rivers. The mathematical representation is produced to allow for grid refinement, if required. The recharge model allows the increase of grid resolution of parts of the study area, if necessary. This requires that the resolution of the numerical rivers matches the spatial resolution of the grid. The numerical rivers are presented in Figure 9.

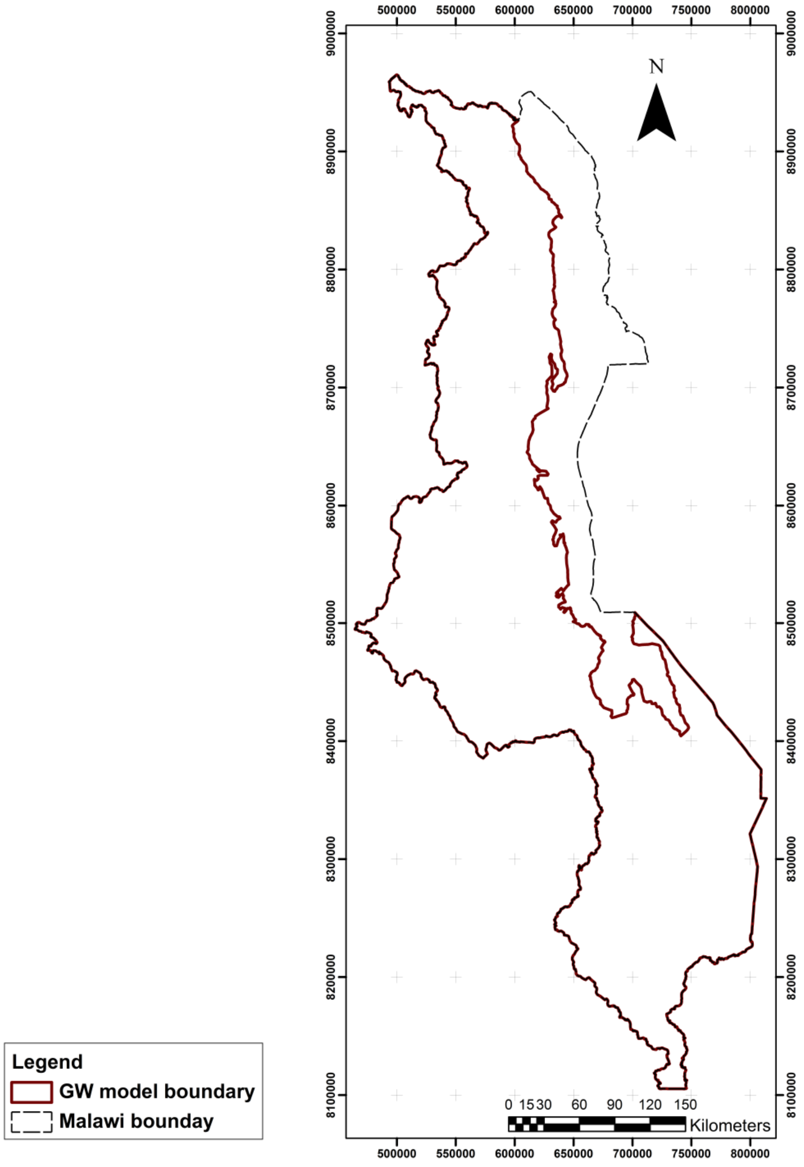


Figure 7. Geographical boundary of Malawi (MASDAP, http://www.masdap.mw/) and groundwater model boundary.

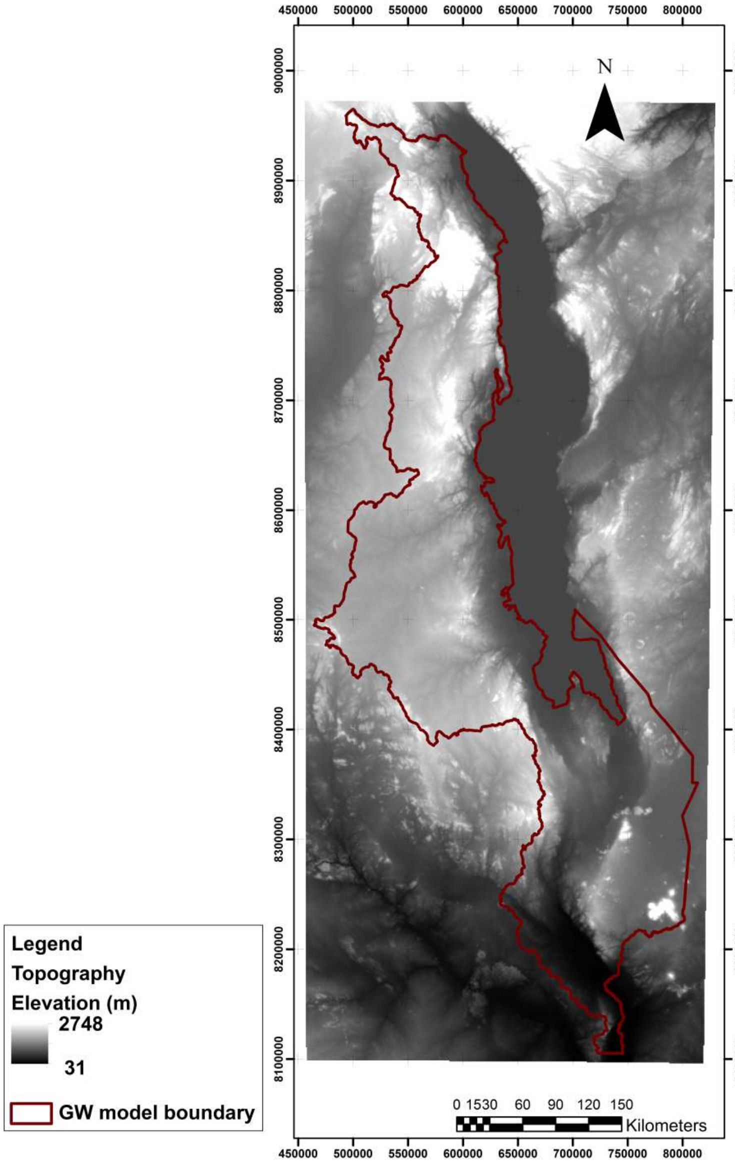


Figure 8. Digital Elevation model and groundwater model boundary. (http://www.diva-gis.org)

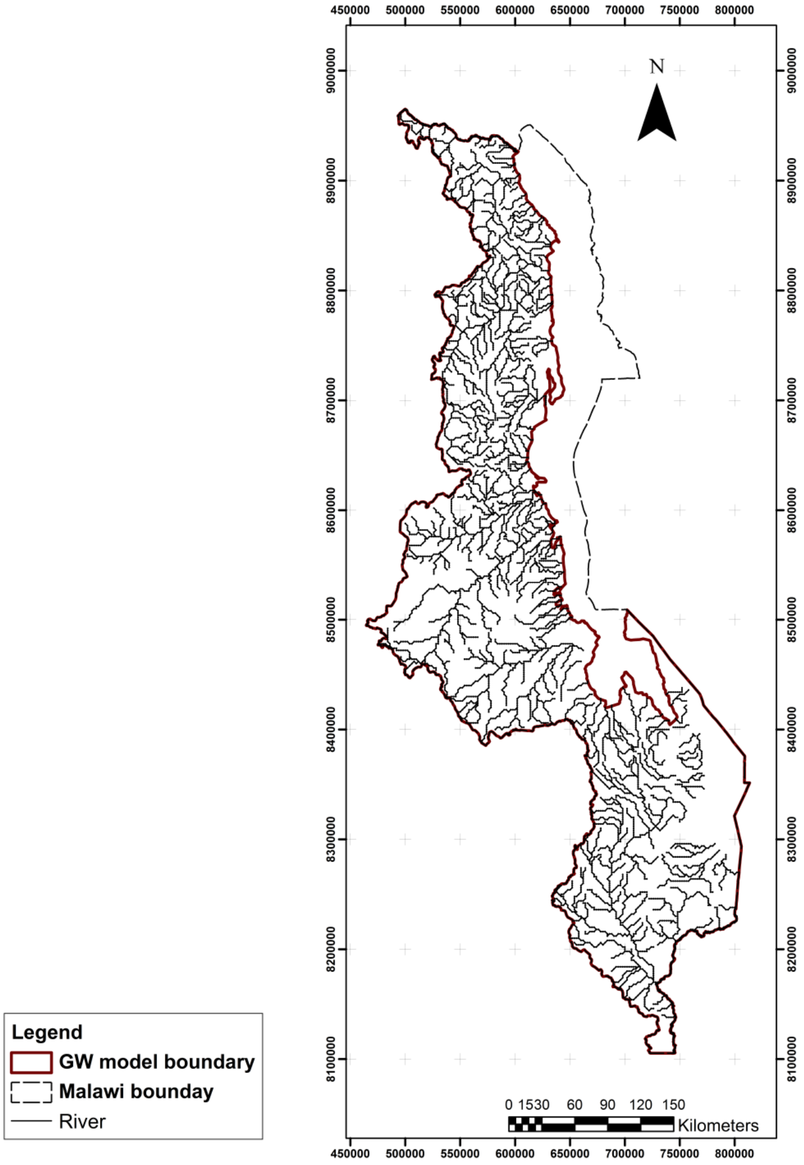


Figure 9. Numerical Rivers. (http://www.diva-gis.org)

4.2.2 Landuse data

Soil and Land cover are obtained from the Malawi Spatial Data Portal (MASDAP, http://www.masdap.mw/). Landuse is classified in 15 classes as shown in Figure 10. For each landuse classification, a root depth and a depletion factor are defined.

Natural forest is mainly Miombo woodland (http://www.fao.org/docrep/004/ab585e/AB585E04.htm). "Agriculture in forest area" is extensive agriculture (20-70% cultivated land), within forested areas, often smallholdings. Dambo are areas along natural drainage patterns in flat and undulating areas. "Dambos" can be considered as riverbeds of intermittent rivers, prone to flooding during wet seasons and therefore uninhabited. The ground cover is grass, often used for grazing. Soil and moisture conditions make parts of the dambos favourable for cultivation in many cases. The main economic products of Malawi are tobacco, tea, cotton, groundnuts, sugar and coffee, and the main food crops are maize, cassava, sweet potatoes, sorghum, bananas, rice, and Irish potatoes. However, the types of the crop cultivated within the agricultural zones shown in Figure 10 are not explicitly defined. It was not possible, therefore, to define the parameter values of these crop types accurately in the model. To overcome this problem, the characteristics of the different landuse types shown in Table 3 are used. The maximum and minimum values are altered in the different model runs, in order to obtain a suitable estimates of the root depth for the recharge calculation.

Table 3. Root depth and depletion factors for different landuse classifications. After (*Allen et al.*)

Type	Class	Root depth min (m)	Root depth max (m)	Crop
Forest	1	2	5	Miombo root depth, depletion conifer tree
Agriculture in forest area	2	0.3	1	Maize
Dambo area / Agriculture	3, 14	0.3 1	1 1.5	Maize Sudan grass
Water	13	3	3	
Agriculture/Settlement	4	0.3	1	Maize
Plantation and Agriculture	5	0.25	0.8	Tobacco
Grass	6	1	1.5	Sudan grass
Built up	7	0.9	0.9	
Agriculture in mainly grass area	8	1	2	Sorghum grain
Bare land	9	0.001	0.001	
Forest plantation	10	2	5 1-1.5	Eucalyptus Conifer trees
Shrub	11	0.6	1.2	Berries (bushes)
Unclassified	12	0.7	0.7	

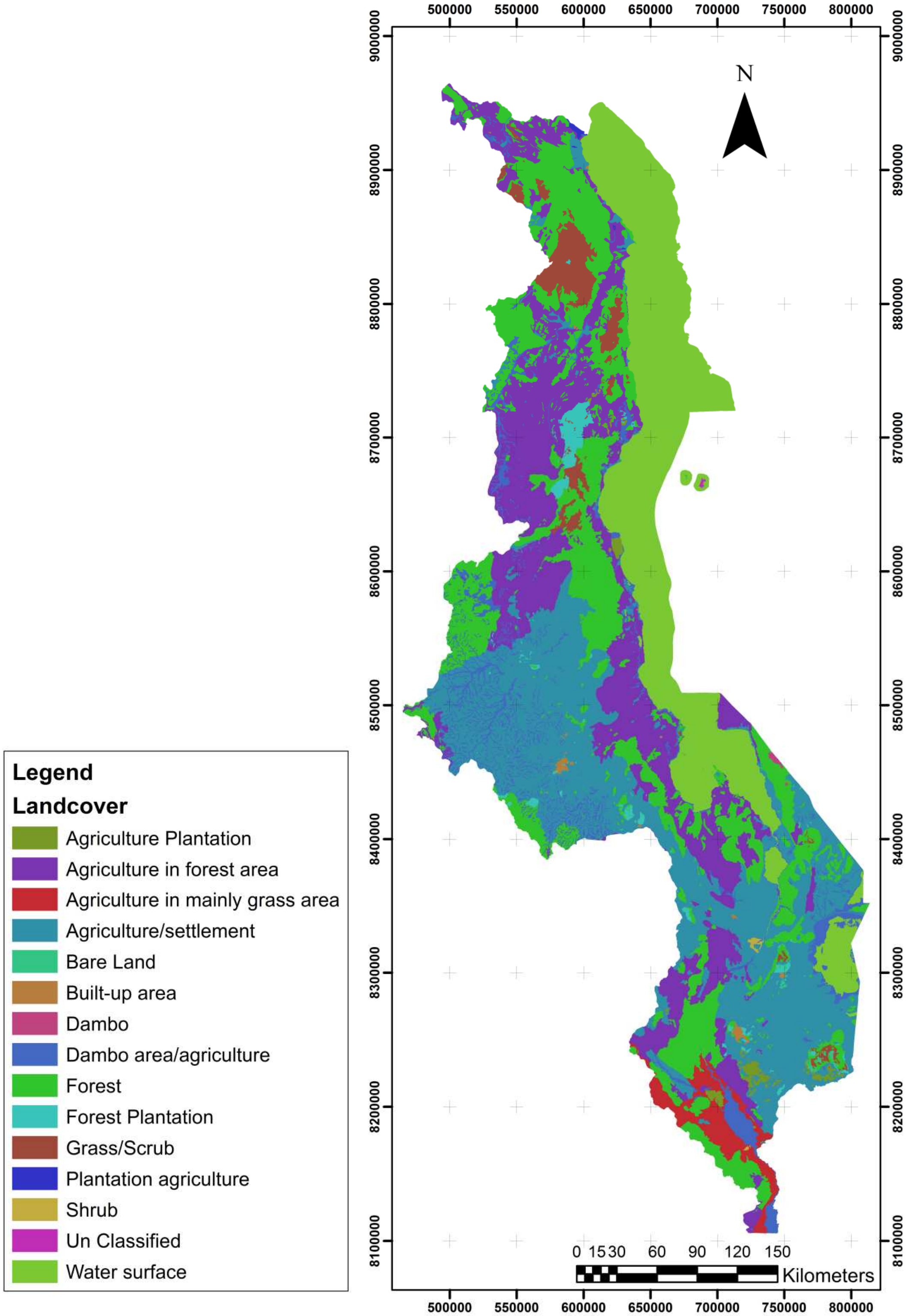


Figure 10. Land cover classification. (MASDAP, http://www.masdap.mw/)

4.2.3 Soil data

The spatial definition of soil type is also required by the model to calculate volumes of the total available water and the readily available water within the soil. The parameters involved include the water contents at field capacity and at wilting point. Unfortunately, we could not find estimates of these parameters for the Malawi soils within the metadata associated with the different soil classes that were available to us. These metadata, however, provided one value for the available water content of 150 mm/m for all soil types. The available water capacity, or available water content (AWC), is the range of available water that can be stored in soil and be available for growing crops. This concept assumes that the water which is readily available to plants is the difference between the water content at field capacity (θ_{FC}) and the permanent wilting point(θ_{WP}):

$$AWC = \Theta_{FC} - \Theta_{WP} \quad (21)$$

Other applications involving soil in Eastern Europe give values of AWC ranging between 140 mm/m and 190 mm/m (http://eusoils.jrc.ec.europa.eu/ESDB_Archive/raster_archive/sgdbe_display_attributes.html#). For the initial run, the water contents at field capacity (θ_{FC}) and the permanent wilting point (θ_{WP}) are set in the model to give an AWC value of 170 mm/m. These values were varied in subsequent runs to investigate their impact on the estimated recharge values.

4.2.4 Runoff coefficient zone map

The applied recharge calculation method splits the excess water, calculated after accounting for evapo-transpiration and filling the soil store, into recharge and surface water. The separation of excess water is done using runoff coefficient values that are defined over different zones within the study area. It is anticipated that the runoff coefficient values vary from one location to another within the study area depending on soil texture, landuse, topographical gradient and rainfall intensity. In this application, the runoff classification is derived using information related to slope, soil erosion and soil drainage. The next part of this section describes the steps followed to obtain the runoff classification which is also illustrated in Figure 11.

In the first step, using the soil database and topographical information, the possible values for topographical slope, soil drainage and soil erosion are grouped into classes to which a rank is assigned (Figure 12 and Figure 13). Since the runoff coefficient values are not equally influenced by slope, drainage, and erosion. Different weights were assigned to these parameters. For example, slope was given a weight of 2, soil drainage a weight of 3 and soil erosion a weight of 1 indicating that soil drainage is possibly the highest parameter influencing the calculated runoff coefficient values. This weight is multiplied by the rank of each class and divided by the number of classes. The last step involved the classification of the resulting map into 5 runoff classes (Figure 11).

In order to calculate initial runoff coefficient values for each of the 5 runoff classes shown in Figure 12, the following approach was used: First, a number of river gauging stations were selected. Because the recorded river flow is a total flow and we are interested in the overland component of this flow only, a baseflow separation calculation was applied to the river flow time series recorded at these gauging stations. The outcomes of this calculation were two time series, one representing the overland flow (the fast surface water flow component) and the other representing the baseflow (the slow interflow or groundwater flow component) of the river flow. A baseflow index (BFI) can be defined as the ratio of the average baseflow to the average total river flow. For a given catchment the base flow index (BFI) can be approximated using the following equation:

$$BFI = \frac{\alpha_1 A_1 + \alpha_2 A_2 + \alpha_3 A_3 + \alpha_4 A_4 + \alpha_5 A_5}{A_{tot}}$$

where $A_{1\text{-}5}$ are the areas of each runoff class contained within the catchment and

$$\alpha_{1\text{-}5} = 1 - ROCF_{1\text{-}5}$$

where *ROCF* are the runoff coefficient values. A_{tot} is the total area of the catchment upstream the gauging station. This equation was solved for nine catchments simultaneously. Because the number of equations exceed the number of variables to calculate, Monte Carlo simulations were performed to estimate the values that minimize the sum of squared errors of the difference between the observed and the calculated *BFIs*. The ten best estimated series of runoff coefficients are presented in Table 4. It shows that the variability of runoff coefficient values for each class is small. The values given by Run 1, shown in Table 4, are then used as initial runoff values. These are then updated during the calibration process to improve the fit between the simulated and observed river flow time series.

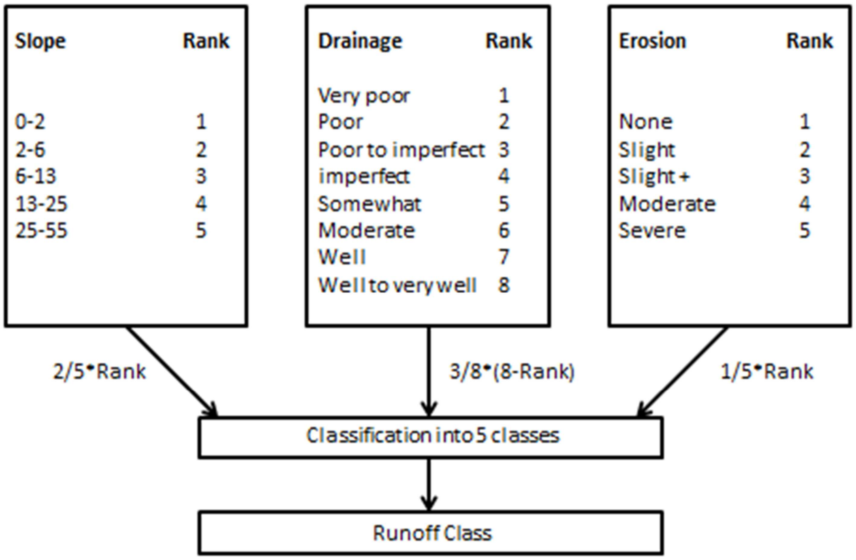


Figure 11. Method of calculating the runoff classification.

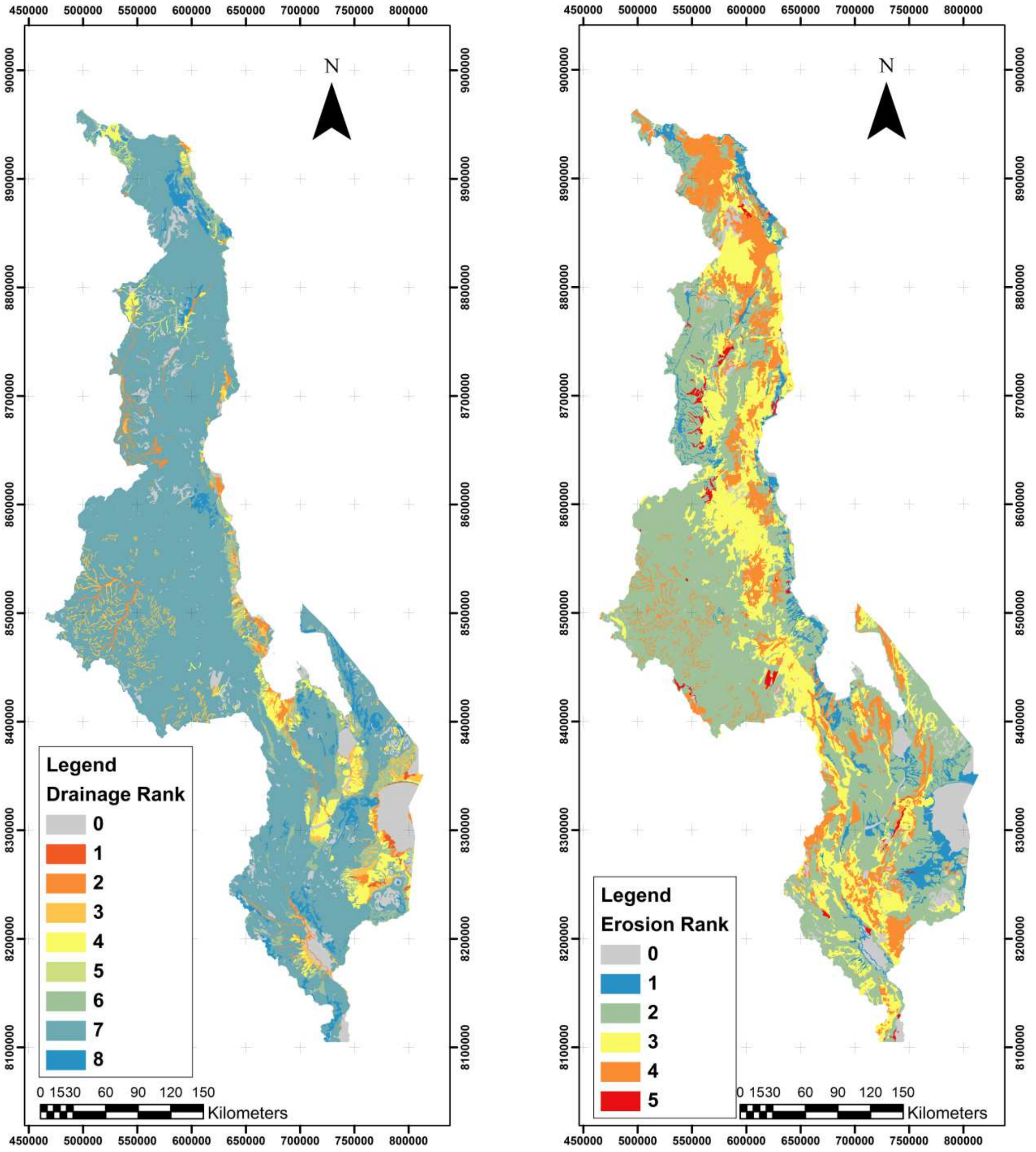


Figure 12. Soil drainage rank and soil erosion rank (MASDAP, http://www.masdap.mw/).

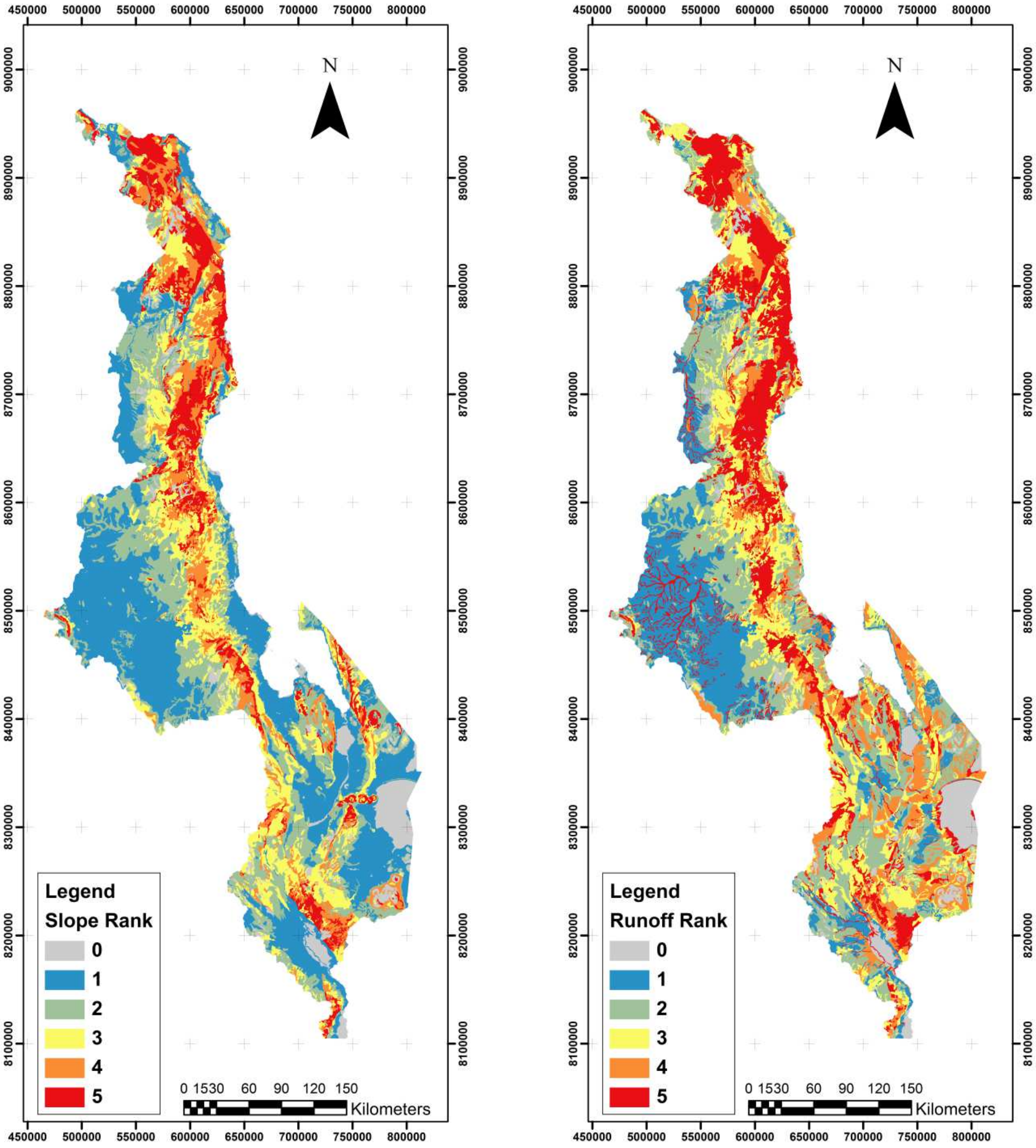


Figure 13. Topographical slope rank and the resulting runoff classification map.

Table 4. Runoff coefficient for different runoff classes.

Runoff Class/ Runoff coefficient	1	2	3	4	5
Run1	0.42	0.42	0.60	0.75	0.80
Run2	0.41	0.42	0.60	0.75	0.81
Run3	0.29	0.42	0.60	0.76	0.80
Run4	0.36	0.41	0.61	0.77	0.81
Run5	0.33	0.40	0.61	0.76	0.81
Run6	0.40	0.42	0.61	0.75	0.81
Run7	0.35	0.42	0.60	0.76	0.81
Run8	0.39	0.44	0.61	0.75	0.80
Run9	0.36	0.44	0.61	0.77	0.80
Run10	0.36	0.40	0.62	0.78	0.80

4.2.5 Weather data

Rainfall and potential evaporation data are the data sets that drive the recharge model. These are passed to the model in the form of daily rainfall or potential evaporation time series recorded at weather stations or in the form of daily gridded ascii maps. It is preferable to use gridded ascii maps because the information they contain is usually quality checked and corrected. The use of time series, on the other hand, necessitates the definition of a substitute gauging station number for every gauging station included in the model. This allows the model to retrieve data from the substitute gauging station where rainfall or potential evaporation data is missing from the record of the currently used gauging station. In addition, to be able to improve the spatial distribution of rainfall when time series are used, a gridded map of long term average (LTA) rainfall is used. In this case, the rainfall at any location within the study area is calculated from the rainfall recorded at a gauging station but scaled using the LTA rainfall value of the gauging station and the LTA value obtained from the map at that location.

In this application the daily rainfall data were obtained from the Tropical Rainfall Measuring Mission (TRMM). The spatial resolution is 0.25*0.25 degrees and the data is available from the 1st January 1998 to the 30st October 2014 (http://gcmd.gsfc.nasa.gov/KeywordSearch/Metadata.do?Portal=GCMD&MetadataType=0&MetadataView=Full&KeywordPath=&EntryId=GES_DISC_TRMM_3B42_daily_V7).

Potential evapotranspiration (PET) is obtained from MODIS and is available at 8-day intervals. Data is available from the 1st January 2000 to the 31st December 2014 and at a spatial resolution of 1000 m (https://lpdaac.usgs.gov/products/modis_products_table/modis_overview).

4.3 MODEL CALIBRATION

The model calibration is performed by comparing the simulated overland flows to the observed ones. The surface component of the observed overland flow is calculated by applying the Institute of Hydrology (IH) baseflow flow separation method (*Gustard et al.*, 1992) to the total flow time series recorded at a gauging station. This method estimates the low flow (baseflow) component of the total river flow which combines the flow within the top soil, also called interflow, and the groundwater flow, i.e. the flow within the aquifers. The surface flow component is then calculated by subtracting the low flow from the total flow.

Nine river gauging stations are selected to perform model calibration. Figure 14 shows the locations of the selected river gauging stations and Table 5 lists the names of the gauging stations together with the average overland flow and the upstream catchment area. These stations are selected because they have river flow records that are long enough to apply the baseflow separation method and they are spread over the different parts of the country.

As the river flow data only cover the time period from 1970 to 1990, it is not possible to use the TRMM precipitation and the MODIS potential evaporation data, since these data cover the period from 2000 to 2014. To overcome this problem, rainfall data that are recorded at rainfall stations and that cover the period from 1970 to 1990 are used in the model for calibration. The names of the rainfall gauging stations and their locations are shown in Figure 15. The rainfall is spatially distributed by attributing one gauging station to the grid nodes that fall within the Theissen polygon constructed for that gauging station. The Theissen polygons of the gauging stations are also shown in Figure 15. For any grid node, the rainfall for any particular day is read from the rainfall time series that the node is related to. However, this approach causes problems at the nodes located along the interfaces of the Theissen polygons. For example, two adjacent nodes that are sitting in two different Theissen polygons may be assigned different rainfall values for a certain day if the rainfall time series recorded at the respective gauging stations are very different. This is unacceptable since these nodes are adjacent and are expected to get similar rainfall during any day.

In order to improve the spatial distribution of rainfall, the distributed long term average (LTA) values are used to correct the rainfall readings obtained from the rainfall gauging stations. The LTA rainfall is calculated from the daily or monthly rainfall time series, as shown in Figure 16. In this application, the rainfall value for any day at any grid node is calculated by dividing the rainfall value of the corresponding gauging station by its LTA rainfall value and then multiplying the result by the LTA rainfall value at the node location. This smoothens the transition between the calculated rainfall values from one Theissen polygon to another.

Regarding the potential evaporation data, one time series of temperature data is only available at one gauging station. The temperature can be converted into potential evaporation using one of the equations reported in the literature, for example the Thornswaiths equation. However, it is believed that the potential evaporation values calculated for this gauging station are not representative of the potential evaporation values throughout the country. Therefore, the MODIS potential evaporation values from 2000 to 2014 are averaged to produce one year of daily averaged potential evaporation values. These values are then used to estimate potential evaporation during the simulation period from 1970 to 1990.

Table 5. Selected river gauging stations.

Station Name	Observed Flow (m^3/s)	Catchment area (km^2)
North Rukuru at Uledi	3.70	1860
Lufira at Mwakasangila	8.24	1410
South Rukuru at Phwezi	6.58	11800
Mkurumadzi at Mlongola	1.57	586
Nkasi at Kalembo	1.13	236
Lilongwe at Nkwenembela	15.18	4940
Bua at S53 Roadbridge	16.46	10600
Lifuliza at Nyoni	2.56	434
Dwangwa at Khwengwere	3.20	2980

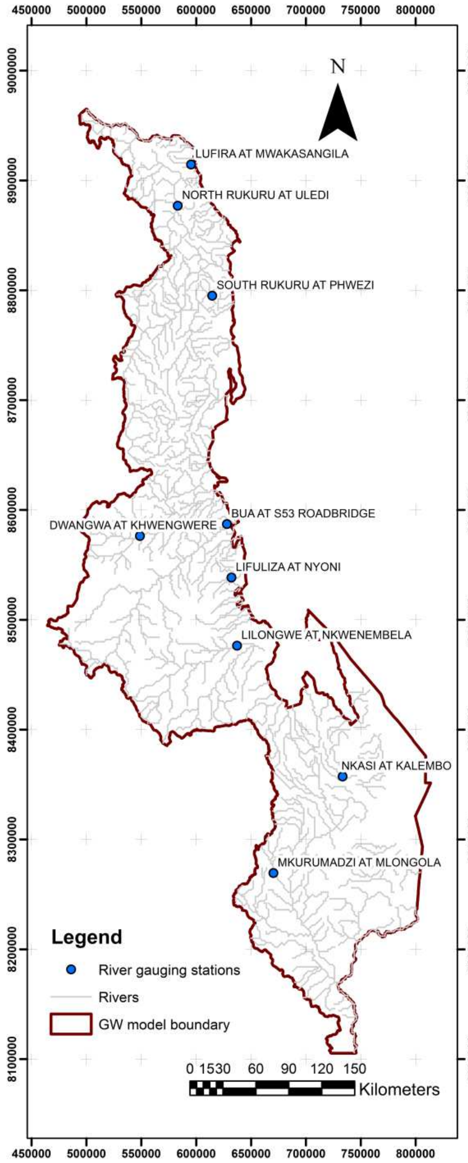


Figure 14. Selected river gauging stations.

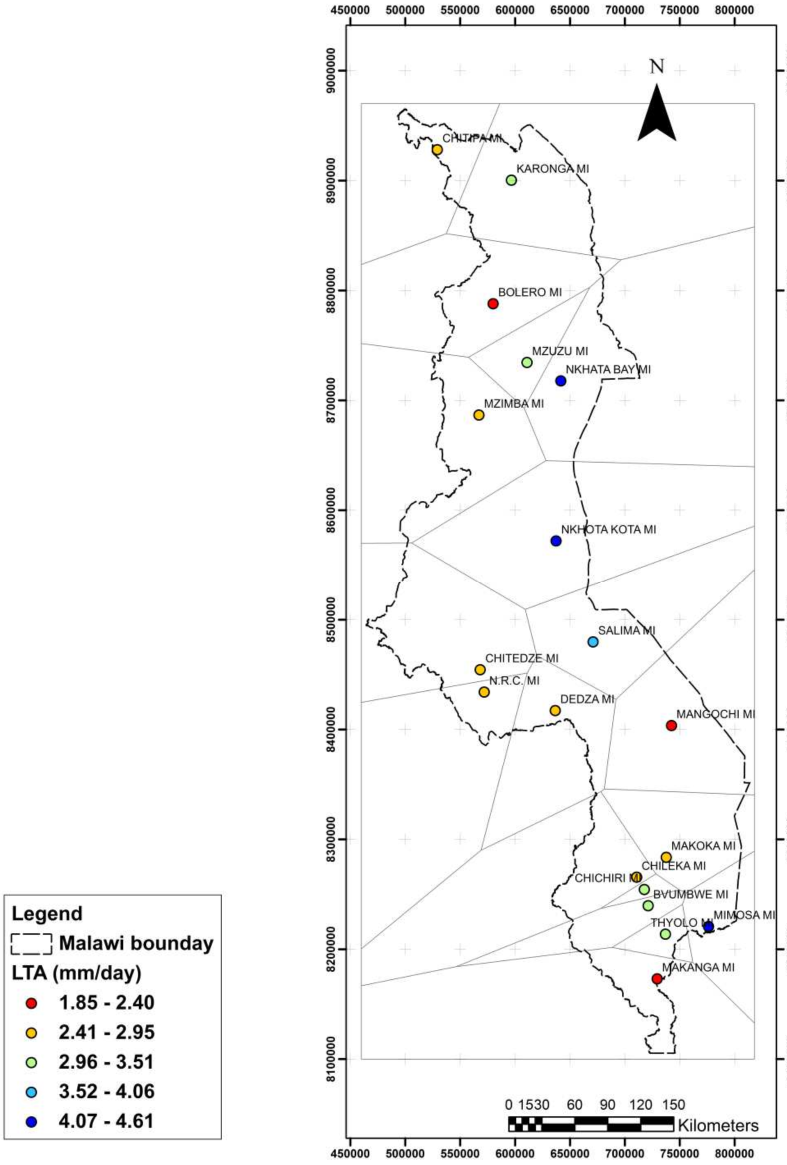


Figure 15. Long term average (LTA) rainfall from stations with daily rainfall measurements and the corresponding Theissen polygons.

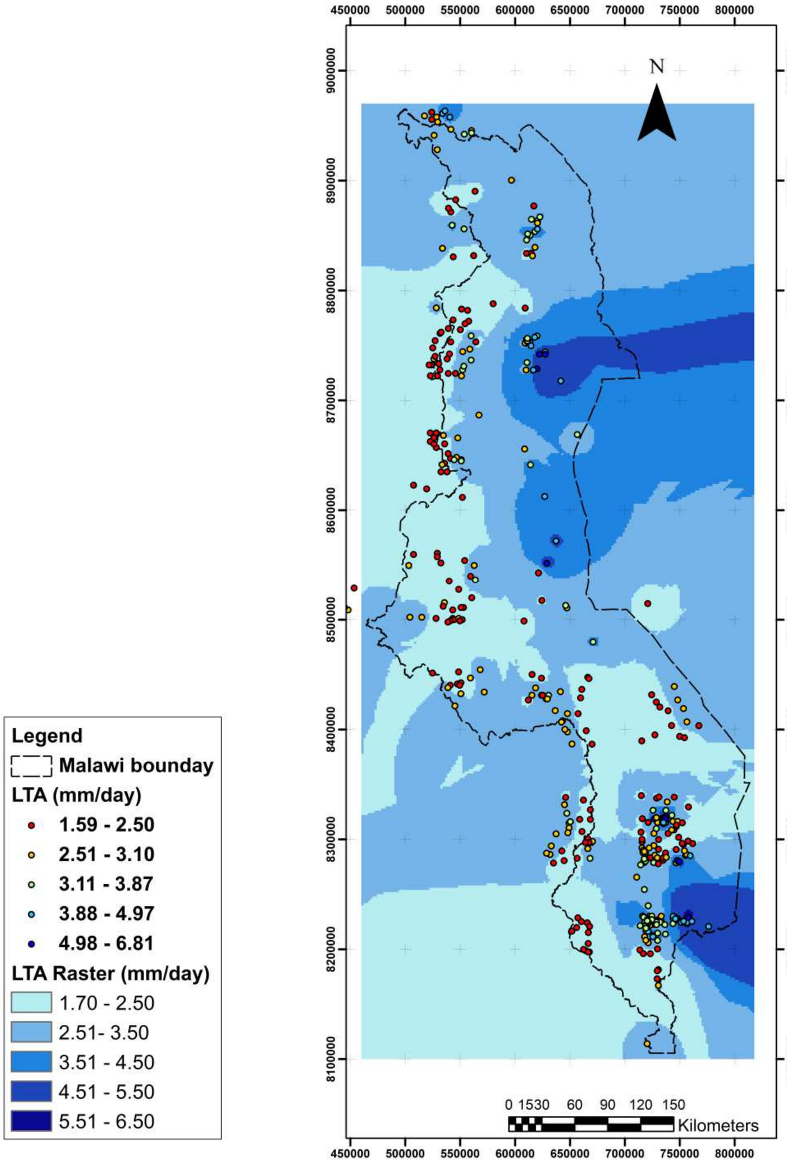


Figure 16. Measured (point data) and interpolated (raster data) long term average (LTA) rainfall data.

Several runs were undertaken to match the simulated overland flows to the observed ones. However, the actual areas of the catchment upstream the gauging stations were expected to be different from the areas of the catchments in the model due to the discretisation of the study area. In addition, the routing directions, which are based on topographical gradients calculated by the model using average ground elevations, may not be exact. This was an additional source of error that needs to be accounted for. An initial comparison between the areas of the actual and the modelled catchments revealed a relative difference of more than 40% in three of the catchments: the North Rukuru at Uledi (River 15), the Lufira at Mwakasangila (River 18), and Nkasi at Kalembo (River 43), had. Therefore, river routing in these catchments was adjusted to reduce the discrepancy between actual and modelled catchment area to less than 10%, except for catchment 15, where it was less than 20% (Table 6).

Table 6. Comparison of simulated and observed catchment area before and after correction.

Station Name	River No	Catchment Area ZOODRM (km^2)	Catchment area observed (km^2)	Difference before correction (%)	Difference after correction (%)
North Rukuru at Uledi	15	1564	1860	40	19
Lufira at Mwakasangila	18	1296	1410	907	9
South Rukuru at Phwezi	23	11859.5	11800	-1	-1
Mkurumadzi at Mlongola	37	624	586	-6	-6
Nkasi at Kalembo	43	228	236	-46	4
Lilongwe at Nkwenembela	69	5119.95	4940	-4	-4
Bua at S53 Roadbridge	70	10475.6	10600	1	1
Lifuliza at Nyoni	78	416	434	4	4
Dwangwa at Khwengwere	87	3112	2980	-4	-4

Then, the runoff coefficients were changed within the range produced by the Monte Carlo simulation (Table 4). However, comparison of the LTA runoff derived from base flow separation at gauging stations and modelled runoff did not been prove successful. Hence, runoff coefficients were altered outside the range suggested by the Monte Carlo simulation by comparing the relative area of the different runoff zones with the observed and simulated runoff.

Furthermore, the fit was improved by assigning different runoff coefficients to the different catchments. Table 7 shows the runoff coefficient values used in the two runs. In Run A, the runoff coefficient values within each runoff zone were kept the same. In Run B, the runoff coefficient values were varied within the different runoff zones by assigning different values to the different catchments. By altering the runoff coefficients of Zones 1-3 in catchment of River 23 and of Zone 1 in the catchment of River 70, the relative difference between observed and simulated runoff could be improved in these catchments from 78% to 51% and from 30% to 5% (Table 8).

Table 7. Runoff coefficients for two different model runs.

Run A		Run B		
Runoff Zone	Entire Model Domain	Within catchments of gauging stations at Rivers 15, 18, 37, 43, 69, 78, 87	Within catchment of gauging station at River 23	Within catchment of gauging station at River 70
1	0.25	0.25	0.03	0.03
2	0.3	0.3	0.04	0.3
3	0.35	0.35	0.08	0.35
4	0.4	0.4	0.4	0.4
5	0.95	0.95	0.95	0.95

Table 8. Comparison of observed and simulated runoff for nine catchments

Station Name	River No	Observed Flow (m^3/s)	Simulated Flow Run A (m^3/s)	Relative difference Run A (%)	Simulated Flow Run B (m^3/s)	Relative difference Run B (%)
North Rukuru at Uledi	15	3.70	2.27	62.70	2.29	61.34
Lufira at Mwakasangila	18	8.24	4.64	77.72	4.73	74.35
South Rukuru at Phwezi	23	6.58	29.46	-77.67	13.53	-51.37
Mkurumadzi at Mlongola	37	1.57	2.11	-25.32	2.21	-28.89
Nkasi at Kalembo	43	1.13	0.45	153.71	0.50	126.61
Lilongwe at Nkwenembela	69	15.18	8.13	86.82	8.51	78.30
Bua at S53 Roadbridge	70	16.46	23.66	-30.44	15.73	4.63
Lifuliza at Nyoni	78	2.56	1.68	52.64	1.74	47.19
Dwangwa at Khwengwere	87	3.20	1.87	71.17	1.22	161.28

In addition, the root depth was varied between the maximum and the minimum estimates presented in Table 3. It was found that the root depth has a large influence on the calculated runoff values. Table 9 shows the values of the different components estimated by the recharge model for the two runs mentioned before, Runs A and B, and two additional runs, Runs C and D, in which the root constant values were modified. The differences in the estimated values of runoff and recharge in Runs A and B are due to the alteration of the runoff coefficient values as described above. However, when higher root depth values were used in Run C and Run D (which have the same runoff coefficient values as Run A and Run B respectively), not only the evapo-transpiration increases, but the amount of runoff and recharge reduces significantly. Recharge decreases from 115 mm/year (Run A) to 58 mm/year (Run C) and from 120 mm/year (Run B) to 64 mm/year (Run D).

This exercise shows that the relative difference between the observed and simulated runoff increases at all stations except for River 23 (South Rukuru at Phwezi) (Table 10). This is expected because the change of the root constant values necessitates the recalibration of the runoff coefficient values. However, the improvement of overland flows calculated for the catchment of River 23 indicates the importance of the accurate representation of landuse in the numerical model. Since there is uncertainty related to this feature in the model, sensitivity analysis will be performed later to study the impact of landuse representation on the calculated runoff and recharge values.

Table 9. Annual water budget for model calibration runs 1970-1990.

Run	Rainfall (mm/year)	Evaporation (mm/year)	Runoff (mm/year)	Recharge (mm/year)
Run A	1014	814	91	115
Run B	1014	814	83	120
Run C	1014	927	46	58
Run D	1014	927	42	64

Table 10. Annual water budget for model calibration runs 1970-1990.

Station Name	River No	Relative difference Run A (%)	Relative difference Run B (%)	Relative difference Run C (%)	Relative difference Run D (%)
North Rukuru at Uledi	15	62.70	299.30	61.34	297.56
Lufira at Mwakasangila	18	77.72	246.68	74.35	239.76
South Rukuru at Phwezi	23	-77.67	-58.03	-51.37	-8.78
Mkurumadzi at Mlongola	37	-25.32	105.49	-28.89	95.06
Nkasi at Kalembo	43	153.71	502.01	126.61	437.16
Lilongwe at Nkwenembela	69	86.82	443.65	78.30	417.32
Bua at S53 Roadbridge	70	-30.44	72.35	4.63	158.25
Lifuliza at Nyoni	78	52.64	249.88	47.19	236.52
Dwangwa at Khwengwere	87	71.17	425.58	161.28	723.44

4.4 MODEL RUNS FOR 2000- 2014

As demonstrated in the previous section, calibration of the model proved to be a difficult task. There were many causes that contributed to this difficulty, for example the definition of runoff zones and their extents, the resolution of the numerical grid and its capability to capture details affecting the generation of runoff, and the impact of landuse on the calculated runoff values. Considering the described complications, it was assumed that Runs A and B are acceptable for the calculation of recharge using the TRMM rainfall data and the MODIS evaporation data.

Runs A and B were rerun using the TRMM rainfall data and the MODIS evaporation data for the simulation period from 2000 to 2014. Table 11 shows the average values of the different components calculated over this simulation period for both runs. This table shows that, on average, the country receives total rainfall of approximately 1048 mm/year. Over 80 % of this rainfall is lost as evapo-transpiration. On average, the amount of calculated recharge and runoff are 117 mm/year and 95 mm/year in Run A and are 128 mm/year and 84 mm/year in Run B. Calculations of recharge using the analytical toolbox (Section 3.2) show that the average recharge values on a national scale vary between 72 mm/year and 157mm/year depending on the method of calculation. The average recharge values calculated using the distributed recharge models fall within the range of the values provided by the calculations using the analytical toolbox. Figure 17 shows the spatial distribution of long term average rainfall values calculated using the TRMM data and Figure 18 gives the spatial distribution of recharge values calculated using Runs A and B.

Spatially, for all model runs, LTA recharge ranges between 0 and 3 mm/day (Figure 18). The recharge is higher in southern part of Malawi compared to northern part, except for the northernmost corner, where rainfall is highest nationally (Figure 17). Generally, there is an inverse relationship between the recharge and the runoff classification (Figure 13). However, there are a few exceptions where recharge is dominated by the landuse classification (small maximum recharge areas in built up areas).

Table 11. Annual water budget for 2000-2013.

Run	Rainfall (mm/year)	Evaporation (mm/year)	Runoff (mm/year)	Recharge (mm/year)
A	1084	880	95	117
B	1084	880	84	128

4.4.1 Sensitivity analysis runs

Given uncertainty in the model parameterisation, a series of runs were undertaken to investigate how changing the soil parameter values and the distribution of landuse affects the estimated recharge values. The parameter values in Run A were changed and four additional simulations were performed. The first two runs involves changing the soil parameters to change the available water capacity (AWC) which is defined as the difference between the water content at field capacity and the water content at wilting point. While the AWC in Runs A and B was set to a value of 0.17, the AWC in Runs C and D was set to 0.1 and 0.3, respectively. The values presented in Table 12 indicate that the runoff and recharge values reduce with increasing AWC because more water is available for plants to evapo-transpire. However, the change of AWC from 0.3 in Run D to 0.1 in Run C altered the estimated recharge values by approximately 60%. The average recharge value estimated in Run D with AWC = 0.3 was approximately 21% lower than the average recharge value estimated in Run A. Conversely the average recharge value estimated in Run C was approximately 30% higher than the average recharge value estimated in Run A.

Two additional runs were undertaken to study the impact of landuse on the estimated recharge values. In these runs, the forest land cover was modified to include another landuse type which was specified as either arable or grass. To achieve this, the percentage landuse cover feature of the distributed recharge model was used. Under this condition, more than one landuse type can be specified at every grid node together with the percentage cover of each specified landuse type. In Run E the grid cells with the dominant land cover of forest were changed to 50% forest and 50% arable. In Run F, these nodes were modified to 30% forest and 70% grass. Compared to Run A, the estimated average recharge value calculated in Run E increased by 11% to a value of 130 mm/year. The estimated average recharge value calculated in Run E, on the other hand, increased by 22% to a value of 143 mm/year.

This exercise indicates that the recharge values calculated in Run A Can change by $\mp 30\%$ by changing the values related to soil characteristics and the spatial distribution of landuse types. These recharge values can be improved, therefore, if the representation of the hydraulic parameters affecting the recharge calculations are improved in the model. This implies that refined values of recharge can be obtained once better resolution maps are available.

Table 12. Water balance of the different undertaken numerical simulations.

Run number	Parent	Notes / changes	Results
Run A	-	• AWC = 0.17	Averages in mm/year: Rainfall 1084 Evapotranspiration 880 Runoff 95 Recharge 117
Run B	Run A	• Runoff coefficients modified	Averages in mm/year: Rainfall 1084 Evapotranspiration 880 Runoff 84 Recharge 128
Run C	Run A	• AWC = 0.1	Averages in mm/year: Rainfall 1084 Evapotranspiration 815 Runoff 124 Recharge 152
Run D	Run A	• AWC = 0.3	Averages in mm/year: Rainfall 1084 Evapotranspiration 940 Runoff 70 Recharge 92
Run E	Run A	• Replace half the forest landuse type with arable landuse type.	Averages in mm/year: Rainfall 1084 Evapotranspiration 855 Runoff 106 Recharge 130
Run F	Run A	• Replace 70% of the forest landuse type with grass landuse type.	Averages in mm/year: Rainfall 1084 Evapotranspiration 824 Runoff 121 Recharge 143

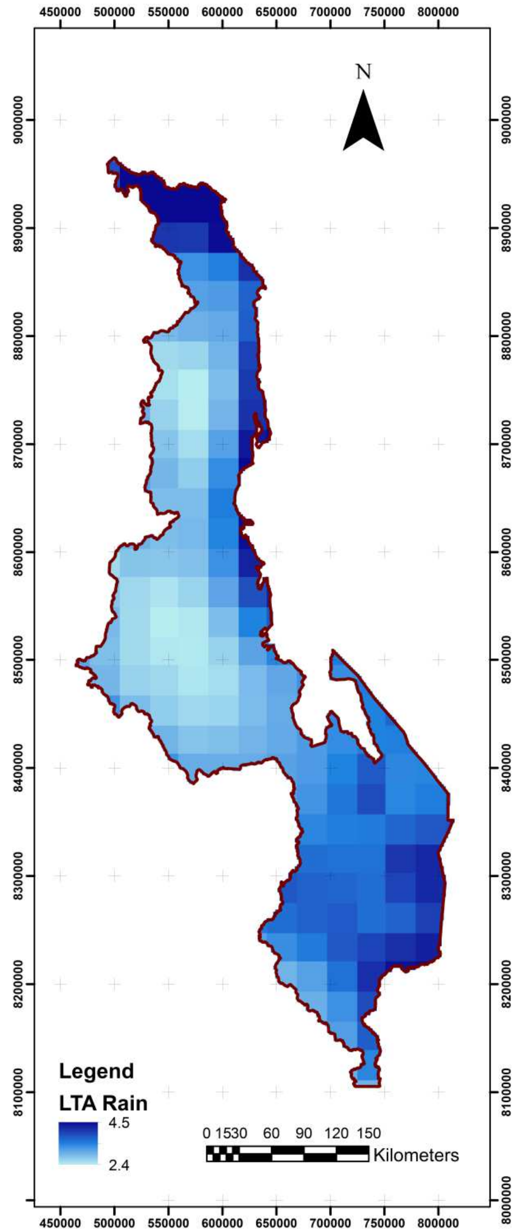
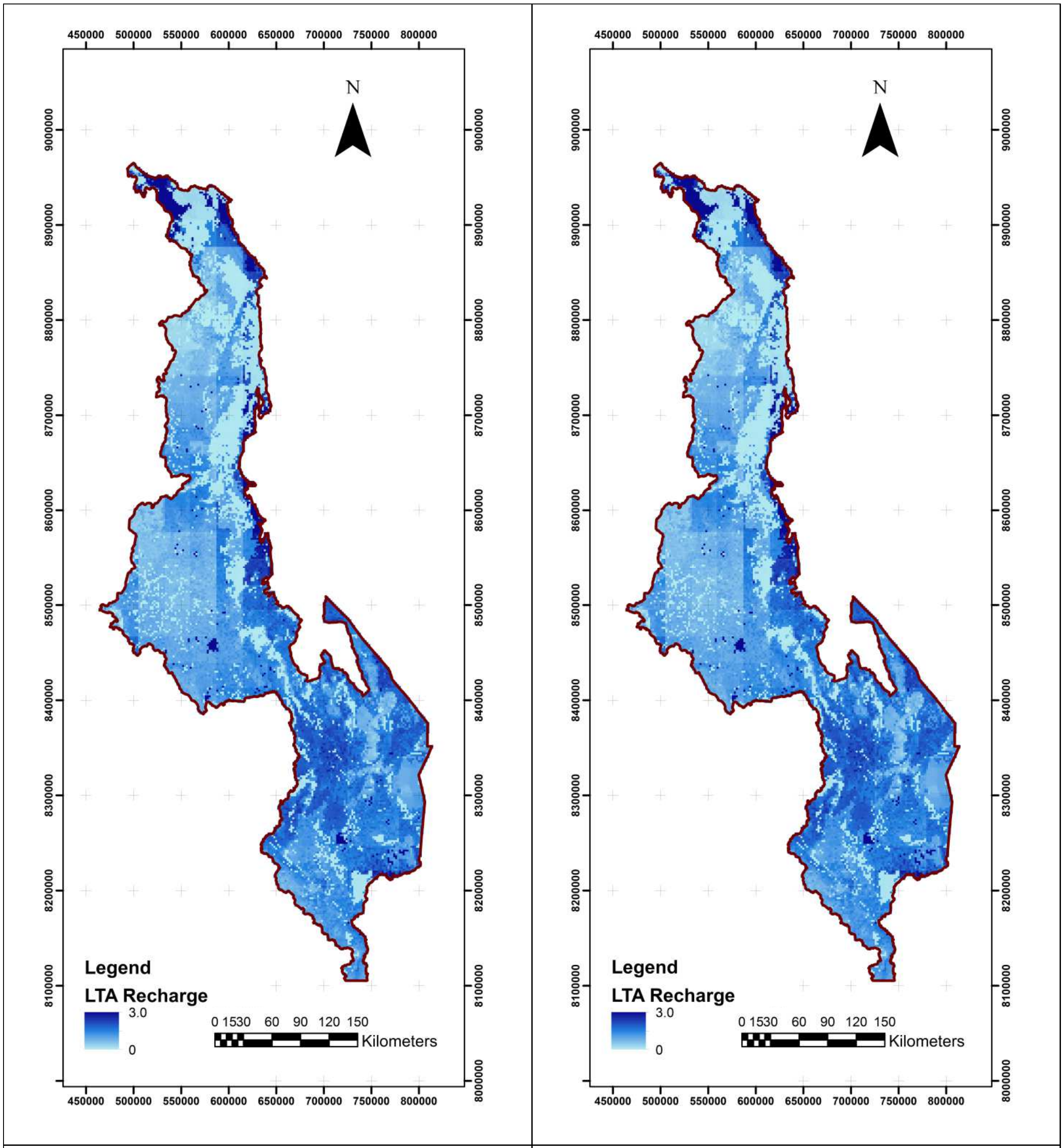


Figure 17. Long term average rainfall (mm/day).



Run A

Run B

Figure 18. Long term average recharge in mm/day for 2000-2014.

4.5 COMPARISON OF RESULTS FROM THE TOOLBOX ANALYTICAL SOLUTIONS TOOLBOX AND THE DISTRIBUTED RECHARGE MODEL

Table 13 shows a comparison between the recharge values estimated from the analytical toolbox and those calculated by the distributed recharge model on a district scale. This table shows that the values estimated by the models agree with values produced by some of the methods implemented in the toolbox, but this agreement is not consistent with one particular method although the WTF method produced the best agreements. In general, the recharge model results lie within the range of values produced by the different analytical methods except for Chikwawa, where the recharge values calculated by the model are underestimated, and for Chitipa, Dowa, Karonga, and Lilongwe, where recharge values calculated by the model are overestimated.

From the range of recharge values shown in Table 13, it is difficult to confidently select one method that is representative to recharge calculation in Malawi. Every method applied is associated with many assumptions and simplifications that is are not always met in this study. In addition, the recharge values calculated from the analytical solutions are based on time series of input data obtained at a couple of observation boreholes in each district. Theoretically, many boreholes must be used when applying the analytical solutions. An average recharge over one district must be then calculated by either an average time series calculated from all the borehole time series or by averaging the recharge values calculated from the individual time series. The use of a small number of observation boreholes may not be enough to calculate a representative recharge rate over the whole of the district area. It is believed that the recharge values calculated from the distributed recharge model are more representative than those calculated by the analytical solutions since they are the average of the recharge values calculated at all nodes within the district areas. However, Table 13 is useful because, acknowledging the uncertainty associated with the data used in the distributed recharge model, it allows to check if these recharge values agree with the recharge values calculated from the toolbox at individual locations.

Table 13. Comparison between the recharge values calculated using the analytical tool box and those calculated using the distributed recharge model.

Method or Model Run / yearly recharge values at districts	CRD	rCRD	mnCRD	RIB	Park	WTF		Run A	Run B
Balaka	265.2	265.2	239.7	194.3	194.7	118		137.5	132.7
Blantyre	302.5	302.5	78.3	202.2	44	84.8		130.9	125.5
Chikwawa	409.7	409.7	194.3	367.7	70.4	136.6		69.1	69.1
Chiradzulu	201	201	86.7	80.8	87.5	92.1		138.9	131.8
Chitipa	42.5	42.5	47.6	45	21.5	52.4		119.0	113.6
Dedza	67	67	178.2	121.5	77.7	63.2		105.3	102.1
Dowa	72.4	72.4	76.6	76.8	35.9	107.1		136.3	144.8
Karonga	95.3	95.3	85.8	86.4	88.8	68.9		124.3	119.5
Kasungu	155.4	155.4	140.2	116.6	31.5	42.1		127.0	146.1
Lilongwe	68.9	68.9	93.8	56.6	38.5	57.8		134.9	138.3
Machinga	330.8	330.8	181.4	399.1	153	194.5		119.0	120.2
Mangochi	45.8	45.8	50.5	33.9	36.9	24.1		103.8	100.5
Mchinji	172.4	172.4	207.4	206.6	135.9	202.3		147.8	197.8
Mulanje	212.1	212.1	90.3	84.1	32.6	101.3		173.9	173.3
Mwanza	280.6	280.6	124.3	111.2	97.1	73.5		104.6	100.1
Mzimba	90.3	90.3	74.2	175.2	12.9	32.1		126.2	165.6
Nkhata_Bay	69.8	69.8	39.7	101.8	77.9	107.1		85.1	122.6
Nkhotakota	55.4	113.8	68.7	60.5	70	53		159.2	157.0
Nsanje	64.1	64.1	70.8	141.7	48.2	47.1		78.3	80.8
Ntcheu	181.2	181.2	135.7	127	129.3	75.3		114.2	107.6
Ntchisi	67.8	67.8	70.8	69.1	28.8	98.9		118.8	112.6
Phalombe	8	15.8	65.8	73.7	60	98.2		154.2	153.4
Rumphi	75.5	75.5	97.7	97.9	35.4	23.9		61.3	84.6
Salima	262	313.7	217.2	188.6	94.8	177.5		187.1	179.3
Thyolo	299.9	299.9	100.4	183.5	91.8	94		108.7	104.8
Zomba	77	77	80	69.5	82.2	132.1		132.4	133.1
Average	**152.8**	**157.3**	**111.4**	**133.5**	**72.2**	**90.7**		**123.0**	**127.6**

5 Summary

This report presents the calculations undertaken to estimate the recharge values over Malawi. It also describes the development of a recharge calculation toolbox in Microsoft Excel using Visual Basics. Two methods were used to estimate the recharge on a national scale. In the first method, the seven analytical solutions that were included in the recharge calculation toolbox were used. The toolbox used rainfall, potential evaporation and groundwater time series to calculate recharge. This is applied at the district scale. In the second method, the numerical distributed recharge calculation model ZOODRM was used to estimate the recharge values on the national scale. The model uses gridded daily rainfall and potential evaporation data as well as gridded landuse, topography, soil and river data to calculate recharge.

The distributed recharge model was calibrated by matching the simulated overland flows to the observed ones at selected gauging stations. The observed overland flows were calculated by splitting the recorded total flows into two components, a slow flow and a fast flow component. This was done using the IH baseflow separation method. However, the calibration of the recharge model proved difficult mainly due to the following reasons:

- The resolution of the model grid is too coarse to capture the full topographical characteristics of the study area that are affecting runoff.
- The number of runoff zones specified in the model are not enough to fully represent the characteristics of the study area.
- There is a need to improve the representation of land cover in the model since the land cover affects the estimated recharge values.

Additional runs were undertaken to study the sensitivity of the estimated recharge values to the soil parameters and the specified land cover. The average national scale values produced from this simulation were: 1084 mm/year for rainfall, 880 mm/year for evapotranspiration, 95 mm/year for runoff and 117 mm/year for recharge. Spatial variability in the recharge values ranged from approximately 0.05 mm/year to 1100 mm/year. These values have to be interpreted with care since, as demonstrated by the sensitivity analysis, they are highly affected by the quality of the data used in the distributed recharge model. Comparing the recharge values estimated from the recharge model and averaged over the district areas to the recharge values calculated using the recharge toolbox, it was clear that the former agree with outputs from at least one of the analytical method in the toolbox. However, the recharge values produced by the distributed model did not agree with one particular method although the WTF method produced the best agreements (Table 13). The sensitivity analysis results indicate that the recharge values are highly affected by the soil type parameter values specified in the model and by the spatial distribution of land cover. To improve the accuracy of the outputs from the distributed recharge model, it is recommended that maps with a better representation of these features are included in the model. In addition, there is a need to repeat model calibration using weather data for the same for which where river flows data are available. This can be achieved in future enhancement of the distributed recharge model.

References

Ahmadi, T., A. N. Ziaei, A. Rasoulzadeh, K. Davary, K. Esmaili, and A. Izady (2014), Mapping groundwater recharge areas using CRD and RIB methods in the semi-arid Neishaboor Plain, Iran, *Arabian Journal of Geosciences*, *8*(5), 2921-2935, doi:10.1007/s12517-014-1321-2.

Allen, R. G., L. S. Pereira, D. Raes, and Smith Crop Evapotranspiration. Guidlines for computing crop water requirements, *FAO Irrigation and Drainage Paper*.

Baalousha, H. (2005), Using CRD method for quantification of groundwater recharge in the Gaza Strip, Palestine, *Environmental Geology*, *48*(7), 889-900, doi:DOI 10.1007/s00254-005-0027-x.

Bredenkamp, D. P., L. J. Botha, G. J. van Tonder, and H. J. van Rensburg (1995), Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity, *WRC Report No TT 73/95*.

Chavula, G. M. (1998), State of Environment Report for Malawi, Water Resources, *University of Malawi*.

Chimtengo, M., C. Ngongondo, M. Tumbare, and M. Monjerezi (2014), Analysing changes in water availability to assess environmental water requirements in the Rivirivi River basin, Southern Malawi, *Physics and Chemistry of the Earth*, *67-69*, 202-213, doi:10.1016/j.pce.2013.10.007.

Chipofya, V., S. Kainja, and S. Bota (2012), Integrated Water Resources Management - Key to Sustainable Development and Management of Water Resources: Case of Malawi, in *Sustainable Development - Energy, Engineering and Technologies - Manufacturing and Environment*, edited, doi:10.5772/29698.

FAO http://www.fao.org/nr/water/cropinfo.html.

Gustard, A., A. Bullock, and J. M. Dixon (1992), Low Flow Estimation in the United Kingdom, *Inst. of Hydrol., Wallingford, England, Report No. 108*, 19-25 pp.

Healy, R. W., and P. G. Cook (2002), Using groundwater levels to estimate recharge, *Hydrogeology Journal*, *10*(1), 91-109, doi:10.1007/s10040-001-0178-0.

Jackson, C. R., and A. E. F. Spink (2004), User's manual for the groundwater flow model ZOOMQ3D, *IR/04/140, British Geological Survey Internal Report*, 94 pp.

Kafumbata, D., D. Jamu, and S. Chiotha (2014), Riparian ecosystem resilience and livelihood strategies under test: lessons from Lake Chilwa in Malawi and other lakes in Africa, *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *369*(1639), 20130052, doi:10.1098/rstb.2013.0052.

Mansour, M. M., and A. G. Hughes (2004), User's manual for the distributed recharge model ZOODRM, *IR/04/150*, *British Geological Survey Internal Report*, 95 pp.

Minister of Irrigation and Water Development (2012), Government of Malawi Integrated Water Resources Management and water efficiency (IWRM/WE) Plan 2008-2012.

Monjerezi, M., R. D. Vogt, P. Aagaard, and J. D. K. Saka (2012), The hydro-geochemistry of groundwater resources in an area with prevailing saline groundwater, lower Shire Valley, Malawi, *Journal of African Earth Sciences*, *68*, 67-81, doi:10.1016/j.jafrearsci.2012.03.012.

NASA(a) http://trmm.gsfc.nasa.gov/

NASA(b) http://modis.gsfc.nasa.gov/data/

Ngongondo, C. S. (2006), An analysis of long-term rainfall variability, trends and groundwater availability in the Mulunguzi river catchment area, Zomba mountain, Southern Malawi, *Quaternary International*, *148*(1), 45-50, doi:10.1016/j.quaint.2005.11.006.

Palamuleni, L. G., P. M. Ndomba, and H. J. Annegarn (2011), Evaluating land cover change and its impact on hydrological regime in Upper Shire river catchment, Malawi, *Regional Environmental Change*, *11*(4), 845-855, doi:10.1007/s10113-011-0220-2.

Park, E., and J. C. Parker (2008), A simple model for water table fluctuations in response to precipitation, *Journal of Hydrology*, *356*(3-4), 344-349.

Robins, N., J. Davies, and J. Farr (2013), Groundwater supply and demand from southern Africa's crystalline basement aquifer: evidence from Malawi, *Hydrogeology Journal*, *21*(4), 905-917, doi:DOI 10.1007/s10040-013-0956-5.

Roche, R. J. (2007), Second National Water Development Project, Project appraisal document, *No: 38457-MW*.

Sun, X., Y. Xu, N. Z. Jovanovic, E. Kapangaziwiri, L. Brendonck, and R. D. H. Bugan (2013), Application of the rainfall infiltration brekthrough (RIB) model for groundater recharge estimation in west coastal South Africa, *Water SA*, *39*(2), 221-230.

Van Tonder, G. J., and Y. Xu (2000), A guide for the estimation of groundwater recharge in South Africa.

Xu, Y., and G. J. Van Tonder (2001), Estimation of recharge using a revised CRD method, *Water SA*, *27*(3), 341-343.

Xu, Y., and H. E. Beekman (2003), Groundwater Recharge Estimation in Southern Africa.

Appendix A

Table A1. LTA estimated January recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	26.0	26.0	9.2	0.7	49.8	37.0	24.8	17.9
Blantyre	33.1	33.1	0.0	7.0	11.0	9.2	15.6	14.1
Chikwawa	47.2	47.2	3.5	23.3	20.1	15.9	26.2	17.6
Chiradzulu	20.1	20.1	17.0	17.7	22.2	22.8	20.0	2.3
Chitipa	2.8	2.8	1.6	0.8	4.8	9.0	3.6	2.9
Dedza	3.2	3.2	0.0	0.0	21.3	10.2	6.3	8.2
Dowa	5.3	5.3	13.2	14.3	10.9	17.9	11.2	5.1
Karonga	2.1	2.1	0.1	0.0	15.0	13.0	5.4	6.8
Kasungu	12.2	12.2	13.5	9.7	8.9	6.8	10.5	2.5
Lilongwe	4.2	4.2	3.2	0.0	10.6	8.3	5.1	3.8
Machinga	28.3	28.3	6.4	46.8	25.8	22.3	26.3	13.0
Mangochi	3.5	3.5	3.2	0.9	8.1	7.4	4.5	2.8
Mchinji	15.3	15.3	15.0	14.6	34.0	36.2	21.7	10.4
Mulanje	20.7	20.7	17.1	17.8	7.8	24.2	18.0	5.6
Mwanza	32.0	32.0	3.1	0.7	25.9	25.3	19.8	14.2
Mzimba	7.1	7.1	0.0	17.2	3.4	3.1	6.3	6.0
Nkhata Bay	1.3	1.3	3.2	0.0	15.9	16.4	6.4	7.7
Nkhotakota	1.8	5.5	0.0	2.1	17.3	5.6	5.4	6.2
Nsanje	6.2	6.2	0.3	15.7	13.6	6.6	8.1	5.6
Ntcheu	18.9	18.9	3.2	0.0	37.4	24.9	17.2	13.9
Ntchisi	4.8	4.8	11.2	9.5	8.4	16.3	9.2	4.3
Phalombe	0.0	0.0	3.0	0.0	7.3	9.2	4.9	4.2
Rumphi	4.2	4.2	1.1	2.5	7.7	2.8	3.7	2.3
Salima	15.7	20.7	0.0	0.0	26.3	18.7	13.6	11.1
Thyolo	31.1	31.1	0.0	13.8	22.9	10.6	18.3	12.4
Zomba	0.8	0.8	0.0	4.9	9.7	14.3	5.1	5.8

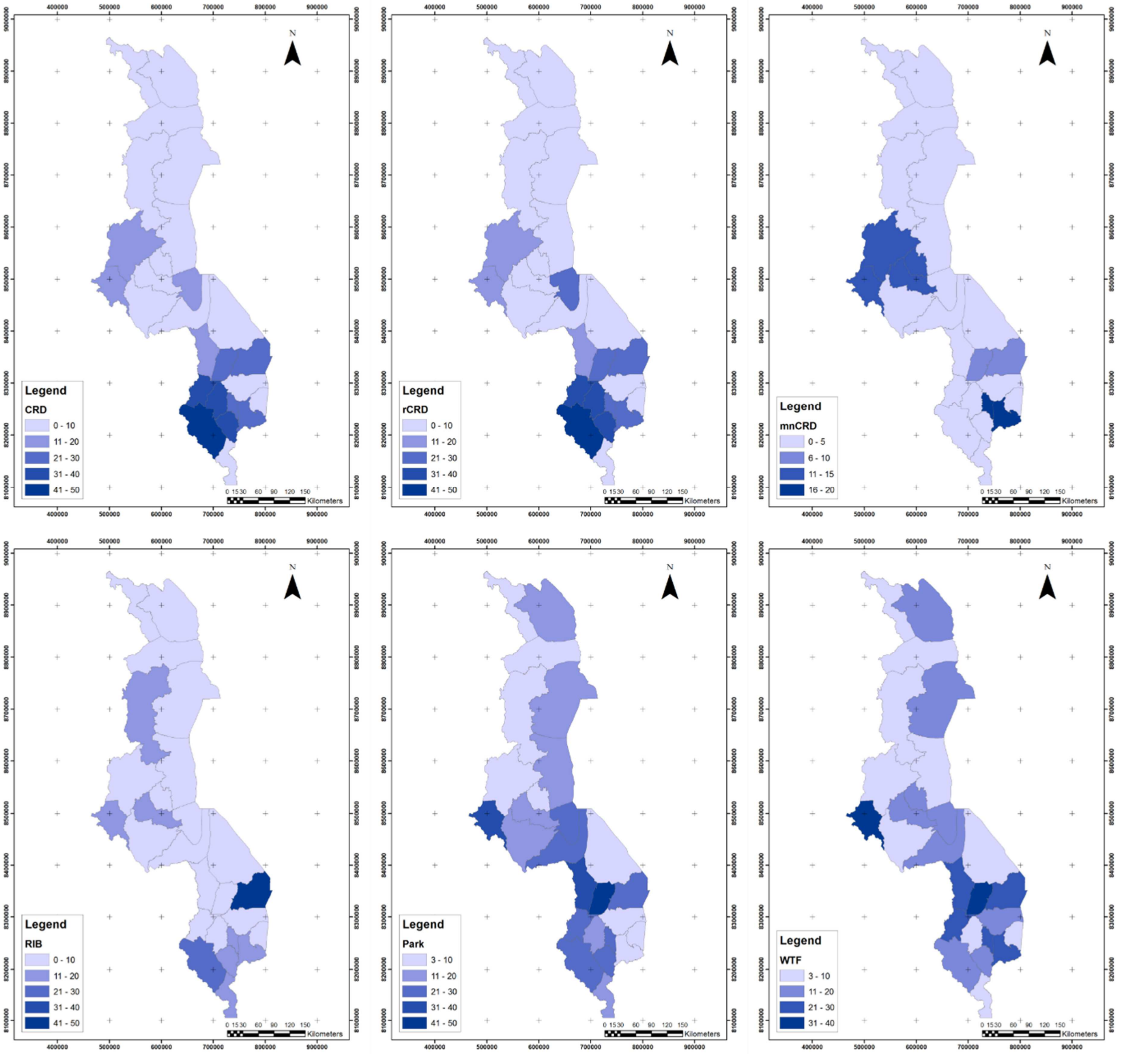


Figure A1. Average January groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A2 LTA estimated February recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	37.9	37.9	38.5	26.2	41.1	39.1	36.8	5.3
Blantyre	39.7	39.7	0.0	10.0	8.7	9.1	17.9	17.3
Chikwawa	62.9	62.9	9.4	10.2	15.7	15.7	29.4	26.0
Chiradzulu	25.2	25.2	23.6	25.1	18.3	23.3	23.4	2.7
Chitipa	4.8	4.8	4.2	2.1	4.0	9.1	4.8	2.3
Dedza	12.3	12.3	0.7	0.0	18.6	9.7	8.9	7.3
Dowa	13.4	13.4	23.0	24.9	9.6	21.0	17.5	6.2
Karonga	4.6	4.6	0.9	0.7	13.4	13.2	6.2	5.7
Kasungu	25.7	25.7	26.1	21.1	8.0	7.0	18.9	9.1
Lilongwe	12.7	12.7	8.6	1.0	9.2	9.1	8.9	4.3
Machinga	45.9	45.9	16.3	27.9	24.2	22.7	30.5	12.5
Mangochi	8.0	8.0	7.0	3.9	6.7	8.3	7.0	1.6
Mchinji	26.9	26.9	42.9	40.4	34.1	39.4	35.1	7.0
Mulanje	27.1	27.1	23.8	25.3	6.5	24.6	22.4	7.9
Mwanza	44.6	44.6	20.0	19.1	19.4	22.7	28.4	12.6
Mzimba	12.4	12.4	0.9	17.5	2.8	3.2	8.2	6.8
Nkhata Bay	6.5	6.5	8.1	4.5	14.4	17.1	9.5	5.0
Nkhotakota	7.3	15.0	0.2	0.1	16.8	5.9	7.5	7.1
Nsanje	10.3	10.3	1.7	6.4	9.9	6.4	7.5	3.4
Ntcheu	31.6	31.6	19.8	12.2	27.7	26.3	24.8	7.6
Ntchisi	11.3	11.3	20.3	25.2	7.6	19.1	15.8	6.7
Phalombe	0.0	0.1	3.8	2.1	6.2	9.3	5.4	3.1
Rumphi	8.6	8.6	1.0	0.0	6.1	2.8	4.5	3.8
Salima	45.0	52.2	0.0	0.0	24.7	20.0	23.6	21.9
Thyolo	39.8	39.8	0.0	13.2	19.2	10.5	20.4	16.2
Zomba	7.3	7.3	2.0	7.5	8.8	14.9	8.0	4.1

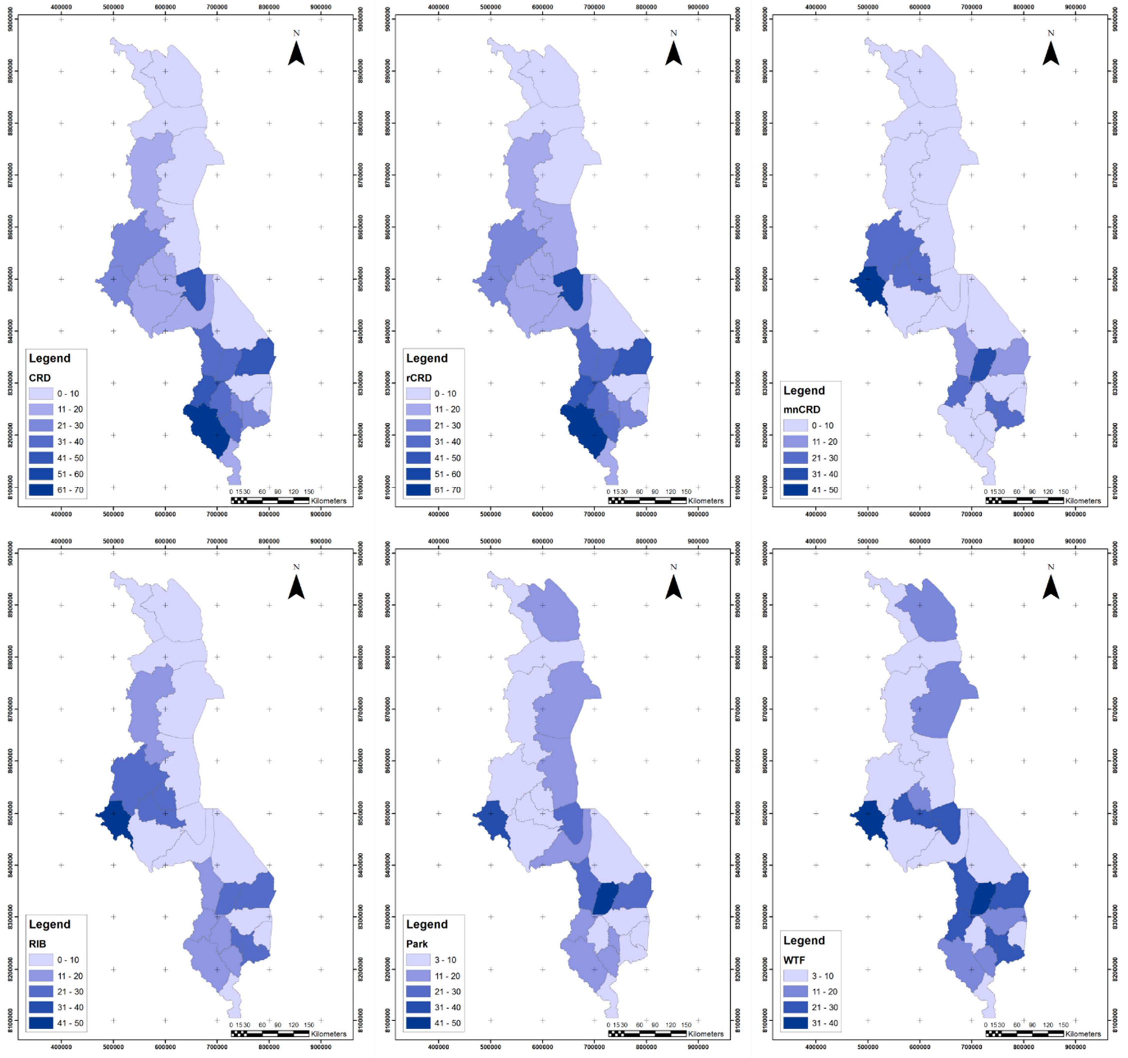


Figure A2. Average February groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A3 LTA estimated March recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	46.2	46.2	56.9	49.3	30.9	25.9	42.6	11.8
Blantyre	48.0	48.0	0.9	17.6	7.0	8.5	21.6	21.1
Chikwawa	69.2	69.2	21.8	15.8	8.7	13.7	33.1	28.3
Chiradzulu	28.4	28.4	24.0	22.8	14.3	18.3	22.7	5.6
Chitipa	7.5	7.5	8.2	6.9	4.3	8.6	7.2	1.5
Dedza	16.7	16.7	11.2	8.9	12.3	9.9	12.6	3.4
Dowa	17.4	17.4	22.9	24.7	5.8	16.8	17.5	6.6
Karonga	17.9	17.9	9.0	7.1	19.5	16.4	14.6	5.2
Kasungu	33.3	33.3	32.1	28.9	5.7	6.9	23.4	13.3
Lilongwe	17.9	17.9	16.5	11.6	6.2	7.7	13.0	5.2
Machinga	56.4	56.4	34.1	30.0	18.4	20.8	36.0	16.8
Mangochi	11.0	11.0	10.7	6.4	5.3	5.5	8.3	2.9
Mchinji	36.4	36.4	56.0	57.1	23.9	34.4	40.7	13.1
Mulanje	31.8	31.8	24.9	23.5	5.4	20.1	22.9	9.8
Mwanza	49.5	49.5	30.7	32.0	13.3	12.6	31.3	16.4
Mzimba	18.8	18.8	3.4	18.1	2.4	3.1	10.8	8.6
Nkhata Bay	14.5	14.5	12.2	10.2	16.0	19.4	14.5	3.2
Nkhotakota	12.6	23.2	2.0	0.0	15.0	5.8	9.8	8.8
Nsanje	12.2	12.2	4.5	12.4	7.0	5.4	9.0	3.7
Ntcheu	38.5	38.5	32.7	25.6	20.0	15.1	28.4	9.8
Ntchisi	15.7	15.7	21.6	21.8	5.2	16.0	16.0	6.0
Phalombe	0.0	0.0	9.5	7.8	4.9	8.6	7.7	2.0
Rumphi	14.8	14.8	2.5	0.7	7.3	2.7	7.2	6.3
Salima	60.4	68.2	2.7	5.6	16.5	18.7	28.7	28.4
Thyolo	46.9	46.9	2.2	13.3	14.4	9.7	22.3	19.6
Zomba	9.0	9.0	5.4	6.3	6.9	14.0	8.4	3.1

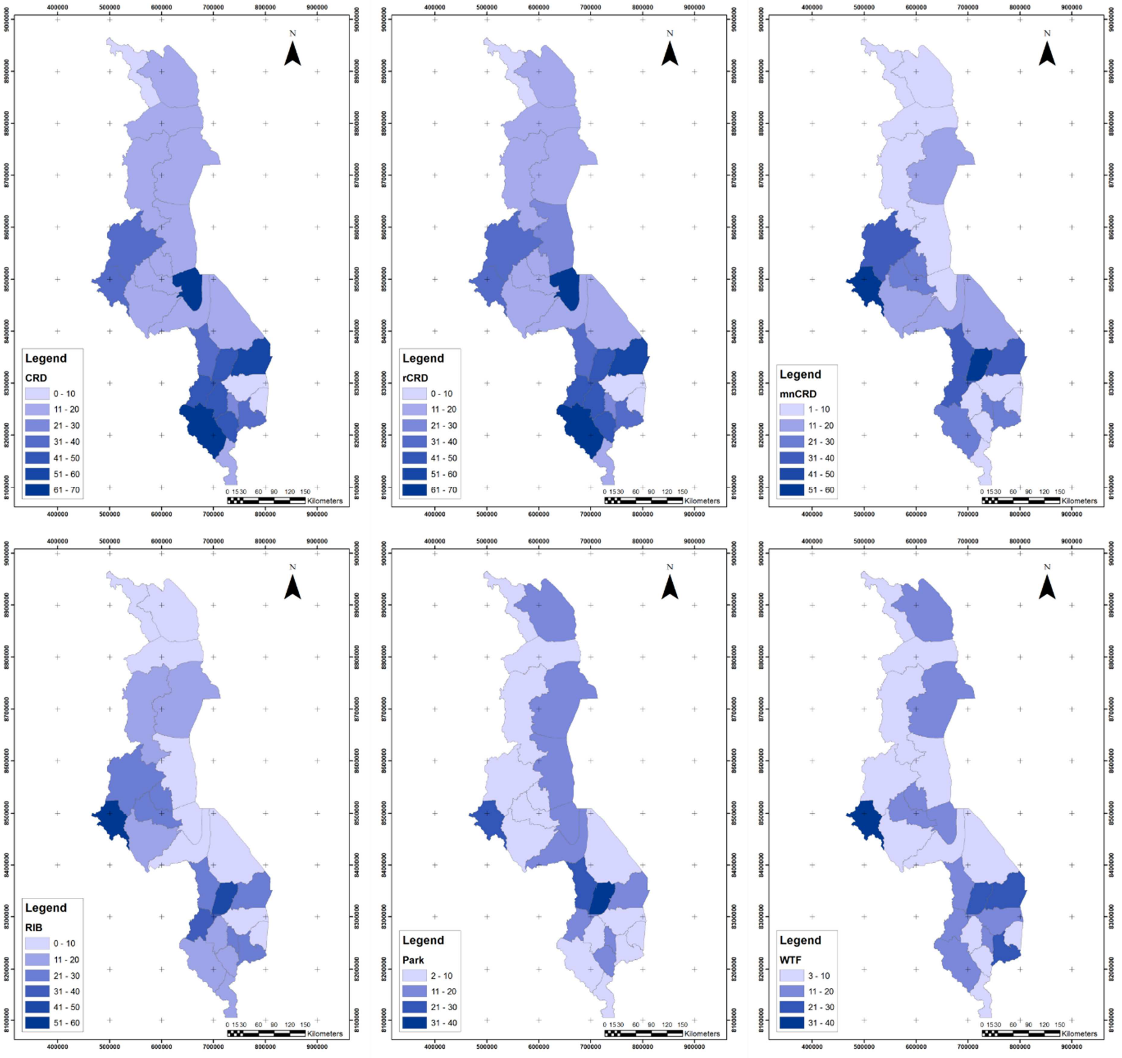
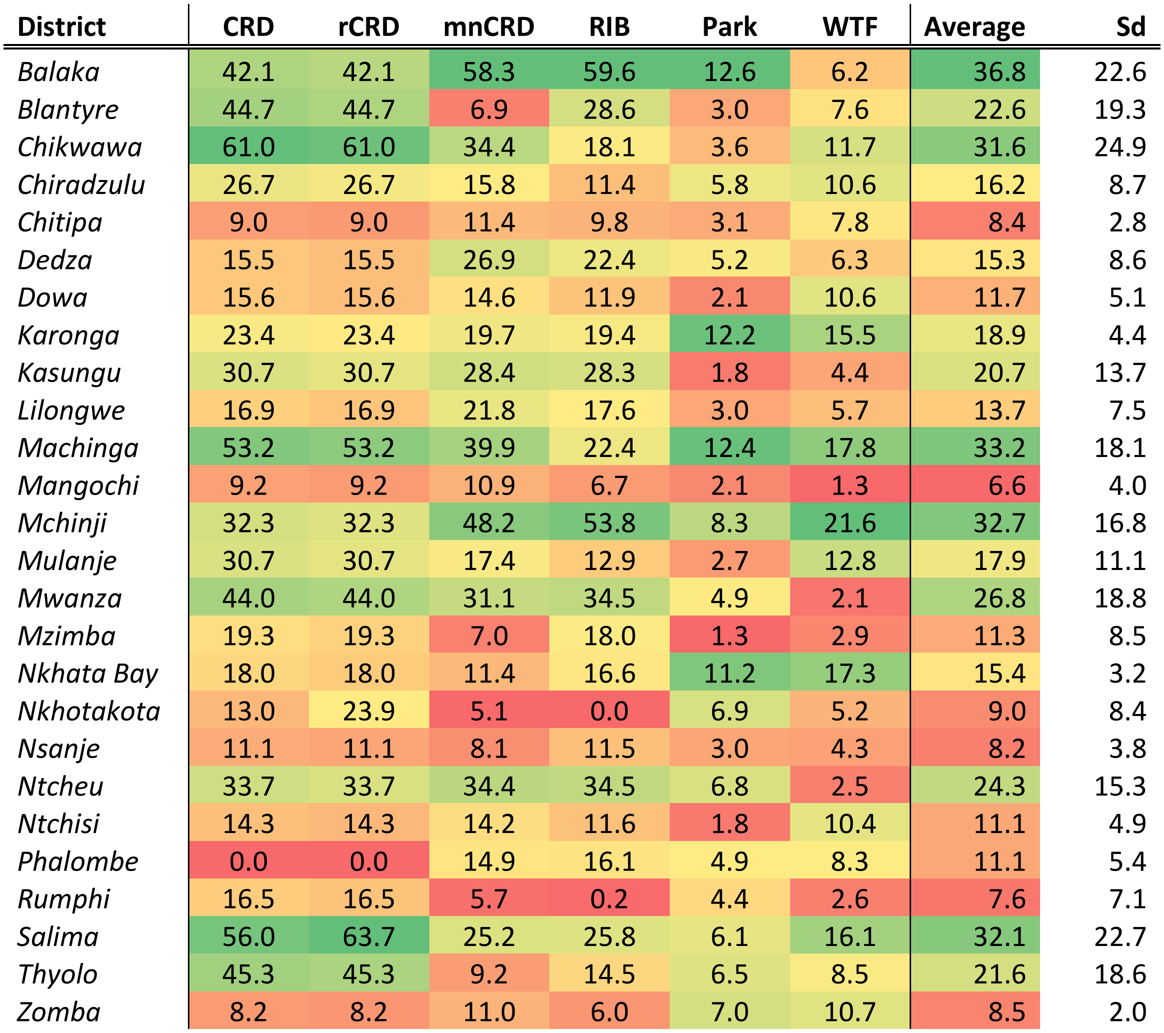


Figure A3. Average March groundwater recharge (mm/month) for the period from 2009 to 2014.

Table 4 LTA estimated April recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).



District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	42.1	42.1	58.3	59.6	12.6	6.2	36.8	22.6
Blantyre	44.7	44.7	6.9	28.6	3.0	7.6	22.6	19.3
Chikwawa	61.0	61.0	34.4	18.1	3.6	11.7	31.6	24.9
Chiradzulu	26.7	26.7	15.8	11.4	5.8	10.6	16.2	8.7
Chitipa	9.0	9.0	11.4	9.8	3.1	7.8	8.4	2.8
Dedza	15.5	15.5	26.9	22.4	5.2	6.3	15.3	8.6
Dowa	15.6	15.6	14.6	11.9	2.1	10.6	11.7	5.1
Karonga	23.4	23.4	19.7	19.4	12.2	15.5	18.9	4.4
Kasungu	30.7	30.7	28.4	28.3	1.8	4.4	20.7	13.7
Lilongwe	16.9	16.9	21.8	17.6	3.0	5.7	13.7	7.5
Machinga	53.2	53.2	39.9	22.4	12.4	17.8	33.2	18.1
Mangochi	9.2	9.2	10.9	6.7	2.1	1.3	6.6	4.0
Mchinji	32.3	32.3	48.2	53.8	8.3	21.6	32.7	16.8
Mulanje	30.7	30.7	17.4	12.9	2.7	12.8	17.9	11.1
Mwanza	44.0	44.0	31.1	34.5	4.9	2.1	26.8	18.8
Mzimba	19.3	19.3	7.0	18.0	1.3	2.9	11.3	8.5
Nkhata Bay	18.0	18.0	11.4	16.6	11.2	17.3	15.4	3.2
Nkhotakota	13.0	23.9	5.1	0.0	6.9	5.2	9.0	8.4
Nsanje	11.1	11.1	8.1	11.5	3.0	4.3	8.2	3.8
Ntcheu	33.7	33.7	34.4	34.5	6.8	2.5	24.3	15.3
Ntchisi	14.3	14.3	14.2	11.6	1.8	10.4	11.1	4.9
Phalombe	0.0	0.0	14.9	16.1	4.9	8.3	11.1	5.4
Rumphi	16.5	16.5	5.7	0.2	4.4	2.6	7.6	7.1
Salima	56.0	63.7	25.2	25.8	6.1	16.1	32.1	22.7
Thyolo	45.3	45.3	9.2	14.5	6.5	8.5	21.6	18.6
Zomba	8.2	8.2	11.0	6.0	7.0	10.7	8.5	2.0

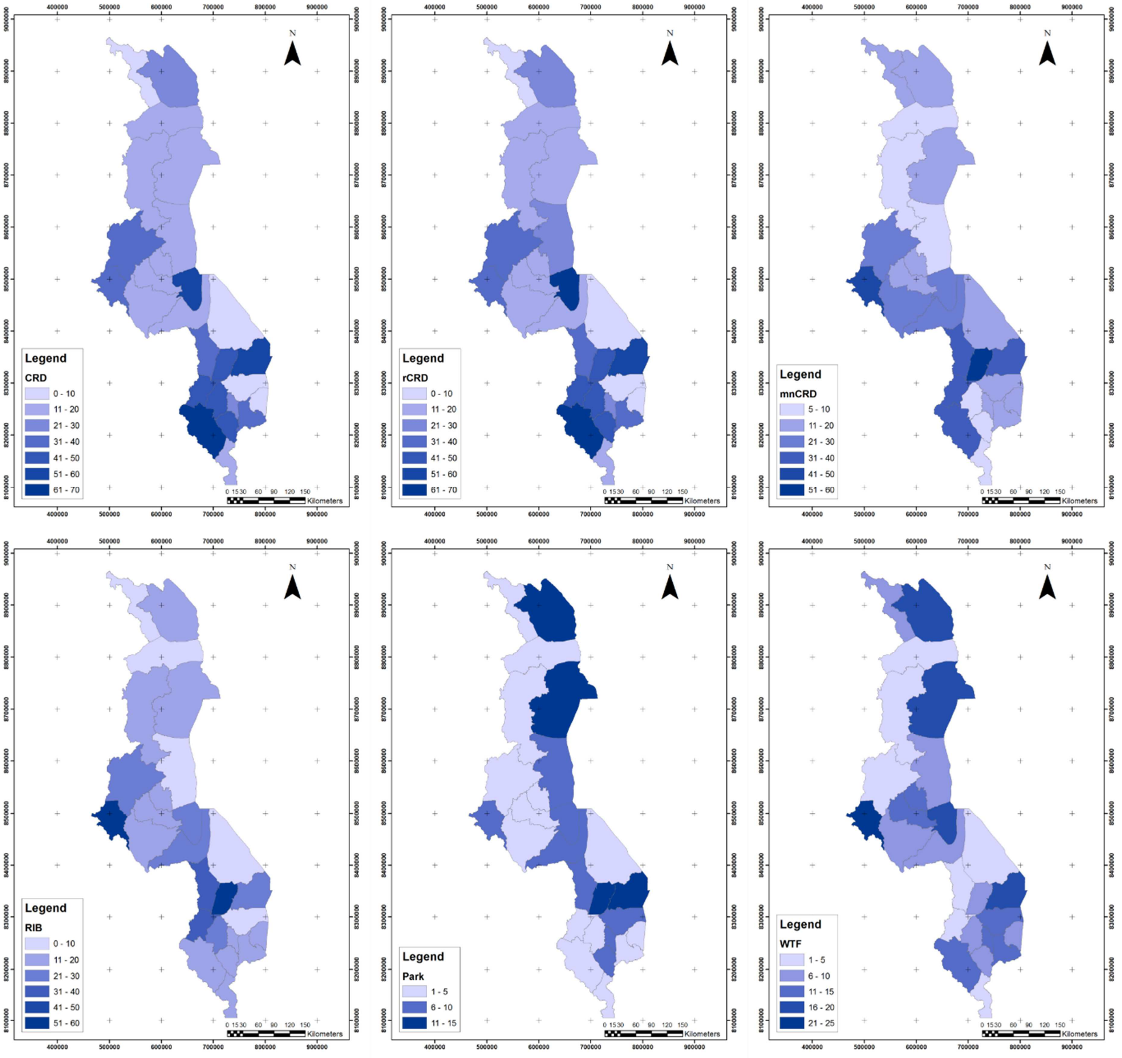


Figure A4. Average April groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A5 LTA estimated May recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	31.2	31.2	43.9	43.9	2.1	0.0	25.4	19.7
Blantyre	35.5	35.5	16.3	42.8	0.4	6.6	22.9	17.5
Chikwawa	48.7	48.7	39.1	28.6	0.7	10.3	29.3	20.1
Chiradzulu	22.1	22.1	3.8	1.2	0.9	2.4	8.8	10.4
Chitipa	7.0	7.0	10.6	10.9	0.4	4.3	6.7	4.0
Dedza	11.0	11.0	37.5	31.0	1.1	3.7	15.9	14.9
Dowa	10.5	10.5	2.7	0.7	0.1	5.8	5.1	4.7
Karonga	20.8	20.8	21.6	24.6	5.4	5.6	16.5	8.6
Kasungu	23.7	23.7	20.8	20.5	0.1	2.2	15.2	10.9
Lilongwe	10.4	10.4	20.2	17.0	0.2	3.8	10.4	7.6
Machinga	38.8	38.8	35.0	30.7	6.5	14.7	27.4	13.6
Mangochi	6.0	6.0	8.0	6.9	1.2	0.0	4.7	3.3
Mchinji	24.0	24.0	30.2	33.2	0.5	9.9	20.3	12.6
Mulanje	24.9	24.9	4.5	1.6	0.4	3.2	9.9	11.7
Mwanza	33.5	33.5	22.9	20.9	0.9	0.0	18.6	15.0
Mzimba	13.3	13.3	11.8	16.5	0.1	2.7	9.6	6.6
Nkhata Bay	13.7	13.7	4.7	20.7	3.4	8.8	10.8	6.5
Nkhotakota	9.9	19.3	9.7	0.0	1.1	4.3	7.4	7.2
Nsanje	8.3	8.3	13.0	12.2	0.6	3.3	7.6	4.9
Ntcheu	23.6	23.6	26.0	32.3	0.9	0.0	17.7	13.8
Ntchisi	10.1	10.1	3.4	0.7	0.1	5.4	5.0	4.4
Phalombe	0.0	0.0	11.6	13.1	4.0	8.0	9.2	4.1
Rumphi	13.3	13.3	10.9	6.4	1.3	2.0	7.9	5.4
Salima	41.4	48.8	45.0	39.2	0.8	13.9	31.5	19.5
Thyolo	36.7	36.7	20.3	19.6	1.1	7.3	20.3	14.7
Zomba	5.8	5.8	14.6	7.2	5.6	9.5	8.1	3.5

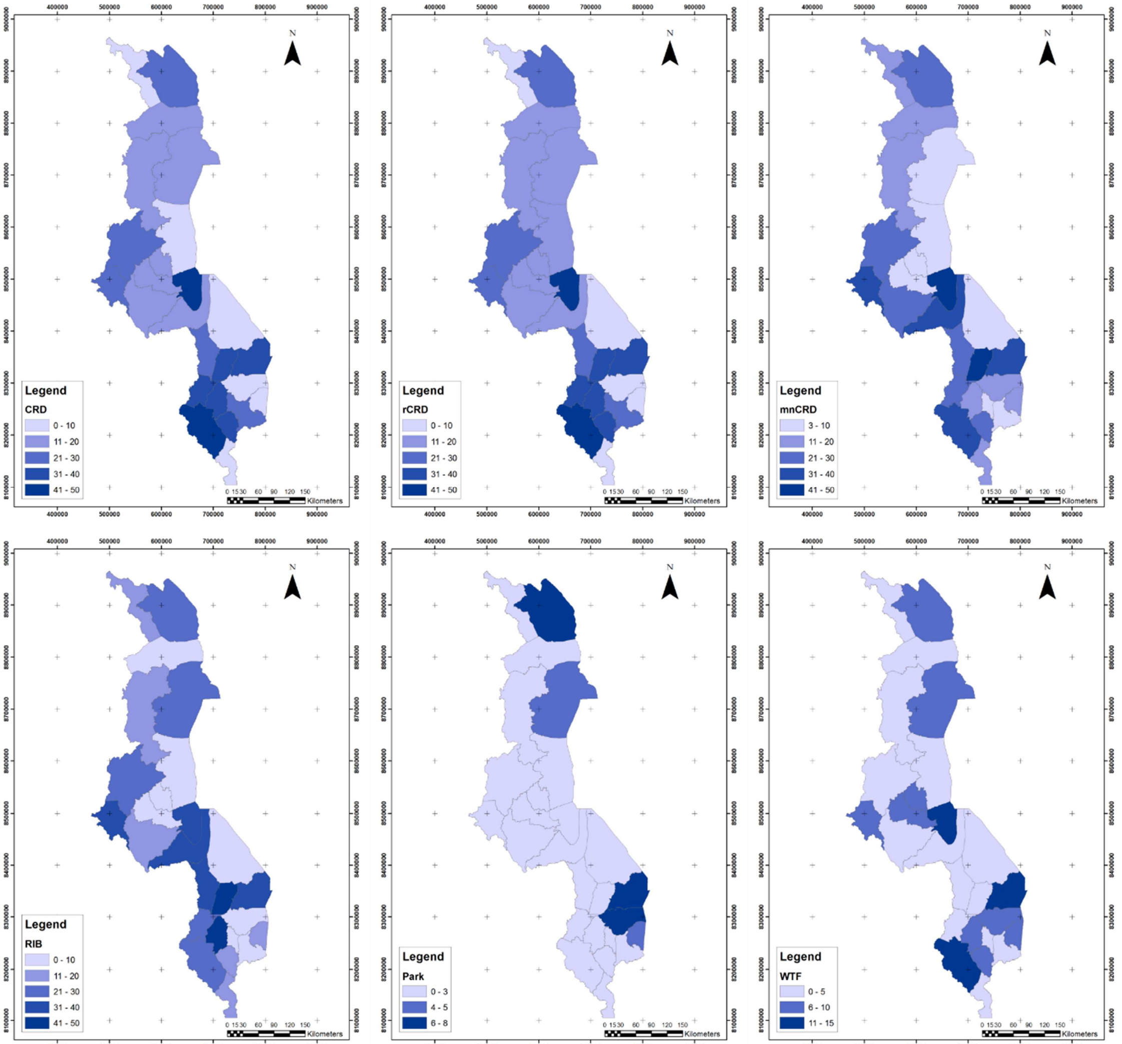


Figure A5 Average May groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A6 LTA estimated June recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	23.6	23.6	23.9	14.6	2.7	0.0	14.7	11.0
Blantyre	28.2	28.2	21.7	45.7	0.3	6.2	21.7	16.5
Chikwawa	37.6	37.6	36.9	36.3	0.4	9.8	26.4	16.8
Chiradzulu	18.2	18.2	0.0	0.0	0.8	0.0	6.2	9.3
Chitipa	4.7	4.7	7.2	8.8	0.1	1.5	4.5	3.3
Dedza	6.3	6.3	39.0	31.1	0.9	3.0	14.4	16.3
Dowa	6.0	6.0	0.0	0.0	0.1	4.1	2.7	3.0
Karonga	14.9	14.9	17.3	19.3	2.7	0.3	11.6	8.0
Kasungu	16.5	16.5	12.9	7.7	0.0	1.9	9.2	7.2
Lilongwe	4.3	4.3	14.1	8.9	0.1	2.9	5.8	5.0
Machinga	27.9	27.9	23.0	29.7	6.9	13.3	21.5	9.3
Mangochi	3.2	3.2	4.7	6.0	1.2	0.0	3.0	2.2
Mchinji	16.5	16.5	11.9	7.5	0.1	5.8	9.7	6.5
Mulanje	19.4	19.4	0.0	0.0	0.3	0.0	6.5	10.0
Mwanza	23.0	23.0	12.1	4.1	0.8	0.0	10.5	10.6
Mzimba	8.7	8.7	15.3	15.7	0.0	2.5	8.5	6.4
Nkhata Bay	8.9	8.9	0.1	20.0	1.0	4.4	7.2	7.3
Nkhotakota	6.4	13.9	13.8	5.7	0.3	3.9	7.3	5.5
Nsanje	5.8	5.8	14.9	12.9	0.1	2.8	7.0	5.7
Ntcheu	14.8	14.8	14.5	19.9	1.1	0.0	10.9	8.2
Ntchisi	6.5	6.5	0.0	0.0	0.0	3.8	2.8	3.2
Phalombe	0.1	0.1	3.2	4.8	4.1	7.8	5.0	2.0
Rumphi	9.3	9.3	15.8	11.1	0.4	1.6	7.9	5.9
Salima	26.4	33.6	51.9	43.7	0.6	13.1	28.2	19.1
Thyolo	29.0	29.0	26.4	35.9	0.4	6.7	21.3	14.2
Zomba	3.0	3.0	13.0	9.3	5.5	9.0	7.1	4.0

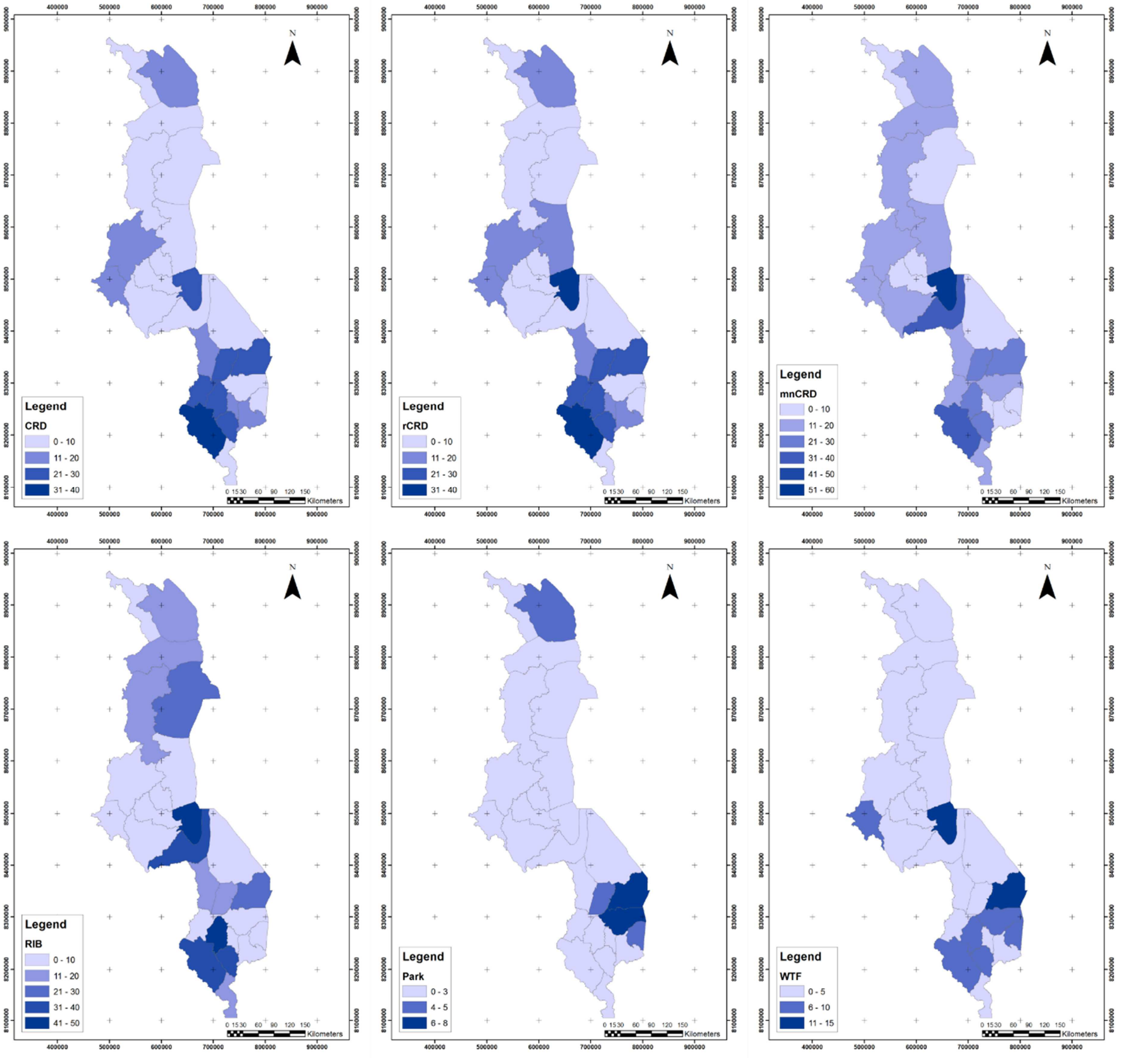


Figure A6. Average June groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A7. LTA estimated July recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	18.5	18.5	7.9	0.0	3.4	0.0	8.1	8.6
Blantyre	21.6	21.6	18.1	30.4	0.6	6.3	16.4	11.0
Chikwawa	28.0	28.0	28.1	40.5	0.9	9.8	22.5	14.4
Chiradzulu	14.6	14.6	0.0	0.0	1.1	0.1	5.0	7.4
Chitipa	3.0	3.0	3.5	4.2	0.0	1.2	2.5	1.6
Dedza	2.1	2.1	32.6	22.0	0.8	2.9	10.4	13.5
Dowa	3.1	3.1	0.0	0.0	0.0	4.1	1.7	1.9
Karonga	8.0	8.0	11.0	11.0	1.8	0.0	6.7	4.7
Kasungu	9.3	9.3	5.1	0.5	0.1	1.8	4.3	4.2
Lilongwe	1.9	1.9	7.5	0.4	0.1	2.9	2.5	2.7
Machinga	26.4	26.4	14.2	30.4	11.0	14.4	20.4	8.2
Mangochi	2.6	2.6	3.0	3.1	1.7	0.0	2.2	1.2
Mchinji	10.1	10.1	1.5	0.0	0.1	5.6	4.6	4.7
Mulanje	14.8	14.8	0.0	0.0	0.5	0.1	5.0	7.6
Mwanza	15.8	15.8	4.1	0.0	1.4	0.0	6.2	7.6
Mzimba	4.8	4.8	14.7	13.1	0.0	2.5	6.7	5.9
Nkhata Bay	4.9	4.9	0.0	15.9	0.8	3.1	4.9	5.7
Nkhotakota	3.1	8.5	14.4	9.2	0.2	3.8	6.5	5.1
Nsanje	3.7	3.7	13.5	12.6	0.3	2.8	6.1	5.5
Ntcheu	9.3	9.3	5.1	2.7	1.1	0.0	4.6	4.0
Ntchisi	3.6	3.6	0.0	0.0	0.0	3.7	1.8	2.0
Phalombe	1.7	3.4	1.1	2.0	7.1	8.6	4.7	3.7
Rumphi	5.4	5.4	17.9	13.2	0.4	1.6	7.3	6.9
Salima	12.7	18.4	45.9	40.1	0.6	13.1	21.8	17.5
Thyolo	22.0	22.0	23.2	31.8	1.1	6.7	17.8	11.5
Zomba	12.6	12.6	10.4	12.7	9.3	11.1	11.4	1.4

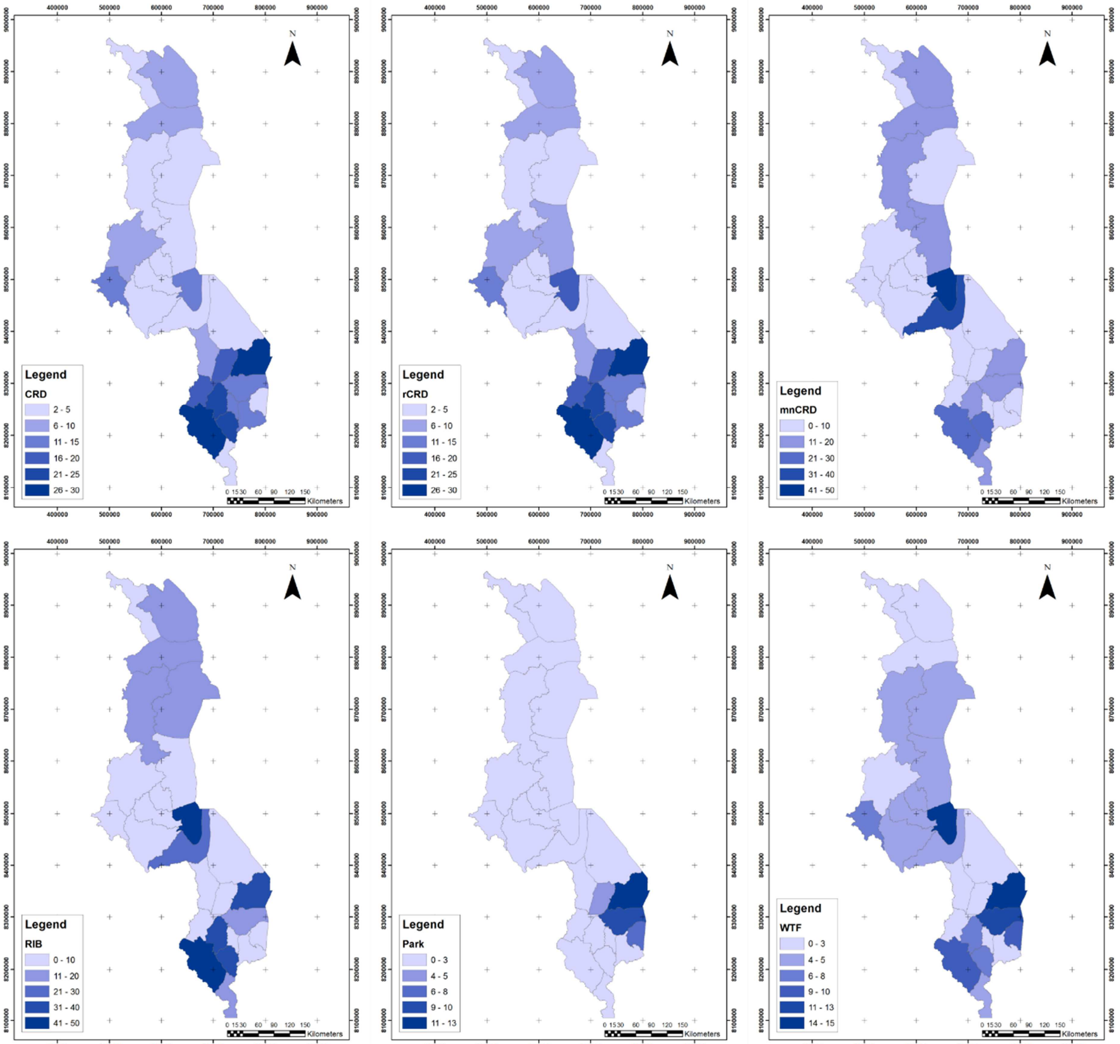


Figure A7. Average July groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A8. LTA estimated August recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	12.8	12.8	1.0	0.0	2.7	0.0	4.9	6.2
Blantyre	15.9	15.9	10.9	10.6	0.4	6.3	10.0	5.9
Chikwawa	18.9	18.9	15.7	40.4	0.6	9.8	17.4	13.3
Chiradzulu	11.7	11.7	0.0	0.0	0.8	0.0	4.0	6.0
Chitipa	1.6	1.6	0.9	1.3	0.0	1.2	1.1	0.6
Dedza	0.0	0.0	21.2	6.2	1.1	3.1	5.3	8.1
Dowa	1.0	1.0	0.0	0.0	0.0	4.1	1.0	1.6
Karonga	2.7	2.7	5.2	4.2	1.0	0.0	2.6	1.9
Kasungu	3.1	3.1	0.8	0.0	0.0	1.9	1.5	1.4
Lilongwe	0.3	0.3	1.9	0.0	0.0	2.9	0.9	1.2
Machinga	20.2	20.2	8.3	35.5	8.6	14.9	17.9	10.1
Mangochi	1.5	1.5	1.9	0.0	1.5	0.0	1.1	0.8
Mchinji	5.1	5.1	0.0	0.0	0.1	5.6	2.6	2.9
Mulanje	11.5	11.5	0.0	0.0	0.3	0.1	3.9	5.9
Mwanza	11.1	11.1	0.3	0.0	0.9	0.0	3.9	5.6
Mzimba	2.7	2.7	10.5	12.3	0.0	2.5	5.1	5.0
Nkhata Bay	1.7	1.7	0.0	9.8	0.3	3.0	2.7	3.6
Nkhotakota	1.0	3.5	11.6	9.7	0.2	3.8	5.0	4.7
Nsanje	2.2	2.2	9.1	12.8	0.4	2.8	4.9	4.9
Ntcheu	5.6	5.6	0.0	0.0	0.8	0.0	2.0	2.8
Ntchisi	1.3	1.3	0.0	0.0	0.0	3.7	1.0	1.4
Phalombe	1.3	2.6	0.4	1.3	5.2	8.9	4.0	3.9
Rumphi	2.2	2.2	16.9	13.6	0.2	1.5	6.1	7.2
Salima	4.1	7.2	31.2	27.5	0.9	13.1	14.0	12.6
Thyolo	14.9	14.9	14.2	17.0	0.9	6.7	11.4	6.2
Zomba	8.3	8.3	7.5	6.3	7.1	13.5	8.5	2.6

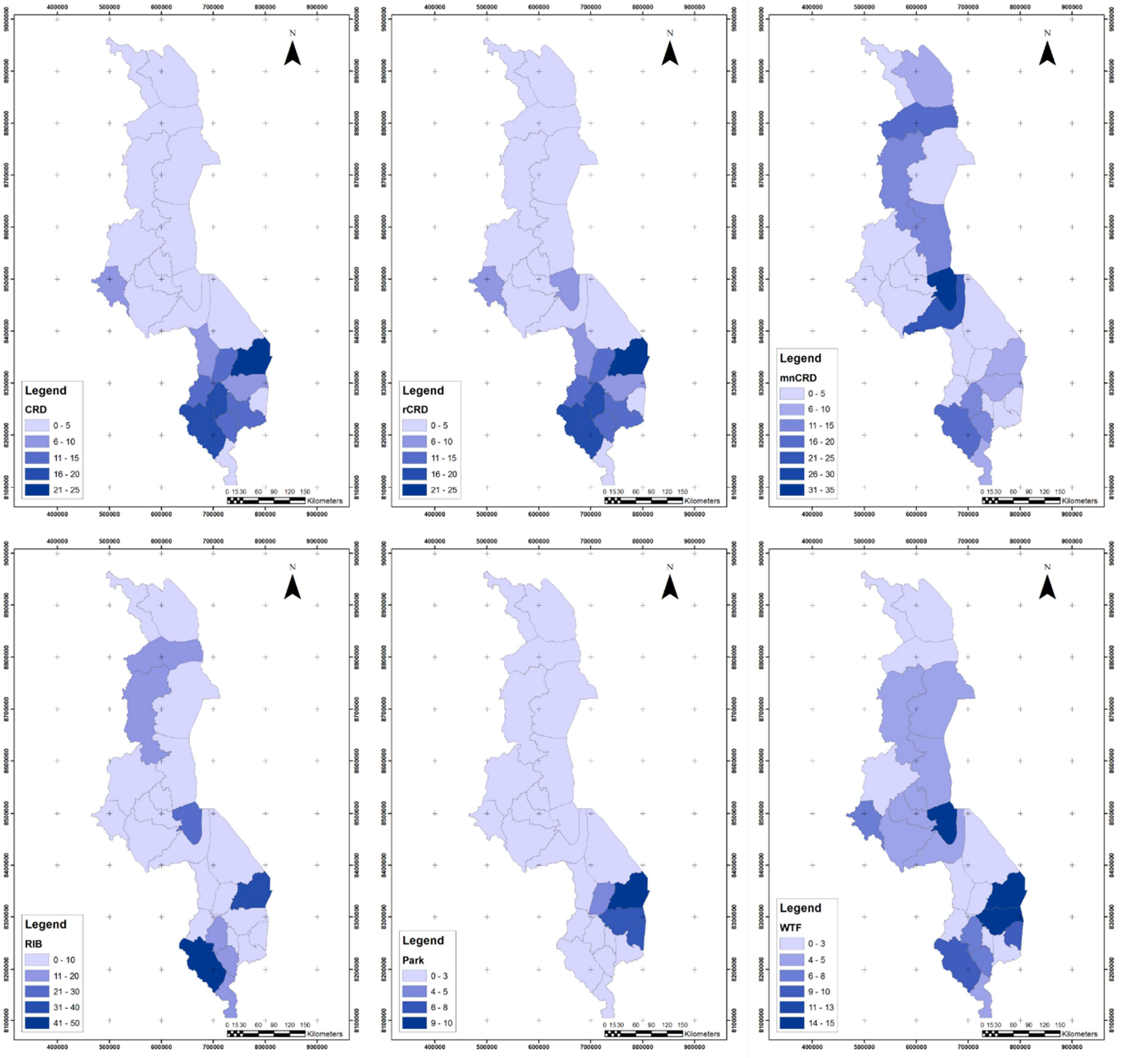


Figure A8. Average August groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A9. LTA estimated September recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	8.9	8.9	0.0	0.0	2.8	0.0	3.4	4.4
Blantyre	10.7	10.7	3.5	4.8	0.6	6.3	6.1	4.1
Chikwawa	11.3	11.3	5.6	40.6	0.8	9.8	13.2	14.0
Chiradzulu	9.3	9.3	0.0	0.0	1.0	0.0	3.3	4.7
Chitipa	0.7	0.7	0.0	0.2	0.0	1.2	0.5	0.5
Dedza	0.0	0.0	8.0	0.0	1.2	3.1	2.0	3.2
Dowa	0.0	0.0	0.0	0.0	0.1	4.1	0.7	1.7
Karonga	0.3	0.3	0.8	0.0	1.1	0.0	0.4	0.5
Kasungu	0.3	0.3	0.0	0.0	0.0	1.8	0.4	0.7
Lilongwe	0.0	0.0	0.0	0.0	0.1	2.9	0.5	1.2
Machinga	14.2	14.2	4.3	34.3	8.6	14.2	15.0	10.3
Mangochi	0.4	0.4	0.8	0.0	1.5	0.0	0.5	0.6
Mchinji	1.4	1.4	0.0	0.0	0.2	5.6	1.4	2.2
Mulanje	8.4	8.4	0.0	0.0	0.4	0.0	2.9	4.3
Mwanza	7.4	7.4	0.0	0.0	1.1	0.0	2.7	3.7
Mzimba	1.5	1.5	5.4	12.1	0.0	2.5	3.8	4.4
Nkhata Bay	0.2	0.2	0.0	4.1	0.2	2.5	1.2	1.7
Nkhotakota	0.2	0.8	6.4	9.8	0.1	3.8	3.5	3.9
Nsanje	1.1	1.1	4.1	12.8	0.4	2.8	3.7	4.7
Ntcheu	2.2	2.2	0.0	0.0	1.2	0.0	0.9	1.1
Ntchisi	0.2	0.2	0.0	0.0	0.0	3.7	0.7	1.5
Phalombe	2.9	5.7	4.4	7.7	5.6	8.5	6.5	1.9
Rumphi	0.7	0.7	13.1	13.9	0.2	1.5	5.0	6.6
Salima	0.3	1.0	13.7	6.7	0.9	13.2	6.0	6.2
Thyolo	9.7	9.7	4.8	15.9	1.0	6.7	8.0	5.1
Zomba	14.1	14.1	5.4	4.0	7.6	11.9	9.5	4.4

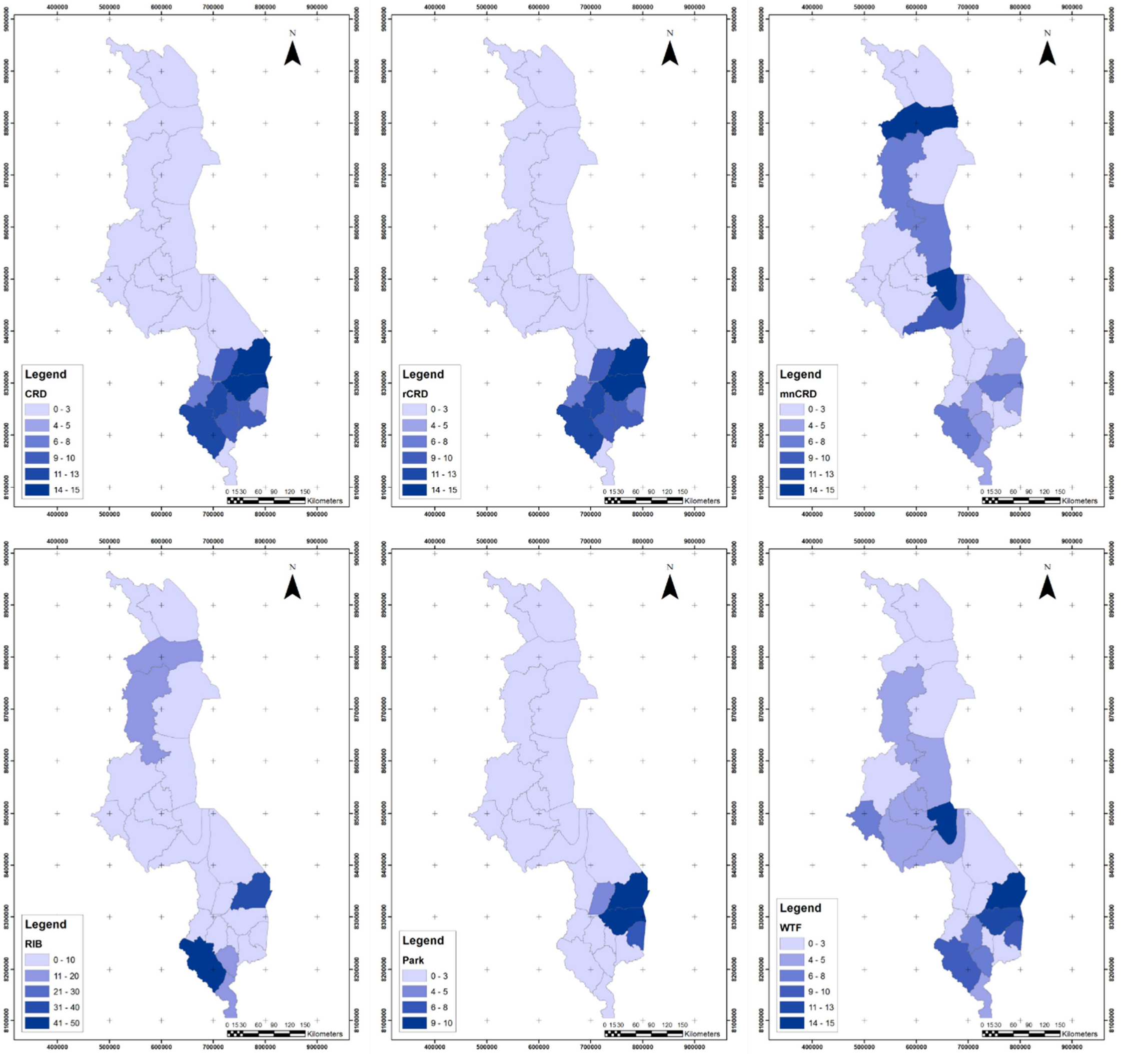


Figure A9. Average September groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A10. LTA estimated October recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	5.1	5.1	0.0	0.0	3.6	0.0	2.3	2.6
Blantyre	6.4	6.4	0.0	2.1	1.1	6.4	3.7	3.0
Chikwawa	4.6	4.6	0.0	41.6	1.2	9.9	10.3	15.7
Chiradzulu	7.5	7.5	0.0	0.0	2.4	0.3	3.0	3.7
Chitipa	0.3	0.3	0.0	0.0	0.3	1.4	0.4	0.5
Dedza	0.0	0.0	1.2	0.0	1.0	3.1	0.9	1.2
Dowa	0.0	0.0	0.0	0.0	0.2	4.2	0.7	1.7
Karonga	0.0	0.0	0.0	0.0	1.7	0.0	0.3	0.7
Kasungu	0.0	0.0	0.0	0.0	0.3	1.9	0.4	0.8
Lilongwe	0.0	0.0	0.0	0.0	0.4	3.0	0.6	1.2
Machinga	7.4	7.4	0.0	39.0	5.3	13.4	12.1	13.9
Mangochi	0.0	0.0	0.1	0.0	0.8	0.0	0.2	0.3
Mchinji	0.0	0.0	0.0	0.0	1.2	6.2	1.2	2.5
Mulanje	6.7	6.7	0.0	0.0	1.0	0.3	2.5	3.3
Mwanza	4.1	4.1	0.0	0.0	2.3	0.0	1.7	2.0
Mzimba	0.3	0.3	3.2	11.8	0.1	2.5	3.1	4.5
Nkhata Bay	0.0	0.0	0.0	0.0	1.1	2.9	0.7	1.2
Nkhotakota	0.0	0.0	3.0	9.8	0.5	3.8	2.8	3.8
Nsanje	0.4	0.4	1.4	13.1	1.2	2.9	3.3	4.9
Ntcheu	0.0	0.0	0.0	0.0	2.2	0.0	0.4	0.9
Ntchisi	0.0	0.0	0.0	0.0	0.1	3.8	0.7	1.6
Phalombe	1.9	3.8	7.5	8.1	3.3	8.0	6.7	2.3
Rumphi	0.0	0.0	7.7	14.3	0.6	1.6	4.0	5.8
Salima	0.0	0.0	1.5	0.0	0.7	13.1	2.6	5.2
Thyolo	6.0	6.0	0.0	3.1	2.4	6.9	4.1	2.6
Zomba	7.9	7.9	4.1	2.4	4.3	9.7	6.1	2.8

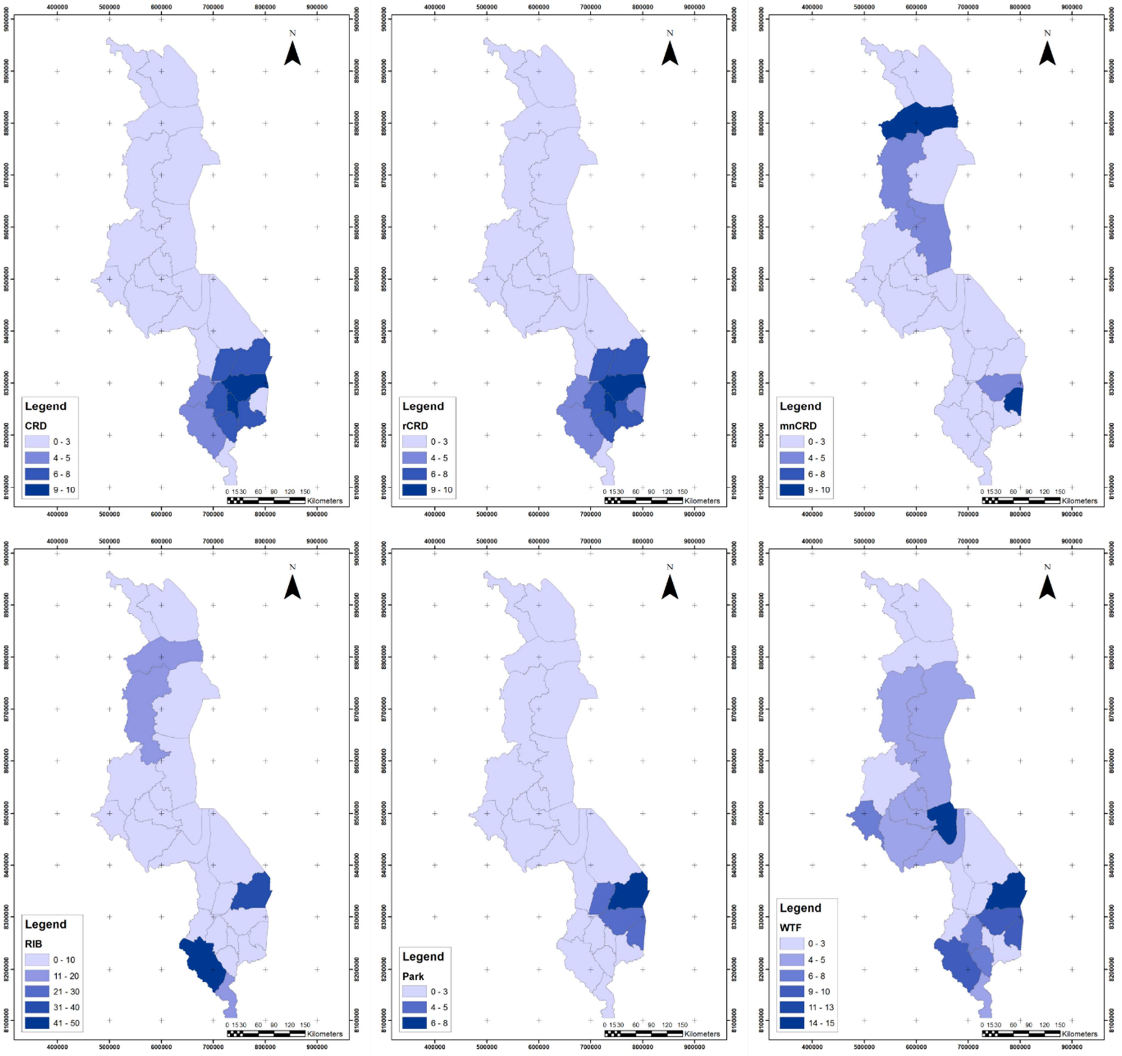


Figure A10. Average October groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A11. LTA estimated November recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	5.2	5.2	0.0	0.0	14.1	0.0	4.1	5.5
Blantyre	7.5	7.5	0.0	1.6	4.1	6.9	4.6	3.2
Chikwawa	6.4	6.4	0.0	48.7	6.1	10.9	13.1	17.8
Chiradzulu	9.2	9.2	0.0	0.0	7.1	4.1	4.9	4.2
Chitipa	0.3	0.3	0.0	0.0	1.3	2.6	0.7	1.0
Dedza	0.0	0.0	0.0	0.0	5.2	3.1	1.4	2.3
Dowa	0.0	0.0	0.0	0.0	2.6	6.4	1.5	2.6
Karonga	0.0	0.0	0.0	0.0	4.4	0.0	0.7	1.8
Kasungu	0.0	0.0	0.0	0.0	2.4	2.1	0.7	1.2
Lilongwe	0.0	0.0	0.0	0.0	3.7	4.2	1.3	2.0
Machinga	3.7	3.7	0.0	45.8	8.7	13.6	12.6	16.9
Mangochi	0.0	0.0	0.0	0.0	2.5	0.0	0.4	1.0
Mchinji	0.7	0.7	0.0	0.0	13.1	12.8	4.5	6.5
Mulanje	8.3	8.3	0.0	0.0	2.8	5.0	4.1	3.8
Mwanza	6.1	6.1	0.0	0.0	10.6	1.4	4.0	4.3
Mzimba	0.6	0.6	1.8	12.5	1.0	2.6	3.2	4.6
Nkhata Bay	0.0	0.0	0.0	0.0	5.0	3.7	1.5	2.3
Nkhotakota	0.0	0.0	2.0	9.4	3.7	4.0	3.2	3.5
Nsanje	0.5	0.5	0.2	12.0	3.7	3.5	3.4	4.5
Ntcheu	0.0	0.0	0.0	0.0	11.3	0.3	1.9	4.6
Ntchisi	0.0	0.0	0.0	0.0	1.9	5.6	1.2	2.3
Phalombe	0.0	0.0	5.0	7.9	3.2	7.4	5.9	2.2
Rumphi	0.0	0.0	4.0	14.9	2.2	1.7	3.8	5.6
Salima	0.0	0.0	0.0	0.0	5.3	13.7	3.2	5.6
Thyolo	7.3	7.3	0.0	3.3	7.6	7.5	5.5	3.2
Zomba	0.0	0.0	5.2	0.0	4.1	6.2	2.6	2.9

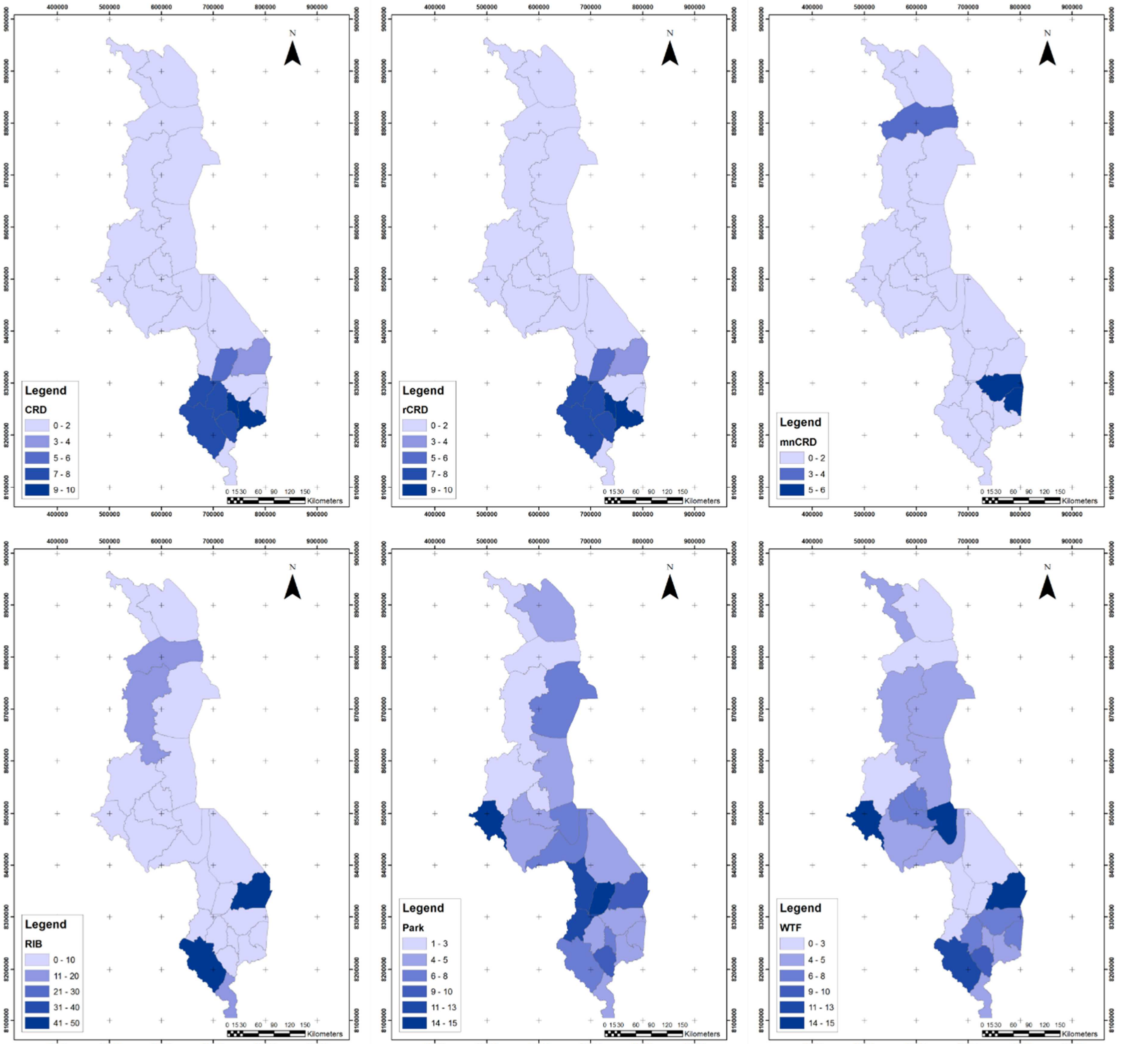


Figure A11. Average November groundwater recharge (mm/month) for the period from 2009 to 2014.

Table A12. LTA estimated December recharge for the period from 2009 to 2014. The colour represents, for each column, the relative value of the recharge from low (red) to high (green).

District	CRD	rCRD	mnCRD	RIB	Park	WTF	Average	Sd
Balaka	10.5	10.5	0.0	0.0	37.6	11.8	11.7	13.8
Blantyre	14.9	14.9	0.0	1.5	9.0	8.1	8.1	6.3
Chikwawa	18.0	18.0	0.0	38.1	15.3	13.2	17.1	12.3
Chiradzulu	11.5	11.5	2.9	3.2	16.9	13.0	9.8	5.6
Chitipa	1.0	1.0	0.0	0.0	4.0	6.0	2.0	2.4
Dedza	0.0	0.0	0.0	0.0	11.9	5.9	3.0	5.0
Dowa	0.0	0.0	0.1	0.3	5.9	11.1	2.9	4.6
Karonga	0.8	0.8	0.0	0.0	13.6	5.9	3.5	5.4
Kasungu	0.9	0.9	0.6	0.0	5.5	4.0	2.0	2.2
Lilongwe	0.3	0.3	0.0	0.0	6.7	6.1	2.2	3.2
Machinga	10.8	10.8	0.0	41.2	21.7	17.7	17.0	14.0
Mangochi	0.4	0.4	0.2	0.0	5.4	1.8	1.4	2.1
Mchinji	4.8	4.8	1.9	0.0	27.1	25.6	10.7	12.3
Mulanje	11.0	11.0	3.1	3.5	5.9	14.1	8.1	4.5
Mwanza	12.5	12.5	0.0	0.0	20.9	11.7	9.6	8.2
Mzimba	1.2	1.2	0.4	15.2	2.3	2.9	3.9	5.6
Nkhata Bay	0.0	0.0	0.0	0.0	11.4	10.3	3.6	5.6
Nkhotakota	0.0	0.3	1.1	7.4	10.4	4.7	4.0	4.3
Nsanje	2.7	2.7	0.0	11.0	10.3	4.9	5.3	4.5
Ntcheu	3.6	3.6	0.0	0.0	24.8	7.6	6.6	9.3
Ntchisi	0.1	0.1	0.0	0.5	4.7	10.0	2.6	4.1
Phalombe	0.0	0.0	2.6	4.7	5.8	8.0	5.3	2.3
Rumphi	0.5	0.5	2.2	11.4	6.1	2.3	3.8	4.2
Salima	0.0	0.0	0.0	0.0	14.5	15.7	5.0	7.8
Thyolo	14.9	14.9	0.0	3.0	18.6	9.0	10.1	7.4
Zomba	0.0	0.0	2.7	3.6	8.1	8.7	3.8	3.8

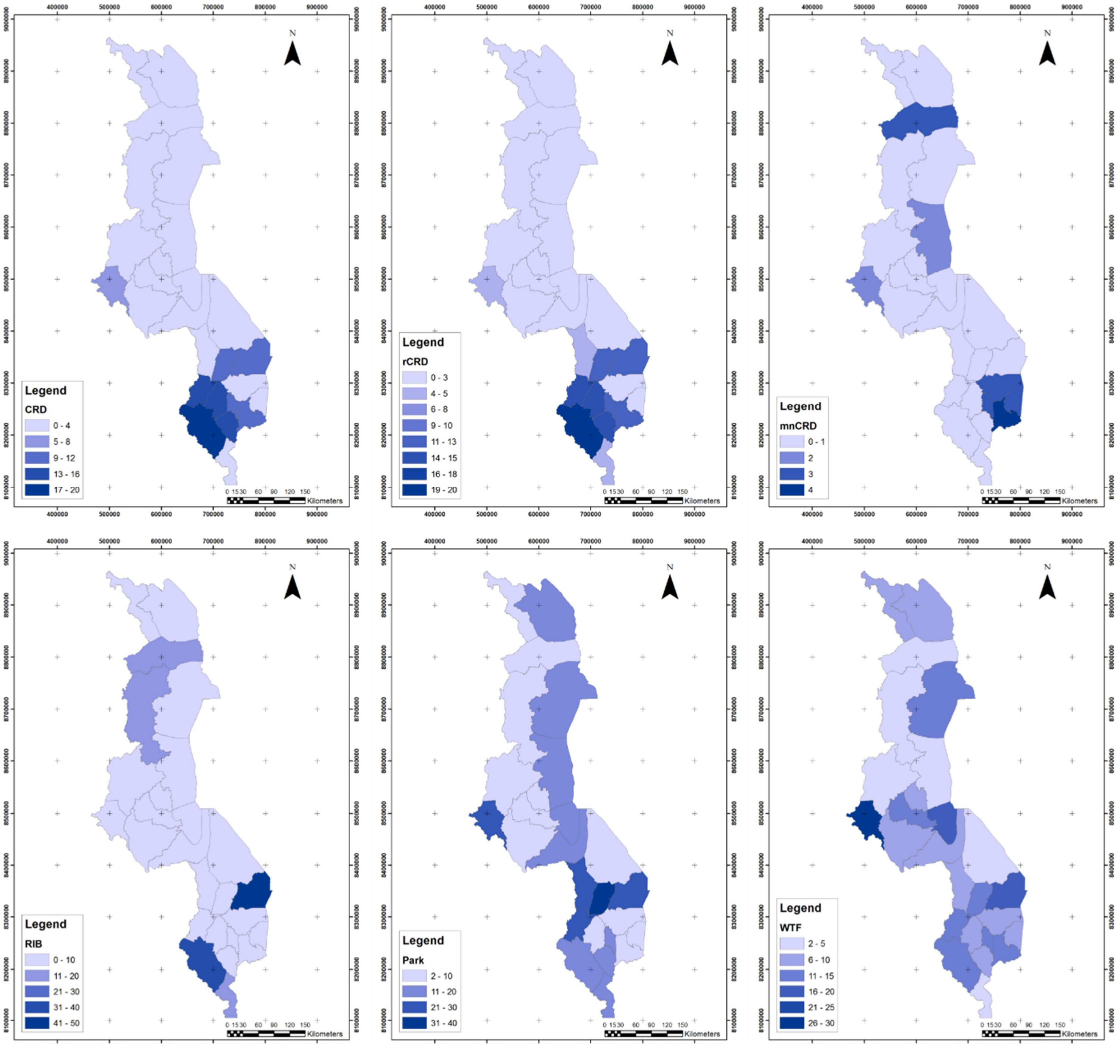


Figure A12. Average December groundwater recharge (mm/month) for the period from 2009 to 2014.