Modelling of the water balances in the Río Turbio aquifer, Mexico

Revision of an existing hydrological model and application to the Río Turbio aquifer, Mexico

M.Sc. Thesis by Martine H.A. Johannes

August 2004

Hydrology and Quantitative Water Management group (WU)
Irrigation and Water Engineering Group (WU)
Instituto Mexicano de Tecnología del Agua (IMTA)

WAGENINGEN UNIVERSITY
WAGENINGEN UR

Modelling of the water balances in the Río Turbio aquifer, Mexico

Revision of an existing hydrological model and application to the Río Turbio aquifer, Mexico

MSc thesis Hydrology and Quantitative Water management (HWM-80326, 26 weeks) submitted in partial fulfilment of the degree of Master of Science in Hydrology and Water Quality at Wageningen University, the Netherlands

Martine H.A. Johannes

August 2004

Supervisor(s):
Dr. ir. H.A.J. van Lanen
Ir. P. Wester

Dra. G. Herrera Zamarrón
M.C. A. Güitrón de los Reyes

Hydrology and Quantitative Water Management group
Irrigation and Water Engineering Group
Wageningen University
The Netherlands
www.dow.wau.nl/whh
www.dow.wau.nl/iwe

Instituto Mexicano de Tecnología del Agua
Mexico
www.imta.mx

Research done as part of the Basin Synthesis Study of the Lerma-Chapala River Basin, Mexico for the Comprehensive Assessment of Water Management in Agriculture Program (CA) of the International Water Management Institute (IWMI).

PREFACE

With writing this preface the period of writing my thesis for the MSc-study Hydrology and Water Quality is coming to an end. It started almost a year ago with writing my research proposal, gathering information about Mexico and planning a flight to Mexico. Within two months of preparation I left for Mexico.

During this project I met many people who helped me to bring the project to an end and to write the report lying in front of you. These people mainly worked at the Instituto Mexicano de Tecnología del Agua (IMTA) in Mexico and at the Wageningen University (WU), The Netherlands. The main part of this project was carried out at IMTA, but it was finished at WU.

Hereby I would like to thank everybody at IMTA who helped me with the project but also everybody of IMTA who made my life in Mexico more pleasant, especially Graciela Herrera Zamarrón and Alberto Güitrón de los Reyes, my supervisors in Mexico. I also would like to say thanks to Henny van Lanen and Flip Wester, my supervisors in The Netherlands, for their guidance and comments.

I especially would like to thank Cipriana Hernandez Arce for letting me live in here house during my stay in Mexico and everything else she did for me.

Finally, I want to say thanks to my family and Roy Beld for their never ending support and trust in me.

Martine Johannes
Wageningen, 19 August 2004

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABSTRACT

The importance of water management is widely recognised. Tools are needed as a basis for developing policies to create and preserve a balance between the environment and humanity. Scientifically based models are an important tool in this respect.

At the Instituto Mexicano de Tecnología del Agua (IMTA) a hydrological model, based on the Stella platform, is available to calculate the distribution of the different amounts of water between the different sub catchments in the Lerma Chapala river basin. In this model groundwater is not incorporated firmly.

The objective of this study was to develop a model, on the basis of the current IMTA model, which describes the interaction between surface water and groundwater better. Based on a literature study the groundwater module of the SWAT-model (Soil and Water Assessment Tool) was found to fit best in the existing IMTA model. This model uses simple equations with available input data or data that are easily obtained. This SWAT-model uses a delay time for calculating the actual recharge. The changes in the aquifer are calculated with simple water balances. By inserting equations for return flow, base flow, percolation and transmission losses in the existing IMTA model an interaction between surface water and groundwater is incorporated in the model.

The final revised model is a spatially lumped, transient model which calculates different balances, but no groundwater or surface water flows. It is lumped due to spatially-averaged parameters and input data over one aquifer. Per aquifer an average is calculated for e.g. initial groundwater level.

In the state of Guanajuato, which is a part of the Lerma Chapala river basin, many studies have been carried out. From this state the Río Turbio aquifer was chosen for a case study. This aquifer is more or less one deep aquifer without disturbing aquitards. In 1995 and 1998 two studies were carried out. From these studies most of the data needed for the case study were available, but there is still a lack of data. For the case study the data set of 1995 was used, completed with assumptions for parameters like specific yield and delay time.

Simulations show that the concept of the model works properly in theory. The lack of data causes unreliability for the model for the Río Turbio aquifer. With more data this model is suitable for the management planning of IMTA. The model is revised in such a way that it can be used for different aquifers in the whole world, as long as the needed input data and boundary conditions are available.

The model is especially sensitive for the initial condition of the soil moisture module, the distribution of the precipitation, the specific yield, the delay time, the inflow at San Germán, the area that is irrigated with groundwater and the boundary flow of groundwater. All these input data are not measured, but estimated, calculated or calibrated. With more measured data the true values can be used as input data, which will improve the results of the model significantly.

The five scenarios that are simulated with the revised model show an indication of how the area reacts to measures. No real values for the area can be calculated due to the uncertainties of input data. But the trends are that the replacement of groundwater extractions by surface water extractions diminishes the drop of groundwater level. If this is

combined with a reduction of irrigated area, more water will recharge and this also has a positive effect on the groundwater level. But it is not likely that farmers will reduce their irrigated area.

1 INTRODUCTION

1.1 Scope and research outline

Irrigation in Mexico has a long history. As early as 1500 B.C. the people developed a system of water control. Nowadays farmers are still irrigating their crops.
In the Lerma-Chapala river basin, which covers some 54,300 km^2 in Central-Mexico, the farmers are irrigating with groundwater and surface water (Wester et al, 2004). Due to the irrigation the Lerma-Chapala river basin faces huge problems with lack of water. So much groundwater is extracted from the basin that the groundwater levels are dropping very fast. The average drop is about 2 m/year (Scott et al., 1999). This drop of the groundwater levels also results in subsidence.
The Lerma river used to be a draining river, nowadays recharge from surface water takes place (river recharge). On the other hand, more surface water is supplied for irrigation than the crops need. This might mean that some return flow to the aquifers takes place.

The Lerma river drains into Lake Chapala. This is the biggest natural lake in Mexico with a length of 77 km and a width of 23 km (Wester et al, 2004). Due to the irrigation with surface water a drop of water level in Lake Chapala takes place. Lake Chapala used to discharge its surplus into the Santiago River, but not in the last few years, due to the intensive use of water in the Middle and Lower Lerma basins. The decline of the surface water level of Lake Chapala also results in diminishing water quality.

Hydrological models can be a useful tool for research, planning and water basins management. There are a lot of different types of models, each with their own specific characteristics. Some are, for example, used to simulate the change of groundwater levels over time, others are used to compute the water balance of a catchment.

At the Instituto Mexicano de Tecnología del Agua (IMTA) a hydrological model is available to calculate the distribution of the different amounts of water between the different sub-catchments in the Lerma-Chapala basin. With this model the management of the Lerma-Chapala basin is planned per year. The model, however, is still not complete. It simulates the surface water part of the catchment, but there is hardly a link with groundwater. The model considers that recharge of the aquifer takes place (Aparicio Mijares et al, 2001. In the model the recharge is modelled with a recharge coefficient. There is a groundwater balance in the existing model, to which the recharge is added and from which water abstractions are subtracted. The calculation of the volume of water in the aquifer does not represent the actual situation. In this thesis a more realistic model for the groundwater module will be developed.

1.2 Problem definition

To come up with feasible solutions for the drop of groundwater levels and surface water levels, a hydrological model might contribute. IMTA already has modelled the Lerma-Chapala river basin, but the interaction between groundwater and surface water is not yet adequately described by these models. This research describes how the model can be revised to get a more robust groundwater model component and to incorporate a better interaction between surface water and groundwater into the model.

1.3 Objective

The objective of this study is to develop a model on the basis of the current model which describes better the interaction between surface water and groundwater. This model can be used to come up with possible solutions to diminish or reverse the decline in both groundwater level and surface water level.

1.4 Main question

This research will answer the following question.

> *How can a hydrological model be developed, based on the current model, so that this revised model can be used for simulating the changes in storage in the aquifer and the interaction between groundwater and surface water in different sub catchments in the Lerma-Chapala river basin to arrive at scenarios to reverse groundwater level decline?*

For this research a case study is done in one of the aquifers in the Lerma-Chapala river basin; the Río Turbio. This aquifer is chosen, because it is a comprehensible small area with clear boundary conditions.

1.5 Structure of the report

The objective of this study is to find a way to change the existing model and to incorporate the groundwater balance in the existing model. To get from the existing model to a model that describes both groundwater and surface water balances, there are a few steps that have to be taken.

In chapter two the area of the Lerma-Chapala basin is described. With the revised model a case study is done in one subcatchment of the river basin and scenarios are simulated. In chapter two the choice of the aquifer for the case study is explained and the area of the case study is described.

Chapter three is about the existing IMTA model using the Stella platform; Stella in general and how Stella has been used by IMTA to develop their hydrological model. With the information in chapter two and three it is more clear what type of model approach is required for changing Stella.

Chapter four reviews different existing models that can describe the groundwater flow. Selection of the most suitable model is discussed and how to fit this in to the rest of the existing model. In this chapter the revision of the existing model is also described.

In chapter five the input data that are used are described, as well as the results of the calibration and the sensitivity analysis.

Chapter six describes the simulation and the results of the scenarios and the associated sensitivity analysis.

In the final chapter, chapter seven, the conclusions and the recommendations are given.

2 DESCRIPTION OF THE AREA

2.1 Lerma-Chapala

The Lerma-Chapala basin covers some 54,300 km^2 (Wester et al, 2004) and is situated in central Mexico. The basin lies in five different states: Querétaro (5%), Guanajuato (44%), Michoacán (28%), Mexico (10%) and Jalisco (13%). The Lerma river runs from the east of the basin, near the city of Toluca at an elevation of 2600 m + MSL, to the west of the basin to end up after a travel of 708 km in Lake Chapala at an elevation of 1500 m + MSL (figure 2.1). With a length of 77 km and a width of 23 km this lake is Mexico's largest natural lake. It is a shallow lake (average depth is 7.2 m) and that causes a lot of problems with the quality of the water. In the past Lake Chapala discharged its water to Santiago river, but the last few years there has been no discharge due to the extractions in the catchment.

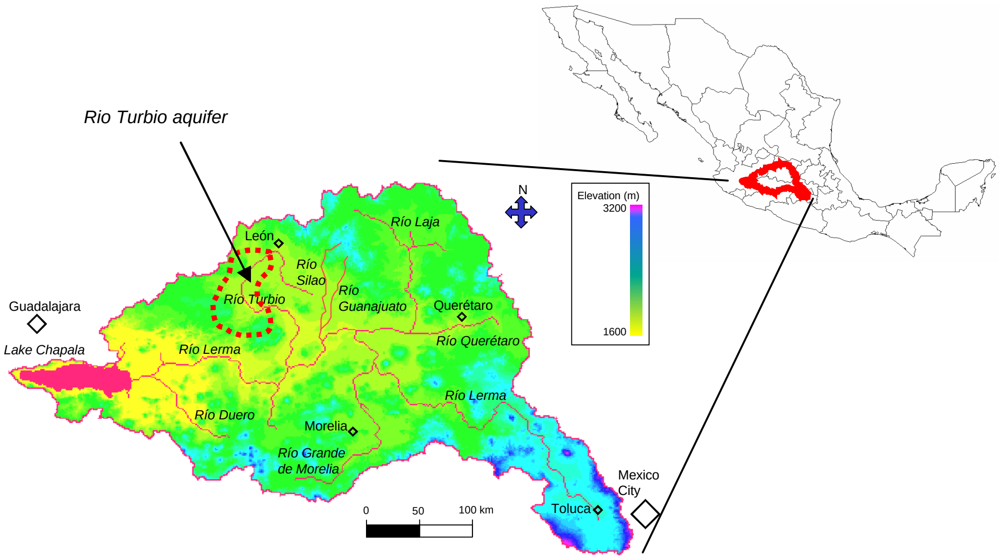


Figure 2.1: Location Lerma-Chapala basin (Wester et al, 2003)

Enormous amounts of surface water and groundwater are extracted which cause low flows in the rivers and falling groundwater levels. For the period from 1982 to 1998 an average groundwater level decline of 2.12 m/yr was calculated for the Middle Río Lerma (Scott et al, 1999). For the rest of the Lerma-Chapala basin this drawdown is also about 2 m/yr.

The mean annual precipitation of the Lerma-Chapala basin is 735 mm. Most of this is concentrated in the south. The northern and central parts have a dryer, semi-arid climate with rain in the summer (from May to October).

The average monthly temperatures vary from 14.6^{0}C in January to 21.3^{0}C in May. Crops can be grown during the whole year. The evaporation has also a peak around April/May with an average annual total of 1900 mm. Throughout the year, except for July and August, the potential evapotranspiration exceeds the precipitation. This shows the importance of irrigation for the basin.

2.2 Río Turbio aquifer region

2.2.1 Choice of aquifer

For the choice of the aquifer for the case study a few different aquifers regions were investigated briefly. All these aquifers are situated in the state of Guanajuato. On most of the aquifers in this state some research has been done; Irapuato, León, Los Apaseos, Penjamo, Rio Turbio and Silao-Romita. In table 2.1 a short description with the advantages and disadvantages is given.

Table 2.1: Information for choice of aquifer

Aquifer name	Basic information	Advantages	Disadvantages
Irapuato	Area: 1683 km^2, rivers: Alto Río Lerma and Rió La Laja	More or less one layer,	Lies in two subcatchments, inflow from other aquifers (considered to be constant), outflow to other aquifers
León	Area: 1100 km^2, rivers: Rio León, Los Gómez, free heterogenic aquifer except for La Muralla (low permeability)	One layer, but really variable in depth	Lies in two subcatchments, inflow from mountain ranges, outflow to other aquifers
Los Apaseos	Area: 1240 km^2, rivers: Rio La Laja and Rio Apaseo, no important lakes or reservoirs, but there is a reservoir from where two irrigation canals leave	No inflow from other aquifers, outflow to other aquifers is considered to be zero, no base flow	Lies in two subcatchment, recharge area outside of the aquifer boundaries
Penjamo-Abasolo	Area: 3425 km^2, rivers: Rio Lerma, Rio Turbio, Rio Guanajuato, three layers as aquifer, shallow and intermediate only partly divided by clay layer, both exhausted, deep aquifer starting from 120 – 130 m of depth, in previous study are the shallow and intermediate aquifer taken as one layer, but the deep aquifer as three	No outflow to other aquifers due to pumping	Lies in two subcatchments, Inflow from other aquifers, three aquifers
Rio Turbio	Area: 3203 km^2 of which 1410 km^2 subcatchment and 914 km^2 aquifer, a lot of faults, rivers: Rio Turbio, one deep aquifer, divided into seven different zones with different depths, mostly free aquifer but some parts semiconfined, two recharge zones	Due to pumping no outflow to other aquifers, one subcatchment	Inflow from other aquifers. It seems that there are three different layers according to hydraulic conductivity, but these will be taken as one
Silao-Romita	Area: 1950 km^2, rivers: Rio Silao and Rio Guanajuato	Within one subcatchment, no outflow due to pumping, no inflow (only recharge in mountains in same subcatchment)	3 different aquifers, divided by aquitards, infiltration along the wells, hardly any information about the shallow aquifer

One of the most important criteria for choosing the aquifer was that the aquifer had to be totally situated within a subcatchment according to the IMTA-division. This criterion leaves only the aquifers of Río Turbio and Silao-Romita. The Silao-Romita aquifer has three different aquifers, divided by aquitards. It would not really be a problem to model this, but no data are available for the shallow and intermediate aquifers. So the Río Turbio aquifer was chosen for the case study.

2.2.2 Location

The Río Turbio aquifer is situated in the northwest of the state of Guanajuato, in the Middle Lerma area. At the west side the state of Jalisco is situated. To the north-northeast lies the aquifer of León, to the east lies La Muralla and to the southeast the aquifer of Penjamo-Abasolo. The aquifer of Río Turbio is divided in three different municipalities, Purísima del Rincón, San Francisco del Rincón and Manuel Doblado. The main cities are San Francisco del Rincón and Manuel Doblado (figure 2.2).

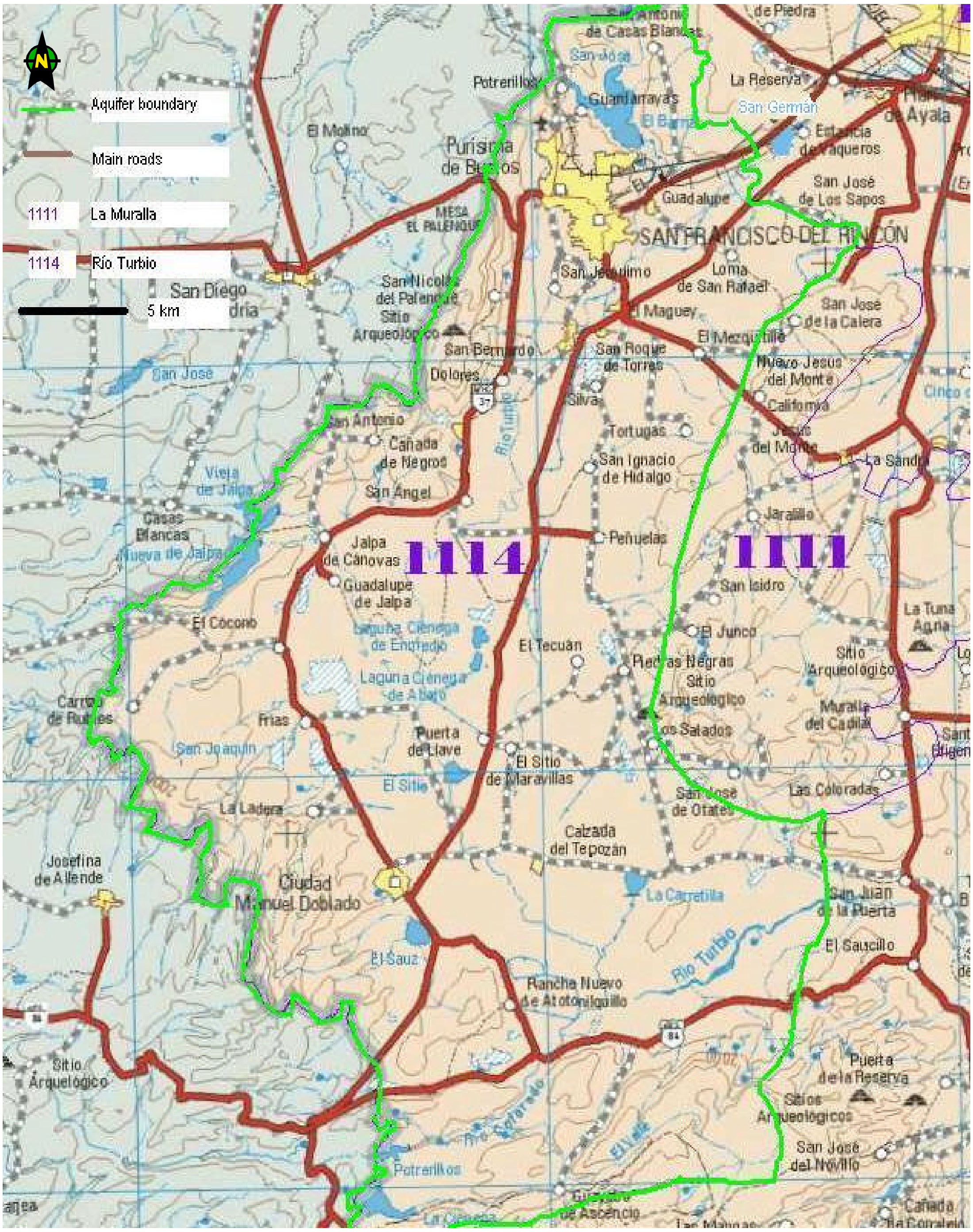


Figure 2.2: Map of the Río Turbio aquifer (CNA, 2004)

The area of the subcatchment of the Río Turbio is approximately 1410 km^2 and of the aquifer covers 914 km^2 (Comisión Estatal de Agua y Saneamiento de Guanajuato (CEASG) and GEOPSA, 1998). The aquifer is situated in a valley, which is surrounded by mountains. The elevation of the valley is about 1730 m + MSL and the mountains around the valley rise to 1800 – 2400 m + MSL. In the centre of the valley the land use is mainly agricultural and around San Francisco del Rincón is also an area with a lot of agriculture. Detailed information about land use was not available for this study. The mountains are not included in the modelled aquifer. The mountains to the north and to the west function as recharge areas (boundary condition for the model), but are not included in the modelled aquifer region itself.

2.2.3 Río Turbio

The main surface water body in this groundwater catchment is Río Turbio. This river runs from the northeast of the aquifer (reservoir San Germán) to the south and turns around Manuel Doblado to southeast to leave the area at gauging station Las Adjuntas. From the reservoir El Palote (north of the city of León) until the gauging station of Las Adjuntas the river is 53 km long (CEASG and IGC, 1995).

The discharge of the Río Turbio has been measured at gauging station Las Adjuntas between 1945 and 1999. The yearly average discharge is given in figure 2.3.

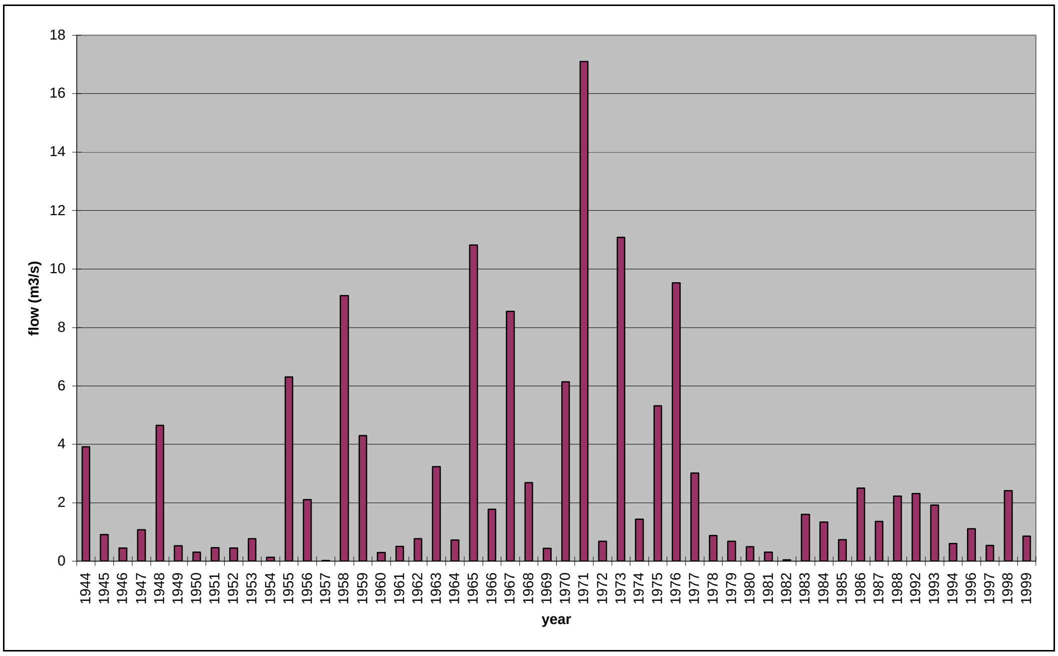


Figure 2.3: Average yearly discharge at Las Adjuntas for the period 1945 - 1999

2.2.4 Climate

The climate in this aquifer region is dry to arid with rains in the summer. The average annual precipitation is 670 mm, with the peak during the months June to September. The yearly precipitation between 1945 and 1999 is shown in figure 2.4. The average annual temperature fluctuates between 7°C and 14°C. In 1988 on gauging station 11159, Presa El Barrial a daily evaporation was measured, which was in total 1932 mm over the whole year.

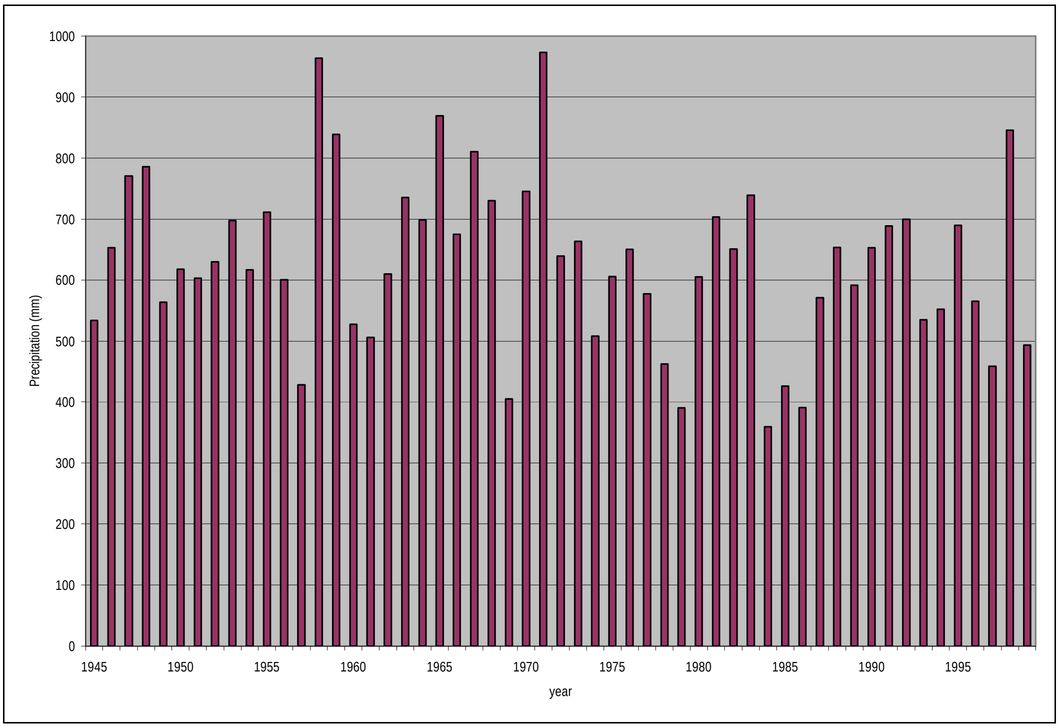


Figure 2.4: Precipitation Adjuntas 1945 - 1999

2.2.5 Geology

The study area that covers the Río Turbio aquifer region is situated between the Cadena Volcánica Transmexicana (C.V.M., Transmexican Volcanic Chain) and El Altiplano Mexicano (the Mexican Plateau). This last one is influenced by volcanism of the Sierra Madre Occidental (S.M.O.). The C.V.M. is a volcanic chain, developed mainly during the Pliocene due to the subduction of the Placa de Cocos underneath the North American Plate. The S.M.O. is also a volcanic chain but is developed by the processes of subduction of the Farallón Plate underneath the North American Plate during Oligocene.
The study area is located within the Central Sector of the Cadena Volcánica Mexicana (Mexican Volcanic Chain), which is tilted in direction WSW-ESE. In this sector several structural and regional volcanic elements exist, which hydrogeologically and geologically control the Valley of the Turbio River. These are: Meseta León Guanajuato, Sierra de Pénjamo and El Graben de Penjamillo (CEASG and GEOPSA, 1998).

Meseta León Guanajuato: this is an enormous volcanic plateau with a height that varies between 1800 and 2000 m + MSL

Sierra de Pénjamo: this is a mountain range of 70 km in length and 30 km in width. The altitude goes up to 2400 m + MSL.

El Graben de Penjamillo: this is a range of 50 km in length by 10 km in width, which is surrounded by faults in N-S direction, which are dislocated by ignimbritical (volcanic) rocks of the Sierra Madre Occidental and lava flows.

The biggest part of the valley consists of alluvial deposits (granular) with an average depth of 100 m and a greater thickness in the northern part, around San Francisco del Rincón.

2.2.6 Geohydrology

The average hydraulic conductivity is 1 to 2 m/day. On the south and the south-west side the aquifer extends as fractured rocks with an average depth of 130 m and an average hydraulic conductivity of 5 to 8 m/day (CEASG and GEOPSA, 1998).
Between the reservoir San Germán and San Francisco del Rincón the area is over-irrigated and this causes a small, not really important saturated zone with piezometric levels of 1710 to 1720 m + MSL. In the northern part there is a small area with a clay layer with low permeability under an alluvial layer which is irrigated. This causes a shallow saturated zone, because the water accumulates on top of the clay layer. But since this is only a small area, this will be neglected in this study. In the rest of the area the piezometric levels are deeper, even as deep as 1680 m + MSL. Figure 4.3 of the synopsis of 1998 (CEASG and GEOPSA, 1998) shows the depths of the piezometric levels in April 1998. Three cones of depression exist in this aquifer; a small one close to San Francisco del Rincón, another one close to the community of El Mesquitillo and the third one is in the central part of the valley, north of Manuel Doblado. Due to this last cone, there is no outflow of groundwater to the south-east anymore. This cone even changed the direction of the groundwater flow; nowadays water is flowing in at the south-east of the valley from the aquifer of Penjamo.
In the east of the valley continental deposits with low permeability of 0.1 m/day are situated. These deposits are mainly clayey sediments and act as a hydrogeological barrier between the aquifers of Río Turbio and León. This area is called La Muralla.

2.2.7 Recharge areas

In the northern part and in the western part the mountains serve as an infiltration area. In these areas the precipitation infiltrates and flows to the valley. From the aquifer of León no water is flowing in, because also in this aquifer a large volume of water is extracted. Besides that, continental deposits with low permeability are situated in the eastern part of the aquifer Río Turbio which functions as a barrier between these two aquifers.

2.2.8 Reservoirs

In the area there is not a big reservoir, but only a number of small ones. In the municipality of Purísima del Rincón there are three reservoirs: El Barrial, Jalpa and Santa Efigenia. The storage capacity of El Barrial is 50 Mm^3, but only 25 Mm^3 is used for agriculture (CEASG and IGC, 1995). Jalpa and Santa Efigenia together have a storage of 48.5 Mm^3.
In the municipality of San Francisco del Rincón the main reservoir is Silva (2.74 Mm^3). Another reservoir is San Germán with a capacity of 0.64 Mm^3.
In the municipality of Manuel Doblado are a few different small reservoirs: Santa Isabel, El Sitio, El Sauz, San Antonio, San Miguel, La Amapola, San Joaquín, El Tabaco, Laguna Tuerta and Ciénega de Galván. These reservoirs together have a storage of 32.70 Mm^3.
The dams of San Juan de la Presa and Cañada de Negros have a capacity of 3 Mm^3 and 0.70 Mm^3 respectively.
So the total capacity of all these reservoirs is 113.28 Mm^3. Table 2.2 gives an overview of all the capacities.

Table 2.2: Capacity of the different reservoirs

Reservoir	Capacity (Mm^3)
El Barrial	25.00
Jalpa and Santa Efigenia	48.50
Silva	2.74
San Germán	0.64
Reservoirs in Manuel Doblado	32.70
San Juan de la Presa	3.00
Cañada de Negros	0.70
Total	**113.28**

2.2.9 Irrigation

The irrigated area in the Valle del Río Turbio covers almost 44,000 hectares, from which 11,000 is in the irrigation zones and units, irrigated with surface water. The most important irrigation zones and units in the aquifer of Valle del Río Turbio are those that receive water form the reservoirs of El Barrial and the system of Jalpa and Santa Efigenia. The small irrigation communities are irrigated with groundwater and cover an area of more or less 33,000 hectares.

The cones of depression are caused by extractions of groundwater. CEASG calculated the extracted volumes of groundwater, based on the capacities and the working hours of the pumps.

3 EXISTING IMTA MODEL

3.1 Stella platform

The Stella platform is a simple tool to simulate changes in stocks (storages). In a graphical way stocks, flows, converters, connectors and decision process diamonds (figure 3.1) can be used to build a model.

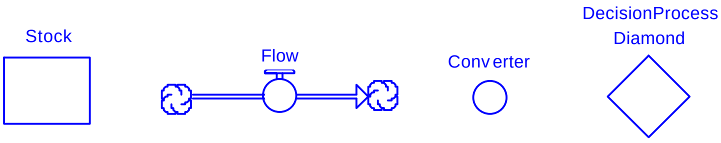


Figure 3.1: Building blocks in Stella

There are four types of stocks: reservoirs, conveyors, queues and ovens. For hydrological models the reservoir type is the most important. The flows can be in- and outflow for the stocks. With these flows the quantity in the stocks changes. The converter can be used in many different ways, for example for describing input data, as a stock substitute or flow substitute. In these converters equations can be inserted. The decision process diamond describes a decision point, from where action can be taken.

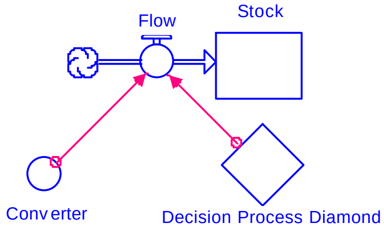


Figure 3.2: Building blocks in Stella, connected with connectors

All these different building blocks are connected by connectors (figure 3.2, pink arrows). For the Stella platform it is not necessary to master a difficult programming language, the graphical development environment makes it easy.

When the different building blocks are connected to each other, every building block has to be modelled. With double clicking on a building block, this block opens and equations, tables or values can be inserted. Figure 3.3 shows a stock. On the top the user can define what kind of stock it is (in this case: a reservoir). In the white field at the bottom the initial value of the stock has to be defined. This can be done by inserting a value, but also by inserting an equation or an equation that uses one of the ‘Allowable Inputs’ in the field above.

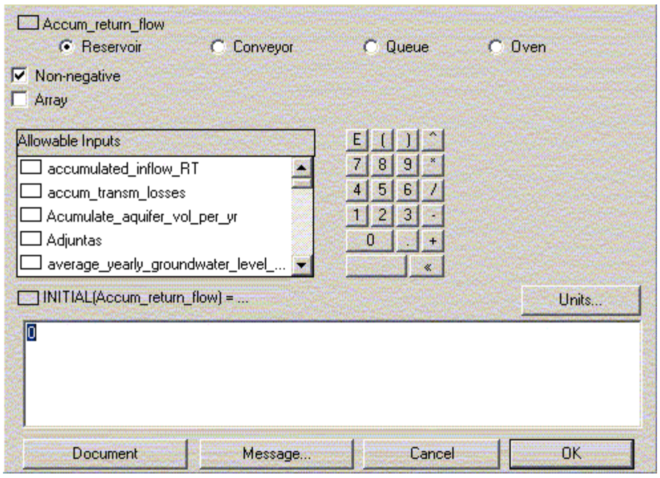


Figure 3.3: Modelling of stocks

The same principle is used with the flows, Decision Process Diamonds and Converters (figure 3.4). In the field with the 'Required Inputs' is a list of the building blocks which are all connected to this specific converter. All these building blocks have to be used in the equation (see marked text in field) which describes, in this case, the Wrchrg. Here you also find predefined mathematical functions or operations, called 'Built-ins'

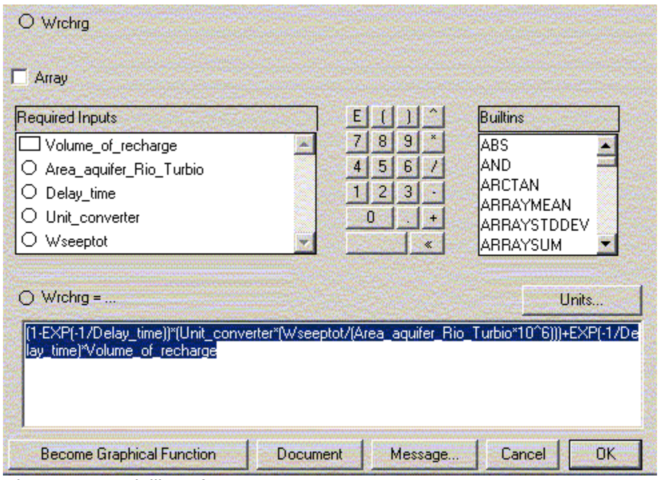


Figure 3.4: Modelling of converters

The output of the calculations in the building blocks can be used as input for other calculations. In that case a copy can be made, this copy is shown as a dashed circle. Output can also be shown in a graph or a table. In figure 3.5 an example of a graph is shown. By double clicking on the graph, the fields behind this graph open and the user can define which results have to be shown in the graph and in what way.

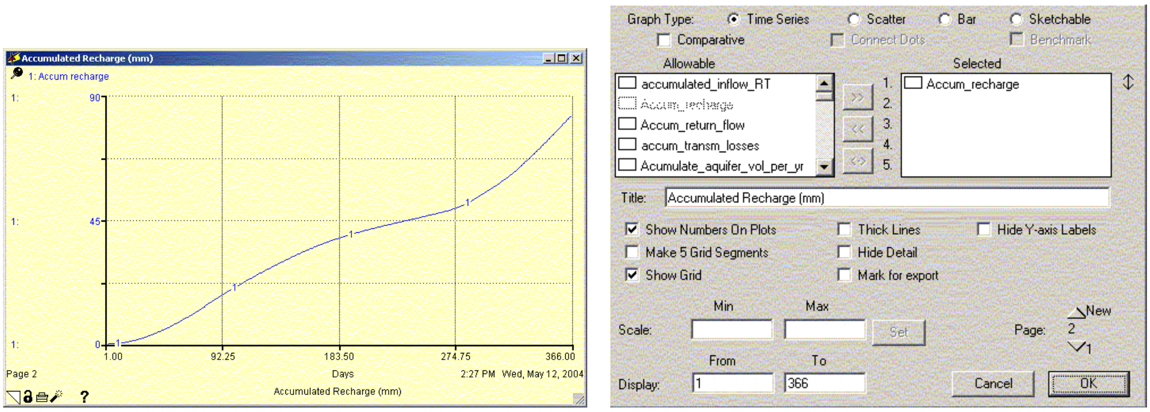


Figure 3.5: Output in graphs

3.2 Application by IMTA

3.2.1 Conceptual model

The hydrological model that was developed by IMTA for the Lerma-Chapala basin, using the Stella platform, was mainly for simulating surface water (Aparicio Mijares et al, 2001). Aquifers were not firmly incorporated in the model.

The conceptual model of IMTA is shown in figure 3.6. The list of Spanish words can be found in appendix 1.

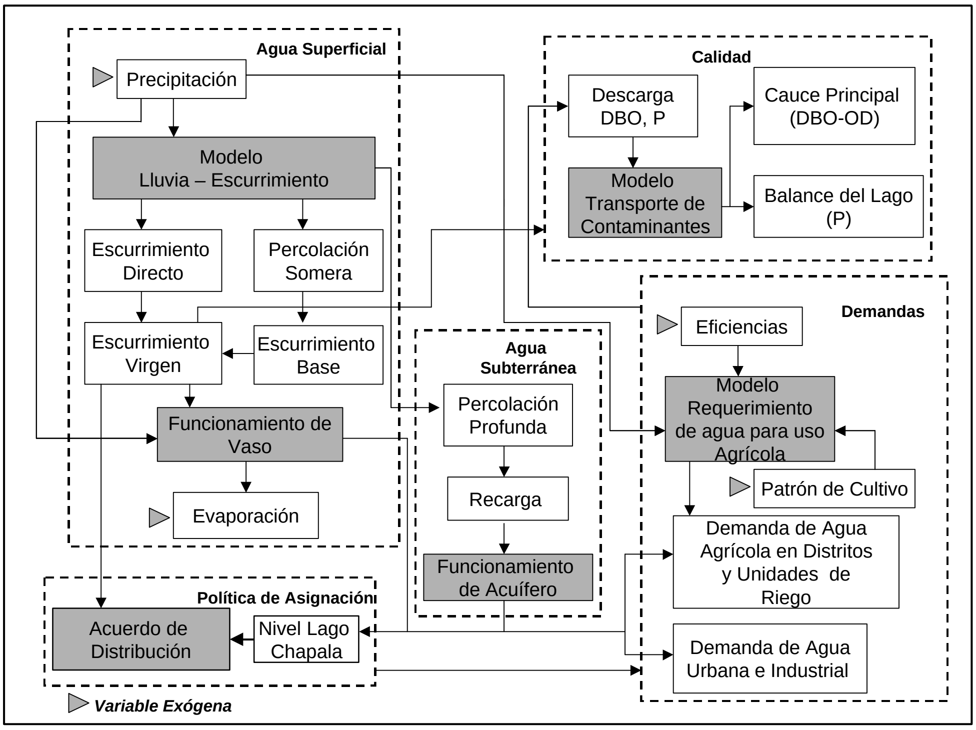


Figure 3.6: Conceptual model for the Lerma-Chapala basin (Aparicio Mijares et al, 2001)

This figure shows five modules, separated by the dashed lines:

- Surface water module, with the rainfall-runoff part (Modelo Lluvia – Escurrimiento) and the reservoir part (Funcionamiento de Vaso). Due to the rainfall, surface runoff and shallow percolation happens. The surface runoff will flow into the reservoir, as well as a part of the percolated water. In the reservoir part of the model, the change of storage is simulated with all the inflows and outflows.
  Due to the rainfall, deep percolation happens as well, this will recharge the aquifer.
- Groundwater module (Funcionamiento de acuífero), this module is connected to the demand module and the allocation policy module.
- Demand module, this module calculates the water demand for irrigation, industry and drinking water. In this calculation the efficiency is included.
- Allocation policy module, this module simulates the rules of distribution with as a result the maximum volume that is permitted to extract per area.
- Transport of contaminants module, which simulates the transport of the contaminants in the rivers and reservoir.

How these different concepts have been translated into modules in Stella will be described in the following section. In this research is focussed on subcatchment Adjuntas, so all the figures and examples will be about Adjuntas, but the described way of modelling in Stella can also be used for other subcatchments.

3.2.2 Precipitation in the existing IMTA

Precipitation in the basin is measured from 1945 onwards. In the model two distributions of precipitation during a year are used; $P(i)_{dry\ year}$ is for a dry year (data from 1997) and $P(i)_{wet\ year}$ is for a wet year (data from 1998), with i = [1..365]. From all the other years only the total precipitation is used. For every subcatchment, according to the IMTA-division, a factor is determined, this factor F_{SC} distinguishes if it is a dry or a wet year.
Per subcatchment a factor F_y is calculated for every year.

$$F_y = P_y/P_{av} \qquad [3.1]$$

where: F_y is the factor for one subcatchment for year y
P_y is the total precipitation for the same subcatchment for year y
P_{av} is the total average precipitation for the same subcatchment

$$P(i)_y = F_y \cdot P(i)_{wet\ year} \qquad \text{if } F_y > F_{SC} \qquad [3.2]$$
$$P(i)_y = F_y \cdot P(i)_{dry\ year} \qquad \text{if } F_y < F_{SC} \qquad [3.3]$$

where: $P(i)_y$ is the daily precipitation for year y
$P(i)_{wet\ year}$ is the time series of daily precipitation for the wet year (1998)
$P(i)_{dry\ year}$ is the time series of daily precipitation for the dry year (1997)
F_{SC} is the factor for one subcatchment to distinguish if it is a dry year or a wet year

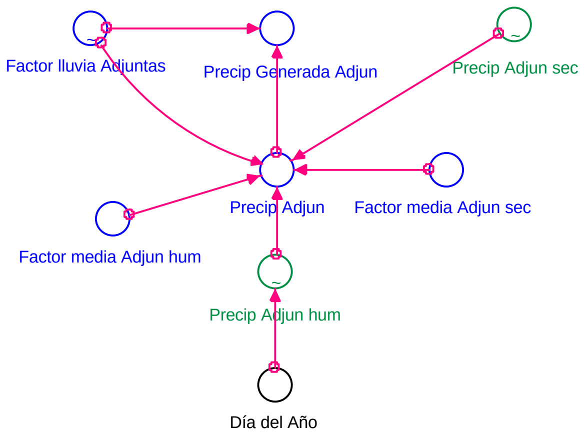


Figure 3.7: Calculation of precipitation in Stella

The factor is calculated for each year and imported in Stella. In Stella the calculation of the precipitation is done according to figure 3.7. The factors for each year are imported in 'Factor lluvia Adjuntas'. The final daily precipitation in a particular for a subcatchment is calculated in 'Precip Generada Adjun'.

3.2.3 Curve number method

This generated precipitation (section 3.2.2) for the subcatchment Adjuntas is used in the next step, the part where the direct runoff is calculated. The direct runoff is calculated with the Curve Number method of the Soil Conservation Service (Natural Resources Conservation Service, 1986), figure 3.8. From the precipitation is calculated what part is direct runoff (lluvia en exceso 11[1] in mm or Escurrimiento Directo Instant 11 in m^3). From here is also calculated what part of the precipitation is infiltrating into the ground, contributing to the soil moisture (Lluvia Efectiva 11). This is also called the effective rain. The direct runoff is gathered in the surface water system and will end up in the reservoirs or flows straight to the gauging station Las Adjuntas.

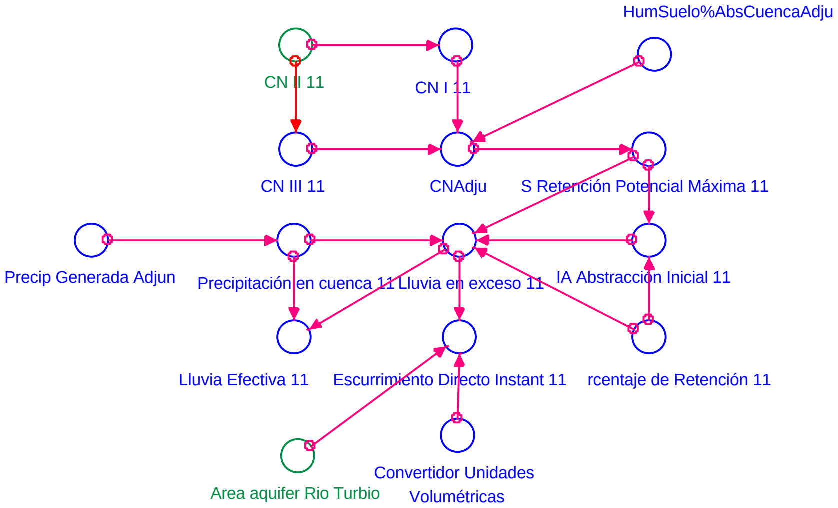


Figure 3.8: Curve Number Method of Soil Conservation Service in Stella

[1] 11 is the number of the subcatchment Adjuntas, according to the IMTA-division

3.2.4 Soil moisture change and evapotranspiration

The effective rain, described section 3.2.3, is input for the calculation of soil moisture changes (figure 3.9). The outputs of this module are evapotranspiration (Salida Evapotransp 11) and percolation to the subsoil (Subsuelo VolAdju). The percolation flows to a shallow aquifer, from where the base flow is calculated (not shown in figure 3.9). The base flow flows into the reservoir. Since the calculation of base flow will be replaced in the revised IMTA model, it will not further be explained here.
The actual evapotranspiration is calculated from a potential evapotranspiration and a relative evapotranspiration. The calculation of this actual evapotranspiration is considered to be correct and will not be adjusted and also not further described in this report.

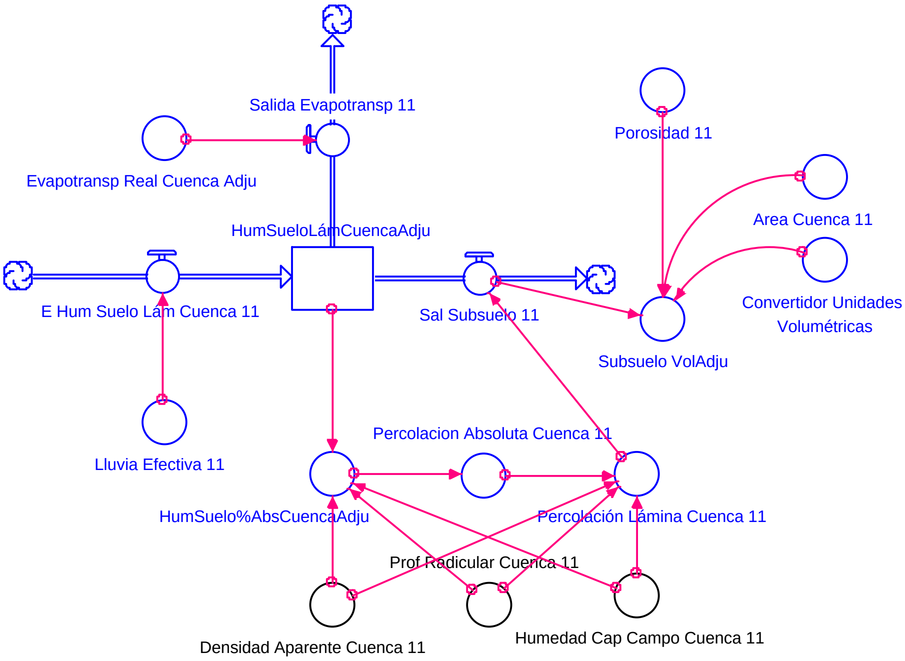


Figure 3.9: Calculation soil moisture changes and evapotranspiration in Stella

3.2.5 Reservoir

In Stella only one reservoir is modelled; a fictitious reservoir. This fictitious reservoir is a combination of all the small reservoirs and dams together (section 2.2.8). A total capacity is calculated and an area-volume curve is estimated. This curve describes the relation between the capacity of the fictitious reservoir and the area of the water surface. With this area the reservoir evaporation is calculated. From the reservoir, water is extracted for irrigation and other purposes (figure 3.6). The quantity that is extracted is based on the demand module. This is a module that calculates the extractions that are needed for irrigation in irrigation districts, but restricted by the policy. The demand module does not account for the small irrigation units, but only for the eight irrigation districts in the whole Lerma-Chapala basin, so it will be removed from the existing model when revising this model.

For the reservoir, the extracted volume cannot be larger than what is available in the reservoir, which means that the extractions from the reservoir can be less than necessary.

As the water level of the reservoir rises above a certain threshold level, the reservoir will spill (Derrames OHDRAdju). This water will flow to the river.

3.2.6 River

The river is not modelled as a network of branches and nodes. The river in the existing IMTA model is modelled as a reservoir as well; every day a certain amount of water flows in and a certain amount of water flows out, which results in a daily water balance.

3.2.7 Deep aquifer

For every deep aquifer a recharge is calculated based on effective rain, area of recharge and a coefficient. Because only yearly recharge data are known, the model does not represent true daily recharge. Due to this uncertainty a considered coefficient of recharge is added. This coefficient is an estimation for the daily recharge for every aquifer. The recharge is calculated with the following equation.

$$V_{rchrg} = P_{eff} \cdot A_{rchrg} \cdot UC \cdot C_{rchrg} \qquad [3.4]$$

where: V_{rchrg} is the daily recharged volume to the deep aquifer [m^3]
P_{eff} is the daily effective rain [mm]
A_{rchrg} is the recharge area [km^2]
UC is a unit converter, because the different parameters have different units
C_{rchrg} is the recharge coefficient

From the aquifer groundwater is extracted for irrigation, drinking water and industry. These extracted volumes are based on yearly volumes.

3.2.8 Water quality

In the existing model a quality module is also incorporated. Since in this study no research is done about the quality and the quality module, this module will not be described in this report.

3.3 Shortcomings in the existing IMTA model

The previous chapters showed that in the existing IMTA model groundwater is not incorporated very well. The way of calculating the storage changes in the aquifer due to recharge were based on a recharge coefficient (section 3.2.7). In the new model a delay time will be incorporated so the recharge does not contribute to the aquifer instantaneously. With a delay time a retardation of the recharge takes place. For the aquifer a water balance will be calculated for every day. With this water balance a spatially-averaged groundwater level for the whole aquifer can be calculated.

In the research area, Río Turbio aquifer, there is no base flow, so this module will be removed from the model. New equations for base flow will be incorporated, but for this case not connected to the rest of the equations, since base flow does not occur in the research area. The new equations might be helpful for further investigations in areas where base flow occurs.

The irrigation module has to be adjusted as well. If more water is extracted than what is used by the crops (effective consumptive use), the excess will be calculated and will flow partly to the surface water and will partly recharge the aquifer. In the existing model there is no calculation of excess water, but it is known that in the Lerma-Chapala basin more water is extracted than used by the crops.

Transmission losses from the river and the reservoirs as well as leakage from drinking water net and sewerage systems are not incorporated in the existing IMTA model. In the revised IMTA model some simple equations will be inserted for these flows.

The surface water module of the existing IMTA model does not need to be revised a lot. The existing groundwater module with the calculations of the recharge (equation 3.4) and the groundwater extractions will be replaced by a new module. This new groundwater module should be simple and with the same kind of reliability as the surface water module. For this groundwater module the input data should also be available or easy to obtain. The simplicity of this module means that, for example, the groundwater level will not be calculated distributed over space within the subcatchment. Only one spatially-averaged groundwater level will be simulated for the subcatchment.

4 REVISED IMTA MODEL

To investigate in what way the existing model can be changed best (section 3.3), a literature study has been done. This literature study was about different models or ways to simulate groundwater flow:

- Chiew et al (1990)
- HBV-model
- Mike Basin
- Olin (1995)
- Peters et al (2003)
- Seibert et al (2003)
- SWAT/Arnold et al (1993)

The different models or equations from the literature were checked on data needs, the difficulties of using this model or equations and if it had the same reliability as the existing model. Only from Mike Basin, Arnold et al (1993) and SWAT a short description, the advantages and disadvantages are given. The rest was not appropriate for using in this particular case.

4.1 Different modelling approaches

4.1.1 Mike Basin

Mike Basin (http://www.dhisoftware.com/mikebasin/index.htm) is a network model. This means that the rivers are represented by a network of branches and nodes. Here you can find a difference with the existing IMTA model, where no river flow is modelled, but only a balance for the whole subcatchment. Mike Basin has a groundwater extension, with which the different interactions can be modelled. These interactions are:

- stream seepage (river to aquifer);
- groundwater recharge (soil to aquifer);
- groundwater discharge (aquifer to river).

The aquifer is modelled as a linear reservoir.

One of the main disadvantages of Mike Basin is the way the rivers are modelled, this does not correspond to the existing IMTA model. In Stella the rivers are not modelled by a network of branches and nodes.

Another disadvantage is that the equations used in Mike Basin are hidden and not known, so not enough information was available to incorporate the principles of the groundwater module of Mike Basin in the IMTA model.

4.1.2 Arnold

In Arnold et al (1993) the same kind of study was done as for this study, a simple groundwater model was added to an existing surface water model. The surface water module in Arnold et al (1993) is quite similar to the surface water module that is used by IMTA. Direct runoff from precipitation is predicted using the Curve Number method of the Soil Conservation Service. A part of the precipitation infiltrates and a part evaporates. The infiltrated rain is assumed to recharge the shallow aquifer. From the shallow aquifer outflow occurs by evaporation, base flow, extractions and percolation to the deep aquifer. The percolation to the deep aquifer is assumed to be water that is lost. It will not return in the water system. The way the groundwater module was incorporated in the surface water model was simple. The model was not calibrated, but previous testing showed that the model was simulating adequately monthly and annual water yields. Most of the input data is data that is measured, like precipitation or groundwater levels, so usually the input data are available or quite easy to obtain.

4.1.3 SWAT

The SWAT-model has been developed by the Texas Water Resources Institute since the early 1990s. SWAT stands for Soil and Water Assessment Tool. On internet is a site (http://brc.tamus.edu/swat/) about the SWAT-model with a manual (Neitsch et al, 2002). This manual refers to Arnold et al (1993).

The SWAT-model is a model that can predict the impact of land and water management on water, sediments and agricultural chemicals yields in a large catchment area. For this study the focus was on chapter 9 of the SWAT-manual (Neitsch et al, 2002). This chapter deals with the groundwater module and the equations of groundwater flows that are used in the model. The SWAT-model can be used for a system with a shallow and a deep aquifer, divided by an aquitard. For the Río Turbio aquifer, as mentioned in chapter 2, this is not the case; here the aquifer is considered to be one deep aquifer on top of an aquiclude.

Because this model uses simple equations with input data that are available (or easy to obtain) and because a lot of information is available about this model, the groundwater approach of this model was chosen to be incorporated in the IMTA model.

4.2 Changes in the IMTA model

4.2.1 Conceptual model

Figure 4.1 shows the conceptual model of the revised IMTA model. The different modules in this model are:

- Rainfall-runoff module, which simulates the direct runoff and the effective rain caused by precipitation, with the specific characteristics of the region and some theoretical considerations. For this part the SCS-CN model is used. This module calculates direct runoff (input for the reservoir module) and effective rain, which is used to calculate evaporation and infiltration (input for the soil moisture module).
- Soil moisture module, this module is calculating the change in soil moisture. This change is caused by inflow of infiltration, leakage from cities (drinking water and sewerage systems) and excess water from irrigation, and outflow due to interflow to surface water bodies and percolation to the aquifer.
- The reservoir module simulates the storage in the reservoirs, with inflows (precipitation, direct runoff) and outflows (evaporation, transmission losses, extractions for irrigation).
- The river module simulates the total daily in- and outflow in the river with inflow (boundary flow, interflow, base flow, effluent, direct runoff) and exits (transmission losses, extractions).
- The groundwater module simulates the water balance. Inflows are transmission losses from surface water bodies, recharge from excess of soil moisture (percolation), recharge from the recharge areas and inflow from other aquifers (boundary flow). Outflows are evaporation (in case of a shallow aquifer), base flow (in case of a shallow aquifer), outflow to other aquifers and extractions by pumping.

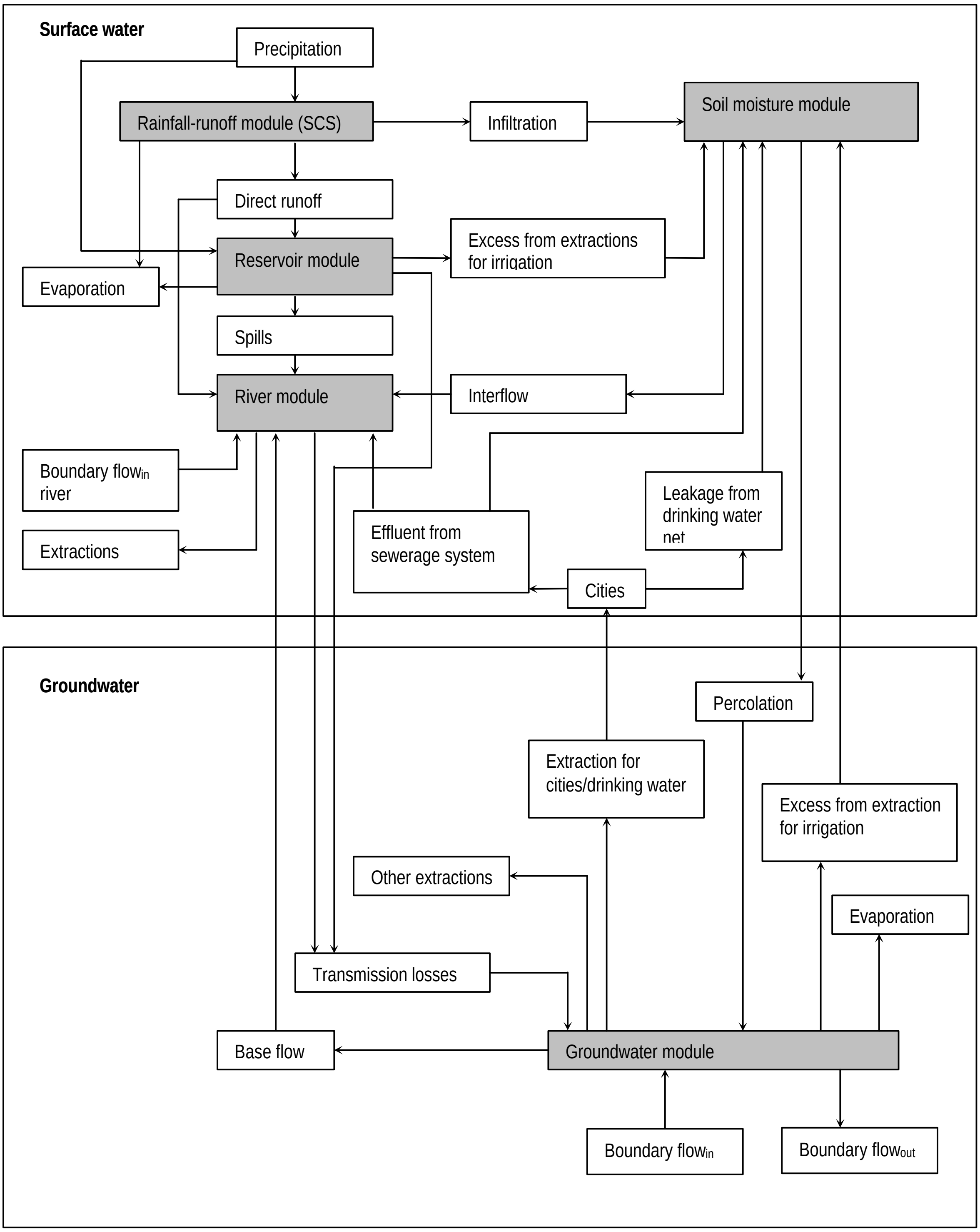


Figure 4.1: Flow chart conceptual model

In this conceptual model base flow is mentioned, but in the model for the Río Turbio aquifer, it is not incorporated, not linked to the river and the aquifer. Also evaporation from the aquifer can be calculated, but this is also not linked to the aquifer in the case of the Río

Turbio. In the revised model the whole groundwater module is new as well as the interflow and the leakage and effluent from the cities.

As mentioned the revised IMTA model is based on the existing IMTA model. For changing the existing model equations of the SWAT-model are used and incorporated. From the existing IMTA model the parts about the precipitation, evaporation, direct runoff, soil moisture changes, reservoir and the calibration options for the surface water are kept in the model, sometimes a bit changed or things are added or deleted. The precipitation, evaporation and direct runoff are still the same in the revised model. The soil moisture changes are calculated in the same way, but the calculation of the base flow is taken out of the model. In the Río Turbio aquifer there is no shallow aquifer, so there is no base flow. The changes in the reservoir storage are calculated in the same way, but in the revised model it is added that rain that falls on the water surface will contribute to the volume in the reservoir.

This conceptual model results in a transient, spatially-lumped model, which calculates balances, no flows. Due to limited time and a limited data set it is chosen to develop this type of model.
This model is suitable for IMTA to make their yearly water balances, by accumulating the daily simulations.

The changes in the surface water calculations are mentioned first, before the groundwater part is explained.

4.3 Changes in the surface water module

4.3.1 Reservoir

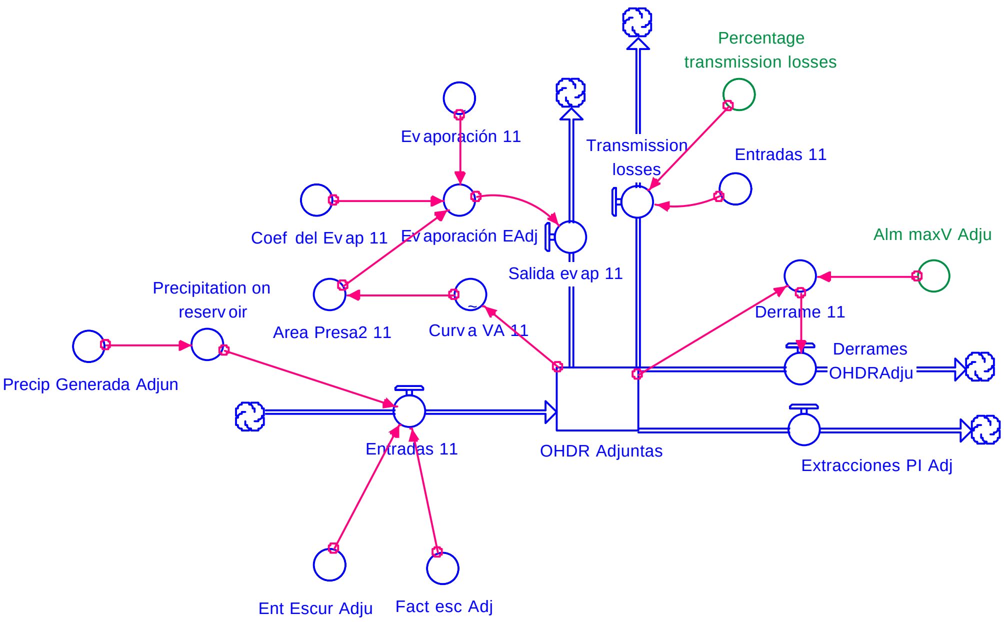


Figure 4.2: Calculation of reservoir in Stella[2]

[2] Some of the figures are partly English and partly Spanish. The Spanish words represent existing parts, the English words represent revised parts.

The fictitious reservoir of the aquifer Río Turbio is fed by a part of the direct runoff of the subcatchment (determined by a factor) and the rain that falls directly on the surface of the reservoir, figure 4.2. The rain that falls directly on the surface of the reservoir is added in the revised IMTA model. Transmission losses from the reservoir were not incorporated in the existing IMTA model, so these were added as well. They are calculated as a percentage from the inflow in the reservoir. From the reservoir, surface water is extracted for irrigation. This will be shown in figure 4.3.

4.3.2 Extractions surface water

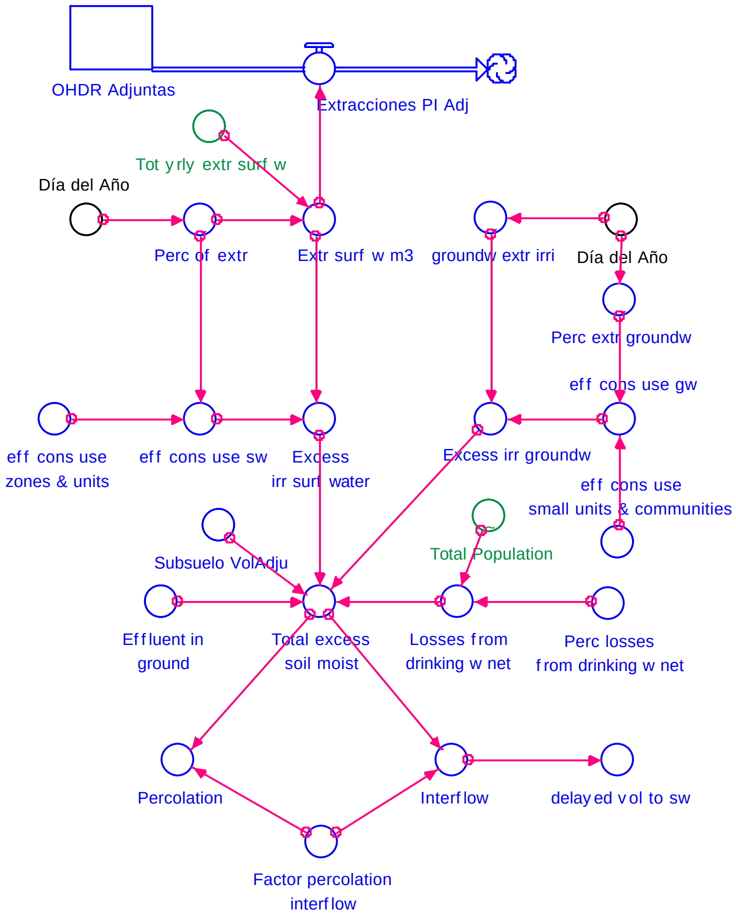


Figure 4.3: Calculation extractions and soil moisture change in Stella

Both surface water extractions and groundwater extractions are shown in figure 4.3. The extracted volumes are not the same and the effective irrigated layers also not. The effective irrigated layers and extracted volumes will be further discussed in chapter 5.

Since irrigation is not operational throughout the whole year, a distribution is made for the extractions within one year. With the extracted volumes and the consumptive uses the excess of irrigated water can be calculated. It is assumed that this excess will infiltrate in the ground and will contribute to the soil moisture.

Losses from the drinking water net will also contribute to the soil moisture (figure 4.1). In section 5.1.5 the calculations will be explained further. Together with soil moisture excess from rain (Subsuelo VolAdju, section 3.2.4), the effluent of sewerage that goes into the ground and the excess of irrigated water, a total excess of soil moisture can be calculated. With a factor (factor percolation/interflow, figure 4.3), which needs to be calibrated, this total excess is distributed over return flow (flows back to the surface water, in the model called 'interflow') and percolation (recharges the aquifer).

4.3.3 In- and outflow river

The return flow will flow with a delay to the surface water, which is modelled in figure 4.4. This 'river' is fed by the return flow (interflow), the spills from the reservoir, a part of the direct runoff (calculated with a factor, which has to be calibrated), boundary flow from outside the area and effluent from sewerage systems. The boundary $flow_{in}$ river (figure 4.1) is an inflow in the Río Turbio aquifer region from the Río Turbio itself. This river starts outside of the boundaries of the aquifer, so in this case a volume should be added as contribution to the river. The calculation of this inflow of the river is given in appendix 2 and will be explained further in section 5.1.8.

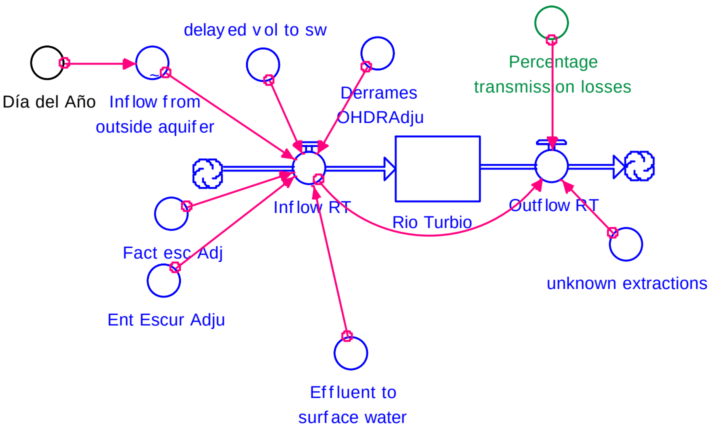


Figure 4.4: Calculation of inflows in the river in Stella

As mentioned, sewerage contributes also to the river volumes. The calculation of the amount of sewerage is given in section 5.1.5.

From the river losses occur; transmission losses and unknown extractions. The total amount of these losses will be described in section 5.1.8.

4.4 Groundwater module

As mentioned before, the whole groundwater module in the revised IMTA model is new. This module is based on the groundwater module of the SWAT-model (Neitsch et al, 2002). In the groundwater module the equations will be mentioned.

4.4.1 Evaporation

From a shallow aquifer water can move into the overlying unsaturated zone during dry periods; capillary rise. From this zone evaporation and transpiration might happen. In SWAT this is called 'revap'. This revap only occurs if the amount of water stored in the shallow aquifer exceeds a threshold value, specified by the user. In SWAT revap is calculated with the following equation:

$$w_{revap,mx} = ß_{rev} \cdot E_o \quad [4.1]$$

where: $w_{revap,mx}$ is the maximum amount of water moving into the soil zone in response to the water deficiencies (mm)
$ß_{rev}$ is the revap coefficient
E_o is the potential evapotranspiration for the day (mm)

The actual amount of revap that will occur on a given day is calculated with:

$$w_{revap} = 0 \quad \text{if } aq_{sh} = aq_{thl} \quad [4.2]$$
$$w_{revap} = w_{revap,mx} - aq_{thl} \quad \text{if } aq_{thl} < aq_{sh} < (aq_{thl} + w_{revap,mx}) \quad [4.3]$$
$$w_{revap} = w_{revap,mx} \quad \text{if } aq_{sh} = (aq_{thl} + w_{revap,mx}) \quad [4.4]$$

where: w_{revap} is the actual amount of water moving into the soil zone in response to water deficiencies (mm)
aq_{sh} is the amount of water stored in the shallow aquifer at beginning of day i (mm)
aq_{thl} is the threshold water level in the shallow aquifer for revap or percolation to the deep aquifer to occur (mm)

In Stella equation 4.1 is calculated according to figure 4.5.

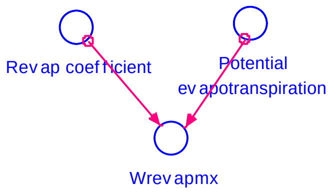


Figure 4.5: Calculation of maximum evapotranspiration in Stella

Equations 4.2, 4.3 and 4.4 are incorporated in figure 4.6.

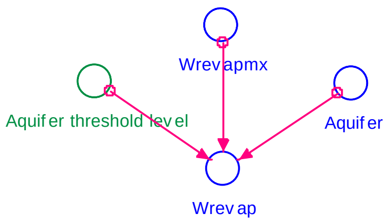


Figure 4.6: Calculation of the actual evapotranspiration in Stella

4.4.2 Recharge

In the Río Turbio area recharge of the aquifer takes place due to, among others, percolation (section 4.3.2), which is delayed in the thick unsaturated subsoil. The daily recharge can be calculated by:

$$w_{rchrg,i} = (1 - \exp[-1/\delta_{gw}]) \cdot w_{seep} + \exp[-1/\delta_{gw}] \cdot w_{rchrg,i-1} \quad [4.5]$$

where: $w_{rchrg,i}$ is the amount of recharge entering the aquifer on day i (mm)
δ_{gw} is the delay time or drainage time of the overlying geologic formations (days)
w_{seep} is the total amount of water exiting the bottom of the soil profile on day i (mm)
$w_{rchrg,i-1}$ is the amount of recharge entering the aquifer on day i –1 (mm)

The delay time δ_{gw} cannot be directly measured. With simulations of the aquifer with different values for δ_{gw} and comparing the simulated variations in water table level with the observed ones the correct δ_{gw} can be estimated. This means that the delay time is a parameter that has to be calibrated.

w_{seep} in equation 4.5 is $w_{seeptot}$ of Stella and is a combination of the amount of excess soil moisture that is percolated and the transmission losses of both the river and the fictitious reservoir, figure 4.7. This is calculated in m^3. In equation 4.5 the units are in mm, so a conversion is also needed.

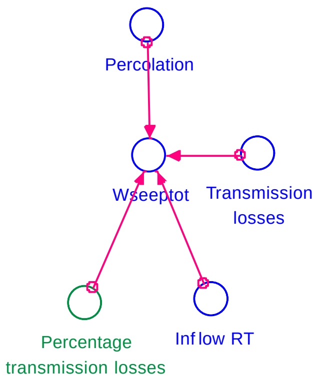


Figure 4.7: Calculation of total seepage in Stella

$w_{rchrg,i}$ is calculated in the converter 'w_{rchrg}', figure 4.8. With the Unit converter and the Area aquifer Río Turbio, $w_{seeptot}$ is converted to mm. $w_{rchrg,i-1}$ is inserted in equation 4.5 from the stock 'Volume of recharge'.

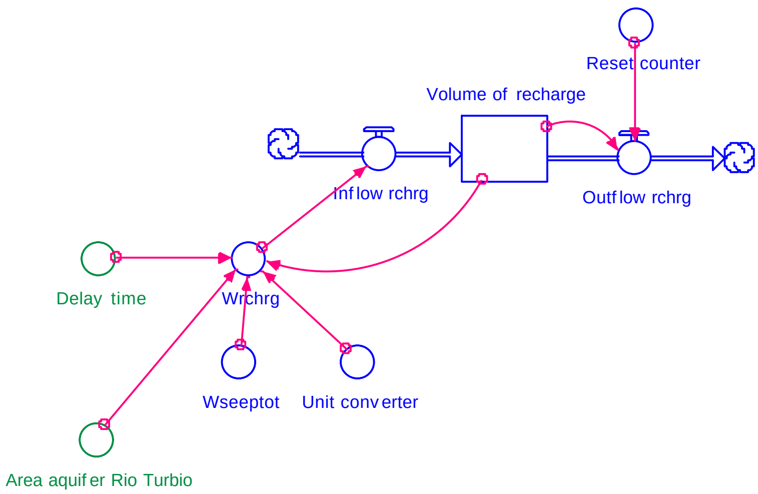


Figure 4.8: Calculation of the recharge in Stella

4.4.3 Base flow

If an aquifer is a shallow aquifer with groundwater levels close to the surface, base flow can be calculated with the following equation:

$$Q_{gw,i} = Q_{gw,i-1} \cdot \exp[-\alpha_{gw} \cdot \Delta t] + w_{rchrg} \cdot (1 - \exp[-\alpha_{gw} \cdot \Delta t]) \qquad [4.6]$$

where: $Q_{gw,i}$ is the groundwater flow or base flow into the main channel on day i (mm)
$Q_{gw,i-1}$ is the groundwater flow or base flow into the main channel on day i –1 (mm)
α_{gw} is the base flow recession constant
Δt is the time step (days)

The base flow recession constant can be calculated with:

$$\alpha_{gw} = 10 \cdot K_{sat} / (\mu \cdot L_{gw}^2) \qquad [4.7]$$

where: K_{sat} is the hydraulic conductivity of the aquifer (mm/day)
μ is the specific yield of the shallow aquifer (-)
L_{gw} is the distance from the ridge or subbasin divide for the groundwater system to the main channel (m)

In Stella the calculation of the base flow is done according to figure 4.9.

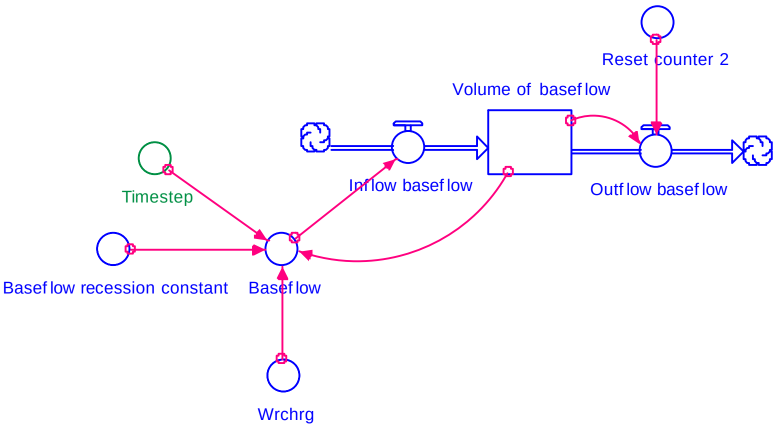


Figure 4.9: Calculation of the base flow in Stella

And the base flow recession constant can be calculated in Stella according to figure 4.10.

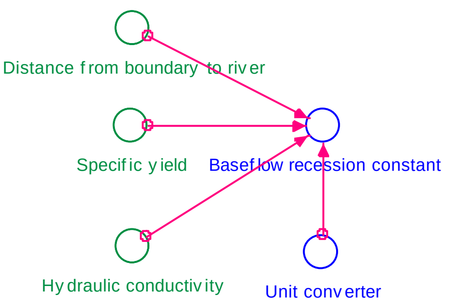


Figure 4.10: Calculation of the base flow recession constant in Stella

4.4.4 Water balance aquifer

The water balance for a shallow aquifer in SWAT is calculated with:

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg} - Q_{gw} - w_{revap} - w_{deep} - w_{pump,sh} \qquad [4.8]$$

where: $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day i (mm)
$aq_{sh,i-1}$ is the amount of water stored in the shallow aquifer on day i - 1 (mm)
w_{deep} is the amount of water percolating from the shallow aquifer into the deep aquifer on day i (mm)
$w_{pump,sh}$ is the amount of water removed from the shallow aquifer by pumping on day i (mm)

For a deep aquifer the water balance in SWAT is:

$$aq_{dp,i} = aq_{dp,i-1} + w_{deep} - w_{pump,dp} \qquad [4.9]$$

where: $aq_{dp,i}$ is the amount of water stored in the deep aquifer on day i (mm)
$aq_{dp,i-1}$ is the amount of water stored in the deep aquifer on day i –1 (mm)
$w_{pump,dp}$ is the amount of water removed from the deep aquifer by pumping on day i (mm)

For the Río Turbio aquifer the equations 4.8 and 4.9 are combined to one equation and inflow from and outflow to other aquifers are also incorporated. This results in the following equation:

$$aq_i = aq_{i-1} + w_{rchrg} - Q_{gw} - w_{revap} - w_{pump} + w_{infl} - w_{outfl} \qquad [4.10]$$

where: aq_i is the amount of water stored in the aquifer on day i (mm)
aq_{i-1} is the amount of water stored in the aquifer on day i - 1 (mm)
w_{pump} is the amount of water removed from the aquifer by pumping on day i (mm)
w_{infl} is the amount of water flowing in the aquifer from another aquifer (mm)
w_{outfl} is the amount of water flowing out the aquifer to another aquifer (mm)

In Stella equation 4.10 is calculated according to figure 4.11.

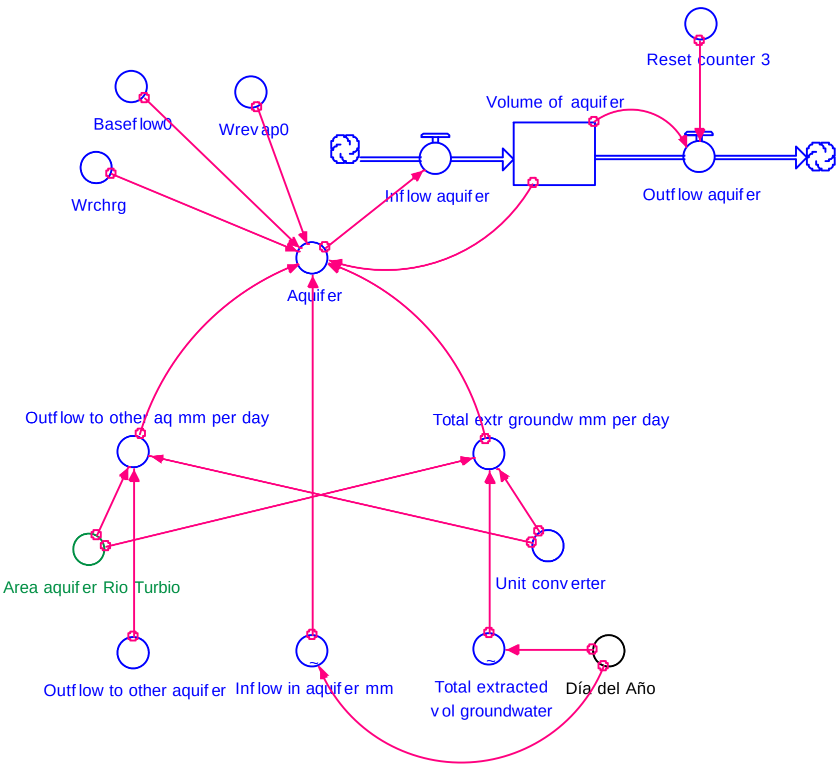


Figure 4.11: Calculation of the groundwater balance in Stella

The base flow (Q_{gw}) and evaporation (w_{revap}) are in the case of Río Turbio zero, because there is no base flow or evaporation from the aquifer. Normally the calculations of base flow and evaporation can be connected here. The base flow and the evaporation are inactive because the water level is deep and there is no physical connection.

4.4.5 Output groundwater level

The output groundwater level is simulated in two steps. The first step includes the calculation of the annual average daily volume of the aquifer (equation 4.11).

$$Vaq_{av} = ?(Vaq_i / 365) \qquad \text{for } i = [1..365] \qquad [4.11]$$

where: Vaq_{av} is the average daily volume of the aquifer in a specific year (mm)
Vaq_i is the volume of the aquifer on day i (mm)

This sum of the volumes is used for calculating the annual average groundwater level in that specific year with the help of the specific yield (equation 4.12).

$$H_{av} = H_{base} + (Vaq_{av} / UC) / Sy \qquad [4.12]$$

where: H_{base} is the base of the aquifer (m + MSL)
H_{av} is the average groundwater level in 1995 (m + MSL)
Sy is the specific yield (-)

5 INPUT DATA, CALIBRATION AND SENSITIVITY ANALYSIS

5.1 Input data

The data, mentioned in chapter two, are in some cases a bit adjusted to convert it to correct input data for the revised model. From the year 1995 most data are available, so this year is used for calibration. In the following sections the input data for the aquifer Río Turbio for the year 1995 are described.

5.1.1 Precipitation

The daily precipitation for 1995 is calculated, as mentioned in section 3.2.2, based on a factor (F_{SC}) and two different distributions (wet and dry year). In the model this is called the generated precipitation. The result of the generated precipitation for 1995 is shown in figure 5.1. This shows a dry period from February to July and precipitation from August to December, with a bit of rain in January.

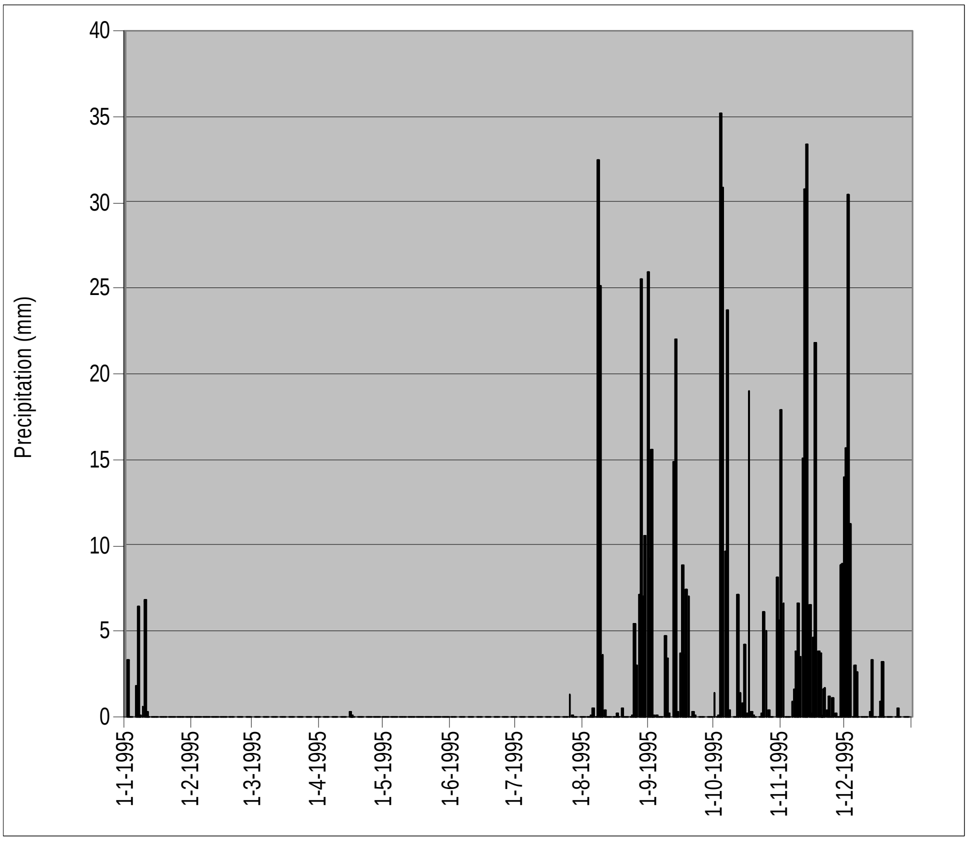


Figure 5.1: Generated daily precipitation in Río Turbio aquifer region for 1995

5.1.2 Evapotranspiration

In the IMTA model it is assumed that the potential evapotranspiration is the same every year, the same distribution and the same values (section 3.2.4). This is a simplification of the truth, which was already incorporated in the existing model and not changed. In figure 5.2 the distribution over the year is given.

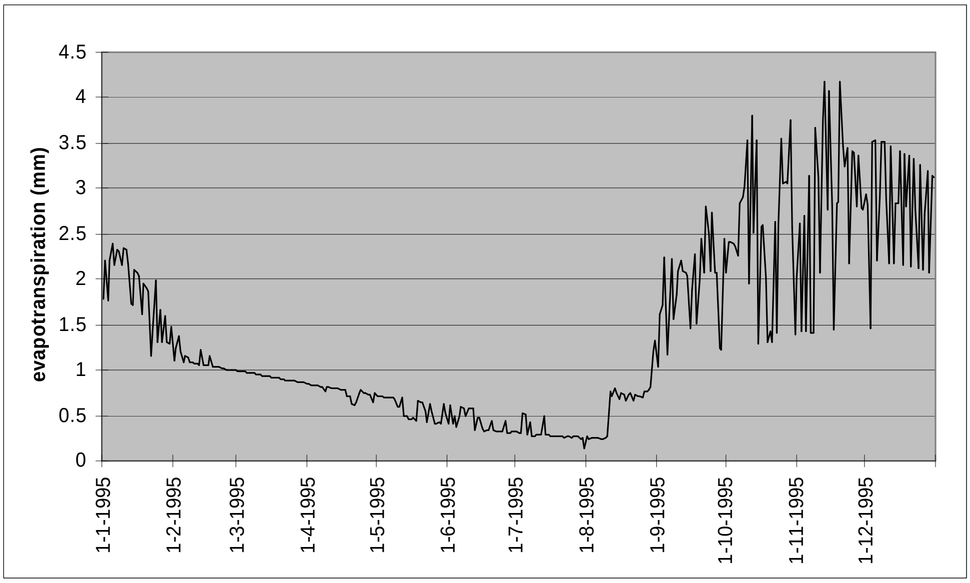


Figure 5.2: Actual daily evapotranspiration in Río Turbio aquifer region for 1995

5.1.3 Initial groundwater level

The revised model simulates a spatially-averaged groundwater level. The calculation of the initial spatially-average groundwater level is based on a groundwater contour map (figure 4.5, CEASG and GEOPSA, 1998). With this figure the surface between the contour lines of the static levels in October 1995 are calculated and multiplied by the average of the two surrounding static levels of this small area. This results in a spatially weighed average level of 1700.4 m + MSL for October 1995, which is used as an initial groundwater level for 1995.

According to this calculation the modelled Río Turbio aquifer is 820 km^2. The average surface level is calculated with 22 points evenly distributed over the modelled area. The average surface level is 1752.5 m + MSL, so the average groundwater depth is 52.1 m.

5.1.4 Boundary flow

The recharge areas in the mountains to the north and to the west (section 2.2.7) are not included in the modelled area. The volumes that are recharged in these areas are incorporated as a constant boundary flow, with no fluctuation during the year. This is done, because hardly any information is available, only the total recharge rates for 1995. From the northern part 31.44 Mm^3/yr is flowing in and from the west 20.27 Mm^3/yr (CEASG and GEOPSA, 1998).

In CEASG and GEOPSA (1998) different values are mentioned for the inflow from the Penjamo-aquifer at the southeast boundary. Since more and more water is extracted in the centre of the valley of Río Turbio, the outflow to Penjamo is reversed and changed into an inflow of groundwater (section 2.2.6). The values that are mentioned are 58.4 Mm^3 and 8.4 Mm^3 among others. 58.4 Mm^3 seems too much, because a few years before there was still outflow to the Penjamo-aquifer, instead of inflow. For the current model it is assumed that 8.4 Mm^3 is the boundary flow from the south-east. In table 5.1 the boundary flow for the Río Turbio aquifer for 1995 is summarised.

Table 5.1: Boundary flow Río Turbio aquifer for 1995 (CEASG and GEOPSA, 1998)

Different flows	**Boundary flow (Mm^3)**
Boundary flow from north	31.44
Boundary flow from west	20.27
Boundary flow from other aquifer at south east side	8.40
Total boundary flow	**60.11**

5.1.5 Population, water use and waste water

In 1990 the population in the catchment of the aquifer Valle del Río Turbio was 153,934 inhabitants (CEASG and IGC, 1995). For 1995 it is calculated that in the same area 172,493 persons were living (CEASG and BURGEAP, 1999). More or less 50% of these inhabitants were living in urban areas and 50% in rural areas. In 1999 the average water use was 257 l/inhabitant/day for urban area and 150 l/inhabitant/day for the population in the rural area (CEASG and BURGEAP, 1999). This gives an average water use of 205 l/inhabitant/day. It is assumed that in 1995 the same amount of water is used as in 1999. Assumed is that 5% (arbitrary chosen) of the total water flow in the drinking water net will infiltrate and contribute to the soil moisture storage (section 4.3.2).

These 172,493 inhabitants produce also waste water. It is assumed that every inhabitant produces 150 l/d. From this volume 30% (arbitrarily chosen) will infiltrate in the ground and contribute to the soil moisture and 70% of this volume will flow into the river.

5.1.6 Extractions

In the small units and communities, groundwater is used for irrigation. In 1995 a volume of 181.2 Mm^3 of groundwater was extracted (CEASG and IGC, 1995). Part of this volume is extracted from wells that are situated outside of the Río Turbio aquifer (in the León aquifer), but counted for Río Turbio. In this study the extracted volumes from the aquifer of León are left out, so that leaves a total extracted groundwater volume of 146.43 Mm^3 for the Río Turbio aquifer in 1995. In table 5.2 the extracted volumes for 1995 are given.

Table 5.2: Use of extracted volumes of groundwater

Type of use	**Extracted volumes from groundwater 1995 (Mm^3)**
Agriculture	106.44
Drinking water	37.45
Domestic use	2.30
Industrial use	0.02
Other	0.22
Total	**146.43**

5.1.7 Irrigation

The irrigated area is 33,000 ha (CEASG and IGC, 1995). Probably this 33,000 ha is gross irrigated area and only 16,125 ha are effectively irrigated (CEASG and IGC, 1995). But if you compare this amount of irrigated area to the extracted volume of groundwater (CEASG and IGC, 1995) a layer of 0.734 m is used.
On 88% of the agricultural area in the state of Guanajuato different types of grain are grown (Silva-Ochoa, 2000). This crop needs a layer of 0.45 – 0.65 m water during the growing season (http://www.fao.org/docrep/S2022E/s2022e07.htm). The farmers in the Río Turbio aquifer are extracting more or less twice as much as the plants need. This means that normally this irrigated layer is around 1 m. In that case the effective irrigated

area can only be around 10,000 ha. In this research it is assumed that 10,000 ha are irrigated with a layer of 1.06 m of extracted groundwater.

The irrigation zones and units are irrigated with surface water. The extracted volumes of surface water are calculated by the effectively used area of irrigated land multiplied by a layer of 1.1 m. More or less 90% of the area is effectively used (CEASG and IGC, 1995). This gives a total yearly extracted volume of surface water. In this case 11.000 ha * 90% * a layer of 1.1 m gives a total extracted volume of 108.9 Mm^3 of surface water.

The effective irrigated layer for surface water extractions is 0.49 m, the effective irrigated layer for groundwater extractions is 0.673 m (CEASG and IGC, 1995).

During the year the extraction for irrigation is not constant. A distribution over the year will be used. The period of irrigation with surface water is in autumn and winter and with groundwater is more or less from October until May (CEASG and IGC, 1995). During these irrigation periods the extraction rates are considered to be constant. In reality this is not true, but for a simulation of a yearly balance, the deviation is acceptable.

5.1.8 River

The daily runoff of the Río Turbio at gauging station Las Adjuntas in 1995 is given in figure 5.3.

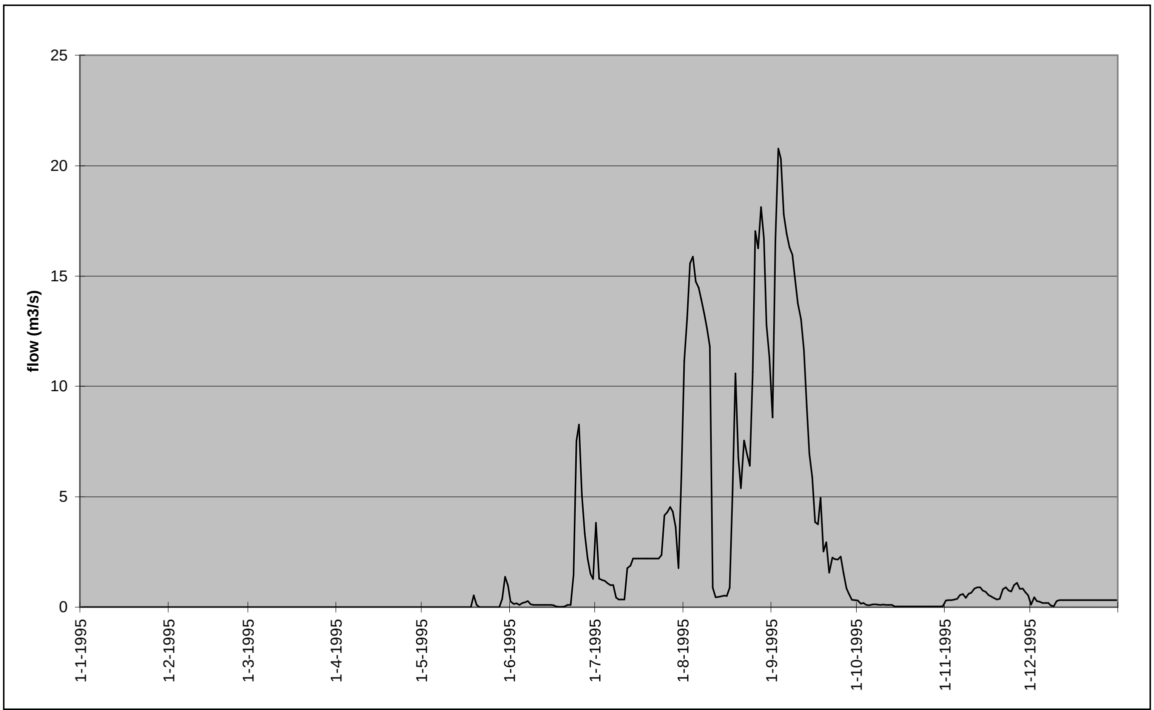


Figure 5.3: Daily stream flow Río Turbio at Las Adjuntas for 1995

The catchment of the Río Turbio is bigger than the modelled aquifer. This means that inflow of the river into the modelled area happens, see also section 4.3.3. In this case the river flows into the model area at the reservoir San Germán. At this point there are no gauging stations, so the inflow of the river at this point is calculated, based on a number of assumptions. Comisión Nacional del Agua (CNA) calculated that the direct runoff of the subcatchment Las Adjuntas was 173 Mm^3 for 1995. From this volume the irrigated volume (surface water), transmission losses and unknown extractions upstream are extracted. This leaves a volume of 37.25 Mm^3 of water that is flowing in the model area at reservoir San Germán in 1995. Details on the calculation of the inflow are given in appendix 2.

In the Lerma-Chapala basin are measurements and calculations on transmission losses. In the whole basin the transmission losses are between 5% and 25% of the surface water flow. For the Río Turbio aquifer the transmission losses are assumed to be 10% of the surface water flow. It is assumed that 10% of the surface water flow is extracted, but not registered, so these extractions are called 'Unknown extractions'.

5.1.9 Reservoir

For the fictitious reservoir of Río Turbio with a total capacity of 113.28 Mm^3 (table 2.2) an area-volume curve is defined, based on the existing curve of the reservoir La Purísima reservoir. This reservoir is also situated in the state of Guanajuato, but in the catchment of the aquifer Silao-Romita. This curve will be used for the Río Turbio. The area-volume curve for the fictitious reservoir of Río Turbio is shown in figure 5.4.

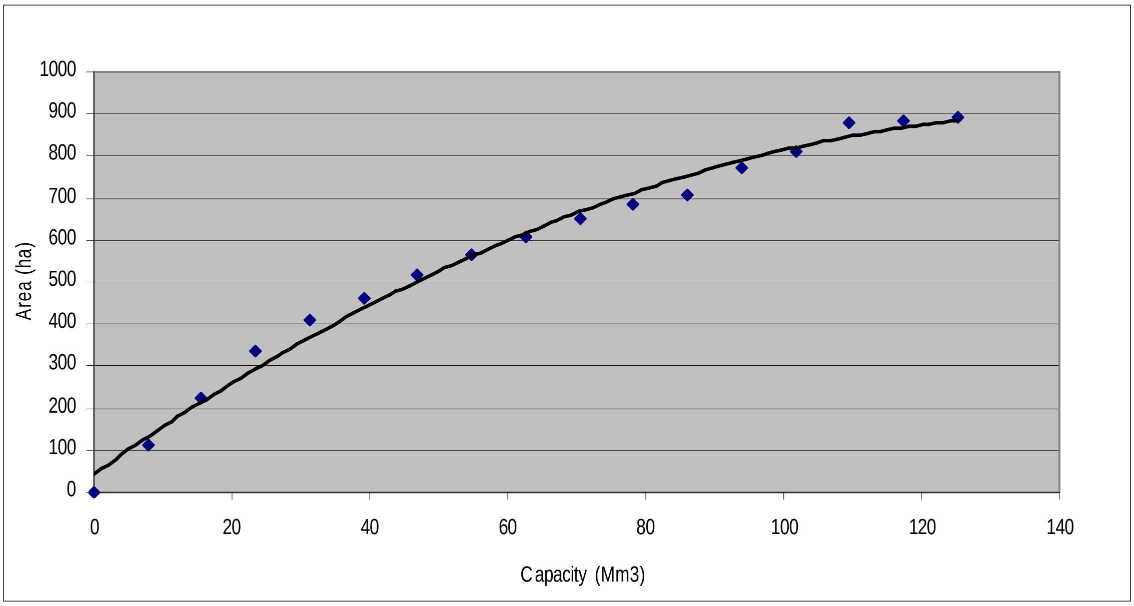


Figure 5.4: Area-volume curve fictitious reservoir Río Turbio aquifer

In the IMTA model half of the maximum capacity is taken for the initial volume, so 62.5 Mm^3 (arbitrarily chosen).

From the fictitious reservoir transmission losses occur. This is assumed to be 10% (section 5.1.9) of the volume that flows into the reservoir.

5.1.10 Base of aquifer

Since there are no clear aquicludes in the catchment of the Río Turbio aquifer, in the IMTA model it is considered to be one aquifer with a thickness of 400 m, so the base of the aquifer is at 1352.5 m + MSL. This level is more or less the same as the base of the aquifer mentioned by CEASG and GEOPSA (1998). This level of the base of the aquifer is needed to calculate the groundwater level with the specific yield from the aquifer volume (section 4.4.5). If no measures are taken and everything stays the same, the aquifer will be emptied in 158 years, starting in 1995 (calculation based on an average groundwater level for 1995 of 1700.4 m and an average groundwater level drop of 2.2 m per year). Another problem that arises when the groundwater level drops so fast, is that the boundary flows will change. In the case of the Río Turbio aquifer this already happened at the southeast side of the aquifer; groundwater flows in from the aquifer of Penjamo.

5.1.11 Specific yield
The specific yield in the previous study (CEASG and GEOPSA, 1998) was calculated based on a water balance and most acceptable results. This resulted in a specific yield of 0.016, which seems quite low for this type of area. In this study the specific yield was considered to be an unknown and therefore it had to be calibrated.

5.1.12 Delay time
In the previous studies no delay time of water in the unsaturated zone (section 4.4.2) was mentioned. But since the groundwater level is more or less 50 m below the surface level (section 5.1.3), the percolated water does not contribute to the aquifer straight away. So in the revised model a delay time is included. From this is also not much known, so this value also had to be calibrated.

5.2 Calibration

Since not all parameters were known, the model had to be calibrated to estimate the values of these parameters. In table 5.4 is shown which values were used for calibrating the parameters.

The input data mentioned in section 5.1 are used to develop a calibrated reference model. This reference model is the baseline model, with which the sensitivity analysis and the scenarios are compared.

When using the most common existing hydrological computer models, such as e.g. MODFLOW, one can use for example the Parameter ESTimation utility (PEST) for estimating the different parameters of the model. PEST is a nonlinear parameter calibration package, that adjusts the parameters until the differences between selected model outputs and field measurements are reduced to a minimum (http://www.bossintl.com/literature/pest.pdf). For this IMTA model in the Stella platform the PEST package is not used for the calibration, the calibration is done manually.

The model can be calibrated on a few different topics. The calibration of these different topics will be described in the same order as the calibration itself. The first parameter that had to be calibrated is the direct runoff in the catchment. For the whole surface water catchment Adjuntas this direct runoff is calculated by CNA and is 173 Mm^3 for 1995. For the Río Turbio aquifer this direct runoff is also calculated, because the 173 Mm^3 applies to the whole surface water catchment and cannot be used for only a part, i.e. Río Turbio.
In the Río Turbio case almost all the reservoirs are fed by direct runoff only. Because the extracted surface water for irrigation is estimated to be more or less 110 Mm^3 per year, the direct runoff should be of the same amount. The direct runoff that is calculated with the model is compared with this 110 Mm^3. By changing the CNII-number of the Curve Number method of the Soil Conservation Service (section 3.2.3) the direct runoff can be calibrated. With a CNII-number of 86.3 the direct runoff, calculated with the model, is 109.91 Mm^3, which is a deviation of 0.08%. A CNII-number of 86.3 is a bit high, the average Curve Numbers are between 60 and 80, with only a few numbers between 80 and 90 (Natural

Resources Conservation Service, 1986). Perhaps the assumption of total direct runoff in the Río Turbio aquifer of 110 Mm^3 should be lower, but in that case the reservoirs are not properly filled up and there is not enough surface water for irrigation. So this Curve Number of 86.3 will be used in the reference model.

At the gauging station Las Adjuntas the daily flow of Río Turbio is measured. For 1995 the total measured runoff was 57.7 Mm^3. In the model a factor is incorporated which indicates how much of the direct runoff will pass first through the reservoir and how much of the direct runoff will flow straight through gauging station Las Adjuntas (section 4.3.1). Calibrating this results in a factor of 0.05. That means that 95% of the direct runoff will flow to the reservoir and 5% will flow straight into the river and gauging station Las Adjuntas.

Another factor has to be calibrated at the same time, because it also affects the river flow. This factor describes the division of the excess of soil moisture in a volume that percolates (figure 4.3, section 4.3.2) and a volume that flows back to the surface water (in the model called 'interflow'). The factor for the division is 0.23 after calibration. This means that 23% of the soil moisture excess is interflow and 77% percolates. With this factor the recharge results in 68.1 Mm^3, which is 10% of the total flow in the aquifer (see appendix 3). The recharge mentioned in CEASG and GEOPSA (1998) is 63.5 Mm^3, so the deviation is 7%. In that same study they had problems with the calibration and after their calibration the recharge was diminished to 35.9 Mm^3. For this study of the revised IMTA model the calibrated numbers are used and considered to be acceptable.

With a factor of 0.05 for the division into reservoir or river and 0.23 for the division between percolation and interflow, the calculated runoff through gauging station Las Adjuntas is 58.1 Mm^3, which is a deviation of 0.6%.

For the groundwater module two parameters had to be calibrated; specific yield and delay time. These parameters were calibrated on the average drop of 2.20 m/yr (CEASG and GEOPSA, 1998). In the model this drop is calculated with the initial groundwater level (section 5.1.3) and the average groundwater level (section 4.4.5). This procedure is not correct if people are interested, as in this study, in the water level at day 365. Equation 4.12 allows computation of the difference between the initial groundwater level (start of simulation at day one of a specific year) and the average groundwater level. In this study this was defined as the drop in the groundwater level over the year, on which the model was calibrated. Of course this was incorrect. This should be the drop calculated with the initial groundwater level and the groundwater level at day 365. In appendix 4 a proposal for changing the model is given, so the daily groundwater level is calculated. Due to the limited time for this research this was not corrected, which means that the results of all the simulations are also not correct, but the model still gives an indication of the water system in the Río Turbio aquifer region and the reactions on different management changes, but no real values.

The specific yield after calibration was 0.016. For this type of aquifer a higher specific yield is expected. The range for this type of aquifer is between 0.01 and 0.30 (Kruseman et al, 1990). But also according to the previous study (CEASG and GEOPSA, 1998) the specific yield in this aquifer is 0.016. Since these results are so similar, it is assumed that the calibrated specific yield is correct.

The delay time in that case results in 77 days. No data are available about the delay time for this aquifer. Table 5.3 gives a summary of the results of the calibration.

Table 5.3: Results of the calibration

Changed parameter of factor	Section	Result of calibration
CNII-number	3.2.3	86.3
Factor direct runoff	4.3.1	0.05
Factor excess soil moisture	4.3.2	0.23
Specific yield	4.4.5 and 5.1.11	0.016
Delay time	4.4.2 and 5.1.12	77 days

In table 5.4 the deviation of the three values on which is calibrated is given.

Table 5.4: Deviation after calibration

Calibrated value	Measured	Simulated	Difference
Direct runoff	110 Mm^3	109.91 Mm^3	- 0.1%[3]
Río Turbio	57.7 Mm^3	58.1 Mm^3	+ 0.7%
Groundwater level	1698.20 m + MSL[4]	1698.20 m + MSL	0.0%

If one takes a look at the volume of the aquifer at the end of 1995 and calculates from this the groundwater level by dividing this by the specific yield, the groundwater level is 1699.02 m + MSL. This means a drop of only 1.38 m instead of 2.20 m. This is caused by the fact that calibration is done with the drop, calculated with the initial groundwater level and the average groundwater level. If the model is calibrated on a drop of 2.20 m, calculated with the initial groundwater level and the groundwater level on day 365, the specific yield will be smaller than 0.016 and the delay time will be larger than 77 days.

5.3 Simulated water balances

The calibrated model (section 5.2) produces a few different water balances. These balances can be used to check how the model is working and reflects what happens in the research area. For the aquifer, the soil, the fictitious reservoir and the Río Turbio the balances were calculated with the revised IMTA model. In the following sections the water balances and some of the balance terms will be explained in more detail.

5.3.1 Water balance aquifer

The results for the aquifer balance are given in table 5.5. The difference between inflow and outflow is 0.20 Mm^3, which is a deviation of 0.14%. This is an acceptable difference.

Extra recharge 77 days

In table 5.5 the term ‘extra recharge 77 days’ is added. This term stands for recharge in the first 77 days of 1995. The number of 77 days is used, because in the calibration the delay time (equation 4.5, section 4.4.2) resulted in 77 days.
Recharge is calculated with the soil moisture module from the percolation together with the transmission losses of the Río Turbio and the fictitious reservoir (figures 4.7 and 4.8). During the year excess soil moisture is generated. But before 1995 starts, so in the last months of 1994, there is also soil moisture excess which causes recharge in the first months of 1995. In the calculation of Stella this is not included.

---

[3] A positive sign means that the simulated value is too high, a negative value means that the simulated value is too low

[4] This is the average groundwater level for 1995

To explore the effects of the first 77 days, the IMTA model is changed and a second year with no boundary flows is simulated. So every term (e.g. evaporation, precipitation, extractions) is assumed to be zero in the second year, except for the recharge.

Table 5.5: Water balance aquifer

In (Mm^3)		Out (Mm^3)	
Actual recharge	*68.06*[5]	Extraction	146.43
Boundary flow North	31.44	Change groundwater storage	*-28.86*
Boundary flow West	20.27	Difference potential and actual recharge	*29.47*
Boundary flow Southeast	8.40		
Extra recharge 77 days	*19.07*		
Total	**147.24**		**147.04**

In the first 77 days of the second year 19.07 Mm^3 (table 5.5) is recharged, this is assumed to be equal to the recharge in the first 77 days of 1995, due to excess soil moisture at the end of 1994. This water balance shows that the initial condition of the excess soil moisture (SME_0) is 19.07 Mm^3 in this case.

Change groundwater storage

In the water balance of the aquifer (table 5.5) the term ‘Change groundwater storage’ is mentioned. This term has a negative sign, because water becomes available from the storage due to the drop of groundwater level, so compared to extractions it needs an opposite sign.

Difference potential and actual recharge

In figure 5.5 the potential recharge is given. This is the total excess simulated with the soil moisture module together with the transmission losses that can recharge and contribute to the aquifer.

[5] The italic numbers in all the sub-waterbalances are simulated values, the rest is prescribed

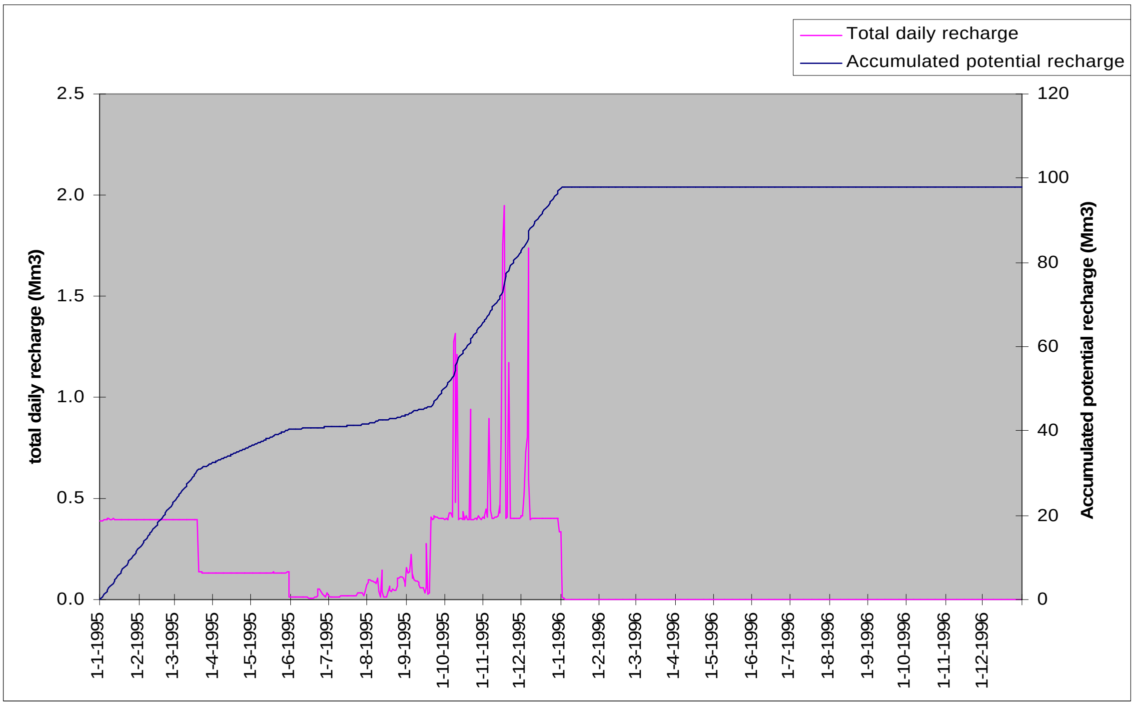


Figure 5.5: Daily potential recharge and accumulated potential recharge for 1995

Not all the water will contribute to the aquifer instantaneously, due to the delay time. So that means that there is a potential recharge and also an actual recharge (figure 5.6). That is the amount of water that actually reaches the aquifer (result of equation 4.5, section 4.4.2).

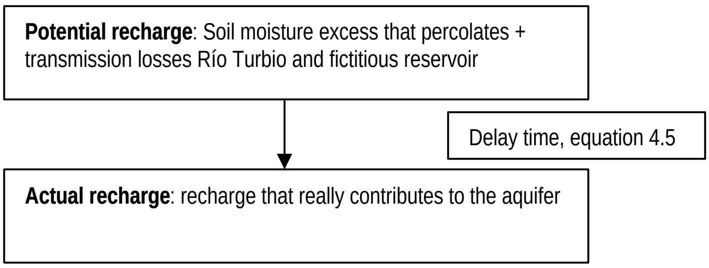


Figure 5.6: Difference between potential and actual recharge

The volume of the aquifer fluctuates. In figure 5.7 the simulated volume of the aquifer for 1995 is displayed.

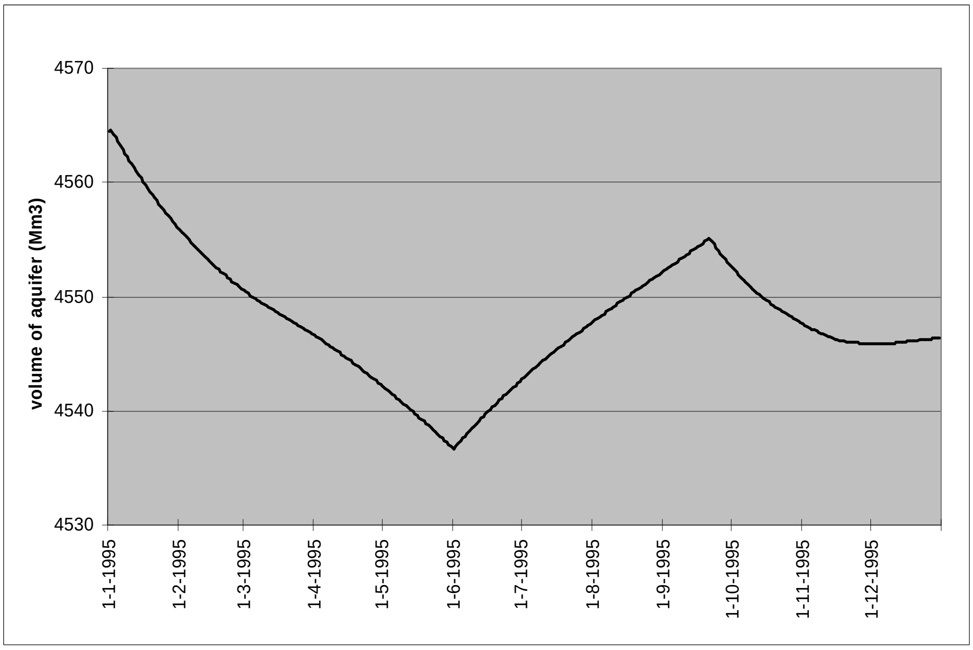


Figure 5.7: Simulated volume of the aquifer for 1995

5.3.2 Soil moisture balance

The balance for the soil moisture is given in table 5.6. The difference between inflow and outflow is 0.01 Mm^3, which is a deviation of 0.01%.

Table 5.6: Soil moisture balance

In (Mm^3)		**Out (Mm^3)**	
Soil moisture after rain	*0.00*	Actual recharge	*68.06*
Effluent	2.18	Difference potential and actual recharge	*29.47*
Excess irrigated surface water	*46.24*		
Excess irrigated groundwater	*30.34*		
Losses drinking water net	0.50		
Transmission losses river	*7.27*		
Transmission losses reservoir	*11.01*		
Total	**97.54**		**97.53**

Soil moisture after rain

In table 5.6 one can see the term ‘Soil moisture after rain’, which is the excess of soil moisture that percolates. This is calculated by the part that calculates the change of soil moisture in the catchment (figure 3.9, Subsuelo Vol Adju).

Explanations for some other terms can be found in the following sections:

- For the term ‘Effluent’ and ‘Losses drinking water net’ the calculation is given in section 5.1.5.
- The ‘Excess of irrigated water’ is calculated from the volume irrigated water minus the consumptive use (section 5.1.7).
- The transmission losses river and reservoir are elaborated in sections 5.1.8 and 5.1.9.

The two out-terms are the same as described for the water balance of the aquifer (section 5.3.1). In the term 'Difference pot and act recharge' the change in storage of the soil moisture excess is included.

5.3.3 Water balance Río Turbio

The water balance for the Río Turbio is given in table 5.7. The difference between inflow and outflow is 0.45 Mm^3, which is a deviation of 0.62%.

Table 5.7: Water balance Río Turbio

In (Mm^3)		**Out (Mm^3)**	
Soil moisture after rain	*0.00*	Outflow at Las Adjuntas	*58.05*
Effluent in ground	0.65	Transmission losses river	*7.27*
Excess irrigated surface water	*13.81*	Unknown extractions river	*7.27*
Excess irrigated groundwater	*9.06*		
Losses drinking water net	0.16		
Effluent directly into river	6.61		
Inflow at San Germán	37.27		
Direct runoff to river	*5.48*		
Spills reservoir	*0.00*		
Total	**73.04**		**72.59**

The first five terms of the Río Turbio water balance are corresponding to the first five terms for the soil moisture balance, except from the values. This can be derived from figure 4.3. The terms are all added up and then multiplied with a factor between percolation (soil moisture balance) and interflow (Río Turbio water balance).
The term 'Effluent directly into river' is 70% of the total amount of waste water, what will be discharged on the river (section 5.1.5).
The direct runoff to the river is calculated by the Curve Number method (figure 3.8, Escurrimiento directo instant 11) and divided between the river and the reservoir using a factor. The simulated direct runoff for 1995 is shown in figure 5.8.

The spills of the reservoir happen when the maximum capacity of the reservoir is reached. If the reservoir starts to spill water, this will flow to the river (section 3.2.5).

The term 'Outflow at Las Adjuntas' is measured but also calculated, so this is a value on which the model was calibrated. The transmission losses and unknown extractions are a priori given (section 5.1.8).

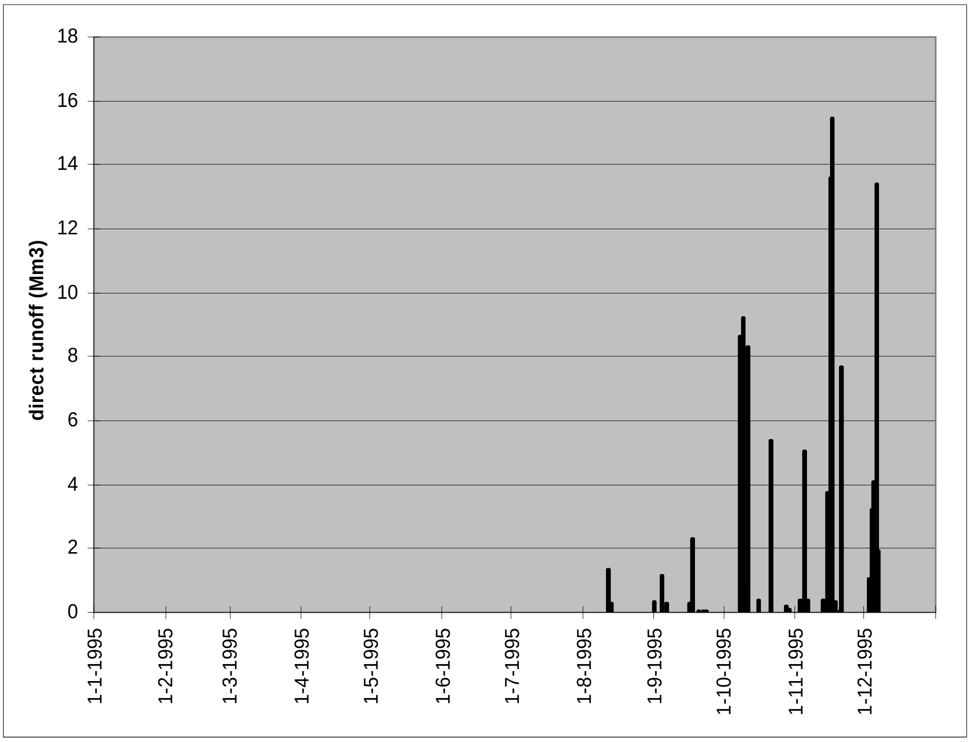


Figure 5.8: Simulated daily direct runoff for 1995

In figure 5.9 the simulated daily flow of the Río Turbio through gauging station Las Adjuntas is shown.

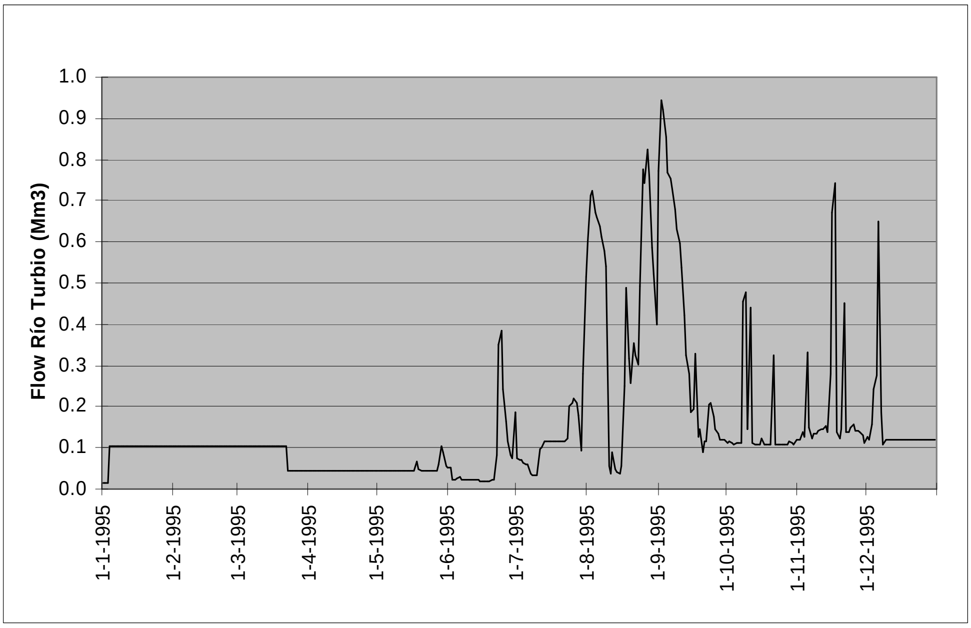


Figure 5.9: Simulated daily flow Río Turbio for 1995

5.3.4 Water balance fictitious reservoir

The water balance for the fictitious reservoir is given in table 5.8. The difference between inflow and outflow is 0.02 Mm^3, which is a deviation of 0.01%.

Table 5.8: Water balance fictitious reservoir

In (Mm³)		Out (Mm³)	
Direct runoff to reservoir	*104.06*	Transmission losses reservoir	*11.01*
Precipitation on reservoir	*6.07*	Evaporation reservoir	*3.90*
		Extractions for irrigation	108.30
		Spills reservoir	*0.00*
		Change in storage	*-13.10*
Total	**110.13**		**110.11**

The direct runoff to the reservoir is calculated by the Curve Number method (figure 3.8, Escurrimiento directo instant 11) and divided between the river and the reservoir using a factor.

The transmission losses of the fictitious reservoir are also assumed to be 10% of the total inflow (section 5.1.9). In figure 5.10 the simulated volume of the fictitious reservoir is given.

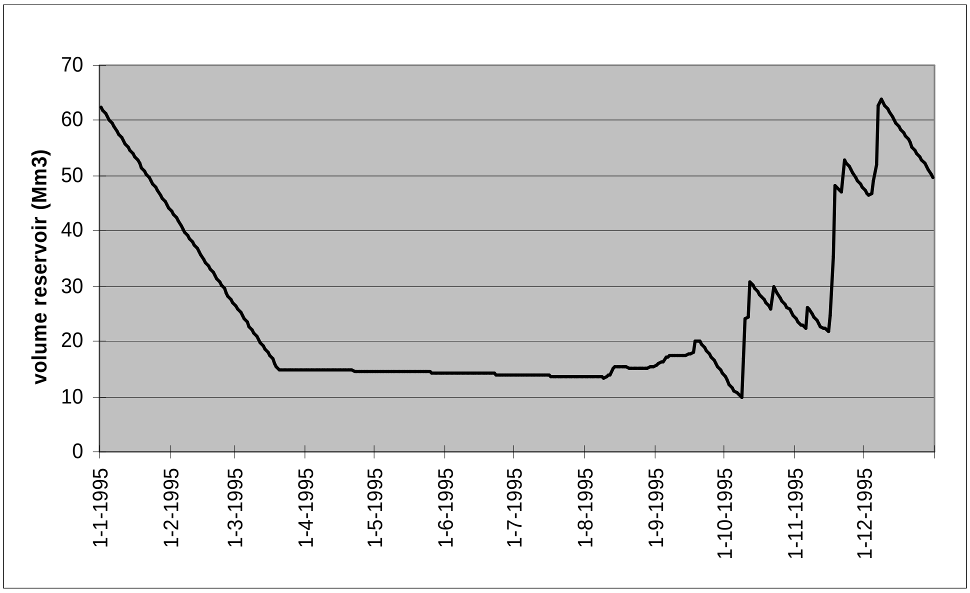


Figure 5.10: Simulated volume of the fictitious reservoir

5.4 Sensitivity analysis

5.4.1 Introduction

Since many parameters and boundary conditions have been estimated, assumed or calibrated in this research, a sensitivity analysis is carried out. This sensitivity analysis here shows the sensitivity for a few different parameters and input data. With this sensitivity the reliability of the model results can be explored. In this section the most important results of the sensitivity analysis are described.

In PEST (section 5.2) a model-independent sensitivity analyzer is included; SENSAN (http://www.bossintl.com/literature/pest.pdf). SENSAN also communicates with a model through the model's own input and output files. The user can identify adjustable parameters in the model input files and also model generated numbers in the model output files, in which the user is interested. The user provides SENSAN with different sets of parameter values and SENSAN runs the model for each set. The parameter values and model output are recorded in spreadsheet format for analysis.
For the sensitivity analysis of this revised IMTA model SENSAN is not used, this sensitivity analysis is performed manually.

The parameters or boundary conditions from the reference model are reduced and increased by 50% and new simulations are carried out with these new values. For three different parameters it is not possible to change by 50%, but they are still simulated in the sensitivity analysis. These three different parameters are the initial soil moisture excess (in the reference model this is zero), the distribution of the precipitation throughout the year, and the distribution of the irrigated volume throughout the year. The results of these new simulations are compared to the results of the reference model.

Table 5.9 shows which output data are evaluated and with what value they are compared to investigate the influence of the different parameters.

Table 5.9: Values of variables (output data) for the reference model

Item	Value
Average annual groundwater level	1698.20 m + MSL
Accumulated runoff Río Turbio at Las Adjuntas over 1995	58.06 Mm^3
Volume fictitious reservoir at end of 1995	49.75 Mm^3
Accumulated direct runoff over 1995	109.91 Mm^3

If the changes in the simulated output are more than 20% they are discussed in the following sections. The results of the initial excess soil moisture and the distribution of precipitation are summarized in table 5.10.

Table 5.10: Most important results of first sensitivity analysis

Parameter	Groundwater level		Runoff Río Turbio		Volume reservoir		Direct runoff	
	Diff (m)	Diff (%)	Diff (Mm^3)	Diff (%)	Diff (Mm^3)	Diff (%)	Diff (Mm^3)	Diff (%)
Initial condition excess soil moisture	+ 2.29[6]	104.1	+ 0.45	+ 0.78	- 6.67	- 13.41	+ 4.67	+ 4.25
Distribution precipitation	+ 0.03	+ 1.36	- 0.98	- 1.69	- 21.35	- 42.91	- 24.53	- 22.32

The results of specific yield, delay time, inflow surface water, irrigated surface area and boundary flow groundwater are shown in table 5.11. Appendix 5 gives an overview of the complete sensitivity analysis.

[6] Positive sign means a rise of level or an increased volume, a negative sign means a drop of level or a decreased volume

Table 5.11: Most important results of second sensitivity analysis

Parameter	Change	Change groundwater level end of 1995		Change runoff Río Turbio end of 1995		Change volume reservoir end of 1995		Change direct runoff end of 1995	
	(%)	(m)	(%)	(Mm^3)	(%)	(Mm^3)	(%)	(Mm^3)	(%)
Specific yield	-50	- 1.24	- 56.4	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 0.24	+ 19.1	0.0	0.0	0.0	0.0	0.0	0.0
Delay time	-50	+ 0.44	+ 20.0	0.0	0.0	0.0	0.0	0.0	0.0
	+50	- 0.33	- 15.0	0.0	0.0	0.0	0.0	0.0	0.0
Inflow San Germán	-50	- 0.02	- 0.9	- 14.90	- 25.7	0.0	0.0	0.0	0.0
	+50	+ 0.03	+ 1.4	+ 14.90	+ 25.7	0.0	0.0	0.0	0.0
Irrigated (gw) surface area	-50	+ 0.75	+ 34.1	+ 6.09	+ 10.5	0.0	0.0	0.0	0.0
	+50	- 0.74	- 33.6	- 6.09	- 10.5	0.0	0.0	0.0	0.0
Boundary flow groundwater	-50	- 1.13	- 51.4	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 1.14	+ 51.8	0.0	0.0	0.0	0.0	0.0	0.0

5.4.2 Initial condition soil moisture module

In section 5.3.1 it was described that the lack of data results in problems with the definition of the initial condition. The storage of excess of soil moisture that can contribute to recharge, starts at zero in the IMTA model instead of an initial condition with already storage of soil moisture excess from the previous year. To investigate the effects of this initial condition ($SME_0 = 0$), the model was run for two exactly the same years, this means that the year 1995 is simulated twice. In the first year the actual recharge was 83 mm, according to the simulation with the reference model. But in the second year the actual recharge was 119 mm or 30.07 Mm^3 (differences with water balances in tables 5.5 and 5.6 are due to rounding up). This means that there is hardly any difference between actual and potential recharge anymore. A recharge of 30.07 Mm^3 would mean an extra difference in groundwater level of 2.29 m than with $SME_0 = 0$ (table 5.10).

If you take this in mind it means that the calibrated values are incorrect. But if you would adjust the delay time (recalibration) from 77 days to 146.5 days the drop of groundwater level in the second year is exactly 2.20 m. In the surface water part, the direct runoff is also too large, that means that the CNII-number or the inflow at San Germán should be adjusted as well.

5.4.3 Distribution precipitation

In the calibrated model a distribution of precipitation for the wet year was used (sections 3.2.2 and 5.1.1). In the sensitivity analysis the distribution of a dry year was used. The annual precipitation is, of course, the same, but the distribution over the year is changed. The precipitation in the dry year is more equally distributed throughout the year than in the wet year and in the wet year the peak rainfalls are higher (appendix 6). The dry year distribution causes that in the dry year more precipitation is infiltrating and less direct runoff occurs. With a more equal distribution of precipitation, the evaporation is also more equal. The direct runoff of both distributions is shown in appendix 7. This infiltration does not contribute to the recharge, because this produces no excess soil moisture (figure 3.9, Subsuelo VolAdju), but only changes the amount of soil moisture stored. Physically this is not logical. If more precipitation infiltrates this should influence the groundwater level. That this does not have influence on the groundwater level, shows that the model is not reflecting the real physical situation well. This also shows that the interaction between groundwater and surface water in the model is not fully working according to the physical situation.

The fictitious reservoir is mainly fed by the direct runoff. With less direct runoff (22%) the volume of the reservoir after one year is smaller (43% smaller).
For the surface water system the precipitation distribution has substantial influence. The best would be to use the observed daily precipitation.

5.4.4 Specific yield

Table 5.11 shows that changes in the specific yield influence the groundwater level substantially. It does not influence the runoff of the Río Turbio, the volume of the reservoir nor the direct runoff. The changes in the groundwater level are not linear with the changes of the specific yield. This is caused by the fact that the specific yield is in the denominator in equation 4.12. The difference between 0.008 and 0.016, but also between 0.016 and 0.024 is the same, but the changes between 1/Sy not (table 5.12)

Table 5.12: Non-linear changes due to specific yield

Sy	1 / Sy	Difference
0.024	41.67	
0.016	62.50	20.83
0.008	125.00	62.50

Since the specific yield influences the groundwater level so substantially, further investigation on the correct value for specific yield is urgently needed.

5.4.5 Delay time

Changing the delay time is also influencing the groundwater level substantially. The delay time does not influence one of the other results of the simulation. The changes in the groundwater level are not linear with the changes in delay time. This probably is caused by the fact that the delay time is incorporated in an exponential term (equation 4.5). Since the groundwater level is influenced substantially by the delay time, further investigation on the correct value for delay time is needed.

5.4.6 Inflow San Germán

When the inflow of the Río Turbio at San Germán increases, the outflow at Las Adjuntas increases as well. The outflow at Las Adjuntas is slightly smaller than the inflow; the difference equals the prescribed 20% losses (transmission losses and unknown extractions). However, the inflow at San Germán is related to the direct runoff in the Adjuntas catchment. This is explained in section 5.1.8 and appendix 2. An increased inflow at San Germán means more direct runoff in the upstream catchment (outside research area) and thus results in a decrease of direct runoff in the Río Turbio aquifer, since the total amount is 173 Mm^3 (CNA). This decrease in direct runoff influences the CNII-number and the volume in the fictitious reservoir.

5.4.7 Irrigated area

The area that is irrigated with groundwater is unclear. In section 5.1.7 an assumption is made. If the area is increased by 50%, the excess of irrigated groundwater becomes less (irrigated groundwater (same amount) – effective consumptive use (increases) = excess irrigated groundwater (decreases)). This decrease in excess water results in a further drop of groundwater level (0.74 m more than the drop of 2.20 m for the reference model) and in a decrease in runoff of the Río Turbio (6.09 Mm^3). The influence of the irrigated area on runoff of the Río Turbio is not large (about 10%). However, it influences the recharge and thus this is an important parameter, which should be investigated further.

5.4.8 Boundary flow

CEASG and GEOPSA (1998) was unclear on how much groundwater was flowing in at the southeast of the aquifer (section 5.1.4). In the reference model 8.40 Mm^3 was prescribed as boundary flow (table 5.1), while in the synopsis also 58.40 Mm^3 was mentioned. In this sensitivity analysis the boundary flow at the southeast of the aquifer is decreased and increased by 50%. This causes a groundwater level change of 1.13 m (≈ 51%) compared to the reference model. It shows that this prescribed boundary flow significantly influences the groundwater level, so this should be further investigated.

5.5 Reliability of the model

As described in section 5.1 several input data are estimated, calibrated or calculated, based on assumptions. Section 5.4 shows that the model is sensitive to these input data. Due to lack of sufficient data one can conclude that the model is not reliable yet. Also the wrong calibration comparison (drop to average groundwater level) described in section 5.2 contributes to a lower reliability. However, it is likely that the model is sufficiently reliable to give an indication. Although the model is not fully reliable, scenarios were simulated. The results of these scenarios are described in chapter six. The exact changes due to the scenarios cannot be determined in this phase, but from the scenarios it can be seen if management changes influence the groundwater level positively.

6 SCENARIOS

With the revised model five scenarios were simulated to explore solutions to stop the decline of the groundwater level. The scenarios that were simulated are:

A) reduction of irrigated volume of groundwater;
B) reduction of irrigated area (groundwater);
C) more storage of precipitation (water conservation) and use of this surface water instead of groundwater (increase the volume of the fictitious reservoir, decrease extracted volume groundwater);
D) more surface water supply (keep extracted volume groundwater the same, but build a bigger reservoir and use more surface water in this way);
E) combination of scenario B and C.

In scenario A groundwater will be used more efficiently and it is interesting to see what the influence of this efficiency is on the groundwater level. Scenario B is simulated to see the functioning of the model, but it is not likely for farmers to reduce their irrigated area. Scenario C is a scenario in which surface water is conserved and groundwater extractions are reduced. Scenario D is simulated to see what effects extra extractions of surface water have.

6.1 Results scenarios

The five scenarios mentioned above were simulated with the revised IMTA model for the Río Turbio aquifer region. The values for the different scenarios are:

- SCEN_A: 75 Mm^3 instead of 106.44 Mm^3 extracted groundwater for irrigation;
- SCEN_B: 7500 ha instead of 10,000 ha irrigated area with groundwater;
- SCEN_C: increase of surface water extractions for irrigation with 27.225 Mm^3 per year and decrease of groundwater extractions for irrigation with 27.225 Mm^3 per year;
- SCEN_D: increase of surface water extractions for irrigation with 27.225 Mm^3 per year and no decrease of groundwater extractions;
- SCEN_E: combination of SCEN_B and SCEN_C.

The five scenarios are compared to the reference model, table 5.9. The results of the scenarios are summarized in table 6.1 and are explained further in the following sections. Appendix 8 gives an overview of the complete results of the scenarios.

Table 6.1: Results scenarios

Scenario	Groundwater level		Runoff Río Turbio		Volume reservoir		Direct runoff	
	m + MSL	Diff (m)	Mm^3	Diff (Mm^3)	Mm^3	Diff (Mm^3)	Mm^3	Diff (Mm^3)
SCEN_A	1698.76	+ 0.56[7]	52.37	- 5.69	49.75	0.0	109.91	0.0
SCEN_B	1698.57	+ 0.37	61.11	+ 3.05	49.75	0.0	109.91	0.0
SCEN_C	1699.28	+ 1.08	58.06	0.0	39.81	- 9.94	109.91	0.0
SCEN_D	1698.80	+ 0.60	62.99	+ 4.93	39.81	- 9.94	109.91	0.0
SCEN_E	1699.66	+ 1.46	61.11	+ 3.05	39.81	- 9.94	109.91	0.0

6.1.1 Scenario A

In scenario A the extracted volume of groundwater for irrigation is arbitrarily decreased by 29.5%. This means that groundwater is used more efficiently. The effective irrigated layer is 0.67 m and the irrigated layer is in this case decreased from 1.06 m to 0.75 m. That means that only 0.08 m is inefficient. The effect of this higher efficiency is that the groundwater does not drop by 2.20 m in 1995 to a level of 1698.20 m + MSL, but only to 1698.76 m + MSL. This means that the groundwater level drop over 1995 is 25% smaller. The runoff of Río Turbio decreases by 9.8%, due to the higher efficiency the excess water is less so the return flow decreases as well.

6.1.2 Scenario B

In scenario B the area that is irrigated with groundwater is decreased by 25%. The irrigated volume is still 106.44 Mm^3 per year, which means that it is less effective. Consequently, there is more excess water and thus more recharge. The groundwater level is 1698.57 m + MSL instead of 1698.20 m + MSL, so the drop is 17% less. The runoff of the river increases by 5%, due to more return flow caused by more excess water.

6.1.3 Scenario C

In scenario C the extractions of surface water are increased and the groundwater extractions for irrigation are decreased by the same amount. In this case the extractions for irrigation with groundwater are partly replaced by surface water. This resulted in a groundwater level of 1699.28 m + MSL instead of the normal groundwater level of 1698.20 m + MSL. The drop of groundwater level is reduced by 49%, so in this scenario it takes more or less twice as much time for the groundwater to experience the same drop as in the reference model.
The volume of the aquifer during 1995 for scenario C is shown in figure 6.1. This figure shows that the volume in the aquifer at the end of 1995 is larger than in the beginning of the year, although the model calculates a drop of groundwater level. This drop of groundwater level is due to the wrong comparison (with the yearly average of groundwater levels in stead of the groundwater level at day 365).

The runoff of the Río Turbio remains the same as in the reference model. The initial storage of the reservoir needed to be increased to keep water in the reservoir during all of the year. If the initial storage is not changed, the reservoir would be empty during a part of the year which means that the extra extractions of 27.225 Mm^3 cannot be fulfilled. The change in storage in the fictitious reservoir is quite large, because the area is not

[7] These differences are compared to the groundwater level, total annual runoff of Río Turbio, volume of reservoir at the end of 1995 and the total direct runoff of the reference model. A positive sign means that the groundwater levels in the scenarios are higher or the volumes have increased and a negative sign means a decrease in the volumes compared to the reference model

increased and there is no extra direct runoff that will fill up the fictitious reservoir. Since the sensitivity analysis has shown that the distribution of the precipitation has impact on the direct runoff and thus on the volume in the reservoir (table 5.10), it is hard to predict a priori if enough direct runoff can be captured in the reservoirs in the area to be able to provide water for the extra extractions of surface water.

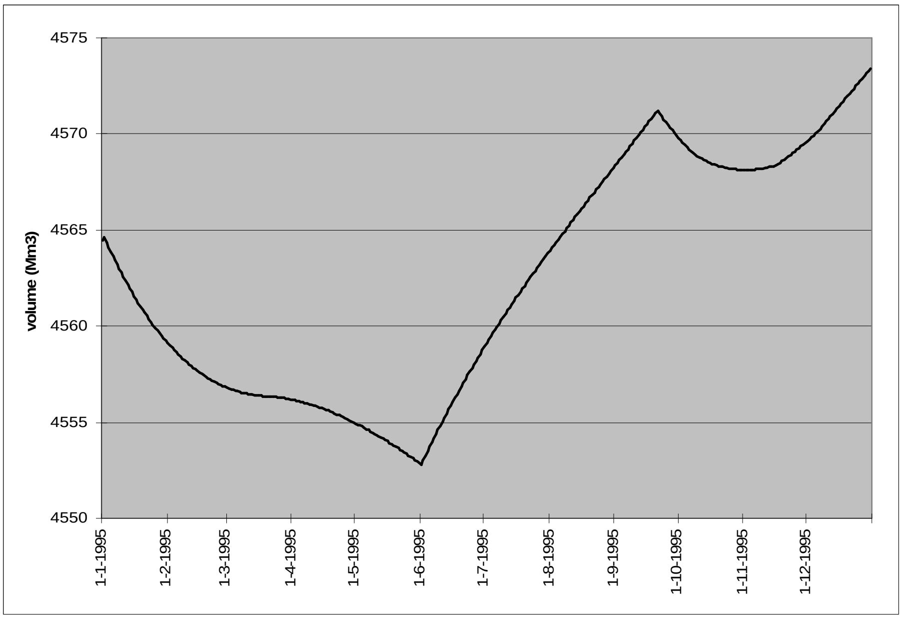


Figure 6.1: Volume aquifer scenario C for 1995

6.1.4 Scenario D

Scenario D is slightly different from scenario C. The extractions of surface water are increased, but the extractions of groundwater for irrigation are kept the same as in the reference model. This scenario shows that the groundwater level drops in one year to 1698.80 m + MSL instead of a drop to 1698.20 m + MSL, a decrease of groundwater level drop by 27%. Since the extractions of surface water for irrigation have been increased and the irrigated area and the effective consumptive use remain the same, more excess irrigated water is available. This causes the higher groundwater level and an increase of the runoff of the Río Turbio by 8%.
In figure 6.2 the volume of the reservoir for scenario D is shown. This figure shows that the volume of the reservoir decreases dramatically and the reservoir is not filled up again at the end of the year. The capturing of direct runoff for scenario C and D was not adapted and only the initial storage of the reservoir was adapted, no other properties of the reservoir were adapted. For these scenarios the same problems apply about the volume in the fictitious reservoir and the problems with a priori predicting the possibilities to capture enough direct runoff as for scenario C.

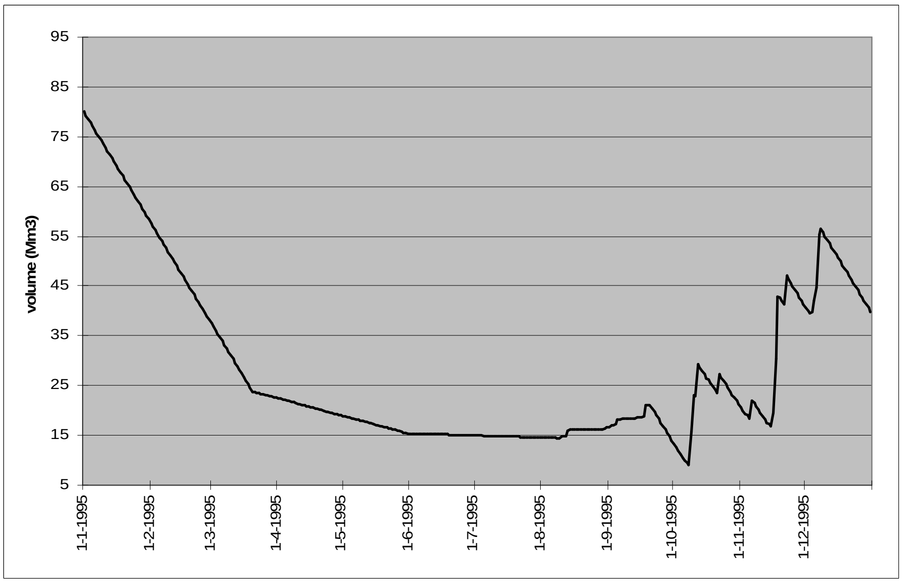


Figure 6.2: Volume reservoir scenario D for 1995

6.1.5 Scenario E

Scenario E is a combination of scenario's B and C, so the irrigated area is reduced and the groundwater extractions were partly replaced by surface water extractions. Due to the reduction of irrigated area there is more excess water. The groundwater extractions are decreased. The combination of these two results in a higher groundwater level than in the reference model. In this scenario the highest groundwater level of all five scenarios occurs i.e. 1699.66 m + MSL. In this scenario the groundwater level only drops 0.74 m instead of 2.20 m. This is a decrease of groundwater level drop by 66%. In figure 6.3 the volume of the aquifer is shown. This figure also shows that the volume in the aquifer at the end of 1995 is larger than in the beginning of the year, although the model calculates a drop of groundwater level. This is also caused by the comparison with the yearly average of groundwater levels instead of the groundwater level at day 365.

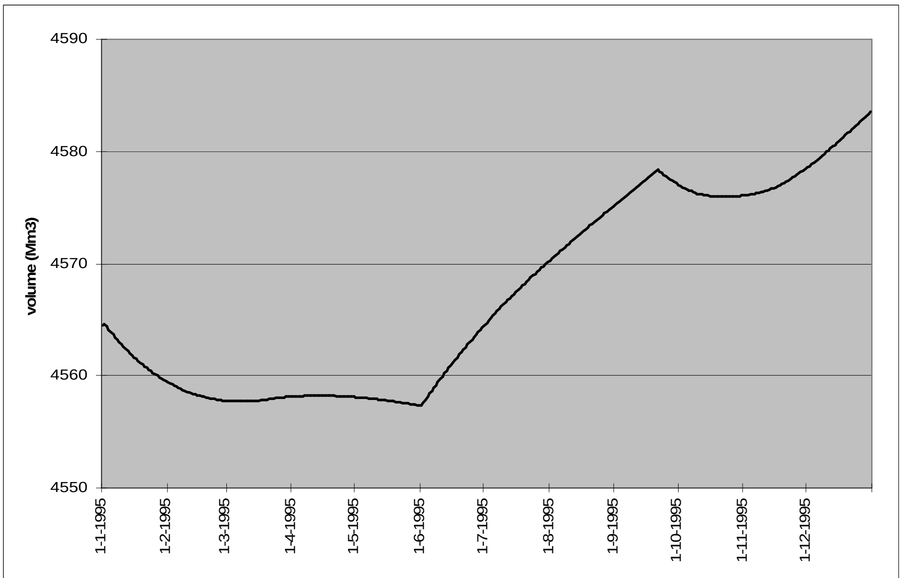


Figure 6.3: Volume aquifer scenario E for 1995

6.2 Sensitivity analysis

6.2.1 Introduction

For every scenario a sensitivity analysis was carried out. The aim of this post-sensitivity analysis is to investigate how large the influence of some poor data is on the predicted impact of some management measures. Section 5.4 shows that a few parameters and boundary conditions have a substantial influence on the groundwater level, the runoff of the Río Turbio, the reservoir volume and the direct runoff. For the sensitivity analysis of the scenarios a few of the most sensitive parameters or boundary conditions from section 5.4 were chosen i.e. specific yield, delay time, inflow of the river at San Germán, boundary flow of groundwater and the distribution of the precipitation throughout the year. This sensitivity analysis was carried out in the same way as described in section 5.4. The results of the sensitivity analysis are compared to the results of every scenario (table 6.1). Appendix 9 gives an overview of the complete results of the sensitivity analysis of the scenarios.

6.2.2 Scenario-independent sensitivity

In tables 6.2 to 6.6 one can see that the change of the inflow of the river at San Germán, the boundary flow of groundwater and the distribution of the precipitation have more or less the same influence on the results for every scenario. These boundary conditions all have a substantial influence on at least one of the output results, so all three data series are important to investigate further to obtain a more reliable impact assessment.

6.2.3 Scenario A

In Scenario A the extracted volume of groundwater for irrigation was decreased from 106.44 Mm^3 to 75 Mm^3 in order to irrigate more effectively. In table 6.2 the results of the sensitivity analysis for scenario A are shown. One can see that both the specific yield and the delay time have a substantial influence on the groundwater level. For example, a change of the specific yield (decrease by 50%) affects the simulated impact of scenario A on the groundwater level by - 42%, which is a drop of 0.69 m (table 6.2). The change in the groundwater level due to the change of specific yield in the sensitivity analysis for all the scenarios is also not linear. The reason for this is described in section 5.4.4.

Table 6.2: Sensitivity scenario A

Parameter	Change	Change groundwater level end of 1995		Change runoff Río Turbio end of 1995		Change volume reservoir end of 1995		Change direct runoff end of 1995	
	(%)	(m)	(%)	(Mm^3)	(%)	(Mm^3)	(%)	(Mm^3)	(%)
Specific yield	-50	- 0.69	- 42.1	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 0.23	+ 14.0	0.0	0.0	0.0	0.0	0.0	0.0
Delay time	-50	+ 0.31	+ 18.9	0.0	0.0	0.0	0.0	0.0	0.0
	+50	- 0.23	- 14.0	0.0	0.0	0.0	0.0	0.0	0.0
Inflow San Germán	-50	- 0.03	- 1.8	- 14.90	- 28.5	0.0	0.0	0.0	0.0
	+50	+ 0.02	+ 1.2	+ 14.90	+ 28.5	0.0	0.0	0.0	0.0
Boundary flow groundwater	-50	- 1.14	- 69.5	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 1.13	+ 68.9	0.0	0.0	0.0	0.0	0.0	0.0
Distribution precipitation		+ 0.02	+ 1.2	- 1.00	- 1.9	- 21.35	- 42.9	-24.53	- 22.3

6.2.4 Scenario B

In scenario B the area that is irrigated is decreased by 25% to 7500 ha. In table 6.3 the results of the sensitivity analysis for scenario B are shown. Since in this scenario more water is extracted than in scenario A, the influence of specific yield is larger. More excess water is available, so the influence of delay time on the groundwater level is larger than in scenario A.

Table 6.3: Sensitivity scenario B

Parameter	Change	Change groundwater level end of 1995		Change runoff Río Turbio end of 1995		Change volume reservoir end of 1995		Change direct runoff end of 1995	
	(%)	(m)	(%)	(Mm^3)	(%)	(Mm^3)	(%)	(Mm^3)	(%)
Specific yield	-50	- 0.87	- 47.5	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 0.30	+ 16.4	0.0	0.0	0.0	0.0	0.0	0.0
Delay time	-50	+ 0.52	+ 28.4	0.0	0.0	0.0	0.0	0.0	0.0
	+50	- 0.38	- 20.8	0.0	0.0	0.0	0.0	0.0	0.0
Inflow San Germán	-50	- 0.02	- 1.1	- 14.90	- 24.4	0.0	0.0	0.0	0.0
	+50	+ 0.03	+ 1.6	+ 14.90	+ 24.4	0.0	0.0	0.0	0.0
Boundary flow groundwater	-50	- 1.13	- 61.7	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 1.14	+ 62.3	0.0	0.0	0.0	0.0	0.0	0.0
Distribution precipitation		+ 0.03	+ 1.6	- 0.98	- 1.6	- 21.35	- 42.9	-24.53	- 22.3

6.2.5 Scenario C

In scenario C a part of the extractions (27.225 Mm^3) of groundwater for irrigation are replaced by extractions of surface water for irrigation. In table 6.4 the results of the sensitivity analysis for scenario C are shown. Compared to scenario A more or less the same amount of groundwater is extracted, but in scenario C there is more excess soil moisture and thus more recharge. This is the reason that the influence of the specific yield on the groundwater level is smaller than in scenario A. Due to the extra excess of soil moisture the delay time gets more important and has more influence than in scenario A.

Table 6.4: Sensitivity scenario C

Parameter	Change	Change groundwater level end of 1995		Change runoff Río Turbio end of 1995		Change volume reservoir end of 1995		Change direct runoff end of 1995	
	(%)	(m)	(%)	(Mm^3)	(%)	(Mm^3)	(%)	(Mm^3)	(%)
Specific yield	-50	- 0.16	- 14.3	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 0.06	+ 5.4	0.0	0.0	0.0	0.0	0.0	0.0
Delay time	-50	+ 0.45	+ 40.2	0.0	0.0	0.0	0.0	0.0	0.0
	+50	- 0.33	- 29.5	0.0	0.0	0.0	0.0	0.0	0.0
Inflow San Germán	-50	- 0.02	- 1.8	- 14.90	- 25.7	0.0	0.0	0.0	0.0
	+50	+ 0.03	+ 2.7	+ 14.90	+ 25.7	0.0	0.0	0.0	0.0
Boundary flow groundwater	-50	- 1.13	- 100.9	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 1.14	+ 101.8	0.0	0.0	0.0	0.0	0.0	0.0
Distribution precipitation		+ 0.03	+ 2.7	- 0.99	- 1.7	- 21.34	- 53.6	-24.53	- 22.3

6.2.6 Scenario D

In scenario D the extractions of groundwater for irrigation are the same as in the reference model, but the extractions of surface water for irrigation are increased. In table 6.5 the results of the sensitivity analysis for scenario D are shown. Compared to scenario A more groundwater is extracted, but there is also more excess of soil moisture in scenario D, so the influence of specific yield and delay time in this scenario are larger than in scenario A.

Table 6.5: Sensitivity scenario D

Parameter	Change	Change groundwater level end of 1995		Change runoff Río Turbio end of 1995		Change volume reservoir end of 1995		Change direct runoff end of 1995	
	(%)	(m)	(%)	(Mm³)	(%)	(Mm³)	(%)	(Mm³)	(%)
Specific yield	-50	- 0.64	- 40.0	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 0.22	+ 13.8	0.0	0.0	0.0	0.0	0.0	0.0
Delay time	-50	+ 0.56	+ 35.0	0.0	0.0	0.0	0.0	0.0	0.0
	+50	- 0.42	- 26.2	0.0	0.0	0.0	0.0	0.0	0.0
Inflow San Germán	-50	- 0.02	- 1.2	- 14.86	- 23.6	0.0	0.0	0.0	0.0
	+50	+ 0.03	+ 1.9	+ 14.90	+ 23.7	0.0	0.0	0.0	0.0
Boundary flow groundwater	-50	- 1.13	- 70.6	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 1.14	+ 71.3	0.0	0.0	0.0	0.0	0.0	0.0
Distribution precipitation		+ 0.03	+ 1.9	- 0.98	- 1.6	- 21.34	- 53.6	-24.53	- 22.3

6.2.7 Scenario E

Scenario E is a combination of the scenarios B and C. In table 6.6 the results of the sensitivity analysis of scenario E are shown. The most striking result is what happens with the groundwater level changes when the specific yield is changed. In the sensitivity analyses of the other scenarios the groundwater level decreased when the specific yield decreased. But in scenario E the groundwater level increases when the specific yield decreases, due to two reasons. The first reason is that, if the groundwater level of the reference model rises above the initial condition of 1700.40 m + MSL, the groundwater level of the decreased specific yield rises even further above the groundwater level of the reference level. The second reason is calculation of the yearly average groundwater level. The average groundwater level for the decreased specific yield is higher than the average groundwater level for the reference model. In figure 6.4 the volume of the aquifer for the three specific yields is manually converted to groundwater level.

Table 6.6: Sensitivity scenario E

Parameter	Change	Change groundwater level end of 1995		Change runoff Río Turbio end of 1995		Change volume reservoir end of 1995		Change direct runoff end of 1995	
	(%)	(m)	(%)	(Mm³)	(%)	(Mm³)	(%)	(Mm³)	(%)
Specific yield	-50	+ 0.21	+ 28.4	0.0	0.0	0.0	0.0	0.0	0.0
	+50	- 0.07	- 9.5	0.0	0.0	0.0	0.0	0.0	0.0
Delay time	-50	+ 0.51	+ 68.9	0.0	0.0	0.0	0.0	0.0	0.0
	+50	- 0.39	- 52.7	0.0	0.0	0.0	0.0	0.0	0.0
Inflow San Germán	-50	- 0.03	- 4.1	- 14.90	- 24.4	0.0	0.0	0.0	0.0
	+50	+ 0.02	+ 2.7	+ 14.90	+ 24.4	0.0	0.0	0.0	0.0
Boundary flow groundwater	-50	- 1.14	- 154.1	0.0	0.0	0.0	0.0	0.0	0.0
	+50	+ 1.13	+ 152.7	0.0	0.0	0.0	0.0	0.0	0.0
Distribution precipitation		+ 0.02	+ 2.7	- 0.98	- 1.6	- 21.34	- 53.6	-24.53	- 22.3

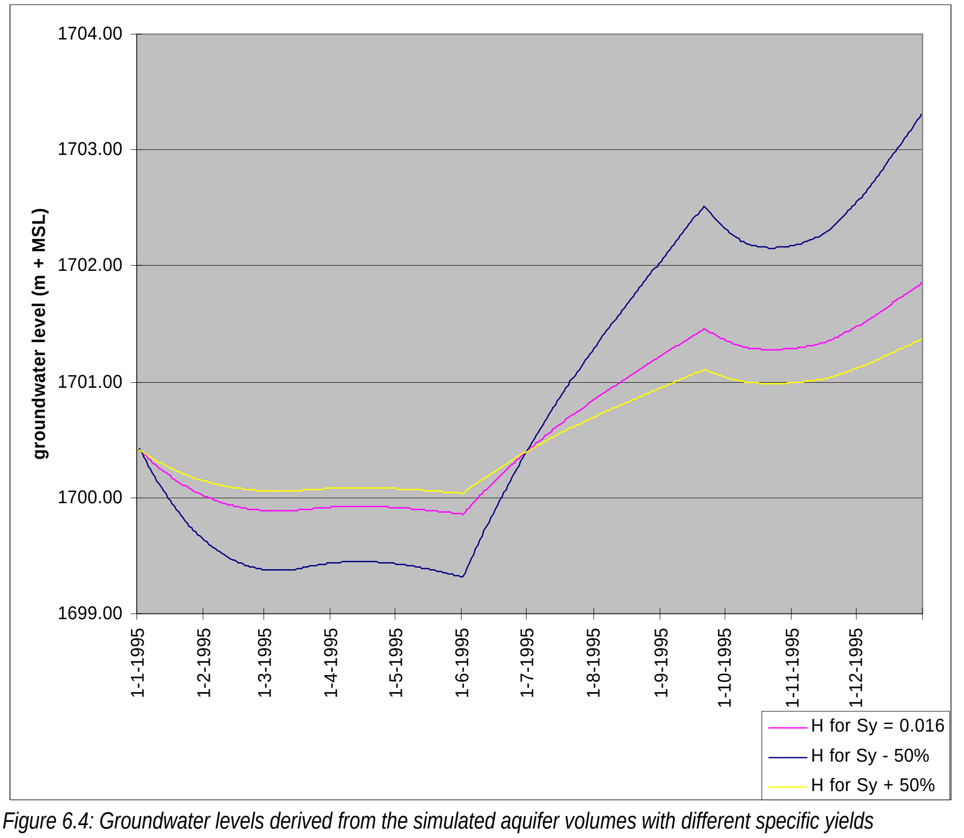


Figure 6.4: Groundwater levels derived from the simulated aquifer volumes with different specific yields

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

- From the literature study and the available input data it can be concluded that the groundwater module of the SWAT-model fits best in the existing IMTA model. By incorporating this groundwater module in the existing IMTA model a revised model is developed that calculates water balances for both groundwater and surface water, but no groundwater or surface water flows. The revised model can be used all over the world, provided that enough input data and all boundary conditions are available.

- The Río Turbio aquifer was most suitable for carrying out a case study to test the revised model. This was the simplest area with most data available, but still there is a lack of data.

- Since only data of 1995 were available, the model is calibrated on these data. There were no additional data from another year available to do a validation. The reliability of the model and the results of the calibration cannot totally be investigated, due to the lack of data and thus no validation. However, the results and the behaviour of the model suggest that the concept of the model works properly, although the model still does not have all physical interactions. The model can be improved with more data and the reliability of the model can be determined by carrying out a validation.

- The revised IMTA model is not a totally integrated model as can be seen in e.g. the lack of changes of the groundwater level if the distribution of the precipitation is changed. Less direct runoff is available with another distribution, which means that more precipitation is infiltrated in the ground, but hardly any effect is seen on the groundwater level.

- Due to lack of time the model could not be revised anymore. Although it affects all simulation results, the results can be used in a qualitative way.

- The sensitivity analysis shows that the model is sensitive to the initial condition of the soil moisture module (+104% change of groundwater level), the distribution of the precipitation (-43% change of reservoir volume), the specific yield (-56% and +19% change of groundwater level), the delay time (+20% and -15% change of groundwater level), the inflow of the Río Turbio at San Germán (±26% change of runoff Rio Turbio), the irrigated area (around 34% change of groundwater level) and the boundary flow of groundwater (around 51% change of groundwater level).
  The input data which are changed in the sensitivity analysis are not measured data, but estimated, calculated or calibrated. For example the initial condition of the soil moisture module is assumed to be zero in the reference model, due to a lack of data, but the sensitivity analysis shows that the soil moisture excess of the last months of the previous year influences the groundwater level, the runoff of the Río Turbio, the volume in the reservoir and the direct runoff. With more and new measurements the correct values of these parameters and input data can be obtained and inserted in the model.

- The simulated results of the five scenarios show that replacing extractions of groundwater for irrigation by surface water extractions is an interesting option (scenario C). This diminishes the groundwater level decline with 1.08 m when 27.225 Mm^3 of groundwater extractions are replaced by 27.225 Mm^3 of surface water extractions. That means that still a drop of groundwater level of 1.12 m occurs. But this drop is calculated with the yearly average groundwater level. In figure 6.1 it is shown that the volume of water in the aquifer at day 365 is larger than at day 1, which means that at day 365 the groundwater level is higher than at day 1, i.e. 0.68 m. The only problem is that it is hard to predict if enough precipitation can be harvested and conveyed tot the reservoirs for replacing the groundwater extractions. These predictions can be done with the real distribution of precipitation.

- Scenario C combined with scenario B (scenario E) gives the best result on the groundwater level; the drop of groundwater level (calculated with the yearly average groundwater level) is the smallest off all scenarios (only 0.74 m instead of 2.20 m). How the measures of all scenarios influence the farmers is not investigated. When the irrigated area is decreased some farmers cannot grow crops any more, so this will affect them badly. Therefore it is not considered to be a possible scenario.

- The sensitivity analysis of the scenarios shows that the model is sensitive to at least four of the five changed input data series in every scenario. Changes of at least 20% are quite common, but in all scenarios the changes on the groundwater level due to changes in boundary flow are larger than 50%. In scenario C and E this boundary flow influences the groundwater level even by more than 100%. This means that the results of the scenarios are not reliable and the results can only be used in a qualitative way.

7.2 Recommendations

Recommendations will be given to improve the revised model. These improvements are not carried out because this was beyond the scope of this study. When IMTA would like to use this revised IMTA model, it would be best to improve the model on the following points:

- In the model excess soil moisture (from irrigation, losses from drinking water net, sewage effluent and transmission losses) is accumulated in the soil moisture module. This soil moisture module generates actual recharge. From the sensitivity analysis it is clear that the initial condition of the soil moisture module was not correct in this study. In this model the initial condition of soil moisture module is taken to be zero ($SME_0 = 0$). This cannot be correct; from the previous year soil moisture excess is available. With more years of available data more years in a row can be simulated. Then the first year of this simulation can be neglected, but this first year creates a correct initial condition of soil moisture excess for the second year. With this new initial condition a new calibration, a validation and new simulations of scenarios can be carried out with the rest of the years.

- In CEASG and IGC (1995) an irrigated area (with groundwater) is mentioned. Compared to the total extractions for irrigation of groundwater the area of 16,125 ha seems quite large. Further investigation is needed to define the correct irrigated area (with groundwater), because the sensitivity analysis shows that the model is sensitive for this. The groundwater level changes with more or less 34% if the area is changed with 50%.

- The sensitivity analysis showed also that the model is sensitive for the distribution of the precipitation throughout the year. Since the total annual precipitation is known, data about the daily precipitation should be available as well. It is recommended to use the daily precipitation in the model.

- In CEASG and GEOPSA (1998) different values are mentioned for the inflow from the Penjamo-aquifer at the southeast boundary. This might be a mistake, but from the sensitivity analysis it is clear that the boundary flow of groundwater is an important boundary condition. It influences the groundwater level substantially. So it is recommended to investigate the real boundary flow at the southeast of the aquifer.

- From the previous studies hardly any information was obtained about the specific yield and the delay time. From the sensitivity analysis it is clear that these two parameters are influencing the groundwater level substantially. It is important that further investigation on these two parameters is carried out.

- If multi-year periods are simulated and the groundwater level drops further, the delay time will probably increase. At the moment no options are incorporated in the model to simulate this properly, but to tackle this problem a logical equation can be inserted (if level < x, then delay time = y).

- In the revised IMTA model the simulated groundwater level at the end of the year is incorrectly set to be equal to the average over the whole year. This causes an incorrect calibration. It is recommended to replace this calculation of the yearly average groundwater level with the calculation of the groundwater level of day 365.

- It is recommended to investigate the possibilities for a further integration of the model, so that all physical interactions are incorporated, e.g. stream-aquifer interaction.

REFERENCES

Aparicio Mijares F.J., Hidalgo Toledo J.A., Acosta Pérez R.A., Hernández Arce C., Huerta Tolís J.M., Luis Flores J. Güitrón de los Reyes A.; *Análisis de la problemática de calidad y cantidad de agua en el lago de Chapala*; Instituto Mexicano Tecnología del Agua, Diciembre 2001

Arnold J.G., Allen P.M., Bernhardt G.; *A comprehensive surface-groundwater flow model*; Journal of Hydrology 142; 47 - 69; 1993

Chiew F.H.S., McMahon T.A.; *Estimating groundwater recharge using a surface watershed modelling approach*; Journal of Hydrology 114; 285 - 304; 1990

Comisión Estatal de Agua y Saneamiento de Guanajuato y GEOPSA, S.A. de C.V.; *Estudio hidrogeológico y modelo matemático del acuífero del valle del Río Turbio, GTO*; 1998

Comisión Estatal de Agua y Saneamiento de Guanajuato y Ingeniería Geológica Computarizada S.A. de C.V.; *Estudio Geohidrológico y modelo matemático del acuífero del Valle del Río Turbio, GTO*; 1995

Comisión Estatal de Agua y Saneamiento de Guanajuato y BURGEAP ingenieros consultores, GEOFISICA DE EXPLORACIONES GUYSA, S.A. de C.V.; *Desarrollo de un modelo integral para el análisis coordinado de las aguas subterráneas y superficiales en las subcuencas de los Ríos Turbio y Guanajuato*; Diciembre1999

Kruseman G.P., Ridder N.A. de; *Analysis and Evaluation of Pumping Test Data, Second edition*; Publication 47; International Institute for Land Reclamation and Improvement; Wageningen; 1990

Natural Resources Conservation Service; *Urban Hydrology for small watersheds, Technical release 55*; June 1986

Neitsch S.L., Arnold J.G., Kiniry J.R., Williams J.R. King K.W.; *Soil and Water Assessment Tool, Theoretical Documentation, Version 2000*; Texas Water Resources Institute; College Station; Texas; TWRI Report TR-191; 2002

Olin M.; *Estimation of base level for an aquifer from recession rates of groundwater levels*, Hydrogeology Journal, v. 3, no. 2; 1995

Peters E., Torfs P.J.J.F., Lanen H.A.J. van, Bier G.; *Propagation of drought through groundwater – a new approach using linear reservoir theory*; Hydrological Processes 17; 3023 - 3040; 2003

Scott C.A., Garcés Restrepo C.; *Conjunctive Management of Surface Water and Groundwater in the Middle Río Lerma Basin, Mexico*; International Water Management Institute; in Biswas A.K. and Tortajada C. (eds); Integrated River Basin Management, The Latin American Experience; Oxford University Press; New Delhi; 176 – 198; 2001

Seibert J., Rodhe A., Bishop K.; *Simulating interactions between saturated and unsaturated storage in a conceptual runoff model*; Hydrological Processes 17; 379 - 390; 2003

Silva-Ochoa P; *Unidades de riego: La otra mitad del sector agrícola bajo riego en México*, IWMI, Serie Latinoamericana: No. 19; 2000

Wester P., Merrey D.J., Lange M. de; *Boundaries of Consent: Stakeholder Representation in River Basin Management in Mexico and South Africa*; World Development Vol. 31; No. 5; 797 – 812; 2003

Wester P., Scott C.A., Burton M.; *River Basin Closure and Institutional Change in Mexico's Lerma-Chapala Basin*; Chapter 8 of the IWMI Book on River Basin Management, prepublication draft, 2004

References web

http://brc.tamus.edu/swat/, access date: December 2003

http://www.bossintl.com/literature/pest.pdf, access date: July 2004

http://www.dhisoftware.com/mikebasin/index.htm, access date: November 2003

http://www.fao.org/docrep/S2022E/s2022e07.htm, access date: May 2004

http://www.smhi.se/sgn0106/if/hydrologi/hbv.htm, access date: December 2003

http://www.water.hut.fi/wr/kurssit/Yhd-12.135/kirja/hbv_des.htm, access date: December 2003

Appendices

Appendix 1

List of Spanish words and glossary

LIST OF SPANISH WORDS

<u>Agua Superficial</u>	- Surface water
Precipitación	- Precipitation
Modelo Lluvia Escurrimiento	- Rainfall-Runoff model
Escurrimiento Directo	- Direct runoff
Percolación Somera	- Shallow percolation
Escurrimiento Base	- Base flow
Escurrimiento Virgen	- Total runoff
Funcionamiento de Vaso	- Functioning of the reservoir
Evaporación	- Evaporation
<u>Agua Subterránea</u>	- Groundwater
Percolación Profunda	- Deep percolation
Recarga	- Recharge
Funcionamiento de Acuífero	- Functioning of the aquifer
<u>Política de Asignación</u>	- Allocation policy
Acuerdo de Distribución	- Distribution Agreement
Nivel Lago Chapala	- Surface water level of Chapalo Lake
<u>Calidad</u>	- Quality
Descarga	- Discharge
Cauce Principal	- Main channel
Balance del Lago	- Balance of the lake
Modelo Transporte de Contaminantes	- Transport model of pollutants
<u>Demandas</u>	- Demands
Eficiencias	- Efficiencies
Modelo Requerimiento de agua para uso Agrícola	- Water requirement model for agricultural use
Patrón de Cultivo	- Pattern of crops
Demanda de Agua Agrícola en Distritos y Unidades de Riego	- Agricultural demand of Water in Districts and Units of Irrigation
Demanda de Agua Urbana e Industrial	- Demand of Urban and Industrial Water
Lluvia	- Precipitation
Seco	- Dry
Húmedo	- Humid
Media	- Average
Generada	- Generated
Día del año	- Day of the year
Suelo	- Soil
Cuenca	- River basin
Retención potencial Máxima	- Maximum potential retention
Abstracción Inicial	- Initial abstraction
En exceso	- In excess
Efectiva	- Effective
Escurrimiento Directo Instant	- Direct Instant Draining

Porcentaje	- Percentage
Retención	- Retention
Convertidor Unidades Volumétricas	- converter volumetric units
Salida	- Exit
Real	- Real
Porosidad	- Porosity
Subsuelo	- Subsoil
Densidad Aparente	- Apparent Density
Campo	- Field
Entradas	- Entrances
Derrames	- Losses
Almacén	- Storage
Extracciones	- Extractions

GLOSSARY

Alluvial deposit	- Clay, silt, sand, gravel, pebbles or other detrital material deposited by water
Aquiclude	- Saturated bed, formation, or group of formations of low hydraulic conductivity which yield inappreciable quantities of water to drains, wells, springs and seeps.
Aquitard	- Geological formation of a rather impervious and semi-confining nature which transmits water at a very slow rate compared with an aquifer.
Base flow	- Part of the discharge which enters a stream channel mainly from groundwater, but also from lakes and glaciers during long periods when no precipitation or snowmelt occurs.
Basin	- Drainage area of a stream, river or lake.
Capillarity	- Phenomenon which is associated with the surface tension of liquids, particularly in capillary tubes and porous media where gas, liquid and solid interfaces meet.
Capillary rise	- Rise of water above the water table through the action of capillarity.
Cone of depression	- Depression, in the shape of a cone with convex upward limits, of the piezometric groundwater surface which defines the area of influence of a well.
Confined aquifer	- Aquifer overlain and underlain by an impervious or almost impervious formation
Deep aquifer	- Permeable water-bearing formation capable of yielding exploitable quantities of water, with a water level deep below the surface level.
Direct runoff	- The runoff entering stream channels most immediately after rainfall or snowmelt. It consists of surface runoff plus interflow and forms the bulk of the hydrograph of a flood. In this report direct runoff stands for only the surface runoff.
Drainage	- Removal of surface water or groundwater from a given area by gravity or by pumping.
Drawdown	- Lowering of the water table or piezometric surface caused by the extraction of groundwater by pumping, by artesian flow from a bore hole, or by a spring emerging from an aquifer.
Hydraulic conductivity	- Property of a saturated porous medium which determines the relationship, called Darcy's law, between the specific discharge and the hydraulic gradient causing it.
Impermeable	- Having a texture that does not permit water to move through it perceptibly under static pressure ordinarily found in subsurface water.
Interflow	- That portion of the precipitation which has not passed down to the water table, but is discharged from the area as subsurface flow into stream channels.
Percolation	- Flow of a liquid through an unsaturated porous medium, e.g. of water in soil, under the action of gravity.
Permeability	- The ability of a material to transmit fluid through its pores when subjected to a difference in head.
Piezometric head	- Elevation to which water will rise in a piezometer connected to a point in an aquifer

Recharge	- Process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation.
Recharge area	- Area which contributes water to an aquifer, either by direct infiltration or by runoff and subsequent infiltration.
Return flow	- Any flow which returns to a stream channel or to the groundwater after use.
Saturated zone	- Part of the water-bearing material in which all voids, large and small, are filled with water.
Seepage	- Loss of water by infiltration into the soil from a canal or other body of water
Semi-confined aquifer	- Aquifer overlain and/or underlain by a relatively thin semi-pervious layer, through which flow into or out of the aquifer can take place.
Shallow aquifer	- Permeable water-bearing formation capable of yielding exploitable quantities of water, with a water level close to the surface level.
Specific yield	- Ratio of the volume of water which can be drained by gravity from an initially saturated porous medium to the total volume of the porous medium.
Subsurface flow	- Any flow below the surface of the ground which may contribute to interflow, base flow or deep percolation.
Transient	- Varying in time.
Transmissivity	- Rate at which water is transferred through a unit width of an aquifer under a unit hydraulic gradient. It is expressed as the product of the hydraulic conductivity and the thickness of the saturated portion of an aquifer.
Unconfined aquifer	- Aquifer containing unconfined groundwater, that is having a water table and an unsaturated zone.
Unsatured zone	- That portion of the lithosphere in which the interstices are filled partly with air and partly with water.

(http://www.cig.ensmp.fr/~hubert/glu/aglo.htm, access date: July 2004, http://amsglossary.allenpress.com/glossary/search?id=hydrological-cycle1, access date: July 2004, http://www.crh.noaa.gov/hsd/hydefa-c.html, access date: July 2004)

Appendix 2

Calculated inflow of the Río Turbio at San Germán

Calculated inflow of the Río Turbio at San Germán

Irrigated area (irrigated with surface water) in whole Adjuntas	127710000	m2
Effective irrigated area (with surface water) in Rio Turbio *	99000000	m2
Effective irrigated area (with surface water) in the rest of Adjuntas	15939000	m2
Used surface water in Rio Turbio (based on a layer of 1.1m)	108900000	m3
Used surface water in the rest of Adjuntas (based on a layer of 1.1m)	17532900	m3
Total used (irrigated) surface water (based on a layer of 1.1m)	126432900	m3
Total natural runoff whole Adjuntas (calculated by CNA)	173000000	m3
Losses in the rest of Adjuntas**	9313420	m3
Inflow at San Germán***	37253680	m3
Inflow at San Germán***	37,25368	Mm3

* effective area is 90% of the total irrigated area
** losses in the upstream part (before reservoir San Germán) are calculated. 10% of the flow in the upstream part is lost by transmission losses and 10% is lost due to unknown extractions (assumption)
*** inflow at San Germán is the water that is left over: 173 Mm3 natural flow - 126.4 Mm3 irrigated surface water in both areas - 9.3 Mm3 losses

Appendix 3

Results recharge and return flow

Results recharge and return flow after calibration

Total area Rio Turbio	820000000	m2	820	km2		
rain 1995 Rio Turbio	0,689	m	689	mm		
rain 1995 Rio Turbio	564980000	m3	564,98	Mm3		
irrigated groundwater	106440000	m3	106,44	Mm3		
irrigated surface water	108900000	m3	108,90	Mm3		
runoff	109913395	m3	109,91	Mm3		
inflow Rio Turbio	37250000	m3	37,25	Mm3		
total flow	670406605	m3	670,41	Mm3		
recharge	68060000	m3	68,06	Mm3	10,15	%
return flow	23348466	m3	23,35	Mm3	3,48	%
specific yield	0,016	-				
delay time	77	days				
water level	1698,2	m + MSL				
draw down after one year	2,2	m				
factor interflow/percolation	0,35					

Appendix 4

Proposal changing IMTA model

PROPOSAL CHANGING IMTA MODEL

In section 5.2 is described that for the calibration of the model the average groundwater level (section 4.4.5) of 1995 in the Río Turbio aquifer is used and that this is not correct. This should be the drop calculated with the initial groundwater level and the groundwater level at day 365. In this appendix a proposal for changing the model is given, so the daily groundwater level is calculated.

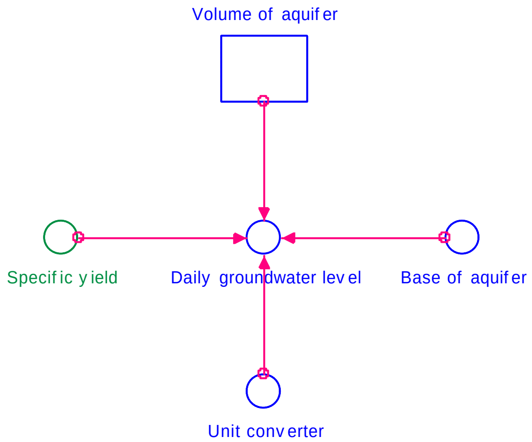


Figure A4.1: Calculation of daily groundwater level

The model already calculates a daily volume of the aquifer in mm's. The base of the aquifer, the unit converter and the specific yield are predefined by the user. In figure A4.1 a way of calculating the daily groundwater level with Stella is given. With equation A4.1 the daily groundwater level can be calculated.

$$H_i = H_{base} + (Vaq_i / UC) / Sy \qquad [A4.1]$$

where: H_i is the groundwater level on day i (m + MSL)
H_{base} is the base of the aquifer (m + MSL)
Vaq_i is the volume of the aquifer on day I (mm)
UC is a unit converter, because the different parameters have different units
Sy is the specific yield (-)

After calculation of the daily groundwater level, the groundwater level on day 365 can be extracted and compared to the groundwater level on day 1 to calculate the drop or rise over one year.

Appendix 5

Sensitivity analysis

						reference level:	**1698,20**	**m+ MSL**		**reference runoff:**	**58,06**	**Mm3**
						gwl	**diff**	**diff**		**runoff RT**	**diff**	**diff**
Parameter	**initial value**		**revised**			**m+ MSL**	**m**	**%**		**Mm3**	**Mm3**	**%**
soil moisture excess	83	mm	119	mm		1700,49	2,29	104,1		58,51	0,45	0,8
change distribution precipitation	wet		dry			1698,23	0,03	1,4		57,08	-0,98	-1,7
distribution irrigated volume	1, 1, 1		0.9, 1, 1.1			1698,25	0,05	2,3		58,07	0,01	0,0

			reference volume reservoir:	**49,75**	**Mm3**		**reference direct runoff:**	**109,91**	**Mm3**
			reserv vol	**diff**	**diff**		**direct runo**	**diff**	**diff**
Parameter			**Mm3**	**Mm3**	**%**		**Mm3**	**Mm3**	**%**
soil moisture excess			43,08	-6,67	-13,4		114,58	4,67	4,2
change distribution precipitation			28,40	-21,35	-42,9		85,38	-24,53	-22,3
distribution irrigated volume			49,59	-0,16	-0,3		109,91	0	0,0

Negative values for differences mean that the water level is lower or volumes are decreased compared to the the reference model, positive values mean that the water level is higher or volumes are increased compared to the reference model

											reference level:		**1698,20 m+ MSL**		
									-50%				**+50%**		
									gwl	**diff**	**diff**		**gwl**	**diff**	**diff**
parameter	**-50%**		**initial value**			**+50%**			**m+ MSL**	**m**	**%**		**m+ MSL**	**m**	**%**
specific yield	0,0080	--	0,016		--	0,0240	--		1696,96	-1,24	-56,4		1698,62	0,42	19,1
delay time	38,5	days	77		days	115,5	days		1698,64	0,44	20,0		1697,87	-0,33	-15,0
curve reservoir	446,21	ha	892,41		ha	1338,62	ha		1698,20	0,00	0,0		1698,20	0,00	0,0
extra inflow San Germán	18,63	Mm3	37,25		Mm3	55,88	Mm3		1698,18	-0,02	-0,9		1698,23	0,03	1,4
Irrigated area (groundwater)	5000	ha	10000		ha	15000	ha		1698,95	0,75	34,1		1697,46	-0,74	-33,6
boundary flow groundwater	30,055	Mm3	60,11		Mm3	90,165	Mm3		1697,07	-1,13	-51,4		1699,34	1,14	51,8
division interflow/percolation	0,115	--	0,23		--	0,35	--		1698,48	0,28	12,7		1697,91	-0,29	-13,2
division waste water	0,15	--	0,3		--	0,45	--		1698,18	-0,02	-0,9		1698,23	0,03	1,4
transmission losses	5	%	10		%	15	%		1698,11	-0,09	-4,1		1698,29	0,09	4,1

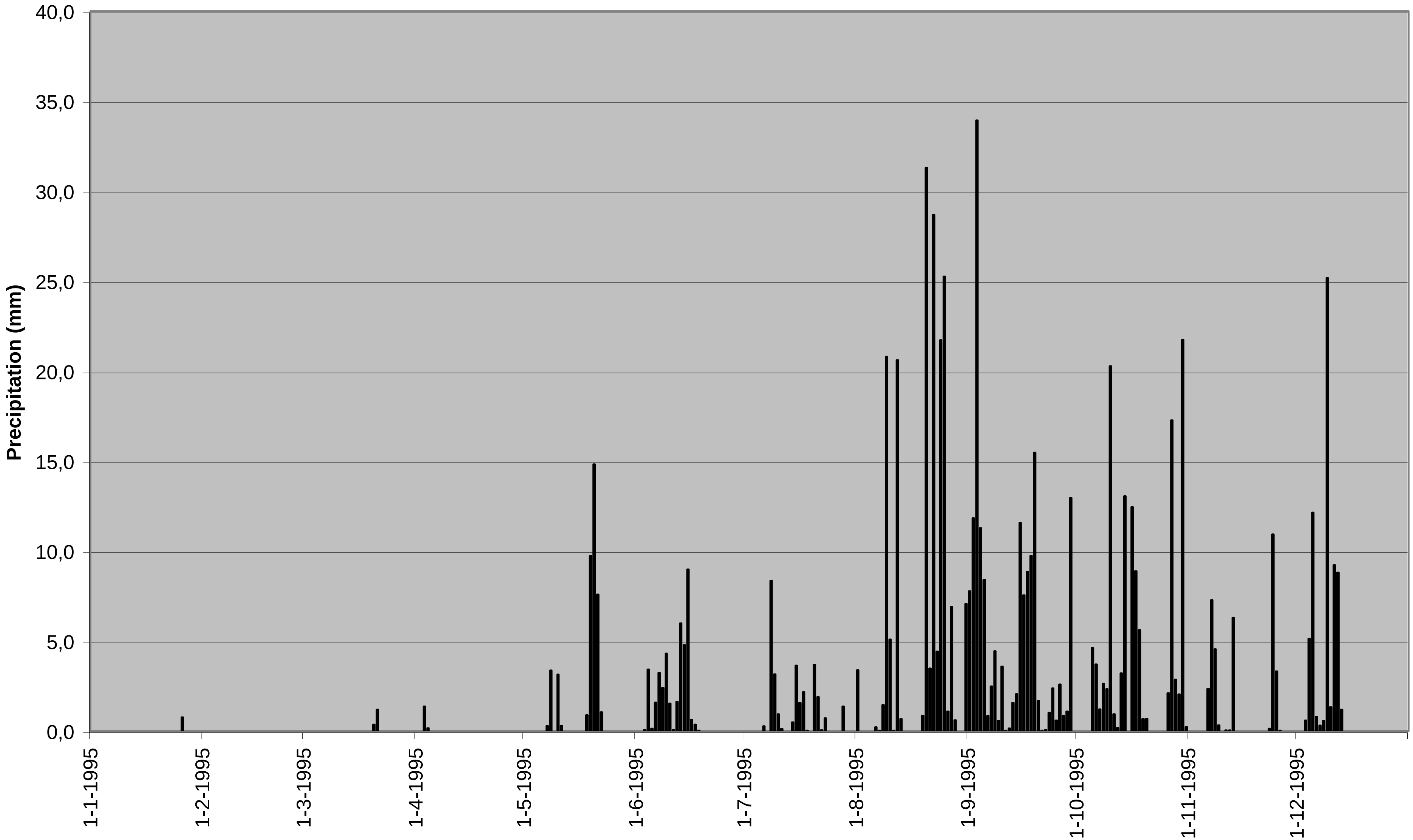
			reference runoff:		**58,06 Mm3**						**reference vol reservoir:**		**49,75 Mm3**		
	-50%				**+50%**				**-50%**				**+50%**		
	runoff RT	**diff**	**diff**		**runoff RT**	**diff**	**diff**		**reserv vol**	**diff**	**diff**		**reserv vol**	**diff**	**diff**
parameter	**Mm3**	**Mm3**	**%**		**Mm3**	**Mm3**	**%**		**Mm3**	**Mm3**	**%**		**Mm3**	**Mm3**	**%**
specific yield	58,06	0,00	0,0		58,06	0,00	0,0		49,75	0,00	0,0		49,75	0,00	0,0
delay time	58,06	0,00	0,0		58,06	0,00	0,0		49,75	0,00	0,0		49,75	0,00	0,0
curve reservoir	58,06	0,00	0,0		58,06	0,00	0,0		51,63	1,88	3,8		48,02	-1,73	-3,5
extra inflow San Germán	43,16	-14,90	-25,7		72,96	14,90	25,7		49,75	0,00	0,0		49,75	0,00	0,0
Irrigated area (groundwater)	64,15	6,09	10,5		51,97	-6,09	-10,5		49,75	0,00	0,0		49,75	0,00	0,0
boundary flow groundwater	58,06	0,00	0,0		58,06	0,00	0,0		49,75	0,00	0,0		49,75	0,00	0,0
division interflow/percolation	48,77	-9,29	-16,0		67,76	9,70	16,7		49,75	0,00	0,0		49,75	0,00	0,0
division waste water	58,93	0,87	1,5		57,19	-0,87	-1,5		49,75	0,00	0,0		49,75	0,00	0,0
transmission losses	61,69	3,63	6,3		54,43	-3,63	-6,3		55,21	5,46	11,0		44,30	-5,45	-11,0

	reference direct runoff:			109,91 Mm3			reference evap reservoir:			3,89 Mm3		
	-50%			+50%			-50%			+50%		
	direct runo	diff	diff	direct runo	diff	diff	evap reser	diff	diff	evap reser	diff	diff
parameter	**Mm3**	**Mm3**	**%**	**Mm3**	**Mm3**	**%**	**Mm3**	**Mm3**	**%**	**Mm3**	**Mm3**	**%**
specific yield	109,91	0,00	0,0	109,91	0,00	0,0						
delay time	109,91	0,00	0,0	109,91	0,00	0,0						
curve reservoir	109,91	0,00	0,0	109,91	0,00	0,0	2,02	-1,87	-48,1	5,62	1,73	44,5
extra inflow San Germán	109,91	0,00	0,0	109,91	0,00	0,0						
Irrigated area (groundwater)	109,91	0,00	0,0	109,91	0,00	0,0						
boundary flow groundwater	109,91	0,00	0,0	109,91	0,00	0,0						
division interflow/percolation	109,91	0,00	0,0	109,91	0,00	0,0						
division waste water	109,91	0,00	0,0	109,91	0,00	0,0						
transmission losses	109,91	0,00	0,0	109,91	0,00	0,0						

Negative values for differences mean that the water level is lower or volumes are decreased compared to the the reference model, positive values mean that the water level is higher or volumes are increased compared to the reference model

Appendix 6

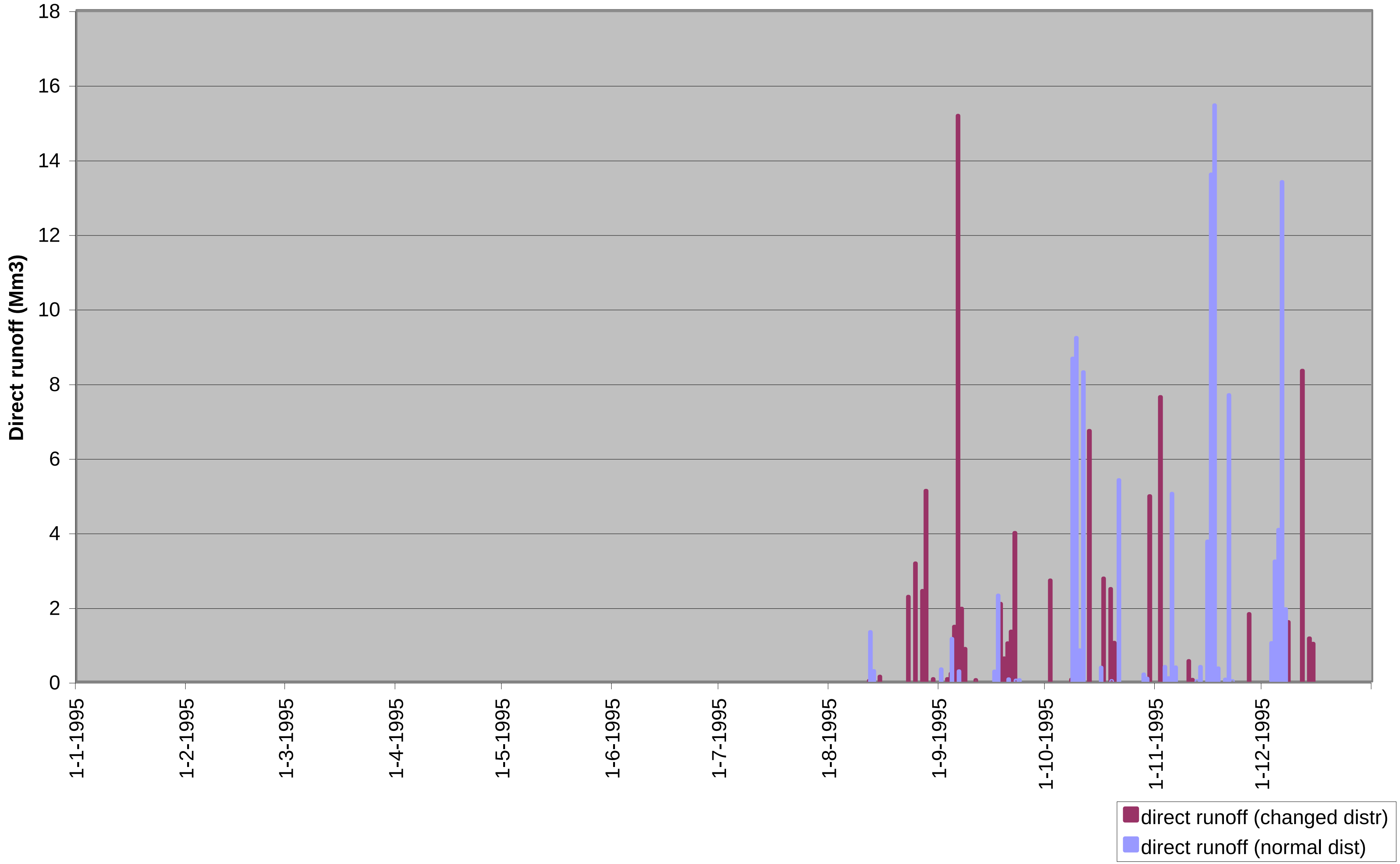
Precipitation dry year distribution



Precipitation (mm)
40,0
35,0
30,0
25,0
20,0
15,0
10,0
5,0
0,0
1-1-1995
1-2-1995
1-3-1995
1-4-1995
1-5-1995
1-6-1995
1-7-1995
1-8-1995
1-9-1995
1-10-1995
1-11-1995
1-12-1995

Appendix 7

Direct runoff both precipitation distributions



18
16
14
12
10
8
6
4
2
0
Direct runoff (Mm3)
1-1-1995
1-2-1995
1-3-1995
1-4-1995
1-5-1995
1-6-1995
1-7-1995
1-8-1995
1-9-1995
1-10-1995
1-11-1995
1-12-1995
direct runoff (changed distr)
direct runoff (normal dist)

Appendix 8

Results scenarios

	reference level:	1698,20	m+ MSL	reference runoff:	58,06	Mm3	reference volume reservoir:	49,75	Mm3	reference direct runoff:	109,91	Mm3
	gwl	**diff**	**diff**	**runoff RT**	**diff**	**diff**	**reserv vol**	**diff**	**diff**	**direct runo**	**diff**	**diff**
scenarios	**m+ MSL**	**m**	**%**	**Mm3**	**Mm3**	**%**	**Mm3**	**Mm3**	**%**	**Mm3**	**Mm3**	**%**
SCEN_A	1698,76	0,56	25,5	52,37	-5,69	-9,8	49,75	0,00	0,0	109,91	0,00	0,0
SCEN_B	1698,57	0,37	16,8	61,11	3,05	5,3	49,75	0,00	0,0	109,91	0,00	0,0
SCEN_C	1699,28	1,08	49,1	58,06	0	0,0	39,81	-9,94	-20,0	109,91	0,00	0,0
SCEN_D	1698,80	0,60	27,3	62,99	4,93	8,5	39,81	-9,94	-20,0	109,91	0,00	0,0
SCEN_E	1699,66	1,46	66,4	61,11	3,05	5,3	39,81	-9,94	-20,0	109,91	0,00	0,0

Appendix 9

Sensitivity analysis scenarios

											reference level:		1698,76	m+ MSL	
									-50%				+50%		
									gwl	diff	diff		gwl	diff	diff
	parameter	**-50%**		**initial value**		**+50%**			**m+ MSL**	**m**	**%**		**m+ MSL**	**m**	**%**
Scenario A	specific yield	0,0080	--	0,016	--	0,0240	--		1698,07	-0,69	-42,1		1698,99	0,23	14,0
	delay time	38,5	days	77	days	115,5	days		1699,07	0,31	18,9		1698,53	-0,23	-14,0
	extra inflow San Germán	18,63	Mm3	37,25	Mm3	55,88	Mm3		1698,73	-0,03	-1,8		1698,78	0,02	1,2
	boundary flow groundwater	30,055	Mm3	60,11	Mm3	90,165	Mm3		1697,62	-1,14	-69,5		1699,89	1,13	68,9
	distribution precipitation	dry	--	wet	--				1698,78	0,02	1,2				
											reference level:		**1698,57**	**m+ MSL**	
Scenario B	specific yield	0,0080	--	0,016	--	0,0240	--		1697,70	-0,87	-47,5		1698,87	0,30	16,4
	delay time	38,5	days	77	days	115,5	days		1699,09	0,52	28,4		1698,19	-0,38	-20,8
	extra inflow San Germán	18,63	Mm3	37,25	Mm3	55,88	Mm3		1698,55	-0,02	-1,1		1698,60	0,03	1,6
	boundary flow groundwater	30,055	Mm3	60,11	Mm3	90,165	Mm3		1697,44	-1,13	-61,7		1699,71	1,14	62,3
	distribution precipitation	dry	--	wet	--				1698,60	0,03	1,6				
											reference level:		**1699,28**	**m+ MSL**	
Scenario C	specific yield	0,0080	--	0,016	--	0,0240	--		1699,12	-0,16	-14,3		1699,34	0,06	5,4
	delay time	38,5	days	77	days	115,5	days		1699,73	0,45	40,2		1698,95	-0,33	-29,5
	extra inflow San Germán	18,63	Mm3	37,25	Mm3	55,88	Mm3		1699,26	-0,02	-1,8		1699,31	0,03	2,7
	boundary flow groundwater	30,055	Mm3	60,11	Mm3	90,165	Mm3		1698,15	-1,13	-100,9		1700,42	1,14	101,8
	distribution precipitation	dry	--	wet	--				1699,31	0,03	2,7				
											reference level:		**1698,8**	**m+ MSL**	
Scenario D	specific yield	0,0080	--	0,016	--	0,0240	--		1698,16	-0,64	-40,0		1699,02	0,22	13,8
	delay time	38,5	days	77	days	115,5	days		1699,36	0,56	35,0		1698,38	-0,42	-26,2
	extra inflow San Germán	18,63	Mm3	37,25	Mm3	55,88	Mm3		1698,78	-0,02	-1,2		1698,83	0,03	1,9
	boundary flow groundwater	30,055	Mm3	60,11	Mm3	90,165	Mm3		1697,67	-1,13	-70,6		1699,94	1,14	71,3
	distribution precipitation	dry	--	wet	--				1698,83	0,03	1,9				
											reference level:		**1699,66**	**m+ MSL**	
Scenario E	specific yield	0,0080	--	0,016	--	0,0240	--		1699,87	0,21	28,4		1699,59	-0,07	-9,5
	delay time	38,5	days	77	days	115,5	days		1700,17	0,51	68,9		1699,27	-0,39	-52,7
	extra inflow San Germán	18,63	Mm3	37,25	Mm3	55,88	Mm3		1699,63	-0,03	-4,1		1699,68	0,02	2,7
	boundary flow groundwater	30,055	Mm3	60,11	Mm3	90,165	Mm3		1698,52	-1,14	-154,1		1700,79	1,13	152,7
	distribution precipitation	dry	--	wet	--				1699,68	0,02	2,7				

		-50%			+50%			-50%			+50%		
		runoff RT	**diff**	**diff**	**runoff RT**	**diff**	**diff**	**reserv vol**	**diff**	**diff**	**reserv vol**	**diff**	**diff**
	parameter	**Mm3**	**Mm3**	**%**	**Mm3**	**Mm3**	**%**	**Mm3**	**Mm3**	**%**	**Mm3**	**Mm3**	**%**
		reference runoff:			**52,37 Mm3**			**reference volume reservoir:**			**49,75 Mm3**		
Scenario A	specific yield	52,37	0,00	0,0	52,37	0,00	0,0	49,75	0,00	0,0	49,75	0,00	0,0
	delay time	52,37	0,00	0,0	52,37	0,00	0,0	49,75	0,00	0,0	49,75	0,00	0,0
	extra inflow San Germán	37,47	-14,90	-28,5	67,27	14,90	28,5	49,75	0,00	0,0	49,75	0,00	0,0
	boundary flow groundwater	52,37	0,00	0,0	52,37	0,00	0,0	49,75	0,00	0,0	49,75	0,00	0,0
	distribution precipitation	51,37	-1,00	-1,9				28,40	-21,35	-42,9			
		reference runoff:			**61,11 Mm3**			**reference volume reservoir:**			**49,75 Mm3**		
Scenario B	specific yield	61,11	0,00	0,0	61,11	0,00	0,0	49,75	0,00	0,0	49,75	0,00	0,0
	delay time	61,11	0,00	0,0	61,11	0,00	0,0	49,75	0,00	0,0	49,75	0,00	0,0
	extra inflow San Germán	46,21	-14,90	-24,4	76,01	14,90	24,4	49,75	0,00	0,0	49,75	0,00	0,0
	boundary flow groundwater	61,11	0,00	0,0	61,11	0,00	0,0	49,75	0,00	0,0	49,75	0,00	0,0
	distribution precipitation	60,13	-0,98	-1,6				28,40	-21,35	-42,9			
		reference runoff:			**58,06 Mm3**			**reference volume reservoir:**			**39,81 Mm3**		
Scenario C	specific yield	58,06	0,00	0,0	58,06	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	delay time	58,06	0,00	0,0	58,06	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	extra inflow San Germán	43,16	-14,90	-25,7	72,96	14,90	25,7	39,81	0,00	0,0	39,81	0,00	0,0
	boundary flow groundwater	58,06	0,00	0,0	58,06	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	distribution precipitation	57,07	-0,99	-1,7				18,47	-21,34	-53,6			
		reference runoff:			**62,99 Mm3**			**reference volume reservoir:**			**39,81 Mm3**		
Scenario D	specific yield	62,99	0,00	0,0	62,99	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	delay time	62,99	0,00	0,0	62,99	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	extra inflow San Germán	48,13	-14,86	-23,6	77,89	14,90	23,7	39,81	0,00	0,0	39,81	0,00	0,0
	boundary flow groundwater	62,99	0,00	0,0	62,99	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	distribution precipitation	62,01	-0,98	-1,6				18,47	-21,34	-53,6			
		reference runoff:			**61,11 Mm3**			**reference volume reservoir:**			**39,81 Mm3**		
Scenario E	specific yield	61,11	0,00	0,0	61,11	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	delay time	61,11	0,00	0,0	61,11	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	extra inflow San Germán	46,21	-14,90	-24,4	76,01	14,90	24,4	39,81	0,00	0,0	39,81	0,00	0,0
	boundary flow groundwater	61,11	0,00	0,0	61,11	0,00	0,0	39,81	0,00	0,0	39,81	0,00	0,0
	distribution precipitation	60,13	-0,98	-1,6				18,47	-21,34	-53,6			

		reference direct runoff:				109,91 Mm3		
		-50%				+50%		
		direct run	diff	diff		direct run	diff	diff
	parameter	**Mm3**	**Mm3**	**%**		**Mm3**	**Mm3**	**%**
Scenario A	specific yield	109,91	0,00	0,0		109,91	0,00	0,0
	delay time	109,91	0,00	0,0		109,91	0,00	0,0
	extra inflow San Germán	109,91	0,00	0,0		109,91	0,00	0,0
	boundary flow groundwater	109,91	0,00	0,0		109,91	0,00	0,0
	distribution precipitation	85,38	-24,53	-22,3				
		reference direct runoff:				**109,91 Mm3**		
Scenario B	specific yield	109,91	0,00	0,0		109,91	0,00	0,0
	delay time	109,91	0,00	0,0		109,91	0,00	0,0
	extra inflow San Germán	109,91	0,00	0,0		109,91	0,00	0,0
	boundary flow groundwater	109,91	0,00	0,0		109,91	0,00	0,0
	distribution precipitation	85,38	-24,53	-22,3				
		reference direct runoff:				**109,91 Mm3**		
Scenario C	specific yield	109,91	0,00	0,0		109,91	0,00	0,0
	delay time	109,91	0,00	0,0		109,91	0,00	0,0
	extra inflow San Germán	109,91	0,00	0,0		109,91	0,00	0,0
	boundary flow groundwater	109,91	0,00	0,0		109,91	0,00	0,0
	distribution precipitation	85,38	-24,53	-22,3				
		reference direct runoff:				**109,91 Mm3**		
Scenario D	specific yield	109,91	0,00	0,0		109,91	0,00	0,0
	delay time	109,91	0,00	0,0		109,91	0,00	0,0
	extra inflow San Germán	109,91	0,00	0,0		109,91	0,00	0,0
	boundary flow groundwater	109,91	0,00	0,0		109,91	0,00	0,0
	distribution precipitation	85,38	-24,53	-22,3				
		reference direct runoff:				**109,91 Mm3**		
Scenario E	specific yield	109,91	0,00	0,0		109,91	0,00	0,0
	delay time	109,91	0,00	0,0		109,91	0,00	0,0
	extra inflow San Germán	109,91	0,00	0,0		109,91	0,00	0,0
	boundary flow groundwater	109,91	0,00	0,0		109,91	0,00	0,0
	distribution precipitation	85,38	-24,53	-22,3				