Chapter 4: Impact of Future Scenarios

"Model results are only as reliable as the model assumptions"

(S. Sorooshian and V.K. Gupta)[1]

This chapter first presents a review of modelling exercises conducted in the HKH region. For the prediction of future parameters important to water availability, flood generation, and sediment transport in the catchments — water balance and streamflow in particular — three models were applied to the data observed from the Jhikhu Khola catchment. The models are briefly described and the calibration of all models is discussed. Three scenarios are presented and their impact on the water balance, water availability, and the streamflows estimated.

It is important to note that the calculation of scenarios is in its preliminary stages and will receive further attention in the coming Phase 3 of the project. Therefore the results below should be considered initial trials with first successes and failures.

In a time of great consciousness about change, the desire to predict the future is felt increasingly. Unprecedented changes are likely to occur, such as climate change (IPCC 1998), globalisation (Jodha 2000; in print), or the collapse of the natural resource base due to population pressure in many parts of the world (Allen 2000). The impact of these changes on the hydrological cycle and processes cannot be foreseen, due to the limitations of hydrological measurement techniques (Beven 2001). Such an impact can only be simulated and approximated by the use of various techniques. At the same time, computer power has increased many times over in recent decades and can now support complex systems analyses. Complex systems have to be described in order to minimise haphazard assumptions (see citation above).

Over the last century a large amount of data has been collected which can provide a firm underpinning to these analyses. This is certainly correct for large parts of the developed world. For developing countries, however, the database for this kind of analyses is limited and further marginalised in the mountainous parts of these countries. A number of global water availability scenarios have been presented (e.g., Alcamo et al. 2000; Shiklamonov 2000; Seckler et al. 1998) and were briefly discussed in Chapter 1. On a smaller scale, presentations of the likely impact of changes in driving forces, such as climate, population, or policy decisions in this region, have been detailed in numerous studies. Some of these studies with respect to hydrological modelling are discussed below.

Note: The modelling was only carried out in the Jhikhu Khola catchment, mainly for reasons of data availability. The first year will have to be set aside in order to be able to simulate the boundary conditions. For statistical reasons, Sorooshian and Gupta (1995) suggest that two to three years of calibration data are sufficient. This suggests that at least three complete years of data and a first monsoon are required, i.e., 1997 (monsoon) to 2000. An additional one to two years are then required for the validation of the models. With the availability of the 2001 and 2002 data the models can also be applied in the other catchments.

[1] Sorooshian and Gupta (1995)

In order to assess the impact of possible future developments (here called scenarios) on water availability, flood generation potential, as well as to a limited extent sediment transport, three case studies in the form of three scenarios are presented. These scenario analyses by no means try to be representative, but merely strive to show possible ways of discussing up-coming issues in the PARDYP catchments and potential ways of treating forecasts of future developments.

4.1 METHODS OF ASSESSMENT

The approaches for assessing possible future developments in this study are based mainly on catchment modelling (see next section) as far as the impact on runoff and discharge is concerned. In terms of water demand, scenarios from the literature were extrapolated using local water demand figures for present and projected values taking into account increased living standards and possibilities for the rural population in the catchments.

4.1.1 Catchment modelling

Hydrologists have a long tradition of working with mathematical models for a variety of purposes (Jayatilaka and Connell 1995). In over one century, different models for different applications were developed. Ibbitt and McKerchar (1992) describe the role of models in hydrology as tools to describe hydrological processes and predict the system response to changes. One of three basic purposes for modelling according to WMO (1990) is prediction, planning, and design. For these the long-term prediction of hydrological parameters relevant to the planning process, including the extrapolation of the observed conditions or the prediction in view of changes (e.g., climate, land use), and the actual planning and design of the hydraulic structures are mentioned. Linsely (1982) includes such applications as record extension, operational simulation, data fill-in, and data revision under this category. Hydrological models present the opportunity to extend the range of hydrological research. At present, the influence of climate change or the El Nino/La Nina phenomenon on hydrological processes is of major interest to hydrological model users. The effect of land-use change has been the topic of a variety of model applications in the past for research. Models are also frequently employed in process studies.

4.1.1.1 Review of catchment modelling in the HKH

Many models for different purposes have been developed worldwide over the last decades. Most of these models were developed in areas completely different to the mountain ranges of the HKH. Jain (1990) discusses a number of models which were applied and which seem to be appropriate for mountainous catchments. He concludes that the use of models in the mountains has been limited due to limited access to data, either because of non-availability of data or problems typical of mountain areas. He sees a major opportunity in the improvement of remote sensing and GIS technology. He also cautions on the application of models without prior testing of the models for given conditions. He further recommends the development of a GIS rainfall-runoff model valid for Indian mountain catchments.

The trend to date has, however, been the application of existing models from other regions of the world. Many researchers have applied models to HKH mountain catchments. A number of recent modelling studies in the HKH are reviewed below.

Shah et al. (1998) used the UBC catchment model to simulate the flows into the Tarbela and the Mangla Dam in the Upper Indus Basin. The results, however, were not satisfactory due to lack of data. The same model was used by Singh (1998) and Singh and Kumar (1997) to simulate the hydrological response of the Spiti River basin, a tributary of the Sutlej, under changed climatic scenarios. The main reason for using the UBC catchment model was its capability to increase and decrease the accumulation of snow in a mountainous basin with only sparse meteorological data. The UBC model was also used for the Sutlej River in a study described by Singh and Quick (1993) and Quick and Singh (1992). They concluded that the complexity of the precipitation distribution in the Himalayas was a major problem during modelling. They argued that a semi-distributed approach dividing the catchment into sub-catchments with similar precipitation would give better results. Shakya (1997) investigated the impact of forest clearing on the hydrological behaviour of the Khageri River in Chitwan district in Nepal by applying the UBC catchment model. The results obtained are very interesting but, as the author admitted, they are biased under the given conditions with the lack of data from the catchment itself.

The Sacramento soil moisture accounting model (SAC-SMA) was used by Buchtele et al. (1998) to investigate the sensitivity of runoff towards environmental changes. This study was carried out in three experimental basins of the Nepal Himalayas: the Modi , the Langtang , and the Imja Khola. It showed that the selected modelling approach was adequate and able to simulate runoff in the complex environment of the Himalayas.

Braun et al. (1993) implemented the HBV/ETH model on the Langtang Khola. After further measurements of key parameters and sensitivity analysis, Grabs et al. (1998) applied the conceptual model in the same basins as above for the prediction of flow. The model successfully simulated the hydrograph of the rivers. The original HBV was used for the modelling of the inflow catchment into the Tarbela dam in Pakistan.

Parida (1998) applied the SRM model in the Goriganga catchment of the Middle Himalayas in India to estimate snowmelt runoff for successful planning and design of water resources projects. Kumar et al. (1993) applied the model on the Beas and the Parbati basins in Himachal Pradesh, India. They concluded that it is useful, especially in a basin with limited meteorological and hydrological data. Seidel et al. (2000) presented the application of SRM for the Ganges and Brahmaputra river basins and concluded that the model was able to handle these very large basins with acceptable accuracy, although some of the data were only available on a monthly basis.

Boorman et al. (1998) developed a rainfall-runoff model on the basis of the probability distributed storage principle as presented by Moore (1985). The model successfully simulated the general flow regime and the wetting up during rainfall events of the monitored catchments in the Lhikhu Khola catchment. Towards the end of the event the flow is underestimated, however.

In Bangladesh, which is affected by the flow behaviour from the Himalayan rivers, MIKE 11 was successfully used for flood modelling (DHI 1994; Paudyal 1994). A new version of MIKE11 is now used operationally in Bangladesh for flood forecasting.

The Xinanjiang model is widely used in China. According to Zhao et al. (1995), the model was successfully applied for many parts of China except the Loess plateau. The applications included river forecasting on the Yellow , the Huai , and Yangtze rivers with real-time adjustments in some cases. It also included water resources' planning, design flood estimation, and water quality accounting. Recently the model was used for macroscale hydrological modelling.

The Tank model was used in a study investigating the impact of land-use changes on the hydrology of headwater regions in Uttar Pradesh, India (Chander and Gosain 1995). It was also applied in other mountainous areas of India like the Western Ghats in South India. Ramasastri (1990) concluded that it is suitable for Indian catchments.

SHE has been extensively used in India (Refsgaard et al. 1992; Jain et al. 1992).

In recent years, the importance of GIS in hydrological modelling has increased. Several studies have been conducted using GIS in combination with different hydrological models. NIH (1998) applied the German NASMO model in the Western Ghats. The NASMO model uses the SCS curve number method for calculation of direct runoff. They concluded that this approach could be applied for other Indian catchments, therefore including catchments in the Himalayas. A study was recently completed applying GIS in connection with the SCS curve number method. Pradhan (2000) modelled daily runoff in the Bagmati River at Sundarijal. He concluded that this method was not satisfactory. A similar study was conducted by Kumar (1997) in the Bandel catchment. Another model, which has been often associated with GIS, is the TOPMODEL (e.g., NIH 1997).

For the assessment of water availability in the Sutlej River in India, Jain et al. (1998) used the Canadian SLURP catchment model. They have shown that the combined use of GIS derived input parameters and the model gave good results. Further studies on the model application in the area will be conducted for final comments.

The review of the modelling approaches in the HKH can be concluded as follows:

- data availability is a major constraint for the successful application of rainfall-runoff models in mountainous regions;
- many models have been successfully applied but a comparison of different models under the same conditions is widely missing;and
- distributed models seem to be more appropriate for mountainous conditions due to the highly variable and heterogeneous conditions in mountain areas; however, the data requirements are often not appropriate.

NIH (1988) lays down certain criteria for models to be applicable in the mountain regions of India. The model should have the capability to estimate snowmelt and incorporate it into the system. It should also be physically based on, or its parameters should be derived from, regionalisation. Interception has to be an important parameter, as many mountainous catchments have good forest growth. Distributed models seem to be better suited for local conditions.

4.1.1.2 The models selected

For the purpose of the catchment modelling in this study three different models were applied and their outputs compared (Table 4.1): the UBC Catchment model (Quick 1993); the Tank model (Sugawara 1995); and the PREVAH model (Gurtz et al. 1997). The selection of these models was according to:

- availability and support;
- applicability to mountainous terrain;
- different levels of conceptualisation; and
- different levels of spatial aggregation.

Table 4.1: **Compilation of the main characteristics of the models used**

Model name	Causality	Space distribution	Time resolution	Remarks
UBC	Deterministic conceptual	lumped	1 hour to 24 hours	adapted for limited data availability in mountainous areas
TANK	deterministic conceptual	lumped	24 hours	includes genetic optimisation algorithm
PREVAH	deterministic conceptual	distributed	1 hour to 24 hours	

4.1.2 UBC Catchment Model

The lumped continuous UBC catchment model was developed by the Mountain Hydrology Group of the University of British Columbia, Vancouver/Canada, to describe and forecast the catchment behaviour of mountainous areas (Quick 1993). This introduced several important design constraints because data in such regions are usually scarce, particularly at higher elevations. A major design consideration resulting from this was to provide the model with the ability to interpret meteorological data at a point in terms of basin-wide conditions.

The UBC model operates using the input of hourly to daily meteorological data, including maximum and minimum temperatures and precipitation. The basic structure of the model segregates the catchment into bands according to the elevation. The model simulates daily outflow from a catchment, soil moisture content, soil and groundwater storage, and information on contributions to runoff from different sections of the catchment, including surface and subsurface components. Given continuous meteorological input data the model will operate continuously, accounting and depleting the snow-pack and producing estimates of stream-flow. The model includes the following components (Quick 1995; a flow chart of the model is included as Appendix 4.1):

- *Meteorological sub-model*
  This module distributes the input data to all elevation bands on the basis of a temperature lapse rate algorithm and an algorithm for precipitation. The latter is divided into an algorithm describing purely the orographic enhancement of precipitation with elevation, and another algorithm modifying precipitation for variations in temperature.

- *Soil moisture sub-model*
  In this module, the evaporation losses and the subdivision of rainfall and snowmelt into four components of runoff (fast, medium, slow, and very slow) are controlled. The central control parameter is the soil moisture deficit (Figure 4.1). When this deficit reaches zero, the catchment reaches its maximum runoff potential (with the exception of flash and fast runoff, which depend on a defined precipitation intensity in the case of flash runoff or the impermeable area identified in the catchment in the case of fast runoff). Fast runoff generation is first priority, followed by soil moisture retention and evapotranspiration. When the soil moisture deficit is satisfied, groundwater percolation occurs. Only if excess moisture is available does interflow occur.

- *Catchment routing sub-model*
  The different components of runoff are subjected to a routing procedure based on the concept of linear storage reservoirs. The fast and medium runoff components are subjected to a cascade of reservoirs essentially identical to the unit hydrograph. The slow components of runoff use a single linear storage.

- *Routing sub-model*
  This module combines the different catchment flows and routes these flows through a river, lake, or reservoir system.

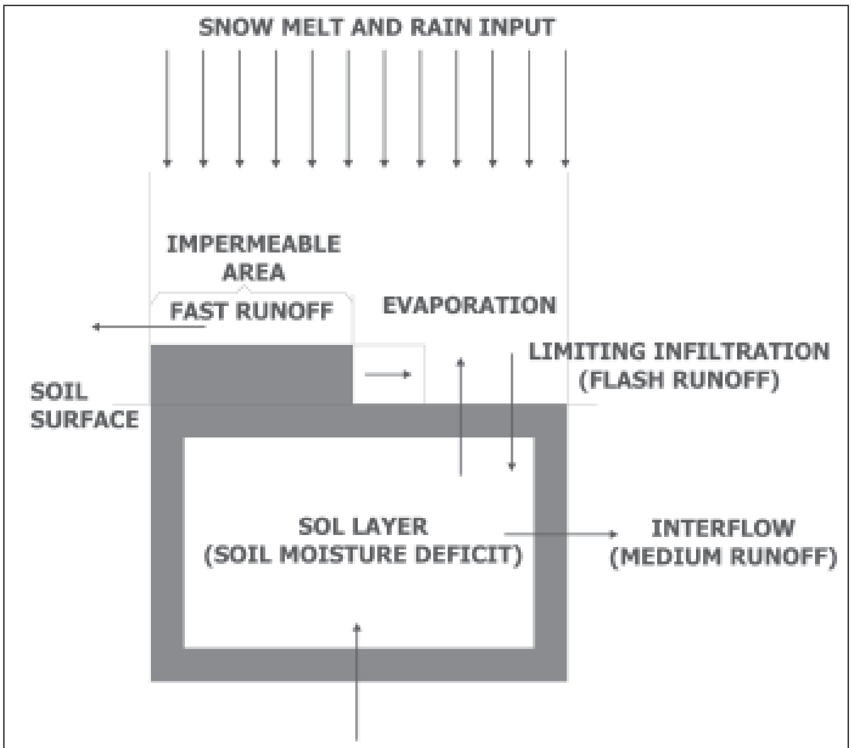

Figure 4.1: **Soil moisture model in UBC catchment model** (from Quick 1995) For more details refer to Quick (1993) or Quick (1995).

Model applications

A number of applications of the UBC model were referred to in the review of modelling in the region above. Further applications are listed in Quick (1995). In general, these applications were for the purpose of short-term river flow forecasting or estimating seasonal runoff volumes and the probable pattern of runoff for the purpose of supporting reservoir operation (Quick 1995). The model has also been used for the extension of time series, when streamflow records did not exist, but for which meteorological data have been available. Geographically, the model has been applied to catchments in Canada (British Columbia in particular) and catchments in South Asia.

4.1.3 Tank Model

The Tank model was originally developed by Sugawara (1961) and has since then undergone a lot of development. In general, the Tank model is very simple and is composed of a defined number of linear storages laid vertically in series with defined outputs from the side and bottom outlets. For the present study, the Tank model as coded by Bastola et al. (2002) was used. This model is a continuous, lumped, deterministic model and comprises four vertical tanks with the provision of primary and secondary storage (Figure 4.2.). The top and the second tank contribute to surface runoff, the third and fourth tank to base flow. Input data required are precipitation and temperature. The model uses automatic optimisation algorithms for calibration and therefore reduces time requirements to a minimum. For further details about the model used in this study refer to Bastola (2002) and to Sugawara (1995) for information on the Tank model in general.

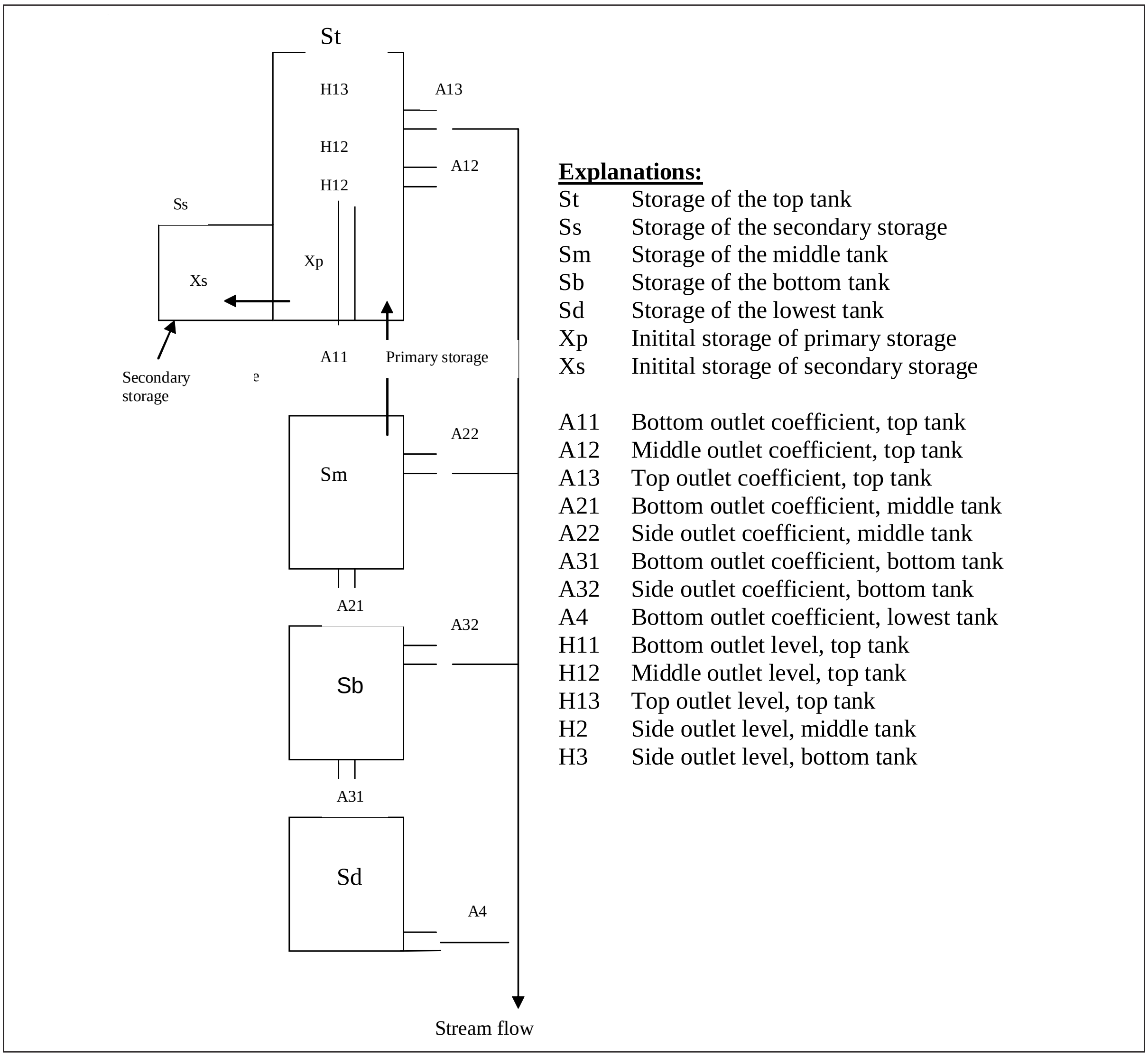

Figure 4.2: **Schematic diagram of the Tank model** (from Bastola 2002)

4.1.3.1 Model applications

The Tank model has been widely used in the mountainous areas of Japan, the model's country of origin, but it has also been applied to basins in Asia, Africa, Europe, and the USA, giving good results (Sugawara 1995). The model has also been applied in the context of comparative studies of the conceptual models used in operational hydrological forecasting (WMO 1975) as well as for real-time forecasting (WMO 1992).
Several studies have applied the Tank model with optimisation algorithms, e.g., Bastola et al. (2002), Kim et al. (2001).

4.1.4 PREVAH Model

The spatially distributed **P**recipitation-**R**unoff-**EVA**potranspiration-**H**ydrotope (PREVAH) model was developed at the Institute of Geography at the Federal Institute of Technology (ETH) in Zurich (now the Institute for Atmospheric and Climate Science, ETH Zurich) with the aim of representing the heterogeneous characteristics of mountainous areas using parameters as far as possible based on physical principles (Gurtz et al. 1999).

PREVAH uses the hydrological response unit (HRU) or hydrotope approach (Ross et al. 1979; Engel 1996; Moore et al. 1993; Fluegel 1997; Zappa 2002) to represent the distributed catchment information. It basically overlays five layers of information to generate the HRUs, including the drainage network and catchment area, meteorological input data, topography, land use and vegetation, and soil and geological characteristics (Gurtz et al. 1999). The HRUs are generated with the help of the software package **HY**drological **RE**sponse **U**nit – **ETH** (HYREUETH) developed by Zappa (1999) for fast pre-processing of spatial information.

Temporal and spatial interpolation of the meteorological data is carried out by altitude dependent regression (ADR) and inverse distance weighting (IDW), applying the interpolation tool of WaSim-ETH discussed in further detail in Schulla and Jasper (1999). This tool is of particular importance for the accurate estimation of the input variables, as methods such as Thiessen often misrepresent the rainfall input in mountainous catchments.

The model's response is governed by five linear storages, including snow cover, interception, soil moisture, upper runoff, and lower runoff storages. The following modules are included in PREVAH (for more details, including the equations, refer to Zappa 2002; a flow chart of the model is included as Appendix 4.2. [only the modules relevant to this study are described]).

- *Adjustment of precipitation*
  The precipitation input can be tuned by adjusting the measured precipitation. This adjustment allows compensation for measurement errors and mistakes in the precipitation interpolation (Sevruk 1986).

- *Evapotranspiration module*
  PREVAH's evapotranspiration module offers different equations to calculate water losses through evapotranspiration: the Penman-Monteith equation (Monteith 1975); the Wendling equation (Wendling 1975); Turc equation (Turc 1961); and Hamon (1961). The Hamon approach was used for this study due to the non-availability of many required parameters for the Penman-Monteith approach. Hamon's equation is based only on mean daily temperature. For Wendling and Turc air temperature and global radiation are also required.

- *Snow accumulation module;* not required in the Jhikhu Khola catchment.
- *Snow melt module;* not required in the Jhikhu Khola catchment.
- *Glacial melt module; not* required in the Jhikhu Khola catchment.
- *Interception module*
  This module is based on Menzel (1997) where the interception storage varies with the vegetation type and water from this surface evaporates at the potential rate as long as there is sufficient humidity in this reservoir.

- *Soil module*
  The soil module was adapted originally from the HBV-model (Bergstroem 1976), which was further developed by Jensen (1982). At the conceptual level it consists of the plant-available water storage in the aeration zone of the soil (SSM; see Figure 4.3), which provides the link between the loss of water by evapotranspiration (E) and runoff (DSUZ). The inflow to this storage is provided by rainfall (P) that reaches the ground and snowmelt (SRM). The storage's capacity (SFC) is dependent on the soil depth, the effective root depth, and the plant-available field capacity of the soil. The moisture that is not able to evaporate or be withheld as soil moisture flows to the upper zone of the runoff generation module (DSUZ).

- *Runoff generation module*
  The model's structure provides three different flow mechanisms. The fastest runoff is fast surface runoff (RS), usually associated with an impervious surface, saturated overland flow, and Hortonian overland flow. This is followed by interflow (RI), governed mainly by the soil characteristics in the catchment. Finally, the slowest flow is the base flow (RG) generated by a combination of two linear groundwater reservoirs with a fast (SG1) and a delayed component (SG2). The percolation from the upper runoff storage (SUZ) to the groundwater storages is governed by the deep percolation rate (PERC).

PREVAH always runs at a one-hour time step (Zappa 2002). However, if only daily input data are available, 24 identical values are assumed. The model is described in more detail in Gurtz et al. (1997) and Zappa (2002) (see also Figure 4.3).

4.1.4.1 Model applications

The model has been applied in different studies under different conditions.

- Gurtz et al. (1997) and Gurtz et al. (1999) modelled parameters of the hydrological cycle in the Thur river basin, a pre-alpine basin in north-eastern Switzerland. Gurtz et al. (1997) aimed to study the impact of different climate variations on the hydrological cycle. The model successfully simulated possible changes in the behaviour of precipitation, snowfall, evapotranspiration, discharge, high and low flows, and different storages. Gurtz et al. (1999) mainly focused on discharge and evapotranspiration.
- Zappa (1999) applied the model to simulate the discharge of the Verzasca River, a snow and rainfed mountain river in southern Switzerland. In this study it successfully simulated the water balance and selected flood events.
- Vitvar et al. (1999) studied the water residence times in a small pre-alpine catchment of north-eastern Switzerland, the Rietholzbach catchment.
- Zappa (2002) used PREVAH to model hydrological systems of different spatial scales, including catchments of 3 to 1700 km^2 in the Swiss Alps, the Volga source area in Russia, and the whole of Switzerland. While in the different Swiss catchments the evaluation of single modules and the performance of the model in various conditions and smaller scales were targeted, the performance in simulating different water balance components at the large scale was evaluated in the simulation of the whole of Switzerland. In the Russian experiment, PREVAH was used in connection with regional climate (RCM) and global climate models (GCM), which provided the meteorological input data.

4.2 APPLICATION OF THE MODELS TO THE PRESENT

For calibration[2] and validation[3] of the catchment models, they were firstly applied to the current conditions as observed in the Jhikhu Khola catchment. For this purpose the daily data from 1996 to 1998 were used for calibration of the models (Table 4.2). The data from 1999 and 2000 were then used for validation. The selection of years was based on the analyses of Bastola (2002). The data from the years 1993, 1994, and 1995 had shown that the efficiency calculated by trial simulations with the Tank model of independent years was low. For the years 1996 onwards, the efficiency improved with

[2] Process of appropriate parameter selection (Sorooshian and Gupta 1995)
[3] Process of parameter verification on a new dataset previously not used in the calibration procedure (Sorooshian and Gupta 1995)

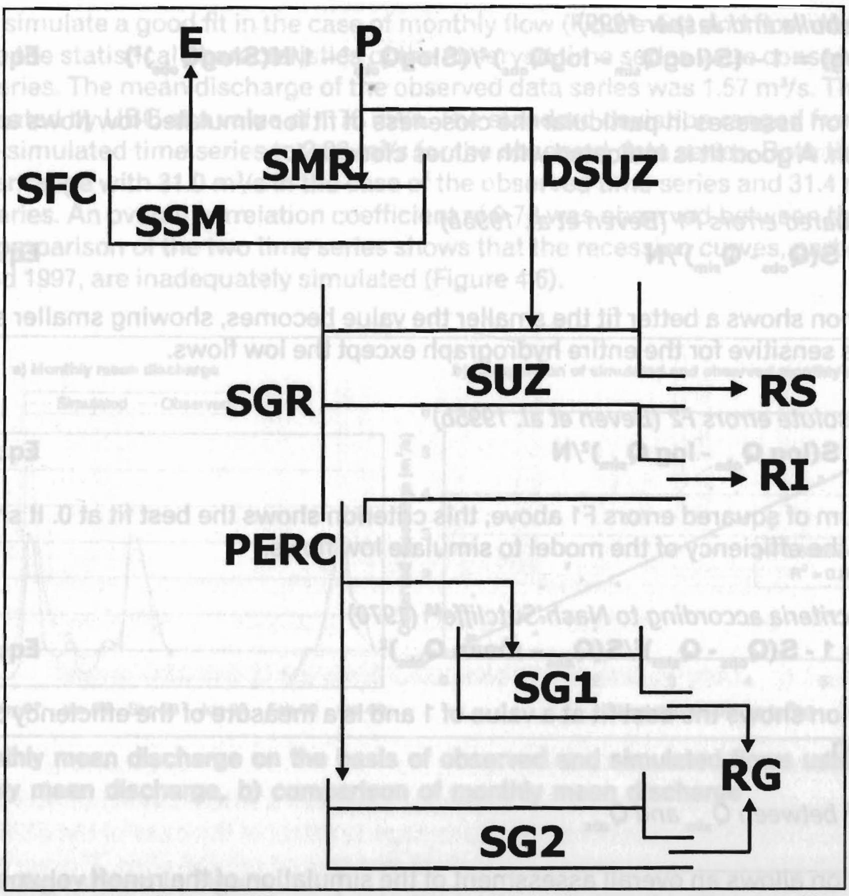

Figure 4.3: Schematic representation of the soil and runoff generation modules of the PREVAH model (all abbreviations discussed in the text; adapted from Zappa 2002)

Table 4.2: **Data used for modelling**

	1993	1994	1995	1996	1997	1998	1999	2000
Not used	X	X	X					
Calibration				X	X	X		
Validation							X	X
Base for simulation					X	X	X	

a problem of water balance calculation in 1999. The reason for this problem is assumed to be the exceptional event in October where, depending on the site, between 8 and 12% of the annual rainfall occurred.

To assess the performance of the models, the following criteria were used (* implemented in PREVAH and used for calibration; & implemented in Tank model and used for calibration; $ implemented in UBC model and used for calibration):

- *r^2 (lin)* (Schulla and Jasper 1999)*

$$r^2\,(\text{lin}) = 1 - (S(Q_{sim} - Q_{obs})^2/(S\,Q_{obs}^{\;2} - 1/N(SQ_{obs})^2) \qquad \textbf{Equation 4.1}$$

This criterion ranges from $-\infty$ to +1 with values below 0 indicating a bad fit and values close to 1 a good simulation with respect to the observed data set. r^2(lin) is important in the assessment of the model's performance in simulating the flood peaks.

- *r^2(log)* (Schulla and Jasper 1999)*

  $$r^2 \text{ (log)} = 1 - (S(\log Q_{sim} - \log Q_{obs})^2 / (S\log Q_{obs}{}^2 - 1/N(S\log Q_{obs})^2) \qquad \textbf{Equation 4.2}$$

  This criterion assesses in particular the closeness of fit for simulated low flows and the entire hydrograph. A good fit is indicated with values close to 1.

- *Sum of squared errors F1 (Beven et al. 1995b)*

  $$F1 = S(Q_{obs} - Q_{sim})^2/N \qquad \textbf{Equation 4.3}$$

  This criterion shows a better fit the smaller the value becomes, showing smaller errors. This criterion is sensitive for the entire hydrograph except the low flows.

- *Sum of absolute errors F2 (Beven et al. 1995b)*

  $$F2 = S(\log Q_{obs} - \log Q_{sim})^2/N \qquad \textbf{Equation 4.4}$$

  Like the sum of squared errors F1 above, this criterion shows the best fit at 0. It shows in particular the efficiency of the model to simulate low flows.

- *Efficiency criteria according to Nash-Sutcliffe[&$] (1970)*

  $$Eff = 1 - S(Q_{obs} - Q_{sim})^2/S(Q_{obs} - \text{mean } Q_{obs})^2 \qquad \textbf{Equation 4.5}$$

  This criterion shows the best fit at a value of 1 and is a measure of the efficiency of the entire hydrograph.

- *Balance[*&$] between Q_{sim} and Q_{obs}*

  This criterion allows an overall assessment of the simulation of the runoff volume.

4.2.1 Application of the UBC model

For the Jhikhu Khola catchment, the UBC model was calibrated and validated by Bastola (2002) using 1996 to 1998 data for calibration and 2000 data for validation. The reason for excluding 1999 data was mainly the availability of rainfall data for a high elevation site during that year. For the calibration period, the data for Site 9 at 1560 masl were used, while in 2000 the data for Site 19 at 1700 masl were used for validation as Site 9 was closed down at the end of 1998. For further details on the calibration and validation of the UBC model, refer to the report of Bastola (2002). The UBC model parameters suggested by Bastola (2002) for the Jhikhu Khola catchment are compiled in Appendix 4.3.

The overall efficiency of the simulation was poor, ranging from Nash-Sutcliff's criteria of 49% during calibration, to 67% after validation (Table 4.3). The peaks are modelled satisfactorily as indicated by higher r^2 values for the linear data. The low flows on the other hand were simulated very poorly. The water balances were very well predicted in 1998 and 2000, while they were largely overestimated for the year 1997.

Table 4.3: **Efficiency of the UBC catchment model on the basis of daily data**

	r^2(lin)	r^2(log)	Balance	F1	F2	EFF
Calibration						
1996*	0.68	0.34	0.1	5.38	0.15	0.61
1997	0.59	0.28	-304.7	2.71	0.26	0.49
1998	0.73	0.49	2.8	2.44	0.13	0.61
Validation						
1999	-	-	-	-	-	-
2000	0.82	0.52	18.2	1.09	0.13	0.67

* Initial year, required for setting the boundary conditions.

The model could simulate a good fit in the case of monthly flow (Figure 4.4) and flow duration curves (Figure 4.5), while the statistical characteristics of the observed time series were conserved by the simulated time series. The mean discharge of the observed data series was 1.57 m³/s. This was slightly overestimated by UBC at a value of 1.76 m³/s. The standard deviation ranged from 2.35 m³/s in the case of the simulated time series to 2.68 m³/s for the observed data series. Both time series observed a similar range with 31.0 m³/s in the case of the observed time series and 31.4 m³/s for the simulated time series. An overall correlation coefficient of 0.78 was observed between the two time series. A visual comparison of the two time series shows that the recession curves, particularly in the years 1996 and 1997, are inadequately simulated (Figure 4.6).

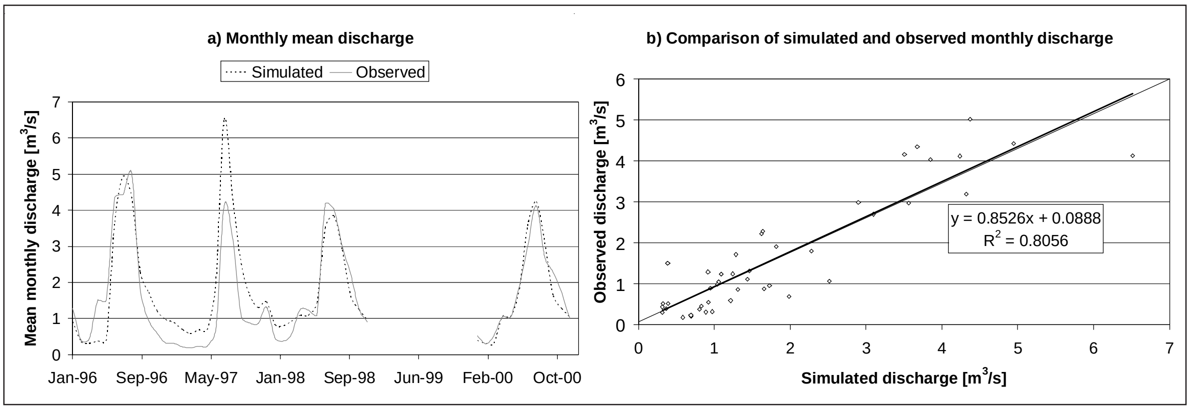

Figure 4.4: Monthly mean discharge on the basis of observed and simulated flows using the UBC model: a) monthly mean discharge, b) comparison of monthly mean discharge

The monthly discharge shown in Figure 4.4 shows, in general, a good fit with the exception of 1997. The overall correlation coefficient for monthly flow between the simulated and the observed time series was 0.90. The linear trend line comparing the two time series follows the ideal line with a regression coefficient of 0.81. In 1997, the monthly flow was overestimated by the model during the monsoon season and underestimated during the winter and pre-monsoon seasons.

The duration curve is very well simulated with a correlation coefficient of 0.99 between the observed and the simulated time series (Figure 4.5). The linear trend line follows the ideal line closely with a regression coefficient of 0.98. The flows of higher exceedance probability are, in general, well simulated up to about 7 m³/s. Above this the values are generally underestimated up to about 15 m³/s. The high flows are randomly estimated with good fits, underestimated, or overestimated values.

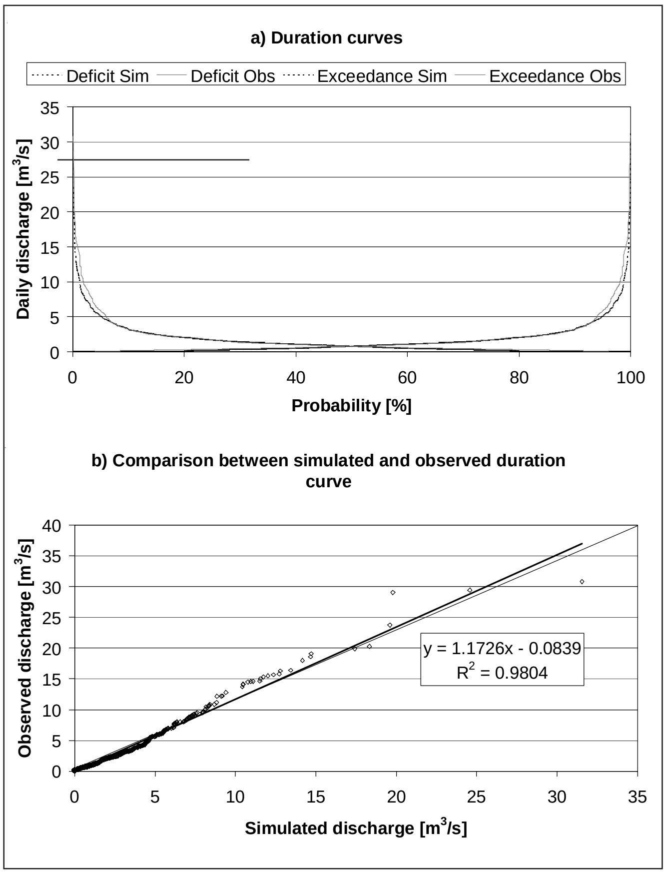

Figure 4.5: Observed and simulated duration curve using UBC model: a) duration curves of exceedance and deficit, b) comparison between observed and simulated curves

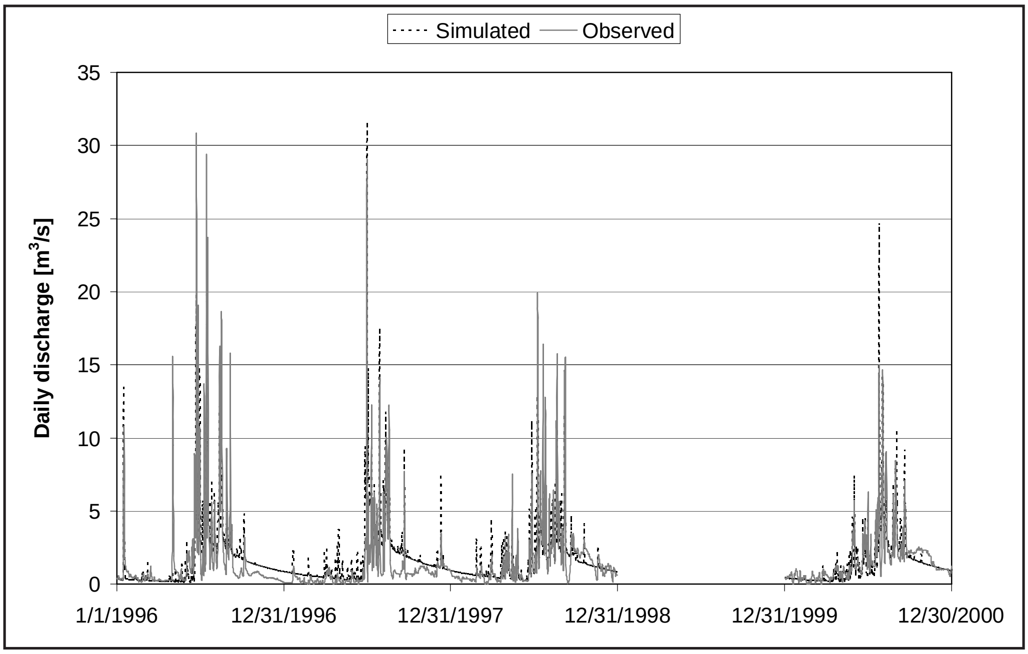

Figure 4.6: **Daily observed and simulated flows using the UBC model**

4.2.1.1 Remarks on the use of the model

The UBC model shows the largest advantages in catchments with a small number of rainfall stations. As Bastola (2002) mentions, this advantage is offset in the case of the Jhikhu Khola catchment with the large number and rather well-distributed rainfall sites. The very restrictive data input format and the calibration of the UBC model are demanding of time and labour. Improvements in the model's efficiency can be achieved mainly by better discharge data sets, particularly in the low flow regime.

4.2.2 Application of the Tank model

The Tank model was calibrated using the genetic optimisation algorithm implemented in the Tank model version 1.0.0 coded by Bastola et al. (2002) on the basis of the tournament selection process. The input data consisted of the daily precipitation interpolated using the interpolation module of WaSim-ETH (Schulla and Jasper 1999), monthly reference evapotranspiration calculated according to the FAO-Penman-Monteith method (FAO 1998), and the daily observed discharge at Site 1 of the Jhikhu Khola catchment. The model parameters suggested after the calibration and used in the validation of the model are shown in Appendix 4.4. For a first comparison of the observed and simulated flows using this model, refer to Figure 4.7, the daily observed and simulated flows.

The statistical characteristics of the observed hydrograph were preserved by the simulated hydrograph. A mean of 1.57 m^3/s was calculated for the observed discharge, while the mean of the simulated discharge was 1.41m^3/s. The standard deviation was 2.62 m^3/s for the observed discharge and 2.47 m^3/s for the simulated discharge. The range was about 30 m^3/s in the observed discharge and 27 m^3/s in the simulated discharge. The overall correlation coefficient between observed and simulated discharge was 0.78. These values roughly correspond with the values proposed by Bastola (2002) who used a different rainfall input series as well as a different evapotranspiration input series.

The qualitative comparison of the simulated and observed discharges on a daily basis shows that the simulated peaks are generally lower than the observed peaks. The simulated recession curves after the monsoon season reach the low base flows later than the observed recession curves. In addition, the simulated hydrograph is smoother than the observed hydrograph.

The comparison of the duration curves (Figure 4.8) shows that, in general, the model was able to simulate the duration curve rather well. An overall correlation coefficient between the observed and the simulated duration curve of 0.99 was achieved with a linear trend line approximately following

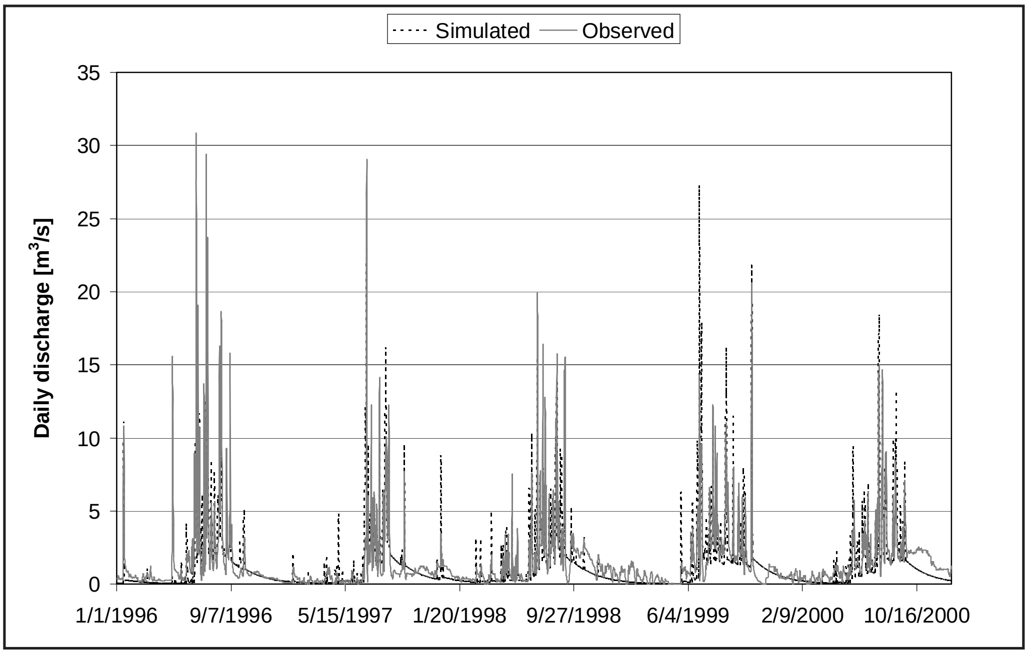

Figure 4.7: **Daily observed and simulated flows using the Tank model**

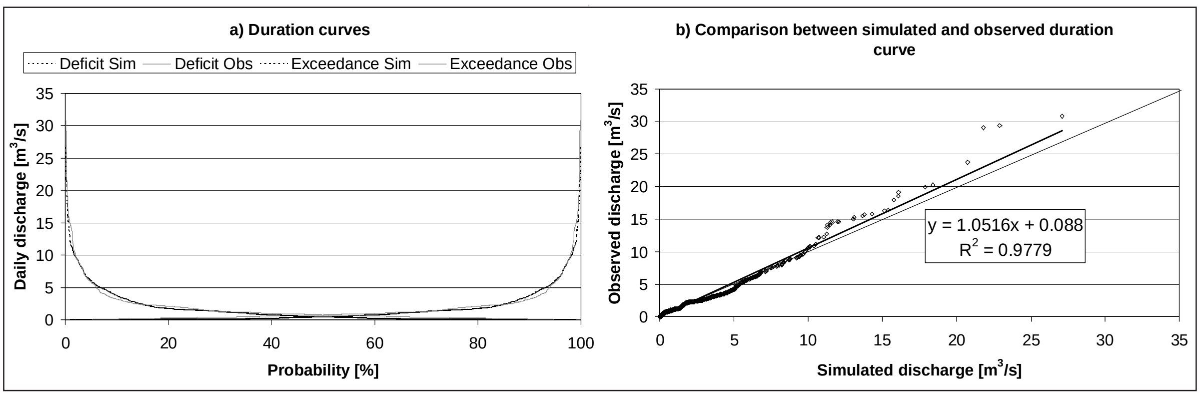

Figure 4.8: **Observed and simulated duration curve using the Tank model: a) duration curves of exceedance and deficit, b) comparison between observed and simulated curves**

the ideal line and a linear regression coefficient of about 0.98. The simulated discharge tends to slightly overestimate the high flows above about 10 m³/s, which corresponds to about $Q_{2(exc)}$.

A comparison of the monthly mean discharge shows that, in general, a good simulation can be achieved with the Tank model (see Figure 4.9). However, the low monthly flows during the dry season generally are underestimated by the model. The overall correlation coefficient between the observed and the simulated monthly mean discharge was 0.91 and the linear regression coefficient was 0.82 (Figure 4.9b). The linear trend line roughly follows the ideal line.

The efficiency of the model for the daily data expressed with different parameters was quite poor (Table 4.4) with an r^2 for linear data ranging from 0.66 to 0.80. This shows that the peaks are in general better simulated than the low flows as indicated by r^2 for logarithmic data ranging from 0.1 to 0.6.The efficiency expressed with the Nash-Sutcliffe criterion ranged from 0.53 to 0.63. Bastola (2002) obtained similar efficiencies with a rainfall dataset interpolated using the Thiessen polygon approach and a different evapotranspiration data set.

The annual water balance was simulated with an error of 5 to 20% in relation to the observed annual values, which corresponds to 24 to 110 mm (excluding the initial year 1996).

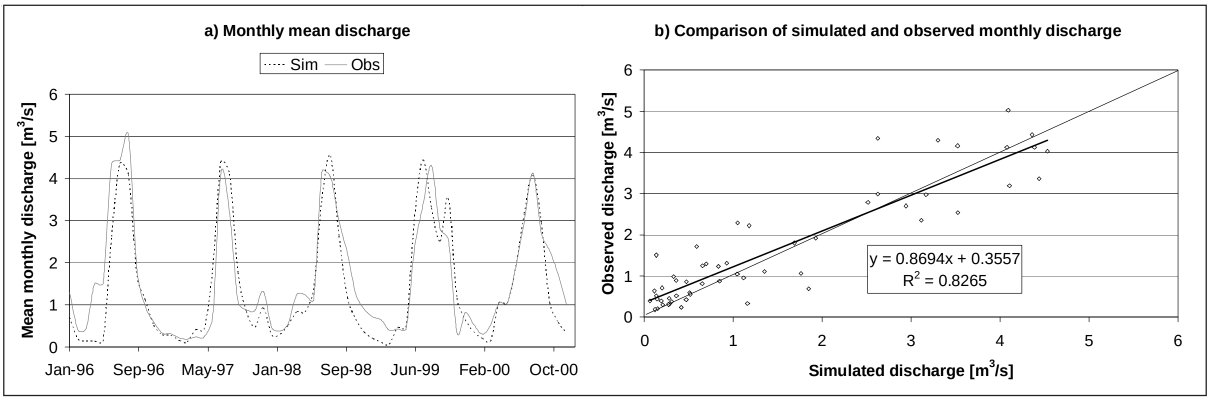

Figure 4.9: **Monthly mean discharge on the basis of observed and simulated flows using the Tank model: a) monthly mean discharge, b) comparison of monthly mean discharge**

Table 4.4: **Efficiency of the Tank model on the basis of daily data**

	r^2(lin)	r^2(log)	F1	F2	Balance	Nash-Sutcliffe
			Calibration			
1996*	0.66	-0.30	5.79	0.30	167.2	0.58
1997	0.69	0.57	2.04	0.16	-65.2	0.61
1998	0.71	0.43	2.57	0.15	102.6	0.58
Validation						
1999	0.67	0.42	2.67	0.50	-24.1	0.53
2000	0.80	0.09	1.21	0.25	113.1	0.63

* Initial year, required for setting the boundary conditions

The validation period from 1999 to 2000 showed comparable values with the calibration period from 1996 to 1998.

4.2.2.1 Remarks on the use of the model

A major advantage of this model is the simple data input format, the low input data requirements, as well as the fast and simple calibration process through the application of the genetic algorithm. The simplicity in terms of data input, however, is on the cost of the use of this model for studies related to land-use change. The model does not allow the input of catchment characteristics as they are not required to run this model, but are necessary for land-use change studies. For the application of climate scenarios, however, this model can be used.

The low efficiency of the model is assumed to be a direct cause of the quality of the discharge data, mainly in terms of low flows. The differences in peak discharge can probably be attributed to the temporal resolution of the data. Most discharge events and herein the peaks of these events only last for a few hours and are often the direct cause of heavy rainfall intensities. In the temporal resolution of one day, this effect is not properly reflected. The efficiency of this model could presumably be enhanced with improved discharge data quality as well as with more adequate evapotranspiration input data.

4.2.3 Application of PREVAH model

4.2.3.1 Data preparation

The spatial data requirements of PREVAH are quite extensive. Besides the digital elevation model (DEM) it requires land-use and a number of soil parameters (Table 4.5). In the case of the Jhikhu Khola catchment, a DEM was generated from the 1:20,000 map with contours of 50 m equidistance (Integrated Survey Section 1989). The land-use maps (*.pus and *.use) were prepared from the 1:20,000 land-use map produced from 1996 aerial photos with detailed ground verification by Bhuban Shrestha, PARDYP, Nepal. Soil depth information for the entire catchment was derived from the

Table 4.5: **Input data information for the application of the PREVAH model**

Catchment	Jhikhu Khola
Period for calibration	1996-1998
Period for validation	1999-2000
Spatial input data ([unit]; PREVAH file extension)	- elevation ([m]; *.dhm) - land use/cover ([PREVAH categories]#; *.use) - land use/cover ([PREVAH categories]; *.pus) - soil depth ([m]; *.btk) - soil depth ([class]; *.pat) - soil depth ([class]; *.art) - available field capacity ([vol%]; *.pfc) - saturated hydraulic conductivity ([mm/h]; *.kwt) - saturated hydraulic conductivity ([m/s]; *.kms)
Spatial resolution	50 m * 50 m cell size --> 44,429 cells
Meteorological input data	- precipitation of 11 sites - temperature of 9 sites
Discharge data	- discharge of Site 1 main hydro station
Temporal resolution of input data	1 day

\# For PREVAH categories refer to Zappa (1999)

sediment source survey (MRE 2002). The remaining soil parameters were estimated from measured and mapped texture during the land systems' mapping (Maharjan 1991) using the soil texture triangle by Saxton et al. (1986). All base maps were provided as grids of 50 m*50 m cell size.

The meteorological input data consisted of the daily precipitation data of 10 sites and the daily temperature data of 9 sites in the Jhikhu Khola catchment. Additionally, the daily rainfall data from Nagarkot (DHM 2000) were used as there are no stations in the western and upper parts of the catchment at present. For calibration the daily streamflow data at the outlet of the Jhikhu Khola catchment at Site 1 were used.

The Jhikhu Khola catchment consists of 44,429 grid cells of the size 50 m*50 m. This is on the basis of the DEM generated catchment area of 111.1 km^2. The entire catchment was classified into 14 height zones with a range of 100 m, ranging from 800 to 2200 m, five aspect classes (NW-NE, NE-SE, SE-SW, SW-NW, flat), four slope classes (0-10, 10-22, 22-36, >36), and five classes each for soil topographic and area topographic index. On the basis of these classes, 1163 hydrotopes were generated using the criteria height zone (intersected with catchment ID), exposition, land use, and soil-topographic index.

4.2.3.2 Model calibration and validation

Although a number of parameters required for the model can be extracted from the catchment characteristics imported with the spatial data as discussed above, a number of other parameters have to be calibrated using the measured discharge as a reference. These parameters are compiled in Table 4.6 with the resulting values after the calibration and validation. For this purpose, the year 1996 as initial year and the years 1997 and 1998 as calibration years were chosen (see also above). The efficiency results achieved through this process are compiled in Table 4.7.

Table 4.6: **Parameters calibrated for the PREVAH model**

Value	Parameter	Description
0.0	PKORF	correction for rain [%]
0.8	CREDV	reduction factor for open and vegetated land
0.4	CBETA	exponent, soil moisture recharge parameter
0.1	Cu	relative part of field capacity below which EA<ET0
0.6	CRSZ	maximum portion
2	SGRLUZ	threshold content of SUZ for generation of surface runoff [mm]
5	K0H	storage time for fast runoff R0 [h]
100	K1H	storage time for delayed runoff R1 [h]
1500	K2H	storage time for slow runoff R2 [h]
700	CG1H	storage time for fast baseflow R [h]
0.0	SLZ1MAX	storage capacity for fast baseflow R [mm]
0.9	CPERC	infiltration intensity [mm/h]

Table 4.7: **Assessment of performance of the PREVAH model**

	r^2(lin)	r^2(log)	Balance	F1	F2	EFF
			Calibration			
1996*	0.70	-1.73	5.06	0.63	80.5	0.63
1997	0.76	0.67	1.55	0.12	-44.6	0.71
1998	0.72	0.55	2.52	0.12	146.7	0.59
			Validation			
1999	0.75	0.44	2.06	0.43	19.4	0.64
2000	0.73	0.45	1.66	0.15	-8.0	0.50

* initial year, required for setting the boundary conditions

The balance is simulated by PREVAH, with errors ranging from 1 to 25% with reference to the observed values. This corresponds to absolute errors of between 8 and 150 mm per year. The balance is very accurately predicted in the validation period. Overall, the efficiency of the modelling using PREVAH on a daily time basis is satisfactory but far from good. In all years a Nash-Sutcliffe efficiency of more than 0.50 was achieved with a peak of 0.71 in 1997. The peaks are generally simulated better than the low flows, as shown with higher r^2 values for linear data than r^2 values for logarithmic data.

A qualitative comparison of the daily flows shows that the general recession trend is picked up nicely by the model, but in general the model reaches the low baseflows later than the observed discharge (see also Figure 4.10). In addition to this, the peaks are generally underestimated by the model, which is also shown with a lower range for simulated discharge. While the range for the observed data set is about 30 m^3/s, it is only 26 m^3/s for the simulated data set. The simulated time series preserves the statistical characteristics of the observed time series. The mean of the observed discharge is 1.57 m^3/s. The simulated discharge mean is 1.46 m^3/s. Standard deviations are 2.62 and 2.47 m^3/s for the observed and the simulated time series, respectively. The overall correlation coefficient between the simulated and observed data series is 0.80.

Overall, the mean monthly discharge (Figure 4.11a) shows a generally good fit. This is not only shown visually, but also with an overall correlation coefficient between the observed and the simulated monthly time series of 0.91 and a linear regression, which roughly follows an ideal line (Figure 4.11 b), with a regression coefficient of 0.83. The visual comparison shows a major discrepancy in the monsoon flows of 2000, otherwise it shows a good fit (Figure 4.11a).

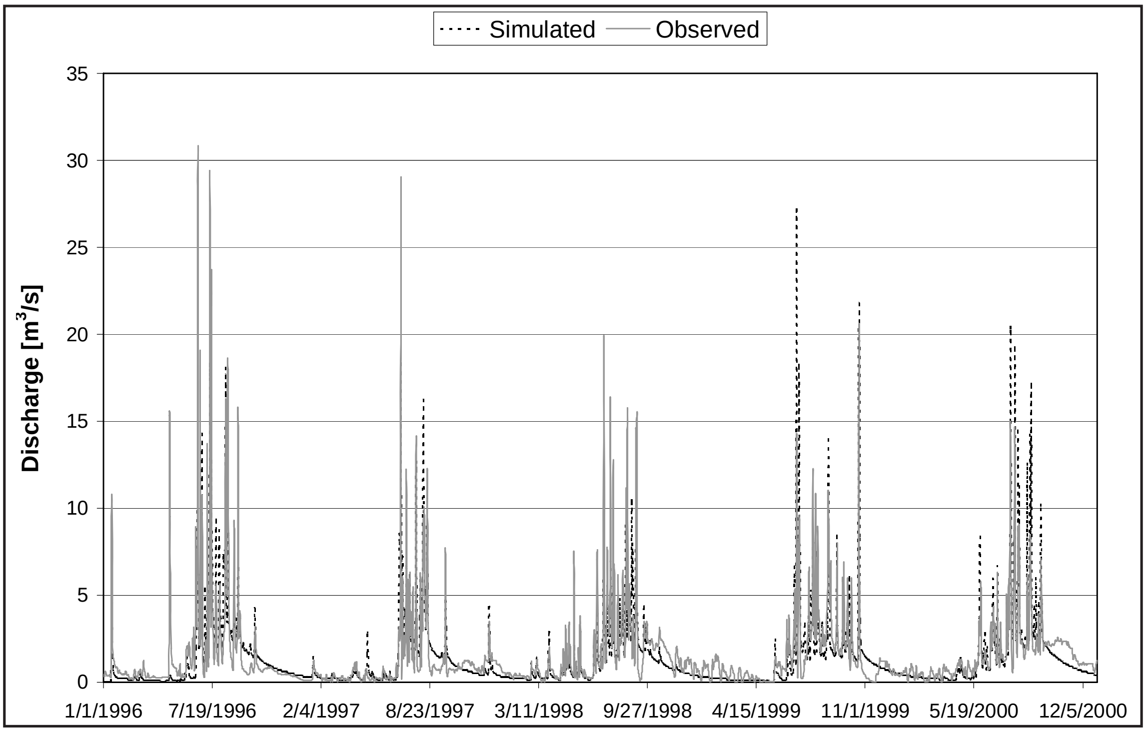

Figure 4.10: **Observed and simulated daily discharge at the main station, Jhikhu Khola catchment**

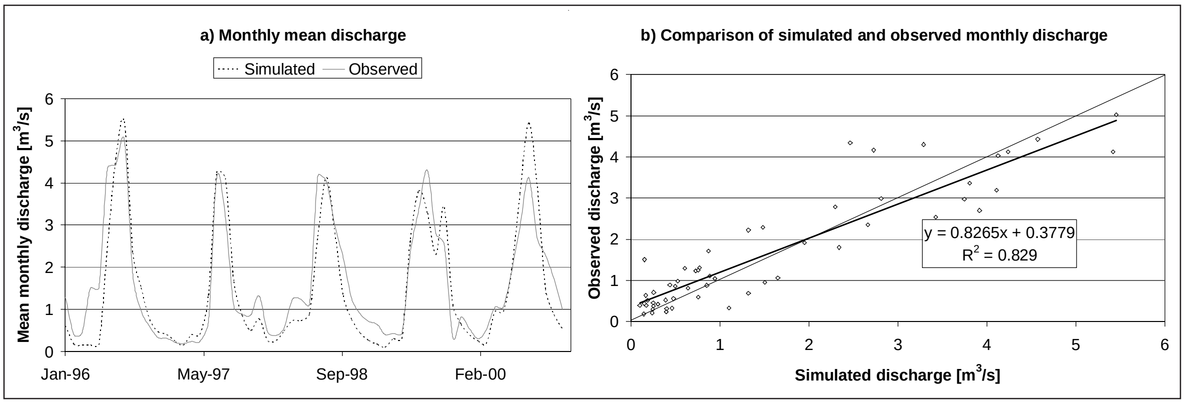

Figure 4.11: Observed and simulated (PREVAH) monthly mean discharge at the main station of the Jhikhu Khola catchment: a) mean monthly discharge, b) comparison of mean monthly discharge

The comparison of the duration curve (Figure 4.12) shows a nearly identical match between the observed and the simulated data series. The correlation coefficient between the duration curves of the two time series is 0.99. The linear regression shows nearly the same direction and position as the ideal line and has a regression coefficient of 0.99. The fit can be observed up to about 20 m^3/s. Only the four biggest events do not fit.

A comparison of the annual simulated evapotranspiration values at the potential rates with the ariel evapotranspiration rates, calculated according to the FAO (1998) method, showed that the simulated evapotranspiration rates are, in general, about 5% lower than the calculated rates. The actual evapotranspiration rates differ by about 20% on an annual basis. This suggests that more attention must be given to this part of the water balance.

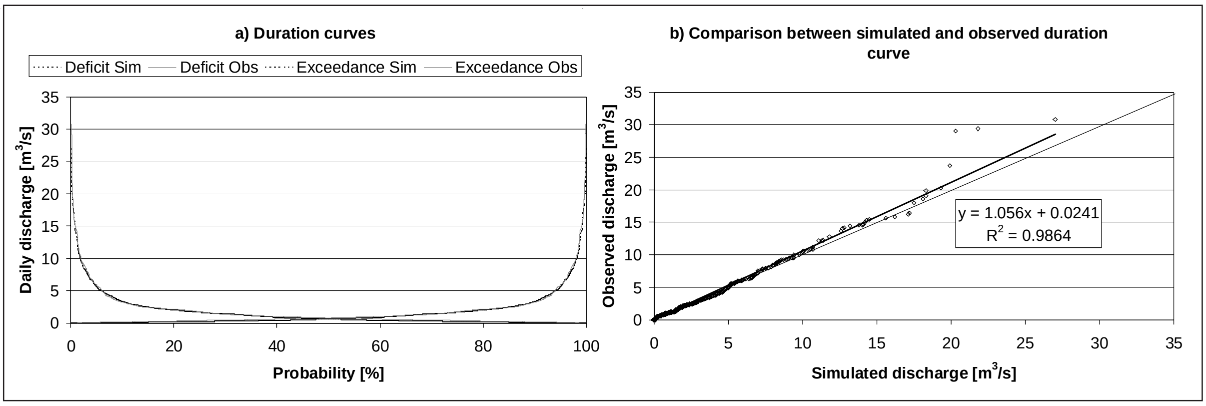

Figure 4.12: Observed and simulated (PREVAH) duration curves at the main station of the Jhikhu Khola catchment: a) duration curves, b) comparison of duration curves

4.2.3.3 Remarks on the use of the model

The PREVAH model has extensive data requirements and is therefore quite labour intensive. Not only the data preparation, but also the calibration process is time consuming. In terms of efficiency, a number of improvements can be made. These include the following.

- Currently the precipitation is imported on the basis of daily data (if daily data are modelled). This daily data are then converted to four equal rainfall amounts distributed equally throughout the day. This however does not take into consideration the large dependency on rainfall intensity or the particular daily rainfall distribution.
- Evapotranspiration in this application of PREVAH was calculated using the approach of Hamon (1961), which only requires temperature data. For better results, other approaches implemented in PREVAH should be used. The measurement network in the Jhikhu Khola has been upgraded accordingly, with relative humidity loggers at all sites and the installation of an automatic weather station additionally monitoring solar radiation and wind.

- The vegetation parameters were used according to the data sets implemented. It is acknowledged that the vegetation parameters for this agricultural system as well as for the prevalent forests in this region do not match. Due to the lack of the respective information, this was however necessary. In recent years, the Integrated Pest Management Project assessed a number of the necessary vegetation parameters, which will probably be available later this year (Herrmann, pers. comm.). The large differences in calculated and simulated actual evapotranspiration rates could herewith presumably be reduced.

4.2.4 Comparison of the models

In general, it has been seen that all models show rather low efficiencies. The low flows in particular tend to be modelled inefficiently, which generally is the easier part in a modelling exercise. In this section the performance of the three models will be compared. With respect to all the efficiency parameters compared, the PREVAH model showed, on average, the best performance (Table 4.8). This is followed by the Tank model and finally the UBC model. In terms of time and labour demand, the Tank model shows the best performance with its simple data input format and the implemented genetic algorithm. In terms of data requirements, the PREVAH model is most demanding and is also very labour intensive. However, this model shows the most scope for further improvement with the addition of a number of meteorological parameters as well as site-specific vegetation parameters. Additionally, improved discharge data quality would lead to an improved efficiency of this model. The efficiency of the other models can only be enhanced with improved discharge data quality.

Table 4.8: **Efficiency parameters compared between the three models**

	UBC				Tank				PREVAH			
	r^2(lin)	r^2(log)	Balance	EFF	r^2(lin)	r^2(log)	Balance	EFF	r^2(lin)	r^2(log)	Balance	EFF
1997	0.59	0.28	-304.7	0.49	0.69	0.57	-65.2	0.61	0.76	0.67	-44.6	0.71
1998	0.73	0.49	2.8	0.61	0.71	0.43	102.6	0.58	0.72	0.55	146.7	0.59
1999	-	-	-	-	0.67	0.42	-24.1	0.53	0.75	0.44	19.4	0.64
2000	0.82	0.52	18.2	0.67	0.80	0.09	113.1	0.63	0.73	0.45	-8.0	0.50
Mean	0.71	0.43	108.6	0.59	0.72	0.38	76.3	0.59	0.74	0.53	54.7	0.61

In Figure 4.13 the outputs of the different models are compared. While the simulated baseflows of the Tank and the PREVAH models are very similar, the baseflows of the UBC model are generally overestimated. It is important to note that all models show inadequate fit of the recession curves after the monsoon season. While the observed dataset immediately recedes to the low flow levels, the simulated results approach the low base flows more gently.

Table 4.9: **Correlation matrix for daily discharge simulated with different models**

	Q_{obs}	Q_{UBC}	Q_{Tank}	Q_{PREVAH}
Q_{obs}	1.00	0.78	0.78	0.80
Q_{UBC}		1.00	0.93	0.90
Q_{Tank}			1.00	0.95
Q_{PREVAH}				1.00

The most similar results are produced by the PREVAH and Tank model shown with the regression line in Figure 4.13a with a regression coefficient of 0.92 and a correlation coefficient of 0.95 (Table 4.9). The correlation coefficient between the observed data sets and the PREVAH model output is likewise the highest at 0.80.

The similar behaviour of the three models in terms of output efficiency suggests that the main limitations have to be sought in the input data set. With the problems of data collection and rating curve establishment as discussed in Appendix A3.1, the main reason has to be the discharge data set.

For further studies and to improve the efficiency of the models, the project should strive for more accurate discharge information mainly in the low flow season (see also Chapter 6). In addition, the impact of the numerous irrigation diversions have to be taken into consideration and further studied in detail.

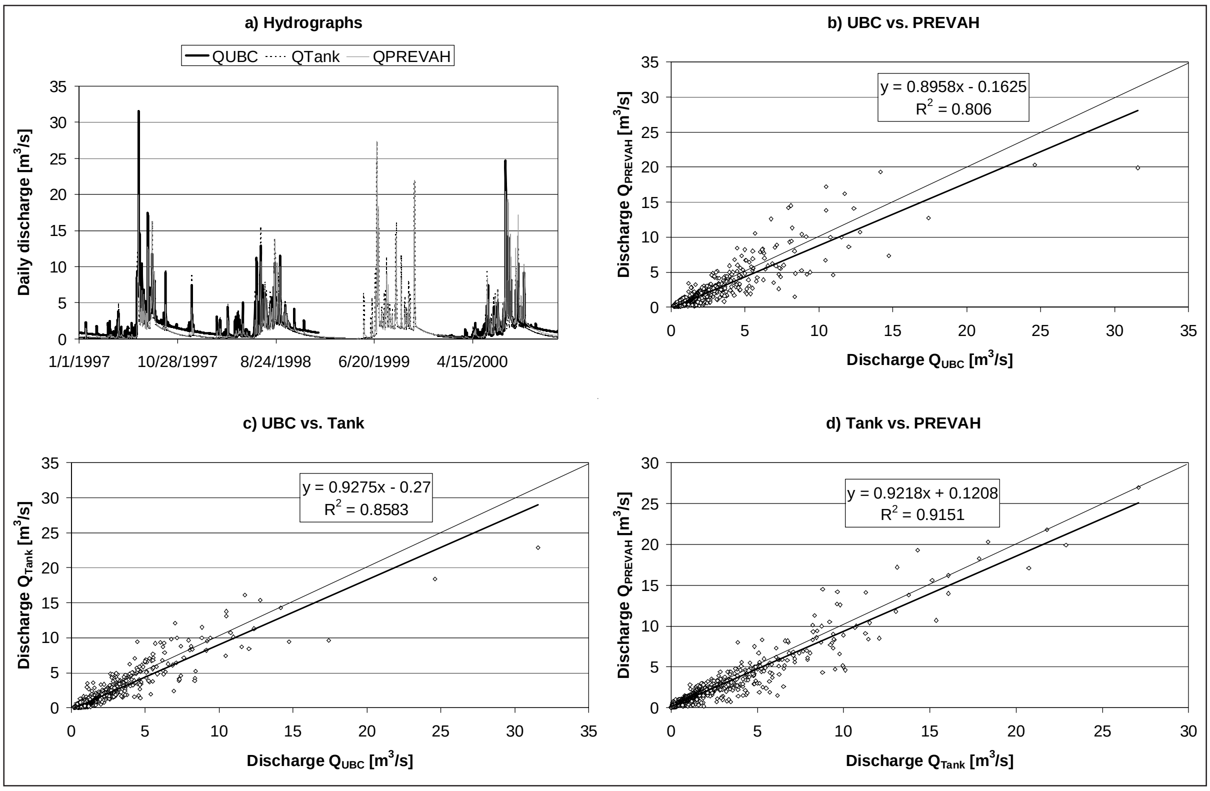

Figure 4.13: **Comparison of simulated daily discharge of UBC, Tank, and PREVAH models**

In terms of the models' use for the scenarios below, the PREVAH model can be applied both to the climate as well as to the land-use scenario. The remaining models, UBC and Tank, can only be applied to the climate scenario as land use/cover has no impact on the Tank model and only limited impact in the case of the UBC model through the percentage of forest cover and impermeable areas. For the sake of simplicity only the two models, PREVAH with the best performance and the Tank model with the easiest handling, were used for the scenario analyses.

4.3 SCENARIOS

A number of external driving forces are responsible for changing water supply and demand scenarios and the change in flood and land-degradation susceptibilities. Schultz (2000) mentions climate change, economic restrictions, ecological restrictions, land-use change, and difference sources of pollution which all have an impact on future water supply. Water demand, according to the same author, shows a major impact as a result of climate change, population growth, changing standards of living, and industrial development. The main external driving forces in the context of the middle mountains in Nepal are considered to be the climate, the population, the economic conditions, and national and district policies (see also Chapter 1). In this respect, three main scenarios were parameterised to assess their impact on the state of the water resources in the selected catchments. These scenarios do not represent a complete set of possible future development, but should show simple examples for the PARDYP Water and Erosion Studies which could be incorporated in the near future for the temporal as well as for the spatial up-scaling exercise proposed in Phase 3 (ICIMOD 2003).

The main questions to be answered below were as follows.

- How can the given scenarios be parameterisd for a middle mountain catchment in the HKH?
- What is the potential impact of the scenarios identified on indicators relevant to water availability, flooding, and land degradation?

4.3.1 Scenario 1: Climate Change

Climate change is one of the most publicised issues in recent decades. A large number of studies into the reasons, impacts, and scenarios of climate change have been undertaken in this time. A very good source for mainstream information on this issue is provided by the Intergovernmental Panel on Climate Change (IPCC). Most of the information below is therefore based on the work of IPCC.

Surface temperature change in the last 100 years ranged from 0.3 to 0.8 °C in the region of Tropical Asia, including the South Asian countries (IPCC 1998). According to the same report, the projected temperature changes for the entire globe between 1990 and 2100 are likely to be in the range of 1.5 to 4.5 °C. For South Asia an above average temperature increase is predicted (Figure 4.14). An even higher increase is foreseen for the Tibetan plateau. Lal (2002) suggests an increase in temperature of 3.5 to 5.5 °C by the end of 2100 of the land regions of the Indian sub-continent. For Nepal, Arun B. Shrestha noted an increase of 0.06 °C per year in the average temperature (Kathmandu Post 2003).

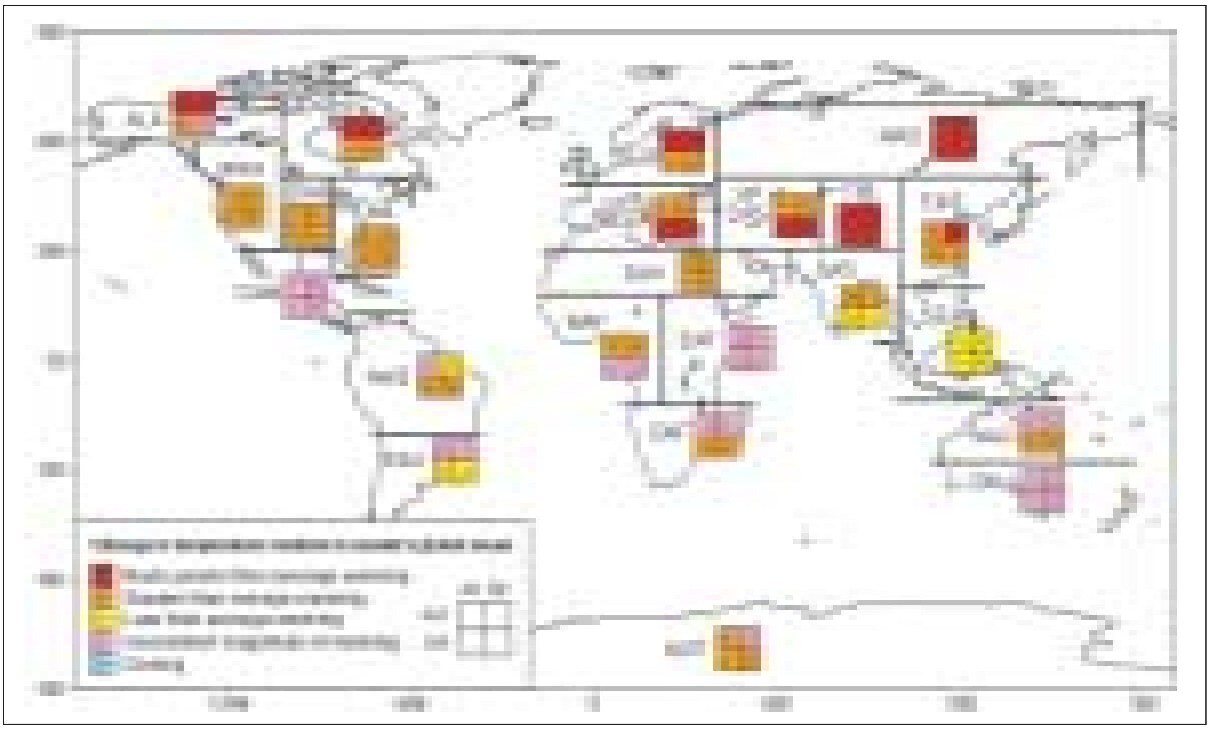

Figure 4.14: **Change in temperature relative to model's global mean** (from IPCC 1998)

Chalise (1994) stresses the importance of understanding the possible impacts of climate change as this will add to the already existing uncertainties of widespread environmental degradation in the region. This author further discusses some possible signs of climate change on the basis of:

- noontime temperature distribution in Kathmandu, which shows a slight increase over recent years;and
- glacier fluctuations in the region, which generally indicate a retreating trend and therefore a warming of the atmosphere.

For tropical Asia, IPCC (1998) suggests an impact on water resources as follows.

- The Himalayas play a critical role in the provision of water to continental monsoon Asia.
- Increased temperature and increased seasonal variability in precipitation are expected to result in accelerated recession of glaciers and increasing danger from glacial lake outburst floods.
- A reduction in the flow of snow and ice-fed rivers, accompanied by increases in peak flows and sediment yields, would have major impacts on hydropower regeneration, urban water supply, and agriculture.

- Availability of water from snow-fed rivers may increase in the short term, as glaciers recede, but decrease in the long term.
- Runoff from rain-fed rivers may change in the future. A reduction in snowmelt water would result in decreases in the dry-season flow of these rivers.
- Large populations and increasing demands in the agricultural, industrial, and hydropower sectors will put additional stress on water resources.
- Pressure will be most acute on drier river basins and those subject to low seasonal flows.

Recently, the focus of global climate change discussions has been on the type of precipitation, and in particular the proportion of precipitation, that falls as snow. Amongst others, Harrison et al. (2001) studied climate change and its impact on the snowfall pattern in Scotland. It is important to note that global climate change not only has negative impacts. Positive impacts could also be envisaged, such as longer growing seasons for higher altitudes.

Table 4.10: **Climate change parameters (by 2080)**

Scenario	Temperature	Precipitation	Reference
- annual	+5.6 °C	+9.9 %	Lal (2002)
- winter	+6.3 °C	-25 %	
- monsoon	+4.6 °C	+15 %	

Lal (2002) projects for the Indian sub-continent decreasing rainfall in winter and increasing rainfall during the monsoon (Table 4.10). A decrease of 10 to 20% in winter is simulated by 2050. During the monsoon an increase of 30% or more in precipitation over India is projected. Lal (2002) further suggests that the variability in the monsoon's onset will increase. However, there is conflicting information on the basis of different GCMs (global climate models). Lal et al. (1995) found a decline in mean summer monsoon rainfall of about 0.5 mm/day over the South Asian region. This decline in summer monsoon rainfall has also been suggested by some experiments referred to in IPCC (1998).

The changes in temperature and in precipitation are expected to have a major impact on the availability of water resources in the region. For the meso-scale catchments, the expected primary impact of this scenario as presented in Table 0.10 may show the following impact chain:

1) increase in temperature during dry season months/decrease in precipitation → increased evapotranspiration rates → faster reduction of seasonal soil moisture and groundwater storage → reduced groundwater and spring yield → reduced runoff → increased pressure on water resources;and
2) increase in precipitation during the monsoon season months → increased runoff → increased susceptibility to floods and land degradation caused by water.

The disaggregated scenario with different values for the winter and monsoon was calculated using the models Tank and PREVAH.

4.3.2 Scenario 2: Population

Population has been increasing tremendously in the Indian sub-continent. Many authors caution from further increase and project a collapse of the natural resource base in case of further population stress (e.g. Allen 2000). Other authors argue that, with increasing population, the people would introduce innovative management technologies and practices to cope with the worsening resource situation (Paudel and Thapa 2001). There is, however, no argument that more people need more water and more food.

In Nepal, the annual population growth rate for the eco-regional zone of the hills was calculated at 2% for the period between 1991 and 2001 (MOPE 2002). The annual population growth rate for the Jhikhu Khola catchment was assessed to be 3.1% for the period from 1947 to 1990 and 3.5% between 1947 and 1996. While these growth rates are important parameters, they are not very useful for long-term projections. For this purpose, a number of additional parameters such as fertility rate, number of births, number of deaths, and migration rates are required. These parameters are not available for the Jhikhu Khola catchment, therefore two population projections by Lutz and Goujon (2002) were used (Table 4.11). The two projections a1b1 and a2 were used for the emission estimates of the IPCC Special Report on Emission Scenarios (Nakicenovic and Swart 2000) as lower and upper estimates for the world's population. The projections firstly produced regional datasets for 13 world regions, which were then disaggregated to country level.

Table 4.11: **Population and water demand parameters (by 2080)**

Parameter	Value	Remarks	Reference
Population projection a1b1	196 % of the population in 1990	low fertility/low mortality/central migration	Lutz and Goujon (2002)
Population projection a2	344 % of the population in 1990	high fertility/high mortality/central migration	Lutz and Goujon (2002)
Low domestic water demand	20l $person^{-1}day^{-1}$	current water demand in the Jhikhu Khola catchment	Merz et al. (2002)
Medium domestic water demand	50l $person^{-1}day^{-1}$	basic water demand	Gleick (1996)
High domestic water demand	100l $person^{-1}day^{-1}$	double the basic water demand above	

The projection a1b1 shows a low fertility/low mortality/central migration scenario and projects a world population of 8.7 billion in 2055, which decreases to 7.1 billion in 2100 (IIASA 1999). The projection a1 represents a high fertility/high mortality/central migration scenario and projects a world population of about 15 billion at the end of the 21st century. The disaggregated data for the country level of Nepal forecasts a population of about 36,000,000 in the case of the a1b1 scenario and about 63,000,000 in the case of the a1 scenario by 2080. The population growth rates for the entire kingdom were used for the estimation of the population in the Jhikhu Khola.

It is further assumed that the people in the future will aspire to higher living standards and therefore use more water, e.g., for flush toilets (Verma et al. in prep). In addition to the population parameters a low, medium, and high water demand scenario was calculated and compared with the available water resources on the basis of existing as well as predicted water resources. The water demand values are based on the current water demand in the Jhikhu Khola catchment (Merz et al. 2002) in the case of the low water demand, and projected for medium and high water demands based on Gleick (1996). The basic water demand standard as proposed by Gleick (1996) is composed of 5 l/day for drinking, 20 l/day for sanitation, 15 l/day for bathing, and 10 l/day for cooking, all values per person. For the high domestic water demand, this basic water demand was doubled.

Expected primary impact of this scenario:

Increased population → increased demand for domestic water → increased demand for food (intensification of land use is hardly possible on the basis of the present intensities. Expansion is discussed as an impact on land use in scenario 3).

4.3.3 Scenario 3: Land-use change due to poverty and landflucht (migration from the land)

Land-use change may have a major impact on the water resources, at the micro- to meso-scale in particular (FAO 2002). As shown above, there is no clear evidence for a major land use shift at present in the catchments. However, as indicated in Chapter 2 and on the basis of the population projections, a change in land use could be well be possible. For future developments two different potential sub-scenarios were identified:

Landflucht (outmigration of people from rural to urban areas; urbanisation from the perspective of the rural areas)

In general, a trend towards increased urbanisation can be observed in Nepal and many other countries of South Asia (UNFPA 2001). The urban growth rate in Nepal for the period 2000-2005 is projected to be 5.1% (UNFPA 2001). In 2001, 14% of Nepal's population lived in urban centres (MOPE 2002). This process affects the rural population. Urban migration is also the reason for a high percentage of migrants in Nepal (K.C. et al. 1998).

In the Jhikhu Khola catchment, a number of fields are not being cultivated as their owners live in Kathmandu and have not given the land for tenancy. Often these owners have left their parental home for higher education or jobs in the capital or abroad. At the time of the parents death, or if the parents follow them to the city, the land remains uncultivated. Another reason for abandoning the land is the low economic return from many fields, in particular in the upper catchment areas. It is not likely that abandoned land will be taken over by another family, as the return is too marginal. Another reason for outmigration is poverty (Adhikari and Bohle 1999), although these people often do not leave large plots of land behind and therefore do not contribute to land-use change due to outmigration.

In terms of spatial distribution of the land, the most likely land to be abandoned is in the upper elevation areas. These are the marginal lands with steep slopes, often low soil fertility, and a high tendency towards soil erosion. The rainfed land on the border to the irrigated lands is more fertile and easier to cultivate due to accessibility and favourable slope. These lands would readily be taken over by other farmers in case of outmigration by the owners.

Expansion to marginal lands

Increasing population pressure and the need for cultivated land is believed to cause an expansion to marginal and less suitable land (UNEP 2001). This process occurred in Nepal during the 1970s and was the basis of the Theory of Himalayan Environmental Degradation (Eckholm 1970; Ives and Messerli 1989). However, many of the marginal areas on steep slopes have now been protected by inclusion into community forestry areas. For this reason, the community forestry regulations were incorporated in the scenarios and only shrub and grassland were subject to potential change to agricultural land (Table 4.12). It is acknowledged that some of these areas have also been included in the community forest areas as shown in Table 4.13, but in general these areas are small and negligible at the catchment scale.

On the basis of these two sub-scenarios the parameters compiled in Table 4.12 were determined.
Expected primary impacts of this scenario:
1) Landflucht → increased area of grassland → increased flood volume and more frequent peaks

or

2) Expansion to marginal areas → increased area of cultivated land → decreased flood volume and reduced number of peaks.

This scenario was only calculated by using the PREVAH model.

Table 4.12: **Land-use change parameters (by 2080)**

Scenario	Remarks
Landflucht 1(L1) – High rate of abandoning	All the rainfed land above 1250 masl is abandoned and becomes grassland
Landflucht 2 (L2) – Medium rate of abandoning	All the rainfed land above 1500 masl is abandoned and becomes grassland
Expansion 1(E1) – High rate of expansion	All shrub and grasslands below 1250 masl are newly cultivated and become rainfed agricultural land
Expansion 2 (E2) – Low rate of expansion	All shrub and grasslands below 1500 masl are newly cultivated and become rainfed agricultural land

Table 4.13: **Community forest areas in the Jhikhu Khola catchment**
(based on unpublished data by Bhuban Shrestha/PARDYP Nepal; all figures in km^2)

	Rainfed land	Forest	Grass	Shrub	Other
Total in the catchment	42.7	33.2	6.1	7.8	3.3
Protected by community forest	1.2	11.8	0.4	0.9	0.2

4.4 IMPACT ASSESSMENT

The impact assessment of the scenarios described above should show preliminary results of possible analyses to be further pursued and investigated in more detail in the PARDYP framework. For the calculation of the scenarios, the data of 1996 to 1999 was used as a base (Table 4.2). Results from 1996 were omitted as these data were used to set the boundary conditions, e.g., the soil moisture content or the groundwater.

4.4.1 Scenario 1: Climate change

The PREVAH and Tank models were used to assess the potential impact of a global climate change scenario as discussed above. The scenario was assessed on the basis of the data of 1997 to 1999. Overall, it can be observed that on a seasonal basis the runoff is considered to increase for the monsoon season and to decrease in the remaining seasons, particularly in the pre-monsoon season (Figure 4.15).

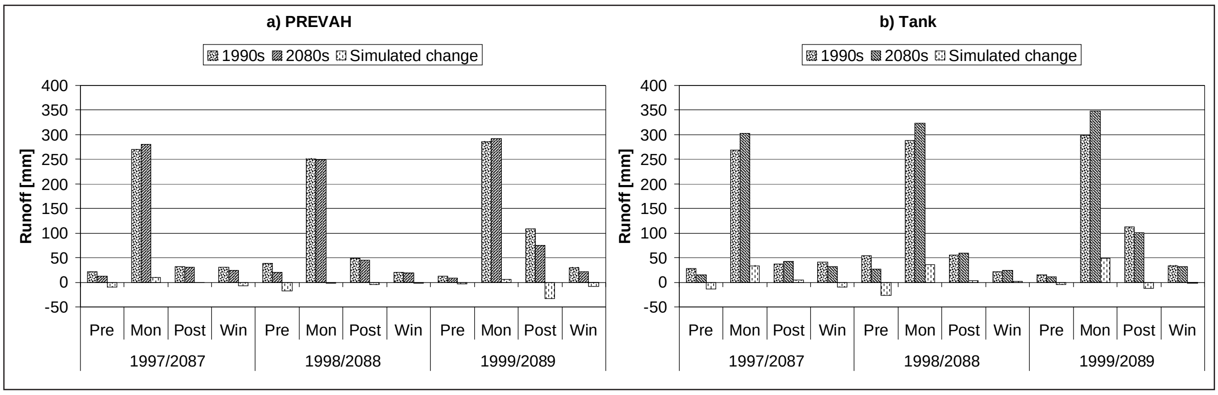

Figure 4.15: **Seasonal changes with global climate change applying a) PREVAH model, b) Tank model**

On the basis of the PREVAH model, potential evapotranspiration will increase by about 40% from 1990 to 2080 if the climate change scenario occurs. The actual evapotranspiration rates would change by about 10% on an annual basis. As these figures are still very preliminary due to the inappropriate vegetation datasets, no further disaggregation into different months or seasons is presented here, although this would be of particular interest for the different areas in the catchment.

Comparing the duration curves for the data in the 1990s with the predicted values on the basis of the climate scenario for the 2080s, no difference can be observed by applying the PREVAH model (Figure 4.16a). Using the Tank model on the other hand, the slope of the regression line has a slope greater than 1, which indicates that significantly higher discharge values are expected on the basis of this model's predictions (Figure 4.16b). The uncertainty shown by the results indicates that basing stream flows on the past data records may be inappropriate in future as the conditions may change. Great care will have to be taken in the design of structures.

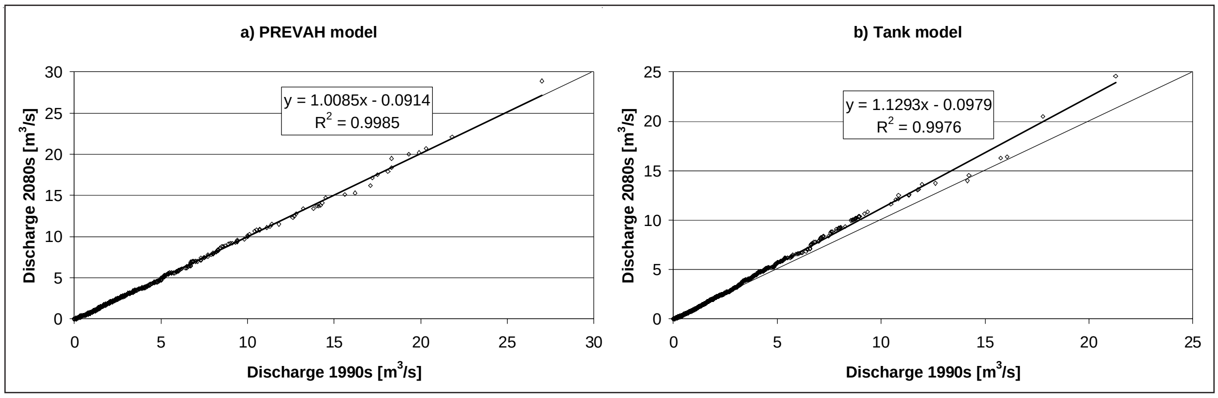

Figure 4.16: **Comparison of duration curves for 1990s and 2080s using a) PREVAH model, b) Tank model**

In terms of flood peaks, an increase in the number of peaks above 10 m^3/s daily discharge is expected on the basis of both models (Table 4.14). The simulated change in the number of peaks is greater in the case of the Tank model than the PREVAH model. It should be noted that the number of peaks observed is closer to the number of peaks estimated by the PREVAH model in the 1990s than the number of peaks simulated by the Tank model.

Table 4.14: **Number of peaks > 10 m^3/s for 1990s and 2080s with different models**

	1990s		2080s		Simulated change	
Year	PREVAH	Tank	PREVAH	Tank	PREVAH	Tank
1997/2087	4	2	5	5	+1	+3
1998/2088	3	2	3	2	0	0
1999/2089	7	7	8	11	+1	+4

In 1997, 6 peaks were observed; in 1998, 8 were seen; and in 1999, another 6. In addition, the PREVAH model shows slightly better fits for the high flows than the Tank model (see above in Table 4.8). Summarised, with a global climate change according to IPCC (1998) and changes in temperature/precipitation in South Asia according to Lal (2002):

- evapotranspiration rates are expected to increase;
- water availability during the dry season can be expected to decrease;
- water volume during the monsoon can be expected to increase;
- number of flood peaks can be expected to increase; and
- design flows based on the past data records may show underestimated flows.

4.4.2 Scenario 2: Population growth

On the basis of the two population projections by Lutz and Goujon (2002) and the three water demand classes of low, medium, and high-water demand, on the basis of the current water requirements and the basic domestic water requirements according to Gleick (1996), the following predictions can be made for the water requirements in the Jhikhu Khola catchment by 2080 (see also Table 4.15):

Table 4.15: **Projected population and water demand Jhikhu Khola catchment, 2080**

Population	Scenario a1b1	Scenario b2
Population	85,646	150,238
Population density [people/km^2]	769	1349
Water demand		
Low daily demand [mm]	5.6	9.8
Medium daily demand [mm]	14.0	24.6
High daily demand [mm]	28.1	49.2

- population in the catchment will be between about 85,000 and 150,000;
- this corresponds to a population density of 750 to 1400 people per km^2;and
- annual water demand will range from 5 to 50 mm depending on the different water demand scenarios.

The disaggregated information according to the VDCs in the Jhikhu Khola catchment shows that the highest increases in water demand are expected in the VDCs along the Arniko highway and soon also along the Dhulikhel – Bardibas highway where the population is concentrated (Figure 4.17). In 1996, the water demand in all VDCs was between 0 -6 mm. In case of a low daily water demand the VDCs Panchkhal, Patlekhet, Rabi Opi, Dhulikhel, and Phoolbari would show an annual water demand of about 6 -12 mm in the case of a low population growth rate according to scenario a1b1. In case of a high population growth rate as predicted by scenario a2, the same VDCs would experience a water demand of about 12 -18 mm per annum. The remaining VDCs are expected to have a water demand of 6 -12 mm per annum. In securing the basic water requirements, the water demand under scenario a1b1 would shoot up to 15-30 mm in the road-proximate VDCs and up to 15 mm in the remaining VDCs. In scenario a2, Rabi Opi, Panchkhal, Patlekhet, and Phoolbari would demand 30-45 mm per annum. In case of high water demand, the VDCs Devitar, Anaikot, Hokse, Kharelthok, and Methinkot, basically the VDCs along the north south-facing slopes, would show about 0-25 mm annual water demand in case of scenario a1b1. The remaining VDCs are expected to demand 25-50 mm water per annum. In case of high population growth rates, the VDCs on the

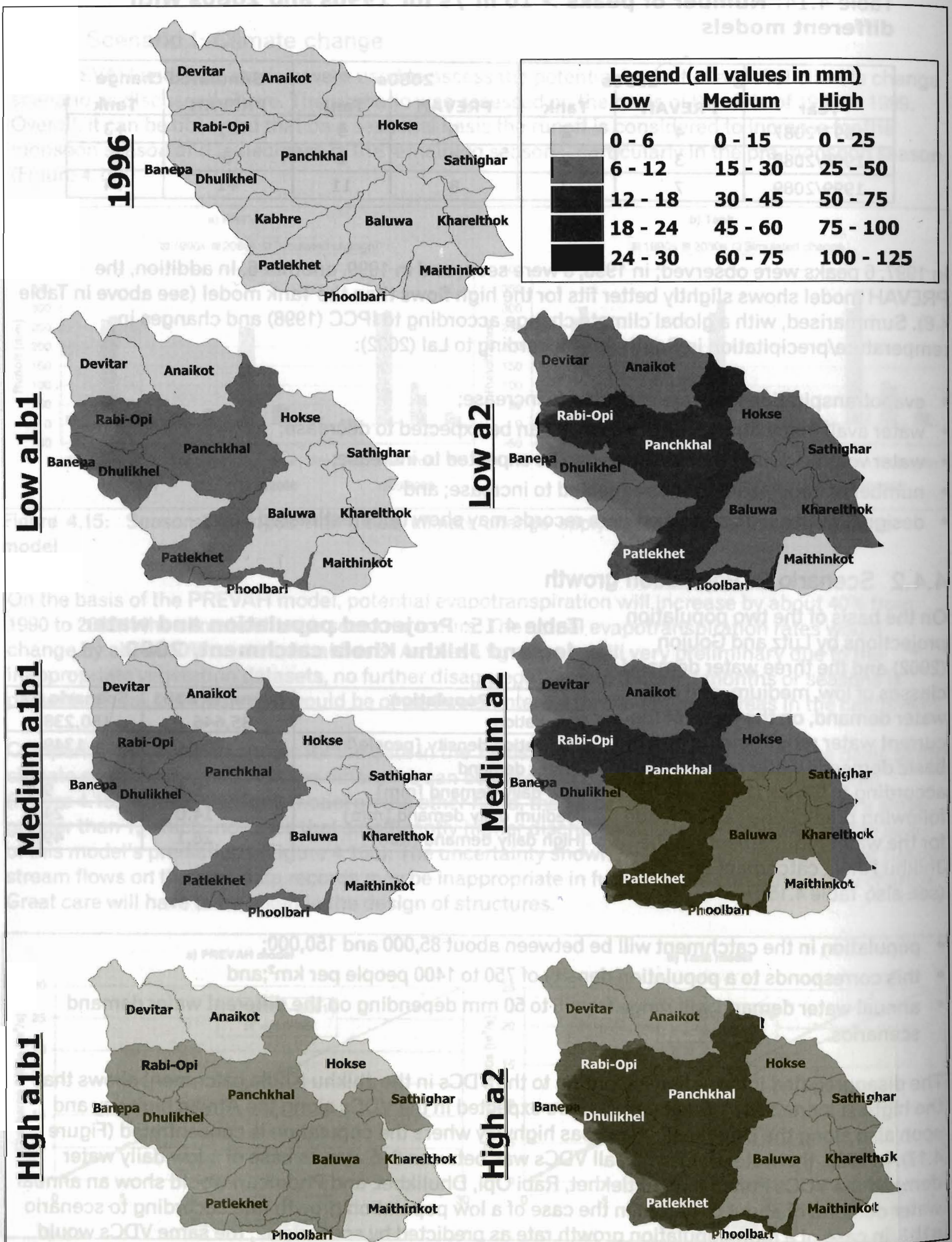

Figure 4.17: **Projected water demand in 2080 in the VDCs of the Jhikhu Khola catchment (note that the colours are the same only within the water demand category, e.g., within low, medium or high)**

south-facing slopes plus Baluwa would be expected to show about 25-50 mm water demand and the remaining VDCs 50-75 mm. Comparing these values with the annual precipitation values or even the monthly precipitation values, there seems no problem of adequate water availability for domestic purposes. However, in this context it has to be remembered that people generally do not use rainwater, but surface water or shallow groundwater for domestic purposes. In this respect, an increase in pollution as was observed in the Jhikhu Khola and documented by Merz et al. (2003b), would put further pressure on the available water resources. In addition, as was mentioned above, the agricultural water demand is more significant.

With the current very high level of agricultural intensity in the catchment (see Chapter 2), only expansion to more marginal lands is possible (see Scenario 3 E1 and E2) if the catchment is to remain self-sufficient in staple food production and still be able to produce cash crops for the markets in the city.

The following summary can be made.

- Water demand for domestic purposes will increase many times over with population growth.
- The main increase in water demand is not expected from population growth, but from increased water demand to achieve a basic water supply according to Gleick's (1996) figures.
- The main water demand increase in the Jhikhu Khola catchment is expected in the VDCs along the two highways crossing the catchment. The VDCs in the upper part will have an important function as recharge areas and water supply for the lower VDCs. This stresses the importance of local-level planning and management of the water resources at the catchment level.

4.4.3 Scenario 3: Land-use change

The calculation of this scenario with the PREVAH model generated a number of open questions, mainly in relation to the observation presented in Chapter 3. In terms of land- use change, the scenarios as presented above result in the expected changes shown in Table 4.16. The scenarios related to Landflucht result in a decrease of rainfed agricultural land with an approximate 10 to 34% decrease depending on the scenario. Grassland increases by 74 to 235% in scenarios Landflucht 2 (L2) and Landflucht (L1), respectively. No changes are expected in the area of shrub land due to grazing and cutting of grasses.

Table 4.16: **Land-use changes on the basis of the land-use scenarios**

Land use	1990s	L1	L2	E2	E2
Rainfed agricultural land	680 ha	448 ha	607 ha	876 ha	822 ha
		-34 %	-10 %	+29 %	+21 %
Grassland	98 ha	329 ha	171 ha	10 ha	37 ha
		+235 %	+74 %	-90 %	-62 %
Shrub land	125 ha	125 ha	125 ha	16 ha	44 ha
		±0 %	±0 %	-87 %	-65 %

Scenarios Expansion 1 (E1) and 2 (E2) are expected to result in the increase of rainfed agricultural land at 20 to 30% depending on the scenario. This is at the cost of grassland (- 60 to 90%) and shrub land (- 60 to 90%).

The impact of these land-use changes simulated with the PREVAH model yield only little change, as shown in Table 4.17. In general, the Landflucht scenarios reduce the runoff, while the expansion scenarios increase the runoff. These results are in strong contrast to the results observed on the basis of event analyses presented in Section3.4. According to these results, catchment runoff increases with an increasing proportion of grassland in the catchment and reduces with the proportion of agricultural land in the catchment. Here the opposite is observed, i.e., the runoff decreases with the proportion of grassland and is the smallest for scenario L1. It is interesting to note that the scenario L1 however shows the highest runoff during the monsoon season.

Comparing the maxima for the four years used for these calculations (Figure 4.18), in three out of four years the Landflucht scenarios, i.e., the scenarios with increased grazing areas, showed the

Table 4.17: **Comparison of the PREVAH outputs with scenarios Landflucht 1 and 2 and Expansion 1 and 2 [all values in mm]**

Season	1990s	2080s_L1	2080s_L2	2080s_E1	2080s_E2
Pre	27.0	26.1	26.7	27.6	27.5
Mon	291.1	291.6	291.1	291.4	291.2
Post	61.4	60.9	61.1	62.0	61.8
Win	26.9	26.4	26.7	27.3	27.2
Annual	*406.4*	*405.0*	*405.6*	*408.3*	*407.7*

peak runoffs. The differences, however, are marginal between the calculated discharges. These results confirm the findings in Chapter 3.4 on the basis of which grassland is decisive in flood generation and the size of a flood peak. For conclusive answers, the findings presented here are, however, not adequate and further improvements have to be made. It is believed that with the availability of the local vegetation characteristics in particular these results will become more conclusive.

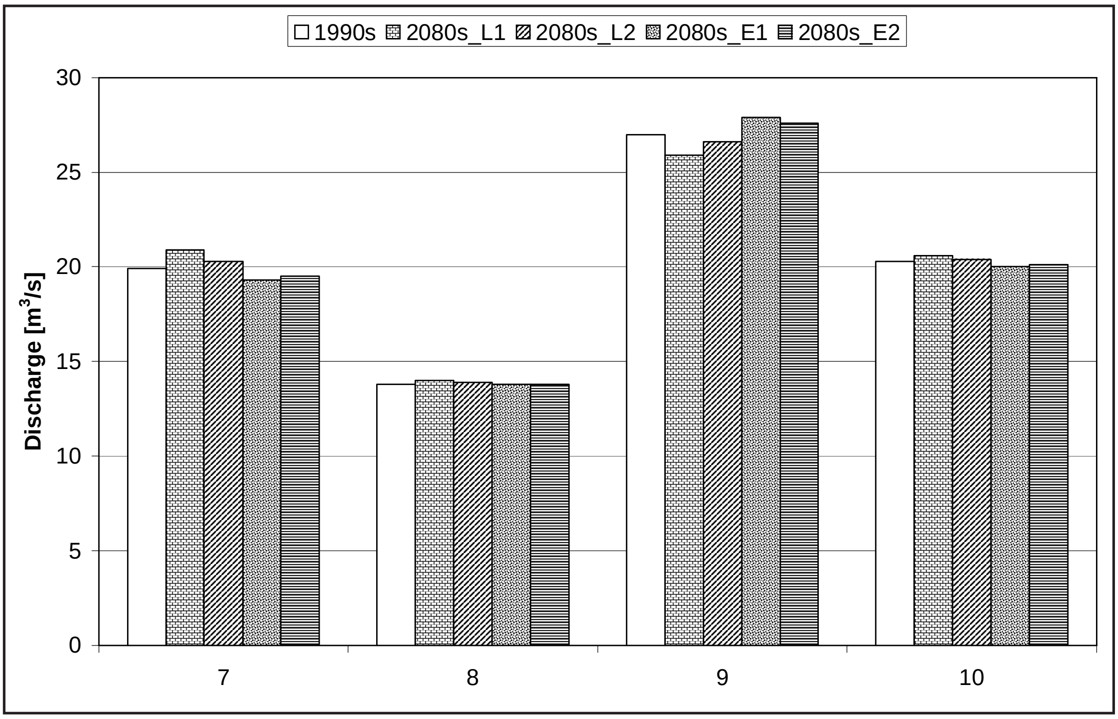

Figure 4.18: **Comparison of maxima**

4.4.4 Discussion

Three different scenarios were parameterised based on global climate change, population development, and land-use change. In brief, it was indicated that potential climate change as well as expected population development might lead to an overall decrease in water availability during the dry season. This is due to a decrease in precipitation during these months, which also has a negative impact on the runoff in the catchment. In addition, water demand is expected to increase many times over on the basis of increased population as well has higher water demands per capita. However, overall, the water demand for domestic purposes is expected to be covered. The parameterisation of agricultural water demand is difficult as the extent to which agriculture can be intensified further is unclear.

During the monsoon season more rain is expected, which leads to a higher susceptibility to flood generation and land degradation. Whether this increase in rainfall also leads to an increase in rainfall intensity and rainfall erosivity still has to be established. On the basis of observations in terms of relationship between maximum rainfall intensity and rainfall amount shown in Section 3.4; and between erosivity (which is calculated on the basis of rainfall intensity; see also Section 3.1) and rainfall amount by Ramprasad et al. (2000; an increase of both these parameters will have to be expected. This increase is further expected to lead to higher and more frequent peaks.

For improved results of the scenario analyses further efforts must be undertaken to improve the efficiency of the models as discussed above. The results of the land-use scenario calculation as presented above are not satisfactory at present, mainly due to the inadequate parameterisation of the local vegetation.

4.4.5 Summary and Outlook

A number of models have been applied for different purposes in the HKH, a detailed comparison with the same datasets as WMO (1975) or WMO (1990) however is missing. The most comprehensive studies undertaken by NIH further concluded that data availability is a major constraint for the successful application of rainfall-runoff models in the mountainous regions. In general, distributed models seem to be more appropriate for mountainous conditions due to the highly variable and heterogeneous conditions in mountain areas, however, the data requirements are often not appropriate.

In this study, three different models were calibrated and validated, the UBC, the Tank model, and the PREVAH model. Of these models, PREVAH showed the best performance, although overall the efficiency for all models was quite low. The main reason for this is the quality of the discharge data, mainly in the low flow regime. In addition, the evapotranspiration in all cases had to be estimated from temperature and none of the more sophisticated methods could be used. With the improvements of the hydrological stations to increase their low flow sensitivity and additional data to calculate evapotranspiration the efficiency could be increased. In the case of the PREVAH model the use of local vegetation characteristics could further improve its efficiency.

The three scenarios based on global climate change, population growth coupled with increasing water demand and rise in living standards, as well as land-use change— both abandoning of marginal land and expansion to marginal fields — showed that overall an increase in water demand has to be expected from all sectors at a time where water availability from precipitation and from runoff during the dry season is presumably going to decrease, and during the wet season is going to increase. This suggests that newly implemented water management options have to increase supply, reduce demand, and enhance water quality. This was discussed in some detail in Merz et al. (2003c).

The use of models on PARDYP data has only just begun, but will receive further attention in the on-going Phase 3. After a model review, which will build on the first overview of model applications in the region based on available literature, modelling exercises will be conducted in all catchments of the PARDYP network with the aim of predicting future developments and spatial up-scaling. In this context it seems to be important to further investigate the impact of the numerous irrigation diversions. Models like WaSim-ETH (Schulla 1997) provide the possibility of including irrigation in the modelling exercise. Other models that could provide good results are expected to be the SLURP model, where there is the possibility of using remotely-sensed data, and which is fully based on land use (Kite 1995); or the SWAT model (Arnold et al. 1998) implemented in an ArcView environment. The Chinese PARDYP team has first experiences with the VIC model, but have not yet produced any conclusive results.

First initiatives towards a regional comparison of hydrological catchment and rainfall-runoff models have been made in the context of the HKH FRIEND project with the aim of conducting a regional workshop on hydrological modelling, followed by regional training on modelling and a regional comparison of different, promising models (Merz 2003).

The impact of these scenarios will be further discussed in Chapter 5 with the impact on the proposed indices.

Synopsis 4: Impact of Future Scenarios

Hydrological models were used to document the potential impact of three scenarios based on global climate change, population growth coupled with increased water demand to meet basic requirements, and local land-use change with expansion to marginal lands or abandoning of marginal fields. The preliminary results for the Jhikhu Khola catchment have revealed that:

- **during the dry season water is becoming more scarce due to decreased precipitation, increased evapotranspiration, and decreased runoff;**
- **flood events during the wet season are becoming more frequent and are of marginally higher magnitude;and**
- **dependency of lower lying administrative units in a catchment on upper administrative units is increasing due to the increase of water demand in these lower areas, which are generally more accessible and productive. This calls for the introduction of catchment-based management of water resources.**

These results suggest that more attention should be paid to the storage of surplus water in the wet season to be used during the dry season, as seasonality will probably become even more pronounced in future. While domestic water use is presently below basic water requirements according to Gleick (1996), water supply should take into consideration both a change in population as well as in terms of daily water demands. This suggests that water management options of the future are to tap all available resources, minimise losses and inefficiencies, and improve considerably the quality of the water.