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Evaluation of the hydrological model India-HYPE
With focus on precipitation driving data and regionalization quality

Rasmus Pierong & Maria Takman

Arbetsgruppen för Tropisk Ekologi
Committee of Tropical Ecology
Uppsala University, Sweden

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Rasmus Pierong & Maria Takman

Supervisors:
Prof. Allan Rodhe, Department of Earth Sciences, Program for Air, Water and Landscape Sciences, Uppsala University, Sweden.
Dr. Ilias Pechlivanidis, SMHI, Norrköping, Sweden.
Prof. Devesh Sharma, Department of Environmental Science, Central University of Rajasthan, Rajasthan, India

ABSTRACT

In the year of 2012 a Sida funded joint project between the Swedish Meteorological and Hydrological Institute and the Central University of Rajasthan was initiated aiming to introduce the hydrological model HYPE in India. The overall aim of the project was to assess the hydrological impact of climate change. Historical precipitation and temperature driving data was used to calibrate the model while climate model projections was used to assess the hydrological impact of climate change.

Within the scope of this Minor Field Study the Indian version of the HYPE model was evaluated with focus on precipitation driving data and regionalization quality. The precipitation driving data used in the joint project was evaluated through frequency analyses and linear regressions. The regionalization quality was evaluated by calibrating the model in one river basin and transferring the best parameter set to two adjacent basins.

The evaluation of precipitation driving data indicated that the quality of the historical precipitation data is high but that the evaluation method might be inadequate due to the lack of raw data information such as rain gauge distribution. Also, the climate model projections were shown to be inadequate as driving data for assessments of the hydrological impact of climate change. In the evaluation of regionalization quality it was shown that the best parameter set was inadequate to transfer to adjacent basins. Possible reasons for the bad regionalization quality were erroneous stream flow data used in calibration and evaluation, erroneous driving data and erroneous model structure. In order to improve the regionalization quality one should focus on the calibration process, high quality stream flow data and the development of HYPE algorithms.

FOREWORD

We conducted this project as part of the Master Programme in Environmental and Water Engineering. The aim was to evaluate the hydrological model HYPE. Simulated stream flow data was to be compared with observed. It was known that the stream flow data availability was limited. We intended to conduct several stream flow measurements as well as interviews in order to extend the evaluation material, both quantitatively (measurements) and qualitatively (interviews).

After our arrival to India, we realized that the measurements we intended to do would be difficult to conduct. We experienced several obstacles when trying to access the measurement sites. Also, even though we visited India during the monsoon, we experienced little rain and almost no stream flow. All in all we were only able to conduct one stream flow measurement using a current meter and levelling equipment. However, we realised later that the measurement that we conducted was unimportant for the model evaluation. The reason was that the available model driving data only extended to 2007, something that we were unaware of before our arrival to India. Simulated stream flow after 2007 could only be based on the output from a climate model. A comparison between simulated stream flow based on driving data from a climate model and observed stream flow is only reasonable if the comparison is based on statistics such as averages and standard deviations over several years. We could not collect such an extensive material since we only spent two months in India.

Instead of focusing the model evaluation on our own measurements we had to rely on existing observations. However, we supplemented the existing observations with soft data through interviews, which turned out to be valuable for the overall evaluation.

Visiting India, and especially the study area, was important for completing this project, even without the need to conduct measurements. The two most important advantages of being in India was the possibility to conduct interviews with locals in the study area and to be able to discuss the progress of our project with our local supervisor Devesh Sharma at the Central University of Rajasthan. Mr. Sharma also provided us with a lot of background information and useful data. Lastly, it was valuable to travel through the study area to examine the land characteristics.

Uppsala. February 2014. Rasmus Pierong and Maria Takman.

Committee of Tropical Ecology, Biology Education Centre, Uppsala University.

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Supervisors

Ilias Pechlivanidis at the Swedish Meteorological and Hydrological Institute.

Allan Rodhe at the Department of Earth Sciences at Uppsala University.

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1. INTRODUCTION

In 2000, the European Union had the EU Water Framework Directive (WFD) legislated, aiming for better water quality in all member states (European Commission, 2013). Implementation of the WFD in Sweden required better knowledge about the water quality. To meet the new requirements the Swedish Meteorological and Hydrological Institute (SMHI) developed a new hydrological model (Lindström et al., 2010). The model was spatially distributed and able to simulate several water variables such as stream flow. It was named Hydrological Predictions for the Environment (HYPE). The first model version was mainly developed between 2005 and 2007. It was built to meet Swedish conditions and named S-HYPE. Later model versions have been built to meet conditions outside Sweden such as in Europe, South America, Nigeria and the Arctic region (SMHI, 2013a). In 2012, a Sida funded joint project between SMHI and the Central University of Rajasthan (CURAJ) was initiated aiming to introduce HYPE in India. The overall aim of the project was to assess the hydrological impact of climate change (SMHI, 2013b).

Enhanced computational power and better understanding of hydrological systems have over the last decades increased the complexity and the potential performance of hydrological models (Chapra, 2011). As a consequence it is often the quality of driving data rather than the model itself that limits hydrological modeling. It is therefore important to evaluate the driving data quality prior modeling. Pre-modeling driving data analysis is a concept addressed by Kauffeldt et al. (2013). Driving data to HYPE is precipitation and temperature. Two different sources of precipitation data were used in the joint project of SMHI and CURAJ. The first source was Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation of the Water Resources (APHRODITE), in which daily temperature and precipitation data based on observations was provided. The other source was Coordinated Regional climate Downscaling Experiment (CORDEX), in which future projections of temperature and precipitation data was provided. The APHRODITE data was used for calibration and evaluation while the CORDEX data was used to assess hydrological impacts of climate change.

Most hydrological models, for example HYPE, must be calibrated in order to give reliable output data. However, calibration is not possible in ungauged basin. This problem has been addressed by the International Association of Hydrological Sciences (Sivapalan et al., 2003). To obtain adequate model output data in an ungauged basin different regionalization approaches are utilized. One approach is to calibrate the hydrological model in a gauged basin similar to the ungauged, and to transfer the obtained parameter set to the ungauged basin. The quality of this regionalization approach can be evaluated by transferring the obtained parameter set to another gauged basin similar to the ungauged basin. If the transferred parameter set yields a high model performance in the gauged basin it is believed to do so in the ungauged basin as well.

1.1 AIM

The aim of this study was to

- evaluate the quality of the APHRODITE and CORDEX precipitation driving data used in the joint project of SMHI and CURAJ,
- investigate the regionalization quality of India-HYPE when transferred from one basin to adjacent basins.

1.2 RELATED RESEARCH DONE BY SMHI

The work done within the scope of this study is related to and dependent on precedent and concurrent research done by SMHI. India-HYPE was under development throughout the duration of this study. The basic model structure had been constructed so that simulations could be done. However, parts of the model structure such as the area delineation and some process algorithms were likely to be updated in later model versions. The model version used in this study was the latest one available, India-HYPE version 1.0.

1.2.1 Precipitation driving data

SMHI initiated an evaluation of the APHRODITE precipitation driving data prior this study. They compared the number of rainy days and accumulated precipitation with a dataset provided by the Indian Meteorological Department (IMD). The analysis was based on the assumption that similarities between the two datasets would imply high data quality.

The quality of the APHRODITE precipitation driving data was, according to SMHI, sufficiently high to use for model calibration and evaluation. The mean annual APHRODITE precipitation in the major part of India over the period 1976 to 2003 was within ± 20 % of the IMD data (Figure 1).

1.2.2 India-HYPE

SMHI calibrated India-HYPE to describe the water dynamics of 42 basins in different parts of India (Figure 2). Good model performance measured as the Nash-Sutcliffe efficiency was obtained in most of them with a median Nash-Sutcliffe efficiency of 0.61 (Pechlivanidis, 2013). A basin with a high Nash-Sutcliffe efficiency was the Mahi basin with a value of 0.72 (Pechlivanidis, 2013). SMHI did not obtain high Nash-Sutcliffe efficiencies in all basins. A basin with a low Nash-Sutcliffe efficiency was the Sabarmati basin with a value of less than -2 (Pechlivanidis, 2013). The Mahi and the Sabarmati basins were subject for further analysis within the scope of this project. They are described in section 3.1.

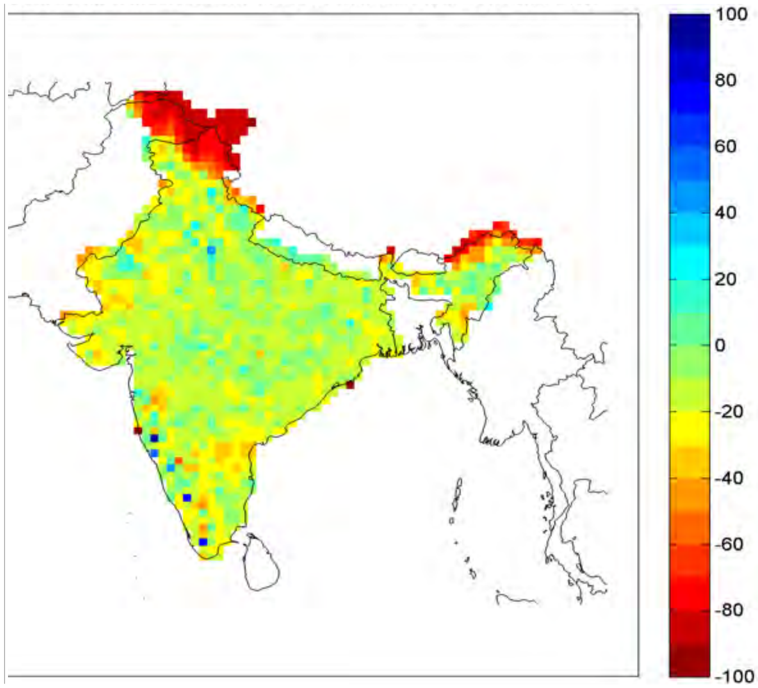

Figure 1. Mean annual accumulated precipitation over the period 1976 to 2003, APHRODITE relative IMD [%]. With permission from Pechlivanidis (source: SMHI).

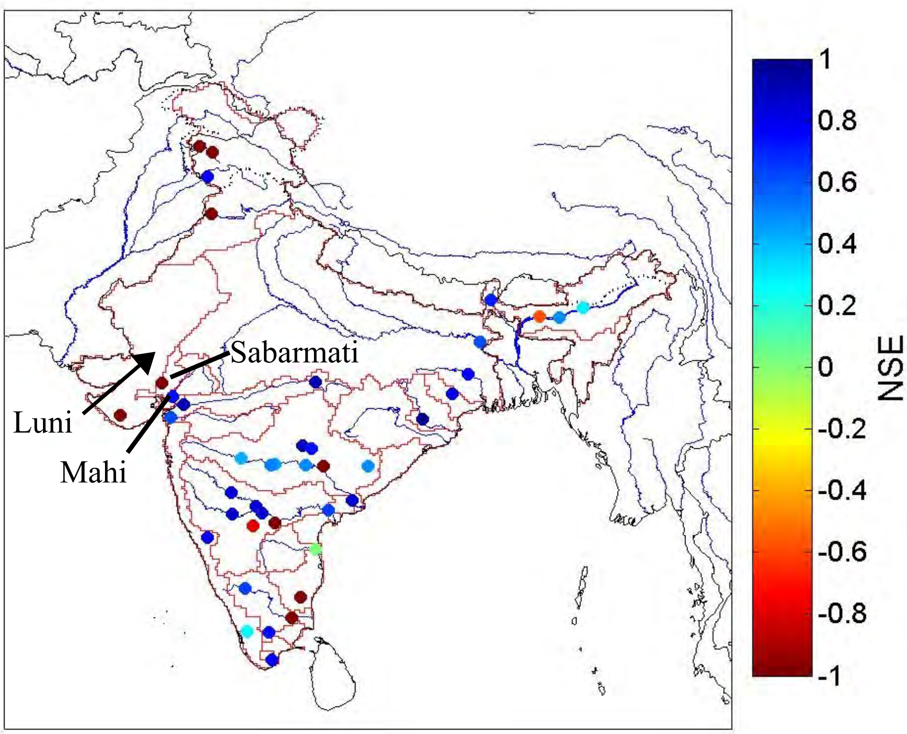

Figure 2. Model performance measured as the Nash-Sutcliffe efficiency. Calibration done by SMHI. Each dot represents a GRDC gauging station for which observed stream flow data was available. No GRDC stream flow data was available for the Luni river basin. The basin location is marked with an arrow. With permission from Pechlivanidis (source: SMHI).

2. THEORY

This chapter includes theory of the HYPE model, the regionalization quality and the short time Fourier transform (STFT).

2.1 THE HYPE MODEL

The HYPE model is complex and only the relevant aspects are addressed in this section. More comprehensive descriptions are given by Lindström et al. (2010) and in the HYPE model description (SMHI, 2012).

2.1.1 Basic components

HYPE is a spatially semi-distributed model that describes water dynamics with a relatively high spatial resolution. The spatial domain of the model is the basin. Each basin is divided into sub-basins which are the smallest geographical units of the model. Sub-basins can vary in size from a few to several hundred square kilometres. A sub-basin consists of classes. A class is a combination of land use and soil type, for example crops and coarse soil. It can have an elevation different from the sub-basin mean and the soil layer thickness can vary and be divided into up to three layers. Classes are given as fractions of the sub-basin area and are hence not spatially distributed.

Each sub-basin contains one main river that represents a real river (Figure 3). The stream flow of main rivers can hence be compared to and calibrated after observed stream flow. All other rivers that may exist in reality are lumped into a local river (Figure 3). The stream flow in the local river has no equivalent in reality. This is one of the spatial limitations of the HYPE model.

The sub-basins can also contain outlet lakes and internal lakes. Outlet lakes represent real lakes and they are located in the end of the main rivers so that the outflow from an outlet lake enters the downstream sub-basin. Variables from the outlet lake such as water level and temperature can be compared to and calibrated after observations. All other lakes that may exist in reality are lumped into an internal lake. Hence the variables of the internal lake have no equivalents in reality.

The point where the main river or the outlet lake enters a downstream sub-basin is referred to as a forcing point. This is the point where simulated stream flow is compared to observed. Each forcing point is referred to with the id number of the corresponding sub-basin.

2.1.2 Water courses

The water enters a sub-basin as precipitation or as inflow from upstream sub-basins. Water from upstream sub-basins can either enter the main stream as stream flow or the soil layers as regional groundwater flow. The precipitation infiltrates the soil layers or reaches the local stream via saturated overland flow. Soil water above field capacity reaches the local stream as runoff. A fraction of the water in the local stream goes to the local lake from where it continues to the main river. The rest goes directly to the main river. The main river either transports the water to the downstream sub-basin or to an outlet lake. The outflow from the outlet lake reaches the main river of the downstream sub-basin.

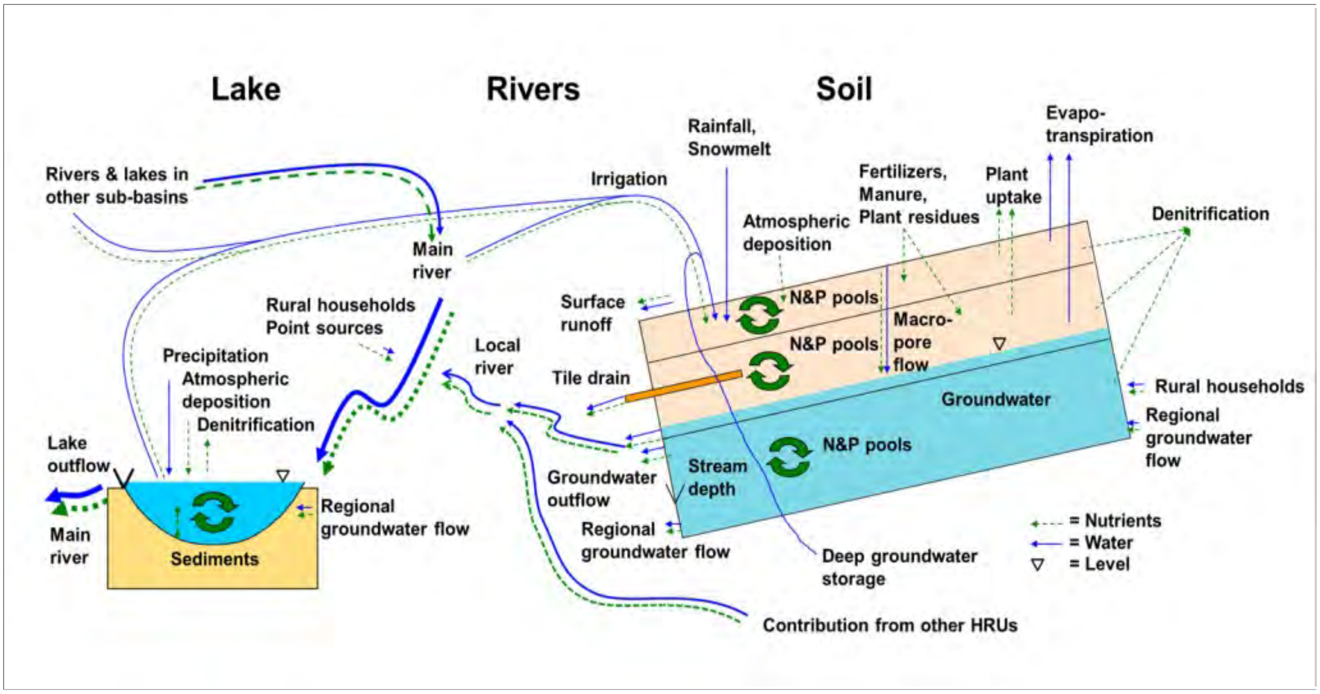

Figure 3. Schematic description of the HYPE model. Both water and nutrient dynamics are illustrated. However, only water dynamics are addressed within this study. With permission from Pechlivanidis (source: SMHI, 2013c).

2.1.3 Variables and driving data

Daily sub-basin averages of precipitation and temperature are given as driving data. This driving data can be adjusted to elevation or uniformly increased or decreased over all sub-basins. Adjustment to elevation is for example done if the resolution of the driving data is low and if it is likely that the driving data does not capture the precipitation hight dependency.

Many variables exist that can be used for model analysis and calibration, for example stream flow in main rivers, water level of output lakes and water temperature of output lakes. Other variables that are of great importance in many HYPE applications but outside the scope of this project are the nutrients phosphorus and nitrogen.

2.1.4 Parameters

Model parameters are categorized as general, regional, land use dependent or soil type dependent. There are 28 general, seven regional, five land use dependent and 15 soil type dependent parameters. Each general or regional parameter can only take one value while the land use and soil dependent parameters can take one value for each land use or soil type, respectively. All parameters addressed in this study are listed in this section with their respective value prior to calibration (Table 1 through Table 3). A comprehensive list of all existing parameters and their respective value prior to calibration is attached in Appendix A.

Table 1. Initial values of the general parameters studied in this project

Parameter number	Parameter	Initial value
1	*cevpam* [-]	0
2	*cevpph* [days]	0
3	*rcgrw* [-]	0.12
4	*lp* [-]	0.95
5	*rivvel* [m/s]	1
6	*damp* [-]	0.5
7	*pcelevadd* [-]	0.05
8	*pcelevth* [m]	550
9	*pcelevmax* [-]	1

1 and 2. The parameters *cevpam* and *cevpph* are used to calculate the seasonal variation of potential evapotranspiration (PET) according to

$$epotcorr = 1 + cevpam \cdot \sin\left(2 \cdot \pi \cdot \frac{(dayno - cevpph)}{365}\right), \tag{1}$$

$$epot = (temp - ttmp) \cdot epotcorr \tag{2}$$

where *epot* is the PET, *temp* is the temperature, *ttmp* is a threshold temperature above which evapotranspiration occurs, *epotcorr* is the seasonal variation adjustment and *dayno* is the day number. A high value of *cevpam* makes the PET more sensitive to season. A high value of *cevpph* shifts the period with high PET towards a later season, as default from spring towards summer.

3. The parameter *rcgrw* is a recession coefficient for regional groundwater flow, that is flow from one sub-basin to another. The regional groundwater flow goes from the lowest layer of one sub-basin to the lowest layer of the downstream sub-basin and is calculated according to

$$grwflow = rcgrw \cdot (soil(3) - wp(3) - fc(3)) \tag{3}$$

where *grwflow* is the groundwater flow, *soil(3)* is the water content of the lowest soil layer in the sub-basin from which the water flows and *wp(3)* and *fc(3)* is the wilting point and the field capacity of the same layer, respectively. Flow only occurs if the water content of the layer exceeds field capacity plus wilting point, as represented in equation (3). A high value of *rcgrw* enhances groundwater flow.

4. Actual evapotranspiration (AET) equals PET when the soil water content reaches the field capacity multiplied by *lp*. The value of *lp* must be in the interval [0 1] and it should be close to 1. A value of *lp* close to 0 would make the AET equal PET even when the soil is dry, which is unrealistic.

5. The parameter *rivvel* defines the maximum velocity of water flow in rivers. A higher value of *rivvel* reduces the transit time in rivers.

6. The parameter *damp* defines the fraction of the delay in a river that also causes damping. A large value of *damp* makes each peak flow lower and longer.

7, 8 and 9. The parameters *pcelevadd*, *pcelevth* and *pcelevmax* are used to adjust precipitation based on elevation. The correction is applied for classes with an elevation higher than *pcelevth*. The maximum correction is defined as a fraction of the original precipitation, the fraction *pcelevmax*. The correction is calculated according to

$$preccorr\_hight = \frac{basinelev + deltah - pcelevth}{100} \cdot pcelevadd\,, \tag{4}$$

$$prec = preci \cdot (1 + preccorr\_hight) \tag{5}$$

where *prec* is the precipitation after adjustment, *preci* is the precipitation prior adjustment, *preccorr_height* is the precipitation adjustment, *basinelev* is the sub-basin average hight and *deltah* is the class elevations deviation from the sub-basin average.

Table 2. Initial values of the land use and soil dependent parameters studied in this project

Parameter number	**Parameter (land use or soil type)**	**Initial values**
10	*cevp* [-] (crops)	0.221
11	*wcfc* [-] (coarse/medium/fine)	0.229/0.316/0.293
12	*wcep1* [-] (coarse/medium/fine)	0.2055/0.1325/0.0306
13	*wcep2* [-] (coarse/medium/fine)	0.1935/0.116/0.0308
14	*wcep3* [-] (coarse/medium/fine)	0.2065/0.139/0.0293

10. The parameter *cevp* is used to adjust the PET uniformly over all seasons according to

$$epot = epot \cdot cevp. \tag{6}$$

The parameter is land use dependent. It has one value for each one of the land uses crops, forest, open, urban, desert, glacier and lake. Only the value coupled to crops was adjusted in this study.

11, 12, 13 and 14. The parameter *wcfc* defines the field capacity of the soil and the parameter *wcep* defines the effective porosity as the soil fraction available for drainage water. The effective porosity varies between soil layers. *wcep3* is for example the effective porosity of soil layer 3. *wcfc* and *wcep* are soil dependent parameters. They have one value for each one of the soil types coarse, medium, fine, organic and shallow. Only the values coupled to coarse, medium and fine soil were adjusted in this study. The absolute values of the field capacity and the effective porosity of a soil layer is calculated from the fractions (for example *wcfc* and *wcep3*) and the soil layer thickness. The absolute values of the third soil layer are referred to as *fc(3)* or *ep(3)* as in equation (3).

Table 3. Initial values of the regional parameters studied in this project

Parameter number	**Parameter**	**Initial value**
15	*rrcscorr* [-]	0
16	*cevpcorr* [-]	0
17	*tempcorr* [-]	0
18	*preccorr* [-]	0

15. The parameter *rrcscorr* is used to adjust the recession coefficients of all soil layers. Those recession coefficients are used to calculate local runoff to local streams. The parameter *rrcscorr* also adjusts saturated overland flow. A high value of *rrcscorr* will increase the runoff from all soil layers as well as the overland flow.

16. The parameter *cevpcorr* is used to adjust the PET according to

$$epot = epot \cdot (1 + cevpcorr). \tag{7}$$

A high value of *cevpcorr* increases the PET uniformly over all seasons.

17 and 18. The parameters *tempcorr* and *preccorr* are used to correct temperature and precipitation according to

$$temp = temp \cdot (1 + tempcorr), \tag{8}$$

$$prec = prec \cdot (1 + preccorr). \tag{9}$$

High values of the parameters increases temperature and precipitation uniformly over all sub-basins and classes.

2.2 REGIONALIZATION QUALITY

It is not always suitable to transfer a parameter set from a gauged basin to an ungauged basin in order to obtain stream flow data in the ungauged one. To achieve a high regionalization quality the basins must have similar characteristics and domains. The quality of the obtained stream flow will also depend on the quality of the regionalization approach and it is important that the hydrological model is conceptually correct.

The basins must have similar characteristics such as rainfall and evaporation values as well as fractions of land uses and soil types. If a characteristic, such as the land use crops, is absent in the basin where the calibration is done, the parameters coupled to that characteristic will not be accurately calibrated. An example of such a parameter is the PET correction *cevp* as described in equation (6). This is not a problem if the parameter set is transferred to another basin with a neglectable fraction of crops. However, the model performance would likely, due to the inaccurate calibration, be low in basins dominated by crops. Another important characteristic is the basin area. The two basins should be similar in size since the basin area affects several other characteristics such as the river length. It is likely that different processes dominates at different geographical scales.

It is important that the domains of the basin where the calibration is done cover the domains of the recipient basin to which the parameter set is to be transferred. The domain can for example be the range of precipitation or the range of elevations. If the calibration only includes low elevations it will not capture the processes that might occur at higher elevations. The model will hence not be able to describe such processes in the recipient basin.

The processes in the model must represent real processes so that the calibration improves the model performance for the right reasons. A model that describes the real system poorly may yield accurate outputs after calibration. However, such a model will perform poorly in other basins.

2.3 SHORT TIME FOURIER TRANSFORM

The Fourier transform is used to transfer a signal from the time domain to the frequency domain. It enables detection of possible frequencies in a signal, which can be difficult in the time domain. The definition of the Fourier transform in discrete time is

$$X(\omega)=\sum_{n=1}^{N} x(n)\cdot e^{-\left(\frac{2\pi i}{N}\right)(n-1)(\omega-1)} \tag{10}$$

where *n* is the sample time, *N* the number of samples, *x(n)* the subject signal, *ω* the frequency and *X(ω)* a measure of the intensity of the frequency *ω* (MathWorks, 2013).

The short time Fourier transform (STFT) utilizes the Fourier transform in a way that makes it possible to detect changes in frequencies over time. The analyzed data series are divided into overlapping time frames and the Fourier transform is conducted for each frame. An increase in the length of a time frame decreases the time resolution but increases the frequency resolution, and vice versa (Rowan University, 2013).

The output from a frequency analysis can be interpreted in different ways. A detected frequency in precipitation data of for example 0.5 $year^{-1}$ means that the precipitation is cyclic with a period of 2 years. Apart from this interpretation, similarities in the STFT output between two precipitation datasets imply similarities in precipitation peak magnitude and standard deviation.

3 MATERIAL

River basins constitute the geographical domain of the HYPE model. The study area of this project included the Mahi basin, the Sabarmati basin and the Luni basin (Figure 5 and Figure 6). Basin characteristics are presented in section 3.1.

Data material was taken from APHRODITE, IMD, CORDEX, the Global Runoff Data Center (GRDC), the Central Water Commission (CWC) and the Moderate Resolution Imaging Spectroradiometer (MODIS). Precipitation data from APHRODITE, IMD and CORDEX was analysed in the evaluation of precipitation driving data. Precipitation and temperature data from APHRODITE and CORDEX was used as driving data in the calibration and the evaluation of the HYPE model. The calibration and evaluation were also based on stream flow data from GRDC and CWC, soft data collected within the scope of this study and PET and AET from MODIS. All data material is presented in section 3.2.

3.1 STUDY AREA

Basin characteristics such as basin area, land uses and soil types were built into India-HYPE by SMHI. This information sometimes differed from that of other sources, in particular the basin areas. Therefore the information about each basin was divided into two sections. One section describes the basin as it was modelled by SMHI (“In the model”) while the other describes the basin according to other sources (“In other sources”). A summary of the presented information is found in the end of section 3.1 (Table 4).

Each basin contains one or several gauging stations at which simulated stream flow was compared to observed. The location of the gauging stations coincide with the forcing points described in section 2.1.1.

3.1.1 The Mahi basin

The Mahi basin is located in Rajasthan (47 %), Gujarat (34 %) and Madhya Pradesh (19 %) (India-WRIS, 2012). Its modelled area does not differ much from the basin area specified in other sources (Table 4). Simulated stream flow was compared to observed values at forcing point 62232. The basin area of this point equals the modelled basin area (33 994 km²) since the point is the outlet of the modelled basin.

In the model

The modelled basin area is 33 994 km².

Mountainous areas characterise the basin. About half the basin is above 300 m a.s.l. The elevation of Mahi's sub-basins ranges from 37 m a.s.l. to 522 m a.s.l.

The land use is dominated by crops (85 %) while the soil is dominated by medium (43 %), fine (29 %) and coarse (24 %) soil types.

In other sources

The Mahi basin is bounded by the Aravalli mountains in the north and in the north-west, by the Malwa Plateau in the east and by the Gulf of Khambhat in the west, where the basin outflow is located (India-WRIS, 2012). The total basin area is 34 842 km² (India-WRIS, 2012) while the basin area upstream the gauging station is 33 670 km² (GRDC, 2013a).

Mahi is the main river of the basin with a length of 583 km and elevations ranging from sea level at the Arabian Sea to 500 meters in the Aravalli range (India-WRIS, 2012).

Agricultural land dominates the basin and occupies approximately 64 % of the area (India-WRIS, 2012).

Precipitation pattern is largely affected by the South-West monsoon covering a period from the middle of June to early October (India-WRIS, 2013a). 90 % of the precipitation is received during this period (India-WRIS, 2013a). The average annual basin precipitation is 785 mm (India-WRIS, 2013a). There is no positive correlation between precipitation and altitude since precipitation is high in some areas with low elevation and low in some areas with high elevation (India-WRIS, 2012).

3.1.2 The Sabarmati basin

The Sabarmati basin is located in the states of Gujarat (81 %) and Rajasthan (19 %) (India-WRIS, 2012). Its modelled basin area differs somewhat from the basin areas specified in other sources. Simulated stream flow was compared to observed at forcing point 32341. The basin area of this point equals the modelled basin area (8 650 km²) since the point is the outlet of the modelled basin. However, the forcing point does not coincide with the outlet of the basin according to India-WRIS (2012).

In the model

The modelled basin area is 8 650 km².

Mountainous areas characterise the basin. About half the basin is above 300 m a.s.l. Its share of high elevation areas is larger than that of the Mahi basin. This makes the Sabarmati basin more sensitive to precipitation adjustment as described in equation (4) and (5). The elevation of Sabarmati's sub-basins ranges from 90 m a.s.l. to 732 m a.s.l.

The land use is dominated by open vegetation (53 %) and crops (40 %) while the soil is dominated by medium (49 %) and coarse (44 %) soil types.

In other sources

The basin is bounded by the Aravalli mountains in the north, the Rann of Kutchh in the west and the Gulf of Kambhat in the south. The total basin area is 21 674 km² (India-WRIS, 2012) while the basin area upstream the gauging station is 12 950 km² (GRDC, 2013a).

Sabarmati is the main river of the basin with a length of 371 km and elevations ranging from sea level at the Arabian Sea to 762 meters in the Aravalli range (India-WRIS, 2012).

Agricultural land dominates the basin and occupies approximately 75 % of the area (India-WRIS, 2012).

Precipitation pattern is largely affected by the South-West monsoon covering a period from the middle of June to early October (India-WRIS, 2013b). The average annual basin precipitation is 787.5 mm (India-WRIS, 2013b). There is no positive correlation between precipitation and altitude since the precipitation is high in some areas with low elevation and low in some areas with high elevation (India-WRIS, 2012).

3.1.3 The Luni basin

The Luni basin is located in Rajasthan (CWC, 2006). Its modelled basin area differs much from the basin area specified in other sources. The main reason is probably that the plains north-west of the Luni river aggravates delineation. Simulated stream flow was compared to observed at forcing points 3106 and 8322 located at the gauging stations of Balotra and Gandhav, respectively. Comparisons were also done with the soft data collected at forcing points 13057 and 13006.

In the model

The south-west boundary of the basin is close to Gandhav and the north-east boundary is located north of the Sambarh Lake, covering the Aravalli mountains in the south-east and the flat lands around Barmer in the north-west. The total area of the basin was modelled as 77 194 km². This area was divided into 84 sub-basins. The basin areas of Balotra and Gandhav were modelled as 28 987 km² and 57 763 km², respectively.

Mountainous areas characterise the basin. About 30 % of the sub-basins have an elevation higher than 300 m a.s.l. Its share of high elevation areas is smaller than that of the Mahi basin. This makes the Luni basin less sensitive to precipitation adjustment as described in equation (4) and (5). The elevation of Luni's sub-basins range from 24 m a.s.l. to 477 m a.s.l.

The land use is dominated by open vegetation (52 %) and crops (40 %) while the soil is dominated by medium (49 %) and coarse (43 %) soil types.

The precipitation within the Luni basin varies both spatially and temporarily. The APHRODITE precipitation driving data varied spatially between 150 mm and 550 mm per year over the period 1978 to 2005 while the basin average was about 300 mm per year over the same period (Figure 4). The corresponding numbers for the CORDEX data were 200 mm, 1500 mm and 450 mm, respectively (Figure 4).

In other sources

The basin area is 34 866 km² according to Sharma (1997) and 32 879 km² according to CWC (2006). Both sources defined the basin as the area bounded by the Aravalli range in the south-east and the basin's main river, the Luni river, in the north-west. Hence they excluded the flat lands north-west of the main river and the north-eastern extension towards the Sambarh Lake. The main tributaries join the Luni river from the western slopes of the Aravalli mountains and not from the areas north-west of the Luni river or the north-eastern extension towards the Sambarh Lake. The basin areas of Balotra and Gandhav are, according to CWC (2012), 19 000 km² and 32 010 km², respectively.

Mountainous areas cover about 52 % of the basin (Sharma, 1997). The Luni river has its sources in the western slopes of the Aravalli mountains at a maximum altitude of 772 m a.s.l. and its outfall in the Rann of Kutchh (CWC, 2006). The total length of the Luni river is 511 km (CWC, 2006).

Agricultural land dominates the basin (India-WRIS, 2012).

The precipitation varies both spatially and temporarily. It is highest in the Aravalli mountains in the south-east with an annual mean of 600 mm and lowest in the north-west with an annual mean of 300 mm (Sharma, 1997). 93 % of the precipitation falls during the monsoon period of June to September (Sharma, 1997). The river system of the Luni basin only contains water as a response to strong precipitation since the pan evaporation of 2 640 mm/year largely exceeds precipitation (Sharma, 1997).

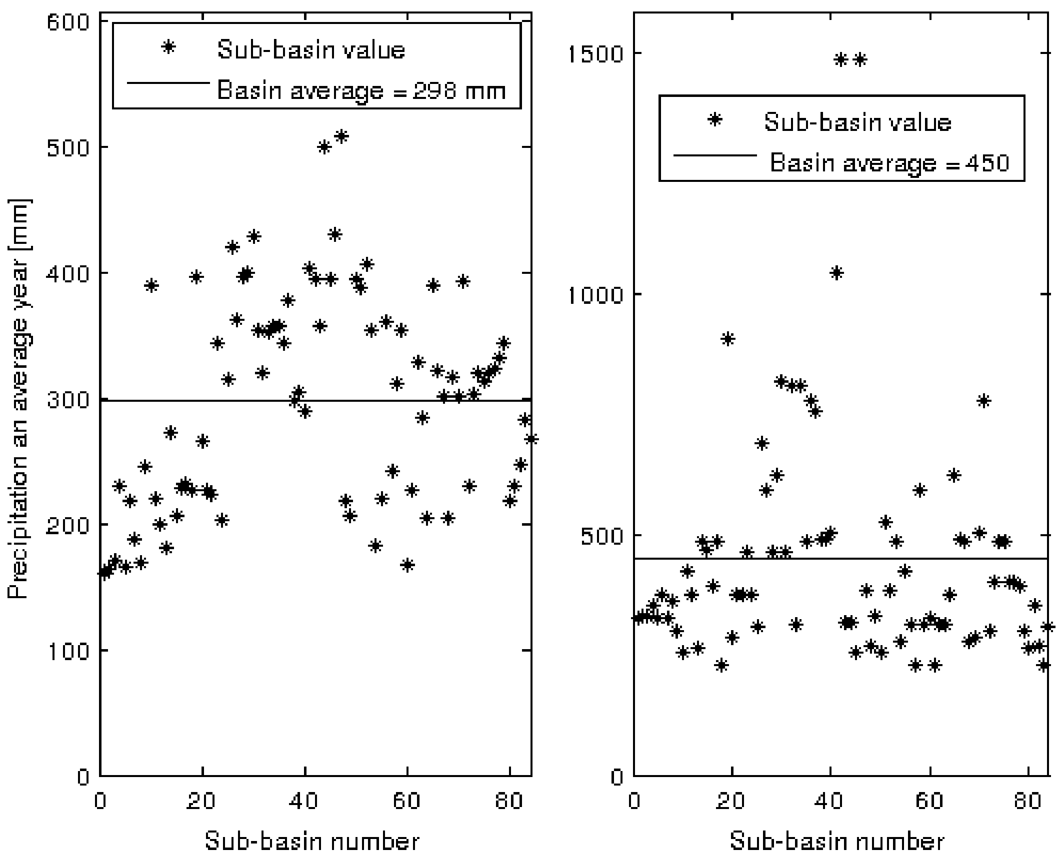

Figure 4. Mean annual precipitation in Luni's 84 sub-basins over the period 1978 to 2005. Left: APHRODITE. Right: CORDEX.

3.1.4 Summary

Table 4. Summary of the geographical study area

Characteristic	Mahi	Sabarmati	Luni
Area [km²]	33 670[f], 33 994[c]	12 950[f], 8 650[c]	34 866[d], 32 879[b], 77 194[c]
River length [km]	583[a]	371[a]	511[b]
Maximal elevation [m a.s.l.]	522[c]	732[c]	772[b] 477[c]
Agricultural land [%]	64[a], 85[c]	75[a], 40[c]	40[c]
Annual precipitation average [mm]	785[e]	787.5[e]	300 – 600[d], 150 – 550[c]
Forcing point id	62232	32341	3106 (Balotra), 8322 (Gandhav), 13057, 13006

[a] India-WRIS, 2012. [b] CWC, 2006. [c] Values used in HYPE. [d] Sharma, 1997.
[e] India-WRIS, 2013a and India-WRIS, 2013b. [f] GRDC, 2013a.

Figure 5. Illustration of Indian basins as defined by India-WRIS (2012). 10 and 11 mark the Mahi basin and the Sabarmati basin, respectively. 20 marks several basins including the Luni basin. With permission from Paithankar (source: India-WRIS, 2012).

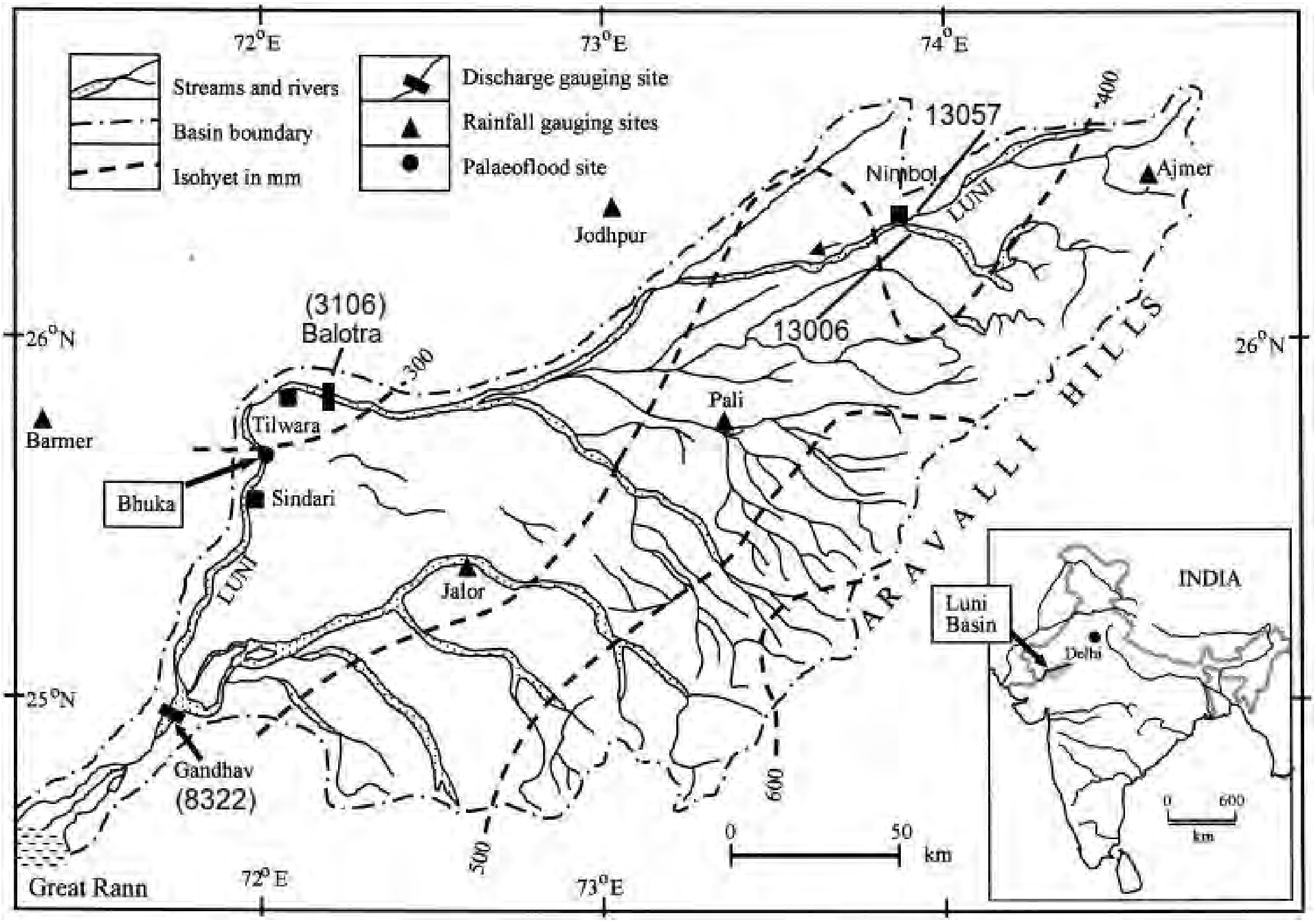

Figure 6. Illustration of the Luni basin. The forcing points 3106 and 8322 are marked as Balotra and Gandhav, respectively. The forcing points 13057 and 13006 are located just upstream Nimbol. 13057 is located in the northern stream and 13006 in the southern. With permission from Pechlivanidis (source: SMHI).

3.2 DATA

3.2.1 APHRODITE data

The APRODITE project was initiated in 2006 with the purpose to develop daily precipitation data on high resolution grids covering all of Asia (Yatagai et al., 2012). To develop gridded data the project staff utilized compiled data from the Global Telecommunication System, compiled and probably quality checked data from several organizations and projects, and crude data from national organizations in several countries, for example India (Yatagai et al., 2009). The gathered precipitation data covered an extensive network of between 5 000 and 12 000 rain gauges (Figure 7). To obtain values of precipitation at all grid points, observations from the rain gauges were interpolated (Yatagai et al., 2012). APHRODITE does not provide information about the rain gauge locations (Yatagai et al., 2012). It is hence difficult to evaluate the quality of the gridded data in terms of spatial heterogeneity. Precipitation observations from India were partly taken from IMD (APHRODITE's Water Resources, 2013). Temperature data was added to the APHRODITE project using the same methodology as for precipitation. Crude temperature data was collected from several sources and interpolated to create gridded temperature data (Yasutomi et al., 2011).

The APHRODITE data covers the period 1961-01-01 to 2007-12-31 and it has a spatial resolution of 0.25° x 0.25°.

The quality of the APHRODITE data was, as discussed in section 1.2, considered relatively high by SMHI.

3.2.2 IMD data

IMD is an Indian governmental department whose tasks include providing meteorological data and statistics that for example can be used in management of water resources (IMD, 2013a). One of the products provided by IMD is daily gridded precipitation data with the spatial resolution 0.5° x 0.5° covering the period 1971-01-01 to 2005-12-31 (IMD, 2013b).

3.2.3 CORDEX data

CORDEX is a program sponsored by the World Climate Research Program. The aim of the program is to produce local- and regional scale scenarios for global climate change (Santander Meteorology Group, 2013). Beside this aim the CORDEX program has two essential purposes (Giorgi et al., 2009). The first purpose is to provide a framework for model performance evaluation, referred to as the model evaluation framework. The second purpose is to design experiments in order to produce climate projections, referred to as the climate projection framework. Within the CORDEX program, regional climate models are used to downscale and increase the spatial resolution of global climate predictions (Giorgi et al., 2009).

The domains of CORDEX include the majority of the land areas in the world. The Asian continent is divided into three domains, one of which is centered at the Indian monsoon (Giorgi et al., 2009).

SMHI contribute to the CORDEX project through the Rossby Centre's climate model RCA4, which is used to downscale global climate predictions. The CORDEX data used in this study was prepared by RCA4.

The CORDEX data used in this study was not bias corrected. It was given on daily basis for the time period 1976-01-01 to 2100-12-31 and it had a resolution of about 0.44° x 0.47°.

3.2.4 GRDC data

GRDC is an international archive for stream flow data. The archive was established two decades ago and it possesses daily and monthly stream flow data from nearly 9 000 stations in 157 countries (GRDC, 2013b).

Stream flow data from forcing points 62232 and 32341 (the outlets of the modelled Mahi basin and Sabarmati basin, respectively) was used within this project. Both time series were on monthly basis covering the period of 1968-01 to 1979-12. No data existed for the year of 1975.

SMHI considered the quality of the GRDC data as potentially low. They identified several errors in the GRDC data coupled to other basins and it was hence considered likely that errors would occur in the GRDC data coupled to the Mahi and Sabarmati basins as well (Pechlivanidis, 2013).

3.2.5 CWC data

CWC is an office attached to the Ministry of Water Resources under the Government of India. They are responsible for control, conservation and utilization of water resources (CWC, 2013) and they provide information such as stream flow data from several rivers within India.

Stream flow data from forcing points 3106 and 8322 in the Luni basin (the gauging stations of Balotra and Gandhav, respectively) was taken from CWC:s Integrated Hydrological Data Book. Information were taken from the editions of 2006 and 2012. One dataset was given as monthly averages from the period 1995 to 2010 (CWC, 2012) while the other was given as annual values (from June to May). The annual values for Balotra was given for the periods 1989 to 1996 (CWC, 2006) and 1999 to 2010 (CWC, 2012). The annual values for Gandhav was given for the periods 1986 to 1996 (CWC, 2006) and 1999 to 2010 (CWC, 2012).

SMHI considered the quality of the CWC data as very low due to a poor measurement strategy. Measurements were not conducted continuously. They were conducted once during the monsoon period and extrapolated in time.

3.2.6 MODIS data

MODIS is an instrument attached to two satellites that orbit the earth. The instruments return information that makes it possible to calculate PET and AET (MODIS, 2013).

The MODIS data used in this study was PET and AET data provided by SMHI. It was given as sub-basin specific daily values. The datasets covered the period of 2000 to 2005.

SMHI considered the quality of the MODIS data as low. The MODIS data is usually biased and erroneous in several areas (Pechlivanidis, 2013).

3.2.7 Soft data

Soft data was collected at forcing points 13057 and 13006 within the Luni basin via interviews with locals. The interview procedures are presented in section 4.1 and the collected data is presented in section 5.1.

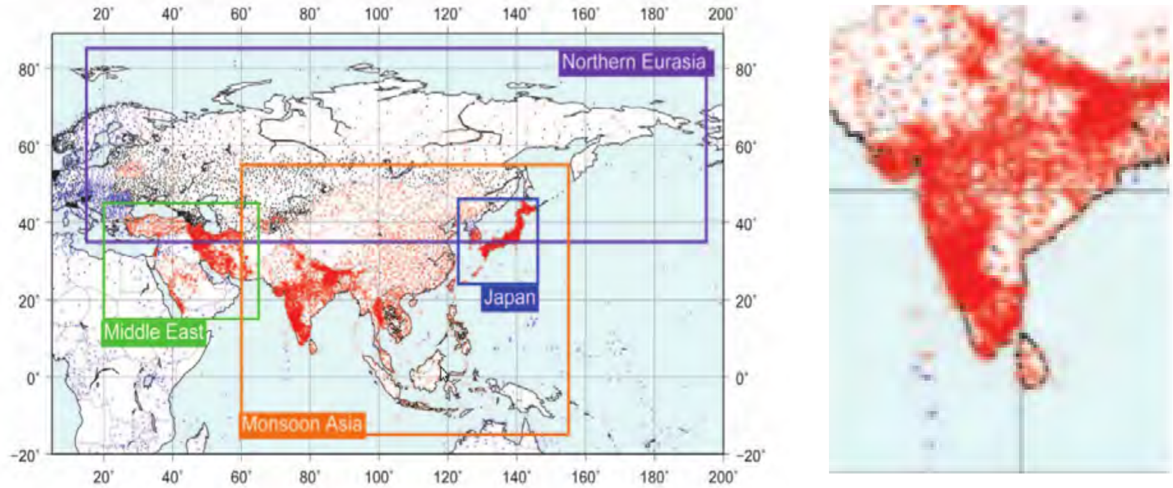

Figure 7. Left: The domains and rain gauge distributions used in APHRODITE. Right: A zoom in on the Indian subcontinent. APHRODITE utilized compiled data from the Global Telecommunication System (blue dots), compiled and probably quality checked data from several organizations and projects (black dots) and crude data from national organizations in several countries (red dots). With permission from Pechlivanidis (Source: Yatagai et al., 2012).

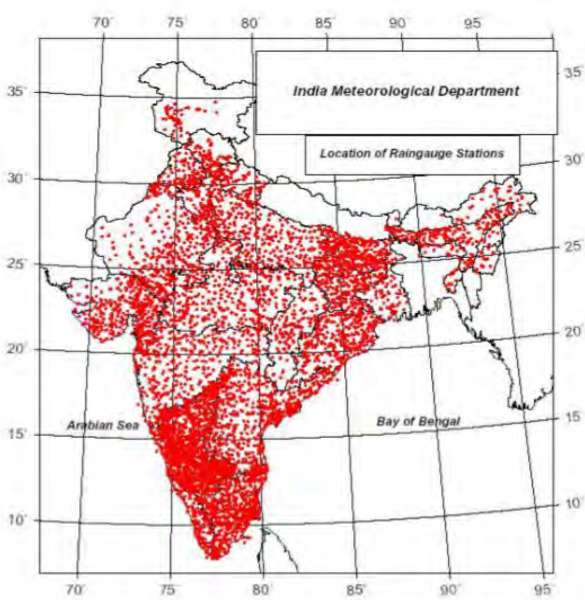

Figure 8. The rain gauge distribution used by IMD. With permission from Pechlivanidis (Source: Rajeevan and Bhate, 2008).

4 METHODS

Soft data was collected via interviews from the locations of forcing points 13057 and 13006 (Figure 6). This was done in order to extend the evaluation material.

The quality of the APHRODITE and CORDEX precipitation driving data as compared to the IMD data was evaluated by frequency analyses and linear regressions. The precipitation datasets from the three sources were analyzed with the STFT. The results were compared, and the comparison was complemented by a linear regression. The analysis was conducted in the Luni basin.

To investigate the regionalization quality of the HYPE model, the model was first calibrated in the Mahi basin. The parameter values obtained from the calibration were transferred to and evaluated in the Sabarmati and the Luni basins.

4.1 SOFT DATA

Soft data was collected at forcing points 13006 and 13057 (Figure 6). The data was collected through interviews with locals, mainly residents of Nimbol. The interview protocol is found in Appendix B.

Dr. Babo, a veterinarian and resident of Nimbol since 2007, and a friend of his, also resident of Nimbol, were the main subjects of the interviews. They answered all questions at forcing point 13006 and all questions apart from the two first ones at forcing point 13057. Two local farmers answered the first three questions at forcing point 13057. All subjects seemed very confident in their answers. However, there were some discrepancy between the sources in that they gave different starting dates for the flood of 2007. The discrepancy adds uncertainty to the soft data.

Dr. Babo was asked in advance to participate in the interview. The two farmers were asked on site, without prior notice. A CURAJ staff translated the interview with the farmers since they spoke little English. The communication with Dr. Babo and his friend was direct since they spoke good English.

4.2 EVALUATION OF THE PRECIPITATION DRIVING DATA

The datasets from APHRODITE and CORDEX were analyzed and compared to IMD data following the assumption that similarities between the datasets imply accuracy and high quality. The datasets were analyzed through frequency analyses using the STFT, and linear regressions.

The grid points of the APHRODITE, CORDEX and IMD data had different coordinates, aggravating comparisons. To make the datasets comparable, spatial precipitation averages for the Luni basin were calculated following the methodology used in HYPE. Each sub-basin was assigned the precipitation value of the closest APHRODITE, IMD and CORDEX grid point. For the APHRODITE data, this was done by SMHI. For the IMD and CORDEX data, it was done within the scope of this project. To calculate the basin average, each sub-basin area [m^2] was multiplied by the corresponding precipitation [$mm \cdot day^{-1}$], all products were added together and the sum was divided by the total area of the Luni basin.

4.2.1 Short time Fourier transform

In the frequency analysis the STFT was used to evaluate the precipitation data from APHRODITE, IMD and CORDEX. Analyses were conducted over the reference period 1976 to 2005 for all three datasets and over the period 2006 to 2100 for the CORDEX data alone. Analyses were done on monthly and annual scale based on monthly and annual averages, respectively. When analyzing the period 1976 to 2005 on monthly basis a time frame of 5 years was used. For the same period on annual basis the number of precipitation data points were to few to conduct a STFT analysis, therefore the fast Fourier transform was used. When analyzing the data for the period 2006 to 2100 on monthly basis a time frame of 10 years was used. When analyzing the data for the same period on yearly basis a time frame of 40 years was used. The results from the frequency analyses were compared. The frequency analyses were conducted using MATLAB.

4.2.2 Linear regression

Linear regressions were made to complement the frequency analyses. The linear regressions were made on monthly and daily basis between the APHRODITE and the IMD datasets.

4.3 MODEL IDENTIFICATION IN THE MAHI BASIN

Calibration was conducted in the Mahi basin using GRDC stream flow data and MODIS PET and AET. Two initial model runs were conducted prior to calibration in order to evaluate the initial parameter set listed in Appendix A. One covered the period 1969-01-01 to 1974-12-31 and was focused on runoff. The other covered the period 2000-01-01 to 2005-12-31 and was focused on PET and AET. The initial model runs were used as a basis for calibration.

The calibration was done over the same periods as the initial model runs. It was conducted in several steps. The first step was to improve the model performance with respect to PET and AET. This was done by single model runs and manual adjustments of parameters. The second step was to improve the model performance with respect to runoff. This was done by calibrating general parameters in a Monte Carlo calibration and regional parameters by single model runs and manual adjustments. The result of the calibration, the best parameter set, was evaluated in the Mahi basin over the period 1976-01-01 to 1979-12-31. The evaluation was based on runoff alone.

4.3.1 Calibration of general, land use and soil type dependent parameters to improve model performance with respect to PET and AET

Parameters adjusted to improve model performance with respect to PET were the general parameters *cevpam* and *cevpph* and the land use dependent parameter *cevp*. The land use dependent parameter has one value for each land use. Only the value coupled to the land use "crops" was adjusted since this land use dominates the Mahi basin as described in section 3.1.1. How the parameters affect the model performance with respect to PET is described in section 2.1.4. The PET dynamics were considered approximately homogeneous within the basin. Therefore the calibration was based on the PET in one sub-basin alone, sub-basin 62232.

Parameters adjusted to improve model performance with respect to AET were the soil dependent parameters *wcfc* and *wcep*. The soil dependent parameters have one value for each soil type. Only the values coupled to the soil types “coarse”, “medium” or “fine” were adjusted since those soil types dominate the study area. The parameters affect the AET by regulating the amount of water available for AET. Decreasing the *wcfc* and increasing the *wcep* decreases the water storage capacity of the soil. More water will contribute to runoff to streams and lower layers. Consequently, the water available for evapotranspiration decreases, as does the AET. The calibration was based on the spatial average of the entire Mahi basin.

4.3.2 Calibration of general parameters to improve model performance with respect to runoff

General parameters considered likely to affect the model performance with respect to runoff were *rcgrw*, *lp*, *rivvel*, *damp*, *pcelevadd*, *pcelevth* and *pcelevmax*. How the parameters affect the model performance is described in section 2.1.4. Their importance was empirically evaluated in a sensitivity analysis and the most important parameters were included in a Monte Carlo calibration. The calibration was based on stream flow from the outlet (forcing point) of sub-basin 62232, that is the outlet of the entire modelled Mahi basin.

Sensitivity analysis

Each parameter was, one at a time, varied within reasonable intervals. The effect on model performance with respect to runoff was measured with the Nash-Sutcliffe efficiency and the difference between simulated and observed runoff over an average year (1969-01-01 to 1974-12-31). The effect on model performance with respect to AET was measured as the difference between simulated and MODIS AET over an average year (2000-01 01 to 2005-12-31). The model performance with respect to PET was considered to be unaffected by changes in the above listed parameters and was hence not monitored. Parameter values that made the model performance decrease significantly with respect to AET were not tolerated even if they retuned high Nash-Sutcliffe efficiencies since such parameter values generated good model performance with respect to runoff for the wrong reasons.

Monte Carlo calibration

All parameters that were shown to potentially improve model performance were included in the Monte Carlo calibration. The calibration was aimed to optimize the model performance with respect to runoff measured by the Nash-Sutcliffe efficiency. The parameters were calibrated within intervals defined in the sensitivity analysis presented in section 5.3.2. The Monte Carlo calibration included 20 000 simulations.

4.3.3 Calibration of regional parameters to improve model performance with respect to runoff

As a last step of the entire calibration process regional parameters were calibrated to increase the overall model performance. The aim was, based on the results from the calibration of general parameters, to make some final adjustments to the water balance without decreasing the achieved Nash-Sutcliffe efficiency too much.

Regional parameters considered likely to affect the model performance were *rrcscorr*, *cevpcorr*, *tempcorr*, and *preccorr*. How the parameters affect the model performance is described in section 2.1.4. A sensitivity analysis was conducted to empirically evaluate the sensitivity of the model performance with respect to each one of the parameters.

4.3.4 Model evaluation

The result of the calibration process, that is the best parameter set, was evaluated in the Mahi basin over the period 1976-01-01 to 1979-12-31. The evaluation was based on runoff alone since the evapotranspiration data from MODIS only covered the relatively short period of 2000-01-01 to 2005-12-31. The evaluation was based on the Nash-Sutcliffe efficiency and ocular investigations of the time series.

4.4 REGIONALIZATION ANALYSIS

The best parameter set obtained in the calibration process was transferred to and evaluated in the Sabarmati and Luni basins in order to evaluate the regionalization quality.

4.4.1 Evaluation in the Sabarmati basin

The evaluation of stream flow was based on stream flow data from the outlet (forcing point) of sub-basin 32341, that is the outlet of the entire modelled Sabarmati basin. The evaluation of AET was based on the spatial average of the entire Sabarmati basin. The PET dynamics were considered approximately homogeneous within the basin. Therefore the calibration was based on the PET in one sub-basin alone, sub-basin 32341.

Simulated stream flow was compared to the data series provided by GRDC covering the periods 1969-01-01 to 1974-12-31 and 1976-01-01 to 1979-12-31. Simulated PET and AET were compared to the data series provided by MODIS covering the period 2000-01-01 to 2005-12-31. Simulations were based on the APHRODITE driving data.

4.4.2 Evaluation in the Luni basin based on data from the Central Water Commission

The evaluation of stream flow was based on stream flow data from the outlet (forcing point) of sub-basin 3106 (Balotra) and 8322 (Gandhav). The evaluation of AET was based on the spatial average of the entire Luni basin. The PET dynamics were considered to be approximately homogeneous within the basin. Therefore the calibration was based on the PET in one sub-basin alone, sub-basin 8322 (Gandhav).

Simulated stream flow was compared to the data series provided by CWC. CWC provided monthly averages from the period 1995-06-01 to 2010-05-31 (Balotra) or 2010-03-31 (Gandhav) and annual values (June to May) covering the periods 1989 (Balotra) or 1986 (Gandhav) to 1996 and 1999 to 2010. Since the APHRODITE driving data only extends to 2007-12-31 evaluations in the Luni basin were based on the CORDEX driving data. Simulated PET and AET were compared to the data series provided by MODIS covering the period 2000-01-01 to 2005-12-31.

4.4.3 Evaluation in the Luni basin based on data collected within the frames of this study

Simulated stream flow at forcing points 13057 and 13006 were compared to the soft data collected within the scope of this study. Simulations were based on APHRODITE driving data from 1979 to 2005 and on CORDEX driving data from 2006 to 2007.

5 RESULTS

5.1 SOFT DATA

According to the interviews presented in section 4.1, similarities exist between the flow dynamics at forcing point 13057 and 13006. Examples of this is the years of 1979, 1998 and 2007 when high flow was observed at both locations (Table 5 and Table 6).

Table 5. Soft data collected at forcing point 13057

Year	Flow characteristics
2013	Flow during two or three days starting the 27th of July.
2012	Flow during 12 to 15 hours during the 13th of August.
2008 – 2011	Drought.
2007	Flow during 15 days starting in early July. High flow with a water depth of 1.5 m to 1.8 m.
1999 – 2006	Medium flow.
1998	Very high flow with a water depth more than 2.1 m. The village of Nimbol, close to the forcing point, was flooded.
1980 – 1997	No information.
1979	Flow during six month starting in July. Many villages in the area were flooded, one of them Nimbol.

Table 6. Soft data collected at forcing point 13006

Year	Flow characteristics
2008 – 2013	Drought.
2007	High flow during 15 days.
1999 – 2006	No information.
1998	Very high flow during three months starting in July. Higher flow than in 2007.
1980 – 1997	No information.
1979	High flow during six month starting in July.

The basin of forcing point 13057 is hilly and reaches towards Pushkar. The hilly basin makes the response time short and there can be stream flow even after a minor rainfall. The basin of forcing point 13006 is flat, which is why stream flow only occurs after heavy rainfall. The stream flow at forcing point 13006 is generally lower than at forcing point 13057 and it usually starts two or three days later.

In addition to that, the stream flow at both forcing points is in general higher every second year.

5.2 EVALUATION OF THE PRECIPITATION DRIVING DATA

Both the frequency analysis and the linear regression showed similarities between the APHRODITE and the IMD data while the CORDEX data differed from the two datasets.

5.2.1 Short time Fourier transform

The frequency analysis showed similarities between the APHRODITE and the IMD data both on monthly and annual scale, while the CORDEX data differed from the two datasets.

Monthly data

The frequency analysis conducted on monthly scale over the period 1976 to 2005 showed a prominent frequency of 1 $year^{-1}$ for all three datasets, representing the annual monsoon. The energy of the frequency varied over time, for the APHRODITE and IMD data in a similar way, and for the CORDEX data in a way that differed from the two datasets (Figure 9). For example, in the period 1990 to 1995 there was a prominent frequency of 1 $year^{-1}$ for the APHRODITE and IMD datasets, but not for the CORDEX dataset. There was also a prominent frequency of 2 $year^{-1}$ in that period for the APHRODITE and IMD datasets, which was not visible for the CORDEX dataset. The frequency of 1 $year^{-1}$ was more prominent for the IMD data than for the APHRODITE data.

The monthly analysis of CORDEX data for the period 2006 to 2100 showed a frequency of 1 $year^{-1}$. The energy of this frequency varied over time, but it was always the most prominent frequency.

In each dataset, there was also a prominent frequency of 0 $year^{-1}$. This is an effect of the Fourier transform that occurs because the mean value of the precipitation is above zero.

Annual data

The frequency analysis conducted on annual basis over the period 1976 to 2005 showed similarities between the APHRODITE and the IMD data while the CORDEX data differed from the other two datasets (Figure 10). In the APHRODITE and IMD data prominent frequencies of about 0.07 $year^{-1}$ and 0.45 $year^{-1}$ were detected. The frequency of 0.45 $year^{-1}$ corresponds to a periodicity of about two years, which means higher rainfall every second year. The frequency of 0.07 $year^{-1}$ corresponds to higher rainfall approximately every 14th year. For the CORDEX data, a frequency of about 0.15 $years^{-1}$ was detected, which was also visible for the APHRODITE and, especially, the IMD data. This corresponds to higher rainfall every sixth to seventh year. For the CORDEX data a very broad spectrum of approximately equally prominent frequencies was detected, which was not the case for the APHRODITE data or the IMD data.

The frequency analysis conducted on annual basis over the period 2006 to 2100 for the CORDEX data showed that frequency changed over time (Figure 11). For the years 2006 to 2035 a prominent frequency of approximately 0.4 to 0.45 $year^{-1}$ was visible, which corresponds to heavier rainfall approximately every second year. After 2035, the precipitation periodicity changed, and a frequency of about 0.2 $year^{-1}$ was prominent. This correspond to heavier rainfall every 5th year. After 2065, the precipitation periodicity changed back to 0.45 $year^{-1}$.

Also in these results, there are frequency peaks at 0 $year^{-1}$ which is due to the fact that the mean value of the precipitation is above zero.

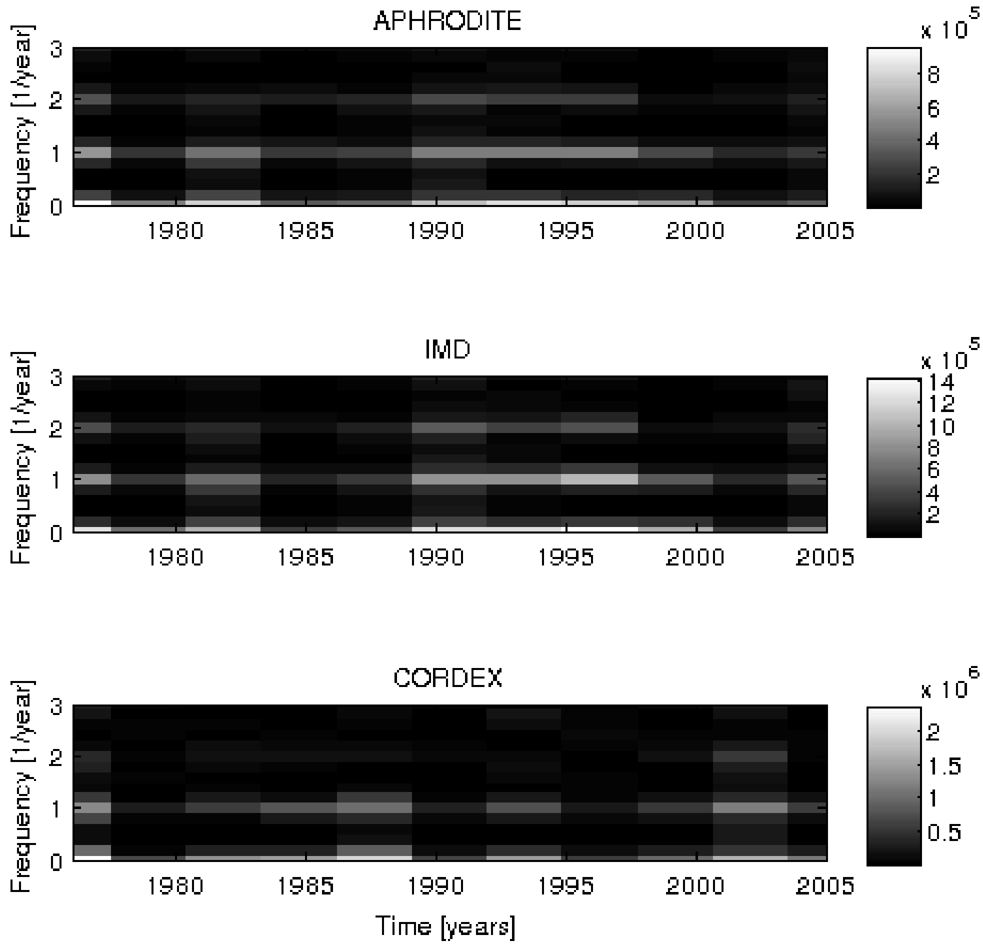

Figure 9. Frequency analysis on monthly basis using the STFT on the APHRODITE, IMD and CORDEX data, for the period 1976 to 2005. The colour represents the frequency energy.

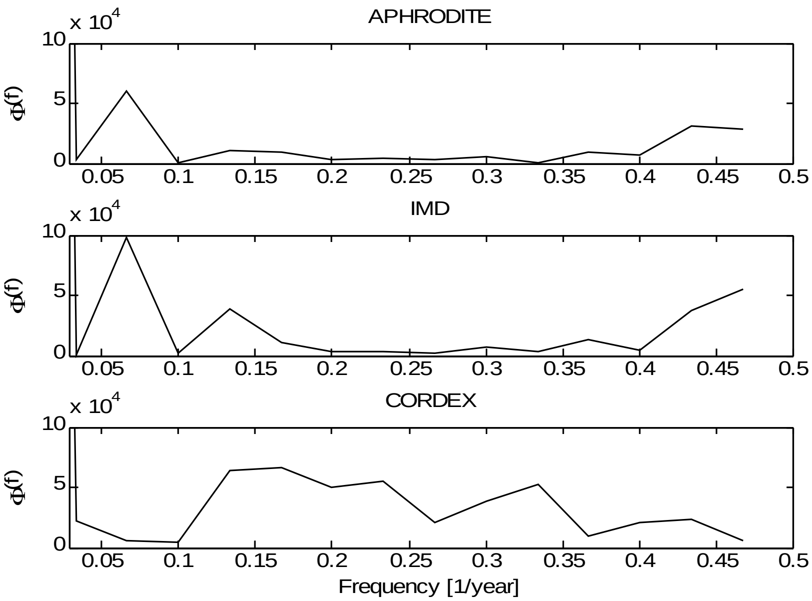

Figure 10. Frequency analysis on annual basis using the discrete Fourier transform on the APHRODITE, IMD and CORDEX data, for the period 1976 to 2005. The y-axis shows the frequency energy.

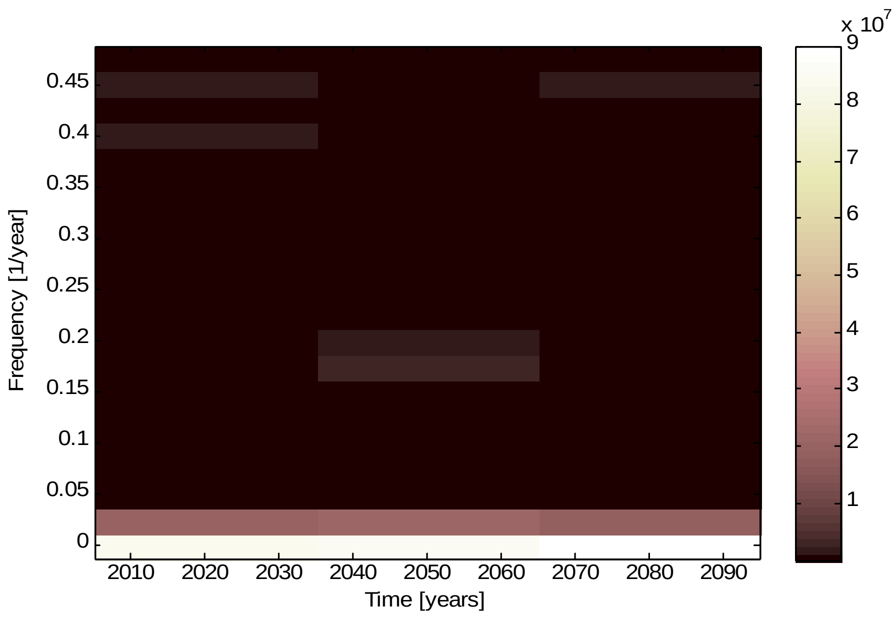

Figure 11. Frequency analysis on annual basis using the STFT on the CORDEX data, for the period 2006 to 2100. The colour represents the frequency energy.

5.2.2 Linear regression

The linear regression of the IMD and APHRODITE data showed similarities between the datasets (Table 7). APHRODITE underestimated the precipitation somewhat as compared to IMD (Figure 12).

Table 7. R^2 values for comparisons of precipitation datasets for the period 1976 to 2005

Compared data	R^2
IMD and APHRODITE, monthly	0.8079
IMD and APHRODITE, daily	0.4740

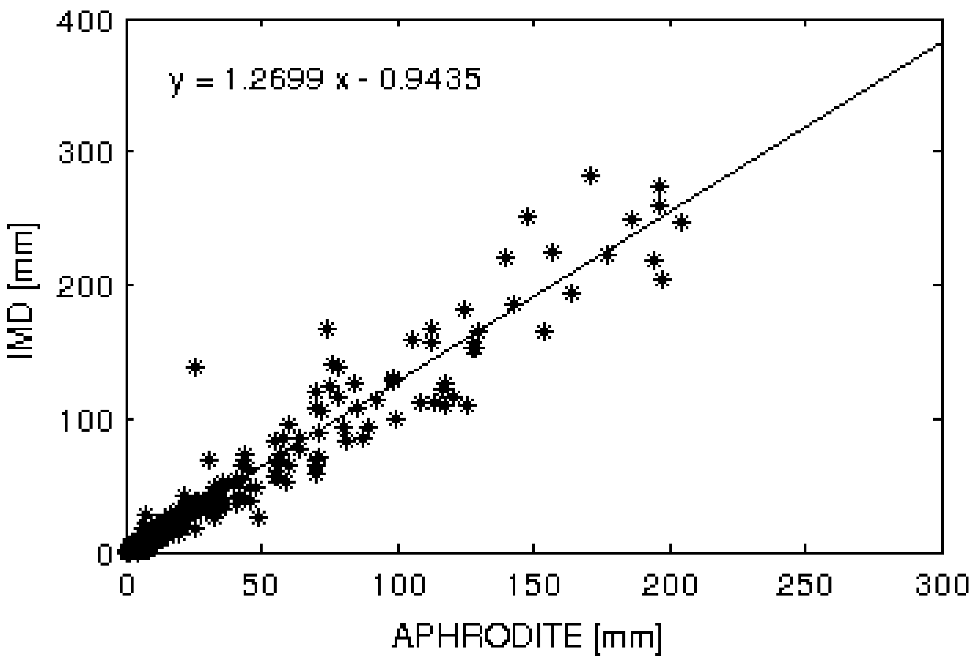

Figure 12. Linear regression for comparison of the IMD data and the APHRODITE data on monthly basis for the period 1976-2005.

5.3 MODEL IDENTIFICATION IN THE MAHI BASIN

The two initial model runs showed a poor model performance with respect to PET, AET and runoff (Figure 13 and Figure 14).

PET and AET were evaluated over the period of 2000-01-01 to 2005-12-31. The model did not capture the PET dynamics and the AET was overestimated. The simulated AET was in average 129 % of the MODIS data over the scope of one year, that is 118 mm larger. The overestimation varied a lot within the basin (Table 8).

The evaluation of runoff over the period of 1969-01-01 to 1974-12-31 yielded a Nash-Sutcliffe efficiency of 0.60. A major drawback of the model performance was the underestimation of runoff. The simulated runoff was in average 40 % of the observed over the scope of one year, that is 199 mm smaller.

Table 8. The ten sub-basins with the largest AET overestimations and their specifications

Sub-basin id	Overestimation over an average year [mm]	Soil types, land uses and notes
7764	170.8	93 % class 4: coarse soil, crops
7754	170.9	90 % class 4: coarse soil, crops
7510	172.4	47 % class 5: medium soil, crops
181	173.1	57 % class 5: medium soil, crops
315	184.7	74 % class 6: fine soil, crops
7184	185.0	73 % class 4: coarse soil, crops
7563	198.2	78 % class 4: coarse soil, crops
89	216.7	81 % class 5: medium soil, crops
51	788.3	100 % class 1: fine soil, lake
72	1287	91 % class 1: fine soil, lake

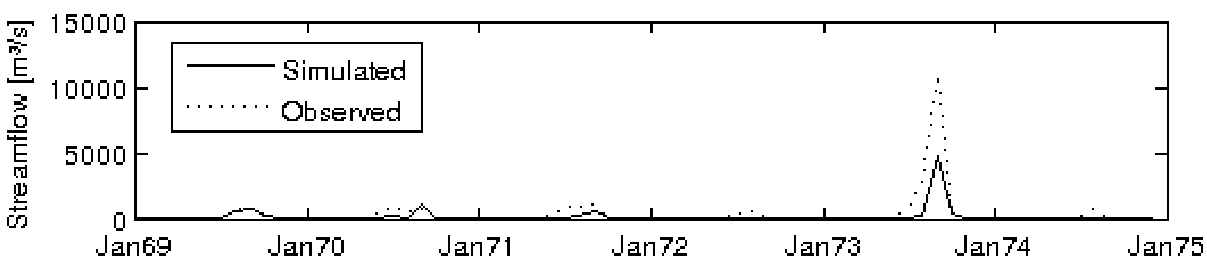

Figure 13. Simulated and observed stream flow. Simulation based on the initial parameter set.

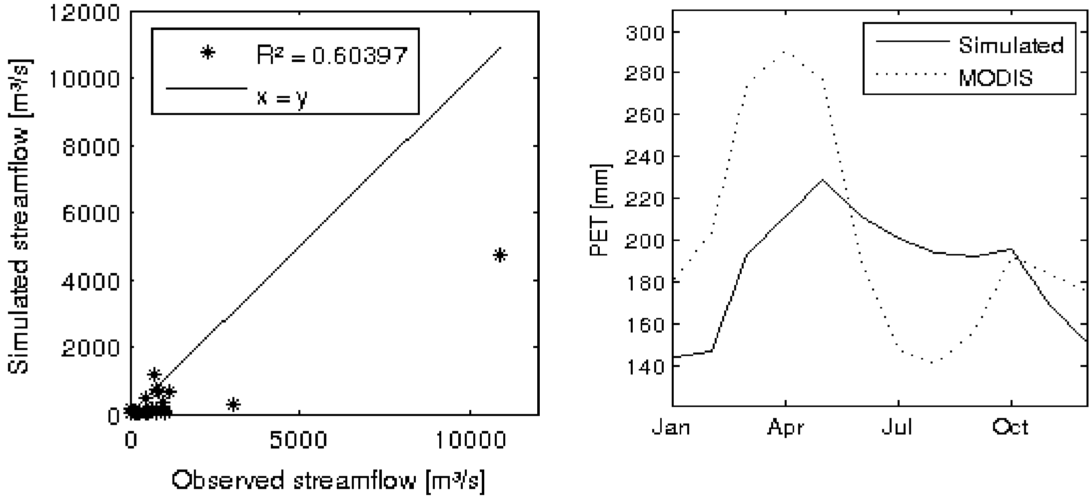

Figure 14. Simulation based on the initial parameter set. Left: Simulated stream flow against observed. The Nash-Sutcliffe efficiency (R^2 value) was 0.60. Right: Simulated and MODIS PET dynamics over an average year (2000 to 2005)

5.3.1 Calibration of general, land use and soil type dependent parameters to improve model performance with respect to PET and AET

In order to improve model performance with respect to PET the general parameters *cevpam* and *cevpph* and the land use dependent parameter *cevp* coupled to the land use "crops" were changed from 0, 0 and 0.221 to 0.3, -30 and 0.251, respectively. The adjustments improved the model performance with respect to PET (Figure 15).

The adjustments also lowered the overestimation of AET somewhat making the simulated AET 125 % of the MODIS AET instead of 129 %.

In order to improve model performance with respect to AET the soil dependent parameters *wcfc* and *wcep* coupled to the soil types "coarse", "medium" and "fine" were decreased and increased by 0.2, respectively (Table 9).

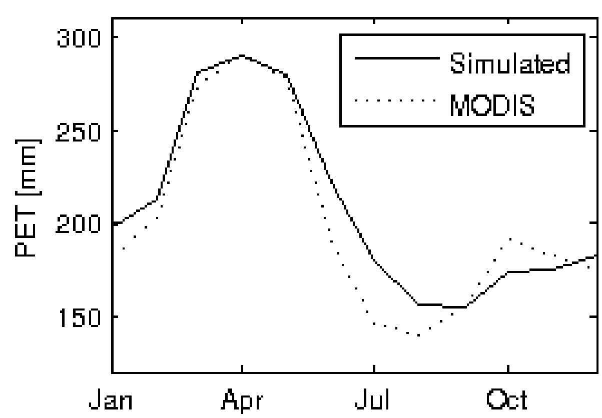

Figure 15. Monthly averages of simulated and MODIS PET after calibration of cevpam, cevpph and cevp. 2000 to 2005.

Table 9. Values of the soil dependent parameters wcfc and wcep before/after calibration

Parameter \ Soil type	Coarse	Medium	Fine
wcfc	0.229/0.029	0.316/0.116	0.293/0.093
wcep1[1]	0.2055/0.4055	0.1325/0.3325	0.0306/0.2306
wcep2[1]	0.1935/0.3935	0.116/0.316	0.0308/0.2308
wcep3[1]	0.2065/0.4065	0.139/0.339	0.0293/0.2293

[1]*wcep1*, *wcep2* and *wcep3* refers to *wcep* in layer one, two and three, respectively.

The adjustments improved the model performance with respect to AET much. Simulated AET was lowered from 125 % of the MODIS AET to 101 % making the average annual overestimation 4 mm.

The combined adjustments of *cevpam*, *cevpph*, *cevp*, *wcfc* and *wcep* improved the model performance with respect to runoff. The Nash-Sutcliffe efficiency was increased to 0.70 and the simulated runoff was increased to in average 85 % of the observed over the scope of one year, that is 49 mm smaller.

5.3.2 Calibration of general parameters to improve model performance with respect to runoff

Sensitivity analysis

A sensitivity analysis was conducted to evaluate the importance of the general parameters *rcgrw*, *lp*, *rivvel*, *damp*, *pcelevadd*, *pcelevth* and *pcelevmax* and to define reasonable calibration intervals. A comprehensive summary of the sensitivity analysis is found in Appendix C.

Based on the sensitivity analysis the parameters *rcgrw*, *lp*, *pcelevadd* and *pcelevth* were included in the calibration (Table 10).

Table 10. Parameters included in the Monte Carlo calibration and their intervals

Parameter	*rcgrw*	*lp*	*pcelevadd*	*pcelevth*
Interval	[0.012 0.24]	[0.9 1]	[0.05 0.2]	[300 550]

Monte Carlo calibration

The Monte Carlo calibration returned a best parameter set with a Nash-Sutcliffe efficiency of 0.75 (Table 11). The simulated runoff was increased to 103 % of the observed instead of 85 %, making the annual average overestimation 9 mm.

Table 11. Best parameter set obtained in the Monte Carlo calibration of general parameters

Parameter	*rcgrw*	*lp*	*pcelevadd*	*pcelevth*
Value	0.2111	0.9408	0.1966	300.1377

The calibration also affected the AET. The simulated AET was increased to in average 105 % of the MODIS AET over the scope of one year. Hence, the Monte Carlo calibration decreased the model performance with respect to AET somewhat. The PET was not affected by the calibration.

5.3.3 Calibration of regional parameters to improve model performance with respect to runoff

The sensitivity analysis showed how the model performance responded to changes in the regional parameters. A comprehensive summary of the sensitivity analysis is given in Appendix D. The model performance was particularly sensitive to changes in the parameters *cevpcorr* and *preccorr*.

The regional parameters were adjusted based on the sensitivity analysis of regional parameters. The parameters *cevpcorr* and *preccorr* were decreased slightly in order to decrease the PET overestimation and the amount of water entering the basin, respectively. The parameters *rrcscorr* and *tempcorr* were increased and decreased, respectively, in order to increase the runoff and decrease the AET. The parameters *rrcscorr*, *cevpcorr*, *tempcorr* and *preccorr* were set to 0.2, -0.03, -0.2 and -0.03, respectively.

The model performance with respect to PET was increased somewhat. The simulated AET was in average 102 % of the MODIS AET over the scope of one year, that is 8 mm larger. This value should be compared to the earlier value of 105 %.

The evaluation of runoff yielded a Nash-Sutcliffe efficiency of 0.74 to be compared with the earlier value of 0.75. The simulated runoff was in average 100 % of the observed over the scope of one year. This value should be compared to the earlier value of 103 %.

5.3.4 Model evaluation

The evaluation of the best parameter set over the period of 1976-01-01 to 1979-12-31 yielded a Nash-Sutcliffe efficiency of 0.76 (Figure 16). The simulated runoff was in average 81 % of the observed over the scope of one year, that is 88 mm smaller. With the initial parameter set the Nash-Sutcliffe efficiency was 0.35 and the simulated runoff was in average 34 % of the observed. Hence the calibration process improved the model performance a lot (Figure 17).

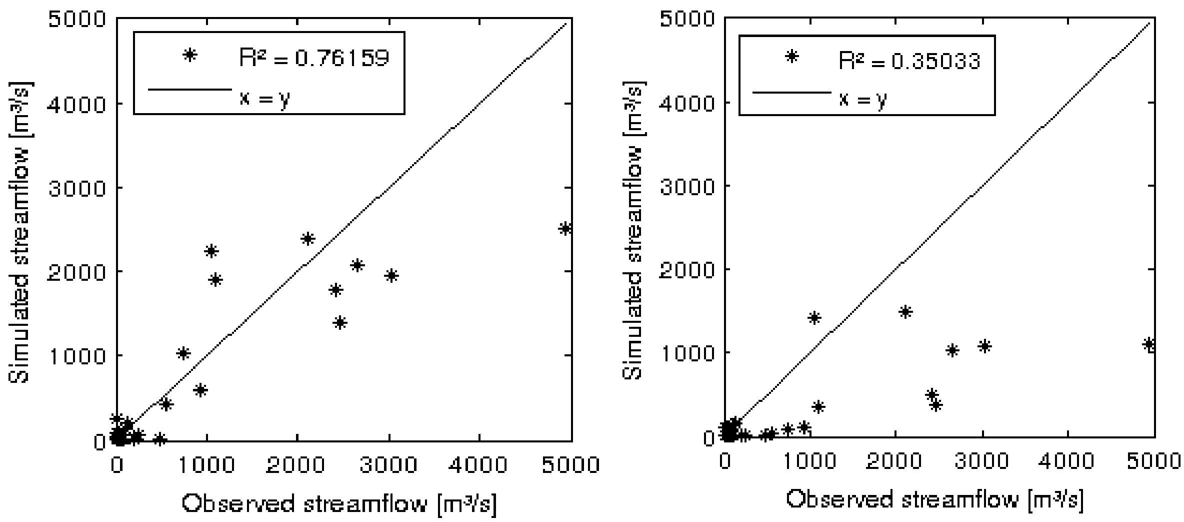

Figure 16. R^2 values. Left: Best parameter set. Right: Initial parameter set.

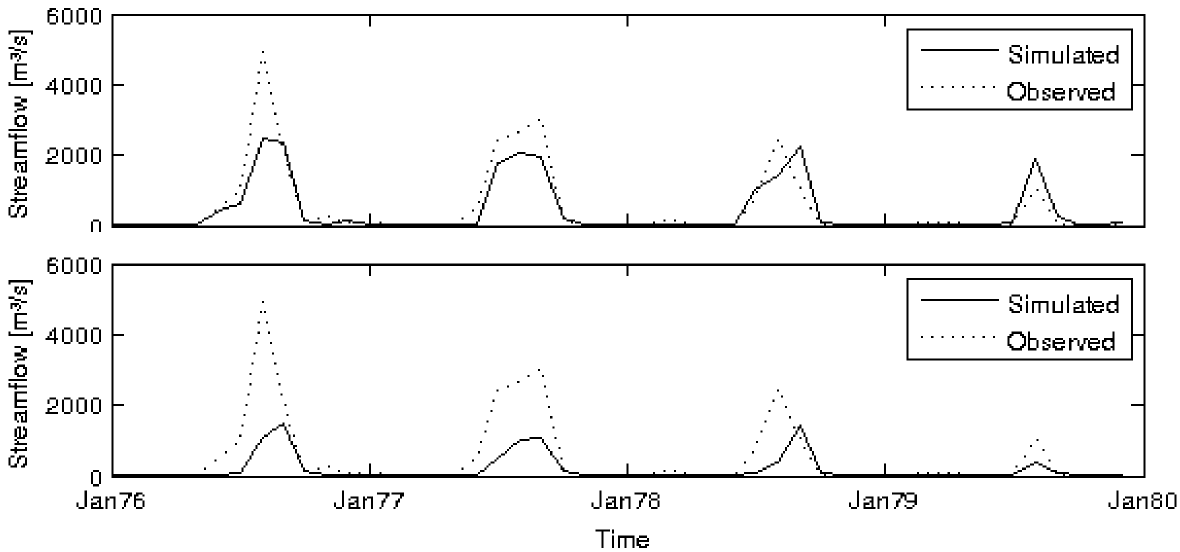

Figure 17. Simulated and observed stream flow. Top: Simulation with the best parameter set. Bottom: Simulation with the initial parameter set.

5.4 REGIONALIZATION ANALYSIS

The best parameter set obtained in the calibration process was evaluated in the Sabarmati basin and the Luni basin.

5.4.1 Evaluation in the Sabarmati basin

The evaluation of PET in sub-basin 32341 over the period 2000-01-01 to 2005-12-31 showed that the model captured the PET dynamics rather well (Figure 18).

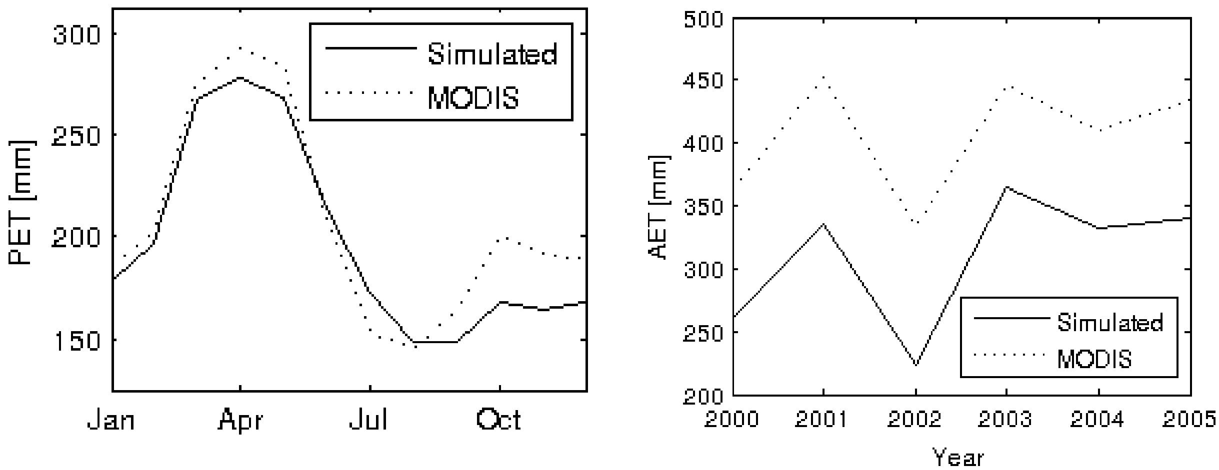

Figure 18. Left: Simulated PET and MODIS PET in sub-basin 32341 as monthly averages over the period 2000-01-01 to 2005-12-31. Right: Simulated AET and MODIS AET over the period 2000-01-01 to 2005-12-31 in sub-basin 32341. The underestimation in this particular sub-basin was larger than the spatial average.

The evaluation of AET over the period of 2000-01-01 to 2005-12-31 showed that the AET was somewhat underestimated. The spatial average of simulated AET was in average 94 % of the MODIS AET over the scope of one year, that is 25 mm smaller. It was shown that the underestimation was uniformly distributed over the simulation period (Figure 18). However, this was only investigated for sub-basin 32341.

The evaluation of runoff over the period of 1969-01-01 to 1974-12-31 (Figure 19) yielded a Nash-Sutcliffe efficiency of -9.14. The simulated runoff was in average 323 % of the observed over the scope of one year, that is 191 mm larger. The evaluation of runoff over the period of 1976-01-01 to 1979-12-31 (Figure 19) yielded a Nash-Sutcliffe efficiency of -2.24. The simulated runoff was in average 186 % of the observed over the scope of one year, that is 155 mm larger.

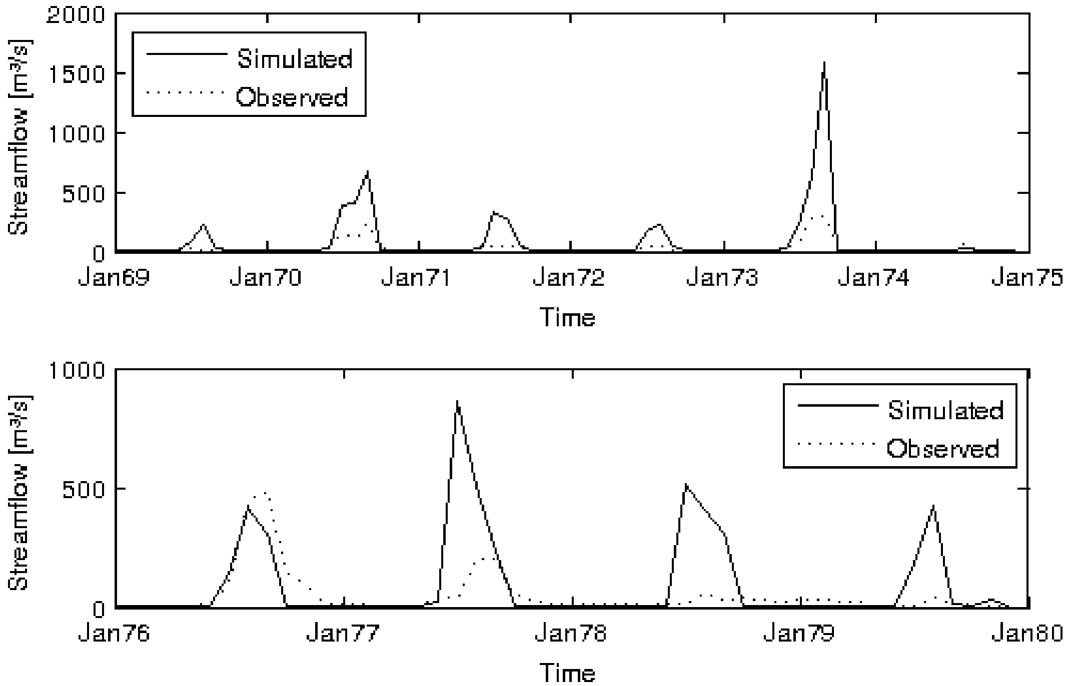

Figure 19. Simulated and observed stream flow at forcing point 32341 over the periods 1969-01-01 to 1974-12-31 (top) and 1976-01-01 to 1979-12-31 (bottom).

5.4.2 Evaluation in the Luni basin based on data from the Central Water Commission

The evaluation of PET in sub-basin 8322 over the period of 2000-01-01 to 2005-12-31 showed that the model failed to capture the PET dynamics (Figure 20).

The evaluation of AET over the period of 2000-01-01 to 2005-12-31 showed that the AET was overestimated. The simulated AET was in average 178 % of the MODIS AET over the scope of one year, that is 142 mm larger.

The evaluation of runoff in terms of monthly averages over the period of 1995-06-01 to 2010-05-31 (Balotra) or 2010-03-31 (Gandhav) exposed a poor model performance (Figure 21). The simulated runoff at Balotra was in average 62 times bigger than the observed over the scope of one year, that is 187 mm larger. The simulated runoff at Gandhav was in average 102 times bigger than the observed over the scope of one year, that is 150 mm larger.

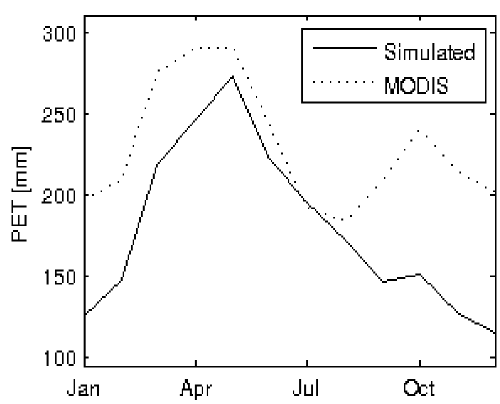

Figure 20. Simulated and observed PET in sub-basin 8322 as monthly averages over the period 2000-01-01 to 2005-12-31.

The evaluation of runoff at Balotra in terms of annual values over the periods of 1989-06-01 to

1996-05-31 and 1999-06-01 to 2010-05-31 exposed a poor model performance (Figure 22). The simulated runoff was in average 31 times bigger than the observed over the scope of one year, that is 173 mm larger.

The evaluation of runoff at Gandhav in terms of annual values over the periods of 1986-06-01 to 1996-05-31 and 1999-06-01 to 2010-05-31 exposed a poor model performance (Figure 22). The simulated runoff was in average 43 times bigger than the observed over the scope of one year, that is 150 mm larger.

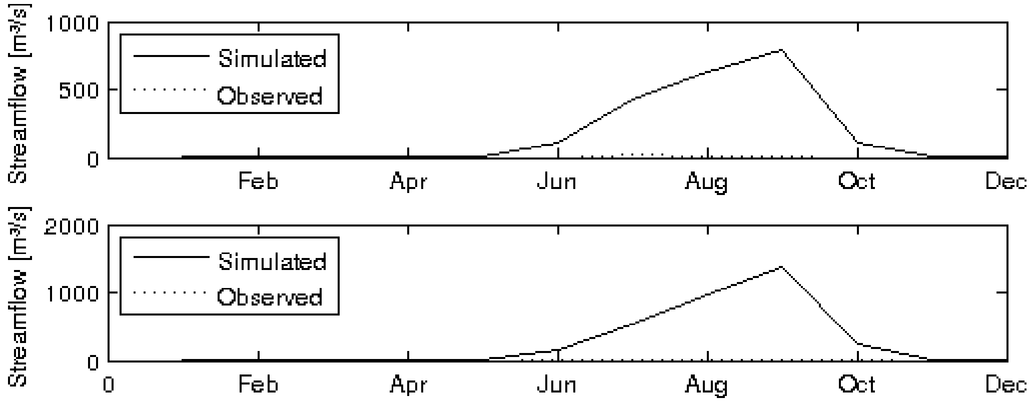

Figure 21. Simulated and observed stream flow at Balotra (top) and Gandhav (bottom). Monthly averages from the period 1995-06-01 to 2010-05-31 (Balotra) or 2010-03-31 (Gandhav) .

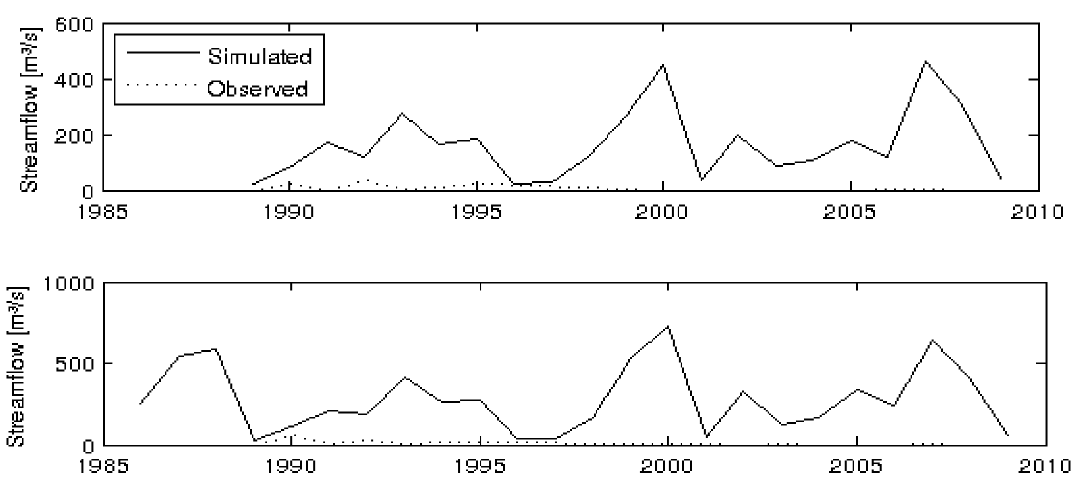

Figure 22. Simulated and observed stream flow at Balotra (top) and Gandhav (bottom), annual values.

5.4.3 Evaluation in the Luni basin based on data collected within the frames of this study

An evaluation in the Luni basin was done based on the soft stream flow data collected within the scope of this study. The observed stream flow was compared to simulated stream flow created with APHRODITE driving data (1979 to 2005) and CORDEX driving data (2006 to 2007).

High flow was observed in 1979, 1998 and 2007 as presented in section 5.1. The year of 1979 had the worst flood followed by 1998. Those extremes were not captured by the model (Figure 23). According to the simulation the stream flow was, contradicting the observations, of medium size in 1979 and 1998, and close to zero in 2007.

According to observations the stream flow at forcing point 13006 is generally less than at forcing point 13057 and it usually starts two or three days later, as discussed in section 5.1. These characteristics were captured by the model. However, the time lag was often more than three days.

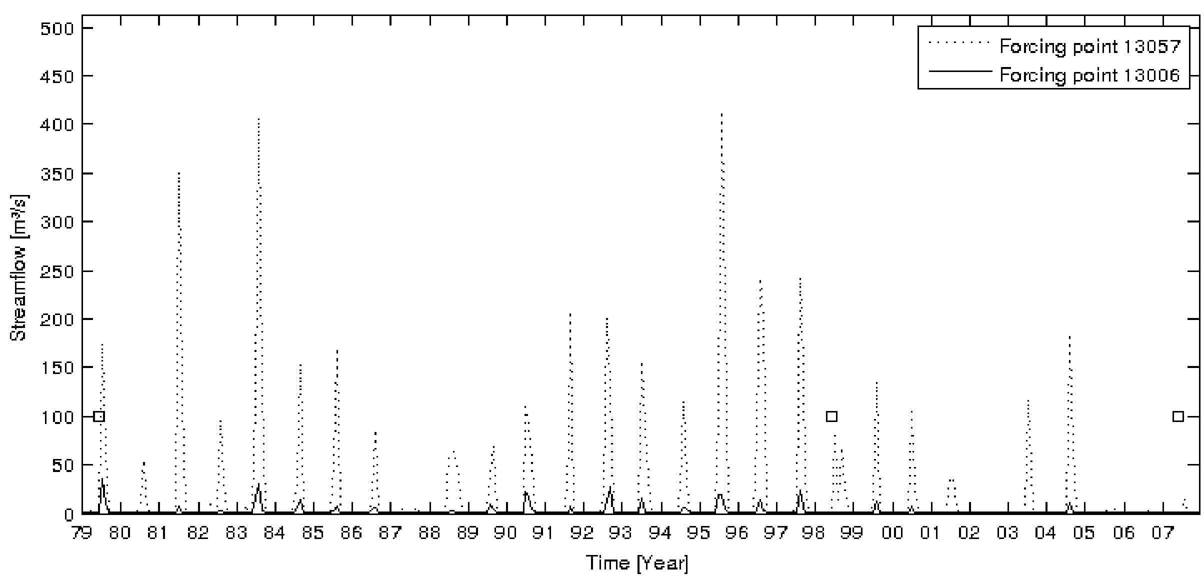

Figure 23. Simulated stream flow at forcing point 13057 and 13006. Three years with high observed stream flow at both forcing points, 1979, 1998 and 2007, are marked with squares.

6 DISCUSSION

This study provided new information about

- the quality of the APHRODITE and the CORDEX precipitation driving data, and
- the regionalization quality of India-HYPE when transferred from the Mahi basin to the Sabarmati and the Luni basins.

The obtained information is discussed in this section and used as a basis for discussions on how to improve India-HYPE.

6.1 EVALUATION OF PRECIPITATION DRIVING DATA

Frequencies of less than 1 $year^{-1}$ were only detected on annual scale, not on monthly. A reason why these frequencies were not detected in the monthly data could be that they had a negligible energy as compared to the frequency of the annual monsoon, that is 1 $year^{-1}$.

The frequency analysis showed similarities between the APHRODITE and the IMD data on monthly and annual scale while the CORDEX data differed from the other two datasets on both scales (Figure 9 and Figure 10). The frequency of 0.45 $year^{-1}$, corresponding to a period of approximately two years, detected in the IMD and the APHRODITE data (Figure 10) agrees with the soft data that describes a general pattern of higher rainfall every other year, as discussed in section 5.1.

The frequency of 0.45 $year^{-1}$ is prominent in the CORDEX dataset over the periods 2010 to 2035 and 2065 to 2100 (Figure 11). In between those periods another frequency of 0.2 $year^{-1}$ dominates. The first period may reflect today's dynamics with higher rainfall every other year. The change of prominent frequency may reflect a climate change that prolongs the monsoon return period. Before the CORDEX data is used in climate projections it should be investigated if such a climatic change is reasonable.

According to the linear regression APHRODITE underestimated precipitation in the Luni basin somewhat as compared to the IMD data (Figure 12). However, the R^2 value of 0.81 imply extensive similarities between the two datasets.

The evaluation of precipitation driving data was based on the assumption that similarities between datasets imply accuracy and high quality. Following this assumption the analyses imply that the quality of the APHRODITE data is high on monthly and annual scale while the quality of the CORDEX data is low on both scales. This is illustrated in the frequency analysis as well as in the linear regression.

6.1.1 CORDEX data

Since the CORDEX data is a product of a climate model it was only analysed through frequency analysis and not through linear regression. A climate model is supposed to capture dynamics, not specific values. The discrepancy between the CORDEX data and the other two datasets (Figure 9 and Figure 10) implies that CORDEX failed to capture the precipitation dynamics of the analysed periods. Since CORDEX failed to describe historical precipitation dynamics in the Luni basin it will likely fail to describe future precipitation dynamics as well. Based on the results of this study, the CORDEX data is not considered sufficient for hydrological predictions. However, the analysed CORDEX data was not bias corrected. Before judging the sufficiency of the data it is necessary to evaluate also the bias corrected data.

6.1.2 APHRODITE data

The similarities between the APHRODITE and the IMD precipitation driving data that SMHI detected were confirmed within this study, both in the linear regression and in the frequency analysis. The assumption that similarities between the datasets imply high quality was the basis of the precipitation evaluation of this study. It is in general reasonable to make such an assumption. However, in this specific case the APHRODITE data is partly based on the IMD data. This is a shortcoming that is difficult to assess due to the lack of raw data information. As described in section 3.2 the APHRODITE project does not provide information about their raw data in terms of rain gauge locations. It is hence not possible to know how much the raw material of APHRODITE differs from that of IMD. Therefore an evaluation based on a comparison with the IMD data does not necessarily, as SMHI suggests, qualify as a just quality check.

The quality of the precipitation driving data can be evaluated using other methods than the IMD comparison. In theory, the quality of the spatial resolution may be addressed based on the distribution of rain gauges that provided raw precipitation data for APHRODITE. However, due to the lack of such information it is difficult to estimate the quality of the precipitation input data.

Based on the comparison with IMD data and the lack of detailed raw data information it is difficult to judge if the APHRODITE precipitation data is sufficient for calibration and evaluation of the HYPE model in the Luni basin.

6.2 REGIONALIZATION ANALYSIS

The regionalization analysis showed that the parameter set calibrated in the Mahi basin was inadequate to transfer to the Sabarmati basin or the Luni basin. PET, AET and runoff were evaluated in both recipient basins. The only good model performance was obtained for PET and AET in the Sabarmati basin. The good model performance implies that the parameter values of *cevpam*, *cevpph*, *cevp*, *wcfc* and *wcep* from Mahi work relatively well in Sabarmati even though the two basins differ from each other in terms of land uses and soil types. Even though the model performance was good with respect to PET and AET in the Sabarmati basin, this does not necessarily imply that the calibration of the corresponding parameters was correct, as will be discussed in section 6.3.1.

Apart from the PET and the AET in Sabarmati the model failed to describe the stream flow dynamics of the recipient basins. The generally low model performance may be due to erroneous

- stream flow and MODIS data,
- delineation,
- APHRODITE and CORDEX driving data and
- model structure.

An obstacle when analysing the results was that the evaluations of AET and runoff covered different time periods. In Sabarmati, for example, the evaluation of runoff and AET was conducted over the time periods 1969-01-01 to 1974-12-31 and 2000-01-01 to 2005-12-31, respectively. However, it was considered reasonable to extrapolate the evaluation results from one period to the other, enabling comparison. An extrapolation of the runoff results was considered reasonable since the runoff is overestimated every single year except one, not just as an average (Figure 19). An extrapolation of the AET results was considered reasonable of the same reason (Figure 18). This was only investigated for the Sabarmati basin, not the Luni basin.

6.2.1 Evaluation in the Sabarmati basin

According to the evaluation of PET and AET the model performance was relatively good. The PET magnitude and dynamics were well captured (Figure 18) and the AET was just slightly underestimated over an average year. According to the evaluation of runoff the model performance was relatively poor. The runoff overestimation exceeded the AET underestimation by far. It is therefore likely that too much water was added to the system as precipitation.

The overall bad model performance agrees with the results produced by SMHI since they also obtained a low model performance in the Sabarmati basin. The fact that two independent calibration processes yielded the same result implies that something else than the calibration approach causes the bad model performance in the Sabarmati basin. Potential reasons to the bad model performance are discussed in section 6.2.3, 6.2.4, 6.2.5 and 6.2.6.

6.2.2 Evaluation in the Luni basin

The dynamics of the PET was relatively well captured even though the magnitude was too low (Figure 20). The simulated AET was almost twice the observed. According to the evaluation of runoff the model performance was very low. The simulated runoff was many times larger than the observed. Even though the overestimation was huge in relative terms it was not huge in absolute terms. Since both runoff and AET were overestimated in the Luni basin it is likely that too much water were added to the system as precipitation. This evaluation was based on simulations done with CORDEX driving data. Since the CORDEX data is based on a climate model this analysis was not supposed to yield a high Nash-Sutcliffe efficiency. However, the magnitude of the simulated stream flow should equal the magnitude of the observed.

Specific flow events at forcing points 13057 and 13006 were reported by locals as represented in section 5.1. The specific flow events were not captured by the model. The evaluation was based on simulations done with APHRODITE driving data from 1979 to 2005 and with CORDEX driving data from 2006 to 2007. Hence, the model should capture specific historical flow events between 1979 and 2005, including the observed floods of 1979 and 1998. The observed flood of 2007 should however not be captured by the model since the simulated stream flow is based on driving data from a climate model. Even though the model failed to reproduce the observed floods it captured the dynamics between the two forcing points. This implies that the quality of the APHRODITE driving data is low in the region while the model captures the water dynamics within the basin.

6.2.3 Stream flow and MODIS data

The stream flow datasets used in the evaluations and in the calibration are major sources of error. As stated in section 3.2.4 and 3.2.5 the quality of the GRDC data was considered potentially low while the quality of the CWC data was considered very low. The quality of the GRDC data may lower the quality of the Sabarmati evaluation somewhat. However, no extraordinary values were found in the GRDC data within the scope of this study. On the contrary, the quality of the CWC data makes the evaluation in the Luni basin more or less useless. However, it is still reasonable to present other possible reasons for the low model performance.

The quality of the MODIS data was also considered low. According to SMHI the data was erroneous and biased in several areas. Erroneous or biased data in the Mahi basin would have affected the calibration and hence result in erroneous parameter values.

6.2.4 Delineation

Evaluations from both basins imply that too much water was added to the systems. However, it is important to remember that the quality of the Luni evaluation is very low. The excess of water may be due to an incorrectly modelled basin area since a modelled basin area larger than in reality would yield an overestimation of runoff.

The modelled basin area of Sabarmati was smaller than the basin area according to GRDC (2013a). A potential error would hence not result in a larger runoff. The modelled basin area of Luni was about twice as big as the basin area according to CWC (2006). This could in theory make the modelled runoff larger than the observed. However, the areas differ because CWC (2006) only includes areas that hydrologically contributes to runoff while the delineation used within India-HYPE includes the entire basin (Pechlivanidis, 2013). The discrepancy between the India-HYPE delineation and CWC (2006) is therefore not a problem as long as the dry areas included in the India-HYPE delineation are modelled as dry. However, according to the APHRODITE and CORDEX precipitation data all sub-basins in the Luni basin were subject to an average annual precipitation of at least 150 mm or 200 mm, respectively. It might be so that areas that in reality are dry according to the model contribute to runoff. A sub-basin specific investigation and separate calibration would clarify this issue.

6.2.5 APHRODITE and CORDEX driving data

Another potential reason for the stream flow overestimations is the APHRODITE driving data in the Sabarmati basin and the CORDEX driving data in the Luni basin. SMHI deemed the quality of the APHRODITE data high. However, as discussed in section 6.1 the comparison between APHRODITE and IMD data is not necessarily a good evaluation approach. Also, the comparison with soft data implied that the APHRODITE data was incorrect in the studied region.

The large overestimation of stream flow in the Luni basin was possibly caused by an unreasonable high precipitation. The CORDEX precipitation data was shown to be much higher than the APHRODITE ditto (Figure 4). This may be because the CORDEX data used in this study was not bias corrected.

6.2.6 Model structure

Bad model performance may in theory be due to the model structure. The structure of the HYPE model is not necessarily suitable for the characteristics of the study area. The model was developed to describe Swedish water dynamics, not Indian. However, the model structure is relatively flexible.

The precipitation adjustment done within the model might cause too much water to enter the system. The general parameters *pcelevth*, *pcelevadd* and *pcelevmax* were introduced to increase the precipitation in the Mahi basin. Given the low spatial resolution of the APHRODITE driving data it was considered reasonable to introduce precipitation adjustment to elevation. This adjustment was likely to describe the processes in the Luni basin well since the precipitation is positively correlated with elevation in that basin as presented in section 3.1.3. However, the precipitation in the Mahi or the Sabarmati basins is not positively correlated with elevation as discussed in section 3.1.1 and 3.1.2.

6.3 IMPROVEMENTS OF INDIA-HYPE

There are several components and procedures of India-HYPE that should be addressed in order to improve the model. Such components and procedures that have been identified in this study are

- the calibration,
- the stream flow and MODIS data and
- the modelled PET.

6.3.1 Calibration

The easiest thing to adjust in order to improve the model performance of India-HYPE is probably the calibration process. Some steps done in the calibration process of this study have been identified as potential oversimplifications or falsifications that, if they are adjusted, may improve the model performance. Those steps are

- the calibration to improve model performance with respect to PET,
- the calibration to improve model performance with respect to AET,
- the calibration to improve model performance with respect to evapotranspiration in general and
- the calibration of the soil type dependent parameters.

The parameter *cevp* was calibrated in order to improve model performance with respect to PET as described in section 4.3.1. The parameter is land use dependent and as such it can take one value for each land use. Only the value coupled to the land use crops was calibrated since this land use dominates the Mahi basin as described in section 3.1.1. However, the recipient basins are not dominated by crops but by open vegetation. The parameter value coupled to open vegetation should preferably also be calibrated in order to increase the model performance in the recipient basins. This would be difficult since open vegetation is uncommon in the Mahi basin. The discrepancy in basin characteristics lowers the regionalization quality as discussed in section 2.2. It might be necessary to change subject basins in order to improve the regionalization quality in this aspect.

The calibration with respect to AET was based on the basin average rather than on separate values for each sub-basin. This simplification lowered the calibration complexity, but also the quality. The differences between simulated and observed AET were shown to vary much within the Mahi basin (Table 8). It was particularly large in the two sub-basins that represented outlet lakes. It is likely that the reason behind poor model performance with respect to AET varied between different sub-basins.

One sub-basin can for example be subject to erroneous PET while an other may be subject to a false representation of land use, soil type or area. If the reason behind poor model performance with respect to AET varies between sub-basins a calibration method based on the basin average will fail to capture the true AET dynamics. Therefore the AET calibration in future applications might improve if based on sub-basin specific values rather than the basin average.

As discussed in section 6.2.3 the MODIS data includes errors and is biased in several areas. The calibration approach of this study was to capture the PET and AET magnitudes and the PET dynamics. Since the MODIS data might be biased, a better approach would be to focus on the dynamics alone, both for PET and AET. An alternative would be to analyse the MODIS data thoroughly to ensure a high quality prior calibration.

In the calibration of soil dependent parameters, the effective porosity was increased to values around 20 % (fine soil) and 40 % (coarse soil) at the expense of field capacity that was decreased to values between 2 % (coarse soil) and 12 % (medium soil), as described in section 5.3.1. Due to the increased model performance these parameter values were chosen, even though they are unrealistic as soil characteristics. Realistic values of the "effective porosity" of a fine soil may vary between 2 % and 5 % while the effective porosity of a coarse soil typically varies between 5 % and 15 % (Rodhe, 2013). Realistic values of the field capacity is higher than in the model. The field capacity of four agricultural clay soils has been shown to vary between 30 % and 54 % while the field capacity of an agricultural sand soil has been shown to vary between 18 % and 33 % (Eriksson et al., 2005). Since agricultural lands dominates the Mahi basin field capacities between 18 % and 54 % would be reasonable. The unrealistic values used in the model were shown to improve the model performance. However, the model performance was improved for the wrong reasons. In a future calibration process, it would probably be better to improve the model performance as much as possible without violating physical laws.

6.3.2 Stream flow and MODIS data

As discussed in section 6.2.3, the quality of the stream flow data is very low (CWC) or potentially low (GRDC). The quality of the stream flow data is probably a major reason for poor model performance, especially in the Luni basin. In order to improve India-HYPE the stream flow data used for calibration and evaluation must be of high quality. The same holds for the MODIS data.

6.3.3 Modelled PET

Apart from the seasonal correction, the modelled PET is a function of temperature alone, as presented in section 2.1.4. This is a simplification that reduces the complexity but also the quality of the model. A new algorithm will be introduced in the next version of India-HYPE. The new algorithm will probably describe PET as a function of temperature, radiation, minimal and maximal temperatures, wind speed and humidity (Pechlivanidis, 2013).

7 CONCLUSIONS

The evaluation of CORDEX data indicated low quality. Since the CORDEX data failed to describe historical precipitation dynamics it was considered inadequate as driving data for future predictions. However, the analysed data was not bias corrected. The evaluation of APHRODITE data indicated high quality. However, the evaluation method was potentially inadequate due to the lack of raw data information such as rain gauge distribution.

The regionalization analysis showed that the parameter set calibrated in the Mahi basin was inadequate to transfer to the Sabarmati basin or the Luni basin. The poor regionalization quality may be due to erroneous stream flow data, MODIS data, delineation, APHRODITE driving data, CORDEX driving data and model structure. The major reason is probably the low quality of the stream flow data in the Luni basin.

There are several components and procedures of India-HYPE that can be addressed in order to improve the model. Such components and procedures that have been identified in this study are the calibration, the stream flow data, the MODIS data and the modelled PET.

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8.1 PERSONAL COMMUNICATION

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APPENDIX A – INITIAL PARAMETER SET

GENERAL PARAMETERS							
ttpd	-2						
ttpi	0						
rcgrw	0.12						
cevpam	0						
cevpph	0						
lp	0.95						
gratk	2						
gratp	3						
rivvel	1						
damp	0.5						
tcalt	0.6						
tcelevadd	0						
tcobselev	0						
pcaddg	0						
pcelevadd	0.05						
pcelevth	550						
pcelevmax	1						
gldepi	5						
epotdist	3.5						
snowdens0	0.13						
snowdensdt	0.0016						
sswcorr	0						
iwdfrac	0						
regirr	0						
irrdemand	0						
immdepth	0						
limqprod	0						
rrcs3	0.0002						
LAND USE DEPENDENT PARAMETERS	Crops	Forest	Open land vegetation	Urban	Bare/Desert	Glacier	Lake
cmlt	2.5	2.5	2.5	2.5	2.5	2.5	2.5
ttmp	0	0	0	0	0	0	0
cevp	0.221	0.255	0.256	0.238	0.208	0.157	0.237
frost	2	2	2	2	2	2	2
srrcs	0.05	0.05	0.05	0.05	0.05	0.05	0.05
REGIONAL PARAMETERS							
rrcscorr	0						
cevpcorr	0						
tempcorr	0						
preccorr	0						
pirrs	0						
pirrg	0						
irrcomp	0						
SOIL DEPENDENT PARAMETERS	Coarse	Medium	Fine	Organic	Shallow		
wcwp	0.1	0.1	0.1	0.1	0.1		
wcfc	0.229	0.316	0.293	0.487	0.182		
wcep3	0.2065	0.139	0.0293	0.221	0.174		
wcep2	0.1935	0.116	0.0308	0.211	0.179		
wcep1	0.2055	0.1325	0.0306	0.199	0.171		
trrcs	0.15	0.2	0.3	0.15	0.15		
srrate	0.06525	0.04165	0.0481	0.0836	0.0583		
sfrost	1	1	1	1	1		
rrcs2	0.062	0.1125	0.0697	0.066	0.303		
rrcs1	0.1445	0.3015	0.433	0.36	0.375		
mperc2	35.65	61.85	38.5	66	108		
mperc1	35.3	58.9	40	59.1	117		
mactrsm	0.6585	0.588	0.414	0.659	0.629		
mactrinf	33.5	24.9	30.2	22.2	25.9		
macrate	0.376	0.258	0.366	0.379	0.368		

APPENDIX B – INTERVIEW PROTOCOL

1. How many days with water flow has it been in the river this year?
2. When was the first flow event this year?
3. When was the first flow event last year?
4. When was the last flow event last year?
5. How many days with flow was it last year?
6. Could you describe the flow situation of the last few years (as long back in time as you can remember)? Which years had a lot of flow? Which years had low flow or no flow? Is there any year when it was extraordinary high flow?

APPENDIX C – SENSITIVITY ANALYSIS OF GENERAL PARAMETERS

Parameter	Measure	Initial value	Change to			
Rcgrw		**0.12**	**0.012**	**0.06**	**0.18**	**0.24**
	NSE	0.7	0.69	0.69	0.7	0.7
	Simulated/observed runoff	0.85	0.88	0.87	0.83	0.82
	Simulated/observed AET	1.01	1.01	1.01	1.01	1.01
Lp		**0.95**	**0.9**	**1**		
	NSE	0.6989	0.6982	0.6998		
	Simulated/observed runoff	0.85	0.84	0.87		
	Simulated/observed AET	1.01	1.02	1		
Rivvel		**1**	**0.8**	**1.2**	**1.4**	**2**
	NSE	0.7	0.7	0.7	0.7	0.7
	Simulated/observed runoff	0.85	0.85	0.85	0.85	0.85
	Simulated/observed AET	1.01	1.01	1.01	1.01	1.01
Damp		**0.5**	**0.25**	**0.75**		
	NSE	0.7	0.7	0.7		
	Simulated/observed runoff	0.85	0.85	0.85		
	Simulated/observed AET	1.01	1.01	1.01		
Pcelevadd		**0.05**	**0.2**	**0.2**	**0.2**	**0.1**
Pcelevth		**550**	**550**	**450**	**300**	**300**
Pcelevmax		**1**	**1**	**1**	**1**	**1**
	NSE	0.7	0.7	0.7	0.74	0.73
	Simulated/observed runoff	0.85	0.85	0.87	1.06	0.96
	Simulated/observed AET	1.01	1.01	1.01	1.05	1.03
Pcelevadd			**0.1**	**0.1**	**0.1**	
Pcelevth			**300**	**300**	**300**	
Pcelevmax			**2**	**0.5**	**0.1**	
	NSE		0.73	0.73	0.72	
	Simulated/observed runoff		0.96	0.96	0.93	
	Simulated/observed AET		1.03	1.03	1.02	

APPENDIX D – SENSITIVITY ANALYSIS OF REGIONAL PARAMETERS

Parameter	Measure	Initial value	Change to	
rrcscorr		**0**	**-0.2**	**0.2**
	NSE	0.7467	0.73943	0.7514
	Simulated/observed runoff	1.0276	1.0152	1.037
	Simulated/observed AET	1.0485	1.0486	1.0485
	Simulated/observed PET	1.04	1.04	1.04
tempcorr		**0**	**-0.2**	**0.2**
	NSE	0.7467	0.747	0.7464
	Simulated/observed runoff	1.0276	1.0322	1.0229
	Simulated/observed AET	1.0485	1.0453	1.0517
	Simulated/observed PET	1.04	1.0324	1.0476
preccorr		**0**	**-0.2**	**0.2**
	NSE	0.7467	0.6261	0.7669
	Simulated/observed runoff	1.0276	0.66513	1.4144
	Simulated/observed AET	1.0485	0.94946	1.1241
	Simulated/observed PET	1.04	1.04	1.04