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Malawi Hydrogeological and Water Quality Mapping: Assessing Groundwater Resources Under Extreme Weather

Groundwater Directorate

Commissioned Report CR/15/107

BRITISH GEOLOGICAL SURVEY

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Malawi Hydrogeological and Water Quality Mapping: Assessing Groundwater Resources Under Extreme Weather

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Executive Summary

The distributed recharge model developed by Scheidegger et al. (2015) is used to estimate the recharge values under extreme weather events. Synthetic extreme dry and wet rainfall and evaporation time series are produced by repeating a dry or a wet year within the historical rainfall and evaporation time series. The Standardised Precipitation Index (SPI) method is used to identify the most wet and most dry years. Heat maps showing the severity of drought or wet periods across the country are used. These maps show inconsistencies of the calculated indices across the country, with oddities observed in the north part of the country. Six scenarios are considered in which, the wet year is repeated once, twice, and three times and then the dry year is repeated in the same fashion. The estimated long term average recharge values are compared to the historical ones. On average, the groundwater system is expected to be in shortage of 9% of historical long term average recharge values calculated for the country when four successive years of drought years are considered. The groundwater system contains approximately 11 % more resources than that is calculated historically when four successive wet years are considered.

AquiMod lumped groundwater model is used to estimate representative transmissivity and storage coefficient values for three catchments. Groundwater levels recorded at the boreholes in Chitipa, Endongolweni School, and Namwera are used for this purpose. The numerical model produces acceptable groundwater time series for the first two boreholes but fails to produce the groundwater level fluctuations at the Namwera borehole. It is believed that inconsistencies between the calculated recharge and the groundwater level time series are the reason for this failure. The optimised hydrogeological parameters lead to transmissivity values varied between 20 and 1500 m2/day. Storage coefficient (specific yield) on the other hand varied between 0.02 and 0.3.

The AquiMod models were run using the synthetic meteorological extreme scenarios and the groundwater level fluctuations are compared to those produced using the historical recharge values. The uncertainties associated with the determination of extreme weather periods in the northern Malawi are propagated in this modelling exercise. Whereas the higher extreme weather signals in the south lead to the determination of clearly identifiable extreme weather events, the less clear signals in the north induce the production of incorrect synthetic wet scenarios for this region.

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 studying potential impacts of extreme weather on the flow regime, and groundwater modelling in selected water resources areas as 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 building a recharge model for the whole country. BGS report CR/15/61 (*Scheidegger et al.*, 2015) addresses these tasks. This report only describes the application of the distributed recharge model ZOODRM (*Mansour and Hughes*, 2004) to predict the effects of extreme weather events, aimed at producing groundwater drought vulnerability and water scarcity maps. The recharge model was run to produce different recharge scenarios in which the weather conditions were artificially altered. The produced recharge values were assessed to inform the status of groundwater levels and flows under these conditions. The altered weather conditions were created by running a drought year or a wet year several times during the recharge simulations to produce drought periods or to create flooding periods respectively.

Task 4.5 also includes the development of detailed groundwater models for selected water resources areas. While the intention was to create fully distributed groundwater flow models to simulate the groundwater heads and flows in these areas, it was not possible to undertake this task due to lack of data. An alternative approach for groundwater modelling was used. This consisted of the application of the lumped groundwater simulator AquiMod (*Mackay et al*., 2014) to reproduce the groundwater head fluctuations at the major boreholes of interest. This approach allows the calculation of the transmissivity and storage coefficient values that are representative of the whole catchment corresponding to the borehole under investigation. Once the structure of the lumped groundwater model is defined (number of layers) and the storage coefficient and transmissivity values were determined, the extreme weather recharge values were used to produce new sets of groundwater level hydrographs.

Following this introduction, the second section of this report discusses the modification of historical rainfall values to produce new time series of rainfall representing wet and dry conditions. The third section describes the use of the modified weather data in the recharge model to inform the status of groundwater levels and flows under these conditions. The fourth section describes the use of the AquiMod model and its calibration to produce the representative values of transmissivity and storage coefficient for each studied water resources catchment. Finally, the last section discusses groundwater level status under the altered weather conditions.

2 The alteration of weather data to produce extreme weather periods

The aim of this section is to study the statistical characteristics of the rainfall data in order to produce artificial sequences of dry and wet weather events. The Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), or the Standardized Groundwater Index (SGI) are methods that are commonly used in the literature to determine and describe the historic hydrological extremes. Since precipitation time series are altered only, the SPI method is used. The basic principles on which these indexes are based are given as a start. The historic rainfall data used to estimate the national scale recharge values is described by Scheidegger et al. (2015).

2.1 DESCRIPTION OF THE STANDARIZED PRECIPITATION INDEX (SPI) METHOD TO CALCULATE EXTREME WEATHER INDICES

In hydrological science, a number of methods have been proposed for determining extreme weather events. For example many drought indices have been developed from the 1990s in order to characterise drought severity, duration and spatial extent, and compare different extreme events in a consistent manner (*Mishra et al*., 2010). These indices can be based on meteorological, hydrological, agricultural and other dimensions of extreme. One of the most used methods of meteorological extreme is the SPI (*McKee et al.*, 1993; *Hayes et al*., 2011). The SPI method consists of a normalised index obtained by fitting a gamma distribution to long-term precipitation records, where fitting is done for each calendar month to account for seasonal differences. The monthly fitted distributions are then transformed to a standard normal distribution and the estimated standardised values combined to produce the SPI time series. The SPI has been used widely to characterise meteorological drought and has even been recommended by the WMO as an index of choice for this kind of application (WMO, 2012).

This approach has a number of advantages. Only one relatively commonly available parameter is required (precipitation). It can be estimated for a variety of timescales (by using precipitation data for a range of accumulation periods, e.g. from 1 month to several years). It is relatively simple and spatially constant. On the other hand it requires a sufficiently long precipitation time series, with a consistent length where multiple sites are being evaluated and compared.

The SPEI is an extension of the SPI approach and that includes atmospheric water demand (*Vincente-Serrano et al*., 2010). The SGI builds on the SPI to account for differences in the form and characteristics of groundwater level and precipitation time series (*Bloomfield and Marchant*, 2013). It is estimated using a non-parametric normal scores transform of groundwater level data for each calendar month. These monthly estimates are then merged to form a continuous index.

Concerning the SPI, the index is fitted to a time series of the recorded precipitation at sites for accumulation periods of 1-24 or more months. An example of SPI continuous time series obtained for rainfall accumulation periods of 3 and 12 months at the Makanga gauging station in Malawi is shown in Figure 1. The coloured diagram of this figure shows the SPI values produced for every reading of the time series used, while the black diagram shows the same SPI values but plotted against real dates. A gap in the rainfall readings appears between the years 1990 and 2000 because of the missing precipitation information during that period. The resulting SPI is a continuous variable; however one can arbitrarily define extreme intensity according to the SPI value. For example, *McKee et al*. (1993) denoted SPI<-2 corresponding to extreme drought, -2<SPI<-1.5 corresponding to severe drought, -1.5<SPI<-1.0 corresponding to moderate drought, -1<SPI<0 corresponding to minor drought and SPI>0 corresponding to no drought. Similar intervals can be defined to the intensity of wet weathers. Taking Figure 1 as example, an extreme drought can be observed in 1983, and an extreme wet event in 2001.

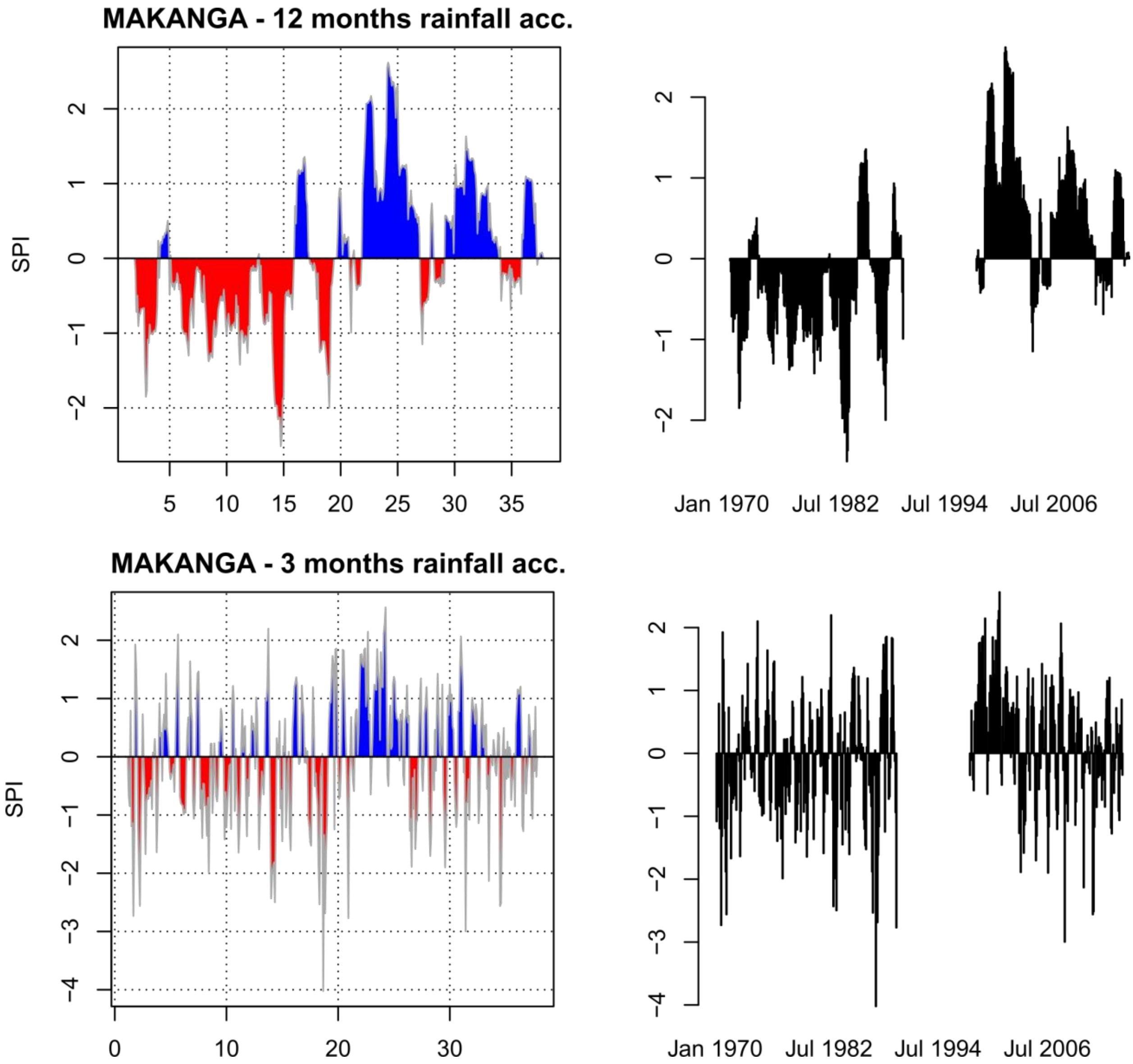

Figure 1 Example of SPI time series obtained for 3 months and 12 months rainfall accumulation for the Makanga gauging station in Malawi. The gap in data that can be observed on the black plots is explained in the following subsection

2.2 PREPARATION OF THE DATASETS

The historical rainfall data available for Malawi are described by Scheidegger et al. (2015). There are two sets of rainfall data. The first set includes time series of rainfall data recorded at 19 gauging stations that are plotted in Figure 2. The time series cover the period from 1970 to 1990 only. These rainfall data were used by Scheidegger et al. (2015) to calibrate the distributed recharge model since river flow data were only available for this period of time.

The second set of rainfall data is gridded daily data that are obtained from TRMM and cover the years from 1998 to 2014. In order to improve the quality of statistical analysis, this set of data was processed and time series of rainfall data were produced at the 19 gauging station locations. Therefore 19 time series covering the periods 1970-1990 and 1998-2014 were obtained corresponding to the locations of the 19 rainfall gauging stations in Malawi. A 38 years' worth of data were therefore available to statistically analyse, however, with a substantial gap between 1990 and 1998. It has to be noted that for the gauging station Chileka, some gauged daily rainfall data are available from 1990 to 2015. However numerous gaps in the dataset exist which prevented the use of these data to produce the statistics regarding the hydrological extremes. The merged rainfall time series are plotted in Figure 3.

The prepared time series are then used to calculate hydrological extreme indexes. The results are summarised in the next subsection.

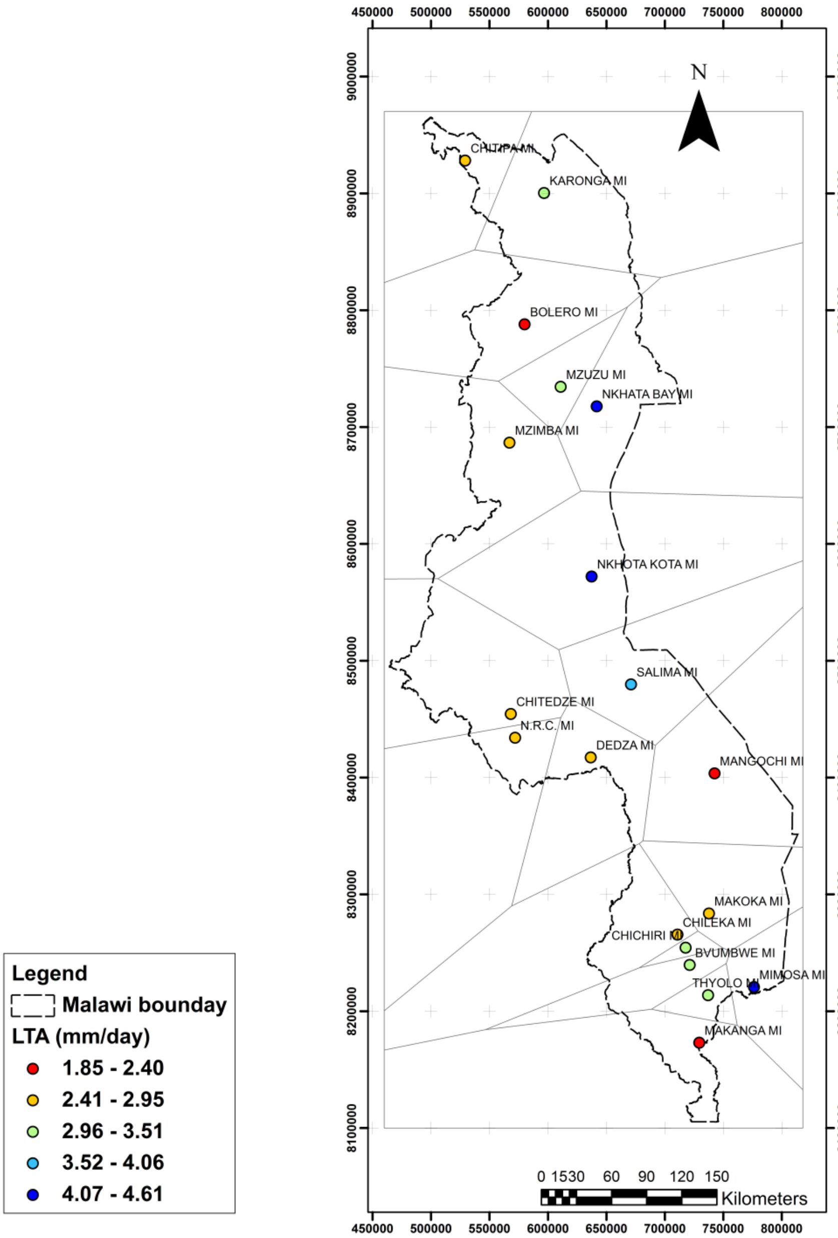

Figure 2 Location of the 19 weather gauging stations used in this study, Geographical boundary of Malawi (MASDAP, http://www.masdap.mw/)

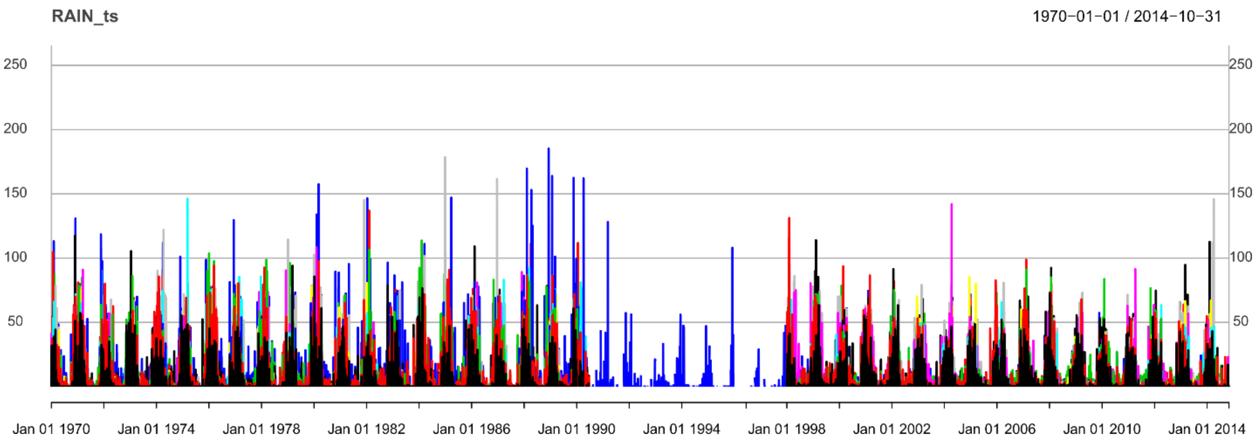

Figure 3 Merged daily rainfall time series (mm/day) for the 19 Malawi gauging stations, extracted from the daily gridded TRMM rainfall dataset

2.3 APPLICATION OF A NUMBER OF DROUGHT/EXTREME INDEXES AND DETERMINATION OF THE EXTREM PERIODS IN THE HISTORICAL DATASETS

SPI time series are produced for different rainfall accumulations (1-24 months) for the 19 gauging stations in Malawi. In order to facilitate the presentation of the results, heat maps were produced using R scripts (*R Core Team*, 2015 and packages SPEI, lattice, lubridate, TTR, xts). These heat maps display the temporal evolution of the SPI for the 19 gauging stations in one figure. The heat map shows a projection of the SPI values along the time axis for each gauging station with the given colour giving the intensity of the SPI values as shown on the scale to the right hand side of the figure (see for example Figure 4).

Six heat maps are presented, 3 representing the SPI for 3 months rainfall accumulation for both the drought and wet SPI indices (Figure 4), the drought SPI indices (Figure 5), the wet SPI indices (Figure 6) and the other three maps showing the same information but for the 12 months rainfall accumulation. The indices of drought and wet event are separated in order to facilitate the observation of extreme events.

For the drought index maps, the darker red colour indicates lower SPI value meaning period with drier conditions. Conversely, for a wet index map, the darker blue colour indicates higher SPI value meaning a period with wetter conditions. A quick glance over these maps allows the observation of patterns that are relatively consistent over the 19 gauging stations (it is more easily observed in the second set of figures representing the SPI calculation for 12 months rainfall accumulation), even if a number of exceptions occur. Relatively intense droughts for Malawi can be observed in 1972, 1983, 1987, 2004 and 2011. Relatively intense wet events for Malawi can be observed in 1974, 1985, 1999 and 2001.

The calculations are compiled and summarised. For each year a mean and median of the SPI is calculated, for each gauging station, for each SPI calculation. The years are then ranked in order to find the years the more likely to be a dry or a wet years. It has been concluded that drought years are 1973, 1983, 1987, 2004 and 2011, and wet years are 1974, 1985, 1999 and 2001; however, the wettest year is believed to be the year 2001 and the driest years is believed to be the year 2004. In the following sections of the report, the distributed recharge modelling and groundwater level time series modelling will be undertaken for the period between 2000 and 2014 (because of the availability of more reliable potential evapotranspiration data). Therefore, the 2004 drought and the 2001 wet event will be used as extreme years for producing the synthetic hydrological extreme scenarios.

It has to be noted that these time period were chosen using the results of the SPI calculations for the entire country. However the occurrence of extreme weather is not necessarily concomitant in every place in Malawi. This can be observed in the heat maps presented in this section. For example, in Figure 7, the 2004 drought period is not observed for the following stations: Bolero, Chitipa, Karonga and Mzimba. These station are situated in the northern Malawi (see Figure 2). Moreover it is generally more difficult to identify clear weather extremes for these stations. The uncertainty for extreme weather identification is therefore higher for the northern part of the country, and this must be kept in mind in each further step of this study.

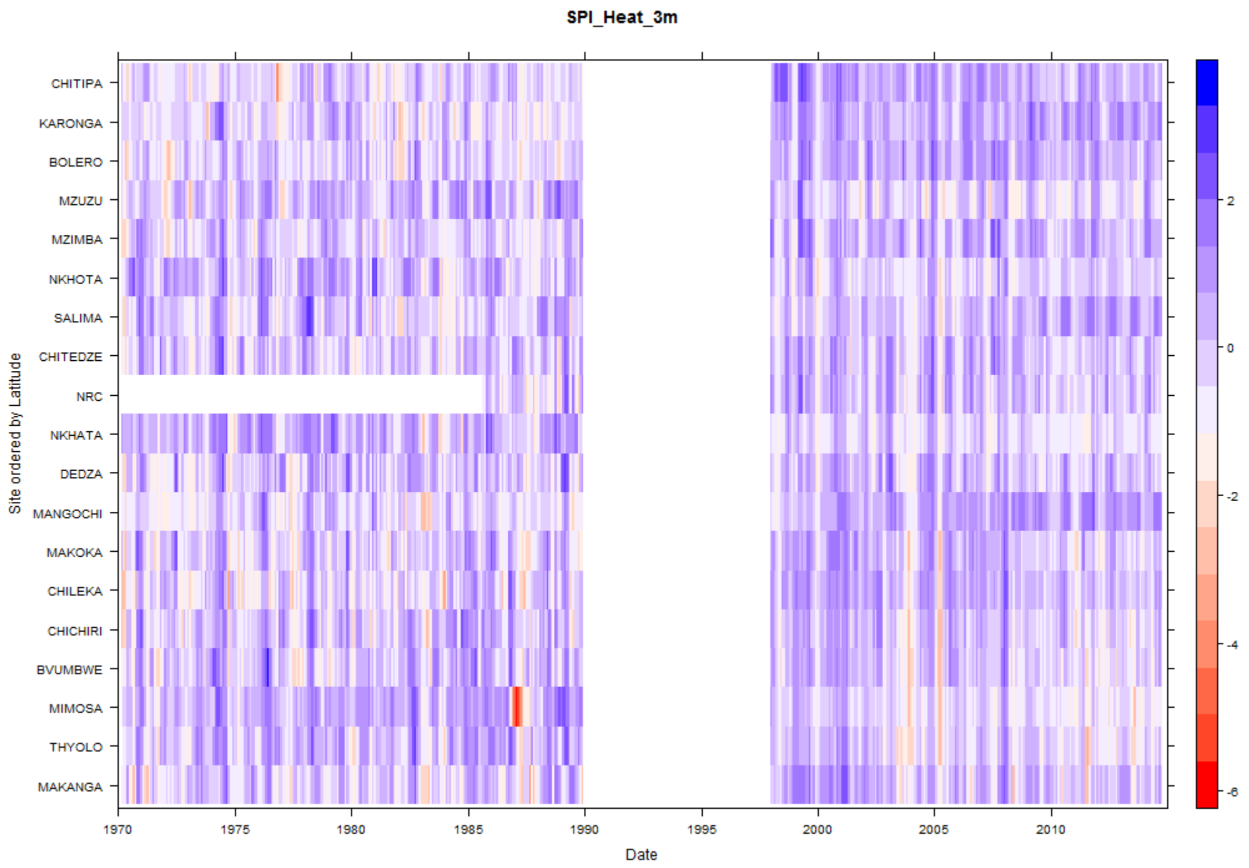

Figure 4 SPI index, calculated for 3 months rainfall accumulation. The sites are ordered according to the latitude, from the south (bottom, Makanga) to the north (top, Chitipa).

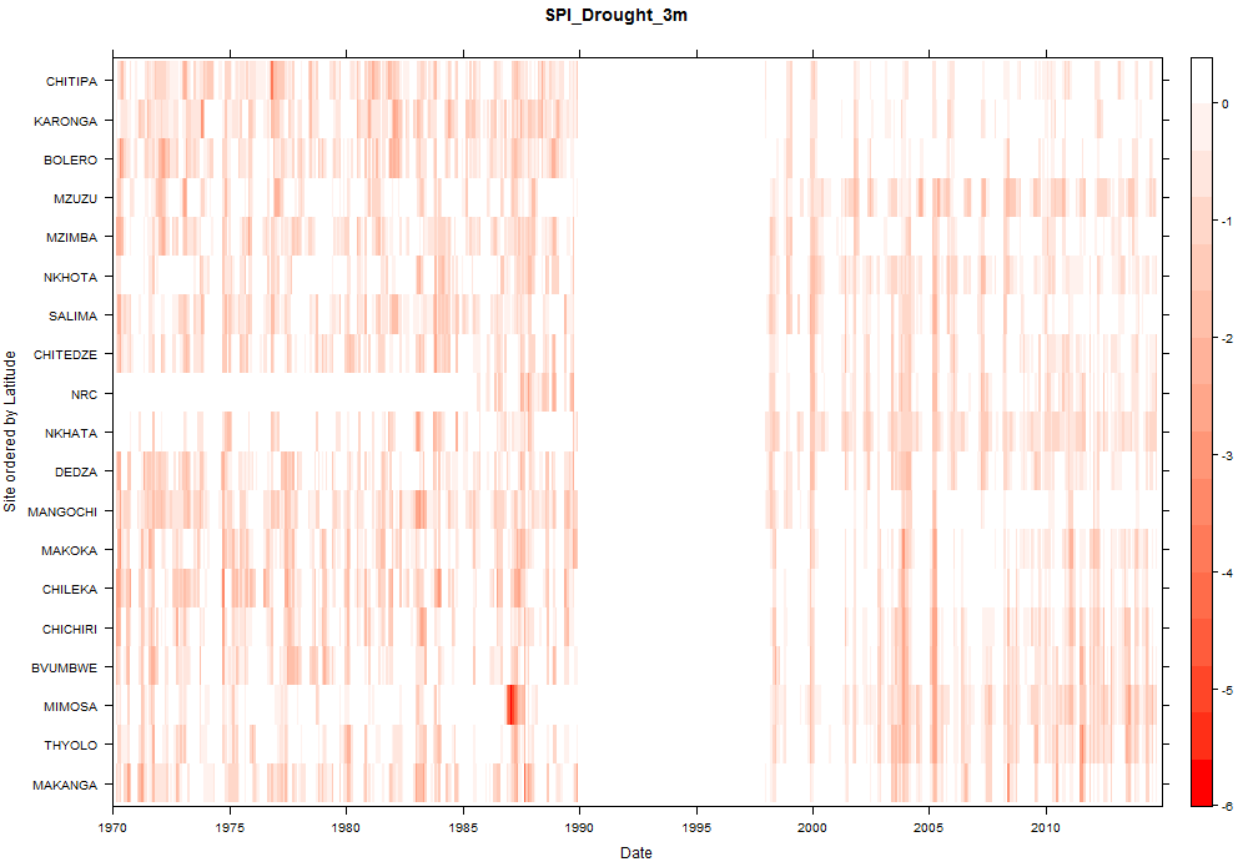

Figure 5 SPI Drought index, calculated for 3 months rainfall accumulation. The sites are ordered according to the latitude, from the south (bottom, Makanga) to the north (top, Chitipa).

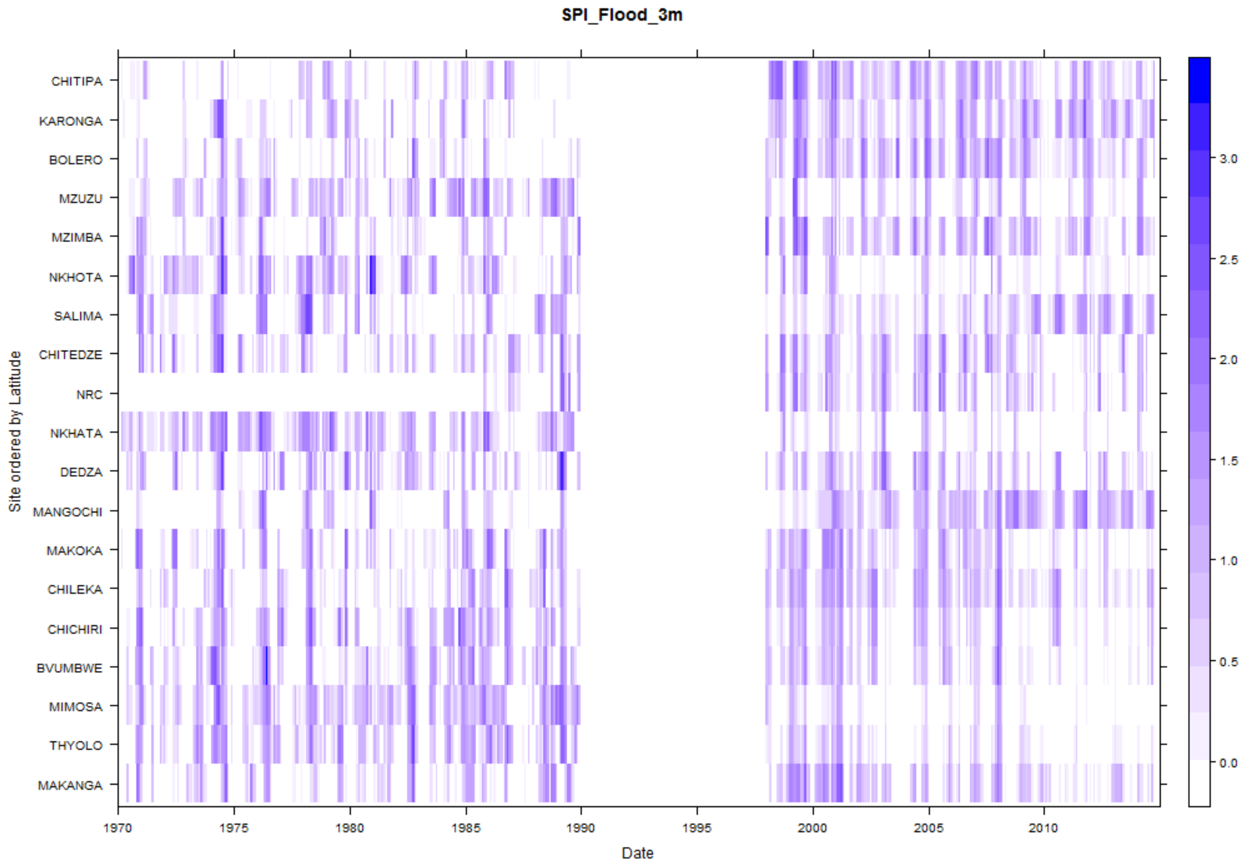

Figure 6 SPI Wet index, calculated for 3 months rainfall accumulation. The sites are ordered according to the latitude, from the south (bottom, Makanga) to the north (top, Chitipa).

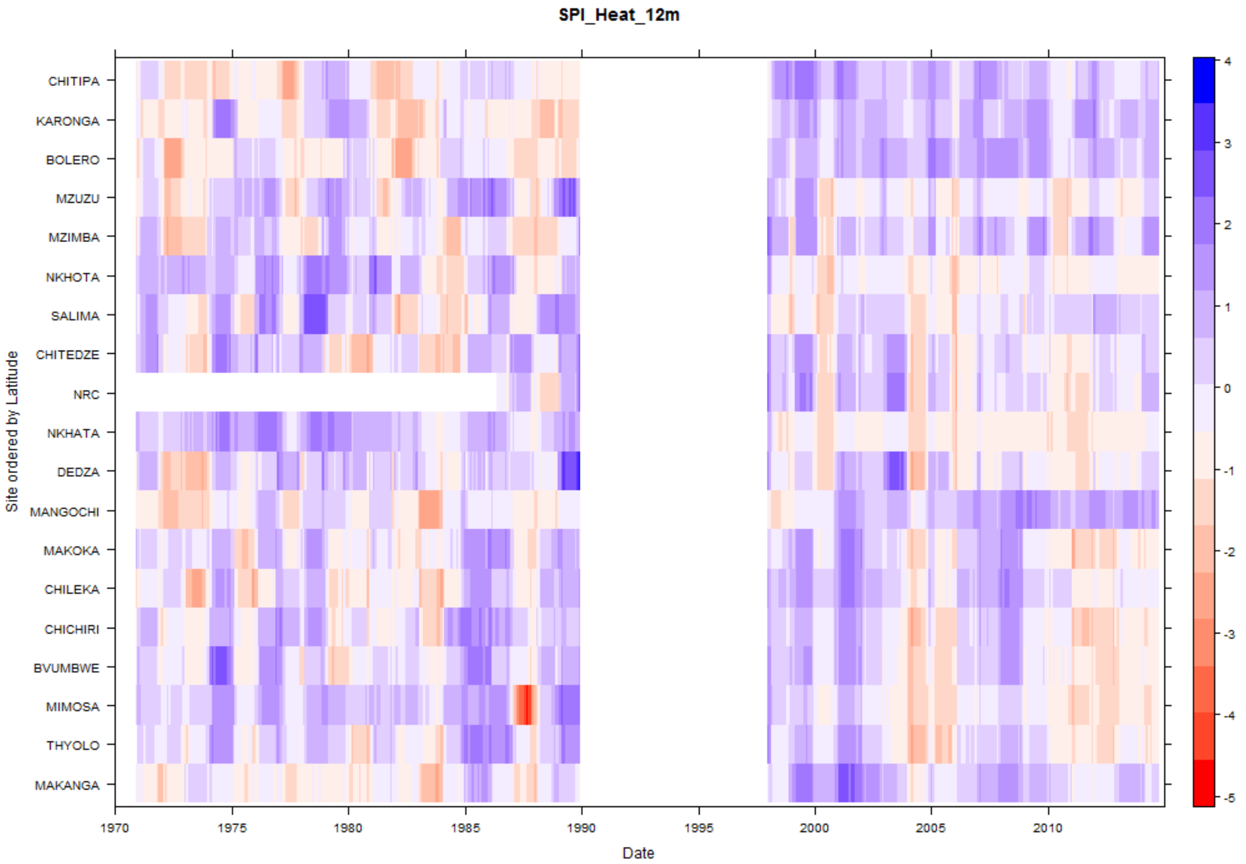

Figure 7 SPI index, calculated for 12 months rainfall accumulation. The sites are ordered according to the latitude, from the south (bottom, Makanga) to the north (top, Chitipa).

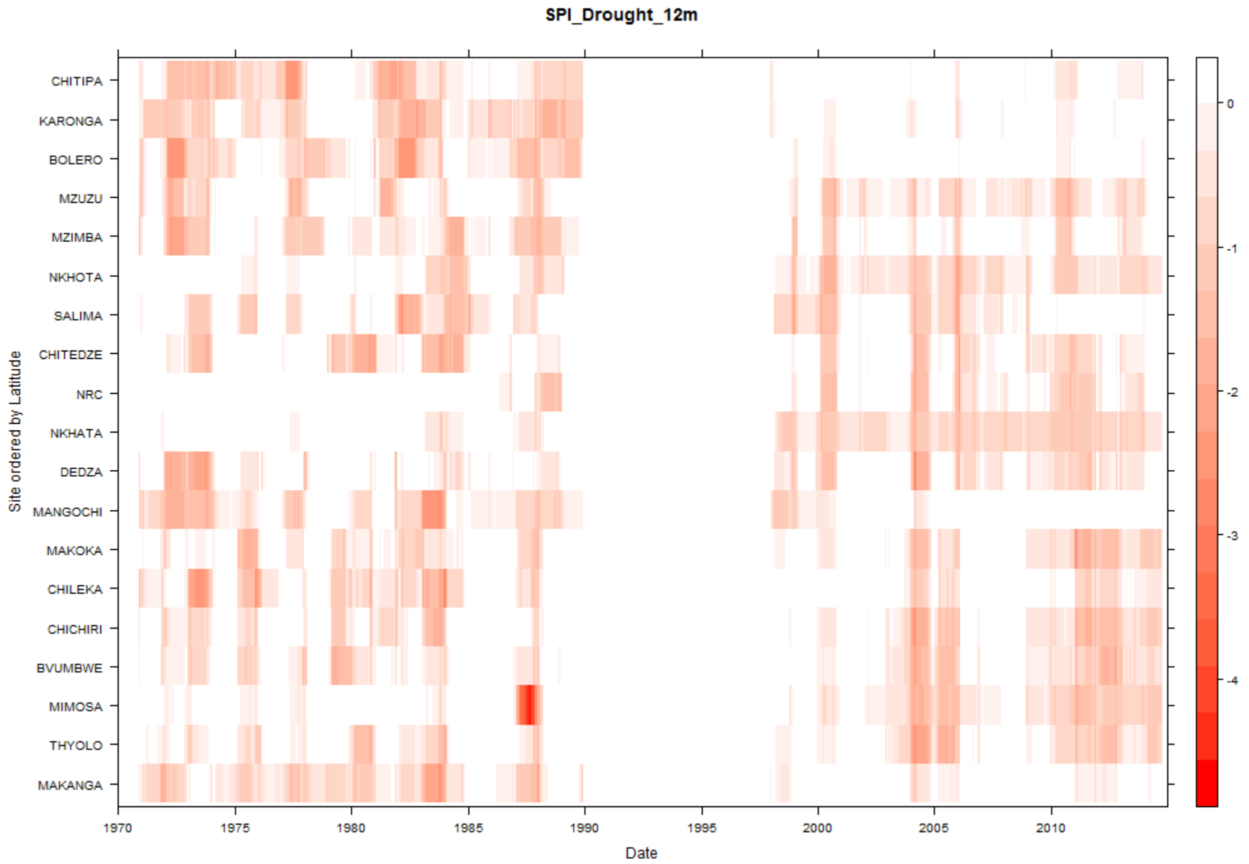

Figure 8 SPI drought index, calculated for 12 months rainfall accumulation. The sites are ordered according to the latitude, from the south (bottom, Makanga) to the north (top, Chitipa).

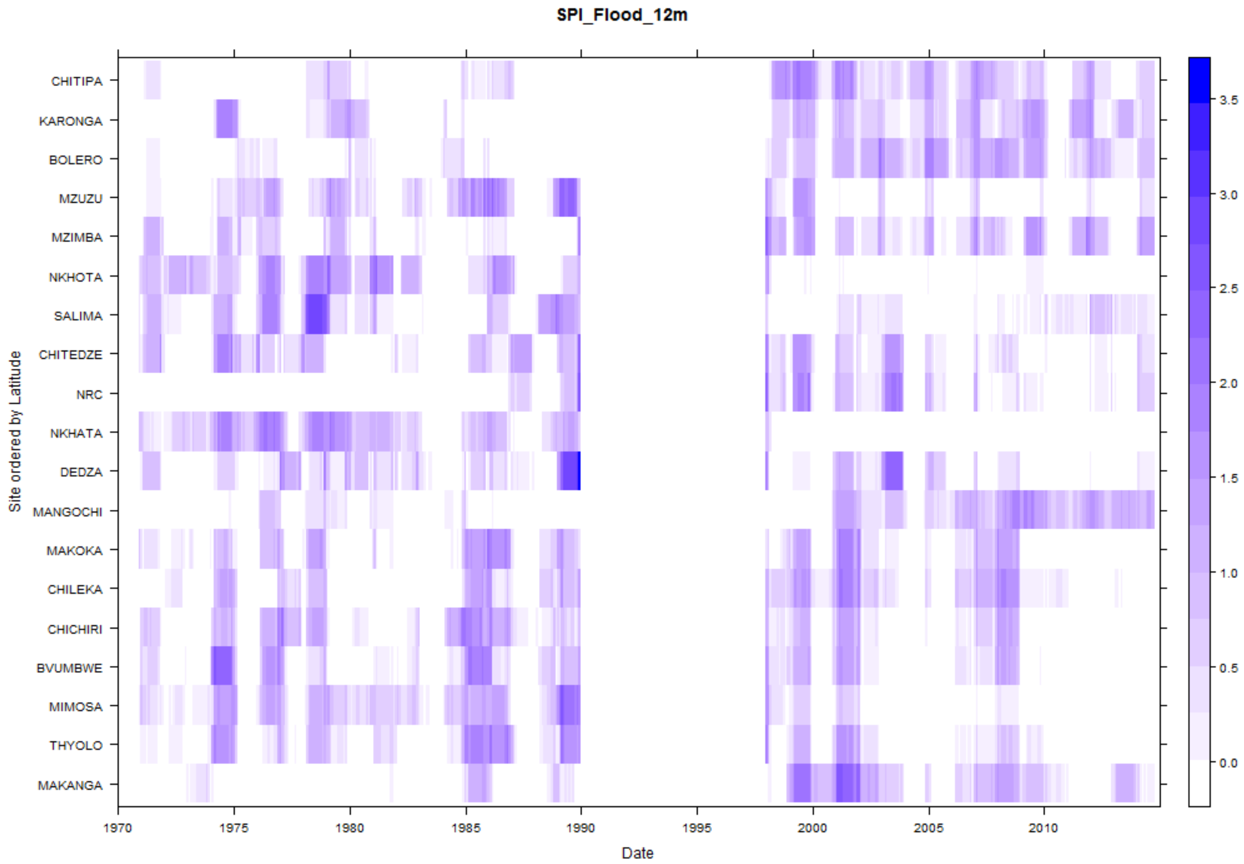

Figure 9 SPI Wet index, calculated for 12 months rainfall accumulation. The sites are ordered according to the latitude, from the south (bottom, Makanga) to the north (top, Chitipa).

3 Distributed groundwater recharge modelling using ZOODRM and synthetic hydrological extremes scenarios

3.1 INTRODUCTION

A distributed recharge model that covers the whole of Malawi was prepared by Scheidegger et al. (2015). This model applies the simplified Food and Agriculture Organisation (FAO) recharge calculation method (*Griffiths et al.*, 2006) which calculates recharge and runoff values from the available excess water after accounting for evapotranspiration and reducing the soil moisture to zero. The recharge model routes the calculated runoff to the river network based on a digital terrain model. The model uses landuse, topographical, soil, and runoff zones maps to calculate spatially variable recharge values. A full description of the model and its application to Malawi can be found in BGS Report 15/061 (*Scheidegger et al.*, 2015).

The time series of weather forcing (rainfall and evaporation) for the 19 gauging stations are altered to produce 6 synthetic hydrological extreme scenarios. The time series are produced for the time period between 2000 and 2014. Three synthetic dry scenarios are first produced using the 2004 drought year.

- Dry 1: the 2004 drought year is repeated over the year 2005 (the rainfall and evaporation time series of the year 2004 are repeated for the year 2005).
- Dry 2: the 2004 drought year is repeated over the years 2005 and 2006 (the rainfall and evaporation time series of the year 2004 are repeated for the years 2005 and 2006).
- Dry 3: the 2004 drought year is repeated over the years 2005, 2006 and 2007 (the rainfall and evaporation time series of the year 2004 are repeated for the years 2005, 2006 and 2007).

Three synthetic wet scenarios are then produced using the 2001 relatively wet year.

- Wet 1: the 2001 wet year is repeated over the year 2002 (the rainfall and evaporation time series of the year 2001 are repeated for the year 2002).
- Wet 2: the 2001 wet year is repeated over the years 2002 and 2003 (the rainfall and evaporation time series of the year 2001 are repeated for the years 2002 and 2003).
- Wet 3: the 2001 wet year is repeated over the years 2002, 2003 and 2004 (the rainfall and evaporation time series of the year 2001 are repeated for the years 2002, 2003 and 2004).

These synthetic scenarios are used in the following to produce recharge calculations over Malawi.

3.2 DISTRIBUTED GROUNDWATER RECHARGE ESTIMATION USING THE SYNTHETIC HYDROLOGICAL EXTREME SCENARIOS

Seven runs were undertaken using the distributed ZOODRM recharge model calibrated and presented in the previous BGS report CR/15/61 (*Scheidegger et al.,* 2015) for the time period comprised between the 01/01/2000 and the 31/10/2014:

- Original (using the initial time series for the rainfall and evaporation)
- Dry 1, Dry2 and Dry3 for the synthetic drought events
- Wet 1, Wet2 and Wet3 for the synthetic wet events

The results are presented using two tables summarising the Long Term Average (LTA) recharge for Malawi and for the different districts in Malawi for the seven previously described runs. Seven maps displaying the distribution of the LTA recharge over Malawi are also provided in Appendix A.

The Long term average recharge are calculated from the recharge time series for the period 2000-2014. The changes are more easily observed in the Southern part of the country. Tables including the values for the whole country and the different districts are provided (LTA recharge values in Table 1, percentage change in Table 2).

As expected Table 1 and Table 2 show that the Dry 3 scenario produces the least LTA recharge over the country and the Wet 3 scenario produces highest recharge values. The LTA recharge values decrease from 0.326 mm/day to 0.295 mm/day on average for the whole of Malawi using the synthetic drought scenarios, and increase to 0.362 mm/day using the synthetic wet scenarios. This pattern is also true for the majority of the districts in Malawi. However, some inconsistencies appear, especially for the districts Chitipa, Karonga, Mzimba, Nkhata_Baty, and Rumphi. It can be noted that the Chitipa, Karonga and Mzimba weather stations, all situated in the northern Malawi, were already mentioned in the previous version as potential sources of uncertainties for the production of extreme weather scenarios. However, the percentage change from the original LTA recharge values calculated for these districts is very small as shown in Table 2. These appeared also during the study using SPI index, revealing the potential heterogeneities of weather pattern over the country. In addition, these districts are situated in the northern part of the country where the weather is becoming more equatorial.

Regarding the percentage changes presented in Table 2, in Malawi the Dry 3 scenario implies a decreasing of 9% of the LTA daily recharge and the Wet 3 scenario implies an increasing of 11% of the LTA daily recharge. Generally, there is more consistency between the districts for the changes incurred by the dry scenarios than for the changes incurred by the wet scenarios.

The uncertainties associated to the heterogeneous character of the rainfall pattern over a whole country appear here. However the results show in general a reasonable consistency, and these scenarios are chosen to be used in the following section for the groundwater level time series modelling.

Table 1 LTA recharge (mm/d) values for Malawi and the different districts, for the original scenario and the six synthetic scenarios. For each site (or row) a colour classification is applied using conditional formatting with a 3-Color Scale: from dark red (lower recharge value) through white (intermediate recharge value) to dark blue (higher recharge value).

	Original	Dry1	Dry2	Dry3	Wet1	Wet2	Wet2
Chitipa	0.429009	0.428985	0.426082	0.419984	0.418728	0.43051	0.413711
Karonga	0.479137	0.478773	0.464499	0.457451	0.458233	0.469203	0.452977
Rumphi	0.259304	0.254417	0.248513	0.240035	0.239939	0.2409	0.236883
Mzimba	0.433543	0.43243	0.42454	0.417211	0.422104	0.430916	0.428094
Nkhata_Bay	0.23257	0.226942	0.222198	0.217938	0.224783	0.228261	0.222366
Nkhotakota	0.447208	0.436082	0.432764	0.423209	0.459788	0.453159	0.470268
Kasungu	0.205194	0.197407	0.193226	0.184009	0.20909	0.206861	0.216193
Ntchisi	0.228496	0.219442	0.216151	0.207568	0.233652	0.230114	0.23991
Dowa	0.257299	0.244	0.235223	0.222822	0.262388	0.258187	0.269766
Mchinji	0.277839	0.262317	0.253866	0.239966	0.283857	0.278251	0.288562
Salima	0.304932	0.296255	0.281252	0.27007	0.310986	0.316687	0.340661
Lilongwe	0.199157	0.183277	0.176195	0.165201	0.199877	0.194486	0.19628
Dedza	0.211941	0.196483	0.190726	0.182829	0.21395	0.203584	0.210449
Mangochi	0.266423	0.257824	0.235462	0.228686	0.276106	0.28384	0.309698
Ntcheu	0.262628	0.252088	0.236139	0.225044	0.274789	0.282335	0.303822
Machinga	0.301301	0.293356	0.27064	0.259276	0.318131	0.333447	0.361399
Balaka	0.478025	0.469098	0.438047	0.41636	0.507865	0.535801	0.574627
Zomba	0.379734	0.376721	0.356925	0.33524	0.411419	0.440494	0.471643
Mwanza	0.214014	0.213207	0.20804	0.195268	0.243913	0.269659	0.301505
Phalombe	0.480555	0.473168	0.438984	0.406185	0.529252	0.573939	0.622335
Blantyre	0.366673	0.365288	0.352116	0.33141	0.407324	0.441193	0.482396
Chiradzulu	0.693115	0.687672	0.655834	0.618953	0.745068	0.792435	0.841927
Mulanje	0.798967	0.785772	0.734636	0.683107	0.867815	0.932781	1.000804
Thyolo	0.411111	0.409093	0.393378	0.369593	0.448077	0.480014	0.519182
Chikwawa	0.211973	0.21149	0.205727	0.19037	0.252881	0.28567	0.331172
Nsanje	0.413104	0.415992	0.411381	0.382845	0.486052	0.540585	0.624226
MALAWI	0.326166	0.319439	0.307989	0.29566	0.335855	0.346677	0.362486

Table 2 Percentage changes of LTA recharge values for Malawi and the different districts, for the original scenario and the six synthetic scenarios. For each site (or row) a colour classification is applied using conditional formatting with a 3-Color Scale: from dark red (higher decrease) through white to dark blue (higher increase).

	Original	Dry1	Dry2	Dry3	Wet1	Wet2	Wet2
Chitipa	0.43	0.00	-0.01	-0.02	-0.02	0.00	-0.04
Karonga	0.48	0.00	-0.03	-0.05	-0.04	-0.02	-0.05
Rumphi	0.26	-0.02	-0.04	-0.07	-0.07	-0.07	-0.09
Mzimba	0.43	0.00	-0.02	-0.04	-0.03	-0.01	-0.01
Nkhata_Bay	0.23	-0.02	-0.04	-0.06	-0.03	-0.02	-0.04
Nkhotakota	0.45	-0.02	-0.03	-0.05	0.03	0.01	0.05
Kasungu	0.21	-0.04	-0.06	-0.10	0.02	0.01	0.05
Ntchisi	0.23	-0.04	-0.05	-0.09	0.02	0.01	0.05
Dowa	0.26	-0.05	-0.09	-0.13	0.02	0.00	0.05
Mchinji	0.28	-0.06	-0.09	-0.14	0.02	0.00	0.04
Salima	0.30	-0.03	-0.08	-0.11	0.02	0.04	0.12
Lilongwe	0.20	-0.08	-0.12	-0.17	0.00	-0.02	-0.01
Dedza	0.21	-0.07	-0.10	-0.14	0.01	-0.04	-0.01
Mangochi	0.27	-0.03	-0.12	-0.14	0.04	0.07	0.16
Ntcheu	0.26	-0.04	-0.10	-0.14	0.05	0.08	0.16
Machinga	0.30	-0.03	-0.10	-0.14	0.06	0.11	0.20
Balaka	0.48	-0.02	-0.08	-0.13	0.06	0.12	0.20
Zomba	0.38	-0.01	-0.06	-0.12	0.08	0.16	0.24
Mwanza	0.21	0.00	-0.03	-0.09	0.14	0.26	0.41
Phalombe	0.48	-0.02	-0.09	-0.15	0.10	0.19	0.30
Blantyre	0.37	0.00	-0.04	-0.10	0.11	0.20	0.32
Chiradzulu	0.69	-0.01	-0.05	-0.11	0.07	0.14	0.21
Mulanje	0.80	-0.02	-0.08	-0.15	0.09	0.17	0.25
Thyolo	0.41	0.00	-0.04	-0.10	0.09	0.17	0.26
Chikwawa	0.21	0.00	-0.03	-0.10	0.19	0.35	0.56
Nsanje	0.41	0.01	0.00	-0.07	0.18	0.31	0.51
MALAWI	0.33	-0.02	-0.06	-0.09	0.03	0.06	0.11

4 Groundwater level time series modelling for representative boreholes in Malawi, using AquiMod, a lumped groundwater model

4.1 INTRODUCTION

AquiMod is a lumped parameter computer model that has been developed to simulate groundwater level time-series at observation boreholes in aquifers by linking simple hydrological algorithms that model soil drainage, the transfer of water through the unsaturated zone and groundwater flow (*Mackay et al*., 2014). It runs on a Windows PC through the command prompt and is configured using a series of text files. The simple structure of AquiMod makes it easy to use in comparison to more complex physically-based distributed models, and therefore should be accessible to those users who are new to the field of groundwater/hydrological modelling. It uses conceptual modelling approaches that are in line with general hydrological understanding and has been used in the past to teach hydrological concepts to Earth Science undergraduates. The main features of the AquiMod software include:

- Fast simulation of groundwater level time-series
- Flexible time-stepping
- Monte Carlo parameter sampling
- Modular structure with multiple process representations
- Choice of objective functions to evaluate model efficiency

It can be applied to any groundwater catchment around an observation borehole with observed groundwater level time-series data. It can be calibrated against these data and used to provide information in the behaviour of groundwater levels beyond observational records. The model has been used in this way for a number of applications, including reconstructing groundwater level records, long term projections of groundwater level under climate change and forecasting groundwater levels into the near future using meteorological forecasts.

AquiMod consists of three modules (Figure 10). The first is a soil water balance module that partitions rainfall between evapotranspiration, runoff and soil drainage. This module simulates the water balance of the root zone, therefore soil drainage is defined as the water that percolates past the root zone and is no longer available for evapotranspiration. Drainage from the soil is then attenuated through an unsaturated zone module which represents percolation to the groundwater as recharge. This recharge is input to the saturated zone module that simulated aquifer storage and subsequent discharge. It is the saturated zone module that calculates the groundwater level time-series. The saturated module can include several numerical layers to represent different hydrogeological layers that have different hydraulic characteristics.

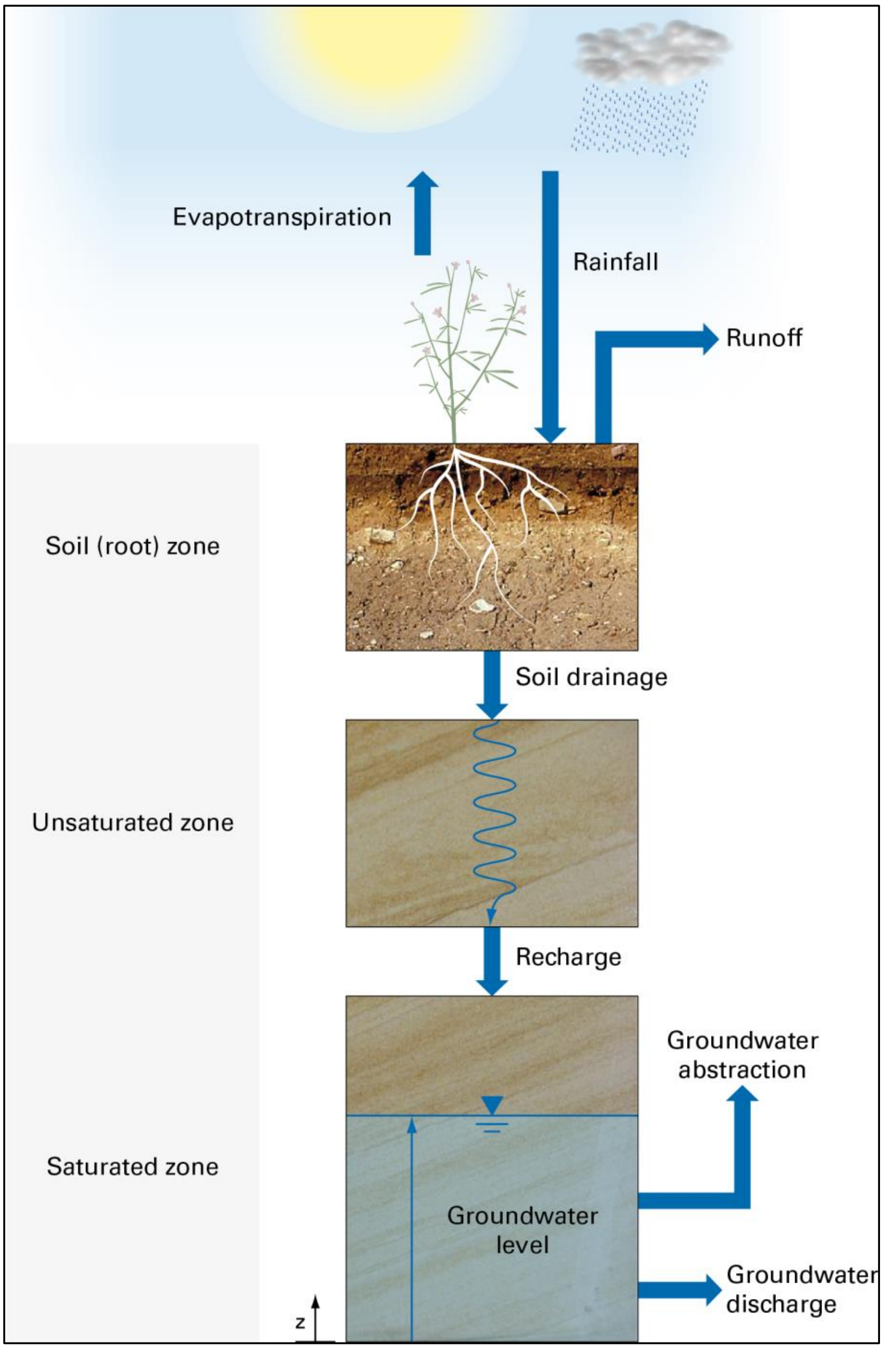

Figure 10 Generalised structure of AquiMod (from Mackay et al., 2014). Contains British Geological Survey materials © NERC [2014]

4.2 CONSTRUCTION AND CALIBRATION OF GROUDWATER LEVEL TIME SERIES MODEL FOR THREE REPRESENTATIVE BOREHOLES IN MALAWI

Using Monte Carlo simulations, optimal sets of parameters are determined for matching as well as possible the groundwater level time series observed at the chosen boreholes. Three boreholes that are characterised by a reasonably long time series and are believed to represent different regions of the country are chosen. These are:

- Chitipa Water Office, in Chitipa district (North)
- Endongolweni School, in Mzimba district
- Namwera Well Field, in Machinga district

The location of these boreholes is shown in Figure 11. The groundwater level time series are available for the time period comprised between 2009 and 2014. Therefore the calibration is undertaken using these values. However the groundwater level time series are simulated for the period 2000-2014, in order to take into account the synthetic extreme scenarios.

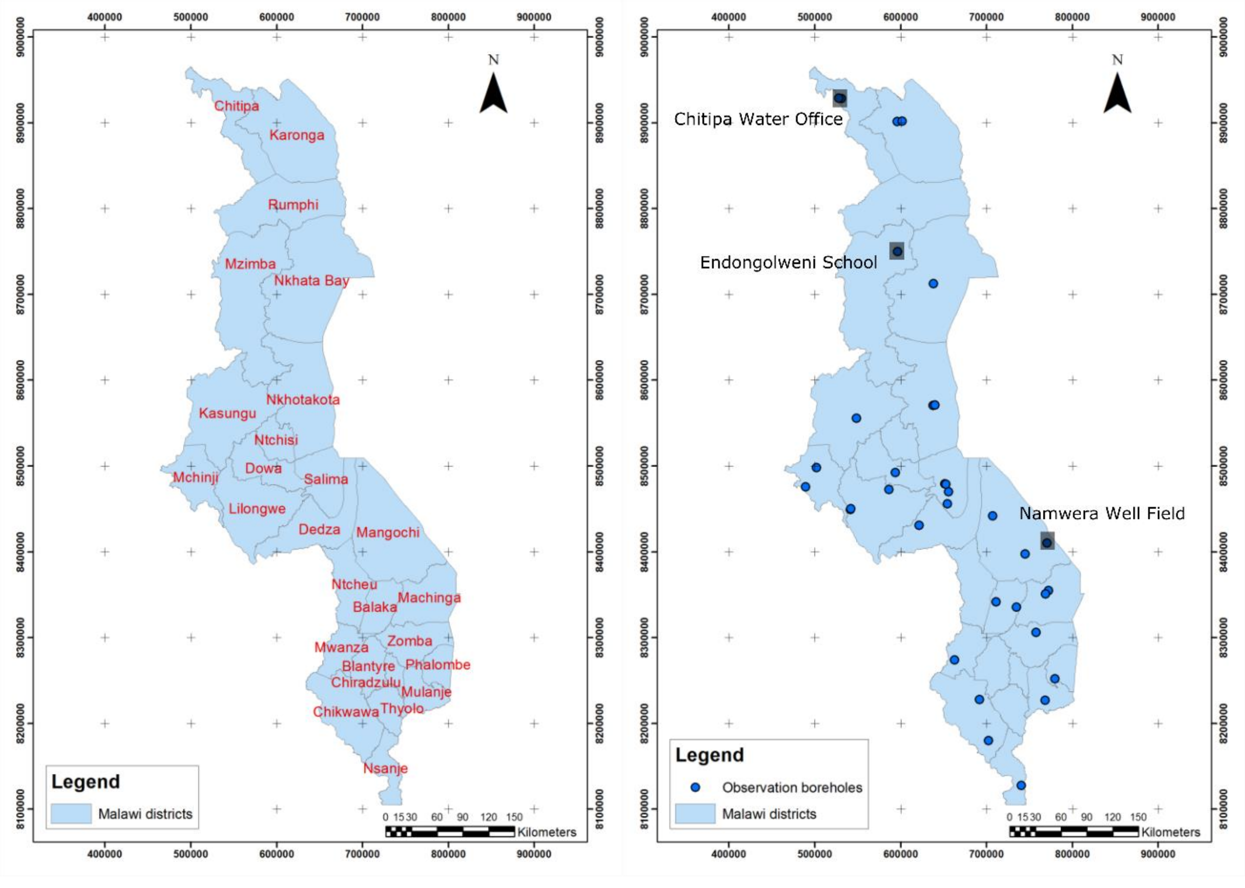

Figure 11 Malawi administrative districts (MASDAP, http://www.masdap.mw/) and observation boreholes, including the three boreholes used in this modelling exercise

Different modelling structures were tested for simulating the time series obtained for these boreholes:

- Representation of the saturated zone using 1, 2 and 3 layers
- Calculation of the recharge using the AquiMod built-in modules
- Using of the recharge calculated using ZOODRM, as described in the previous section

The better and if possible simpler approach is finally selected.

4.2.1 AquiMod simulation of the Chitipa Water Office groundwater level time series

The structure selected for this borehole is:

- Recharge from the distributed recharge model ZOODRM
- Saturated zone represented by one layer

The recharge produced for this borehole is plotted on Figure 12 along with the observed groundwater level time series. The observed groundwater level fluctuations are relatively well correlated to the recharge time series used as input for AquiMod.

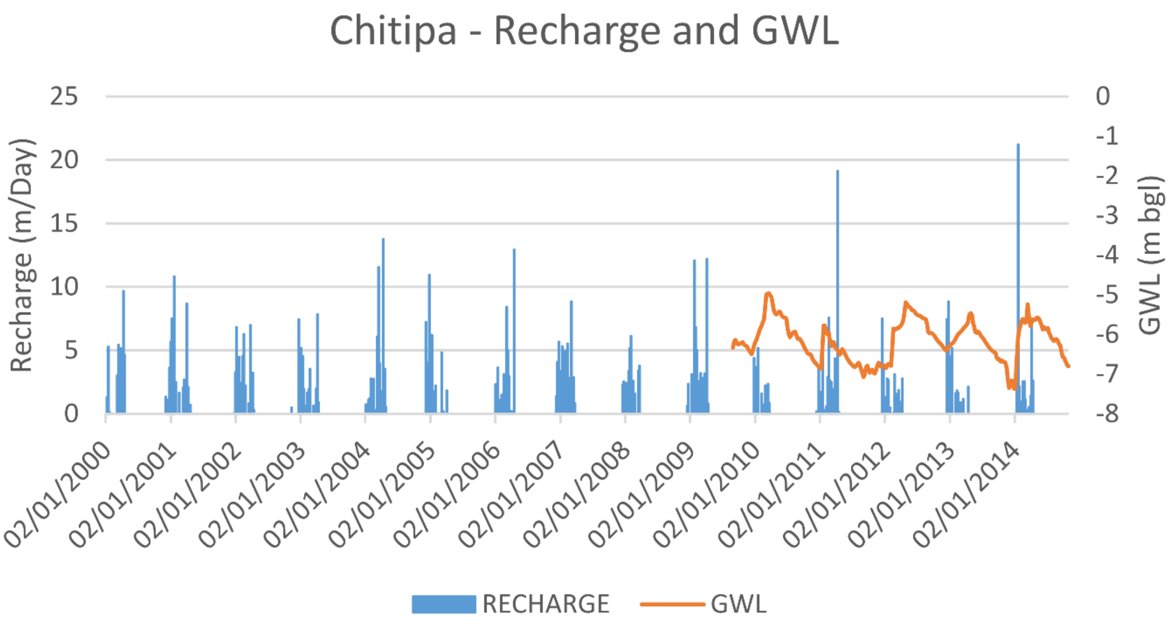

Figure 12 Recharge time series (weekly average of the daily recharge) produced using the ZOODRM distributed recharge model and groundwater level time series (weekly time step) for the Chitipa borehole

More complicated models were tested, but without considerable improvement of the performance. The chosen model leads to a Nash Sutcliffe Efficiency (NSE) criterion of 0.44, while the maximum NSE obtained for a 3 layers model is 0.45.

The modelled and observed time series are plotted in Figure 13 together with the range of groundwater level fluctuations obtained from the 1000 runs with parameters that give the best NSE values. A cross-plot showing the variation of NSE values with the values of the three hydraulic parameters, the hydraulic conductivity, the specific yield, and the mean transmissivity, obtained from these 1000 runs are shown in Figure 14.

The optimal specific yield is between 0.2 and 0.3. The optimal mean transmissivity is less clearly identifiable and is comprised between 10 and 1500 m^2/day. The optimal hydraulic conductivity K1 is lower than 70 m/day.

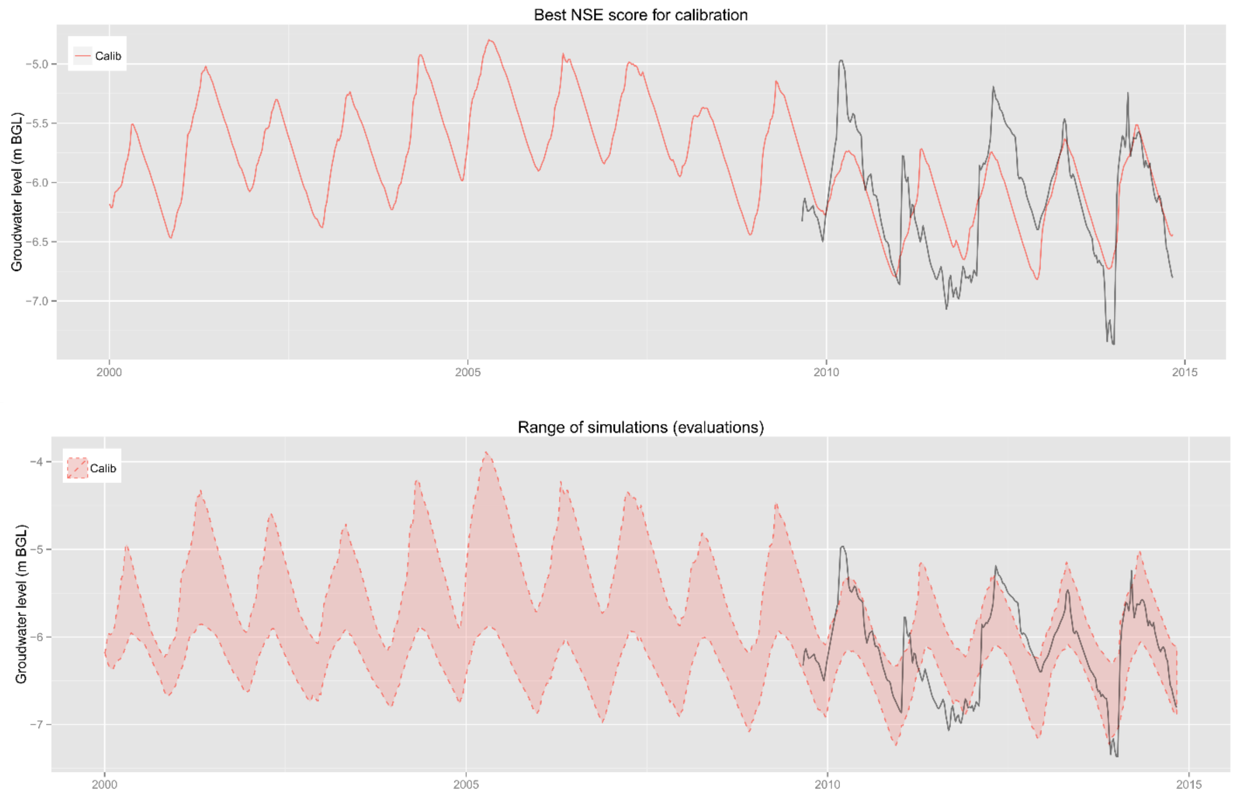

Figure 13 Groundwater level time series obtained using AquiMod and observed time series for the Chitipa borehole

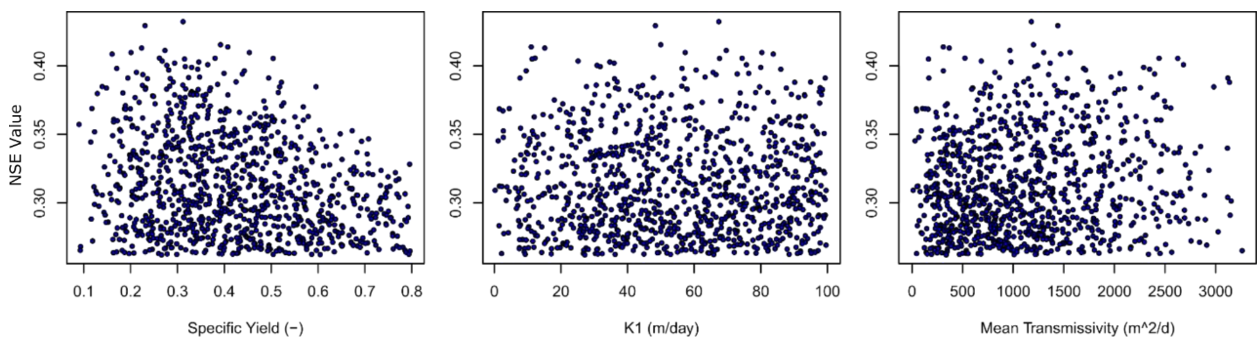

Figure 14 Sensitivity of the hydrogeological parameters for Chitipa WO GWL time series

4.2.2 AquiMod simulation of the Endongolweni School groundwater level time series

The structure selected for this borehole is:

- Recharge from the distributed recharge model ZOODRM
- Saturated zone represented by one layer

The recharge produced for this borehole is plotted on Figure 15 along with the observed groundwater level time series. For this borehole, the groundwater level fluctuations are characterised by a lower amplitude and the general trend decreases until the 2014 recharge season.

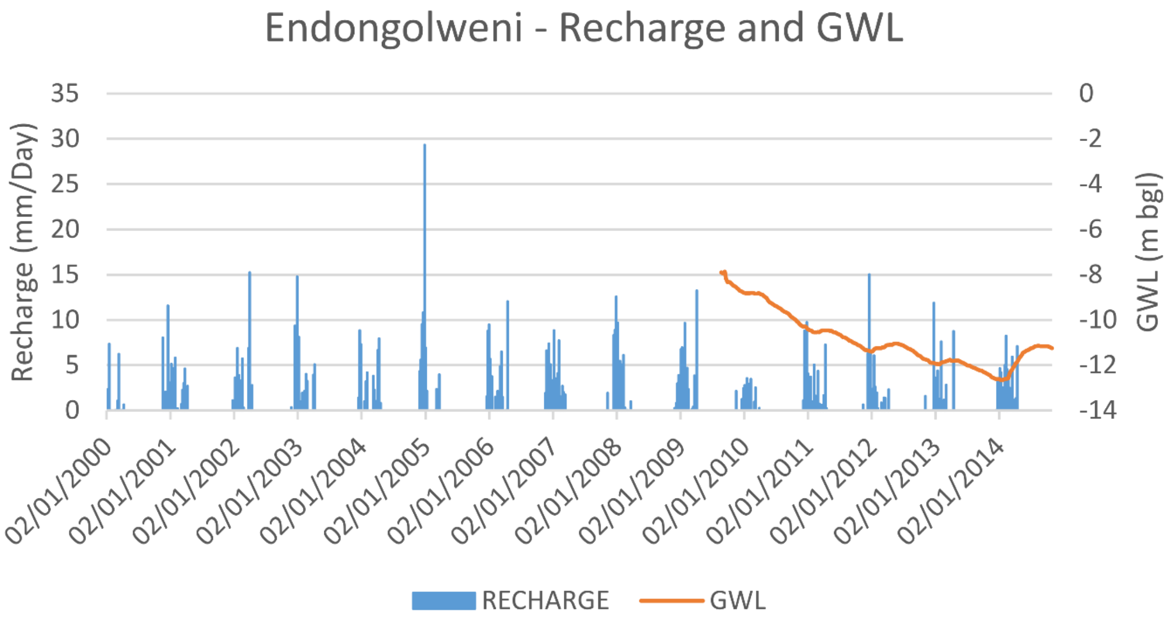

Figure 15 Recharge time series produced using the ZOODRM distributed recharge model and observed groundwater level time series for the Endongolweni borehole

More complicated models were tested, but without considerable improvement of the performance. The chosen model leads to a NSE criterion of 0.74, while the maximum NSE obtained for a 3 layers model is 0.745.

The modelled and observed time series are shown in Figure 16, together with the range of groundwater level fluctuations obtained from the 1000 runs with parameters that give the best NSE values. A cross-plot showing the variation of NSE values with the values of the three hydraulic parameters, the hydraulic conductivity, the specific yield, and the mean transmissivity, obtained from these 1000 runs are shown in Figure 17.

The optimal specific yield is comprised between 0.05 and 0.06. The optimal mean transmissivity is less clearly identifiable and comprised between 10 and 400 m^2/day. The optimal hydraulic conductivity K1 is lower than 10 m/day.

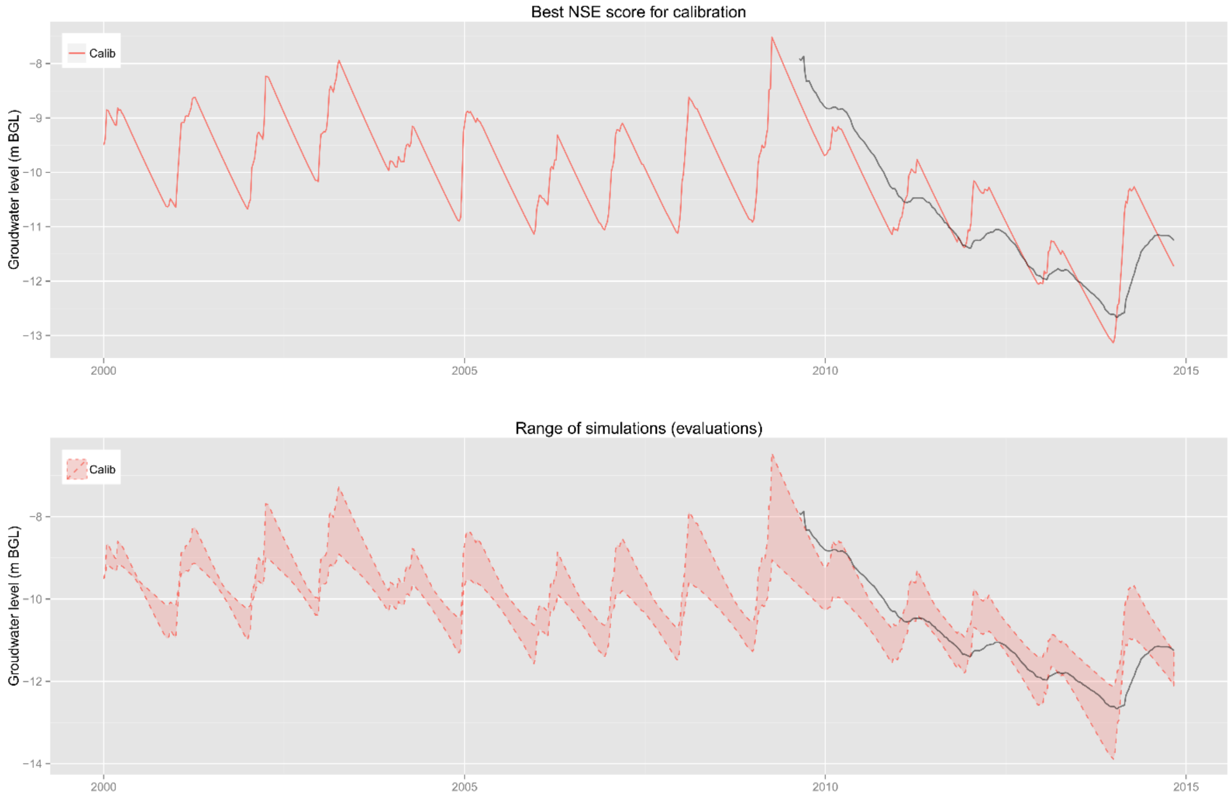

Figure 16 Groundwater level time series obtained using AquiMod and observed time series for the Endongolweni School borehole

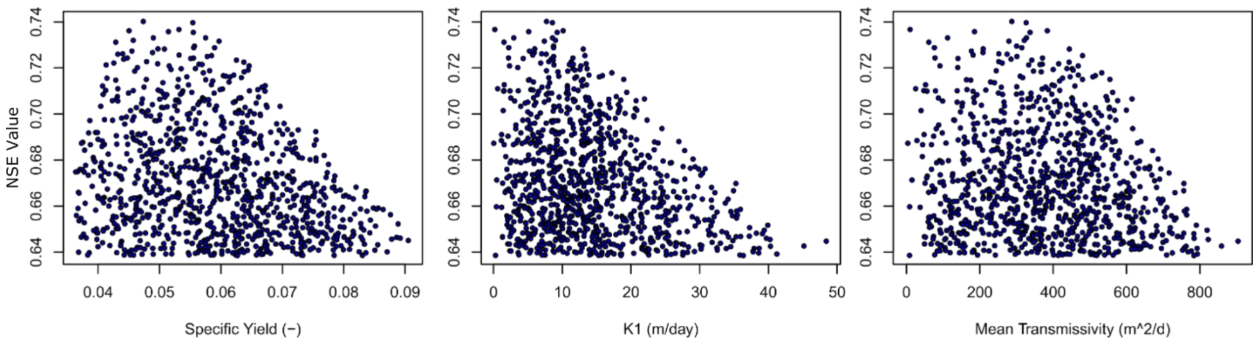

Figure 17 Sensitivity of the hydrogeological parameters for Endongolweni School GWL time series

4.2.3 AquiMod simulation of the Namwera Well Field groundwater level time series

The structure selected for this borehole is:

- Recharge from the distributed recharge model ZOODRM
- Saturated zone represented by one layer

The recharge produced for this borehole is plotted on Figure 18 along with the observed groundwater level time series. The timing of the groundwater rises is consistent with the recharge events. However the recharge appears to be very low in 2011 while the observed groundwater level attains its maximum. This is likely to prevent the lumped groundwater model to obtain accurate results, as it will be discussed in the following.

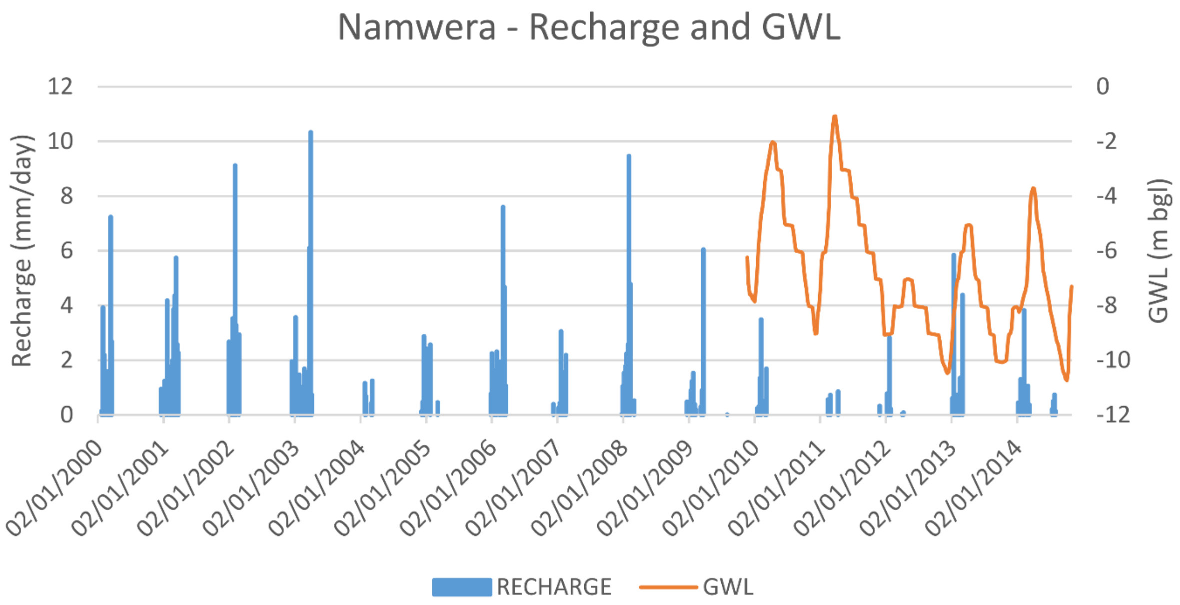

Figure 18 Recharge time series produced using the ZOODRM distributed recharge model and observed groundwater level time series for the Namwera borehole

More complicated models were tested, but without considerable improvement of the performance. The chosen model leads to a NSE criterion of 0.42, while the maximum NSE obtained for a 3 layers model is 0.44. It has to be noted that the range of the fluctuation is not very well matched. This is probably due to the recharge input characterised by a very low recharge for the year 2011, while the higher observed groundwater level is obtained in this same year. It could be linked to the uncertainties associated to the Rainfall dataset, the recharge calculation or to a number of potential factors that are not represented in this modelling approach (such as influence of surface water level, human management, etc.).

The modelled and observed time series are plotted in Figure 19, together with the range of groundwater level fluctuations obtained from the 1000 runs with parameters that give the best NSE values. A cross-plot showing the variation of NSE values with the values of the three hydraulic parameters, the hydraulic conductivity, the specific yield, and the mean transmissivity, obtained from these 1000 runs are shown in Figure 20.

The optimal specific yield is comprised between 0.06 and 0.08. The optimal mean transmissivity is less identifiable and is comprised between 20 and 600 m^2/day. The optimal hydraulic conductivity K1 is lower than 15 m/day.

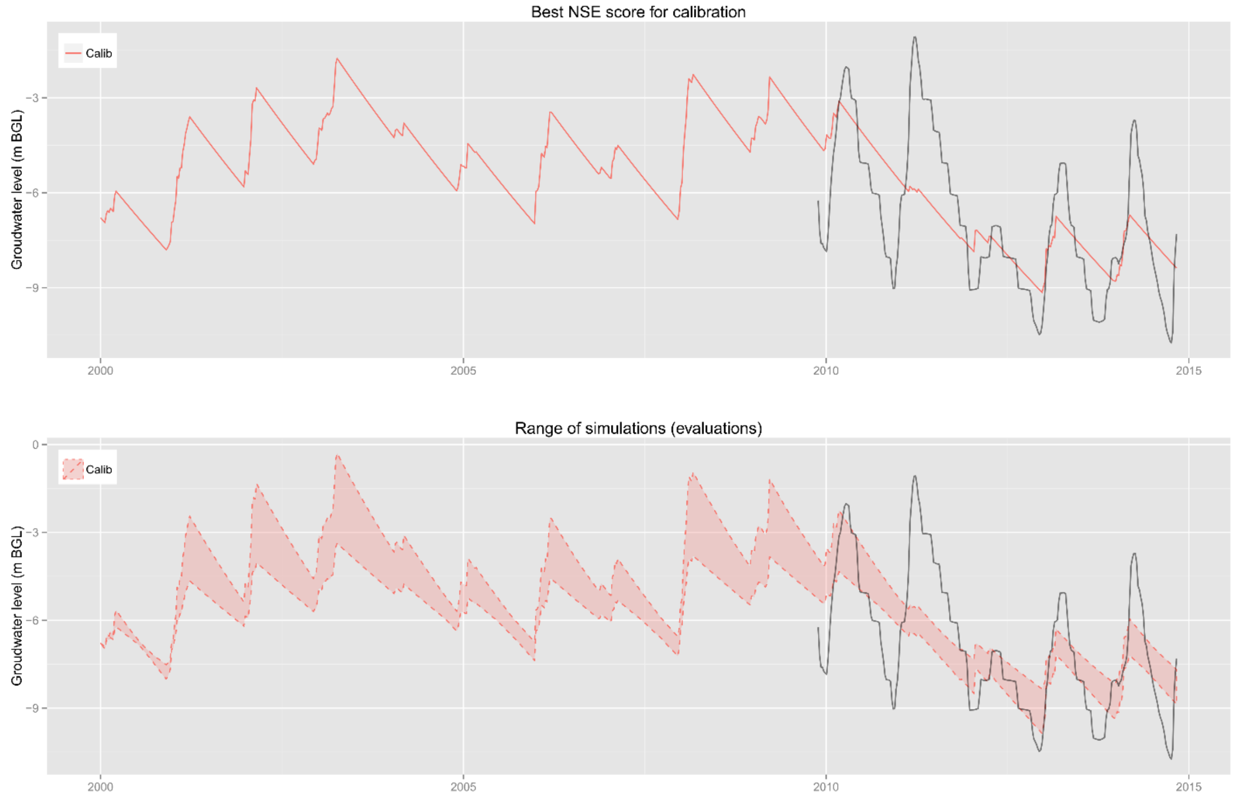

Figure 19 Groundwater level time series obtained using AquiMod and observed time series for the Namwera Well Field borehole

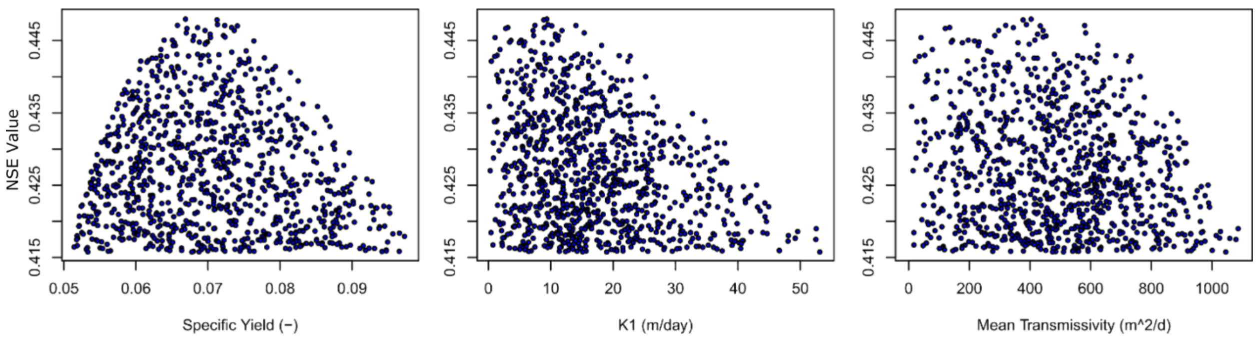

Figure 20 Sensitivity of the hydrogeological parameters for Namwera Well Field GWL time series

However the match between observed and simulated groundwater level is relatively poor as it can be observed on Figure 19. Namely the simulated time series obtained after the calibration process displays considerably subdued fluctuations in comparison with the observed time series. Actually the calibration process within AquiMod tries to find a solution leading to simulated results that are closest to the observed ones along the whole time series period. Using trial and error method it was possible to better reproduce the amplitudes of the observed time series by reducing the storage coefficient value of the aquifer, as shown on Figure 21. However this is on the expense of the simulated time series drifting away from the observed one over the time period comprised between January 2011 and January 2013. Examining again the recharge time series (plotted also on Figure 21), it is clear that there is not enough recharge calculated over the period 2011-2012 to elevate the simulated GWL time series to the observed levels. It is not clear why the recharge amount calculated over this period is so small but this further exercise highlights that the specific yield associated to this particular aquifer is possibly closer to 2% rather than 6% or 8%, as obtained by the calibration process previously described. Besides, the timing of the recharge also appears to be shifted in a number of occasion. An explanation could perhaps be a pumping induced rebound, as this borehole is situated in a well field.

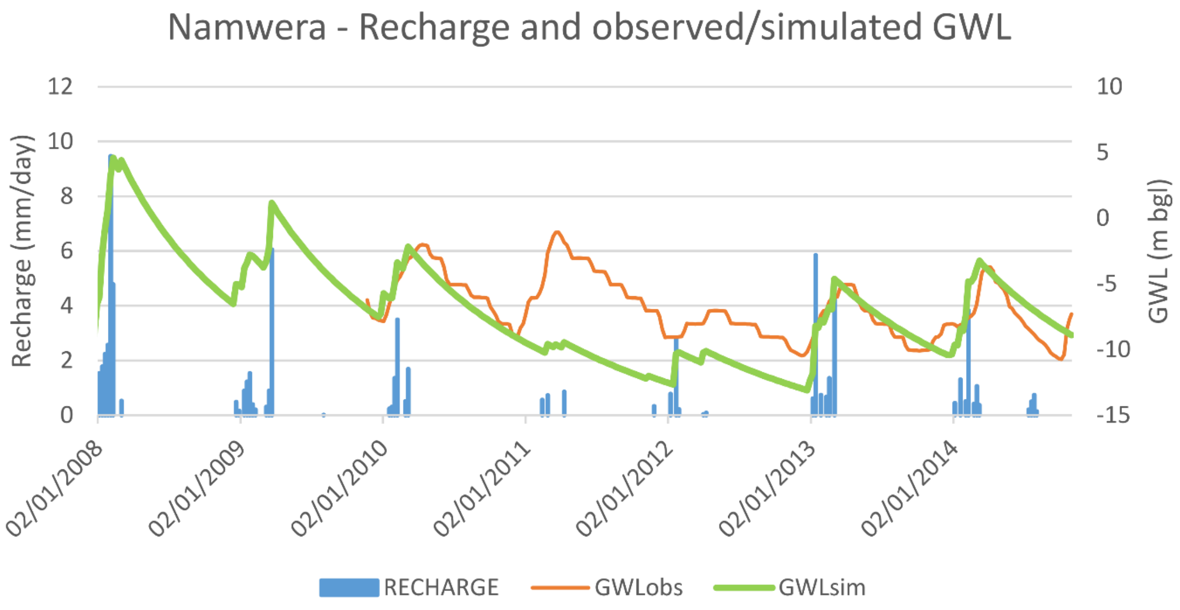

Figure 21 Recharge time series produced using the ZOODRM distributed recharge model, observed groundwater level time series and simulated groundwater level time series obtained using trials and errors with AquiMod

4.3 APPLICATION OF THE SYNTHETIC HYDROLOGICAL EXTREME SCENARIOS TO THE CALIBRATED GROUNDWATER MODELS

The synthetic hydrological extreme scenarios produced and described in sections 2-3 are used as input to run the previously calibrated lumped groundwater models. The results are plotted on different figures: one figure for comparing the simulated groundwater level time series obtained for the dry scenarios, the wet scenarios, and the difference between the simulated time series and the original time series. A common y-scale is chosen for the differences in order to compare more effectively the influence of the synthetic meteorological scenario on the groundwater level time series.

4.3.1 Application of the synthetic hydrological extreme scenarios to the AquiMod simulation of the Chitipa Water Office groundwater level time series

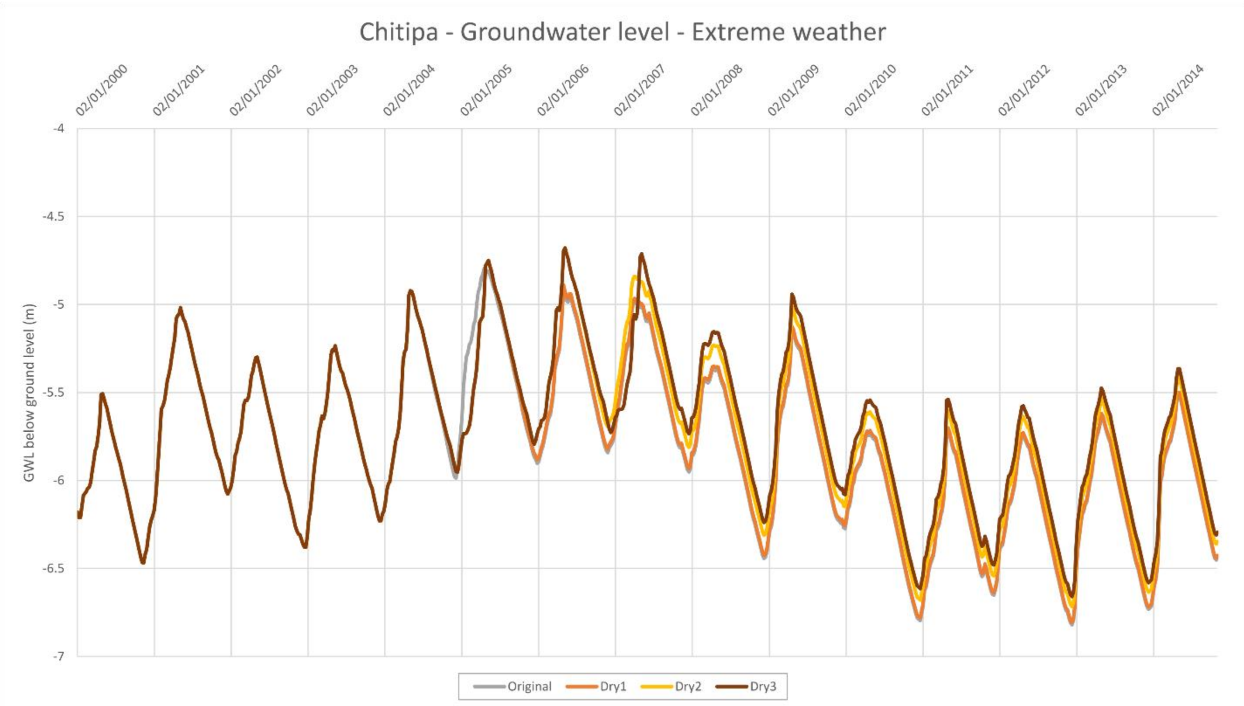

Figure 22 Simulated groundwater level for Chitipa borehole, and for the three dry scenarios (Dry 1, 2, 3)

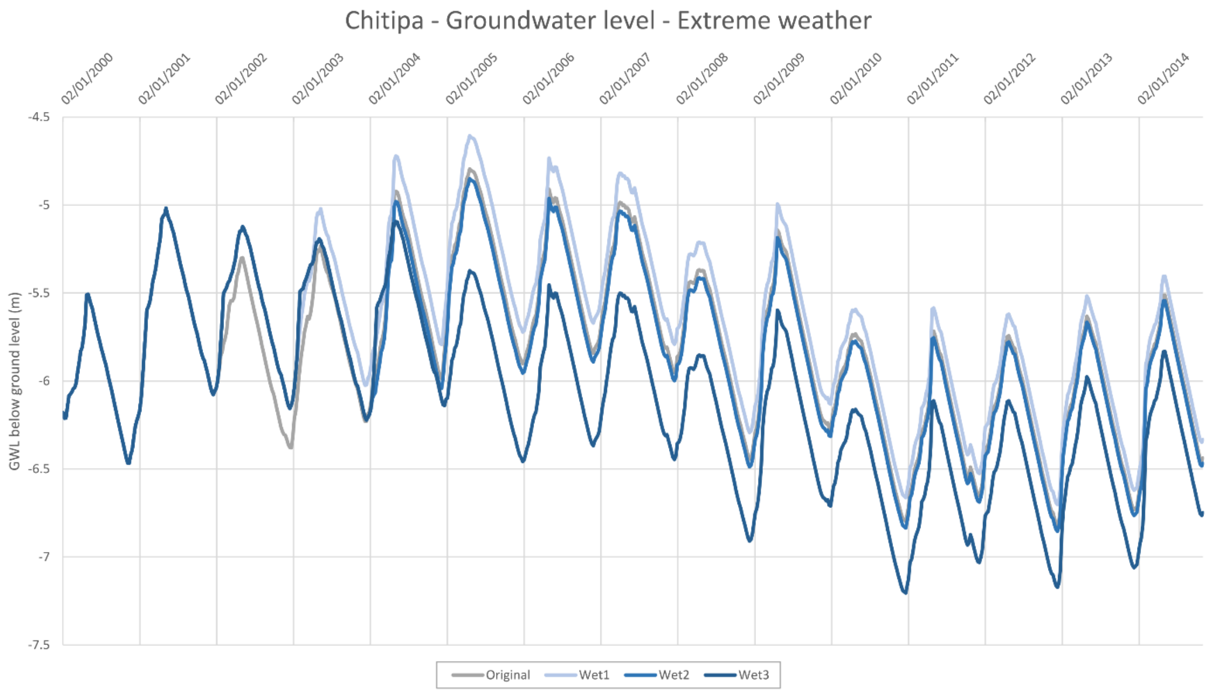

Figure 23 Simulated groundwater level for Chitipa borehole, and for the three wet scenarios (Wet 1, 2, 3)

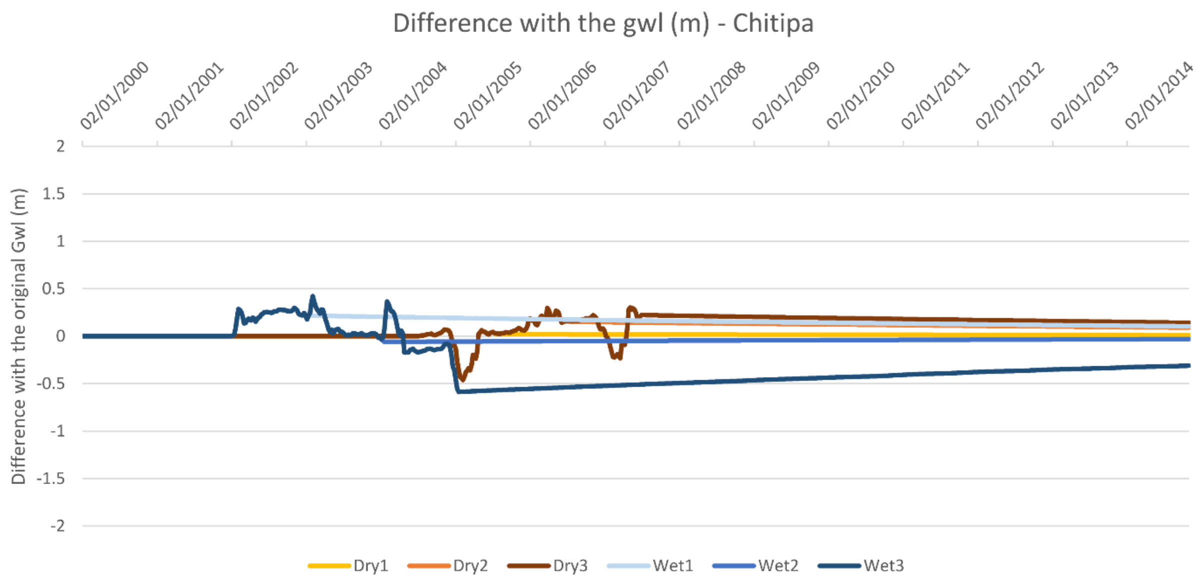

Figure 24 Difference with the original groundwater level for the six dry and wet scenarios for the Chitipa borehole

As observed in the previous sections, this borehole is situated in the Chitipa district which is situated in the extreme north of Malawi. In this region, the rainfall does not follow closely the general pattern of the rainfall in Malawi. Therefore it is not surprising that the influence of the synthetic scenarios is not really apparent. The groundwater level evolution is not consistent with the different scenarios (Figure 22 and Figure 23). The dry scenarios have nearly no effect on the simulated groundwater level (Figure 22). The results obtained for the wet scenarios are clearly inconsistent: the wet 3 scenario induces a decrease of the groundwater level attaining 0.5m. Moreover the difference between the simulated time series obtained for the synthetic scenarios and the original time series is weak (less than -/+0.5 m, see Figure 24).

As anticipated in the previous sections, the uncertainties associated to the determination of extreme weather periods in the northern Malawi are propagated in this modelling exercise. Whereas the higher extreme weather signals in the south lead to the determination of clearly identifiable extreme weather events, the less clear signals in the north induce the production of incorrect synthetic wet scenarios for this region.

4.3.2 Application of the synthetic hydrological extreme scenarios to the AquiMod simulation of the Endongolweni School groundwater level time series

For this borehole, the effect of the dry scenarios is more evident. The scenario Dry 3 make the groundwater level decrease to 13 meters below the ground at the end of 2007, and at 14 meters below the ground in January 2014 (Figure 25 and Figure 26). The decrease of groundwater level attains up to 3 meters in the year 2007 (Figure 26). The scenario Dry 2 induces a decrease of 1.5 meters in 2006, and the scenario Dry 1 a decrease of 2 meters in 2005. Furthermore, the effect of the Dry 3 scenario is still noticeable at the end of the simulation period with a groundwater level 1 meter below the original groundwater level (Figure 26).

The effect of the wet scenarios is not as evident (Figure 27), which is consistent with the previous observation that the wet scenarios have a less consistent effect on the recharge of the different districts in Malawi, namely for the ones situated in the north. Moreover the difference obtained for the wet scenarios is relatively low and inconsistent with the scenario (Figure 28). Again, the high uncertainty of the determination of extreme weather events in the north of Malawi appears.

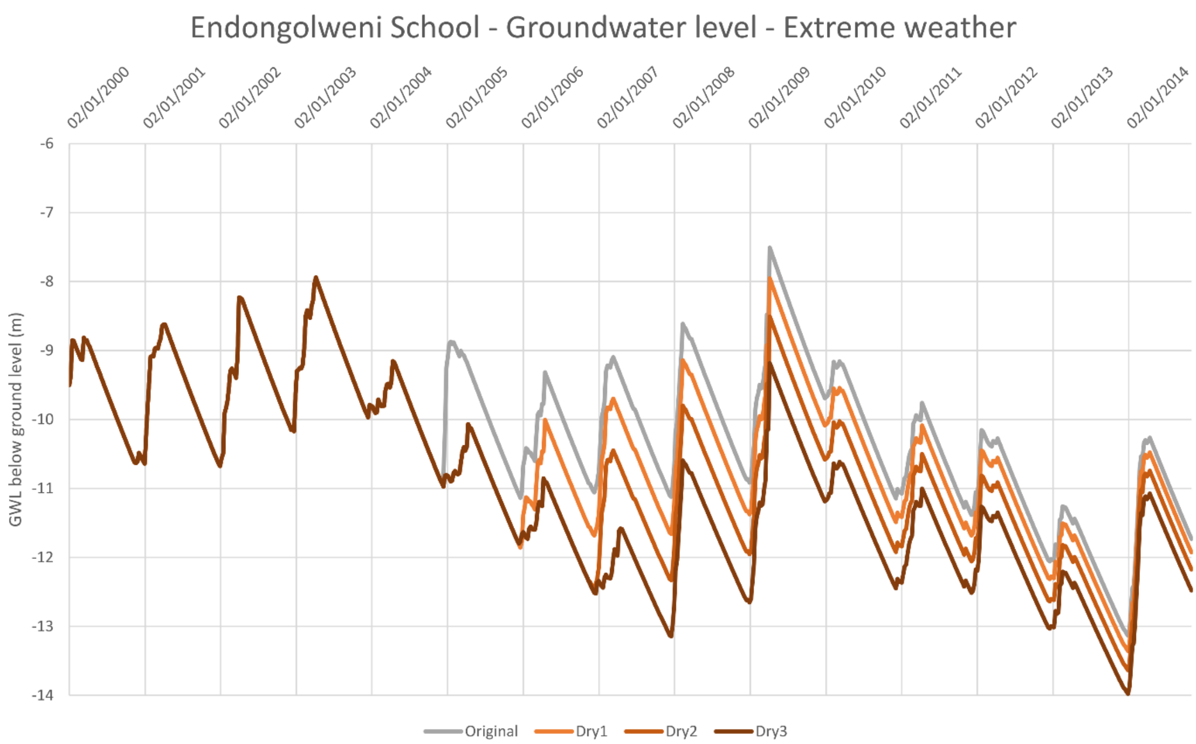

Figure 25 Simulated groundwater level for Endongolweni borehole, and for seven different scenarios the three dry scenarios (Dry 1, 2, 3)

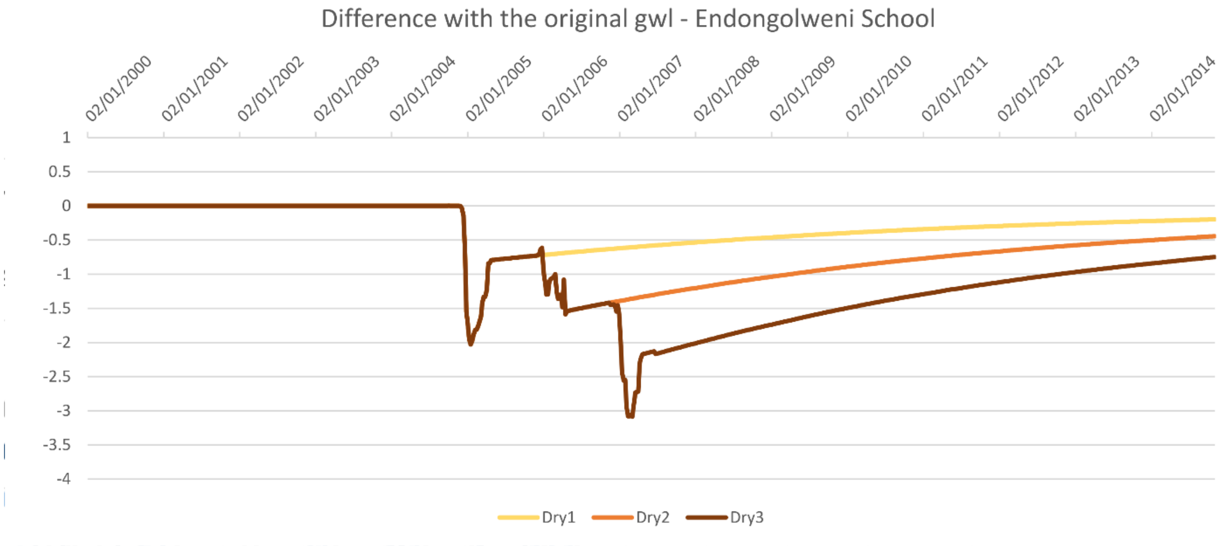

Figure 26 Difference with the original groundwater level for the three dry scenarios (Endongolweni School)

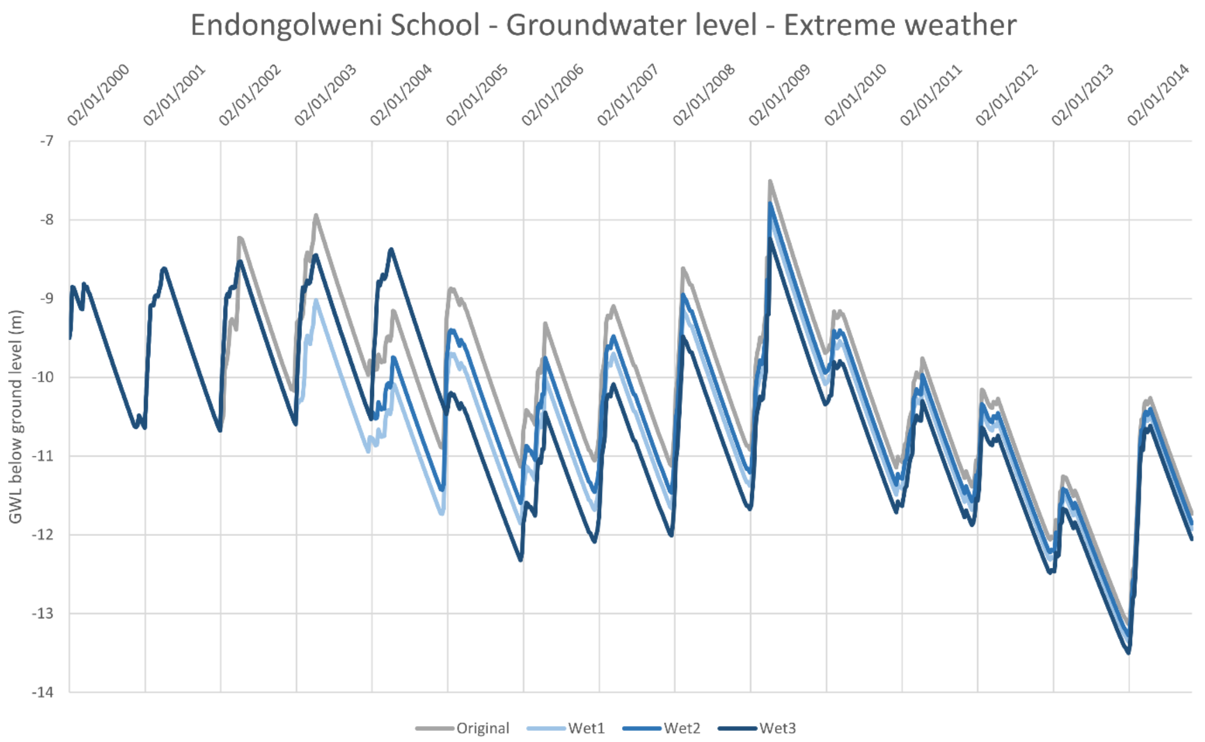

Figure 27 Simulated groundwater level for Endongolweni borehole, and for seven different scenarios the three wet scenarios (Wet 1, 2, 3)

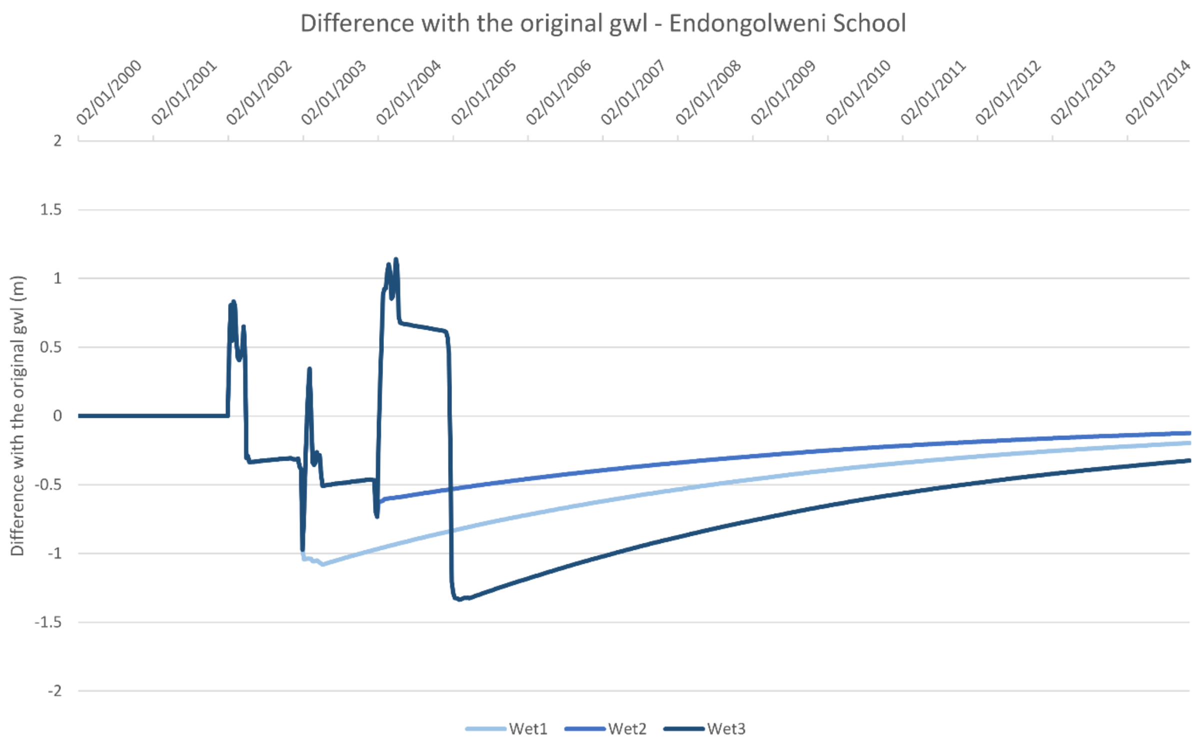

Figure 28 Difference with the original groundwater level for the three wet scenarios (Endongolweni School)

4.3.3 Application of the synthetic hydrological extreme scenarios to the AquiMod simulation of the Namwera Well Field groundwater level time series

This third borehole shows the most evident influence of the extreme scenarios on the groundwater resources. The scenario Dry 1 leads to a minimum groundwater level of -9.5 meters below ground level in January 2013, and a maximum negative difference with the original level of 2 meters in 2005. The events Dry 2 and Dry 3 have a very strong influence and potentially lead to severe drought. The minimum groundwater level is attained in January 2013 (-11m) for Dry 2 and in January 2008/2013 (-11.5m) for Dry 3. Besides, the groundwater level remains considerably below the original level, up to 2014 (Figure 29). The maximum negative difference with the original level is – 2 m in 2005 for Dry 1, - 4 m in 2006 for Dry 2 and – 5 m in 2007 for Dry 3 (Figure 31).

The influence of the wet events is also noticeable. The maximum groundwater level obtained for Wet 1 and Wet 2 is –1 m in 2003, and + 0.5 m in 2004 for Wet 3. The Wet 3 event has a considerable influence, making the groundwater level increase beyond the ground level (potentially incurring flood events) in the early 2004 and 2008 (Figure 30). The differences obtained for the wet scenarios attain + 1 m in 2002 for Wet 1, + 2 m in 2003 and + 4 m in 2004 (Figure 31).

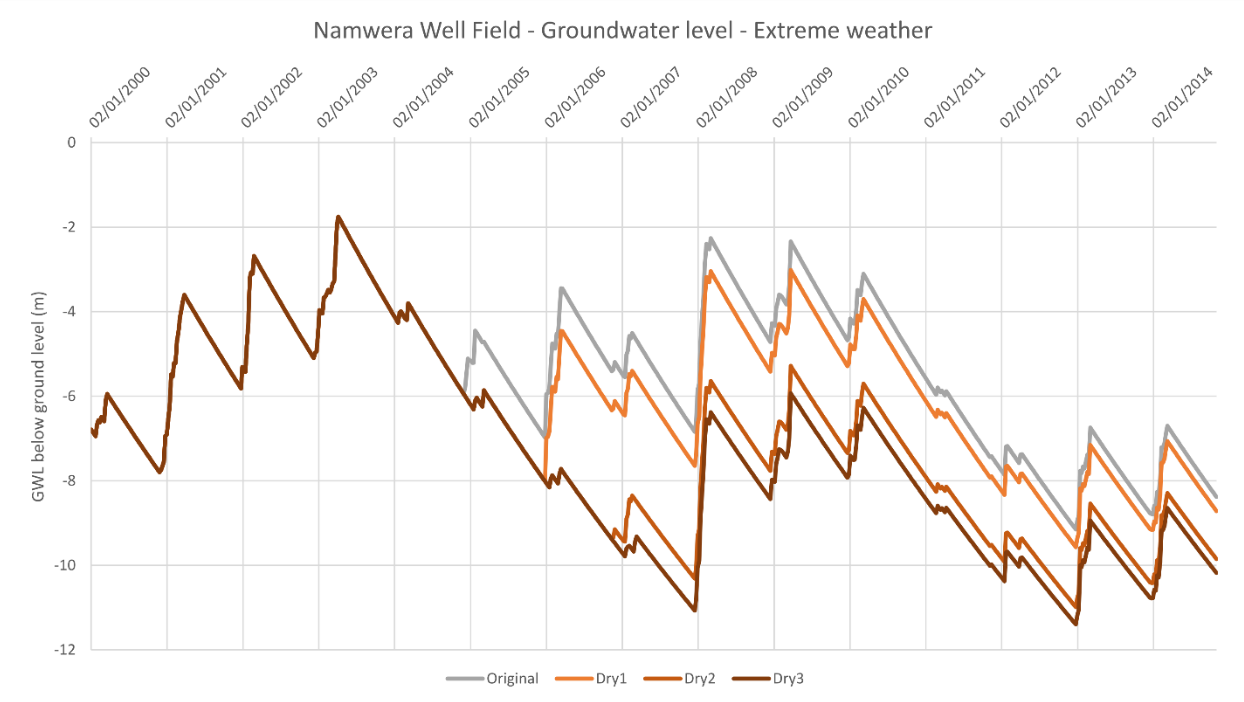

Figure 29 Simulated groundwater level for Namwera borehole, and for seven different scenarios the three dry scenarios (Dry 1, 2, 3)

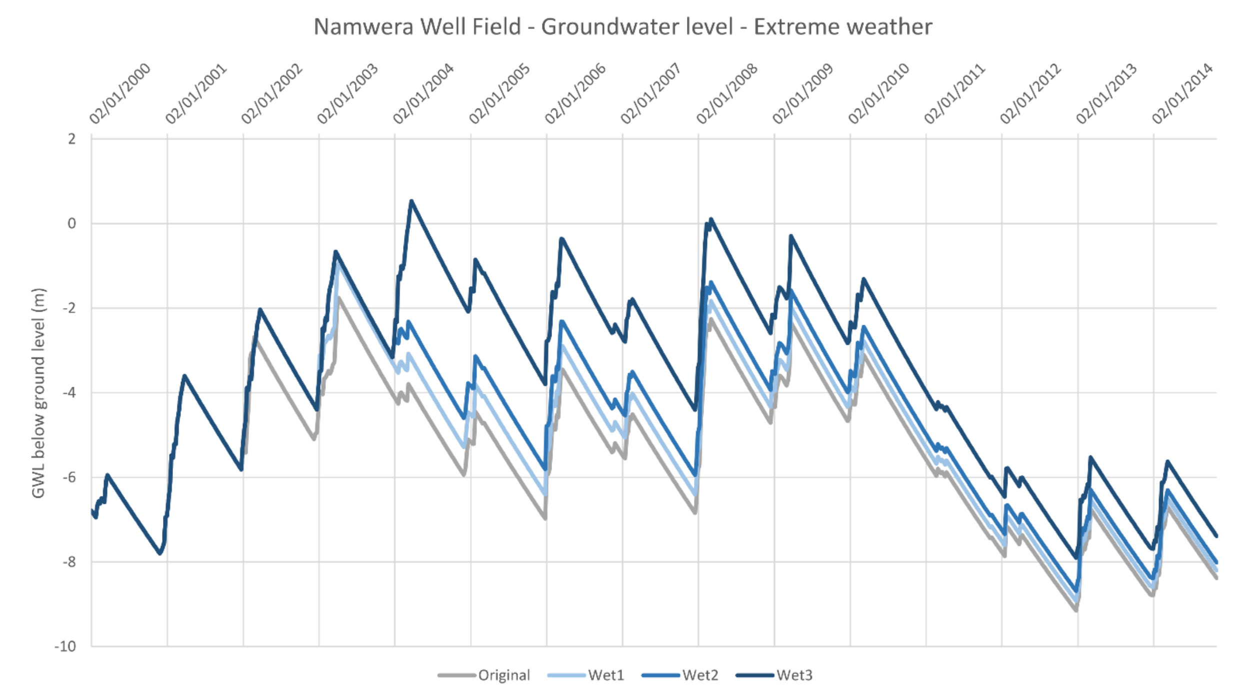

Figure 30 Simulated groundwater level for Namwera borehole, and for the three wet scenarios (Wet 1, 2, 3)

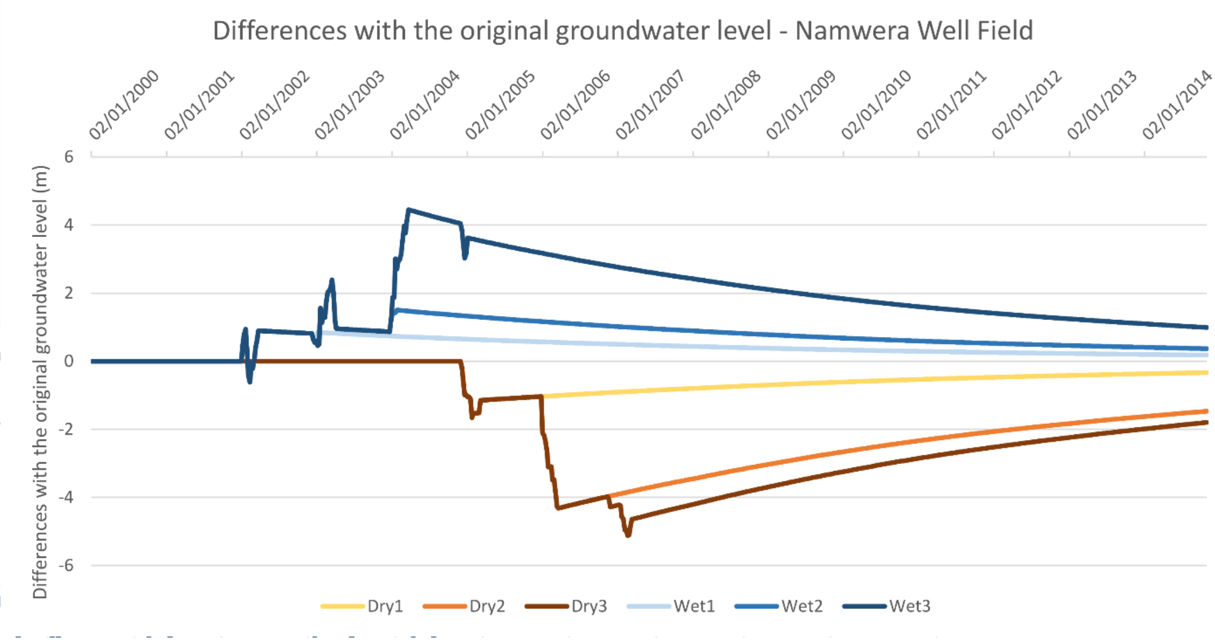

Figure 31 Difference with the original groundwater level for Namwera Well Field borehole, for the six dry and wet scenarios

5 Summary

Using a combination of statistical and modelling tools, the groundwater resources in Malawi under extreme weather conditions were investigated. The calculation of extreme weather indexes using the available rainfall time series allowed defining periods of extreme weather (drought and wet events). These periods were then used to produce synthetic meteorological extreme scenarios. The distributed recharge model (ZOODRM) which is developed by Scheidegger et al. (2015) and used to calculate long term average recharge values over the whole of Malawi, is rerun using the altered rainfall and evaporation time series to produce estimation of recharge values under extreme conditions. These values were examined using maps and tables to assess the consistency of the alteration of the recharge over Malawi.

This exercise shows how the groundwater resources can be impacted by the recurrence of two, three or four years of wet and dry years. On average, the groundwater system is expected to be in shortage of 9% of historical long term average recharge values calculated for the country when four successive years of drought years are considered. The groundwater system contains approximately 11 % more resources than that is calculated historically when four successive wet years are considered. It has been noted that the statistical approach followed to produce the artificial weather sequences was not very successful in producing the desired wet and drought rainfall time series over the districts in the northern parts of the country. Indeed, the extreme weather periods were selected for the whole Malawi. In average for the entire country, these extreme sequences are correct. However the occurrence of extreme weather periods is not necessarily concomitant over the different district. The signals are not as clear in the northern Malawi than in the south, which leads to the production of incorrect synthetic extreme periods for these regions. The numerical model shows inconsistent results with more recharge produced during dry years and less recharge values produced during wet years. However, the percentage changes from the historical LTA recharge values are minimal. This could be caused by the fact that the annual rainfall variations are not significant over these districts due to their proximity to the equator. This is a possible indications that major variations of rainfall pattern is not expected to appear on the short term. Besides the relative proximity to the Lake Malawi could also have an effect on the precipitation, for example at Namwera.

AquiMod lumped groundwater models were then prepared and calibrated for three representative boreholes. Simple structures were chosen and hydrogeological parameters were optimised. Representative transmissivity and storage coefficient values were calculated for the catchments contributing groundwater to these boreholes. The optimised hydrogeological parameters lead to transmissivity values varied between 20 and 1500 m2/day. Storage coefficient (specific yield) on the other hand varied between 0.02 and 0.3. While groundwater level fluctuations were produced to some extent at the Chipita and Endongolweni Boreholes, the model failed to produce the groundwater fluctuations at Namwera. Further investigations using trial and error method were undertaken. It is clear that the recharge produced for this borehole is the main reason preventing AquiMod to produce a good match between observed and simulated time series.

Finally, the AquiMod models were run using the synthetic meteorological extreme scenarios. The heterogeneities appeared again, with a strong influence of both wet and dry events on the groundwater response of the Namwera Well Field borehole (Mangochi district) and nearly no influence (or inconsistent) for the Chitipa Water Office borehole (Chitipa district). As anticipated in the previous sections, the uncertainties associated to the determination of extreme weather periods in the northern Malawi are propagated in this modelling exercise. Whereas the higher extreme weather signals in the south lead to the determination of clearly identifiable extreme weather events, the less clear signals in the north induce the production of incorrect synthetic wet scenarios for this region.

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Appendix A

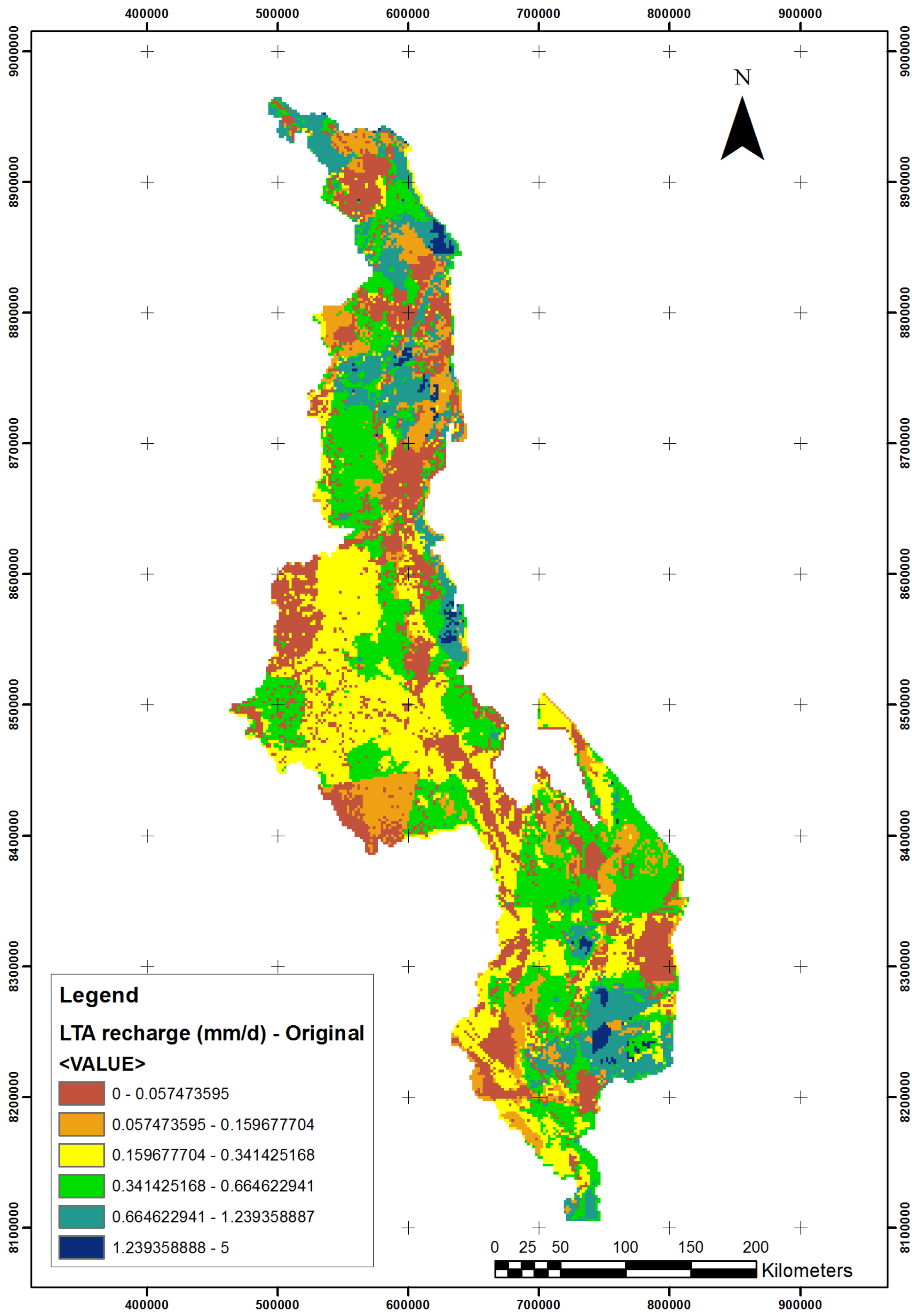

Figure A 1 Long Term Average daily recharge (mm/day) for the time period 2000-2014 for the original meteorological scenario (unaltered rainfall and evaporation time series)

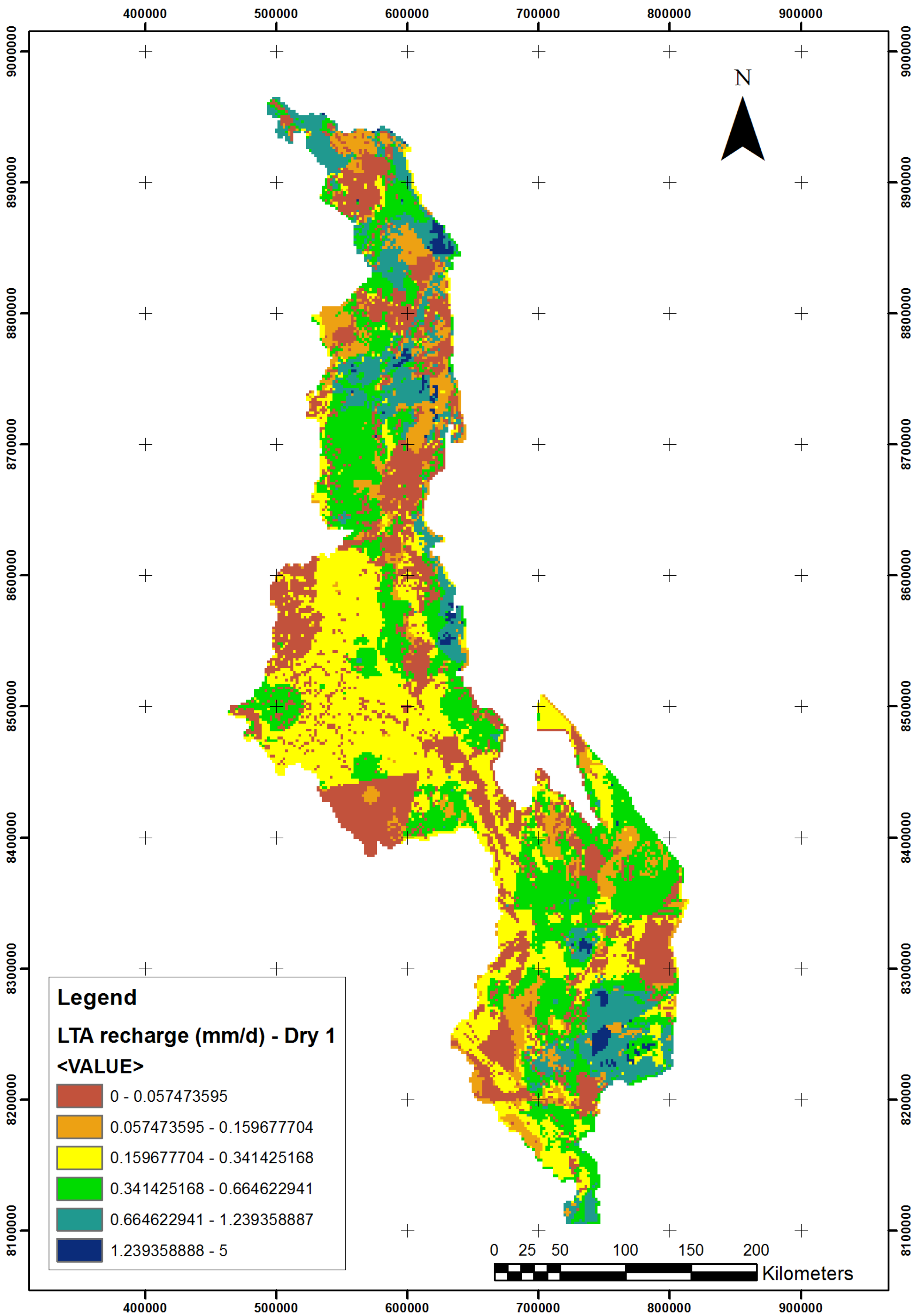

Figure A 2 Long Term Average daily recharge (mm/day) for the time period 2000-2014 for the Dry 1 meteorological scenario

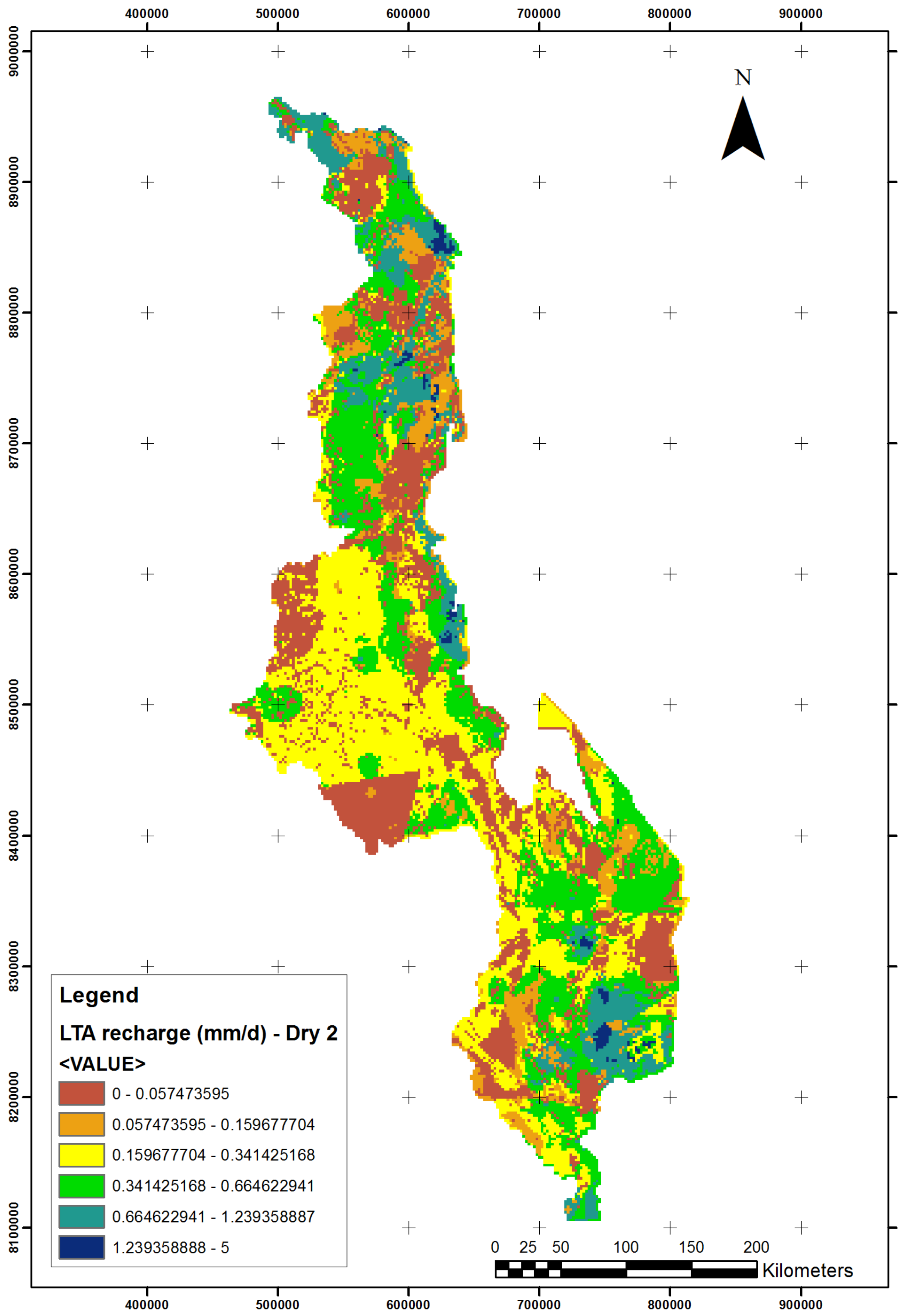

Figure A 3 Long Term Average daily recharge (mm/day) for the time period 2000-2014 for the Dry 2 meteorological scenario

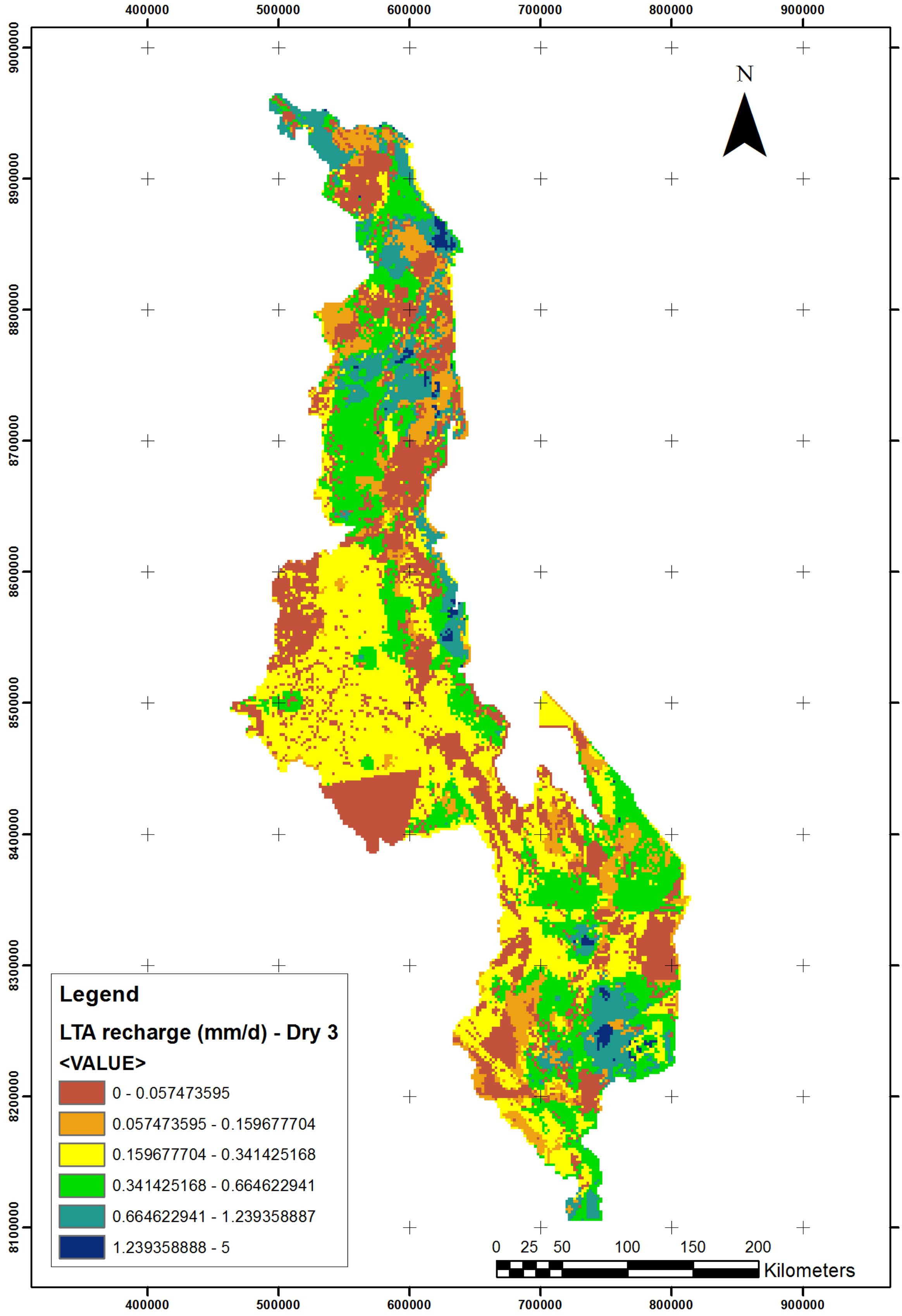

Figure A 4 Long Term Average daily recharge (mm/day) for the time period 2000-2014 for the Dry 3 meteorological scenario

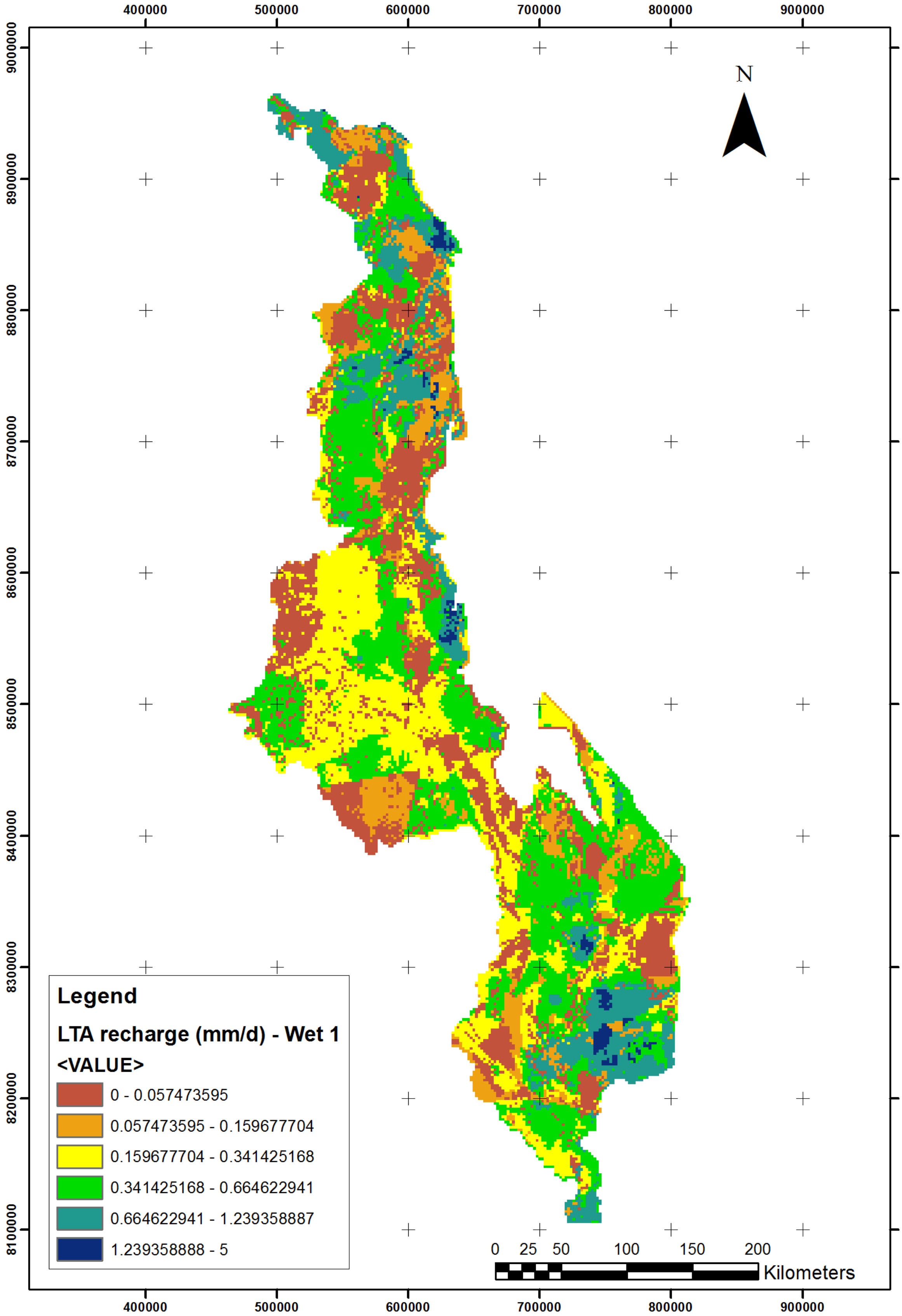

Figure A 5 Long Term Average daily recharge (mm/day) for the time period 2000-2014 for the Wet 1 meteorological scenario

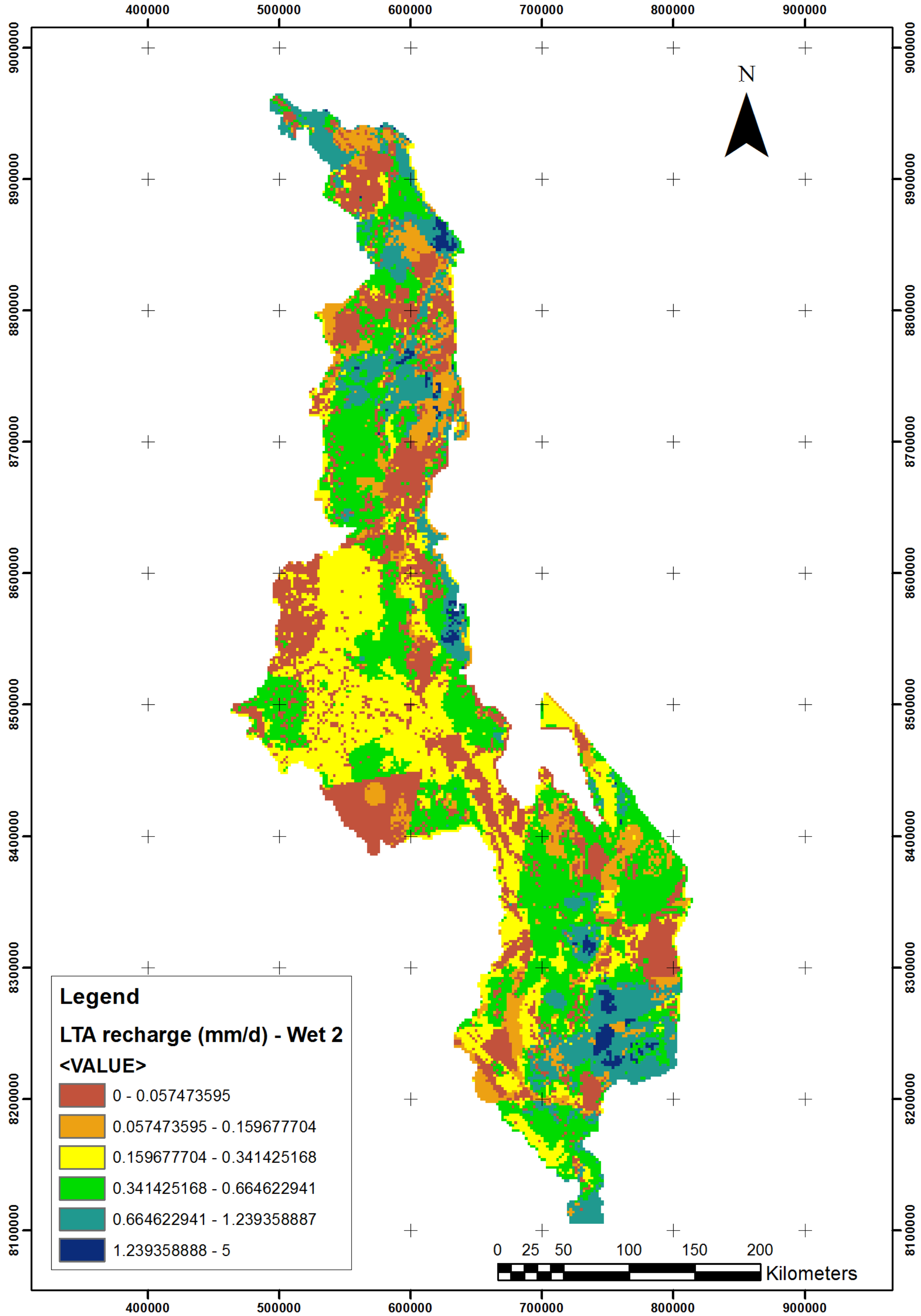

Figure A 6 Long Term Average daily recharge (mm/day) for the time period 2000-2014 for the Wet 2 meteorological scenario

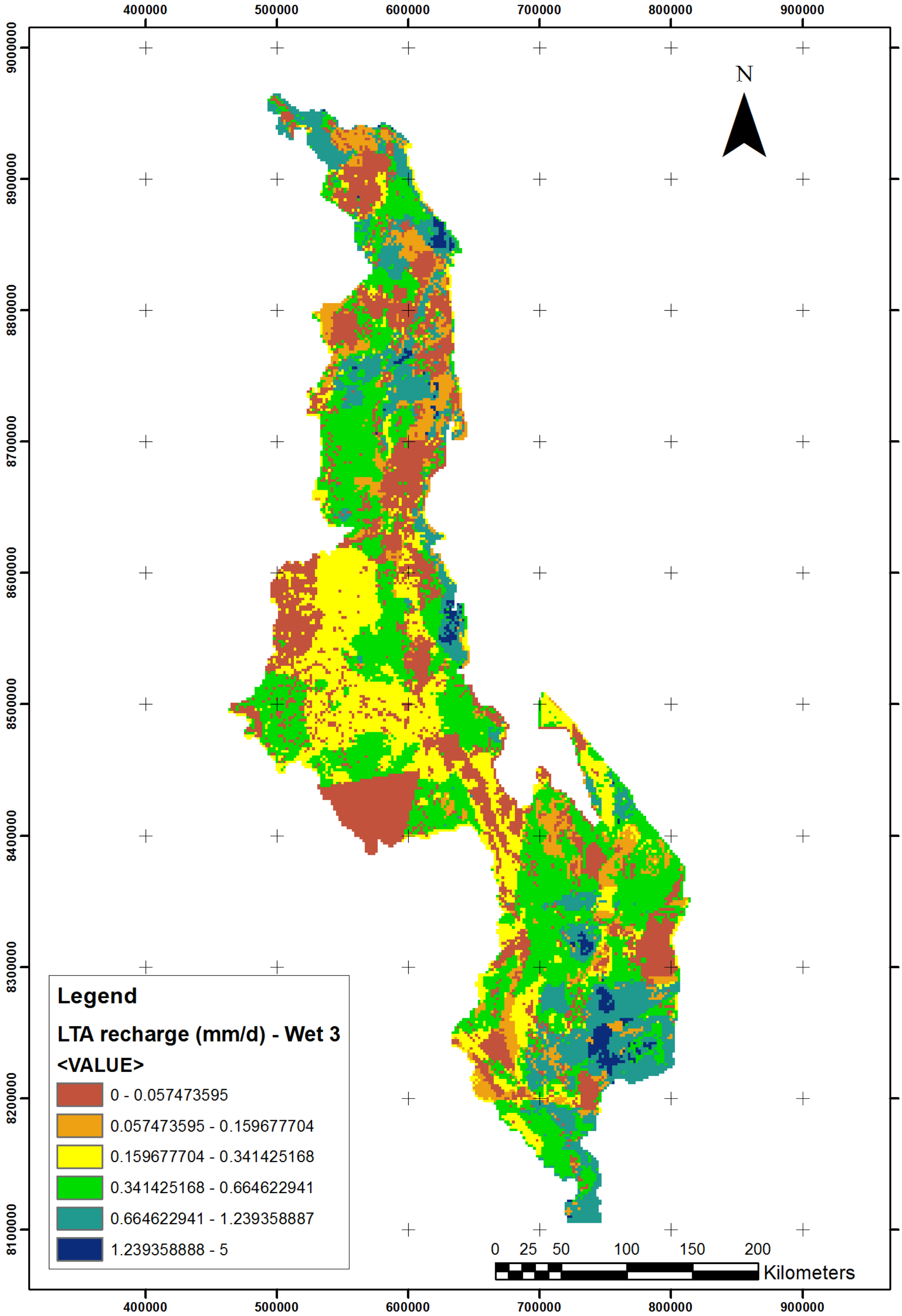

Figure A 7 Long Term Average daily recharge (mm/day) for the time period 2000-2014 for the Wet 3 meteorological scenario