Hydrogeology of the Kabul Basin

Part III:

Modelling approach

Conceptual and numerical groundwater models

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Abstract

Within the framework of the project "Improvement of the protection of groundwater to prevent and face drought periods in Kabul in Afghanistan" commissioned in 2003 by the German Foreign Office, the Federal Institute for Geosciences and Natural Resources (BGR) in Hanover, and in collaboration with the Afghan Government, studies and field investigations were carried out to improve the understanding of the hydrogeology in the Kabul area.

Quantitative as well as qualitative aspects of groundwater resources in the area were investigated, and the results of these studies must provide the relevant information and data to support decision-making in future economic development and town planning projects in the area, as well as the exploitation and protection of water resources, and natural risks management.

Qualitative studies were based on the collection of water samples from shallow wells in the urban Kabul area which were analysed in the BGR laboratory in Hanover. This allowed the characterisation and evaluation of the groundwater quality in the investigated area. Quantitative data was only available from investigations carried out in the sixties.

The aim of the following study is to use this data to establish a conceptual model of the hydrological water cycle and hydrological conditions in the Kabul area. At the same time, the creation of a two dimensional numerical model as a largely simplified representation of the groundwater system in Kabul will make it possible to visualise groundwater flow in the study area. Although it is only a first step in the understanding of the hydrodynamics in the Kabul area, this study nevertheless supported important estimates concerning groundwater recharge conditions and quantities, as well as the hydrodynamic properties and the general flow in the groundwater system.

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Introduction

The Kabul area was studied in the 1960s, and again up to 1979 by different scientific teams. From the 1980s until 2001, scientific research and data recording came to a complete halt in Afghanistan because of a long period of violent conflict.

Since 2001, reconstruction has taken place slowly, and some equipment has been made available for data gathering. The difficulties facing the country and the highly populated Kabul area in particular makes it vital to assess the usable water storage because the water needs of the inhabitants in this region must be satisfied. It particularly concerns the drinking water supply for the population, but also the water used to maintain and support economic development. The current studies and observations proved that the surface water and shallow groundwater are contaminated by uncontrolled sewerage backflow and waste disposal sites in the capital. A measured drawdown of 6-7 m of the groundwater table could be a sign of over exploitation of the aquifer. To ensure sustainable exploitation of the groundwater in this area, the dynamics of the groundwater system and all the other existing and available water resources must be identified, studied and characterised.

Two reports written as part of the BGR Afghanistan project are already available at the BGR website[1]. The first report is a summary from the 1960s and 1970s reports available in the BGR archives, it presents the Kabul area and lists the main characteristics in terms of meteorology, geology, hydrology and hydrogeology. The second report focuses on the chemical characteristics of shallow groundwater in the urban Kabul area. Nevertheless, little data is currently available to improve the understanding of the functioning of the groundwater system in Kabul; moreover, many other factors hinder the collection of new data. There is not enough equipment on site, many zones are still mined and displacements are limited because even if they are not prohibited they are nevertheless risky. Thus, it will take time to obtain long term series of measurements. Considering this current situation, a first step in a modelling approach made it possible to generate additional information from the available data. The aim of this approach was not to obtain exact values of the hydrodynamic properties and water fluxes in the area, but only to give probable orders of magnitude for these values.

The development of a conceptual model is a necessary preliminary stage for the construction of a numerical model. It makes it possible to identify the main components and processes taking part in the water cycle and influencing the water balance. The currently available data was used to establish a quantified water balance which allowed the first estimation of the fluxes in the study area.

Then the design of a numerical model made it possible, from various steady and transient state simulations, to test these initial estimates and to observe the groundwater flows in Kabul.

[1] http://www.bgr.bund.de/groundwater

1 Context and aims of the study

1.1 Current situation in Kabul

1.1.1 A critical situation

Figure 1: Location map of Afghanistan and its main cities, source[2]

The country, affected by a long period of war between 1979 and 2001, currently faces a difficult post-conflict period with the need to solve lots of problems and achieve many goals despite material and financial shortages. A major recent drought period (1998-2003) leading to water scarcity has worsened the situation. The groundwater abstractions in Kabul city considerably increased in recent years as a result of the progressive return and migration of refugees. A drawdown of the piezometric level of approximately 6-8 metres was observed in Kabul by comparison with measurements made in the 1960s (ref 9); the rivers were often dry. Many hand-dug

[2] http://www.infoplease.com reworked by U. GERSDORF

wells and kareze systems (Figure 11) are damaged and were affected by the water table drawdown. Lots of wells had to be deepened. For example, 85% of the wells monitored by the NGO DACAAR (Danish Committee for Aid to Afghan-Refugees) were dry in Kabul in 2002 (ref 14). The supply of drinking water for the population is more and more difficult to maintain. The requirements are estimated to be approximately between 20 and 40 L/d/cap. Currently, less than 20% of the population has access to a suitable water supply system. The rest is supplied by thousands of manual or motorised pumps fixed to both shallow and deep wells (ref 1).

The main current problems are:

- A lack of suitable equipment and town planning. The main hydraulic equipment such as irrigation and drinking water distribution networks, sewerage systems, wells and karezes are either non-existent or damaged. Major volumes of water due to the combined effect of rain and melting snow sometimes cause flooding during the spring period;
- Significant needs. When the war ended, a large number of refugees returned to Afghanistan; they tend to leave the countryside and crowd into big cities like Kabul. The capital had 320 000 inhabitants in 1962 (ref 2), the current estimates are about 3 million people and maybe more, in 2010 the population could reach 3.5 million (Chapter 2.1.2.2.2). Moreover, economic development (agriculture and industry) in the area will increase the water demand.

The two previous sections explain the precarious living conditions in Kabul. The lack of efficient waste disposal and sewage collection systems leads to the contamination of shallow groundwater (Figures 2 and 3).

Figure 2: Uncontrolled disposal site in Kabul (G.HOUBEN)

Figure 3: Kabul River in August 2005 (T.KREKELER)

Chemical analysis revealed high levels of coliforms in approximately 50% of the wells in the urban area (ref 12). Because shallow groundwater and surface water are the main water supply used for consumption, the population is frequently affected by contaminated water related diseases, and the children are the most vulnerable with a death rate that reached 142‰ in 2002[3]. The damaged irrigation networks and the recent droughts led to poor agricultural conditions which may not satisfy the needs of the increasing population.

In the long run, the current situation in Kabul presents risks of severe contamination of rivers, shallow groundwater and soils in the urban zones, as well as a risk of overexploitation of the water resources. The structure of the groundwater system is not clearly known, but if it consists of several distinct aquifer layers, abstraction of deep water could lead to the pollution of this resource by the leakage of shallow contaminated water. The drawdown also risks the drying out of other wells and/or springs in the area.

1.1.2 The need for better water resource management

The situation in Kabul is critical and the management of water resources is one of the major keys to the improvement and development of the living conditions of its inhabitants. The priorities in the short term should be the supply of adequate quantities of potable drinking water for the inhabitants and the prevention of shallow water and soil contamination. In other words, the aim should be the restoration and implementation of efficient waterworks necessary for the proper exploitation, distribution and collection of water. In the long run, the aim is to set up a sustainable water management policy according to the available resources and the human needs. A risk management policy is also needed to prevent and tackle crisis and conflict situations associated with drought and floods.

This implies a good knowledge of the local hydrology and hydrogeology. The problem of the lack of data, and particularly the lack of time series covering long observation periods makes the scientific studies difficult. Generally, the scientists have of little data to accurately characterise the geology, climatology and hydrogeology in the Kabul area. In the following study, data from the 1960s to the 1980s from the BGR archives was used (Chapter1.1.4).

Different organisations like UNESCO (United Nations Educational, Scientific and Cultural Organisation), USGS (United States Geological Survey), DACAAR, BGR and others have carried

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3 http://www.populationdata.net/

out investigations in the field since 2002 to collect new data and improve the knowledge base. Databases have been created to gather and distribute the results of these campaigns. However, there seem to be problems with coordination and dialogue between the different local and international organisations. With regard to the local Afghan scientists, there are also shortages of technical support and theoretical training. There are also many technical problems arising from the lack of equipment and energy supplies.

Improvement of the knowledge base and the assessment of the water management in the area must be done by:

- The implementation of climatic, hydrometric and piezometric monitoring networks;
- The estimation of water demand;
- Increasing public awareness of the sustainable use of water to avoid water wastage and to avoid pollution;
- In agriculture, it is particularly necessary to assess the needs of the different types of irrigated crops and to set up appropriate irrigation methods;
- The creation of management tools (GIS (Geographical Information System), databases) and documents (thematic maps, town planning documents) to support decision making. These documents must be harmonised;
- Teaching new methods of field investigation and laboratory analysis in the universities, as well as the theory and awareness of sustainable exploitation and quality control of water resources;
- The revision and update of the old Water Law from 1981.

1.1.3 Actions carried out by BGR

Carrying out studies makes it possible to better understand the phenomena which must be taken into account to improve the water resource management.

Analysis of the physicochemical and microbiological parameters of water samples taken in wells located in urban zones, make it possible to characterise the different types of groundwater in the investigated area and also to evaluate its quality as drinking water (Figure 4). In July 2005, all of the results were presented in two final reports. The first one presents the characteristics of the area in terms of geology, climate, hydrology and hydrodynamic properties of the groundwater system[4]. The second one deals with the study of the physicochemical and microbiological characteristics of groundwater in the urban Kabul area[5].

[4] and [5] http://www.bgr.bund.de/EN/Themen/Wasser/Projekte/TZ/TZ__Afghanistan/hydrogeology__kabul__basin__fb.htm

Figure 4: Continuous analysis of physicochemical parameters in a tube well in Kabul (T.TÜNNERMEIER)

One of the main aims of the project was to transfer scientific and technical knowledge to Kabul. Indeed, a policy for the sustainable management of water resources must be supported by the Afghan authorities. This is why the co-operation with local scientists and actors has had a significant priority within the project. Training courses were proposed for Afghan scientists in particular to present the new methods and techniques of:

- Groundwater prospecting and chemical analyses;
- Well construction;
- Sustainable use and resource management.

The appropriate equipment to take measures and to carry out analyses were transferred to the scientists in Kabul (Figure 5).

Figure 5: Installation of a groundwater level recorder in a tube well for the continuous observation of piezometric level variations (T.Krekeler)

The organisation of a conference entitled "Co-operation between Germany and Afghanistan in the Water Sector" organised in Kabul on 2 and 3 August by BGR, GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit), DED (Deutscher Entwicklungs Dienst) and KfW (Kreditanstalt für Wiederaufbau), allowed conclusions to be drawn on the current work thanks to this co-operation. The participants (one hundred) represented the two governments, scientists and other consultants, University of Kabul and Polytechnic University of Kabul, BGR, CAWSS (Central Authority for Water Supply and Sewerage) water supply managers in Afghanistan and different other organisations and NGOs working in the framework of international co-operation (CARE, DACAAR, USAID (United States Agency for International Development), GTZ, DED, USGS, BGS (British Geological Survey)). The main topics discussed were the management of water at a basin scale, the presentation of available knowledge on groundwater in Kabul, and the proposed solutions and means to ensure its protection (quantitative and qualitative aspects), the estimation of the water demand and its evolution, the problem raised by droughts, and the need for a risk management policy (Appendix 1).

1.1.4 Available data

1.1.4.1 Bibliography

The Kabul area was studied during the 1960s and 1970s by Russian, German, Canadian, French and probably other scientists. Much data was lost during the long period of conflict between 1979 and 2001, and no data was recorded during this period. However, some reports available in the BGR archives made it possible to make a brief summary of the climatic, geological and hydrogeological conditions in the area (ref 9). A German hydrogeologist, E.G Böckh, has restored part of the studies undertaken in the 1960s by the Russian and German missions.

Russian experts carried out investigations in 1962 and 1963; many wells were drilled, pumping tests, geophysical surveys, chemical and bacteriological analyses of water samples were carried out, and gauging stations were set up on rivers and irrigation channels to study water exchange between the groundwater and the surface water. The study zones were the southern Kabul plain between the villages of Bagrami and Nawesta (Appendix 2a) and the Darulaman basin, the zone between the villages of Gulbackh and Jangalak/Kala-e-Wazir along the Kabul river, and the zone located along the Paghman river between the Cheltan-Paghman confluence and upstream of the confluence with the Kabul river (Appendix 2b). The step-discharge tests were carried out and interpreted using Dupuit's method. The results of these field surveys were gathered in a study report by Böckh in 1971 (ref 3). The data used for the present study records the characteristics of the aquifer in the study area. The hydrodynamic properties are from the interpretation of pumping tests carried out in wells drilled along transverse profiles. The structure and the lithology of the reservoir are presented in transverse lithological profiles that were obtained by interpolation of the layers between the observation wells, and may thus not be representative of the whole aquifer (Appendix 3).

Between 1964 and 1968, investigations were carried out by the German geological mission and the "German group for water management". The studies consisted of hydrogeological inventories, cartography, drilling, piezometric studies of the groundwater level as well as chemical analyses of water samples. Between 1965 and 1967, a team of geophysicists took part in the investigations by carrying out many surveys covering large parts of the Darulaman and Kabul Basins. The results are presented in a distribution of the possible thicknesses of aquifer formations in the study area (Appendix 4).

River discharge time series are available for the gauging stations at Pule Sohkta, Tangi Saydan, Sange Nawesta and Tangi Gharu (Appendix 5); they result from observations made between 1959 and 1964 and found in the "Afghan annual hydrological book".

Infiltration studies were carried out over one year (1962-63) by comparing the upstream and downstream discharges along some portions of the rivers (Paghman and Kabul in the Darulaman basin, and Logar River in the Kabul Basin). Nevertheless, the reliability of this study is difficult to evaluate because the possible intakes and inflows between the observation points at the river gauging stations were not taken into account and thus the results were not used in this study.

The climatic data that was used also figured in the report by Böckh. It consists of local parameters such as the air temperature and air humidity, rainfall, snow-cover and the wind speed and the main wind directions.

French scientists also made investigations at the end of the 1960s in the Kabul area, and data recently found in a report by J.Pias (ref. 4) is used in this study for comparative purposes. The available data is thus: the monthly average values measured at the weather station at Kabul airport (1803 m) for the period 1957-1977 for temperature, air humidity, and rainfall (in mm), and the snow cover for the period 1958-1971 (in cm). Other values measured between 1959 and 1970 in Kabul (1791 m, Latitude 34°33N Longitude 69°1É) appear in the report by J.Pias (ref. 4). Information from reports by French scientists made it possible to improve the interpretation of the study area and its characteristics, particularly the geological history (ref. 4, 5, 6, 7 and 8).

1.1.4.2 Cartographical and numerical data

Four paper maps, 1/50000 and 1/25000 (made by the DGIA, Ministry of Defence of the United Kingdom-2002) and two 1/25000 (made by the National Imagery and Mapping Agency, US-1997) are available at BGR. They present topography, main roads, rivers and channels, names of specific zones or districts in the city, as well as important buildings and monuments. Other specific maps found in reports or in the Internet site[6] of AIMS (Afghanistan Information Management System) also made it possible to establish localities (villages, districts, mountains, rivers...).

A Digital Elevation Model (DEM), made it possible to precisely visualise the topographical characteristics of the zone and to create the ground surface in the numerical model. With a 90 m by 90 m resolution raster, it was created by USGS and bought via the Internet[7].

Recent recordings of the fluctuations in piezometric levels were obtained from monitored wells belonging to the NGO DACAAR, as well as static groundwater levels measured by USGS in about 200 wells of which 34 concerned the study area.

DACAAR also provided BGR with exact measurements of co-ordinates and elevations for some of the BGR installations (groundwater level recorders).

The download of the GoogleEarth program available in the Internet since August 2005[8] is a source of satellite images of the area. Various layers of information can be visualised and geographical co-ordinates and elevations are provided for any point. Elevation data was checked, and confirmed an accuracy from 1 to 10 m compared to the measurement made by DACAAR. The map of the zone makes it possible to appreciate the topography and identify the irrigated zones (the cultivated parcels along the rivers in particular in the high valleys are particularly easy to identify).

A significant number of photographs, as well as discussions with people that worked in the field, allowed a better interpretation of the study zone and thus eased the evaluation of the processes that may occur in the area.

1.2 Aims of the following study

Despite the fact that more information is available on the area from the work of several organisations, the data still remains sparse overall, difficult to obtain and of doubtful quality (exact localisation of wells, discharge estimates, quality of chemical analysis).

Within this framework, a modelling approach can be useful. The aim is to gather and compare the existing data in order to generate new information. Even if they are only preliminary assumptions based on little data, the estimates made in this study still make it possible to carry out an initial interpretation of the hydrology and hydrogeology in Kabul. Such an approach is

[6] http://www.aims.org
[7] http://www.mapmart.com
[8] http://earth.google.com/

also a way of assessing the available data and identifying gaps, and thus indicating where more field work is required. In the long run, the result of a modelling approach is an estimate of the volume of renewable groundwater.

1.2.1 The advantages of a modelling approach

The study area is located in Kabul (Figure 1 and Chapter 2.1.2.1). Little data is currently available to improve the understanding of the groundwater system in this zone; moreover many factors hinder the collection of new data. The initial step in a modelling approach should generate additional information from the currently available data without major fieldwork. The aim of such an approach is not to obtain exact values of the hydrodynamic properties and fluxes in the area, but only to give probable orders of magnitude for these values.

The development of a conceptual model is a necessary preliminary stage in designing a numerical model. It makes it possible to identify the main components and processes taking part in the water cycle and having an influence on the water balance. The translation of the information provided by the conceptual model into the numerical model involves making assumptions about the spatial and time distribution of the processes and associated fluxes. Within this framework, a typical theoretical hydrological year is created and will be useful for carrying out transient state simulations (Appendix 6).

The advantage in working with a numerical model is that it makes it possible to do a significant number of different simulations with various sets of input parameters within a relatively short time. Moreover, as long as new information is available (new fieldwork or any other information that controls the more or less accurate estimates made with the model), the model can be modified and improved to carry out new simulations and to very quickly obtain better results.

1.2.2 Modelling theory and SPRING software

1.2.2.1 Basics of modelling

A model can be simply defined as the simplified representation of a real system or process. A conceptual model is a set of assumptions concerning the functioning of a system or a process and can be quantitatively expressed in the form of a mathematical model. The processes are then represented by equations; the physical properties by constants or coefficients appearing in these equations, and measures representing variables describing the state of the system.

There are different types of models, but two major orders can be distinguished. The **deterministic** models take into account the properties conditioning the functioning of the system. They refer to relations expressed in Darcy's Law and the principle of the conservation of mass, and make it possible to simulate the behaviour of the studied system. The **black-box** models try to establish a function between an input and an output variable but do not take into account the properties of the system. (ref 15).

In a deterministic numerical model, space and time are discretised and the continuous variables are replaced by discrete variables which are defined at specific meshes, nodes and time steps. The variable values of the internal properties and boundary conditions are then approached by numerical methods such as finite difference or finite element methods. The value of a variable in a zone of the model then depends on the values of the surrounding ones. For the calculation, the model proceeds by either iterative or direct matrix methods to approach the solutions to the equations (ref 15).

The aim of a model is to approach the real functioning of a system as well as possible, in order to provide valuable representations of it and to make valuable forecasts on its possible evolution. A model must therefore be calibrated and tested. The calibration is done by comparing the observed values to the ones computed by the model. This requires data time series over long periods sufficient to be representative of the system.

The first stage in the design and application of a numerical model is to define the nature of the problem and the aims of the model. The determination of a suitable type of model and of its degree of complexity depends on the judgement and experience of the analyst, the aims of the study, and the number and quality of the initial information available on the studied system. The balance between the accuracy of the results and the costs must be evaluated and weighted. Because of the small amount of data available, the numerical model in the present study is a two dimensional horizontal model.

1.2.2.2 Presentation of SPRING

SPRING software[9] allows the development of deterministic models and the simulation of groundwater flow and transport processes using the finite element numerical method. The software has two programs, XSUSI and XPLT, containing several different modules with distinctive functions (Appendix 22 and 23). The main files in SPRING are ASCII-files which contain the complete model information. They are created and changed with the help of the XSUSI software. Manual editing using any text editor is also possible. The DADIA module reads the ASCII-files and saves the data as binary files. The other modules read the necessary data from these binary files and also save their results as binary files. Using the XPLT software, the input and output data plots can be shown on the screen, edited and output to a plotter or a printer. It is also possible to export the data in various formats (txt, dxf, arc, shp). The values of the input parameters are integrated within the model in XSUSI or directly in the corresponding text file. The parameters are represented by various functions (Appendix 7). The modules used to carry out the simulations of this study were DADIA, SITRA and PLOGEO.

[9] http://www.delta-h.de/index.htm

Kabul

2 Conceptual model

2.1.1 Introduction

2.1.1.1 Modelling and aims

The study area is located in the urban Kabul area and covers a sedimentary basin (Figure 8). It is also important to know that it is situated downstream of the Kabul river basin and is the outlet of a large catchment area (Figure 13).

The aim of this study is to understand the hydrology by studying the water cycle and establishing an initial water balance, and to understand the hydrogeological behaviour of the groundwater system by numerical modelling with SPRING software. The model only simulates the groundwater flow in the saturated zone. The surface phenomena (run-off), and these occurring in the non-saturated zone (NSZ) (infiltration) are not taken into account. Interactions between the groundwater system and its environment will be taken into account by the boundary conditions (Chapter 3.1.2.2).

The realisation of a conceptual model is a preliminary step towards any realisation of more complex mathematical or numerical models. The hydrological balance enables the identification of the main processes required to understand the functioning of the system. Any components which could not be quantified were initially estimated. Moreover, monthly or annual mean values were calculated and integrated into the numerical model for simulations (Appendix 6).

2.1.1.2 Water cycle and water balance

The functioning of a groundwater system depends on its configuration and internal properties as well as its interaction with the surroundings. The study of the water cycle in the area is necessary to consider the groundwater system in its environment and thus to improve the understanding of possible mutual interactions. The most interesting time scale is the monthly study of the behaviour of the system over a one year period because it allows identification of high and low water, and thus the possible recharge period.

Even if it is possible to estimate the inflows and outflows in the delimited study area, quantifying the recharging process remains difficult because there are too many unknown components like the losses occurring in the zone by evaporation or abstraction, and also too little information is available on the recharge conditions (infiltration processes).

The establishment of a water balance is difficult overall because the available data result from more or less spot recordings in time and space. For example, the measured discharges of most rivers are monthly mean values and only available for 1959 to 1964; for the Paghman river, the record only covers 1964.

Another difficult aspect of this study lies in the change in the state of the system over the last 40 years. The main investigations were carried out from the 1960s to 1978, the groundwater table was observed 2 to 5 m underground; in these days, there was less human impact on the groundwater system than today. The groundwater table is currently deeper and the impact of human activity has increased. The area was also affected by a recent drought period (1998-2003).

The human activities include:

- The increase in water abstraction which seems to contribute to the drawdown of the water table;
- The expansion and densification of urban areas as well as the construction of infrastructures like roads, dams, channels (Figures 7 and 8).

Figure 6: Densification of urban areas in Kabul (T.KREKELER)

Figure 7: Kargha reservoir in the upper Paghman valley (T.KREKELER)

All of these factors could have modified the surface and groundwater flows as well as the infiltration properties of soils on the valley flanks and in the plain. The recharge conditions could therefore also have been affected. The recent drought period implied limited recharge conditions (missing or reduced components and/or reduced area or period for recharge occurrence); it led to the disappearance of the vegetation cover in some areas where erosion processes are now favoured. The evapotranspiration due to the vegetation cover could then be less significant, but on the other hand, the evaporation processes in soils could be increased. Erosion processes and the disappearance of vegetation could also have changed the infiltrability of the soils. Floods sometimes occurring in spring could also cause and/or worsen soil erosion.

If the environment and the external pressures could have led to the modification of the state of the system, this possible new state can imply modifications of the functioning of the system and of the processes occurring within its environment. For example, with regard to possible evaporation processes which could affect the aquifer, the assumption could be made that, if evaporation occurs, this could have been important when the groundwater table was very close to the ground surface (2-3m deep). This assumption would be supported in the past by the fact that salt marshes were observed in the Kabul plain in the 1960s. Because the current water table is deeper, it can be assumed that the aquifer would now be less affected by such processes if at all. Because phenomena related to evaporation of groundwater are currently not very well known, these are only assumptions, and more fieldwork must be carried out into evaporation processes in the Kabul Basin.

All this implies that great care is required when conducting and interpreting the simulations. The use and/or the comparison between data, information, and interpretations covering the two different periods (current period and earlier period in the 1960s) must always be done carefully. It is important to remember that the state of the groundwater system, as well as disturbances and recharge conditions, were not the same for these two periods.

The hydrological water balance shown here is a largely simplified representation of reality and it can be assumed that other complex processes could intervene and modify it. However, without more precise knowledge of the study area and because these complex processes are sometimes difficult to appreciate and measure in the field, they could not be taken into account in this study. Missing knowledge relates to all processes of infiltration and circulation of water from the surface to the saturated zone:

- Infiltration of a part of the effective rain ;
- Infiltration from the river beds ;
- Evaporation and capillary rise in the non-saturated soil zones;
- Snow melting and the resulting meltwater (it would also be interesting to evaluate the possibility of sublimation of the snow cover. It depends mainly on the temperature of the snow cover and the air moisture)

In the first step, each known component is identified and the associated flux estimated or calculated where possible. In a second part, the water balance equation is set and several assumptions made to try to better understand the hydrological and hydrogeological functioning in the area. First estimates concerning the groundwater recharge are then possible.

2.1.2 Identification of the main components and processes

2.1.2.1 Delimitation of the study area

The boundaries of the numerical model should reflect natural geological or hydrogeological boundaries. The study area is thus determined by the available geographical and geological characteristics of the area (Chapter 3.1.1.1).

The zone corresponds to the geological basin that can be identified as the southern part of the Kabul Basin in the figure below:

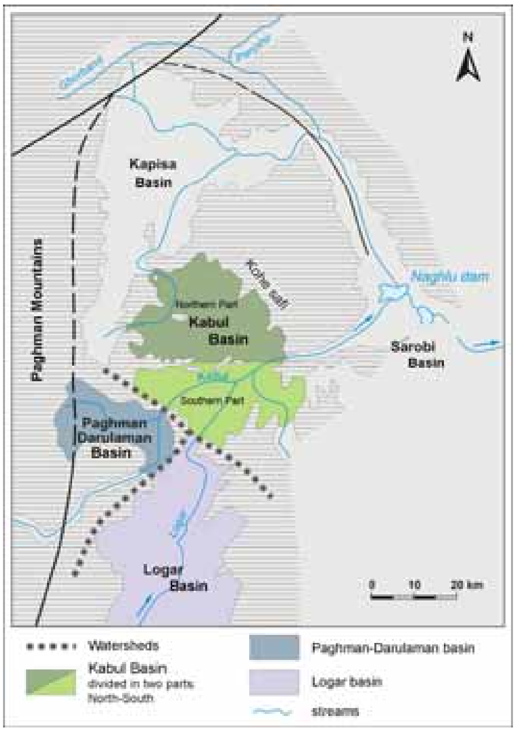

Figure 8: Geological basins identified in the Kabul area

According to this geological information and observed topography (Figure 9), the western and southern limits of the study area are the borders with the Darulaman and Logar basins. The calculated groundwater flows entering the study area along these two borders were very small and were therefore ignored as being non-representative of the main processes playing a role in the recharge of the groundwater system in the Kabul Basin. Thus, they were not taken into account in this study. This was also highlighted in simulations carried out with an old numerical model that took into account a part of the Darulaman Basin (Appendix 8). In the northern part, the study area is also closed along the border with the northern part of the Kabul Basin. The outlet of the basin is identified as the Tangi Gharu gorges. Although the gorges can be easily identified in the elevation model, the river gauging station Tangi Gharu (1770 m) measuring the outflow of the basin could not be located with accuracy. It was thus considered that the study area would be closed at the beginning of the gorges (Figure 19). The discharge observed in Tangi Gharu must then be interpreted assuming that if the gauging station is actually situated further downstream, there can be important amounts of water coming from the abrupt slopes of the gorges.

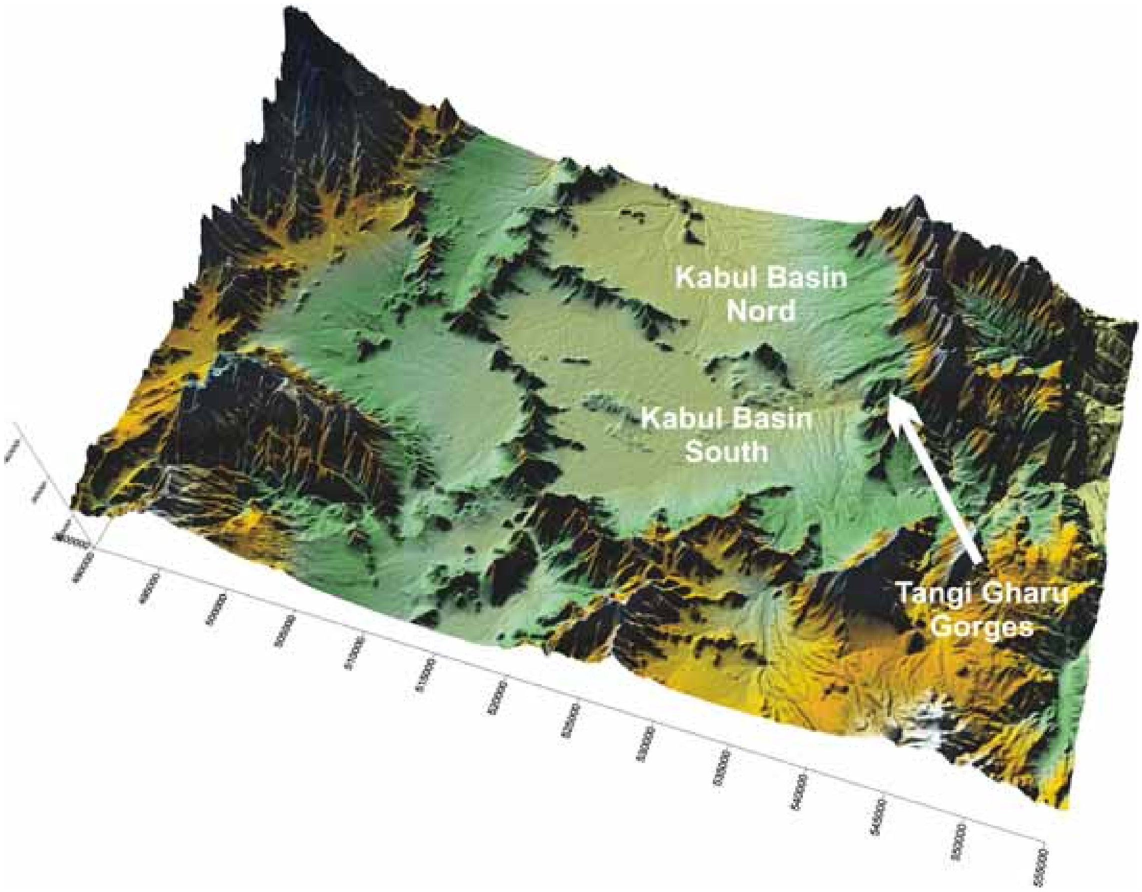

Figure 9: Elevation model, source USGS-OFR 2005-1107, data 2000, 90-metre resolution, WGS 84, UTM projection, Zone 42N

The watersheds in the area can be determined from the elevation model. The mountains bordering the basin range in height of around 2250 m in the northern part, 2600 m in the south-western part, and reach 3000 m in the south-eastern part. This information is important for improving the assessment of the size of the volumes of snow meltwater entering the study area.

The main processes and components that have to be taken into account in this study are the contribution of the surface water in the area as inflows (rain, snow and rivers), and human activities, evaporation processes, and discharge from the basin as outflow (Figure 10). The importance and occurrence of each component will be determined to carry out transient state simulation with the numerical model.

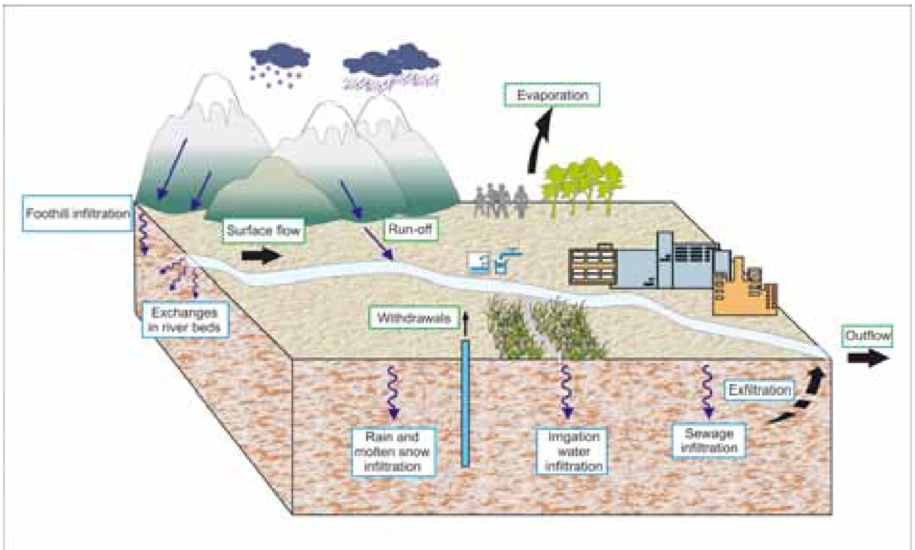

Figure 10: Water cycle in the study area

2.1.2.2 Available information and analysis

It should be remembered that the region has a semi-arid and continental climate with cold winters and hot summers. The Hindu Kush Mountains protect Kabul from the cold arctic air masses coming from the north. However, long periods of clear skies and the high altitude of the zone (about 1800 to 2500 m) allow temperatures to drop below freezing during winter and the accumulation of important amounts of snow on the mountains surrounding of the basin. In the late spring, a sub-tropical high pressure area moves northward and covers the country during the summer months. Under these stable conditions, the weather is clear, hot and dry. The geographical location of this land-locked country, far from the air mass moisture of oceans and seas, is a factor explaining the low rainfall that can be very variable from year to year. Studies showed that spring rainfall often occurs first in the Kandahar sector, then Gazni and finally the Kabul sector (ref 2 and 16). The main rivers flowing through the Kabul plain, the Kabul and Logar rivers, are considered as permanent streams but are mostly dry during the summer; they drain a catchment area of about 12 890 km². The valley is occupied by Kabul city. The population increased from 320 000 to about 3 million between 1962 and 2005.

2.1.2.2.1 Inflows

This includes precipitation in the form of rain and snow and their accumulation and drainage in the study area; but also the water coming from the upper parts of the catchment area via the surface drainage network. A part of this available volume of water can infiltrate, and constitutes potential recharge for groundwater. The recharging infiltration includes effective rainfall, snow meltwater and rivers; and also the infiltration from irrigation channels, irrigated land and effluent (sewage, industrial emissions). Given the available data, only the following components can be quantified.

<u>Rain</u>

The annual average value is 330 mm according to the available data (329 mm in the report by J.Pias), which reflects a dry climate (Appendix 9). The annual study of rainfall shows significant variations in different years (only 155 mm in 1970, and 520 mm in 1959) and highlights the alternation between “normal” periods and very dry periods such as 1958, 1966, 1969 to 1971 and 1973 to 1977 (below 330 mm/a). The average monthly values show that about 20 to 80 mm occur during the spring and winter months and that rainfall is less than 3 mm in the summer period (June to October) (Appendix 10). A Whisker diagram shows that the annual variations are explained by variations in rainfall during winter and spring because the summer is generally very dry in the Kabul plain (Appendix 11). The rainiest months are March and April. Rainfall sometimes occurs at the end of the summer when the Indian monsoon system extends into the zone.

According to the calculation of the actual evapotranspiration using the Turk formula, the effective rainfall is 27 mm/m²/a, which represents a total available volume of $10*10^6$ m^3/a for the whole surface of the study area (370 km², Chapter 3.1.1.1).

The values obtained using the Turk formula are mean annual values; however, the calculation of actual evapotranspiration using the Ivanov formula, which takes into account monthly mean values, shows that the recharge period from rain can only occur between December and April. For the water balance, the annual amount of water obtained using the Turk formula will be used but spread over the months December to April (Appendix 12).

According to the soil infiltrability, the amount of effective rain can either directly infiltrate or be subjected to run-off and evaporation; re-evaporation by capillary rise before reaching the saturated zone is also possible. We have little information concerning these phenomena and it is thus difficult to estimate the amount of water likely to reach the water table.

Nevertheless, estimates can be made from the USGS geological map (Appendix 13) and using the Hénin-Aubert drainage index which allows calculation of the amount of water D in mm that could infiltrate in a specific type of soil according to mean annual values of rainfall P and temperature T.

$$D=\gamma' P^3/(1+\gamma' P^2) \qquad \text{where } \gamma'=\alpha\gamma \qquad \text{and } \gamma=1/(0.15T-0.13)$$

where α=1 for silts, 2 for sand and 0.5 for clay. This index was calculated for the Kabul area in a report by J.PIAS (ref 4):

Table 1: Hénin-Aubert drainage index for the Kabul area according to soil type

Kabul	Silty soil	Sandy soil	Clay soil
D in mm	20.5	39.1	10.8

It shows that the soil infiltrability in Kabul is 39.1 mm for sandy soils and 20.5 mm for silts. These two values are used according to the extent of the different types of soils identified on the geological map and represented in the numerical model (Chapter 3.1.2.2). Considering an ideal infiltration of 100% of effective rainfall (27 mm/m²/a, except where the loess cover is present (214 km²) where 20.5 mm/m²/a is applied) and the surface of the different zones available shown in the numerical model, the total maximum amount of water that could infiltrate and recharge the groundwater **is $8.6*10^6$ m^3/a**.

<u>Run-off water from the surrounding mountains</u>

Run-off water such as rain and snow meltwater from the surrounding mountains is assumed to infiltrate along the valley flanks or join the plain and the main rivers via small local drainage networks or kareze and channel systems. The USGS geological map shows sand and gravel formations along the borders of the basin that have accumulated as a result of erosion of the mountains (Appendix 13 and ref 20). A cross section available in the USGS report also clearly indicates the existence of coarse materials on the boundaries of the basin (Appendix 14). Moreover, the functioning of the kareze system used in the Kabul Basin highlights this phenomenon (Figure 11)

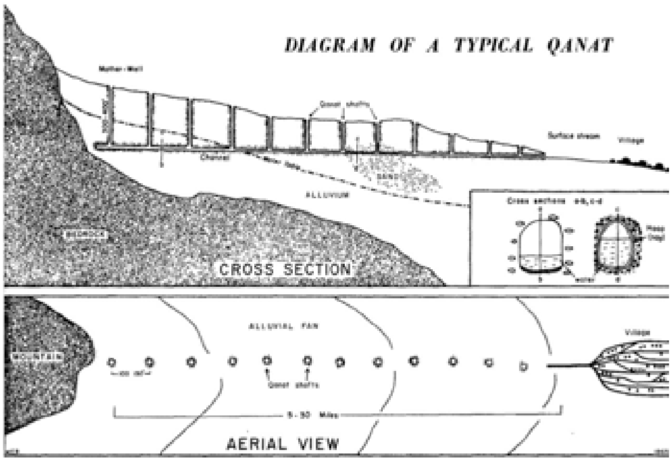

Figure 11: Schematic cross-section and aerial view showing the functioning of a kareze

These zones are taken into account in the model as preferential zones for the foothill infiltration of run-off waters coming from the mountains, and especially snow meltwater (Figure 12). These contributions can be significant because of the important slopes and high altitudes of the surrounding mountains (2200 to 3000 m). The measurements at the airport in the Kabul plain show that the main months with important snowfall are January and February with a mean cover of 15 cm (Appendix 15). In the report by J.Pias (ref 4), measurements made in higher zones revealed that the snow cover can reach 60 cm in January and February at 2183 m and that it can be up to 4 m high between February and April at 3172 m. Apart from the direct inflow from the surrounding mountains, the snowmelt in upper parts of the catchment basin can also feed the Kabul and Logar rivers. The higher zones of the catchment area reach 4000 m where permanent snow cover is observed (ref 4).

However, there is no additional information with which to precisely quantify the possible amount of water associated with snowmelt. The aim of the simulations with the numerical model is to estimate the recharge of groundwater related to this phenomenon.

Figure 12: Snow cover on the surrounding mountains in the Kabul area (G.HOUBEN)

Rivers

Two important rivers enter the study area and have to be taken into account in the water balance. The Kabul River flows west to east and is joined by various tributary streams before reaching the Indus in Pakistan. One of its main tributaries, the Logar river, drains the catchment area of the Logar valley situated to the south (about 10 000 km²). The confluence of the two rivers occurs to the east of the city in the centre of the basin (Figure 13).

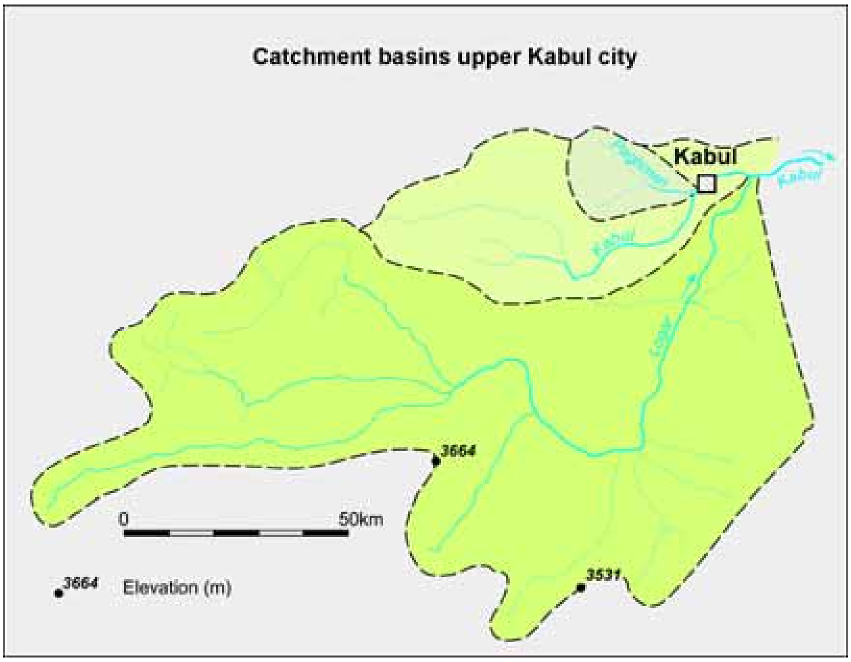

Figure 13: Catchment area of the Kabul river in the upper Kabul Basin

Four river gauging stations are situated at the approximate limits of the study area (Appendix 5). Mean monthly discharges values are only available for two to five years and may therefore not by representative of the hydrology (the mean discharge is normally calculated over a 10 year period). Nevertheless, they were used to make coarse estimates of the fluxes entering and leaving the study area.

The river discharges (Figure 14) start increasing in October, especially in the Logar river. The first rain and snow only appears in November and December in the Kabul Plain. The rise in the river discharges for this period could be explained by the fact that the rivers may be fed by other more important rain events in upper zones of the catchment basin. The highest water flows occur between March and May, which are also the months with the most important rainfall. It is also a possible period for the beginning of snow melt as the monthly mean temperature rises rapidly from February (Appendix 16). The discharges start to decrease in April or May and remain significant until June or July in the upper Kabul River.

The difference observed between the Logar and the Kabul discharges could be explained by the characteristics of the catchment basins upstream of these valleys (Appendix 17).

The important inflows of water observed for the Logar in October could be explained by the fact that its catchment basin is long and covers a large area; thus, rain occurring in the upper part of this basin may already feed the Logar in October. In spring, the rapid fall of the Logar discharge could be explained by the fact that this period corresponds to the start of irrigation. The contributions of the upper basin would then be intercepted along the Logar valley where large areas of land are under irrigation before the water reaches the Kabul area.

Unlike the Logar catchment area, the upper catchment basin of the Kabul river is a small basin with high elevated mountains (parts of the Paghman range) where the river mainly flows through narrow gorges before reaching the main part of the valley in the Darulaman Basin. This could explain the fact that if rain occurs in October it may be directly stored as snow cover that melts in spring and rapidly but continuously feeds the Kabul river whose discharge diminishes slowly until July.

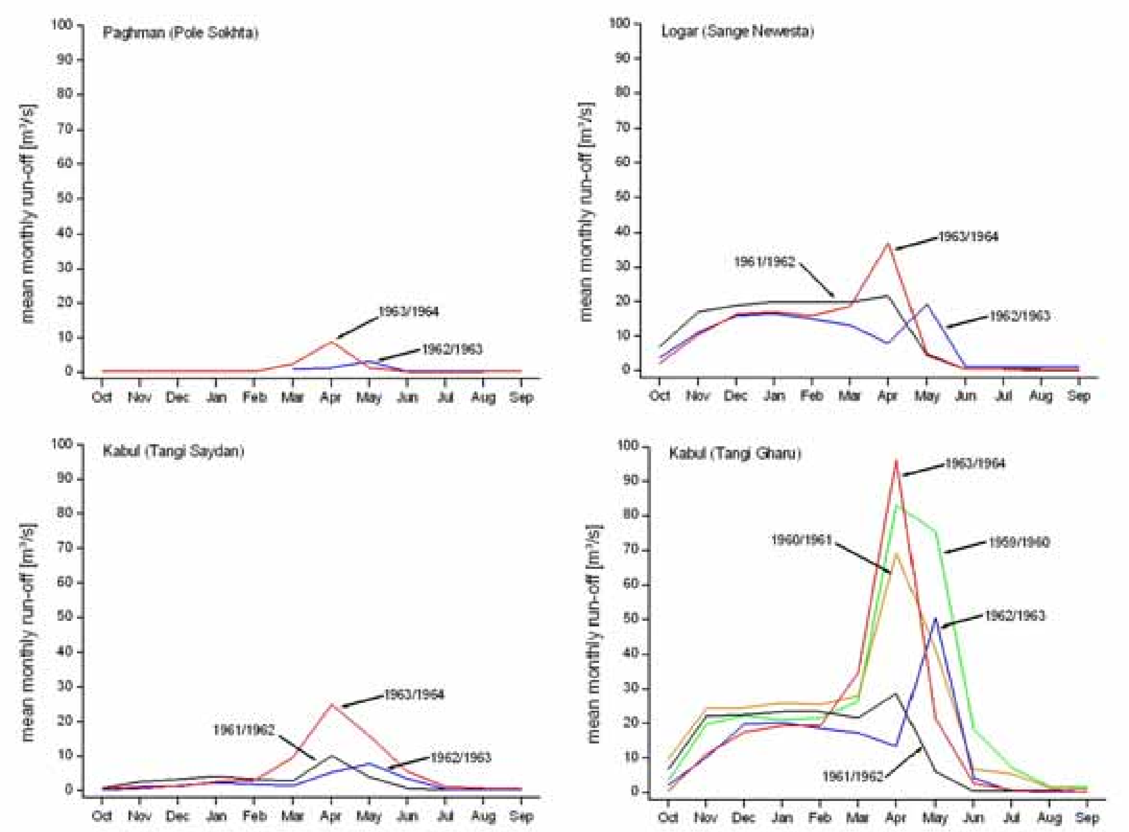

Figure 14: Monthly mean values of the river discharges from observations carried out in four river gauging stations (3 upstream and 1 downstream of the study area)

The discharge of the Kabul river is monitored at the Tangi Saydan river gauging station situated before the confluence with the Paghman river (Appendix 5). The drainage area above the station is estimated to be about 1650 km². The annual mean discharge for the period October 1961 to September 1964 varied between 2.2 to 5.6 m^3/s. Minimum monthly mean discharges under 1 m^3/s were observed during six months of the year in 1962, 4 months in 1963 and only two months in 1964. The minimum daily discharge observed was 0.20 m^3/s during 11 days in July 1962 (ref 3).

The discharge of the Logar is monitored at the Sange Nawesta river gauging station (Appendix 5). The drainage area above the station is estimated to be about 10 000 km². The annual mean discharge for the period October 1961 to September 1964 varied between 8.9 and 10.8 m^3/s. Minimum monthly mean discharges under 1 m^3/s were observed during four months per year in 1962 and 1964. The minimum daily discharge observed was 0.05 m^3/s during 79 days between June and September in 1964 (ref 3). The hydrograms clearly show that the Logar river makes an important contribution to the total flow in the Tangi Gharu outlet and that it is the main contributing river from October to February.

Table 2: Mean discharges in the upstream parts of the rivers and associated fluxes

Rivers and their gauging stations	Monthly mean discharge in m^3/s (1962-64)	Annual amount of incoming water in million m^3
Paghman (Pule Sohkta)	0.88	27.9
Kabul (Tangi Saydan)	3.54	111.7
Logar (Sange Nawesta)	10.07	317.6
Total	14.50	457.2

Other tributaries of the Kabul river cited in a report by J.Pias could have an influence on the water balance. They are identified as the Butkhak Khwar or Rodjan on the right bank of the Kabul river after the confluence with the Logar river, and as two small rivers Dwa Khwara and Loy Khwar descending from Khojo Ghare Wali (2990-3020 m) and reaching the left bank of the Kabul river just before the gorges of Tangi Gharu (ref 4). They can also be distinguished on the DEM (Figure 9). The assumption is made that although they can not be considered as perennial rivers, they act as an important drainage network during snow melt in spring. No precise information on them is available.

According to the colmation state of riverbanks and the permeability of the sediments and rocks underlying the river beds, important exchanges could occur with groundwater in the area in the 1960s because the piezometric surface was observed to be very shallow. The levels are currently deeper so it can be assumed that the infiltration process of surface water into the groundwater predominantly involves the exfiltration process. However, no precise and reliable studies are available to assess the infiltration from the river beds. The relationships between groundwater and rivers can be taken into account in the numerical model (Chapter 3.1.2.2.1).

2.1.2.2.2 Outflows

Evaporation and evapotranspiration

The actual evapotranspiration calculated from the Turk formula is already taken into account in the calculation of effective rainfall. However, apart from rainfall it is difficult to estimate the amount of water that could be evaporated or evapotranspirated in the study area. It concerns the evaporation from all surface water such as lakes, marshes, rivers and channels, and water used daily for human activities, as well as the evaporation of soil water. Evaporation could affect groundwater to a varying degree depending on the soil properties and the groundwater level, however, no precise information is available concerning this phenomenon. Nevertheless, it can be taken into account in the model as surface water losses.

Withdrawals

No precise information is available concerning the withdrawals in the study area. Estimates can be made for the water demand according to an assumed daily basic consumption rate and data on the evolution of the population in Kabul. The studies report that there were 320 000 inhabitants in the city in 1962, 590 000 in 1972 (ref 2) and 1.8 million in 2001. Today the population is estimated to be 3 million and maybe more; 3.5 million inhabitants is the prognosis for 2010. By considering different possible basic consumption rates, the following values are obtained:

Table 3: Estimates in 10^6 m³/a of the water demand used for general daily activities

Inhabitants	Consumption in m^3/d/cap			
	0.02	0.04	0.06	0.1
320 000	2.34	4.67	7.01	11.68
590 000	4.31	8.61	12.92	21.54
1 800 000	13.14	26.28	39.42	65.70
3 000 000	21.90	43.80	65.70	109.50
3 500 000	25.55	51.10	76.65	127.75
4 500 000	32.85	65.70	98.55	164.25

With this point data and with the aim of carrying out transient simulations to represent the evolution between the current and the former state of the system, a global trend curve is created to obtain estimates of the evolution of consumption over time. This was made assuming a basic consumption of 0.04 m^3/d/cap (Figure 15):

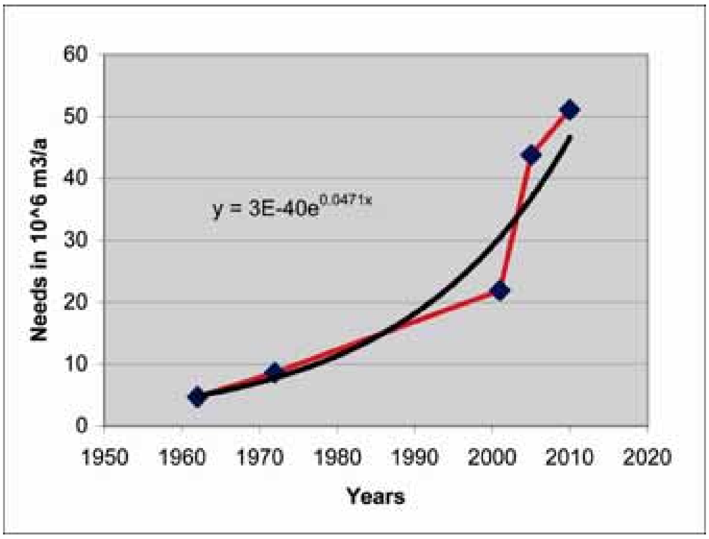

Figure 15: Evolution of drinking water needs according to the evolution of the population in Kabul

No precise information is available on industrial needs and abstractions. Nevertheless, the results of pumping tests carried out in the 1960s and 1980s make it possible to estimate their importance. Pumped wells used to supply drinking water to some districts of the city like Microroyan, had discharges of about 25 to 40 L/s, whereas the discharge of a well in a textile factory was 100 L/s. Over one year, such a discharge already represents a withdrawal of $1.24*10^6$ m^3 (when considering a pumping regime of 12 h/d and 6 d/week). This shows the major water consumption of industrial activities. To gain more information about these withdrawals it would be necessary to make an inventory of all industrial activities in the area likely to need significant amounts of water and to contact the managers of these industries for precise water withdrawal figures. The Afghan Ministry of Mines and Industry (MMI) may possibly have or easily acquire such information.

The withdrawals used for irrigation are difficult to estimate. The irrigation season starts in April and finish in October with a more intense period between June and September (ref 3). For more precise information it would be necessary to know the exact withdrawals. This would be very difficult because it would imply an inventory of all possible intake structures, legal contracts specifying the rights and conditions of water use, and the transfer of information between the farmers and the irrigation authorities. The 1981 Water Law has already established water rights and guidelines for the organisation of irrigation programmes, but the current situation in Afghanistan does not favour the application of this law. A new Water Law is currently under preparation. Precise knowledge of withdrawals would also require the use of appropriate measuring equipment. The feasibility of measuring the volumes depends on the irrigation method: for pumped irrigation it would be possible to install water meters, but no simple and reliable system of measurement exists when the water is supplied by kareze systems or the diversion of rivers and channels. Nevertheless, estimates could be made knowing the water requirements and the irrigated surface area of each cultivated crop in the area.

Irrigation activities can affect surface water (diversion) as well as groundwater (pumping) but could also be considered as a contribution to groundwater recharge depending on the irrigation method, the properties of soils and the evaporation rate.

Figure 16: Satellite image of Bagrami village, GoogleEarth

It is also important to identify the irrigated zones because this activity does not concern the whole study area, it occurs only in the southern and south-eastern parts (Figure 16). Irrigation is mainly carried out in the upper parts of valleys using kareze systems and river diversion systems (Figure 17).

Figure 17: Upper Paghman valley, August 2005 (T.KREKELER)

Outlet of the basin

Discharges were observed for the years 1959 to 1964 at the Tangi Gharu river gauging station situated downstream of the basin on the Kabul river in the zone of the Tangi Gharu gorges.

These are considered as the main outlet of the basin on the basis of the elevation model (Figure 9). The drainage area above the station is estimated to be about 12 890 km². The annual mean discharge for the period October 1959 to September 1964 varied between 13 and 25.2 m^3/s. Minimum monthly mean discharges under 1 m^3/s were observed between June and October during four months in 1962, and three months in 1963 and 1964. The minimum daily discharges of between 0.12 and 0.15 m^3/s were observed in 1962, 1963, 1964 (2 to 13 days in summer); and between 0.5 and 0.6 m^3/s in 1960 and 1961 (1 to 2 days).

The downstream flows of the basin could normally be explained by the upstream flows, it is thus necessary to look at the same years to be able to compare them. The only available values for the upstream stations refer to 1962 to 1964; one should thus take into account only these years to calculate the outflow in Tangi Gharu.

Table 4: Mean discharge observed in Tangi Gharu and associated outflow flux

River and its gauging station	Mean discharge in m^3/s (1962-64)	Annual amount of water flowing out in million m^3
Kabul (Tangi Gharu)	15.0	474.3

2.1.2.2.3 Storage changes

They are explained by the outflow or inflow of water in the groundwater system and can be observed by a drawdown or a rise of the piezometric level. They can represent the annual groundwater level fluctuations when considering a short-term observation and the associated volume of water is then known as the regulating storage. Considering a long-term observation, the storage change is zero if the system is stable, which means the piezometric level remains constant. If the system is not stable over many years, as is the case for Kabul, it is necessary to evaluate the storage change considering the reservoir porosity and an observed variation of the water table.

For an unconfined aquifer, **the piezometric variation Δh** in m leads to a variation in the wetted section of the aquifer and can be associated with a **volume V of reservoir** ($V=A*\Delta h$, where A is the surface of the reservoir). The **storage change ΔS**, the volume of water in m^3 entering or exiting the system, depends on the capacitive function of the reservoir and is calculated from the assumed volume of reservoir V and the **effective porosity n_e** (dimensionless) of V. One must use the effective porosity because only mobile water is taken into account.

$$+/- \Delta S = V * n_e$$

In a confined aquifer, the storage changes do not result in a variation of the wetted section. The variations in the piezometric level represent an increase or decrease in the pressure within the system. The associated volume of water then depends on the **storage coefficient So** of the aquifer.

$$+/- \Delta S = V * So$$

In this study, it is assumed that the aquifer extends to the whole geological basin. The groundwater system is considered as confined in zones with thick loess cover, as indicated in the USGS geological map (Chapter 3.1.2.1). Because little data is available concerning the characteristics and extent of the piezometric surface and its evolution over time, and little information is available on the base of the aquifer, it is difficult to estimate the thickness of the reservoir. The general information of a drawdown of piezometric level of approximately 6-7 m will be considered.

The capacitive and conductive functions of the reservoir can vary in space because of the structure and heterogeneity of its constituent materials. A value of effective porosity of 7.5 % characterising the aquifer appears in the report by Böckh but no indication of its origin is provided (ref 3). This value corresponds to these given for alluvium, silty sands or fine sands (Appendix 18). In the Kabul geological basin, the aquifer materials are sands and gravels which tend to have values of effective porosity ranging between 10 to 30 % according to their granulometry (Appendix 18), it can therefore be assumed that 7.5 % is too low a value. However, it could also be explained by the fact that the deeper horizons are assumed to be affected by compaction and cementing phenomena. Carbonate precipitation which is said to occur in the region (ref 4) could maybe also affect the effective porosity of the aquifer materials in the study area. Different values of effective porosity and storage coefficients can be taken into account by the SPRING software with consideration of the zones where the aquifer is defined as free or confined (Chapter 3.1.2.1).

2.1.3 Water balance equation assessment

From the earlier estimates made for the components, a raw water balance equation can be defined. The data used to assess this water balance are from 1960-1970, and thus only representative and interpreted for this period alone, during which the system is assumed to be stable because there is no information revealing the existence of major drawdown or rise in the groundwater level. It is assumed that storage changes are zero, and that for a long term consideration:

Inflow fluxes = Outflow fluxes

It is necessary to distinguish between the total hydrological water balance and the groundwater balance. When considering the hydrological water balance, river discharges and effective rainfall are taken into account. When considering the groundwater balance, only the possible exchanges between the rivers and the groundwater and the recharging infiltration must be taken into account.

For the **hydrological water balance**, surface water as well as groundwater are involved and the equation can be detailed as follows:

Rivers + Effective rain + Run-off from the Mountains	=	**Outflow in Tangi Gharu + Evapo-transpiration**

After replacement with the calculated or estimated values, the equation gives in million cubic metres per year:

$$457_{(1962\text{-}64)} + 10_{(1957\text{-}77)} + \text{R-M} = 474_{(1962\text{-}64)} + \text{ET}$$

that is **467 + R-M = 474 + E-ET**

The withdrawals due to human activities are assumed to be water diverted or pumped in the study area, thus the assumption is made that these amounts either flow out of the basin in Tangi Gharu, infiltrate the aquifer or are evaporated and evapotranspirated. These withdrawals are thus not taken into account in the hydrological water balance. But they can affect the functioning of the groundwater system and must be considered in **the groundwater balance** as follows:

Infiltration from drainage surface network + Foothill Infiltration + Rain Infiltration + Sewage Infiltration + irrigation water infiltration	=	Exfiltration in drainage network + Withdrawals (for drinking water, Irrigation and Industry) + Evapotranspiration

Here many components are unknown, but the aim of the numerical model is to assess them, especially for the water exchanges with the drainage network and the foothill infiltration.

2.1.3.1 Monthly study of upstream and downstream surface water flows

When working on the assumption that the Tangi Gharu gorges represent the outlet for the surface as well as for the groundwater in the basin, the monthly study of the variations in upstream and downstream fluxes entering and flowing out of the study area allow the identification and quantification of different components such as the amount of water coming from the valley flanks and losses occurring in the area. Indeed, this comparison makes it possible to dissociate the different contributions to the outflow of the basin within different periods of the year. The flows measured upstream represent the surface water entering the zone in rivers. In the study area, this water can remain in the drainage network or infiltrate. The other contributions to the outflow in Tangi Gharu are thus the amount of rainfall and snow meltwater in the basin. The effective rainfall entering the study area was estimated earlier and the snowmelt contribution can thus be assessed.

Table 5: Comparison of upstream and downstream river flows with consideration of monthly mean discharges

Month	Total upstream river discharges in m^3/s	Downstream discharge measured in Tangi Gharu in m^3/s	Water gain in m^3/s	Water losses in m^3/s
January	21.277	21.133		
February	19.970	20.567	0.597	
March	23.750	24.633	0.883	
April	40.903	46.167	5.263	
May	21.187	26.073	4.887	
June	4.080	2.583		1.497
July	1.408	0.670		0.738
August	1.172	0.540		0.632
September	1.213	0.310		0.903
October	5.177	3.293		1.883
November	14.577	14.533		
December	19.250	19.967		

The total upstream river discharges is generally similar to the downstream flow but with minor differences for particular periods such as the rainy and snow meltwater period and the summer period.

The downstream flow is higher than the upstream flow for **March, February, April and May** (note that the evaporation component can be ignored during this period). This results in a contribution of $30.39*10^6$ m^3 (assuming a mean discharge of 2.91 m^3/s applied to 121 days) especially significant for May and April which is the most important rainy period and the period of snow melt. By subtracting the effective rainfall ($10*10^6$ m^3), the remaining value of **$20.39*10^6$ m^3** can be regarded as **a first estimation of the contribution of valley flanks** in the Kabul Basin for this period and especially for the months **April and May,** which also corresponds to **22.5 mm/m²/month** (for these two months). If this value corresponds to an incoming amount of water available in the zone for this period, it is nevertheless difficult to determine if it is the run-off water flowing directly out of the basin or if it can represents recharging water for the groundwater system and in which proportions.

The downstream flow is lower than the upstream flow for **June, July, August, September and October**. This results in **a loss of $14.85*10^6$ m^3** (mean discharge of 2.908 m^3/s applied to 152 days) in the study area. This period corresponds to the irrigation season and has the highest potential evapotranspiration rate. This value however does not allow any differentiation between losses from **irrigation withdrawals** and **evaporation processes,** but it can be regarded as a first estimate of these components in the study area **between June and October** which represents a **loss of 8 mm/m²/month** (for these five months)**.**

2.1.3.2 Study of the fluctuation in the water table

2.1.3.2.1 General drawdown of 6-7 m of the water table

The observed drawdown of the piezometric level over the last 40 years suggests a deficit in the groundwater balance. The phenomena can be explained by different factors but particularly by more important withdrawals related to the development of human activities and by the period of drought that affected the area in recent years and which could have reduced the annual recharge of the groundwater for some years.

However, the rising population in Kabul in recent years inevitably involved a strong increase in withdrawals which can easily be estimated (Chapter 2.1.2.2.2). If the drought period has affected the groundwater recharge it can be assumed that this can worsen the deficit in the groundwater balance but cannot be considered as the only explanation. The number of years necessary to produce the observed drawdown of 7 m in piezometric level can be calculated by ignoring the possible impact of droughts and only considering the impact caused by human withdrawals.

Because the groundwater system is assumed to have been stable in the 1960s in this study, the increase in withdrawals that could have affected it must be calculated as the difference between current and past abstractions. Without any precise data to consider the evolution of withdrawals due to irrigation and industrial activities, the following calculations are carried out only by consideration of the estimated drinking water needs at a basic consumption of 40L/d/cap and for 1.8, 3 and 3.5 million inhabitants:

Table 6: Number of years necessary to observe a 7 and a 10 m fall in piezometric level versus the change in population and considering different effective porosities.

With an effective porosity of 7.5%	Withdrawals $10^6 m^3/a$	Number of years necessary to observe a 7 m drawdown	Number of years necessary to observe a 10 m drawdown
1800000	21.61	9.0	12.8
3000000	39.13	5.0	7.1
3500000	46.43	4.2	6.0
With an effective porosity of 13%	Withdrawals $10^6 m^3/a$	Number of years necessary to observe a 7 m drawdown	Number of years necessary to observe a 10 m drawdown
1800000	21.61	15.6	22.3
3000000	39.13	8.6	12.3
3500000	46.43	7.3	10.4

Because no information is available on the total extent and importance of the aquifer in the basin, the reservoir volume was calculated from the piezometric variation and a surface A which is the area of the model (370 km²). The results are thus probably overestimates.

2.1.3.2.2 Water level fluctuations of the aquifer

The water level fluctuation observed in the sector between 1962-1963 was approximately 1 to 2 m and reached 5 m in the southern parts of the Kabul valley (ref 3). Another reported value lies between 0.2 and 2 m (ref 2). The currently observed fluctuations are of approximately 1 m (Figure 18). The high water levels occur during the spring season and are seen in March to May. The low water levels occurring in the autumn period concern September to November.

The associated storage change can be estimated using a value of effective porosity and an idealised volume of reservoir (the 370 km² surface of the model is used). The effective porosity of the reservoir can vary according to the depth and its constitutive layers. The study of the annual water level fluctuations in the aquifer would make it possible to estimate the effective porosity of the upper layer of the aquifer and also to estimate the groundwater recharge during high water. Because these last two parameters are currently unknown there are two ways of obtaining initial estimates. By making different assumptions of the possible recharge during the high water period to find out the effective porosity, or vice versa, to use the different assumptions of effective porosity to explain the piezometric level variations in terms of the precise amount of recharge water. The piezometric variations are quite well known from studies carried out in the 1960s and 1970s, and current observations are possible from the implementation and monitoring of observation well networks by DACAAR, BGR and probably other organisations.

Table 7: Storage changes in 10^6 m^3 considering piezometric variations and different values of effective porosity

Δh en m	Effective porosity		
	0.075	0.1	0.13
1	**27.75**	37.00	**48.10**
2	55.50	74.00	96.20

From a monitored well belonging to DACAAR, the variation in piezometric level has been known since October 2003 (Figure 18). The measurements are taken every week and revealed a fluctuation of 1 m during high water for the observed period, as well as a sustainable drawdown of about 0.40 m in one year[10]. This indicates that **groundwater recharge always takes place during the spring period** in Kabul.

According to the calculations, this water level fluctuation could represent an amount of water ranging from **27 to 48*10^{6} m^{3}** (Table 7). The earlier estimates made for the **available amount of water during high water** showed that it could reach **30.39*10^{6} m^{3} due to rainfall and valley flank contributions** (Chapter 2.1.3.1). The volumes of water remain at the same order of magnitude which proves that the estimates are reliable. Nevertheless, this information does not help find out the origin of the amount of water that explains the piezometric fluctuations. Indeed, on the one hand, the estimated contribution (30.39*10^{6} m^{3}) is based on 1960s data. It is thus difficult to know if they are still valid for the current piezometric variations. On the other hand, the part that could explain the piezometric fluctuations is only the part that could infiltrate the groundwater.

It is also necessary to take into account the possible additional contribution from influent streams in groundwater recharge to explain the observed time series. The aim of the groundwater model will be to clarify the relations between rivers and groundwater over one hydrological year and to improve these estimates.

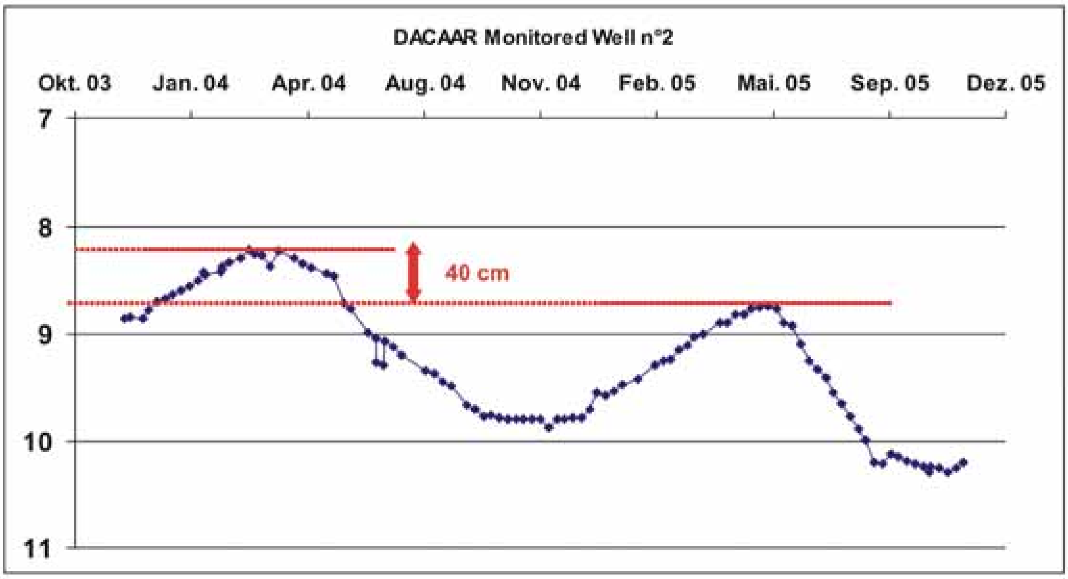

Figure 18: Piezometric level variations observed in monitored well situated in the north-western part of Kabul.

Although this record appears to indicate current recharge of groundwater, the observed permanent drawdown of 0.4 m indicates an alarming fall in piezometric level. Because it is only a point measurement it may not represent the state of the whole system, especially because this observation well is also a pumped well. But it could nevertheless be considered as an indicator of groundwater overexploitation in the area.

[10] The observation well is subject to daily withdrawals since the beginning of the measurement period. The measurements were also always made early in the morning before the pump is operated. The interpretations made from the observed variations are thus only viable if the pumping rate is constant over the observation period, because the resulting disturbance would then not affect the global variations. The problem is that no information is available on the change in the pumping regime during this period. Nevertheless, because the curve presents regular variations except at a few points, it can be assumed that the impact of the pumping is negligeable.

Summary and hydrological year: hypothesis concerning the groundwater recharge processes in the study area

The zone has a wet season in spring and a dry season in summer. The high and low groundwater periods were identified using the new field data (Figure 18). The high water occurs during the spring season and affects February to May. The low water occurring at the end of summer and autumn periods affects August to November.

Rain is not very important (27mm/m²/a for effective rain) but snowmelt can provide considerable amounts of water due to the high altitudes of the surrounding mountains. Rainfall occurs from December to April. Snowfall peaks in January and February. Rainfall peaks in March and April and this also coincides with the beginning of snow melt. According to the soil infiltrability, only a part of it will infiltrate in preferential zones like valley flanks or on the plain in drainage networks. The part that does not participate in groundwater recharge is the part that will flow out of the basin via drainage networks (small drainage networks on the valley flanks and in the two large rivers), or that will be affected by evaporation or evapo-transpiration processes. From the observed discharges in Tangi Gharu in April and May, $30*10^6$ m^3 of water are available in the study area for this period (Chapter 2.1.3.1). Considering that effective rainfall can reach $10*10^6$ m^3, the possible contribution from snow meltwater in the basin could be $20*10^6$ m^3.

Considering the fact that the area is in the downstream part of a big catchment basin, the two rivers Kabul and Logar entering the study area also represent an important source of water and are considered to play a major role in groundwater recharge. Important exchanges could occur as infiltration and exfiltration processes in river beds.

The river discharges start increasing in October (Figure 14), especially for the Logar river, even though the first rain and snow falls only appear in November and December in the Kabul Plain. The rise in the river discharge at this period could be explained by the rivers being fed by other more important rainfall in the upper zones of the catchment basin. This period also corresponds to low water for groundwater and fluctuations in water levels currently observed (Figure 18) show a rise from this period. Hence, it can be assumed that the groundwater is being recharged by rivers at the end of autumn.

The river discharges show a strong rise at the beginning of March (or April in 1963) and reach a maximum in April (or May). These two months have the most important rainfall and are also possible periods for the beginning of snow melt. The high water in rivers and groundwater levels can be explained as a consequence of the accumulation of important amounts of water in the area in that period.

The discharges then start to decrease from April or May but remain important until July, especially in the upper Kabul river. **Irrigation** starts in **April and finishes in October** with a more **intense period between June and September**. Irrigation activities can affect surface water (diversion) as well as groundwater (pumping) but it could also be considered as a contribution to groundwater recharge where the soils are permeable and the evaporation rate is not too high. It is also important to **identify the irrigated zone** because this activity does not concern the whole area of the study zone. Indeed, an important part of the study area is the urban Kabul area and irrigation mainly takes place in the southern part of the study area in the Bagrami-Kamari-Shewaki sectors (interpretation of internet satellite images).

The **groundwater recharge** can therefore theoretically take place **from October to June**. The relationships between groundwater and rivers are difficult to assess over time and should be highlighted better by simulations performed with the numerical model.

3 Numerical model

3.1 The model development

The different steps in developing the model concern its architecture and internal properties and they were made using the methodological approach described for the use of SPRING software. They highlight the main characteristics of the model as follows:

- The definition of a relevant delimited area ;
- The choice of a grid fitting the aims of the study (form and size of elements, refining) ;
- Internal properties taking into account the hydrodynamic properties of the system (permeability, transmissivity, porosity, storage coefficient) ;
- Geological and hydrogeological boundary conditions representing the existing relations between the system and its environment and constraining the flows in the system (fixed potential and flux conditions, mixed conditions) ;
- Initial conditions that represent all the above parameters characterising a precise time step in the case of transient state simulations.

3.1.1 The architecture of the model

3.1.1.1 The delimitation of the study area

It is located between the northern latitudes 34,4° and 34,6° and the eastern longitudes 69,1° and 69,4°. The geographical coordinate system is associated with the ellipsoid WGS 84 (World Geodetic System 1984) and the cartographical coordinates are issued from a UTM projection (Universal Transversal Mercator) in the S42 zone of the northern hemisphere.

The borders of the model must correspond to natural geological or hydrogeological boundaries where possible. They are thus determined with consideration of the elevation model (Figure 9) and the possible extent of the aquifer. The precise study of the topography in the area led to the selection of the 1830 m contour line for the northern boundary, which corresponds approximately to the base of the mountains, and the 2000 m contour line for the southern border of the model where the slopes of mountains are lower and to take into account the important debris fan (Figure 19 and Appendix 13). The model was closed with the limits of the surrounding geological basins (Figure 8) and the start of the Tangi Gharu gorges interpreted as the outlet of the system (Figure 19).

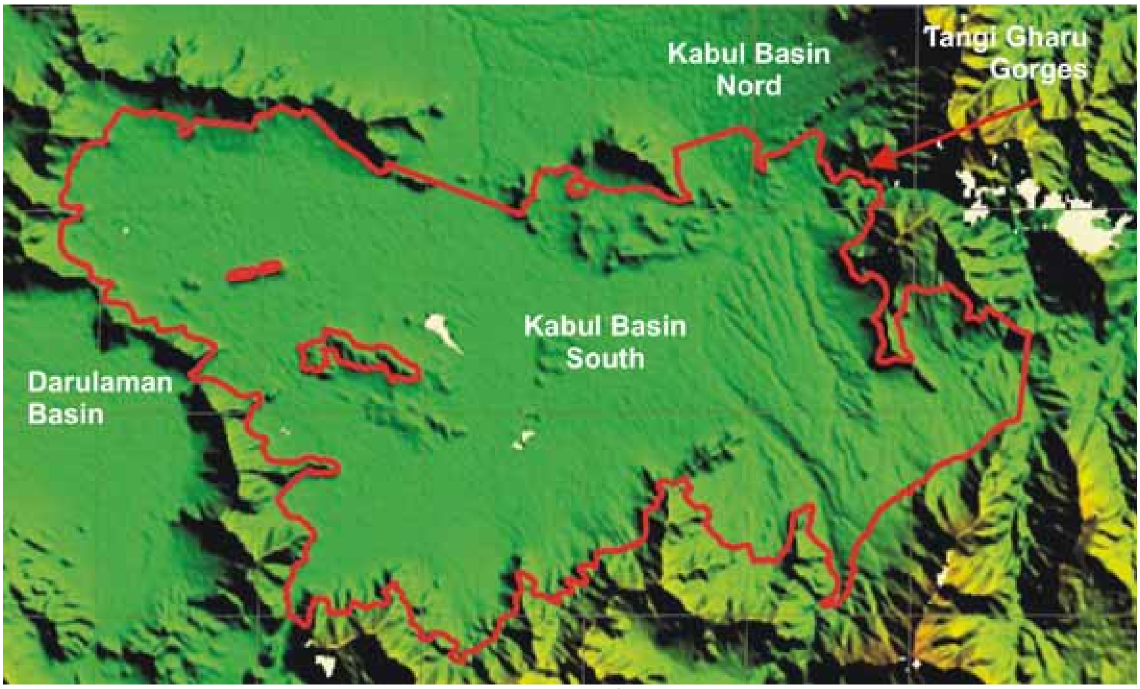

Figure 19: Delimitation of the model area

3.1.1.2 The structures of the model

All linear, point and polygonal objects important for the spatial organisation of the model such as the borders, rivers, wells and recharge zones, have to be created as "structures" in the numerical model (Appendix 19). These objects influence the construction of the grid and the distribution of the parameters in the model and thus have to be identified at the beginning of the study. Structures can still be implemented in the model when the grid is finished but they cannot be integrated in the grid unless this is totally or locally transformed.

The first problem to solve was to find out how these objects could be imported into the XSUSI program of the SPRING software. Its "structure" menu allows the import of different data formats (csv, arc, shp, tif and jpg). Available well data was imported from csv files. Linear or surface structures were directly digitised in XSUSI after importing the different available maps containing the relevant information (topographic surface, rivers, urban areas…); these had to be georeferenced. All of the geographical information imported into the model is then represented in a UTM coordinate system. **The total area of the model is about 370 km² and approx. 27 km long and 16 km wide**.

This study is only a first step in the understanding of the groundwater system in Kabul. The numerical model must therefore be a viable representation of the real world but in a very simplified form. The layouts of the different objects constituting the model were approximated.

The structures of the model define the following objects or areas:

- Linear structures
    - The borders of the model (21 shp lines);
    - Groundwater contours from USGS (9);
    - Rivers (3);
    - Water level elevation in rivers (3);
    - Leakage rate coefficient along the rivers (3);
    - Observation of the leakage rate along river portions (4);

- Surface structures
  - The foothill infiltration zones (2);
  - The rain infiltration zone (1);
  - The urban areas (6);
  - The loess cover (1);

- Point structures
  - 2 wells monitored by DACAAR (1);
  - 34 wells visited by USGS (1);
  - 7 wells from the 1960s (1);
  - 230 estimated values for the base of the aquifer (3).

3.1.1.3 The contours

The “contours” are objects used to create the grid of the model. They constitute the essential basic layout for the generation of nodes and thus of the finite elements. They can be defined as linear objects such as the external borders of the model or the rivers, as well as point objects for wells or springs. They are generally created on the existing structures by cutting them into elementary segments (Appendix 20). These segments can then themselves be cut up into smaller ones according to specific criteria with the XSUSI "contour" menu. The generation and distribution of the nodes depend on this cutting. Indeed the minimum distance for an elementary contour line represents the minimum distance that will separate the nodes and it must be defined according to the desired degree of complexity of the model. The smaller this distance is, the more elements required. The fineness of the grid resolution improves the accuracy of the results, but lengthens the computation time for simulations. The surface of elements depends on the desired working scale. For this study, the minimum distance was set to 250 m to avoid excessive computing times, and because it was not relevant to work at finer scales given the paucity of available data.

3.1.1.4 The grid

Nodes and elements are generated by the program. However, it requires several stages involving the definition of characteristics such as the shape of the elements or specific zones, achieved with the different options in the XSUSI "geometry" menu.

The nodes are generated by creating initial points along the structures with the option “generate boundary nodes”. Then the nodes can be distributed across the model (Appendix 20). However, it is sometimes necessary to carry out manual reworking by creating, moving or removing certain nodes to reach an optimal distribution.

The finite element grid is then created with triangles and quadrilaterals. The option “unbend mesh” makes it possible to improve the grid but certain zones must again be worked over manually. The ratio between the sides of an element must approach one and can be controlled by the option “element-form-control” of the attribute menu. Indeed, long linear elements must be avoided because they lead to numerical instabilities and errors. **The model is made of 10 005 nodes and 11 150 elements.**

Once the architecture of the model is in place, it is necessary to integrate the parameters either to nodes or to elements by way of different functions.

3.1.2 The properties of the model

3.1.2.1 Configuration and internal properties

Even if the model is a two dimensional model, different functions make it possible to differentiate and represent different layers such as the ground surface, the base of the groundwater system and also to take into account the possible effect of the covering loess layer. Considering the small amount of available information, the groundwater system is considered as a unique aquifer assumed to extend over the whole study area.

The **ground surface** is created after importing as structure in XSUSI the data (3D coordinates x,y,z) contained in a 90 m raster elevation model from USGS (Figure 9), and the interpolation of these values to the nodes of the model under the GELA function (Appendix 7).

The **base of the aquifer** was difficult to assess as there is no relevant available data. Nevertheless, to carry out the simulation it had to be approximated in the model. The depths of the wells looked at by USGS were used and considered as a minimum thickness of the aquifer. Other points were integrated into the model. Estimates of the probable thickness of the aquifer layer on the borders of the model were made using knowledge concerning the functioning of kareze systems, the global morphology of a sedimentary basin, observation of photos of the valley flanks and the geological map (Figures 12 and 21, Appendix 13) in order to evaluate the importance of debris deposits. It was thus considered that the thickness of the aquifer materials had a minimum value of 3 m at the borders of the model and could easily reach 30, 20, and 10 m between the borders of the model and the level surface of the Kabul Plain. From the ground surface and these minimum values for the thickness of the aquifer, an underlying layer was obtained after interpolation of the point values in the whole model. The elements of this underlying layer were represented by way of the UNTE function (Appendix 7) and corrected to delete the remaining topographical variations of the ground surface. It is certainly a very rough approximation of the real situation because of the paucity and inaccuracy of the data used to carry out the interpolation.

Figure 20: Coarse erosion materials present on the valley flanks

The thickness of the groundwater system is thus defined in all points of the model as the difference between the underlying layer UNTE and the groundwater table POTE calculated by the model. The third dimension is approached by taking into account a transmissivity value T depending on the distribution of the two parameters, thickness and the coefficient of permeability (T=K*e, where K is the coefficient of permeability and e the thickness of the saturated zone).

The different geological horizons are briefly described on the basis of the available studies (ref 9). Three profiles in the Darulaman and Kabul Basins are available in the report by Böckh (Appendix 3). The conglomerate, sand and gravel layers are said to be the main aquifer horizons. They are covered in part by silty formations and loams, but mostly by loess deposits due to important erosion phenomena in the area.

According to the geological map and the available geological profiles (Appendix 3 and 13), **the loess cover** varies across the basin. It covers the major central part of the study area, but it can be eroded in river beds and at the borders of the basin where loess is intercalated with coarser materials. It is difficult to assess the effect of the loess layer on the behaviour of the aquifer, i.e. should the groundwater system be considered as confined when the loess cover is thick? Permeabilities characterising the loess cover are reported in the range of $5.8*10^{-5}$ to $1.4*10^{-4}$ m/s in the available studies from the 1960s (ref 3). Although two different materials like silt and sand may have the same permeability (1.10^{-4} m/s for example), they may have different effective porosities. In which case the effective porosity of the loess cover could range from 10^{-5} to 10^{-6}. Because of the thickness of this layer (generally 10 to 20 m from the available data) it was decided that it should be represented in the model. The zones were delimited from the USGS geological map (Appendix 13) and given as 10 m thick under the UNDU function attributed to the nodes (Appendix 7).

Orders of magnitude for permeability and porosity can be assessed for the aquifer materials in the area. The permeabilities given vary between $2*10^{-5}$ and $1*10^{-3}$ m/s with a mean value of $3*10^{-4}$ m/s. However, these values result from point studies along profiles and are thus not representative of the whole groundwater system. The porosity 7.5 % is also given in the report by Böckh, but no indication of its origin is provided (ref 3). It is assumed that 7.5 % is actually too low (Chapter 2.1.2.2.3).

The permeability value can be applied to elements by using the KWER function. The PORO function is used to apply a porosity value to the nodes (Appendix 7). The lack of information on the spatial distribution of permeability and porosity led to one unique value of these parameters being used in the whole model. From the creation of the layers GELA, UNTE and UNDU, the model takes into account different values of porosity and storage coefficients depending on the calculated elevation of the piezometric level. The storage coefficient 7.5% is used if this remains under the loess cover, whereas if it reaches the UNDU layer, another value is taken into account by the program (the default value is $3.3*10^{-6}$ and can be changed in the “sitr” file of the computation module).

Boundary conditions
They are essential because they represent the interactions between the system and its environment. From the former estimates made concerning the functioning of the water cycle in the zone and the quantified fluxes, values can be attributed to different parts of the model and for different periods of the year during the transient state simulations.

3.1.2.2 Specified flow boundaries

<u>Inflow zones</u>

Different zones created in the model are associated with positive volumes of inflow water so as to represent a possible recharge of the groundwater by rain and snow meltwater.

The function FLAE (Appendix 7) associated with the sign “*” in the text file makes it possible to assign a volume of water in m^3/m^2/TU (Time Unit) to a list of elements.

The possible infiltration of a part of the effective rainfall is taken into account with a surface structure that encompasses the whole model.

Preferential infiltration zones identified as the border zones of the basin were represented using the USGS geological map (Appendix 13 and 19). The attributed values are calculated from the surface of these zones (47 km² in the north and 103 km² in the south) and a specific available volume of water. The latter is estimated by considering the earlier analysis (Chapter2.1.3.1) and spread between the two zones with regard to the elevation model. Indeed, the southern part of the area has higher mountains and could give rise to larger amounts of water than the northern part.

Outflow zones

Some available data concerning pumped wells in the 1960s in Kabul made it possible to include a few of them in the model. The only information available to assess the amount of water pumped in these wells was the applied discharge during pumping tests which was assumed to be the required expected yield. Only the wells with the most significant discharges (the value 25 L/s was arbitrarily chosen) were selected and implemented in the numerical model. The wells were integrated as structures in the model and the function KNOT is used to assign the withdrawals (Appendix 7). Taking into consideration the last two decades of conflict, it seems obvious that the wells created between 1960 and 1980 may not function anymore or have changed pumping regimes. They can thus only be used to simulate the past withdrawals.

Considering the lack of precise data concerning the current significant withdrawals in Kabul and the fact that thousands of intake points are described in the zone, the current withdrawals can be simulated as surface losses in urban areas which were identified from a map dated 2002 (Appendix 20). The function FLAE* and a negative value is applied in these zones, whose total extent is around 63.3 km².

The evaporation processes can also be taken into account in the same way. The preferential zones for this phenomenon would be areas where water is available and thus urban areas, rivers and channels, irrigated land.

3.1.2.2.1 Specified head boundaries

The rivers were digitised using the 2002 map (Appendix 20). They are taken into account in the model only by the fact that infiltration and exfiltration processes can occur along the drainage network in the study area. From the function VORF (Appendix 7) a potential in metres can be assigned to specific nodes. The program then carries out interpolations between the given values (Figure 21).

The values were defined at the borders of the model area and at the confluence between the Logar and Kabul rivers. Because neither information about the elevation of water levels in rivers nor precise dimensions of the river beds is available, the values were estimated from the elevation model by assuming that river beds are always slightly lower than the general ground surface (an arbitrary value of 4 m was used). The variations in the water level in the rivers were estimated with regard to the available discharge curves (Figure 14) and from photos of the Kabul river bed in order to evaluate the possible maximum water levels (Figures 3 and 30). Mean annual levels were calculated for steady state simulations.

Table 8: River bed elevations and water levels in rivers used for the steady state simulations

Nodes	Ground surface elevation in m	River bed elevation estimates in m	Annual mean water level for steady state simulations
Kabul West	1804.7	1800.7	1802.3
Logar South	1804.7	1800.7	1803.0
Confluence	1779.7	1775.7	1778.2
Tangi Gharu	1770	1766	1768.7

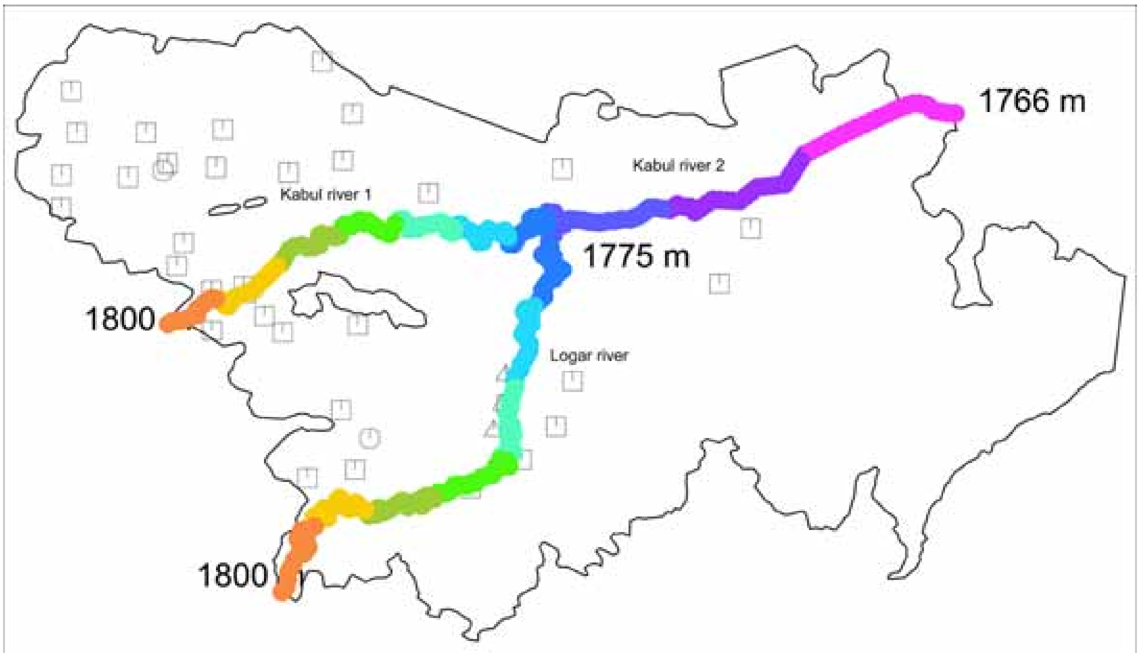

Figure 21: Interpolation of the elevation of river beds from point values and according to the ground surface

The flowpaths and flow rates are defined from the function LERA (Appendix 7) whose value corresponds to a leakage coefficient. The river beds are estimated to be approximately 30 m wide by 2-5 m deep after photo analysis. The scale of the numerical model is such that these lengths are infinitely small and therefore the water exchange occurring between rivers and groundwater can be taken into account along linear structures in the model. These dimensions are taken into account for calculating the leakage coefficient LERA.

LERA [m/TU] = α*b where b is the width of the river bed in m and
α [s-1] = Kf/d where d represents the thickness of the river bed and
Kf the coefficient of permeability of the colmation layer in m/TU

For a value of permeability Kf = $1*10^{-6}$ m/s it gives:
when working with a monthly time step Kf = 2.592 m/month
when working with an annual time step Kf = 946 m/a
where d=0.2 m and b=30 m

The obtained value is LERA=30*2.592 /0.2=388.8 m/month for a monthly time step and =141900 m/a for an annual time step

Thus, the calculated entering or exiting discharges depend on the linear relation that takes into account the leakage coefficient LERA and the potential difference existing between the calculated groundwater level and the fixed surface water levels in rivers. According to the groundwater elevation calculated by the program during a simulation, infiltration or exfiltration processes can be observed and quantified along the river lines (Chapter 3.2.2).

$$Q\ [m^3/s] = K*A*i$$

with K [m/s] = Kf/d =α [s-1]

and A [m²] = b*l

where l represents the distance in m calculated by the module DADIA, as the sum of half the distance separating a node from its neighbours.

After replacement it gives:

Q= α* b*l* i

And if LERA = α*b thus **Q= LERA*l*i**

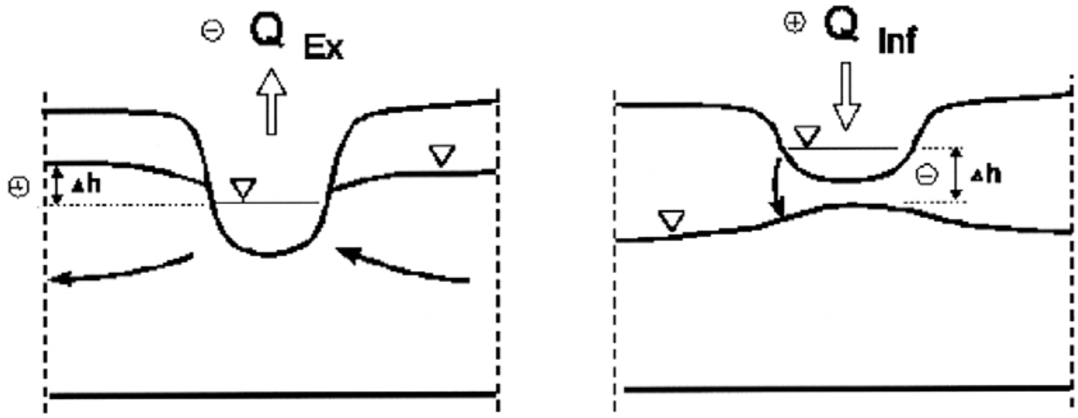

Figure 22: Water exchange relationships occurring between groundwater and surface water

3.2 Simulations and results

3.2.1 Principle

There is little available data and its quality is difficult to validate, thus all the given estimates and calculations can only be rough estimates of the real values. The advantage in making a numerical model is that these estimates can be tested and their sensitivity to the behaviour of the groundwater model is directly observed from the representation of the groundwater contours.

Simulations can be carried out in steady and in transient states. The principle is to change input values in the model and to observe the results obtained at the end of a simulation for a steady state computation and at various time steps for a transient state simulation. Thus, it is necessary to know the spatial and temporal distribution of the variables and to change the values with respect to various possible scenarios. These are chosen so as to validate or to draw aside assumptions.

The time scale used is not significant for a steady state simulation because the results generated at the end of the simulation are representative of a balance reached by the system. Only one result is observed and regarded as representative of the stationary state of the system for the specified input data. Annual mean values were used (Appendix 6). The main variable parameters were the coefficient of permeability and the boundary conditions.

For a transient state computation, the principle is the same except that the input values change over time. The computation modules also use the text-file representing the model, and a second text-file which defines the values of each time step for each of the parameters. In this transient text-file, the values must be assigned to each node or element, this differs from the normal text-file in which the values are assigned to groups of objects (Appendix 21). It can be created from the csv files containing the transient values that are imported into XSUSI and attributed to the different structures. The program can then export a proper txt file and carry out interpolations of the transient values between time steps. Thus, although it is not necessary to give values for every time step, the more values that are given the greater the accuracy of the the results. Greater detail is required for periods with significant changes. It is also necessary to use a stationary state obtained during a steady state simulation as initial conditions of the system before starting a transient state simulation.

3.2.2 Interpretation method

Simulations make it possible to observe the internal hydrodynamic behaviour of the groundwater system, and also to highlight its relationships with the surroundings; in this study in particular it allowed a representation of the water exchange with the surface drainage network.

The software presents the results of the simulations in different graphics and files. The reliability of the results and the input parameters can be evaluated according to the available data and knowledge of the study area. The representation and interpretation of the orientation, form, spacing and values of the groundwater contours obtained at the end of simulations, provide information reflecting flow paths, preferential groundwater flows and global elevation levels. For each simulation, the computation module creates a detailed output file of the calculus carried out. The global water balance is provided, but is also detailed for all the zones that were assigned the function BILK (Appendix 7). Thus, the infiltration and exfiltration volumes along rivers over time are available, and the infiltration and exfiltration zones of water courses can be represented on the graphs (Figure 28). All the wells represented in the model are associated with nodes. To make a comparison between observed and computed data, time series can be ordered for specific nodes while computation. The comparison is carried out from specific text-files which contain the observed data or time series. In this study, times series representing the groundwater level variations in 2 wells monitored by the NGO DACAAR were used (Figure 24). The differences between the calculated groundwater levels and the ones observed by USGS can also be represented on the graphs (Figure 26).

The different scenarios must be selected to generate new information. The time scale must be clearly defined, and the corresponding values used in input files correctly calculated. The month is the most interesting time step and allows the identification of different specific periods within the year, like the snowmelt period or the dry season in summer, that have an influence on the groundwater system. Steps of one year are too long to reveal the dynamics of the groundwater system but are more representative of its evolution over several years when this is subjected to special constraints like increases in withdrawals or recharge reductions.

3.2.3 Steady state simulations

Two different approaches were made. On the basis of the available data, a steady state calibration of the model with the EICHEN module of the SPRING software was envisaged. However, the results indicated that it was impossible to calibrate the model with such a small amount of data. Accordingly, all other simulations were carried out by either applying only one value of permeability for the entire model or using a coarse permeability distribution.

3.2.3.1 The “calibration” of the model

The aim was to assess a coarse distribution of permeabilities and the boundary conditions to obtain a piezometric surface that would reflect the real conditions.

The data used as a reference for the comparison refers to the same period because they must be representative of one state of the groundwater system at a certain time. Because the work is carried out in steady state, the values used are mean values, and the piezometric state reached by the model should therefore be representative of the mean annual level of the aquifer. With regard to the recording of water table fluctuations over the year (Figure 18), it was assumed that the mean annual piezometric levels are the ones observed for the period November to January in winter, and June to July in summer. In this case, the available observations made in winter 2004-05 by USGS could be used as reference data for comparison with the outputs of the steady state model.

The EICHEN module calculates the permeability distribution from the hydraulic head obtained at every point of the model after simulation with the formula:

$$Kcalc = Kini * imes / icalc$$

where Kcalc are the new permeabilities calculated by EICHEN; Kini is the initial permeability that was integrated in the model (a unique value for the whole area for example); imes is the measured hydraulic gradient or the gradient that is considered to be realistic and which should be reached by the model ("EICH" values created from USGS data were used, Chapter 3.2.4.1 and Appendix 7); icalc is the calculated hydraulic gradient that was obtained for the last computation. The module tries to determine a permeability distribution that allows calculation of the desired hydraulic gradient at all points in the model.

Nevertheless, because no precise initial information can be used to describe the permeability distribution, the interpolations did not allow an appropriate realistic representation. The results obtained from EICHEN therefore clearly showed that a satisfactory representation of the permeability distribution values could not be obtained with this method. Moreover, if orders of magnitude of the fluxes occurring in the area can be assessed from the water balance, they are nevertheless imprecise and also do not help with the calibration of the model.

It was then decided to try to create coarse permeability zones from the available information and to try to calibrate the model with the USGS data. It was decided that the permeability values should remain in the order of magnitude of 1.10^{-3} to 1.10^{-6} m/s. Various simulations were carried out and the global groundwater surface observed was compared to the one created by the interpolation of the observed data from 2004-05.

3.2.3.2 Results

The input values for foothill and rain infiltration were calculated for a year time step. Because the data used for comparison reflected the current conditions, the withdrawals that were simulated were for 3 million inhabitants based on the estimates of drinking water needs (40L/d/cap) and they were taken into account as surface losses in the city zones (Appendix 19). The water exchange in river beds is taken into account with a potential head VORF and a leakage coefficient LERA (Chapter 3.1.2.2.1).

Assuming no recharge at the borders of the model, and a uniform permeability value, the infiltration in river beds was always observed at around $25*10^6 m^3/a$ for low permeability values like $1*10^{-4}$ m/s and $3*10^{-4}$ m/s. In these cases, the general water level was always too low in the north-western part of the model, around –40m below the observations ($1*10^{-4}$ m/s) to around -10 and - 5 m ($3*10^{-4}$ m/s). With a higher permeability value of $5*10^{-4}$ m/s, the general water level was observed at around +5, +9 m higher in the north-western part. Finally, if a single value for permeability is used, it should remain between $3*10^{-4}$m/s and $5*10^{-4}$m/s.

In a second approach, all the possible recharge factors like rainfall, foothill and river infiltration were considered and different simulations were made with different values of permeability. Because it was observed that the two zones for foothill infiltration did not properly represent the process, five different zones were created (Appendix 19) in order to attribute different values to each zone. Indeed, the amount of water that is available in these zones mainly depends on the relief.

The study of the north-western zone of the model showed that if the permeability value is low, the amount of foothill inflow necessary to reach the actual piezometric level is around $6*10^6m^3/a$ for a permeability of $1*10^{-4}$ m/s, and $2*10^6m^3/a$ if the permeability is set to $3*10^{-4}$ m/s. The infiltration in river beds was then slightly lower: $22*10^6m^3/a$.

With a permeability value of $3*10^{-4}$ m/s, the maximuml amount for foothill infiltration that could allow good piezometric results was around 1 to $2*10^6m^3/a$ for the north-western part of the model; $1*10^6m^3/a$ for the north-eastern part; $0.5*10^6m^3/a$ for the south-western part, and up to $1*10^6m^3/a$ for the south-eastern part. The general water level was too high (+10m) along the Logar and Kabul rivers but only 2 to 3 m too high in the south-eastern part. In this case the water balance for river bed infiltration was around $13*10^6m^3/a$.

If a higher permeability of $5*10^{-4}$ m/s is assumed, the amount of foothill infiltration could reach $1,6*10^6m^3/a$ in the south-eastern part for the same general water level (2-3 m too high in the south-eastern zone of the model. The global infiltration in river beds would then be around $7*10^6m^3/a$.

Finally, these first simulations showed that it remains difficult to obtain better estimates of foothill infiltration as long as the distribution of permeability values in the basin is not better understood and taken into account in the model. Indeed, the water volumes that can flow into and through the aquifer strongly depend on this distribution (different values on the borders than in the centre for example). Thus, it was decided to create approximate zones based on the available geological information (Figure 23).

The permeability ought to be better along the rivers in the plain where sand and gravel formations were identified from electrical surveys in the 1960s, and which can also be observed on the available geological profiles (Appendix 3 and 4). High permeability could also be found at the borders of the model where coarse erosion debris deposits are described (Appendix 13 and 14). Nevertheless, without any precise data, various possible distributions can be made as well as an infinite number of simulations. The results obtained did not significantly improve the estimates for foothill inflow, especially for the southern part of the model. The following distribution (Figure 23), led however to quite plausible results (Figure 24). The values for foothill infiltration were around $2*10^6m^3/a$ for the north-western part of the basin, around $1*10^6m^3/a$ for the north-eastern part, and around $1*10^6m^3/a$ for the southern part of the basin. These values were assessed for permeabilities within the range $1*10^{-4}$ m/s to $1*10^{-3}$ m/s. The leakage coefficient corresponded to permeability values around $1*10^{-8}$ m/s for the river beds, and the total infiltration reached $17*10^6m^3/a$.

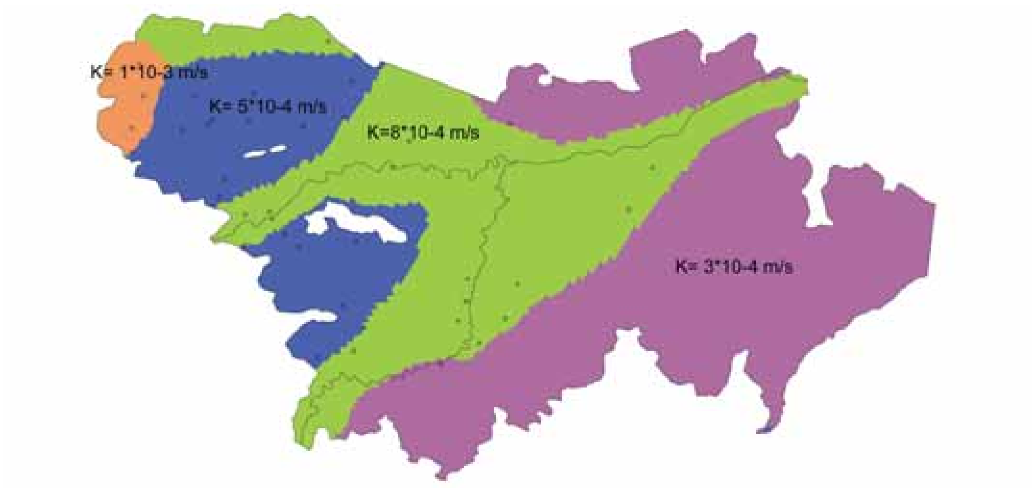

Figure 23: Values of permeabilities used for simulations

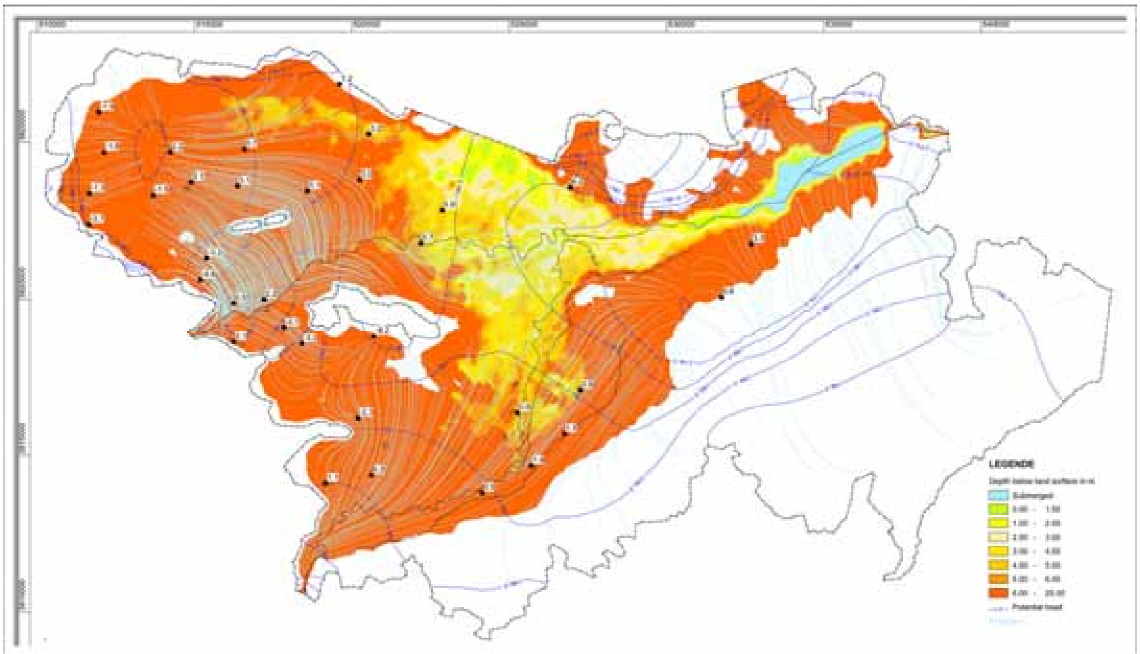

Figure 24: Comparison between the computed piezometric level and the static levels observed by USGS in winter 2004

For quite realistic results obtained after steady state simulation and after observation of the groundwater surface (Figure 24), it can be said that groundwater flows globally from the west to the eastern part of the basin. The rivers recharge groundwater in the western parts of the model and drain groundwater in the eastern part. This can be explained by the global geomorphology of the basin (Figure 30).

The steady state simulations only represent the long term dynamics of the system because all fluxes represent long term averages. Transient simulations will make it possible to consider the distribution of these fluxes over time with values that really represent monthly records. The observed results will allow a better understanding of the aquifer and its environment at different seasons of the year.

3.2.4 Transient state simulations

The simulations were carried out for several years considering the same mean monthly values representative of a typical hydrological year (Appendix 6). It is then interesting to observe:

- if the system remains steady over time;
- the annual water level fluctuations in the aquifer ;
- the flowpath variations over the year;
- the evolution of the exchange between the aquifer and the surface drainage network over the year.

3.2.4.1 Monthly step simulations

In order to create the initial conditions, reference potential head values were integrated in the model as “EICH” structures (Appendix 7) and interpolated to all the nodes. The USGS groundwater contours, representative of the winter period (December 2004, January 2005) were used. Among the available static groundwater levels, many were measured in November 2004 (34 wells). After comparing the groundwater contours from December-January and the local measurement values from November, it was observed that within a distance of 250 m, the difference in static levels were in the range of 1 to 50 cm. It was thus decided that these local measurements from November 2004 could be used to simulate the current groundwater surface during the winter period. Because the initial conditions represent the system during winter, the transient state simulations always started in January. The time-dependent input values, calculated for monthly time steps were incorporated into the model using the transient text file (Appendix 21). The fluctuations of the water table available from DACAAR served as a comparison with the simulation results of the model and helped to indicate the possible response of the system (these time series are represented in red in Figure 25).

Simulations considering only foothill infiltration did not lead to any relevant response in the model which confirmed the major role of river infiltration.

When only the infiltration and exfiltration processes in river beds were considered, with a unique value of permeability of $3*10^{-4}$ m/s and without considering the loess cover, no fluctuations were observed for the northern well and only minor ones in the south. With the distribution of permeabilities created earlier, fluctuations were observed in the wells but the results did not really match the observed variations because the hydraulic reaction was too smooth. This confirmed that permeability values play an important role and that $3*10^{-4}$ m/s is too low for the northern part of the model. The mean value in this zone should be around $5*10^{-4}$ m/s.

Fluctuations approaching the ones observed in DACAAR monitored wells were only reached by incorporating the loess cover in the model.

This first series of transient simulations clearly proved that the effect of the loess cover was not negligible and explained a part of the response of the groundwater system. A pulse such as recharging water in river beds or at the boundaries of the system would propagate as a wave through the aquifer. The part of the incoming water that cannot be stored in the aquifer or in the loess cover is transported downstream.

It is important to note that the main processes explaining the behaviour of the system were identified as foothill and river infiltration. The infiltration and exfiltration rates over the year were calculated for three observation zones representing different portions of the river network (Figures 27a and 27b). “Kabul West” corresponds to the course of the Kabul river upstream of the confluence with the Logar, and “Kabul East” is the course downstream of this confluence.

The differences observed between the calculated piezometric level and those from DACAAR are only around 2 m for the well situated in the South and around 6 to 10 m for the one in the north (Figure 25). The initial aim was not to exactly match the observed fluctuations but to plausibly simulate the general groundwater dynamics.

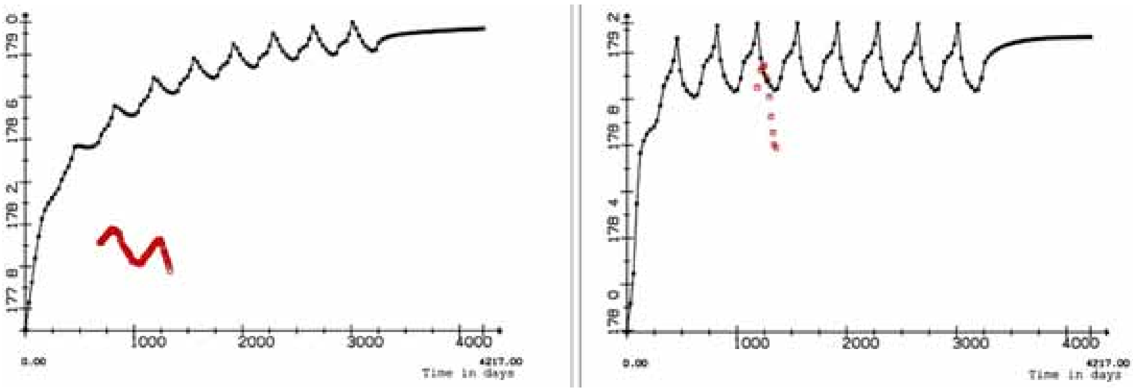

Figure 25: Comparison between the calculated piezometric level and the available time series (in red), on the left, the northern well.

A simulation representing the possible state of the system during the 1960s was also carried out to make a comparison between the two periods, by reducing the withdrawals. The global groundwater level was observed 8 m higher in the north and 5m higher for the well in the south (the well situated in the northern part is more sensitive to withdrawal variations because it is situated in the middle of a large urban zone).

For all simulations, it seemed that the global water level rises over the years. The explanation may be either because other losses like industrial and agricultural withdrawals are not taken into account or because the recharge is too important.

The comparison of infiltration and exfiltration processes showed that, depending on the global groundwater level in the basin, the processes are varyingly important and occur for varyingly long periods during the year.

The following figures show that the main period of infiltration probably occurs from the beginning of March until the middle of April. The main period of exfiltration is probably from the middle of April to the end of autumn and concerns only the eastern part of the drainage network. The Kabul river in the western part of the model acts like a recharge stream throughout the year but infiltration rates are more important when the groundwater level is low (Figure 26b). The Logar and the downstream Kabul rivers also have more important infiltration rates when groundwater levels are low. The results were obtained with leakage coefficients corresponding to permeability values of $5*10^{-7}$ m/s for the upstream course of the Kabul river and $1*10^{-7}$ m/s for the Logar and downstream course of the Kabul river. The foothill recharges were set to $1*10^{6}m^{3}$/month for the north-western part and to $0.7*10^{6}m^{3}$/month for the other zones.

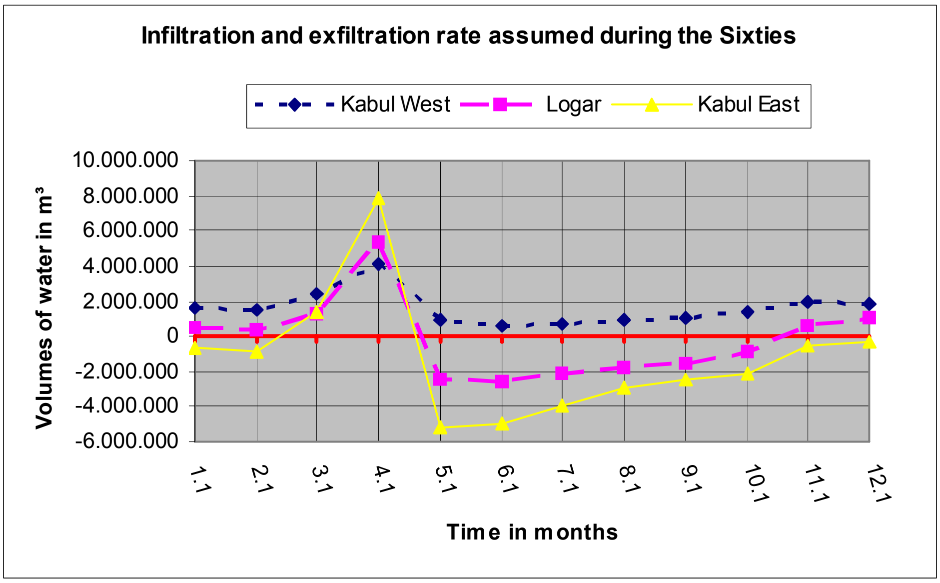

Figure 26a: Infiltration (+) and exfiltration (-) rate in river beds over the year for piezometric levels representative of the 1960s.

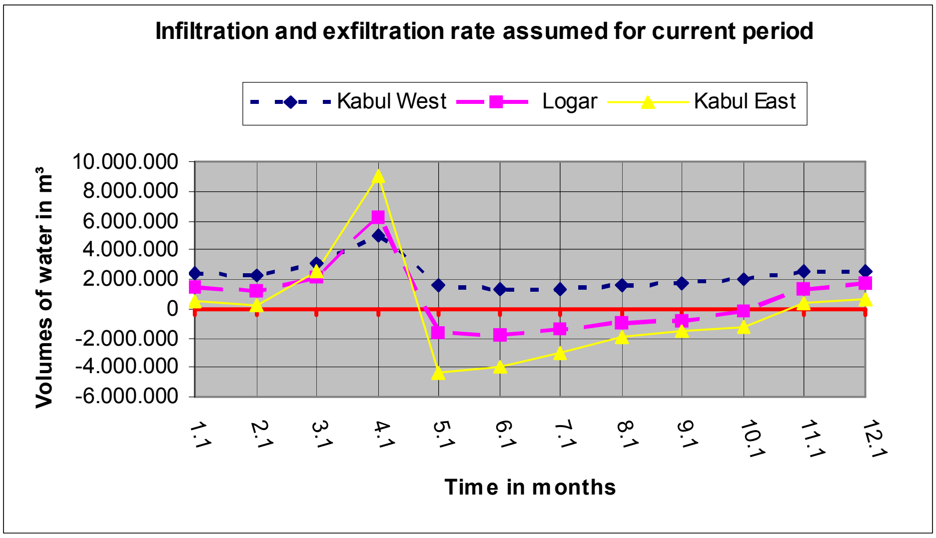

Figure 26b: Infiltration (+) and exfiltration (-) rate in river beds over the year for piezometric levels representative of the current situation.

Because the results on the graphs are difficult to visualise, the following tables (Tables 9 to 11) help to show the difference between the two states of the groundwater system.

For groundwater conditions that represent the 1960s situation of the system, the annual amount of water infiltrated in the upstream course of the Kabul river reached $18.7*10^6 m^3/a$. Exfiltration concerned mainly the downstream course of the Kabul with an annual amount of $14.9*10^6 m^3/a$.

For a lower global groundwater level, the infiltration nearly doubled for the Kabul West portion with an annual amount of $27*10^6 m^3/a$. The Logar river showed lower exfiltration rates and higher infiltration rates up to $7*10^6 m^3/a$. The same phenomenon was observed for the downstream part of the Kabul river which showed a shorter period of exfiltration (May to October instead of May to February) and higher infiltration rates; the annual balance led to an exfiltration of $2.8*10^6 m^3/a$.

The major period of infiltration always occurred during April. For Kabul West, the amount was around 4-5*$10^6 m^3$/month, whereas the infiltration rate for the Logar was around 5-6*$10^6 m^3$/month, and for Kabul East it reached 8-9*$10^6 m^3$/month.

Tables 9 to 11: Comparison of the water exchanges occurring along different stream portions regarding two different global water table levels

Months	Kabul West		
	1 960	2 004	Difference
January	1.6	2.4	0.8
February	1.5	2.2	0.8
March	2.3	3.1	0.8
April	4.1	5.0	0.9
May	0.9	1.6	0.7
June	0.6	1.3	0.7
July	0.7	1.3	0.7
August	0.9	1.5	0.7
September	1.1	1.7	0.7
October	1.3	2.0	0.7
November	1.9	2.6	0.7
December	1.8	2.5	0.7
Annual amount	18.7	27.3	8.6

Months	Logar		
	1 960	2 004	Difference
January	0.5	1.4	0.9
February	0.4	1.2	0.9
March	1.2	2.1	0.9
April	5.3	6.2	0.9
May	-2.4	-1.6	0.8
June	-2.6	-1.8	0.8
July	-2.2	-1.4	0.8
August	-1.8	-1.0	0.7
September	-1.6	-0.8	0.7
October	-0.9	-0.2	0.7
November	0.6	1.3	0.7
December	1.1	1.7	0.7
Annual amount	-2.3	7.2	9.5

Months	Kabul East		
	1 960	2 004	Difference
January	-1	0	1
February	-0.9	0.2	1.1
March	1.3	2.5	1.2
April	7.8	9.1	1.3
May	-5.3	-4.4	0.9
June	-4.9	-4.0	1.0
July	-4.0	-3.0	1.0
August	-2.9	-2.0	1.0
September	-2.5	-1.6	0.9
October	-2.2	-1.3	0.9
November	-0.5	0.4	0.9
December	-0.3	0.6	0.9
Annual amount	-14.9	-2.9	12.1

These results clearly showed that the infiltration process in the surface drainage network is favoured by a deep global groundwater level. Nonetheless, it must be noted that the variations in water level in the rivers that were used are the same in both cases and are based on observations made in the 1960s and no infiltration will occur if the rivers are dry. That's why the infiltration volumes are probably over-estimated for the current period as it is said that the rivers in Kabul are often dried these last years. In order to carry out other simulations and to better assess the possible volumes of groundwater recharge by infiltration in river beds, more information is required on water level variations in rivers in the Kabul Basin.

3.2.4.2 Annual step simulation

The parameters can also change over the years and have an impact on the simulations in the long term. A simulation was therefore carried out to observe the effect of the increase in population in the area. This was simulated as a progressive increase of the withdrawals from earlier estimates (Chapter 2.1.2.2.2).

Other nodes were regarded as time series nodes to better visualise the effect of the withdrawals in the city (Figure 27). The observed results showed a drawdown of around 14 m in the urban area, but only 1 m drawdown in non-urban zones, especially in the eastern part. This means that different zones with different behaviours can be identified. In this model, the withdrawals mainly affect the urban zone but only have a minor effect on the south and eastern part of the model.

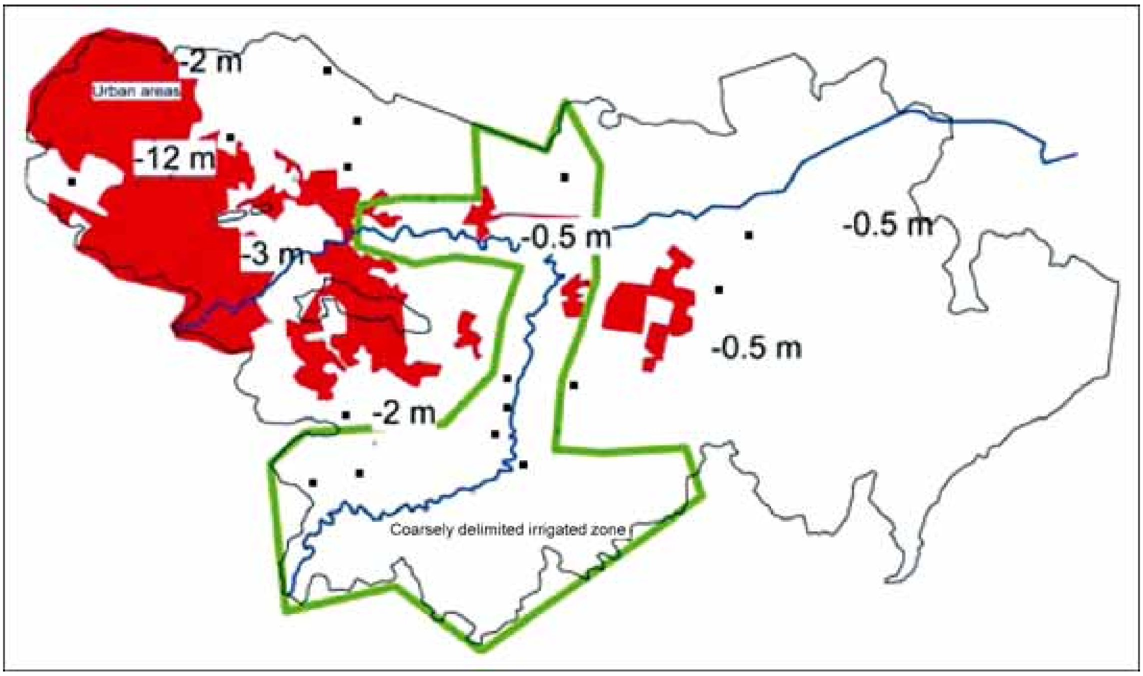

Figure 27: Drawdown of the water table in different zones of the model

3.2.5 Conclusions

This first attempt at modelling showed that it was difficult to calibrate the model because there is too much uncertainty about most of the parameters. The input parameters which can vary and may cause different responses in the system are:

- permeability values;
- amount of water coming from the valley flanks,
- leakage coefficient that controls the exchange between rivers and the groundwater as well as the elevation of water levels in rivers

The permeability values were estimated according to available geological information and mean values calculated from investigations carried out in the 1960s (Chapter1.1.4.1). The volumes of water used to simulate foothill infiltration were based on estimates made in the first part of the study (Chapter2.1.3.1). The subdivision of the inflows along the limits of the model reflected the topography of the surrounding mountains. The order of magnitude of the leakage coefficients was calculated from estimates of the characteristics of river beds (Chapter 3.1.2.2.1). But depending on the size of the river bed and its thickness, the leakage coefficient can easily be twice as high or low. Its variation is also extremely important when the permeability of the river bed is changed. Thus, the values applied in the model can vary considerably. Moreover, only two different values were used, one for the portion of the Kabul river situated upstream of the confluence with the Logar, and one for the Logar and the Kabul river downstream of the confluence. In reality, the characteristics of the river beds, and therefore the values of LERA that could be calculated, are assumed to be more heterogeneous. Moreover, exchange processes in river beds depend on water level variations in stream courses, and these were very roughly estimated according to the available discharge time series. The present day fluctuations in water levels in the rivers are unknown.

The response of the aquifer to recharge not only depends on the input parameters described above but also on its storage capacity. Because the aquifer could be confined or semi-confined by the loess cover, an impervious layer was created. It is represented by unique values for the thickness (set to 10 m) and the storage coefficient ($3*10^{-6}$). Nevertheless, the distribution of these values within this layer could significantly change the groundwater flows. Indeed, depending on these parameters, a pulse of recharge water for instance could be more or less dampened by the potential storage of a part of the water in the loess cover.

The main problem however is that the simulation results can only be interpreted from two wells. The fact that they are situated in two different zones of the model is an advantage but two values constitute too little data. Monitored wells at strategic points, near the rivers and near the valley flanks, are required to improve the work carried out with the model.

Moreover, the observed data and the input data do not refer to the same time period. The outputs of the model which are compared to the current fluctuations result from input data calculated or estimated from measurements made during the 1960s. The current climate conditions and land use are not the same as in the 1960s, and the recharge conditions have thus probably changed. Hence, the comparison is not relevant and data concerning the current climate and hydrology conditions are required to improve the interpretation of the currently observed fluctuations.

Finally, it is difficult to precisely evaluate the quality of the model. It is worth emphasising again here that the aim of this study was not to deliver precise values and information but only to try to learn more about the groundwater system in Kabul and to make initial assumptions about its possible dynamics.

The study confirms the importance of water exchange between groundwater and rivers. Water courses are very important for the recharge of the groundwater system; they also drain the groundwater in the eastern part of the model that is the outlet of the basin. Previous steady state simulations carried out with an old model already revealed the importance of the relationships with the surface drainage network. The response observed with this old model was inaccurate because it did not take into account this exchange in the river beds (ref 17). The study of the relationships between groundwater and rivers from transient simulations made it possible to identify the period of the year when the river network is dominated by infiltration or exfiltration processes.

The study also demonstrated the very likely hydraulic effect of the loess cover. According to the USGS geological map and the results obtained from transient state simulations, the groundwater system could be considered as confined or semi-confined in the major central part of the basin.

It showed that it was very important to create and take into account recharge due to the possible infiltration of varying amounts of run-off water in different zones coming from the surrounding mountains.

Thus, it can be stated that this study reveals important results but also shows the limits of a too simplified, non-calibrated numerical model. For better results, the model has to be improved and calibrated with hydrological time series. This will allow the evaluation of the missing data and makes it possible to propose research and investigation programmes which could be carried out to continue with the hydrogeological study of the Kabul Basin (Chapter 4.3).

4 Summary

4.1 Critical aspects of the study

Several aspects affect the quality of this study.

Firstly, the general lack of data and the poorly controllable quality. The available time series are also not long enough to be considered as representative. Hence, all approaches to quantify the components of the water balance remain uncertain to some extent. The river discharges have only been observed over two or five years. Information concerning the configuration and stratification of the groundwater system is vague. Information concerning the hydrodynamic properties of aquifer materials results from local point investigations and cannot characterise the groundwater system and its heterogeneity as a whole. Averages had to be used in the study to represent a possible typical hydrological year, but the old data does not refer to recent climatic changes. It is difficult to interpret the results of simulations carried out with the numerical model because the input data and the recent observed data do not refer to the same time period.

Moreover, it is difficult to evaluate the quality of the data. Too little information was provided in reports on the way the data was collected, therefore orders of magnitude of errors are not provided as well.

Secondly, the lack of knowledge concerning processes which could have an impact on the water balance in the area. This meant that the study could only make assumptions. For example, if the effective rainfall is calculated from old 1960s data, one cannot precisely determine the part that really infiltrates and takes part in the groundwater recharge because infiltration processes in the loess cover are not studied. Similarly, the recharge from the snow meltwater, as assumed to occur in preferential zones of infiltration on the valley flanks, may also join the groundwater system slowly through the loess cover or flow out rapidly of the basin as run-off water.

Thirdly, even if the study was undertaken with rigour and attention, errors in the reasoning, or miscalculations are always possible.

With regard to the model, it must be remembered that the results cannot accurately represent the real groundwater system in Kabul, and they should thus be used with care and only be regarded as first approximations.

4.2 What is the main information obtained from the study?

First of all, the study made it possible to use the available information in the BGR archives, and obtain new information about the hydrogeology in the area of the Kabul Basin according to the analysis and critical review of currently available data and documentation.

4.2.1 Assessment of the functioning of the aquifer

The groundwater system is assumed to have confined or semi-confined conditions in areas where the loess cover is important. According to the USGS geological map, this area comprises the central part of the basin. The effective porosity values used in this study were around 10% for the whole groundwater system, and around 10^{-5}-10^{-6}% for the loess cover. With little data, it was difficult to create a distribution of permeabilities, but a unique average permeability value must range from $3*10^{-4}$ to $5*10^{-4}$ m/s.

The groundwater is mainly recharged by the infiltration of run-off water from snow meltwater during the spring. The preferential zones of infiltration were identified as river beds and the borders of the basin where erosion debris is present (Appendix 13). The groundwater recharge by rain and snow meltwater in the study area during the winter period between December and May can be estimated at around 10 to $20*10^{6}$ m^3. The infiltration in rivers may reach around $25*10^{6}$ m^3 without considering the valley flank contributions. Thus, the minimum recharge is likely to be around $25*10^{6}$ m^3/a if the input along the borders of the basin does not contribute to groundwater recharge. This could be the case if the run-off process is preferential as the infiltration process. The maximal recharge is assumed to be around 40-45 10^6 m^3/a if all the available surface water contributes during spring to recharging the groundwater system. The corresponding amount of water would then vary between 68 and 108 mm/m²/a.

During the summer, a loss of $15*10^6$ m^3 highlights the influence of evaporation and/or irrigation in the study area (Chapter 2.1.3.1) but there were no indications of whether these losses affect only surface water or also groundwater. More work is therefore required on this aspect. The demands for drinking water supply have increased from $5*10^6$ m^3/a in 1962 to $43*10^6$ m^3/a in 2005, for an assumed basic consumption of 40L/d/cap. At 60L/d/cap for 3.5 million inhabitants, the demand would increase to $77*10^6$ m^3/a.

The turnover rate of the aquifer corresponds to the average replenishment compared to the average total storage. The turnover time is the time needed for the accumulated volume of annual recharge water to equal that of total storage. The average total storage corresponds to the total amount of gravity water stored in the aquifer, and can be estimated with an average value of effective porosity and the dimensioning of the aquifer. The total storage can be estimated from values for the volume of the model and effective porosities. Thus, several estimates can be made as follows:

Table 12: Estimates of the average total storage considering different values of thickness and effective porosity.

Thickness in m	Effective porosity		
	0.075	0.1	0.13
30	833	1110	1443
40	1110	1480	1924
50	1388	1850	2405

Table 13: Turnover rate in % considering different estimates of total storage and annual recharge

Annual recharge of the groundwater system in 10^6 m³	Total storage in 10^6 m³				
	833	1110	1443	1850	2405
25	3.0	2.3	1.7	1.4	1.0
45	5.4	4.1	3.1	2.4	1.9

Table 14: Turnover time in number of years considering different estimates of total storage and annual recharge

Annual recharge of the groundwater system in 106 m³	Total storage in 106 m³				
	833	1110	1443	1850	2405
25	33.3	44.4	57.7	74.0	96.2
45	18.5	24.7	32.1	41.1	53.4

4.2.2 Discussion of problems facing future water management in Kabul.

4.2.2.1 The problem of the dryness of rivers during the summer period

The water levels in rivers are widely assumed to represent abnormal climatic conditions in recent years. More and more sections of the river network were observed to dry out, and not only during the summer. This can apparently be explained by the severe drought period which has recently affected the entire area. Nevertheless, the climatic conditions seem to have improved since 2003-2004 with rainfall and snowfall in Kabul. Therefore, if the rivers are now always observed to run dry more often than in the past, it might actually be due to the fact that the groundwater table is deeper now than in the past. In recent years, as a result of droughts and the increasing population in Kabul city, water scarcity led to the major and uncontrolled exploitation of the groundwater and caused a drawdown in piezometric levels. The potential difference between the aquifer and the rivers created by this deeper groundwater level favour infiltration processes which could explain the increase in the length of time the rivers run dry. The Karghal dam in the Paghman valley allows the controlled release of water (when it is available) in the summer to supply irrigation needs and to maintain a minimum discharge in the Kabul river. However, how far can this water flow before it is totally infiltrated in the ground, or used or evaporated? Would it reach the eastern part of Kabul city?

4.2.2.2 Groundwater recharge and urbanisation

If groundwater recharge mainly involves the infiltration of run-off water from snow meltwater during the spring, then a better analysis of this process in the Kabul Basin might help improve groundwater recharge. The preferential zones of infiltration were identified in this study as the river beds where the loess cover is eroded, and the middle and bottom parts of valley flanks where erosion debris has accumulated. The sources of water available for infiltration in rivers are surely run-off water coming from upper parts of the catchment basin; and on the borders of the plain, run-off water coming from the relief surrounding the basin. The infiltration conditions in the zone down to the saturated zone requires more study. Nevertheless, it can be assumed that some phenomena related to urbanisation could affect infiltration. The canalisation of the Kabul river in the city and the associated sedimentation in the river bed lead to an increase in its colmation (Figure 28). The urbanisation on the valley flanks could disturb infiltration processes (Figure 29).

It is also assumed that the water coming from the mountains surrounding the Kabul Basin also contributes to groundwater recharge in other parts of the basin. The part of the surface water which does not infiltrate would enter the plain and the river network as run-off water. A slow infiltration through the loess cover could be envisaged in local ponds where water can accumulate. It is currently difficult to verify this assumption and to evaluate the amount of water that may be concerned; but if true, the enlargement and densification of the city would lead to a reduction in the permeable surface available for infiltration.

It is therefore possible that the enlargement and densification of Kabul city could irreversibly affect the recharge of the groundwater system if the preferential recharging zones are not properly identified and protected. The urbanisation of the city should be planned taking into consideration the hydrology and hydrogeology of the basin to avoid irresponsible and non economical projects.

Figure 28: The Kabul river in the city

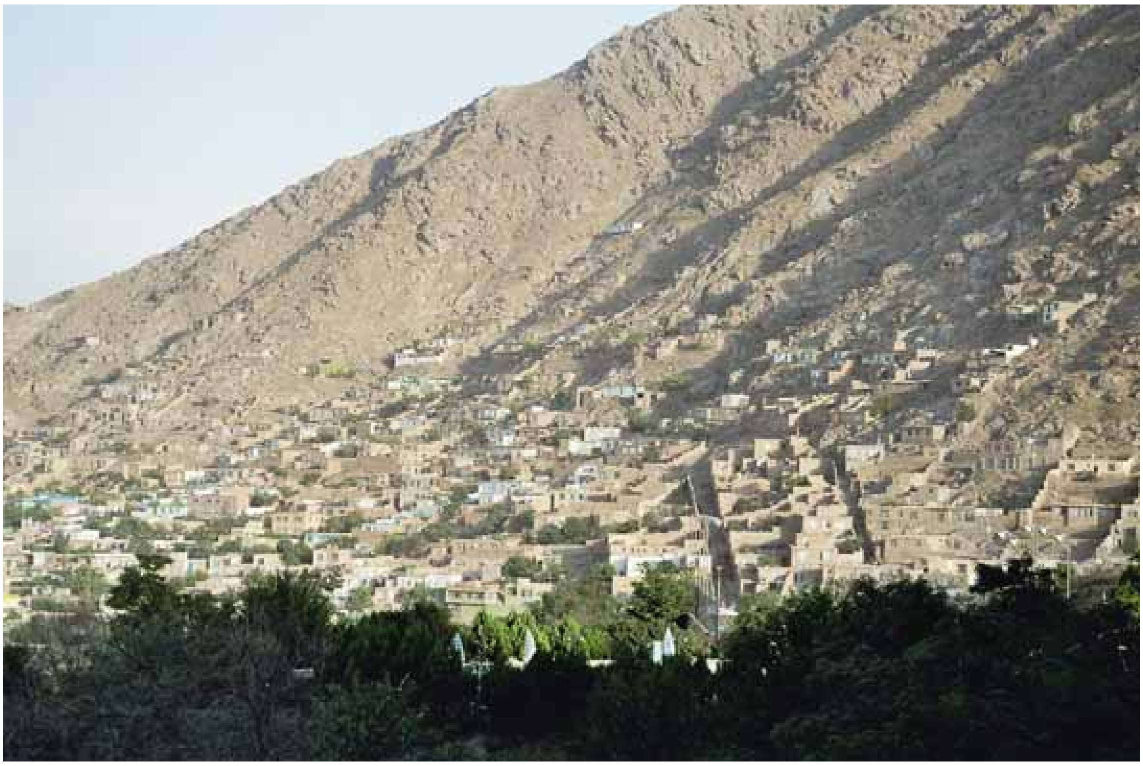

Figure 29: Urbanisation phenomenon on the valley flanks

4.2.2.3 Increase in impervious surface area and flood risks

The densification and enlargement of the city increases the impervious surface area and thus reduces the area available for infiltration. The water coming from the valley flanks will run off if it cannot infiltrate. Major uncontrolled run-off is a known risk factor which can worsen flood problems. The Kabul Basin is already said to suffer floods during the spring period in March and April. It would be interesting to know more about these floods. Are they principally due to the high water in the Kabul river or also to the snow meltwater coming from the surrounding mountains? Are they relatively recent or considered as normal events? Could they be explained by the recent changes in the Kabul area (rapid snow melting because of recent climate changes, increasing run-off due to urbanisation?).

Irregular flooding is present and could be worsened by the increase in impervious surfaces in the basin. The vulnerability of the area is also very high because Kabul city is an important urban zone with up to 3 million inhabitants. The north-western part of the city is surrounded by mountains and lies in a topographical depression (Figure 30).

It is important to study the snow melting process in the Kabul Basin. This implies evaluating the volumes of water concerned and characterising the surface flow-paths to evaluate the risks associated with flooding.

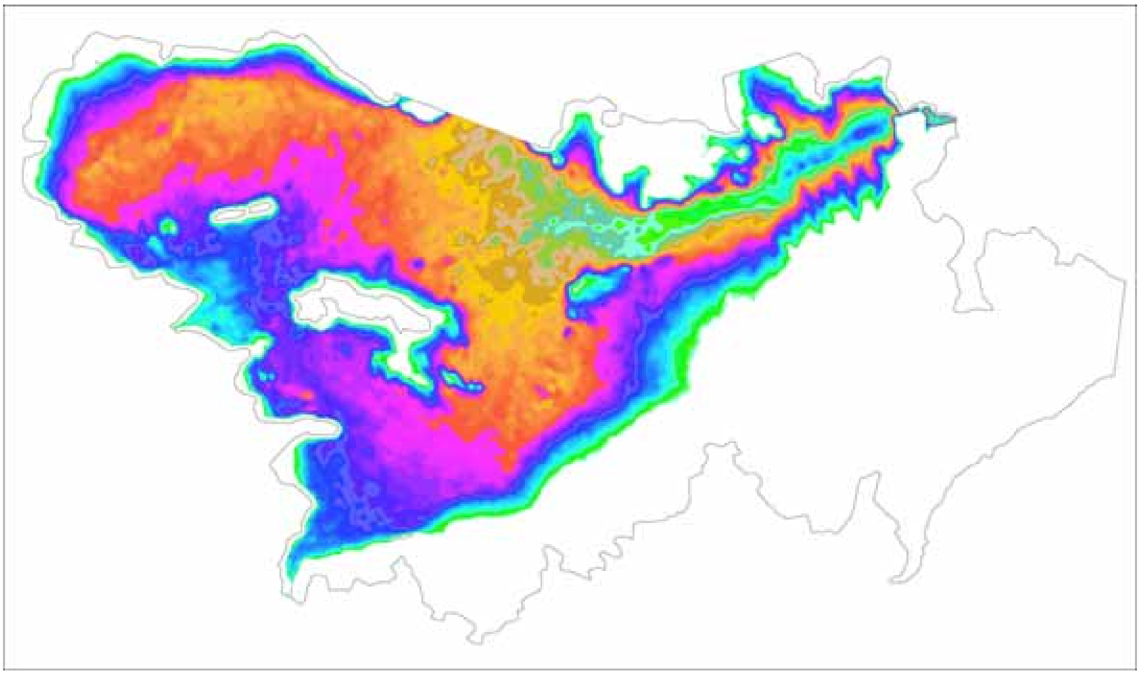

Figure 30: Topographical surface in the north-western part of the Kabul Basin with 1 metre resolution (after interpolation of the 90m raster elevation model)

4.2.2.4 Water needs, water resources and alternatives

<u>Water and uses</u>

The aim for the Kabul inhabitants is to find solutions which improve living conditions as well as support economic development of the area, which respect the importance of the sustainable use of water resources. The sustainable use of water resources means protecting it from pollution and overexploitation. Depending on their qualitative and quantitative characteristics, different types of water have to be used for appropriate activities. For example, international guidelines for water quality are different if the water is used as drinking water or for industrial or irrigation purposes.

Needs

During the 1960s, the surface water and shallow groundwater (rivers, springs and kareze systems) were the major water sources for the population when there were only around 320 000 inhabitants in Kabul city. Currently, the needs have changed: the population has reached approximately 3 million inhabitants with an associated higher demand for drinking water for households and sanitation. Irrigation takes place mainly in the upper parts of the valleys. In the Kabul Basin, it mainly concerns the southern part around the villages of Shewaki, Kamari and Bagrami. As a result of urbanisation, agriculture in the Kabul Basin will probably tend to decrease in the long term. On the other hand, industrial activities will increase and also require important amounts of water.

Water resources and alternatives

The available water resources are the surface water coming from the upper catchment area or directly from the mountains surrounding the basin, and the groundwater.

- Water quality

Chemical analysis programmes carried out in 2004 showed that the shallow groundwater in urban zones is widely contaminated due to the lack of sanitation systems and the presence of uncontrolled disposal sites. Run-off water from snow melt should have natural good chemical properties, but can be contaminated if it washes polluted soils.

- Water availability

Groundwater is available all year with higher levels in spring. Surface water is mainly available in autumn (from the Logar river), and in winter and spring. The rivers tend to dry up in summer.

Groundwater with appropriate chemical composition for use as drinking water should be protected from other major abstraction purposes (industrial) and pollution.

Sewage effluent could be used for irrigation purposes after some degree of treatment. This solution would optimise the use of water and is commonly applied in many countries (ref 19). Nevertheless, this solution requires preliminary studies concerning the chemical properties of the effluent and the vulnerability of the irrigated soils. Indeed, if not properly monitored, the use of sewage for irrigation can lead to the salinisation and contamination of soils and shallow groundwater. Studies carried out in parts of the Kabul Basin already showed that soils and shallow groundwater had high salinities (ref 2, 12). Thus, this activity should only be envisaged where the consequences were found to be acceptable.

It can be assumed that significant amounts of run-off water are available in spring. Most of this resource could be directly lost because rapidly drained out of the basin. This mainly concerns the south-eastern part of the basin. The available information indicated important potential run-off in this part of the basin where the highest mountains reach up to 3000 m. A river identified as the Butkhak Khwar or Rodjan river (ref 4) appears on several maps in this part of the basin. Important erosion features resulting from small drainage networks can be distinguished from the elevation model and on satellite images from Google Earth. Moreover, the elevation model also reveals an important catchment area of about 330 km² including mountains up to 4000 m feeding this part of the basin (Figure 31).

The Karga reservoir located on the course of the Karga river about 12 km west of the confluence between the Kabul and Paghman rivers was built to intercept the surplus water coming from the Paghman valley in spring. However, the problem of dams is that the stored water is directly affected by evaporation during summer months. Seismic activity is also important in the region.

If the surplus of snow meltwater is identified as an interesting source of water, solutions and conditions for its collection and storage need to be studied in more detail.

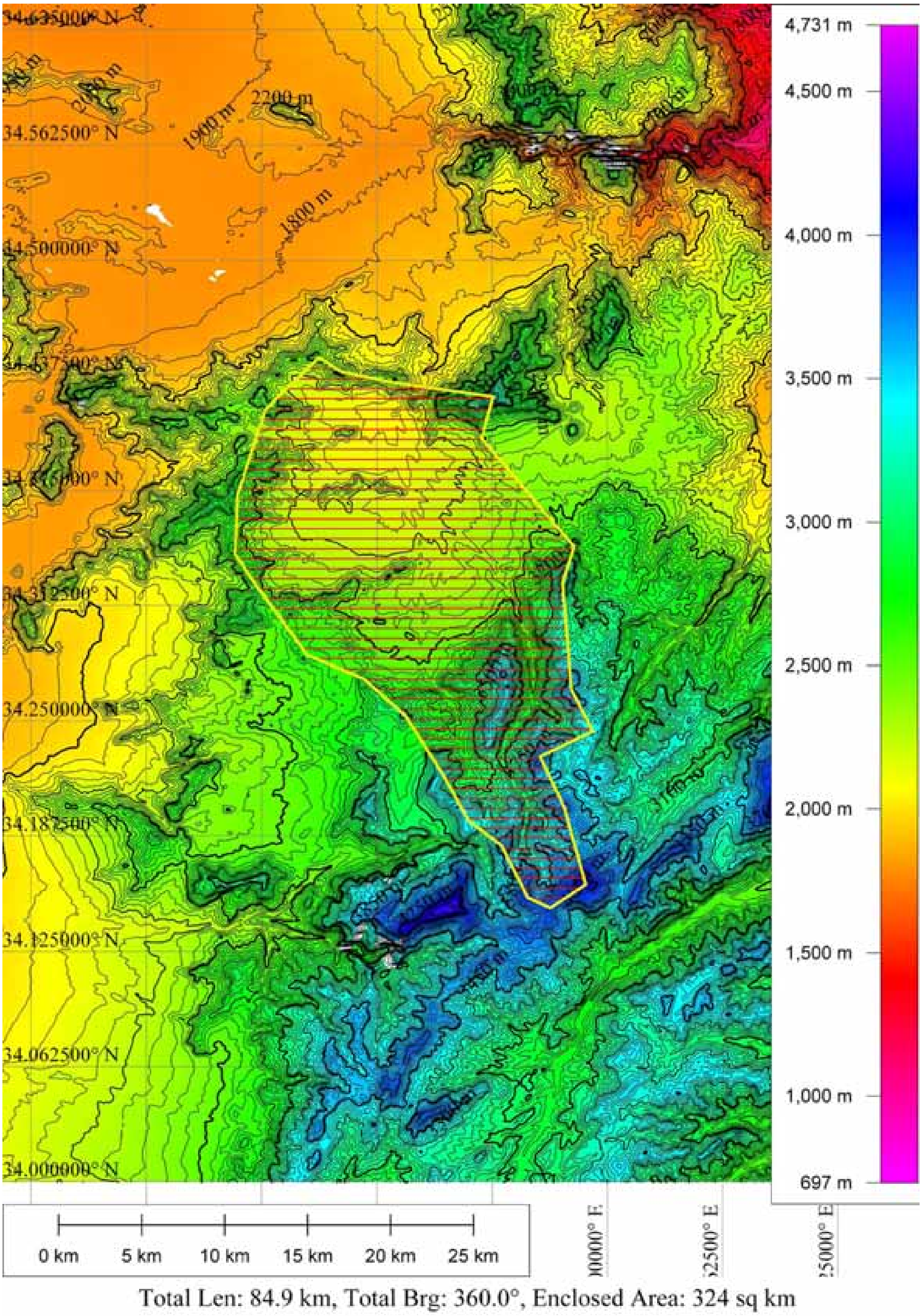

Figure 31: Upper catchment area feeding the south-eastern part of the Kabul Basin

4.3 Evaluation of the missing data and proposals for the continuation of the study

To improve the quantitative management of the groundwater resources in Kabul, more data is essential on the hydrogeological characteristics of the aquifer (structure, hydrodynamic properties) and its dynamic properties (recharge, depletion and groundwater flows).

4.3.1 A short term approach

It is necessary to identify and evaluate the nature and the value of the data which is currently or could easily be collected in the field and improve the results of the present study. The model should be improved with new data, and more transient state simulations should be carried out. For example, new information concerning the groundwater level fluctuations as well as the water levels in rivers is essential for any further improvement of the model.

Research and the collection of information in the study area or other zones with similar climatic and hydrogeological characteristics must be carried out to improve knowledge about the processes which play a significant role in the study area.

The investigations in the field that could quickly bring new information are:

- Direct observation, photography, discussing the phenomena occurring in the Kabul Basin such as snow melt, flooding, run-off flows, dried up rivers;
- Installing water level gauges or the regular manual measurement of water levels in wells and rivers, to get time series in strategic parts of the basin;
- New drilling operations and/or pumping tests would provide information on the stratification and hydrodynamic properties of the different possible aquifer layers.
- Isotopic analysis of rainwater, rivers, snowmelt and groundwater could help to identify and evaluate the different components contributing to groundwater recharge. Studying and characterising the isotopic composition ($\delta^{18}O$, $^{2}H/^{18}O$) of different water samples from groundwater, rivers, rain and snow would highlight possible processes like recharge from rainwater or melted snow, and evaporation processes.

Apart from the first, these investigations would require major funding and technical measures.

4.3.2 A long term approach

To support groundwater recharge and to evaluate the usable groundwater resources, the recharge conditions must be studied in more detail. The preferential zones where recharge occurs must be identified and protected. The factors which influence recharge, drainage and flow conditions in the Kabul area, and their possible consequences on the functioning of the groundwater system, must be evaluated and quantified in more detail.

Installing monitoring networks is necessary to observe long term climate characteristics, the groundwater, and the surface water behaviour. It is necessary to identify and list all the important surface waters (rivers, channels) and groundwater flows flowing into and out of the geological Kabul basin to take them better into account in the water balance. Research is required in particular concerning:

- Snow melt processes and the possible volumes of water available versus the importance of the snow cover;
- The influence of drought periods on groundwater recharge: by studying the climatic evolution in the zone to identify the causes and to characterise the importance and the probability of drought periods; the possible consequences of such climatic changes in terms of the evolution of precipitation, snow cover, melt velocity and evaporation rates;
- The identification of groundwater recharge areas and processes (defined period, available quantity, infiltration conditions). This could be done from satellite imagery, by observing the study area at different periods of the year to study the uses and characteris-

tics of the soils and the surface waters. It could then be possible to visualise urban, cultivated or eroded zones, to more precisely identify periods and zones of snow meltwater and irrigation, and to identify where and when portions of rivers dry out. Infiltration processes and occurrence could be evaluated from soil sampling studies and general research concerning water infiltration and circulation processes in the unsaturated zone of semi-arid soils.

- In the present study, it is considered that the different aquifer levels are totally interconnected and form one aquifer system. However, more knowledge concerning the structure of the aquifer is required, and the possible existence of different layers or stratification in the groundwater system should be studied. This is urgently required to evaluate the possible exchanges between shallow contaminated water and deeper water and thus, to evaluate the risks of the pollution of deep water in the Kabul groundwater system.

Finally, such studies should also result in the production of documents for the decision-making authorities such as thematic maps and databases shared between the different actors concerned in the management of water resources.

4.3.3 Information and data sharing and distribution

Having direct contacts in Kabul is a great opportunity to quickly acquire new data and information. Indeed the persons on site have direct experience and therefore the most realistic assessment of the actual situation: they can carry out investigations in the field and are often directly in contact with the authorities and the population.

Although there is a lack of equipment in Kabul, and even if the most recent data only represents point and sparse information, it is interesting and important to begin recording some important parameters such as the groundwater table variations and the water levels in rivers. That is why better partnership and data exchange should be organised between the different organisations currently working in Kabul.

In the light of the emergency situation in Afghanistan, the available data and studies underpinning an improvement in the qualitative and quantitative understanding of the water resources should be widely shared and distributed. In this context, there should be better co-ordination and identification of the different actions and data already available.

Conclusions

The analysis and synthesis of the data currently available made it possible to establish a preliminary assessment of the hydrology and hydrogeology of the geologically southern part of the Kabul Basin. First estimates concerning the hydrological water balance, as well as the groundwater recharge were made. However, these computed or estimated values are based on very little data whose quality is hard to control, and thus must be used with great care. The realisation of the numerical model is a first step in modelling the groundwater system, and supports an initial assessment of the spatial and temporal distribution of the important fluxes. However, the spatial distribution of the hydrodynamic properties of the aquifer is not precise enough, and the study also shows the limitations of using a highly simplified model. Even if the piezometric representations obtained from this model tend to approach reality, the results must once again be used with care because this study shows that there are always uncertainties and questions to be answered to improve the understanding of the hydrogeology of the Kabul Basin, and therefore of the work that is still required to continue the investigations in the field and to obtain new information.

In order to meet precise needs and to guide the water resource exploitation and management policy in Kabul, a numerical model can be useful to support decision-making, but only if the quality of its results can be evaluated and checked. A proper calibration of a model can only be made with data collected in the field and periodical checks and readjustments of the model from continuous measurements. The incorporation of new information and revisions of the conceptual model are a good means of evaluating the nature and the importance of the forecasting errors and thus lead to an improvement in the quality of the model and how the studied system functions. It is then possible to make forecasts with greater reliability. That is why continuous study and data acquisition in Kabul is essential for future groundwater management.

Different organisations currently aim to implement networks to measure climatic, hydrological and hydrogeological parameters in Kabul. It would be better to identify and co-ordinate these different actions to optimise the work carried out and to share the benefits in terms of data acquisition. Moreover, investigations in the Kabul area must be coupled with field policies concerning aspects such as raising the awareness of the local population to the need to save and protect water; better organisation of the management and exploitation of water resources; as well as the management of water shortages, conflicts of use, overexploitation and the measures to be taken during droughts. The studies should not only focus on groundwater but on all water resources which could be used for the human activities, to anticipate water shortages and to highlight alternative resources. Finally, if scientific studies make it possible to improve the implementation of the sustainable management and use of water resources in Kabul, the latter can only be established with the active and voluntary participation of the population, and by the existence of appropriate and qualified structures for managing the water exploitation and protection.

Acknowledgements

I would first like to thank Thomas Himmelsbach who gave me the opportunity to realise this study, for his confidence in me, and for his support.

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Abbreviations

AA	Auswärtiges Amt
AIMS	Afghanistan Information Management System
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BGS	British Geological Survey
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
BMV	Bundesministerium für Verkehr, Bau- und Wohnungswesen
BMWA	Bundesministerium für Wirtschaft und Arbeit
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung
CARE	humanitary organisation
CAWSS	Central Authority for Water Supply and Sewerage
DACAAR	Danish Committee for Aid to Afghan-Refugees
DED	Deutscher Entwicklund-Dienst
DEM	Digital Elevation Model
PET	Potential Evapo-Transpiration
AET	Actual Evapo-Transpiration
GPS	Global Positionning System
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
KfW	Kreditanstalt für Wiederaufbau
MMI	Afghan Ministry of Mines and Industry
NGO	Non Governmental Organisation
GIS	Geographic Information System
SPRING	Simulation Processes in Groundwater
SRTM	Shuttle Radar Topography Mission
TU	Time Unit
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USAID	United States Agency for International Development
USGS	United States Geological Survey
UTM	Universal Transversal Mercator
WGS	World Geodetic System
NSZ	Non-Saturated Zone

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http://www.mapmart.com
http://srtm.usgs.gov/

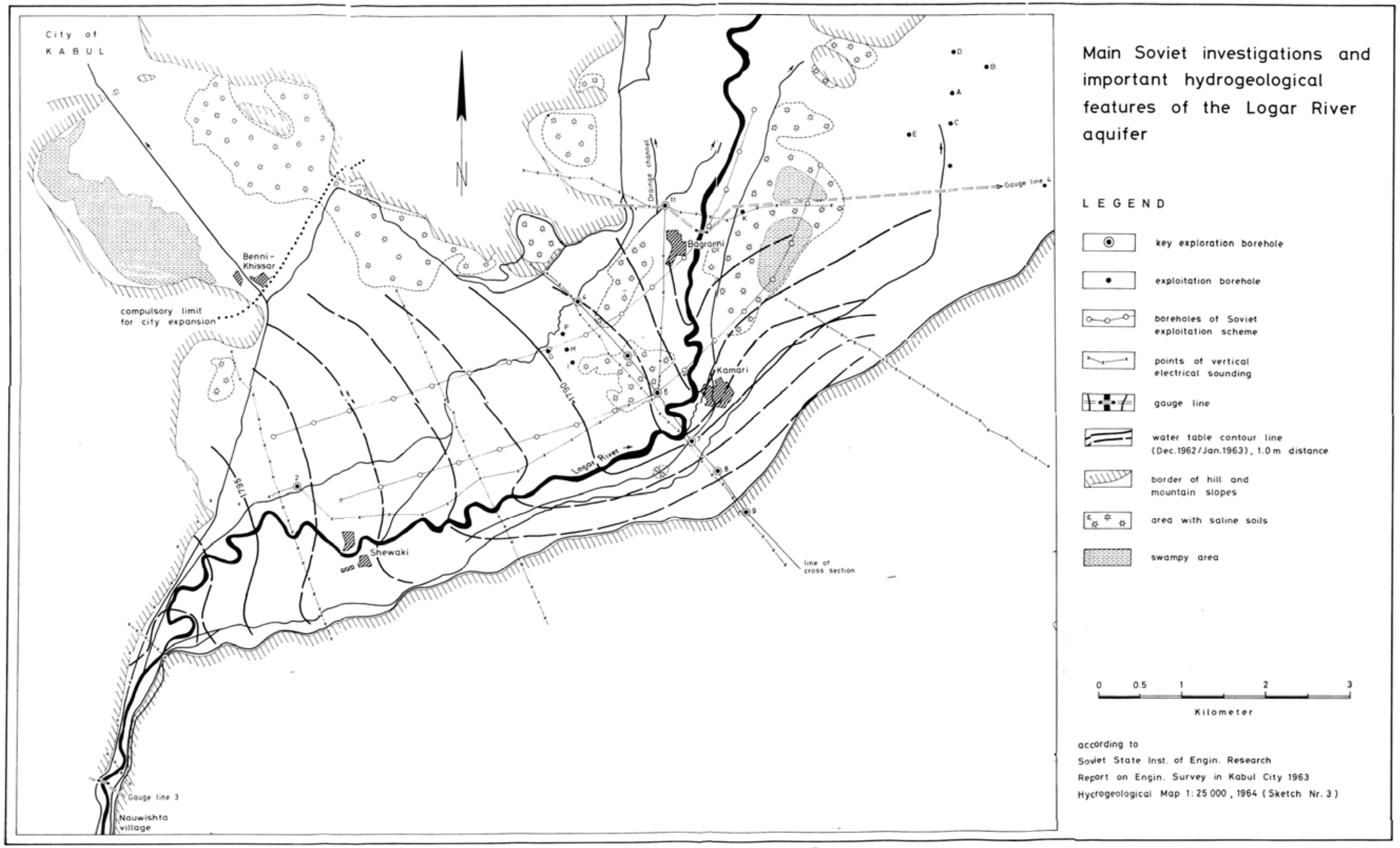
Appendix 1: Programme of the conference that took place on the 2nd and 3rd of August 2005 in Kabul

Time	Subject	Input presented by	Chairman	
02.08.2005				
8:30 – 9:00	Registration, Warming Up			
9:00 – 10:00	Opening Ceremony - Recitation - Opening Addresses	**Mr. Zia Masood** Vicepres. Gov. Afghanistan; **Mr. Ismael Khan** Minister for Energy and Water, **Mr. Mir Mohamed Sediq** Minister for Mines & Industries (Secretary General of High Commission for Coordination in the Water Sector) **Ms Annette Klein** German Deputy Ambassador; **Mr. Michael Schmidt-Thomé** (BGR)		
10:00 – 10:30	Tea Break			
10:30 – 12:00	Presentation: Outlines of River Basin Approach and New Institutional Set-Up of the River Basin Management (45 min), Discussion	**Mr. Sultan Mahmood** Dir. Water Resources, MEW **Mr. Hans Husselman** RODECO/GTZ	Mir Mohamed Sediq, Minister for Mines & Industries (Secretary General of High Commission for Coordination in the Water Sector) (10:30 - 17:00)	
12:00 – 13:30	Lunch-Break and Recitation			
13:30 – 15:00	Introduction (10 min)	**Mr. Thomas Himmelsbach** (BGR)		

	Presentation (40-60 min): Groundwater Resources of the Kabul Basin, Quantity and Quality (Report of the Kabul Groundwater Survey 2003 - 2005)	**Mr. Naim Eqrar** (KU) **Mr. Georg Houben** (BGR)		
15:00 – 15:30	Tea Break			
15:30 – 17:00	- Current State and Outlook of Groundwater Monitoring in Kabul Basin (10 min) - General Options for Groundwater Protection (20 min) - Discussion and Wrap up of the day	**Mr. Thomas Himmelsbach** (BGR) **Mr. Torsten Krekeler** (BGR)		
Second Day				
03.08.2005			Chairman	
9:00 – 9:30	Recitation, Summary 1st day, Overview 2nd day	**Mr. Thomas Himmelsbach** (BGR)**/** **Mr. Nadjib Yussufi** (InWEnt)	Mr. Kamaludin Nezami, Dep. Minister for Energy and Water (9:00 - 12:00)	
9:30 – 10:15	Key Issues of Monitoring and Evaluation (M&E) in the Water Sector (25 min)	**Mr. Werner Klinger** (MEW/GTZ)		
10:15 – 10:45	Tea-Break			
10:45 – 12:00	Critical Issues of Groundwater based Water Supply and Water			

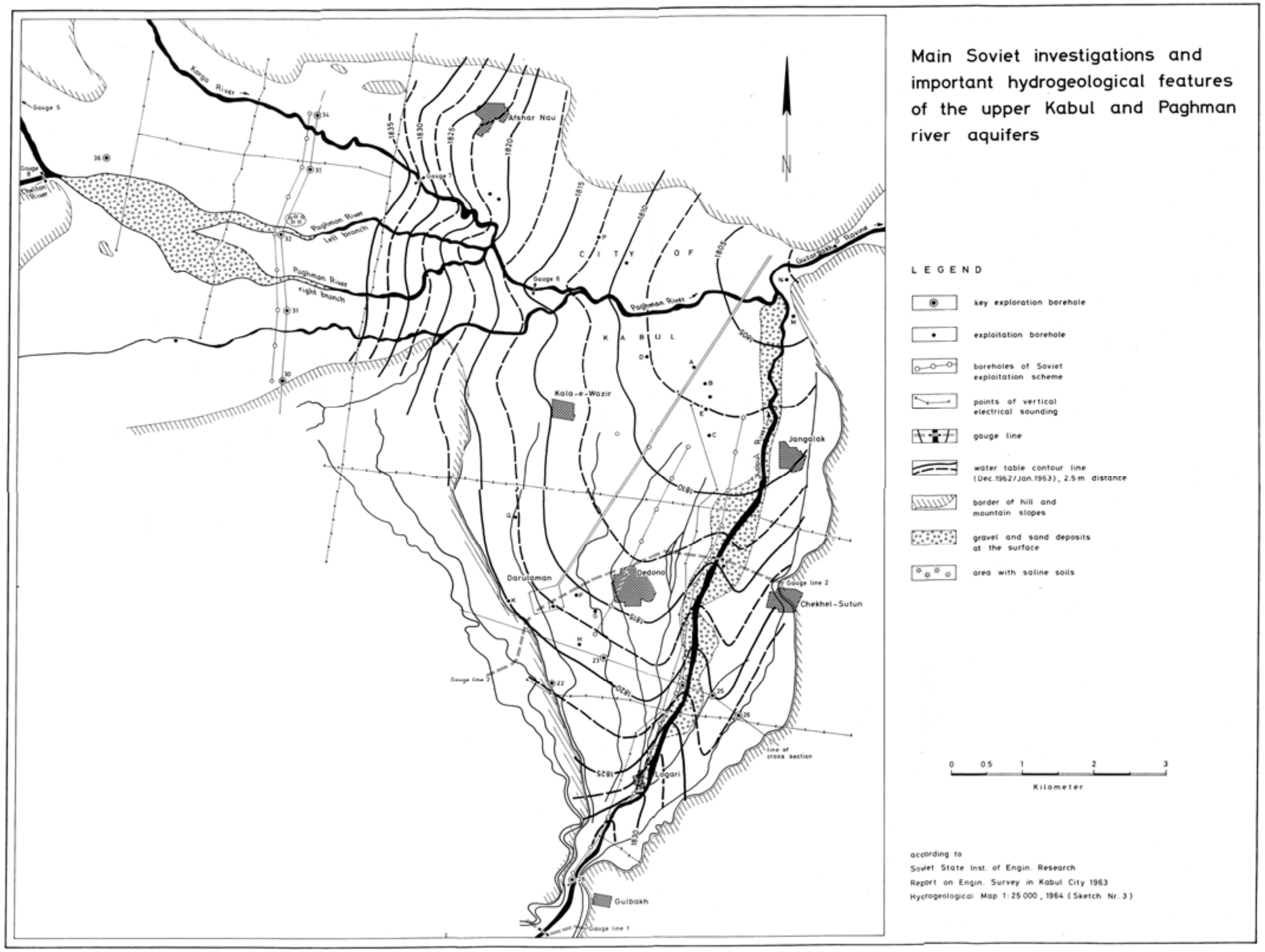
	Resource Management Experience from: - Kabul (20 min) - Kunduz River Basin Program	CAWSS Kabul/ **Mr. Bernd Fischäß** (Beller/KFW) **Mr. Frank Riedmann** (GAA) **Jelle Beekma** (EU Teamleader Kunduz River Basin Authority/ EU/GAA)		
12:00 – 13:30	Lunch break			
13:30 – 14:00	Water Resources Management	**Mr. Yussof Pashtoun** (Dep. Minister for Urban Development and Housing)		
14:00 – 15:00	Capacity Building and Training: Awareness Rising for Water Resource Management to Mitigate Natural Disaster	**Mr. Arez / Mr. Kai Yamaguchi** (InWEnt)	Mr. Yussof Pashtoun, Dep. Minister for Urban Development and Housing (14:00 - 17:00)	
15:00 – 16:00	Discussion - Recommendations from Workshop: Needs, Options and Next Steps in Enhancing the Groundwater Monitoring, Managing and Awareness Rising Capacity (Proposals)	Facilitator: **Mr. Jallalzada** Board members: • **MMI** • **MEW** • **MoUDH** • **BGR/GTZ** Moderator**: Mr. Nadjib Yussufi**		
16:00 – 17:00	Wrap-up and Closing Session Summary / Preparation of Proposals	**All**		

Appendix 2a: Investigations zone in the Kabul basin along the Logar river



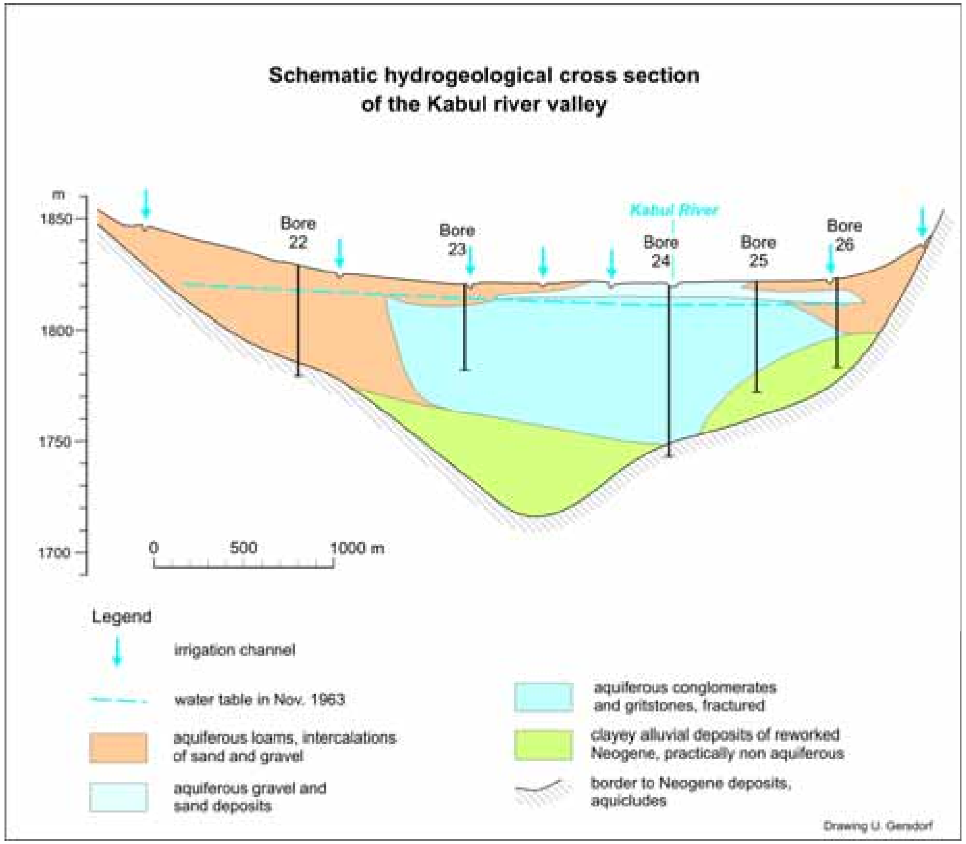
Source BÖCKH, E.G, 1971, Report on the Groundwater Resources of the City of Kabul, Report for BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE [unpublished]; BGR file number: 0021016

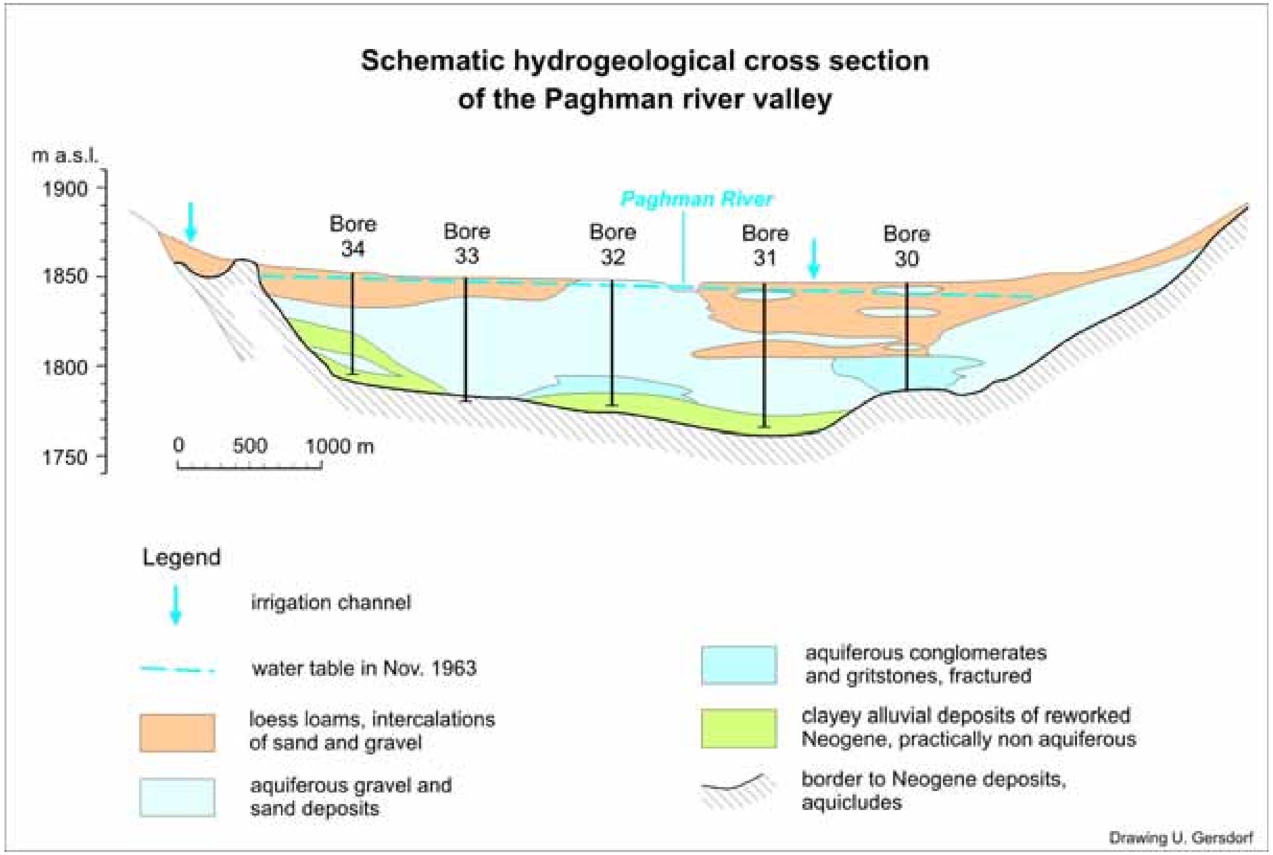
Appendix 2a: Investigations zone in the Darulaman basin

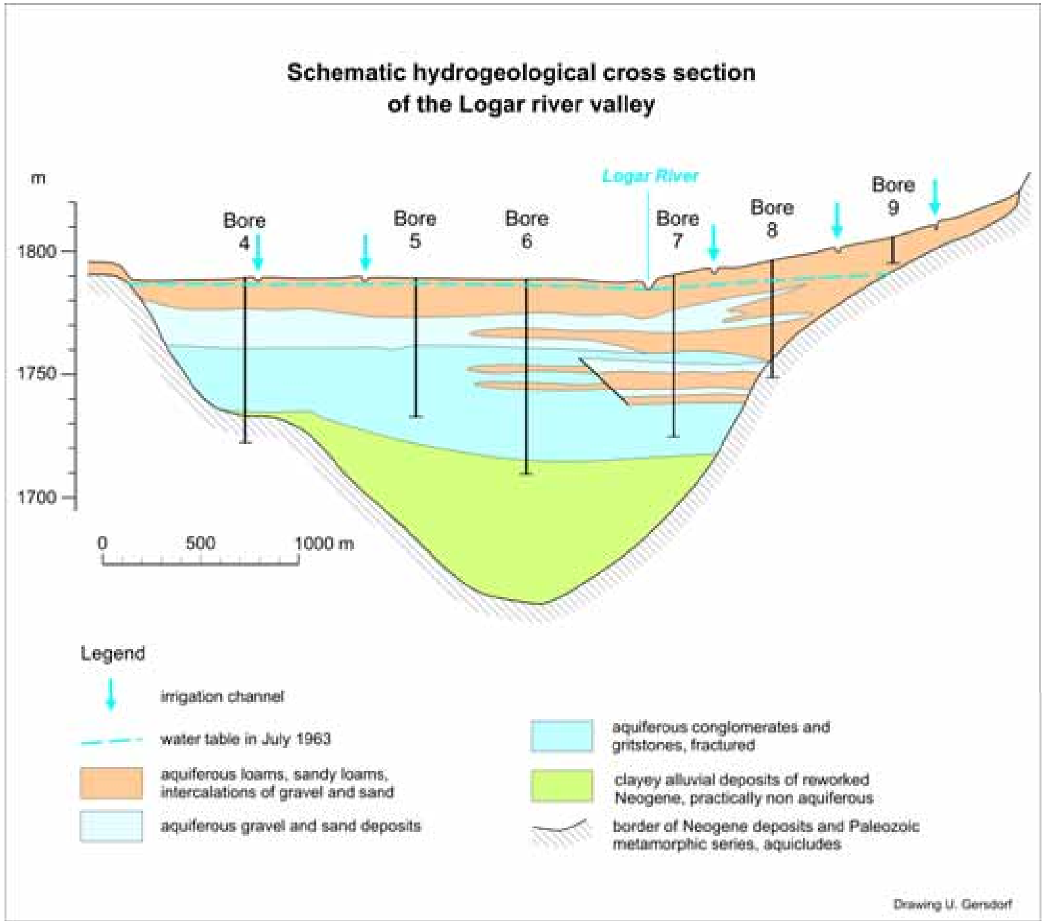


Source BÖCKH, E.G, 1971, Report on the Groundwater Resources of the City of Kabul, Report for BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE [unpublished]; BGR file number: 0021016

Appendix 3: Geological profils available after the russian investigations

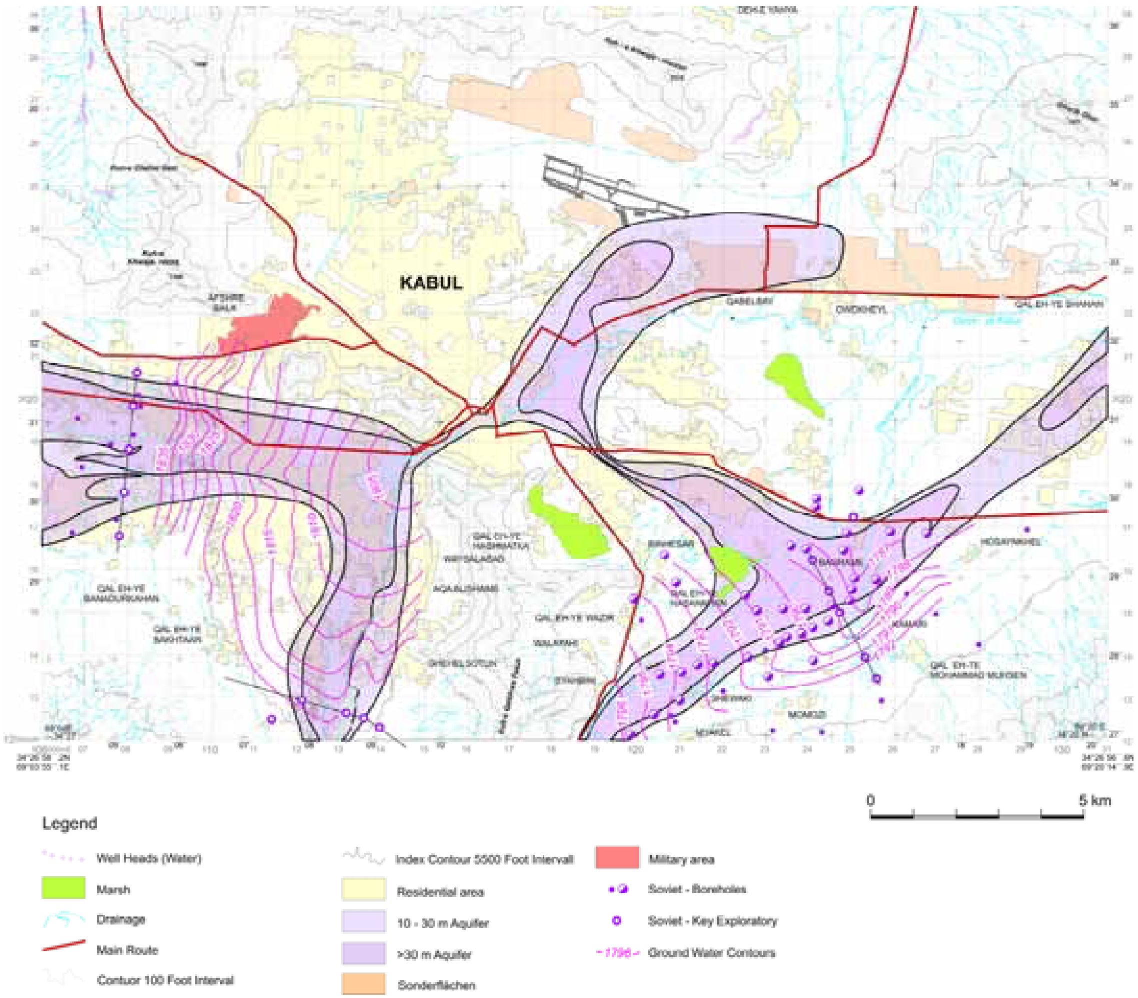



Schematic hydrogeological cross section
of the Paghman river valley
m a.s.l.
1900
1850
1800
1750
Paghman River
Bore 34
Bore 33
Bore 32
Bore 31
Bore 30
0
500
1000 m
Legend
irrigation channel
water table in Nov. 1963
loess loams, intercalations of sand and gravel
aquiferous gravel and sand deposits
aquiferous conglomerates and gritstones, fractured
clayey alluvial deposits of reworked Neogene, practically non aquiferous
border to Neogene deposits, aquicludes
Drawing U. Gersdorf



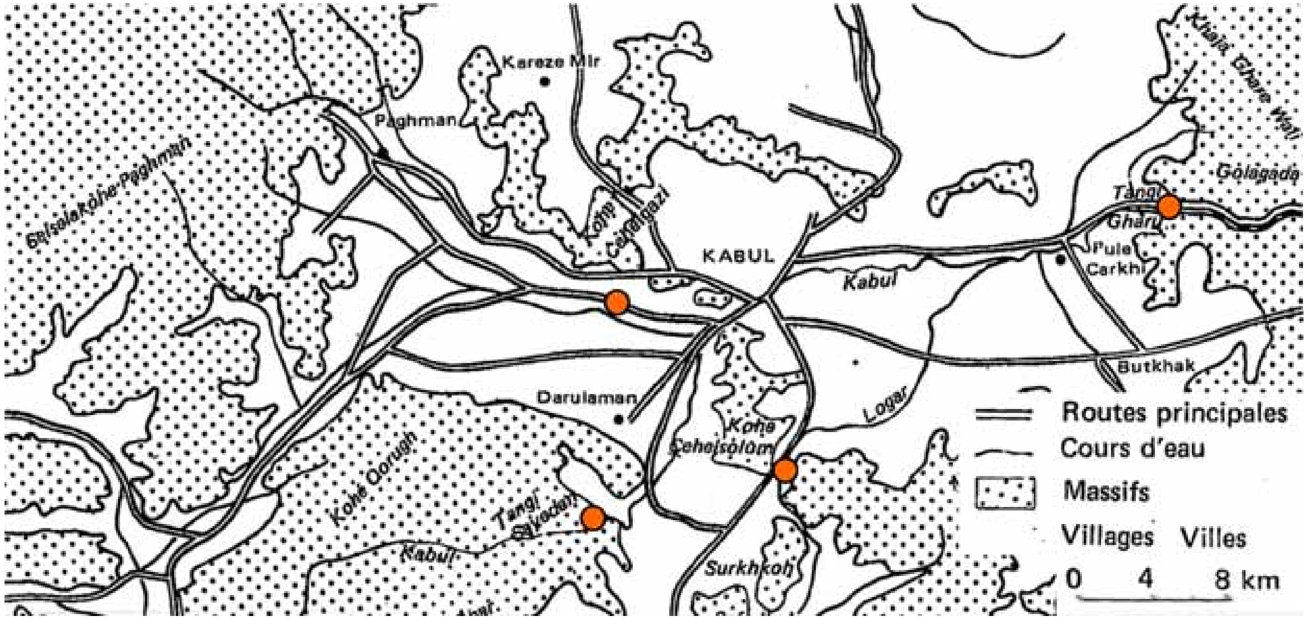
Source BÖCKH, E.G, 1971, Report on the Groundwater Resources of the City of Kabul, Report for BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE [unpublished]; BGR file number: 0021016
Reworked by Ulrich Gersdorf

Appendix 4: Possible orders of magnitude for the thickness of aquiferous layers after electrical sounding geophysics investigations



Source Map 1/25000 made by the DGIA, Ministry od Defense of the United Kingdom-2002 **Information** BÖCKH, E.G, 1971, Report on the Groundwater Resources of the City of Kabul, Report for BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE [unpublished]; BGR file number: 0021016
Reworked by Ulrich Gersdorf

Appendix 5: Rough localisation of the four river gauging stations



Source PIAS. J, 1976, Formations superficielles et sols d'Afghanistan, travaux et documents de l'ORSTOM n°55

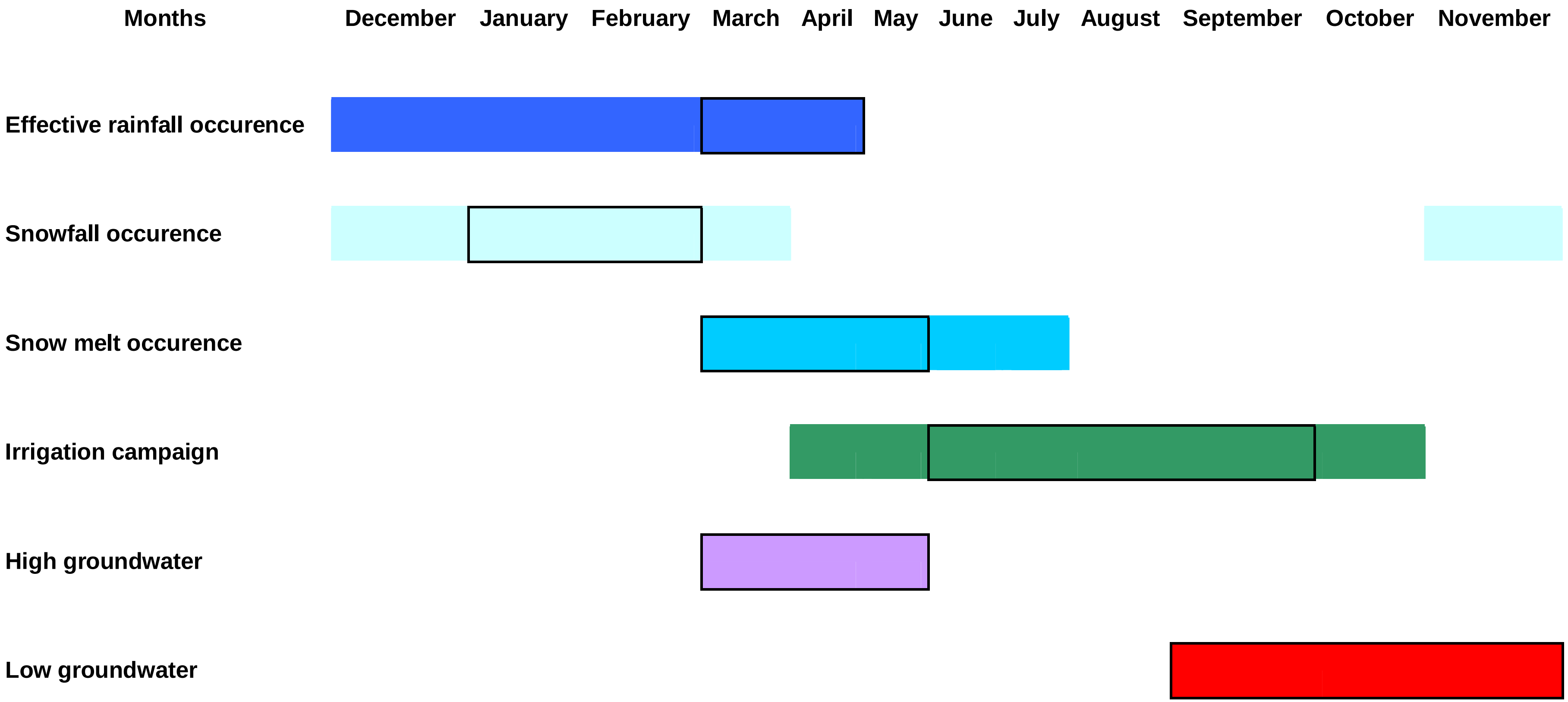
River gauging station:

- Tangi Saydan, 1850 m, upper Kabul ;
- Pule Sokhta, 1805 m, Paghman river upper Kabul-Paghman confluence ;
- Sange Nawesta, 1805 m, Logar river ;
- Tangi Gharu, 1770 m, Kabul river, outlet of the basin.

Source BÖCKH, E.G, 1971, Report on the Groundwater Resources of the City of Kabul, Report for BUNDESANSTALT FÜR GEOWISSENSCHAFTEN UND ROHSTOFFE [unpublished]; BGR file number: 0021016

Appendix 6: Possible hydrological year and values used for simulations

Proposed hydrological year



Potential head in rivers

Nodes	Ground surface elevation in m	River bed elevation estimates in m	Annual mean water level for steady state simulations
Kabul West	1804.7	1800.7	1802.3
Logar South	1804.7	1800.7	1803.0
Confluence	1779.7	1775.7	1778.2
Tangi Gharu	1770	1766	1768.7

VORF Kabul West	**Potential head in m**	Assumed water elevation in river in m
January	1801.7	1
February	1801.7	1
March	1803.2	2.5
April	1805.7	5
May	1804.2	3.5
June	1802.7	2
July	1801.7	1
August	1801.2	0.5
September	1801.2	0.5
October	1801.2	0.5
November	1801.7	1
December	1801.7	1

VORF confluence L-K	**Potential head in m**	Assumed water elevation in river in m
January	1779.2	3.5
February	1779.2	3.5
March	1780.2	4.5
April	1781.7	6
May	1778.2	2.5
June	1776.7	1
July	1776.2	0.5
August	1776.2	0.5
September	1776.2	0.5
October	1776.7	1
November	1778.2	2.5
December	1779.2	3.5

VORF Logar South	**Potential head in m**	Assumed water elevation in river in m
January	1804.2	3.5
February	1804.2	3.5
March	1804.7	4
April	1806.7	6
May	1802.2	1.5
June	1801.2	0.5
July	1801.2	0.5
August	1801.2	0.5
September	1801.2	0.5
October	1801.7	1
November	1803.2	2.5
December	1804.2	3.5

VORF Tangi Gharu	**Potential head in m**	Assumed water elevation in river in m
January	1770	4
February	1770	4
March	1771	5
April	1772	6
May	1770	4
June	1767.5	1.5
July	1766.5	0.5
August	1766.5	0.5
September	1766.5	0.5
October	1766.5	0.5
November	1768.5	2.5
December	1769.5	3.5

Valley flanks incomes (*see also Appendix 19 for localisation)

FLAE* North-western high (1)*	Volumes in m^3/m^2/months
January	0.000
February	0.000
March	0.0170
April	0.0170
May	0.0170
June	0
July	0
August	0
September	0
October	0
November	0
December	0.000

FLAE* North-western low (2)	Volumes in m3/m²/a
January	0.000
February	0.000
March	0.007
April	0.007
May	0.007
June	0
July	0
August	0
September	0
October	0
November	0
December	0.000

FLAE* North-eastern (3)	Volumes in m3/m²/a
January	0.000
February	0.000
March	0.0170
April	0.0170
May	0.0170
June	0
July	0
August	0
September	0
October	0
November	0
December	0.000

FLAE* South-western (4)	Volumes in m3/m²/a
January	0.000
February	0.000
March	0.01
April	0.01
May	0.01
June	0
July	0
August	0
September	0
October	0
November	0
December	0.000

FLAE* South-eastern (5)	Volumes in m3/m²/a
January	0.000
February	0.000
March	0.0170
April	0.0170
May	0.0170
June	0
July	0
August	0
September	0
October	0
November	0
December	0.000

Effective rain possible infiltration

FLAE* Rain	Volumes in m3/m²/a
January	0.023
February	0.023
March	0.023
April	0.023
May	0
June	0
July	0
August	0
September	0
October	0
November	0
December	0.023

FLAE* Rain	Volumes in m3/m²/a
January	0.0046
February	0.0046
March	0.0046
April	0.0046
May	0
June	0
July	0
August	0
September	0
October	0
November	0
December	0.0046

Withdrawals

Withdrawals in wells of the Sixties

UTM latitude in m	UTM longitude in m	KNOT attributed to the node	Volumes in m3/node/month	Volumes in m3/node/a
517175.329	3820013.07	1052	-90720	-1088640
518119.423	3819563.5	10266	-103680	-1244160
516725.76	3820597.51	9204	-64800	-777600
517430.084	3819563.5	1062	-64800	-777600
525117.707	3816362.58	1064	-77760	-933120
524952.865	3815643.27	1063	-90720	-1088640
525027.793	3817231.74	1061	-259200	-3110400

Withdrawals in urban zone

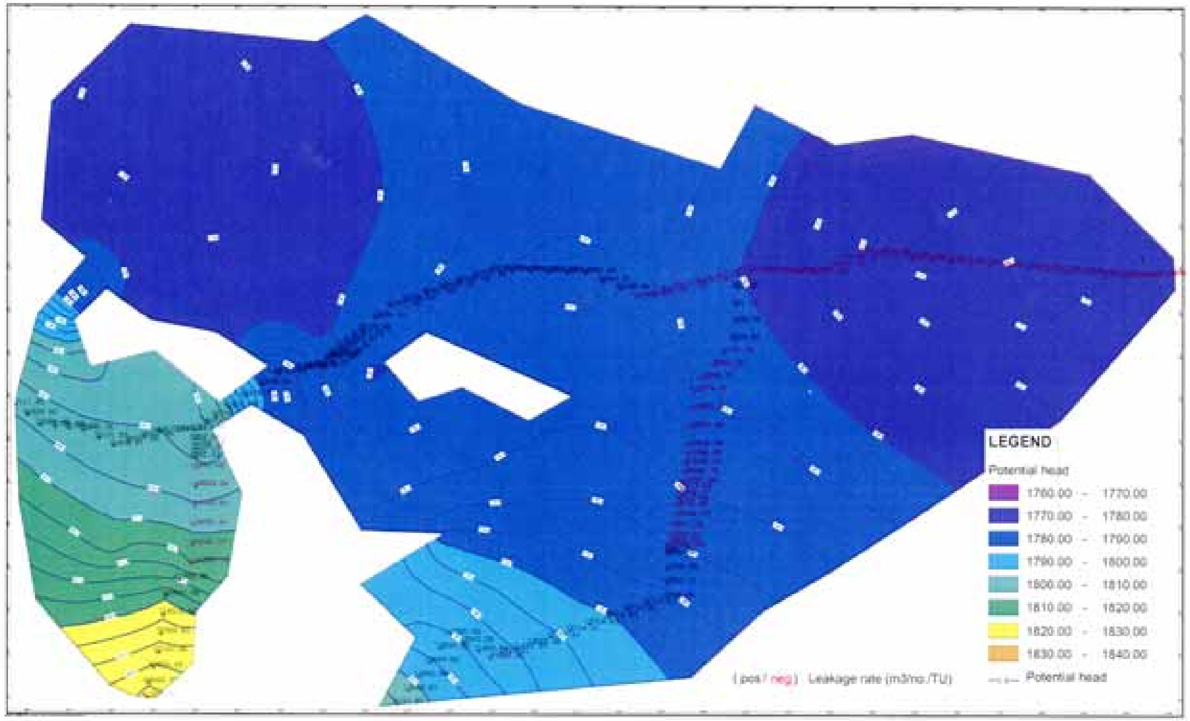
FLAE* volumes in m3/m²/month	-0.055
FLAE* volumes in m3/m²/a	-0.66

Appendix 7: Functions used to take into account different parameters in the model

Functions	Parameters	Attributed to elements E or nodes N	units
BILK et BILE	Mass balance	N or E	without dimension
EICH	Potential head	N	m
FLAE	Infiltration rate	E or area	m³/area/TU (*) or "*" m³/m²/UT
GELA	Ground level	N	m
KNOT	Inflow or outflow rate	N	m³/N/TU ou "/" m³/list/TU
KWER	Hydraulic conductivity	E	m/s
LERA	Leakage coefficient	N	m/TU
MAEC	Thickness	E	m
PORO	Porosity	N	without dimension
POTE	Potential head	N	m
SPEI	Storage coefficient	E	without dimension
UNDU	Impervious layer	N	m
UNTE	Aquifer basis		m
VORF	Potential head along stream courses	N	m

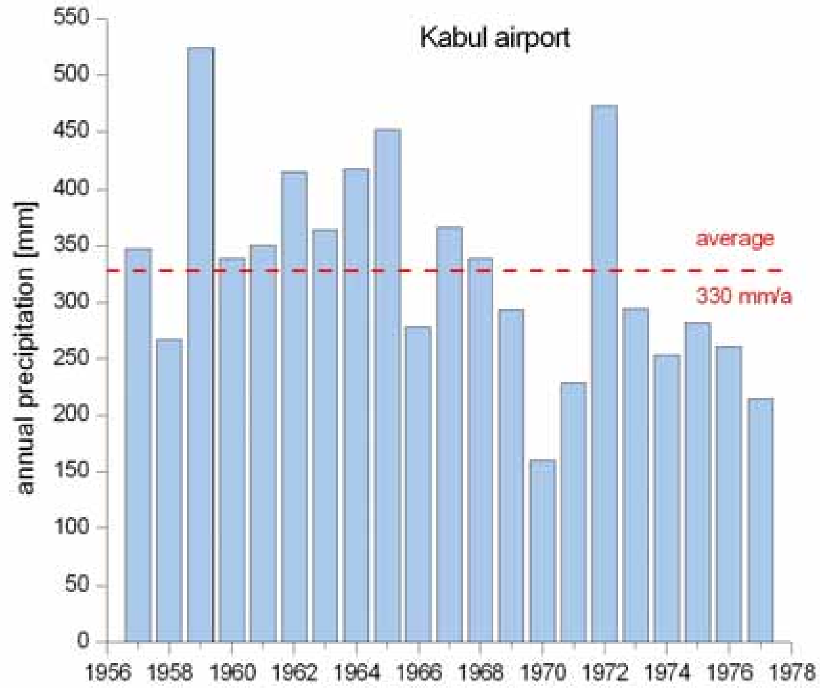
(*) TU Time Unit

Appendix 8: Old numerical model and groundwater flow between the Darulaman and the Kabul basins



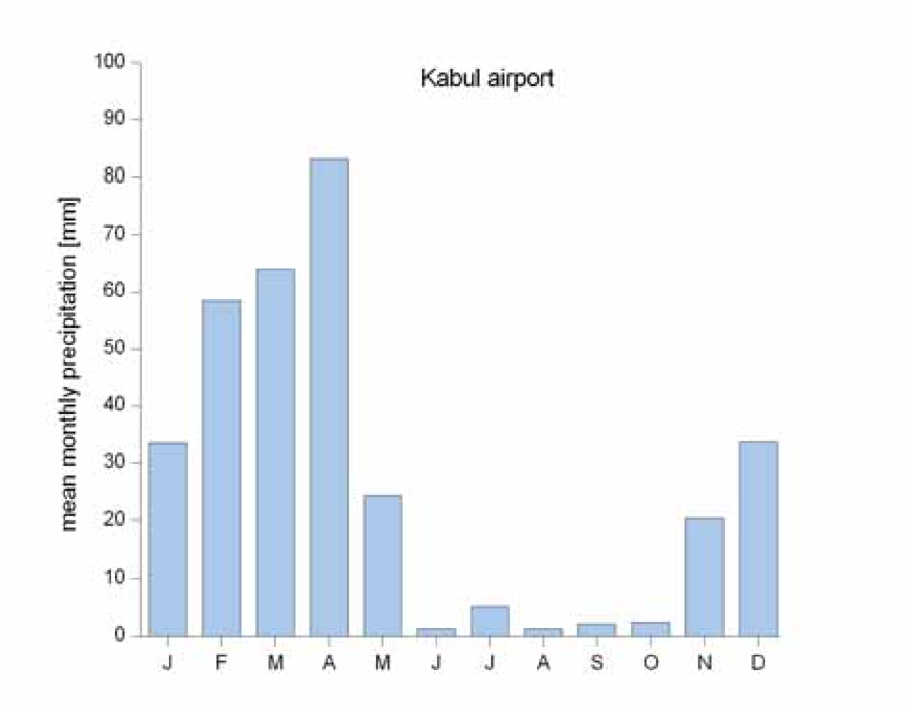
Source NIARD.N, 2005, Approche par modélisation pour améliorer la compréhension du fonctionnement hydrogéologique dans la région de Kaboul, BGR

Appendix 9: Annual mean rainfall

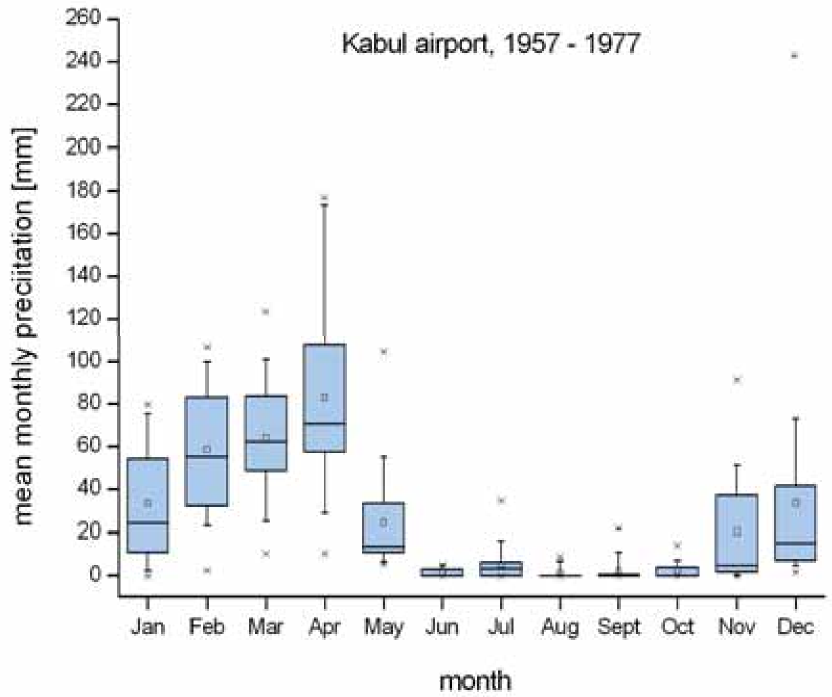


Source HOUBEN. G, TUNNERMEIER.T, 2005, Hydrogeology of the Kabul Basin, geology, aquifers characteristics, climate and hydrography, BGR file number: 10277/05

Appendix 10: Monthly mean rainfall



Appendix 11: Whisker plot diagram showing the spread of the possible monthly rain values



Source HOUBEN. G, TUNNERMEIER.T, 2005, Hydrogeology of the Kabul Basin, geology, aquifers characteristics, climate and hydrography, BGR file number: 10277/05

Appendix 12a: Effective rain calculated after Turc

$$AET_{Turc} = N / [\ 0{,}9 + (N/Jt)^2\ ]^{0,5}$$

With:

- N = Annual amount of rain in mm
- $Jt = 300+25*t+0{,}05*t^3$

t = Annual mean temperature in °C

Years	Annual amount of rain in mm	Annual mean temperature in °C	**Actual ET Turc in mm**	**Effective rain in mm**
1957	347.1	10.40	314.60	**32.50**
1958	267.2	12.51	261.83	**5.37**
1959	523.9	11.75	427.38	**96.52**
1960	339.4	11.98	317.18	**22.22**
1961	350.6	12.22	326.46	**24.14**
1962	415.5	12.00	369.22	**46.28**
1963	364.2	12.88	339.68	**24.52**
1964	418.1	10.27	357.39	**60.71**
1965	451.5	11.38	385.70	**65.80**
1966	278.1	11.90	269.30	**8.80**
1967	366.6	11.29	332.73	**33.87**
1968	339.4	11.04	312.67	**26.73**
1969	293.8	11.80	281.64	**12.16**
1970	159.9	12.98	164.27	**-4.37**
1971	228.3	12.92	228.57	**-0.27**
1972	472.6	10.84	391.89	**80.71**
1973	295	12.03	283.33	**11.67**
1974	253	11.58	247.62	**5.38**
1975	281.7	10.98	269.39	**12.31**
1976	260.8	12.13	255.52	**5.28**
1977	215	13.00	216.56	**-1.56**
Annual mean	329.6047619	11.80321429	302.52	**27.08**

Appendix 12b: Effective rain calculated after Ivanov

$$ETo_{Ivanov} = 0,0011 * (T+25)^2 * (100-U)$$

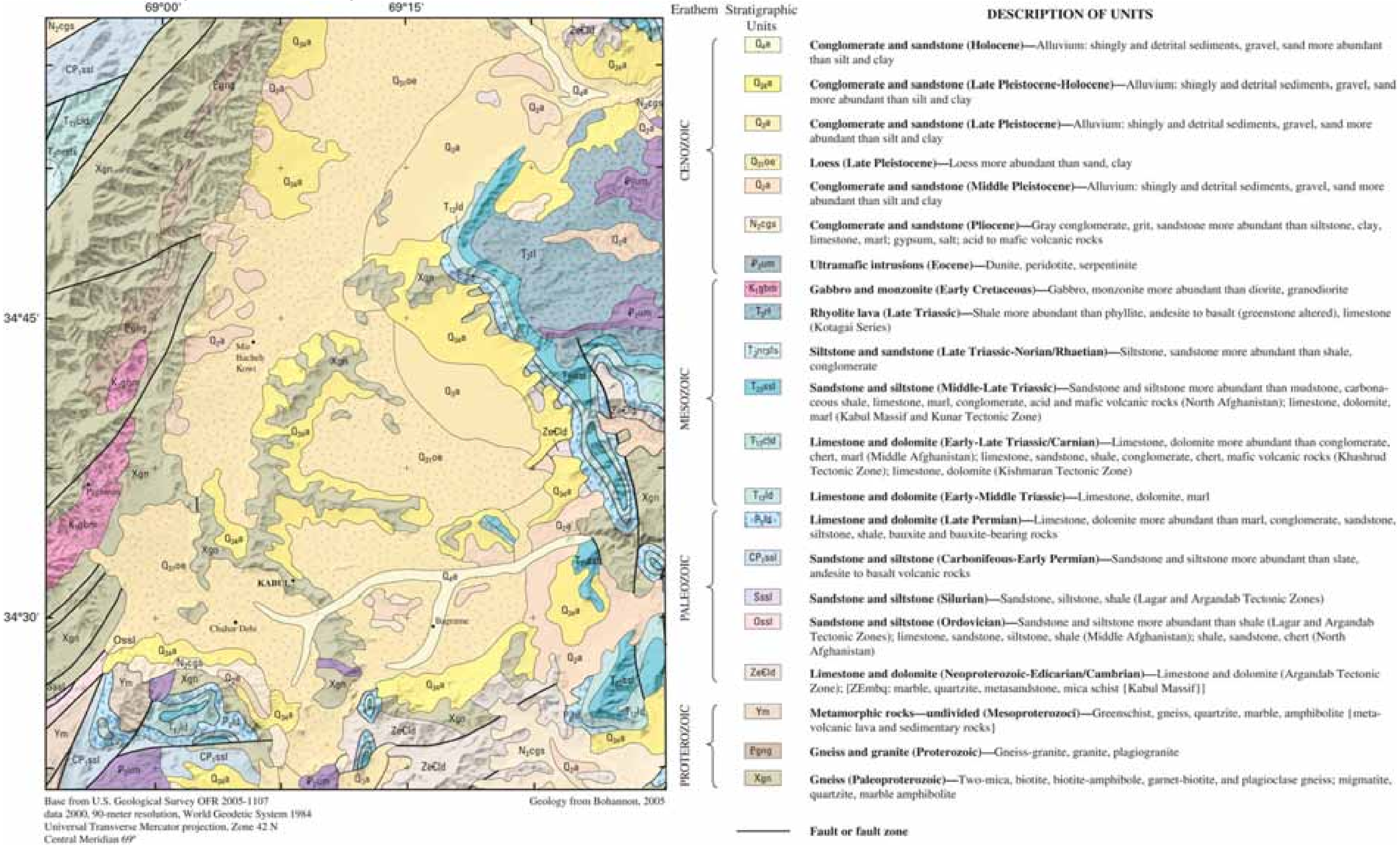
With:
- T = Monthly mean air temperature in °C
- U = Monthly mean air moisture in %

ETo_{Ivanov} = amount of water evapo-transpirated in one month in mm

Months	Monthly mean Rainfall in mm	ETo Ivanov in mm	Effective rain in mm
December	33.61	28.96	**4.65**
January	33.5	19.84	**13.66**
February	58.55	20.87	**37.68**
March	64.01	35.19	**28.82**
April	83.17	51.86	**31.31**
May	24.33	77.19	0
June	1.28	139.1	0
July	5.18	147.29	0
August	1.21	147.61	0
September	2.08	132.53	0
October	2.37	93.2	0
November	20.3	46.34	0
Annual amount	295.98	911.02	111.47

Source NIARD.N, 2005, Approche par modélisation pour améliorer la compréhension du **fonctionnement hydrogéologique dans la région de Kaboul, BGR**

Appendix 13: Geological map of the region



Source E. Broshears, M. Amin Akbari, Michael P. Chornack, David K. Mueller and Barbara C. Ruddy, 2005, Inventory of the ground-water resources in Kabul basin, Afghanistan, Scientific investigations report 2005-5090-USGS

Appendix 14: Schematic geological profil of Kabul basin

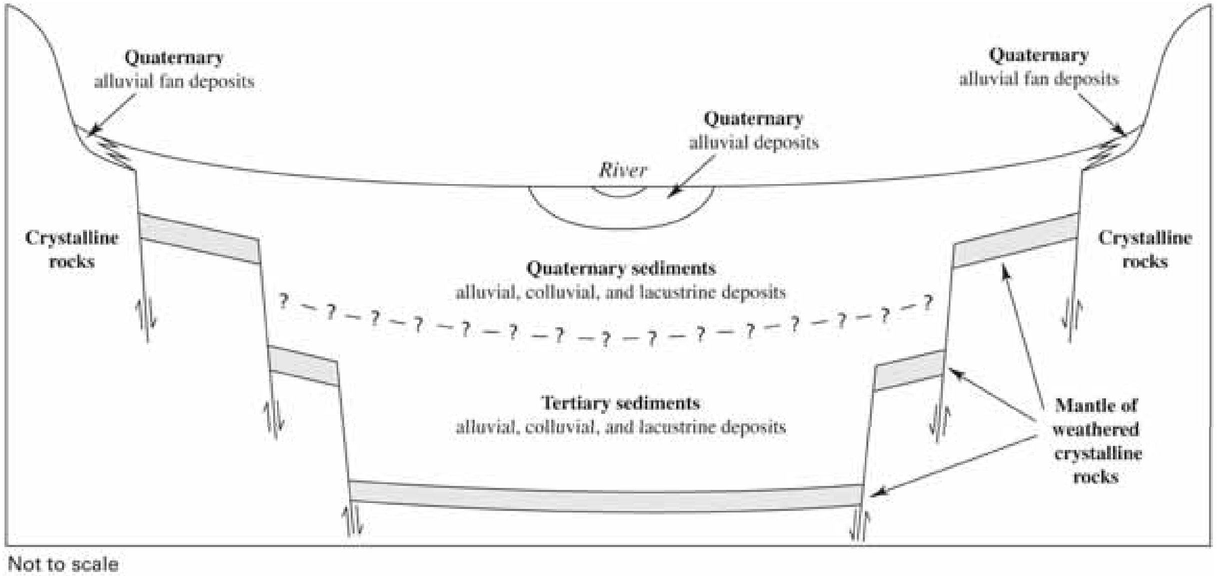
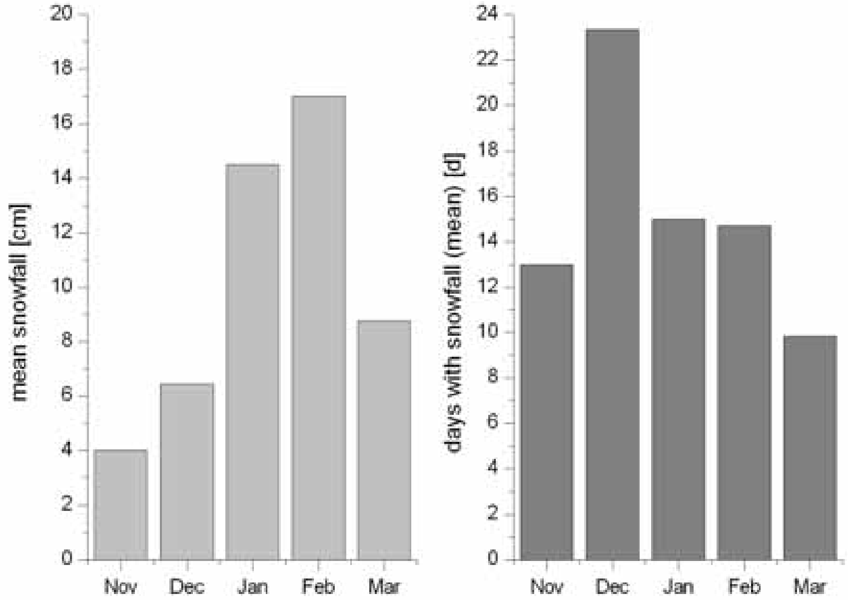


Figure 3b. Generalized section of hydrogeologic units.

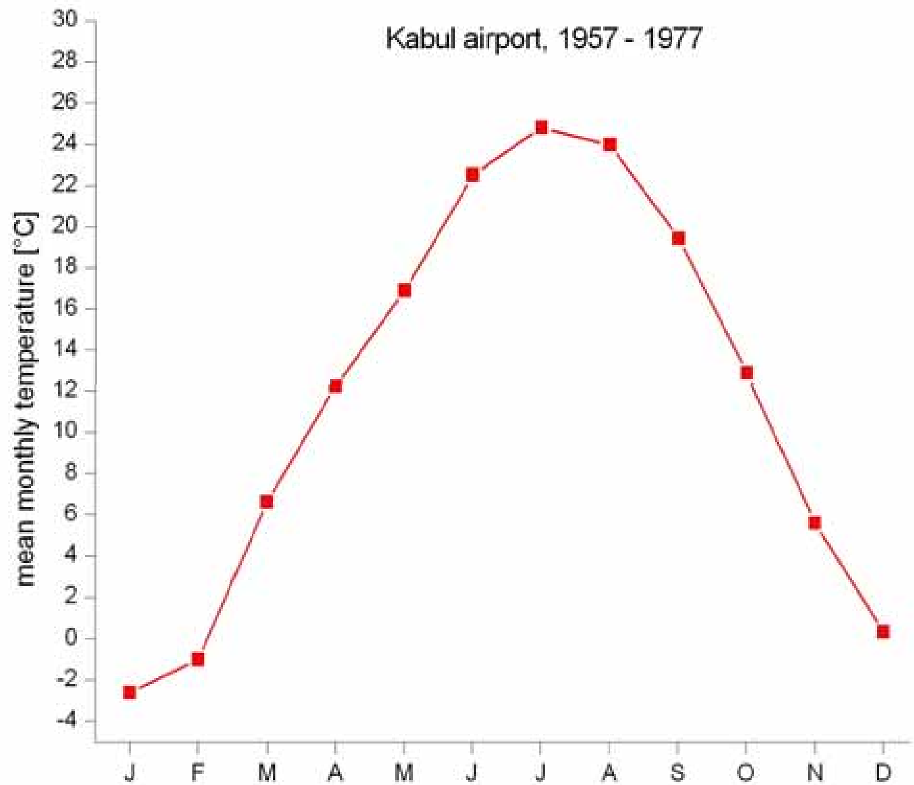
Source *E. Broshears, M. Amin Akbari, Michael P. Chornack, David K. Mueller and Barbara C. Ruddy, 2005, Inventory of the ground-water resources in Kabul basin, Afghanistan, Scientific investigations report 2005-5090-USGS*

Appendix 15: Snow cover and occurrences in Kabul plain



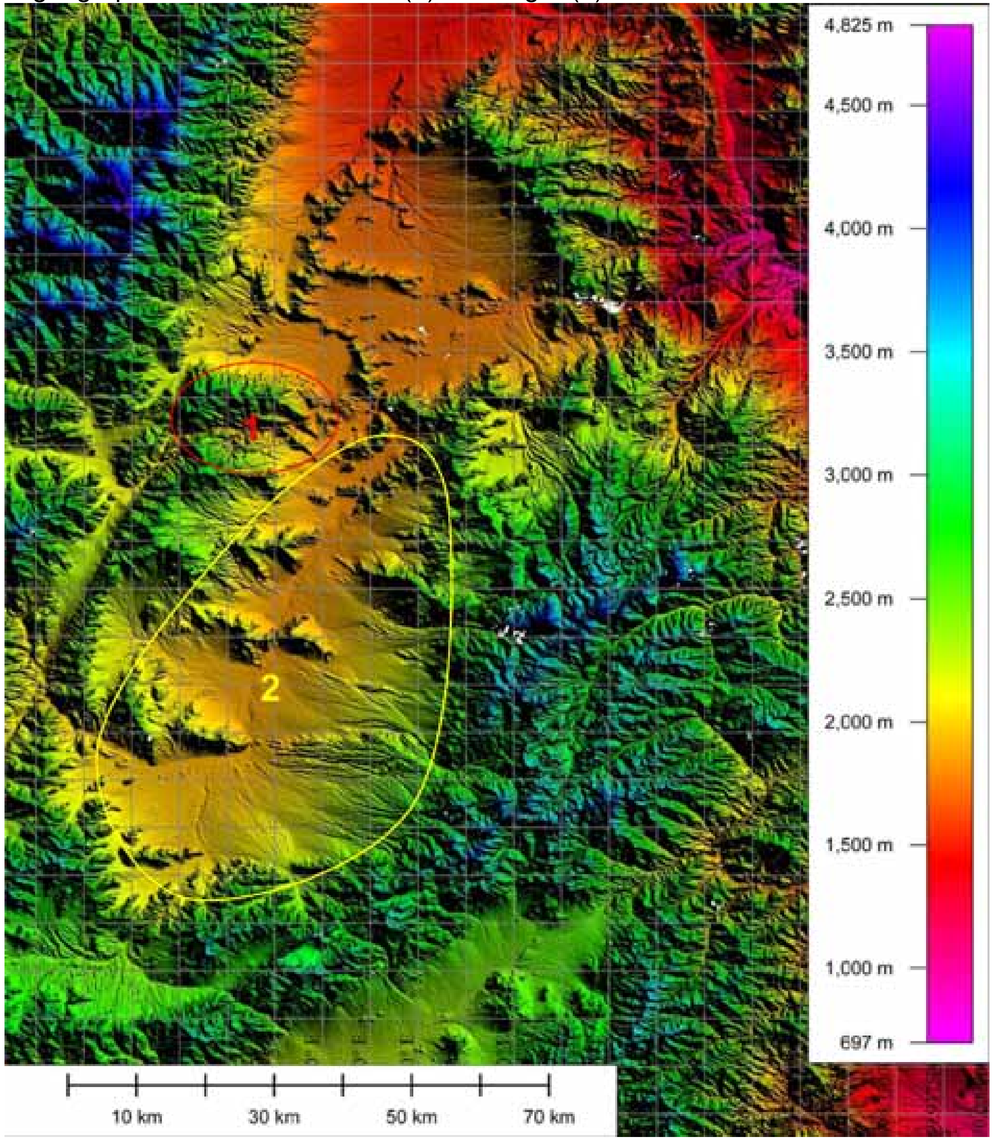
Source HOUBEN. G, TUNNERMEIER.T, 2005, Hydrogeology of the Kabul Basin, geology, aquifers characteristics, climate and hydrography, BGR file number: 10277/05

Appendix 16: Monthly mean temperatures



Source HOUBEN. G, TUNNERMEIER.T, 2005, Hydrogeology of the Kabul Basin, geology, aquifers characteristics, climate and hydrography, BGR file number: 10277/05

Appendix 17: View of the elevation and geographical form of the Kabul (1) and Logar (2) catchment basins



Source SRTM data, **http://srtm.usgs.gov/** The catchment areas are here coarsely made just in order to localise them.

Appendix 18: Effective porosity values given for different types of sediments and reservoirs

Valeurs et facteurs de la porosité efficace

Les valeurs de la porosité efficace sont données dans les tableaux 15 et 16.

Tableau 15 - Quelques caractéristiques de sédiments meubles. D'après documents de l'U.S. Geological Survey.

Types de sédiments	d_{10} mm	n %	n_e %	K m/s
Gravier moyen	2,5	45	40	3.10^{-1}
Sable gros	0,250	38	34	2.10^{-3}
Sable moyen	0,125	40	30	6.10^{-4}
Sable fin	0,09	40	28	7.10^{-4}
Sable très fin	0,045	40	24	2.10^{-5}
Sable silteux	0,005	32	5	1.10^{-9}
Silt	0,003	36	3	3.10^{-8}
Silt argileux	0,001	38	-	$*1.10^{-9}$
Argile	0,0002	47	-	$*5.10^{-10}$

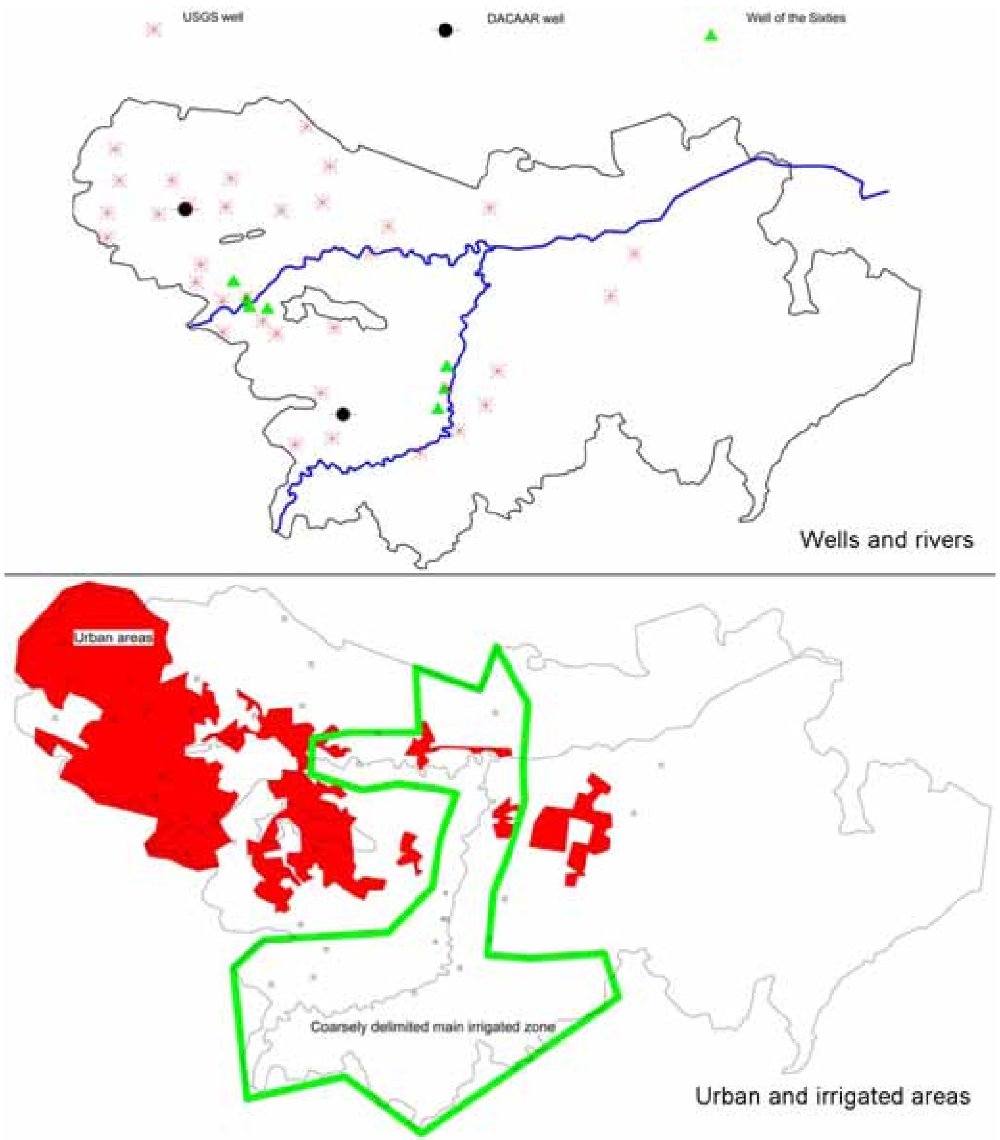
*Valeurs calculées

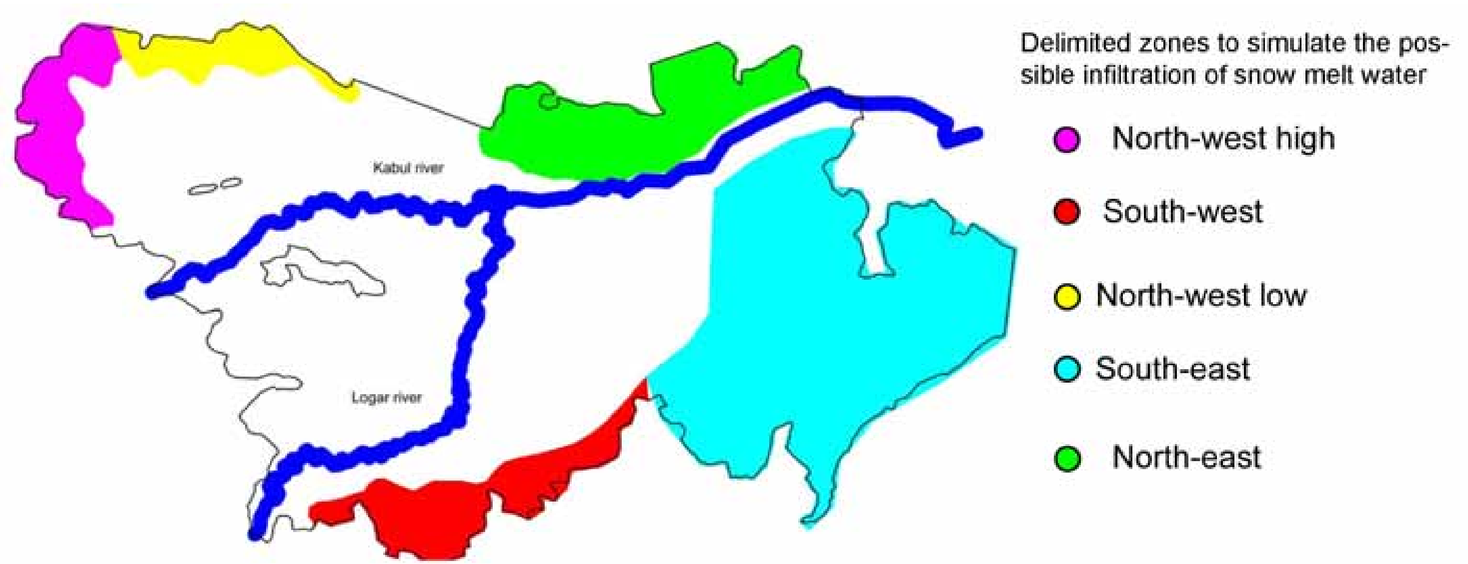
Tableau 16- Valeurs de la porosité efficace moyenne pour les principaux réservoirs

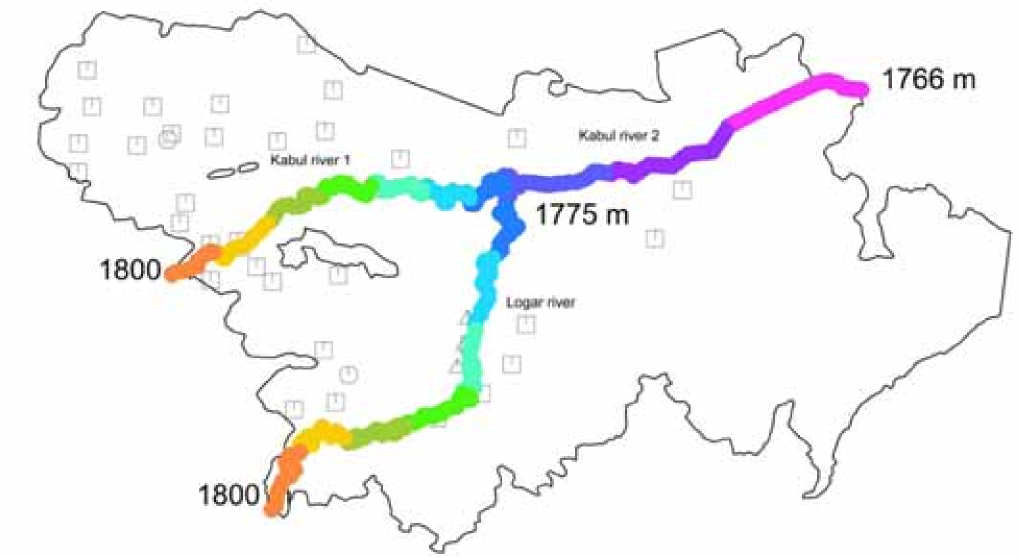
Types de réservoirs	Porosité efficace %	Types de réservoirs	Porosité efficace %
Gravier gros	30	Sable gros + silt	5
Gravier moyen	25	Silt	2
Gravier fin	20	Vases	0,1
Gravier + sable	15 à 25	Calcaire fissuré	2 à 10
Alluvions	8 à 10	Craie	2 à 5
Sable gros	20	Grès fissuré	2 à 15
Sable moyen	15	Granite fissuré	0,1 à 2
Sable fin	10	Basalte fissuré	8 à 10
Sable très fin	5	Schistes	0,1 à 2

Source G. Castany, Principes et méthodes de l'hydrogéologie, ed.Bordas, Paris 1982

Appendix 19: Structures of the model

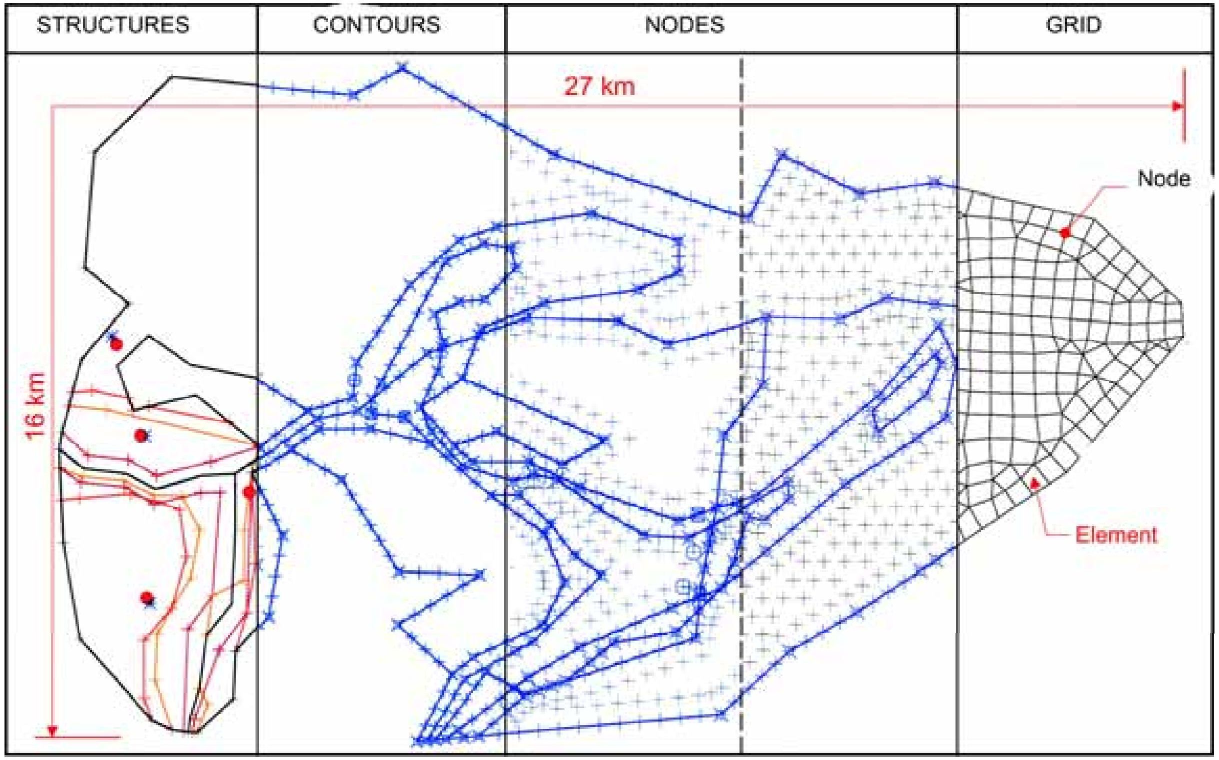






Interpolation of the potential head along river courses

Appendix 20: Different steps in the construction of a numerical model with SPRING, example with the old Kabul model.



Source NIARD.N, 2005, Approche par modélisation pour améliorer la compréhension du fonctionnement hydrogéologique dans la région de Kaboul, BGR

Appendix 21: Example of txt format used in SPRING

Format associated to the model

```
KNOT k 3 :
 1000000.00000 /     3-    12,    14-    18,    24,    27-   101,   131-   169,+
                              171-   172,   175,   179-   195,   519-   522,  1147,  1151,+
                            1166,  1705,  1710,  1727,  2110,
  735487.00000 /   102-   125,   127-   130,   301,   326-   327,  1066,
  223008.00000 /   170,   173-   174,   176-   178,   294,   523,   575-   576,
 -389333.00000 /   408,   654,  1134,  1189-  1190,

KWER e 3 :
       0.00050       1-  1858,  1860-  2392,  2394-  2398,

LERA ks3 :
   97200.00000     123,   208,   210,   209,   212-   213,   211,   215,   214,+
                   216,   218-   219,   217,   220,  1714,  1897,   221,  1894,+
                  1712-  1713,   222,   224-   226,   223,   228,  1729,   227,+
                  1731,  1989,   229,  1737,   231,  1741,   232-   233,   230,+
                   524-   525,   234,   236-   237,   235,   239-   242,   238,+
                   244-   245,   243,   247-   250,   252-   254,   251,   256,+
                   257,   255,   259-   260,   258,   262-   271,   261,   272,+
                   273,    22,
   97200.00000     196,   198,   197,   200-   201,   199,   203,   202,   205,+
                   206,   204,   207,   107,
   97200.00000     246,   275-   277,   274,   279-   281,   278,   283-   285,+
                  1801,   282,  1803,   286,  1807,   533,  1821,   548,  1824,+
                   549,  1830,  2079,   552,  1800,     1-     2,   288,   287,+
```

Format used for the transient state simulations

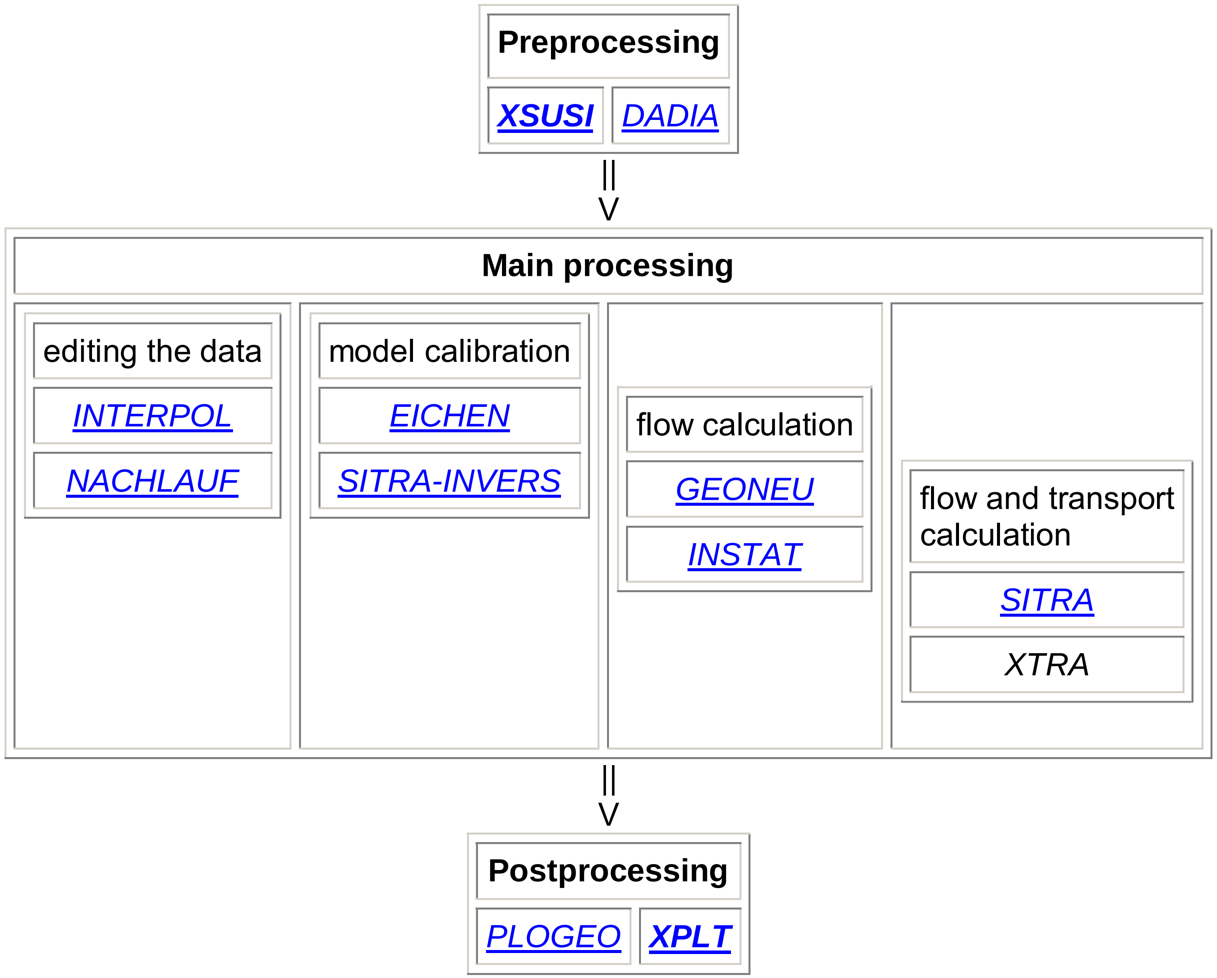
```
Modelisation of the groundwater flow in the area of the Kabul city
Hydrogeology of the Kabul basin - B.1.17 - BGR Hannover GERMANY
Test 0107-1156

ZEITEINHEIT MENG MONAT
ZEITEINHEIT ZEIT MONAT

ZEIT
1.0

KNOT
301   22851     102   22851     103   22851     104   22851     105   22851
106   22851     107   22851     108   22851     109   22851     110   22851
111   22851     112   22851     113   22851     114   22851     115   22851
116   22851     117   22851     118   22851     119   22851     120   22851
121   22851     122   22851     123   22851     124   22851     125   22851
326   22851     127   22851     128   22851     129   22851     130   22851
327   22851     1066  22851
170   22166     173   22166     174   22166     176   22166     177   22166
178   22166     294   22166     523   22166     575   22166     576   22166
408   77867     654   77867     1134  77867     1190  77867     1189  77867

FLAE
1     0.0041    2     0.0041    3     0.0041    4     0.0041    5     0.0041
6     0.0041    7     0.0041    8     0.0041    9     0.0041    10    0.0041
11    0.0041    12    0.0041    13    0.0041    14    0.0041    15    0.0041
16    0.0041    17    0.0041    18    0.0041    19    0.0041    20    0.0041
21    0.0041    22    0.0041    23    0.0041    24    0.0041    25    0.0041
26    0.0041    27    0.0041    28    0.0041    29    0.0041    30    0.0041
31    0.0041    32    0.0041    33    0.0041    34    0.0041    35    0.0041
36    0.0041    37    0.0041    38    0.0041    39    0.0041    40    0.0041
41    0.0041    42    0.0041    43    0.0041    44    0.0041    45    0.0041
46    0.0041    47    0.0041    48    0.0041    49    0.0041    50    0.0041
51    0.0041    52    0.0041    53    0.0041    54    0.0041    55    0.0041
```

Appendix 22: Description of the SPRING modules

- **XSUSI:** Makes it possible a structured generation of models. It provides interactive graphical mesh generation and modification, and allows attributes to be assigned. XSUSI has a menu management for the most SPRING modules;
- **DADIA:** Data processing and control, minimising the band width and index calculation;
- **INTERPOL:** Different algorithms to interpolate any data and assign the results to the finite element mesh;
- **NACHLAUF:** Output of data in any format, interface with ARC / INFO, interface with TECPLOT, calculation of streamlines and path lines;
- **EICHEN:** Automatic calibration of permeability, different algorithms of lowering, possible for 2D, 2D/3D and 3D models;
- **SITRA-INVERS:** Inverse calibration of permeabilities, specific storage coefficients, and leakage coefficients;
- **GEONEU:** Steady-state groundwater flow simulation with 2D, 2D/3D and 3D models, calculation of path lines;
- **INSTAT:** Transient groundwater flow simulation with 2D, 2D/3D and 3D models, calculation of path lines;
- **SITRA:** Steady-state and transient groundwater flow and transport simulation (2D horizontal and vertical models, 3D-models). Saturated / unsaturated, density dependent models and heat transport;
- **PLOGEO:** Plots of the results, e. g. equal-value lines, isosurfaces, breakthrough curves and three-dimensional plots;
- **XPLT:** shows the plots on the screen, where the user can edit them. Finally, the plots can be output to various types of printers and plotters. Besides, XPLT contains dialogue boxes for nearly all modules of SPRING to input the necessary parameters.

Source User’s manual

Appendix 23 Scheme of the functioning of SPRING



Source User's manual