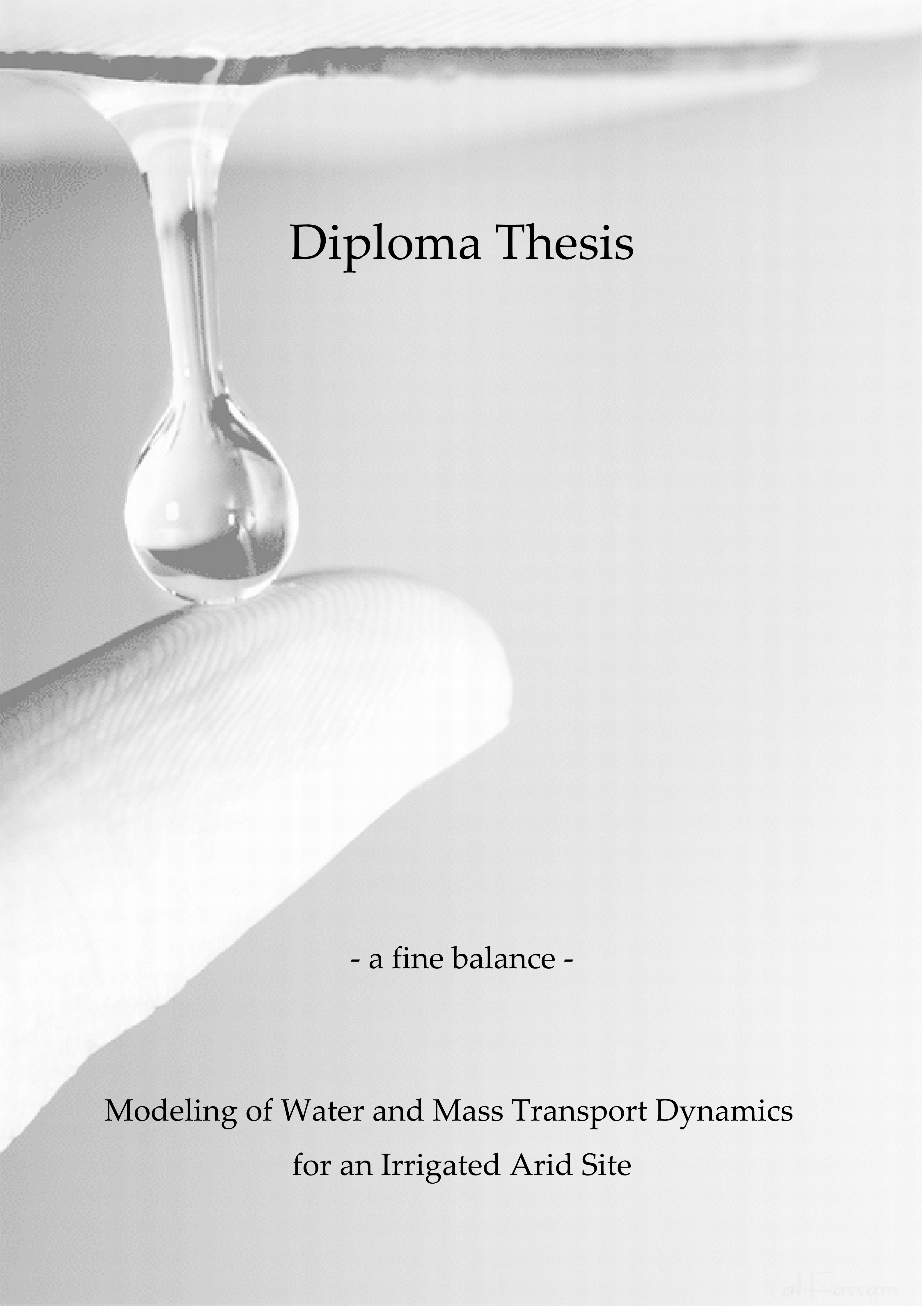

# Diploma Thesis

- a fine balance -

## Modeling of Water and Mass Transport Dynamics for an Irrigated Arid Site

TECHNISCHE
UNIVERSITÄT
DRESDEN

Fakultät Forst-, Geo- und Hydrowissenschaften

Institut für Abfallwirtschaft und Altlasten

# Aufgabenstellung

# für die Diplomarbeit

**Bearbeiter/in:** Björn Helm **geb:** 08.06.1982

**Thema:** Modeling of Water and Mass Transport Dynamics for an Arid Irrigated Site

## Zielstellung:

Models for the simulation of water dynamics in the unsaturated zone are a powerful tool with a broad spectrum of possible applications. Arid regions have a great need for control and management of water recourses, as they are sparse. Due to differing climatic and environmental boundary conditions in arid zones, the driving forces of water movement are much more pronounced than under temperate climate conditions. The demand of tools for a enhanced water management on one hand and the lag of experience in the application of such tools, constitute the motivation for this diploma thesis

Object of the diploma thesis is the application and validation of SiWaPro simulation program for arid conditions. The work will be conducted as a case study for an irrigated site in the Province of Mendoza, Argentina.

Based on a literature study a site is to be chosen where data is available with sufficient spatial and temporal resolution and that represents the situation in Mendoza. If necessary, field and laboratory work should be included in the process of data retrieval. As irrigation is by far the regions greatest water consumer, the work should be dedicated to an aspect related to this theme.

Based on a conceptual model, the data required for the model setup has to be inquired. Necessary steps for their take into use are to be processed. The model is to be developed with respect to further calibration and validation steps.

In a further step, mass transport scenarios should be derived that meet existing contamination problems. For application, the validated water dynamics model is taken into use.

Aim of the work should be to outline bottlenecks and backlog demands in the data situation, experiences and limitations in the model application, recommendation of best management practices to avoid excessive water use and contamination threats.

**Betreuer:** Prof. Dr.-Ing. habil. P.-W. Gräber (TU Dresden)
Dr. Sandra Ibanez (Univers. Nacional de Cuyo, Argentinia)

**Ausgehändigt am:** 01.08.2008

**Einzureichen bis:** 31.12.2008

Prof. Dr.-Ing. habil. Peter-Wolfgang Gräber

**Verantwortlicher Hochschullehrer**

# TECHNISCHE UNIVERSITÄT DRESDEN

## FACULTY OF FOREST, GEO AND HYDRO SCIENCES

## - DEPARTMENT OF HYDROSCIENCES-

Professor in charge: Prof. Dr. Peter-Wolfgang Gräber

Supervisor: Dr. Sandra Ibañez

Granduand: Björn Helm

Matriculation number: 2924566

# EIDESSTATTLICHE ERKLÄRUNG

Ich versichere, dass ich die vorliegende Diplomarbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Aus fremden Quellen übernommene Passagen und Gedanken sind als solche kenntlich gemacht.

Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

Dresden, den 22. Dezember 2008

Björn Helm

# INDEX OF CONTENTS

# INDEX OF FIGURES

# INDEX OF TABLES

# ABBREVIATIONS

ACRE.................................................................................area de cultivos restringidos especiales
BTEX……….......................................................................... benzene, toluol, ethylbenzene, xylene
CdC………….......................................................................................................... Chacras de Coria
CDE........................................................................................... Convection-Dispersion-Equation
CS……………..........................................................................................................climate station
DGI...................... ................................................................. Departamento General de Irrigación
EC…..........................................................................................................electric conductivity
ET…................... ....................................................................................................evapotranspiration
IDW………………….............................................................................. inverse distance weighting
INTA....................................................................Instituto Nacional de Tecnología Agropecuaria
kc………..   ............................................................................................................ crop coefficient
LL……………….........................................................................................................La Libertad
MA…………..............................................................................................................Mendoza Airport
m asl.................................................................................................................meters above sea level
m bsl.................. ...................................................................................meters below surface level
MO………….............................................................................................. Menoza Observatory
MReg………. ............................................................................................. multiple regression
ND……….................................................................................................normal distribution
PAH……….. ....................................................................................... polyaromatic hydrocarbons
PHC………….. ................................................................................petroleum hydrocarbons
PM………....................................................................................................Penman Monteith
PTF..................................................................................................... pedotransfer function
PWP…………. ........................................................................................ permanent wilting point
R…………….. ............................................................................................. correlation coefficient
PP…………… ........................................................................................performance parameter
PU………….. ................................................................................................ performance utility
PV………....................................................................................................porous volume
$R^2$……………..................................................................................coefficient of determination
rH / rh.............................................................................................................relative humidity
RMSE……… ..............................................................................................root mean square error
rRMSE.................. .......................................................................relative root mean square error
SD.......................................................................................................................standard deviation

SV........................................................................................................................sedimentation volume

SM…………… ...........................................................................................................................San Martín

VC....................................................................................................................... variation coefficient

WC.........................................................................................................................................water column

# INDEX OF SYMBOLS AND UNITS

| | | |
|---|---|---|
| a(h) | root water uptake scaling function | [-] |
| awc | available water capacity | [-], L, [%] |
| b(x,z) | water uptake distribution function | [-] |
| $C_x$ | coefficient of friction | $M^{-2}$ |
| d_sol | sunshine duration | T |
| $D_B$ | bulk density | $M/L^3$ |
| $D_P$ | particle density | $M/L^3$ |
| $e_a$ | actual vapour pressure | $M/(LT^2)$ |
| EC | electric conductivity… | $(I^2T^3/ML^3)$ |
| $EC_e$ | soil salinity | $(I^2T^3/ML^3)$ |
| $e_s$ | saturation vapour pressure | $M/(LT^2)$ |
| $ET_0$ | Potential evapotranspiration… | L/T |
| fc | field capacity | [-], L, [%] |
| g | acceleration of gravity | $L/T^2$ |
| h | water pressure / suction head | L |
| h1-h4 | characteristic pressure heads of root uptake function | L |
| k(h) | unsaturated hydraulic conductivity | L/T |
| $K_{ij}$ | components of a dimensionless anisotropy tensor | [-] |
| $k_x$ | coefficient of permeability in direction of x | L/T |
| $L_s$ | transpiration active surface width | L |
| m | transformation parameter | [-] |
| n | increase parameter | [-] |
| p | pressure | $M/L^2$ |
| P | Precipitation | L/T |
| $p_c$ | capillary pressure head | $M/L^2$ |
| pwp | permanent wilting point | [-], L, [%], $M/L^2$ |
| rH | relative humidity | $L^3/L^3$ = [-] |
| $R_n$ | net radiation at the crop surface | L/T |
| s | slope of the vapour pressure curve | $M/(LT^2\theta)$ |
| $S_e$ | relative/effective saturation | $L^3/L^3$ = [-] |
| SV | sedimentation volume | $L^3/M$ |
| $T/T_m$ | mean daily air temperature at 2 m height | $\theta$ |

| | | |
|---|---|---|
| $T_{min/max}$ | minimum/maximum daily air temperature at 2 m height | θ |
| $T_P$ | potential transpiration rate | L/T |
| $u_2$ | wind speed at 2 m height | L/T |
| $v_x$ | velocity of flow in direction of x | L/T |
| $w_0$ | source/sink term | $L^3/T$ |
| $w_0(h)$ | actual water uptake rate | $L^3/T$ |
| wc | volumetric water content | $L^3/L^3$, [-] |
| $w_P$ | potential water uptake rate | $L^3/T$ |
| $\alpha$ | scaling parameter | [-] |
| $\eta$ | dynamic viscosity | $M^2/LT$ |
| $\phi$ | porosity | $L^3/L^3$ = [-] |
| $\lambda$ | tortuosity parameter | [-] |
| $\rho$ | density of the fluid | $M/L^3$ |
| $\theta$ | water content | $L^3/L^3$ = [-] |
| $\theta_s$ | saturated water content | $L^3/L^3$ |
| $\theta_r$ | residual water content | $L^3/L^3$ |
| $\gamma$ | psychrometric constant | $M/(L*T^2\theta)$ |

# ABSTRACT

The efficient management and protection of water resources is one of the most fundamental requirements for sustainable development in arid regions. Water is scarce and the interests and pressures on its use are divergent. Agricultural water consumption accounts for 70 % of the water extraction in Argentina, with Mendoza as its most important oasis. Due to its importance for the region, a lot of research focuses on water resource management in Mendoza.

Physical based model tools of the unsaturated soil zone, for example SiWaPro DSS, can contribute in many aspects to an enhanced comprehension of processes and problems related to water dynamics and mass transport in the soil. So far this aspect has not been investigated in Mendoza and also on an international scale only a few related projects are published.

This thesis documents the application of SiWaPro DSS for modelling of an arid irrigation site in Mendoza. The model is calibrated on measured soil moisture data. A method for the multi-objective evaluation of model performance and modelling quality is presented and performance utility is introduced as an integrated evaluation parameter is introduced. The dynamic of water balance is analyzed on local scale.

Scenarios are developed based on the calibrated model. They are oriented towards problems of a special relevance for Mendoza. Dynamics of soil and leachate salinization is researched and results are compared with balance based approaches. It is found that accumulated salt load is predicted with satisfying exactness. The model gives additional information on spatial and temporal variability of the process. Additionally the water and salt balance of alternative irrigation methods are compared. Drip irrigation has a big potential for the reduction of water consume but salinity control in the root zone is indispensable. The possibilities and limitations of phytoremediation are evaluated for sites contaminated by petroleum extraction.

# KURZFASSUNG

Die effiziente Nutzung und der Schutz von Wasserressourcen ist eine der grundlegendsten Anforderungen an die nachhaltige Entwicklung in ariden Gebieten. Wasser ist knapp und die Interessen und Belastungen für seine Nutzung divergieren. Wasserverbrauch in der Landwirtschaft hat einen Anteil von 70 % an der argentinischen Wassergewinnung zur Nutzung und Mendoza ist die wichtigste Oase des Landes. Auf Grund der Wichtigkeit des Themas für die Region ist die Erforschung der Wasserressourcen ein Forschungsschwerpunkt in Mendoza.

Die physikalisch basierte Modellierung der ungesättigten Bodenzone, zum Beispiel mit SiWaPro DSS kann in vielen Bereichen zu einem verbesserten Verständnis von Prozessen und Problemen des Bodenwasser- und -stoffhaushaltes beitragen. Bislang wurden zu diesem Thema in Mendoza noch keine Untersuchungen durchgeführt und auch international ist nur eine kleine Zahl von Untersuchungen aus ariden Schwellenländern veröffentlicht.

Die vorliegende Arbeit dokumentiert die Anwendung von SiWaPro DSS für die Modellierung eines ariden Bewässerungsstandortes in Mendoza. Das Modell wird auf der Basis gemessener Bodenfeuchtedaten kalibriert. Es wird ein Verfahren zur multikriteriellen Bewertung des Modellverhaltens und der Modelgüte vorgestellt und der Performanz-Nutzwert als integraler Bewertungsparameter eingeführt. Die Dynamik des Wasserhaushaltes wird auf lokaler Skale analysiert.

Auf Basis des kalibrierten Modells werden Szenarien entwickelt die für Mendoza besonders relevante Probleme behandeln. Die Dynamik der Versalzung des von Boden und Sickerwasser wird untersucht und die Ergebnisse mit bilanzierenden Ansätzen verglichen. Dabei zeigt sich dass die Bilanzansätze eine gute Voraussagegenauigkeit für die akkumulierte Salzfracht treffen, durch die Modellierung können aber zusätzliche Aussagen zur räumlichen und zeitlichen Variabilität der Prozesse getroffen werden. Zusätzlich wird der Wasser- und Salzhaushalt für alternative Bewässerungsmethoden untersucht und mit den zuvor gewonnen Ergebnissen verglichen. Das Potential zur Wassereinsparung durch Tröpfchenbewässerung ist groß, allerdings ist eine Steuerung der Salzkonzentration in der Wurzelzone unabdingbar. Des Weiteren werden die Möglichkeiten und Grenzen der Anwendung von Phytoremediation für die in Mendoza vorkommenden Altlasten der Erdölförderung bewertet.

# RESUMEN

El uso eficiente del agua y la protección de los recursos hídricos son unos de los requerimientos más fundamentales para el desarrollo sostenible en ámbitos áridos. La disponibilidad de agua es limitada e intereses y presiones para su uso son divergente. La agricultura contribuye con un 70 % al total de las extracciones para el uso del agua. Mendoza es el oasis mas importante de la Argentina. Debido a la importancia del tema para la región, la investigación de los recursos de agua representa un tema central en la agenda científica de Mendoza.

La modelización de base física de la zona no saturada del suelo, por ejemplo con el programa de simulación SiWaPro DSS es apta para mejorar el conocimiento de procesos y problemas de los balances de agua y substancias en el suelo. Hasta ahora no hay investigaciones sobre este tema en Mendoza y además a la escala global pocos proyectos están publicados desde países emergentes con condiciones áridas.

Esta tesis documenta la aplicación del programa SiWaPro DSS para la modelización de un sitio de regadío árido en Mendoza. El modelo fue calibrado en base a contenidos de humedades medidas del suelo. Un método para la evaluación multi-objetiva es presentado. El parámetro de rendimiento de utilidad (performance utility) es introducido. La dinámica del balance de agua es analizada a escala local

A partir del modelo calibrado, escenarios que tratan problemas relevantes de Mendoza son desarrollados. La dinámica de salinización del suelo y del agua de drenaje es determinada y comparada con un método de balance. Este método muestra una buena capacidad predictiva para la carga acumulada de sales, adicionalmente el modelo de simulación da informaciones sobre la variación temporal y espacial de los procesos determinates. El balance hídro-salino también es revisado para métodos de riego alternativos. El riego por goteo tiene gran capacidad para el ahorro de agua pero un control de la salinización en la rizosfera es indispensable. Además las posibilidades y limitaciones para la aplicación de la fitoremediación con álamos para sitio contaminado con hidrocarburos petroleros son evaluadas.

# 1 INTRODUCTION

The understanding and control of soil water dynamics is crucial in irrigated sites of arid regions. On the one hand water is sparse and only its effective use permits a sustainable development. On the other hand, due to the accelerated climatic driving forces and a soil water balance strongly actuated by evaporation, mismanagement of irrigation systems may lead to rapid loss of their full functionality e.g. caused by salinization.

Within the last four decades the advances in water related process comprehension and computing power opened a new basis for the representation and evaluation of water management practices. In the context of integrated land and water resources management [Calder, 2005] calls the opportunities of model application for an enhanced understanding of water systems and decision support the "blue revolution" that consequential widens the view from structural engineering tasks to system oriented management strategies.

Coupling different sub-systems is not a straight forward task. Processes are driven on different temporal and spatial scales. Water in the distribution channels and on the field surface flows rapidly: velocity accounts with meters per second and traveling time is usually limited to some hours. The water in the unsaturated zone moves with centimeters or millimeters per hour while storage time is up to some weeks. Finally groundwater moves even slower and travel times may reach various years [Dyck, 1995]. Accounting for the spatial extensions surface flow may be captured one dimensionally with several kilometers of lateral movement in contrast to a few meter of cross sectional dimension. Water movement in the unsaturated zone takes place mostly vertically and is often represented sufficiently with two dimensional approaches, yet heterogeneously for differing soil or cultivation situations. The aquifer demands representation for both horizontal and vertical flow, processes and parameters are often connected and related within large spatial extends [Schmitz, 2007], [Dogan, 2005]. The varying spatial and temporal scales and dimensions cause difficulties for defining sensible observation boundaries that cover all three processes. Between the highly dynamic surface flow and large scale groundwater movement, unsaturated zone acts as an agent [Benson, 2007]. Hence special attention should be drawn on the representation of the processes there.

Unsaturated flow is a highly non-linear process, which complicates analysis of reactions of the vadose zone. Consequently, engineers traditionally have used simplified solutions for analysis of unsaturated flow problems [Benson, 2007]. For physical based two dimensional

(2D) modelling of water dynamics in the unsaturated zone few references are available for arid zones although it serves as handy tool. Some work is done in one dimensional (1D) physical based modelling, compare [Dixon, 1999], [Keese, 2005] or with conceptual models [Querner, 2008], [Hsieh, 2001]. [Kavazanjian, 2006] points out the difficulties with modelling the unsaturated soil layer in arid regions.

Root dynamics and soil water models are available for operation on different scales but results for the scale transition are often not consistent [Li, 2006], [Feddes, 2001]. Dynamically coupled models of soil water and root dynamics, e. g. [Hopmans, 1998] are still under development, especially due to a lag of sufficiently resolved data. In order to enhance system comprehension and to validate existing approaches on regional scale as e. g. of [Querner, 2008] it is valuable to consider processes of the unsaturated soil zone at site-scale.

Mendoza is situated in the western part of central Argentina. The environment of the province consists of a desert plain with precipitation about 200 mm/a and the Andes mountain range with important glacial water recourses. The water flows from the mountain range in rivers and is used in elaborate irrigation systems. Oases cover 3 % of Mendoza's province surface [Chambouleyron, 1990] and constitue the most important irrigation region of Latin America [Peyke, 1998]. The cultivation of wine and fruit dominates the agricultural production in Mendoza but, given the increasing demand for wood and biomass [Bustamante, 2008], silviculture constantly gains importance in the cultivation schemes.

Mendoza's irrigation system is one of the most sophisticated in Latin America [Chambouleyron, 1990]. With the expansion of irrigated surface, groundwater is used increasingly for irrigation purposes [Kupper, 2002]. The intensified use causes increased attention for this recourse. As a result various projects are carried out to monitor and evaluate the development, e.g. [Ortíz, 2005], [Mastrantonio, 2006]. Considering projects in Mendoza that focus modelling the water dynamics of agricultural areas [Querner, 2008] has done the probably most integral work.

In the present work, a model was set up to reproduce irrigation and groundwater recharge. As study area a site was chosen that was investigated in a former study about the irrigation of poplars. From the former works detailed climate, soil and water dynamics data were available. It was calibrated with soil moisture data applying a set of multiple performance parameters. The model is validated with irrigation seasons and irrigation regimes other than the calibration data. Based on the calibrated model of water dynamics, mass transport scenarios were applied that comprise some of the environmental problems related to water use in Mendoza region.

One intention of this work is to validate the applicability of SiWaPro, a 2D model of flow dynamics and mass transport in the unsaturated soil zone, under arid conditions. The present work aims to give an example for the dynamics of groundwater recharge on the local scale. It permits the validation of estimates on larger scale and gives an insight into the small scale heterogeneity of the process dynamics.

## 1.1 Situation in Mendoza

### 1.1.1 Generalities

With Buenos Aires, Montevideo, Rosario, Cordoba, Mendoza and Santiago the Chile the six biggest cities of Southern South America are aligned in a band between 31° and 34° southern latitude. Nevertheless environmental conditions are different for each place and thus socio-economic setting. Mendoza is the smallest of the named metropolis and has preserved the most rural character. The city consists of various former towns that grew together because of that agricultural patches are incorporated into the urban area. In most parts one story buildings dominate the townscape because the area is seismically vulnerable. The exceptional appearance is also a direct consequence of the position of the city. Mendoza is situated in western Argentina, at the dry eastern foot of Andes Mountains. Together with the agglomeration a sophisticated irrigation system grew. Agriculture and the consecutive industries build the economical base of Mendoza.

The city of Mendoza is the capital of the homonymous province. Extensions of the province range between 32° – 37° southern latitude and 67° – 70° western longitude. With 1.6 million inhabitants on 148 000 $km^2$ the population density is low. Especially considering the fact that more than one million people are living in the Gran Mendoza agglomeration [DEIE, 2001b]. Together with the neighboring provinces of San Juan, San Luis and La Rioja the region is named Cuyo from the indigenous “land of the sand” [Abraham, 1999]. The land use of the province has a clear division between its oasis and the wasteland in-between. The irrigated areas cover three percent of the province’s surface and they are home to 97 percent of its population [Becerra, 2007]. For the areas with natural conditions this ratio is reverted.

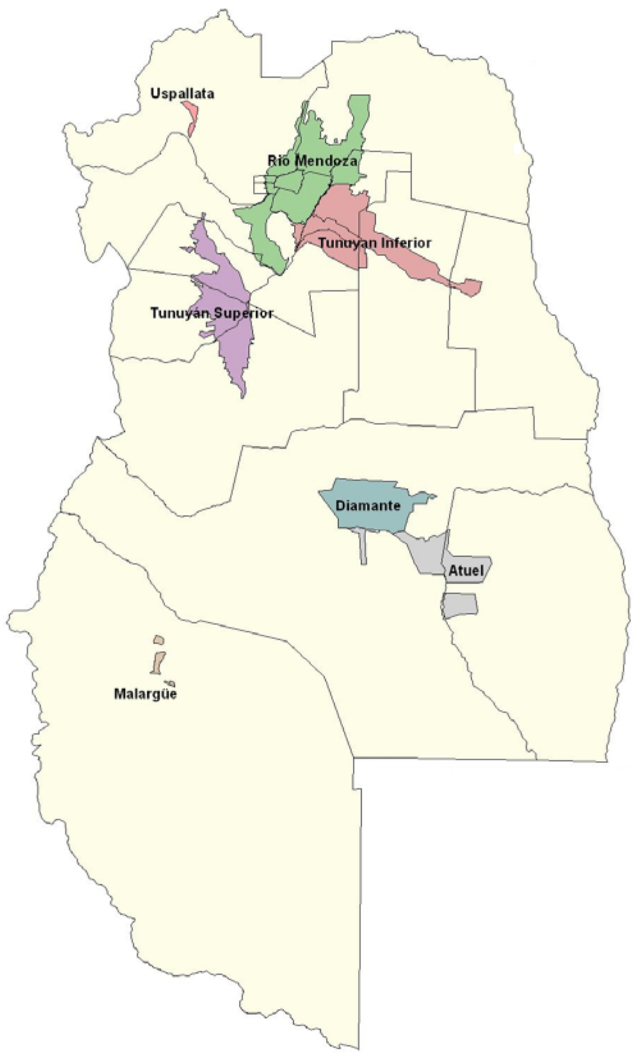


**Fig. 1 Extension of the oasis in Mendoza province [Abraham, 1999]**

### 1.1.2 Climatic Conditions and Ecosystems

Due to the geographic location of the region, Mendoza is exposed to an arid climate. The leeward position of the province on the foothill of the Andes causes regularly dry atmospheric conditions. Especially during the southern hemisphere winter months (June – August) when Intertropical Convergence Zone shifts northwards, Mendoza lies in a subtropical trade wind zone [Schneider, 1998], as a consequence winter is the driest season.

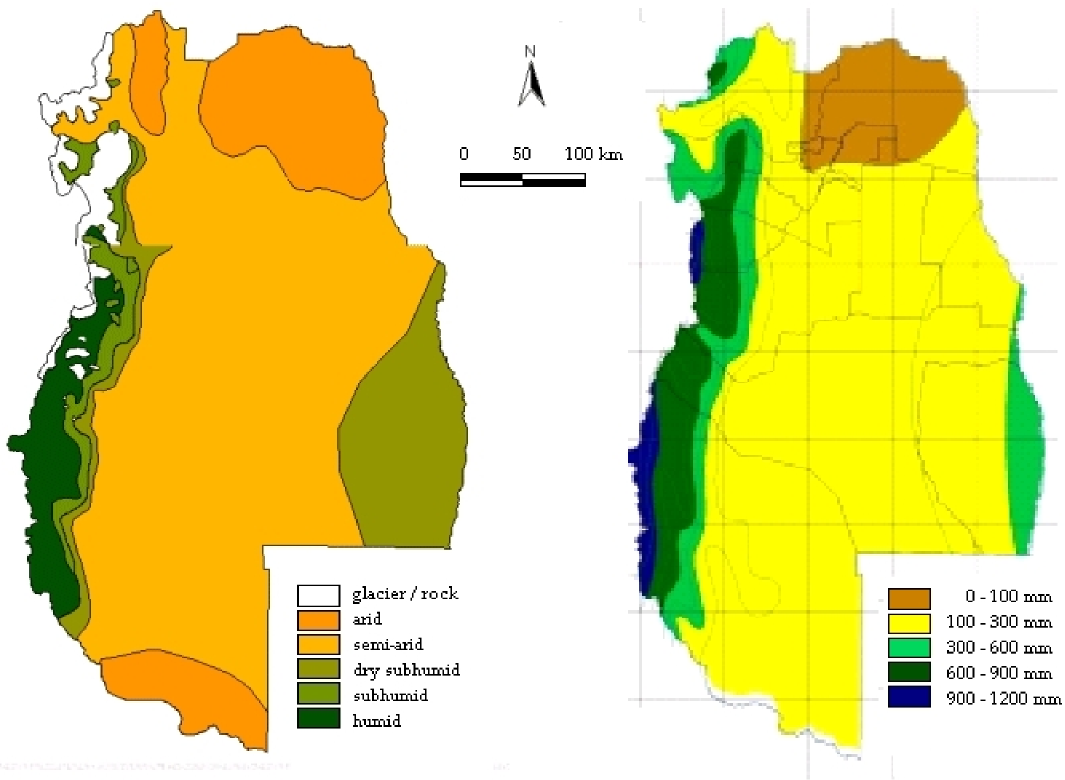


**Fig. 2 Aridity index (l) and annual precipitation (r) for Mendoza province [Roig, 1999]**

Annual precipitation in the desert plain is about 200 mm, rising with increasing altitude but also with distance to the mountain chain westward (Fig. 2), as the leeward influence decreases. Driest areas are found in the Northwestern part of the province. At climate station (CS) "El Retamo" in the North of Mendoza an annual mean precipitation of 81 mm was registered. Highest Precipitation occurs in the main mountain range. Aridity index expresses the ration of annual potential evaporation to annual precipitation, for values smaller than one precipitation does not cover the evaporation demand, for values smaller than 0.5 climate is considered as semi-arid, for values as low as 0.03 (30 times less precipitation than potential evaporation) climate is hyperarid. Fig. 2 displays the aridity index for Mendoza province. Apart from the mountain range and the westernmost zones the climate is semiarid to arid. According to Köppen/Geiger climate is desertic cold (BWk), according to Troll subtropical arid (IV.5) or corresponding to Lauer subtropical continental arid (B.2a).

All numbers in Fig. 3 and Fig. 4 are based on a reference period of 1990 – 2005. In Fig. 3 temperature courses for Mendoza observatory are displayed. The hottest months are December and January with a temperature of 23°C average. The coldest month is July with an average of 7°C. Differences between minimum, mean and maximum daily temperature are quite constant throughout the year and amount around seven degrees constantly. The big differences between highest and lowest daily temperatures can be explained with the arid surrounding, where only small water resources in soil and surface buffer the radiation heat fluxes.

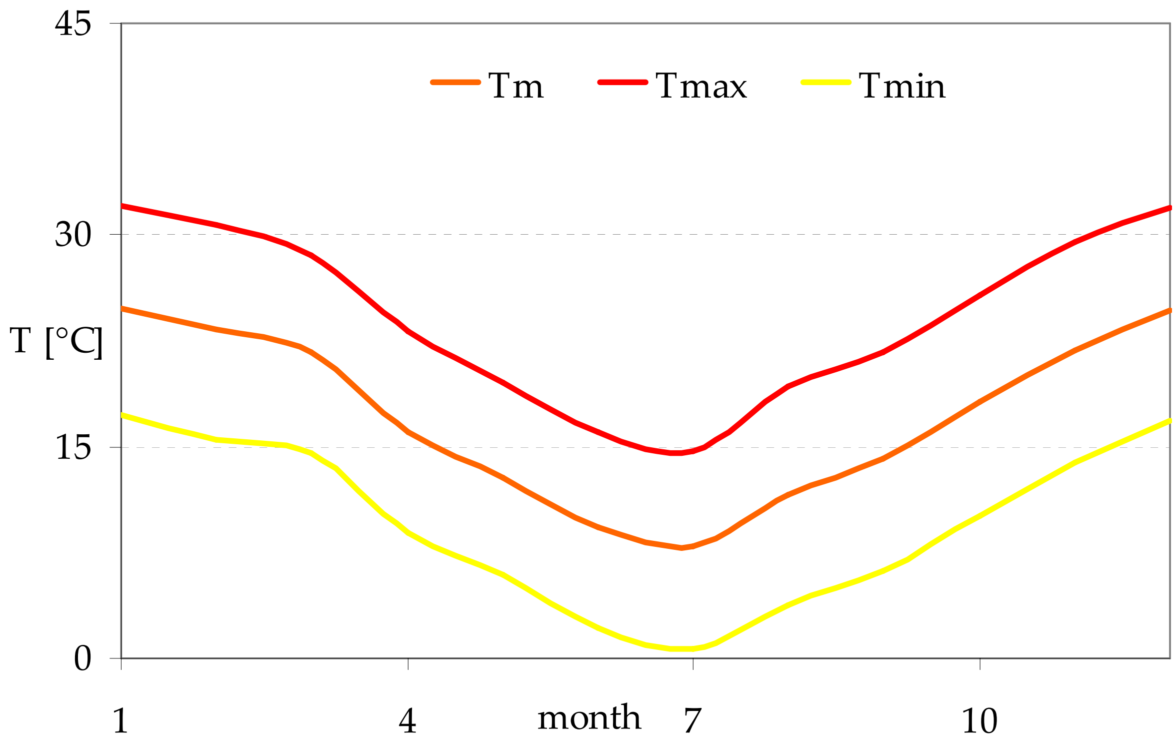


**Fig. 3 Annual course of temperatures for Mendoza observatory climate station**

The course of hydrometeorologic parameters relative humidity (rh), precipitation (P) and potential evapotranspiration (ETP) as well as sunshine duration (d_sol) and wind speed (u) two meters above ground are given in Fig. 4. Precipitation is highest in the summer months January to March. Annual precipitation is 230 mm. Relative air humidity varies between 50 and 60 % and tends to be higher in the autumn and the winter months. Sunshine duration, wind speed and evaporation show unimodal distribution all with highest values in summer. For all these effects elevated solar radiation in summer can be seen in a more or less direct relation as driving force.

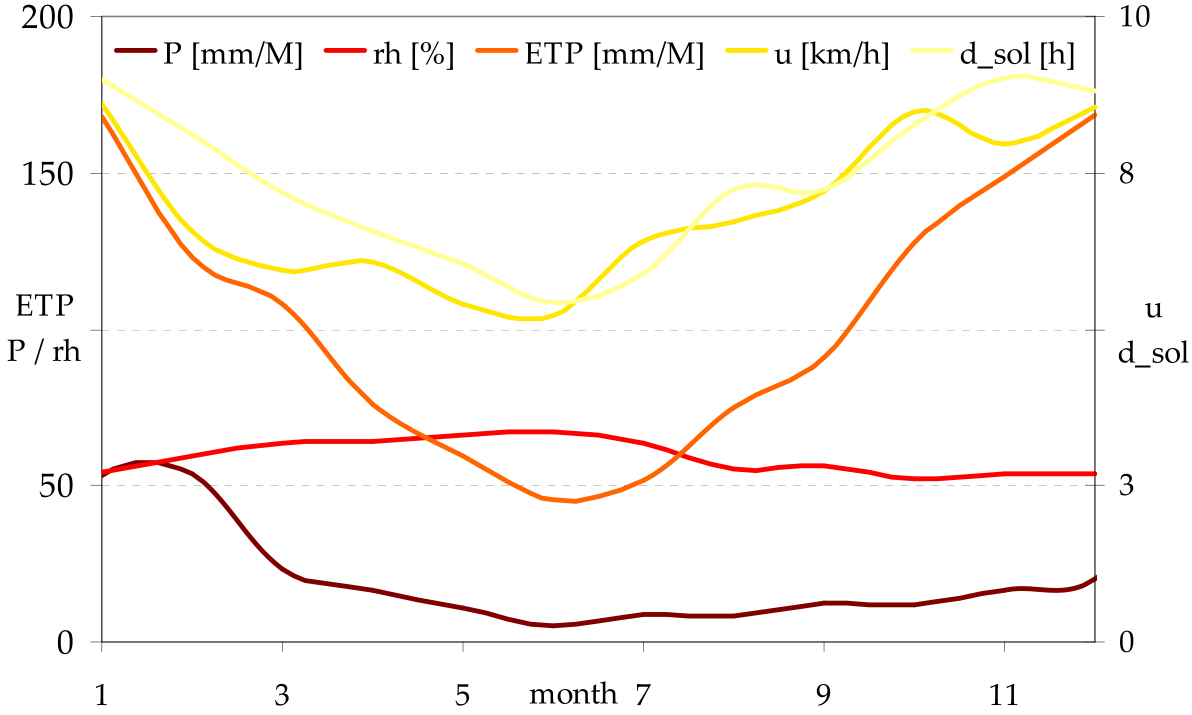


**Fig. 4 Annual courses of sunshine duration (d_sol), wind speed (u), precipitation and relative air humidity (rh) for Mendoza observatory climate station**

The ecosystems are composed of the Andine region with high mountain characteristics in the West, the Monte ecoregion in the East with desertic and steppic character and subtropical continental climate, the Puna a high desert with arid and extreme arid climate in the North and Patagonia in the South a steppic region with cool temperate continental climate [Ongay, 2006]. Natural vegetation in the Cuyo is dominated by the Monte ecoregion [Borsdorf, 2003]. Xerophile plant communities prevail in the environment. They mainly consist of thorny shrubs and bushes mixed with cactuses and solitary trees [Roig, 1972]. Because of their valuable wood, native Algarrobo (Prosopis) forests were timbered and only small relicts retain in remote areas [Schneider, 1998]. Lakes develop in basins, due to the high evaporation rates they often have elevated salt contents. In the arid environment they are an attraction for wildlife especially for water birds. The Lagunas de Guanacache are an evidence for the vulnerability of the lake ecosystems in arid regions. They are situated at the mouth of Río Mendoza into Río Desaguadero. As a consequence of the increased water consumption in the oasis, the lakes fell dry and are nowadays they are flooded only occasionally.

### 1.1.3 Landscape and Hydrology

The landscape can be divided into three main regions: Andes main mountain range and pre-mountain ranges in the west, Llanura plain with some ridges in the east and Payunia complex a volcanic shield in the south [Abraham, 1999]. The Andes are characterized by wide forms of low relief energy mainly due to the lag of water courses in this arid region [Gerbi, 2001]. In the elevated regions predominately plateaus are found. The eastern foot of the mountain chain descents into mesozoic and tertiary sediments. They decline eastwards in huge alluvial fans and form the llanura. During the Pleistocene the fans were intersected by rivers and cuestas developed [Schneider, 1998]. With greater distance from the mountains the slope of the llanura diminishes and sediment material gets finer. They are of fluvial, alluvial or eolic origin and have depths of up to ten meters. On these sandy to clayish underground soils developed that are used today as base for the irrigational agriculture.

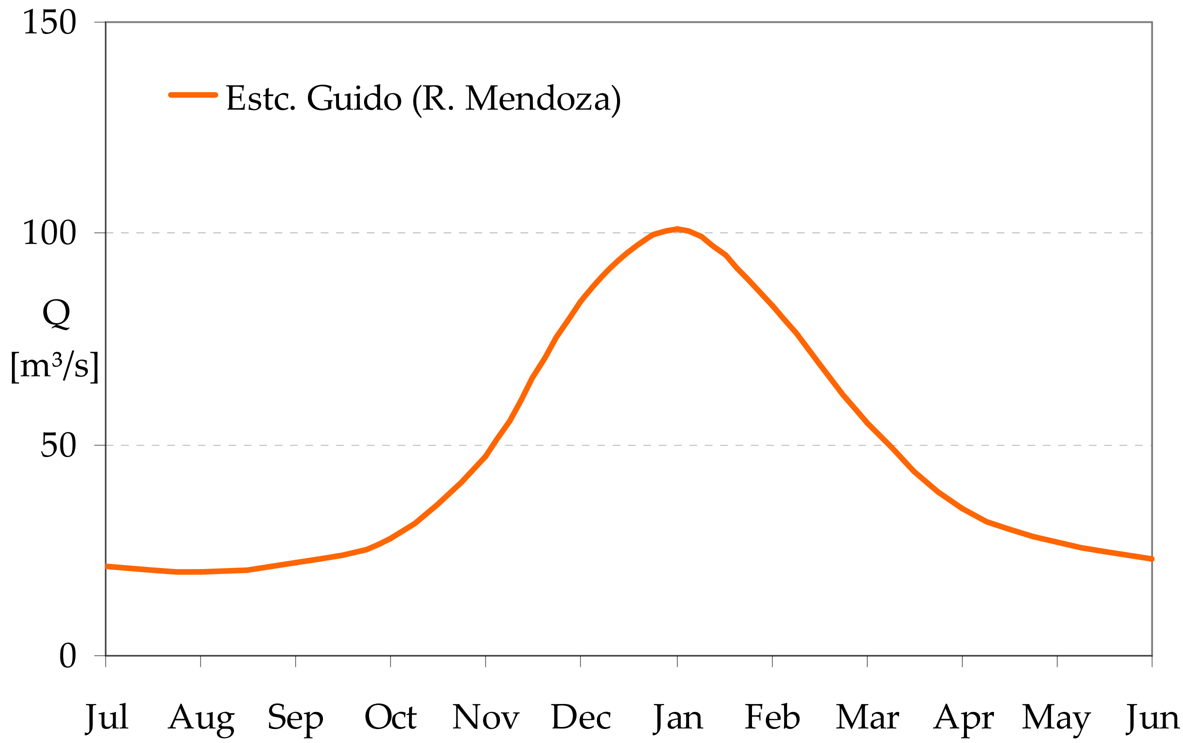


**Fig. 5 Monthly mean discharge of Río Mendoza at Estación Guido [DGI, 2007a]**

Mendoza has six main river systems: Mendoza and Tunuyán in the northern part, Diamante and Atuel in the central part, Malargüe and Barrancas/Grande at the southern border. Apart from small regions in the Andes mountain range and the endorheic Río Malargüe all rivers belong to Río Colorado catchment and drain into the Atlantic. Discharge regime in all rivers is nival [Gudiño de Muñoz, 1991], with mean flow maxima during the summer when snow, glacier and frost melting water feeds the rivers. [Peter, 1998] points out that water yield in the oasis mainly depends on storage changes above the snow line and that without the availability of these resources the existence of the oasis would be unthinkable. Since the 1980's a constant loss in the mass balance of glaciers described [Leiva, 2007]. [Corripio; 2007] found that although melting water availability increases in the medium term, accelerated glacier depletion will cause a strong reduction of annual discharge in the long term.

In addition to the snow and ice melt, summer months December to February have highest precipitation rates (compare above). The annual hydrograph shows a pronounced peak in the warmest months. Fig. 5 shows the hydrograph at Estación Guido, the last gauge before Potrerillos reservoir controls discharge course, the reference period is 1956 – 2006 [DGI, 2007a]. Summer storm events may cause extreme floods that occasionally cause big damages [Rodríguez Aguilera, 2006] discharges. Up to 15 000 $m^3/s$ are reported for Río Mendoza [Montes, 1995].

Aside from Río Grande flow patterns are heavily influenced by human activity. As a consequence it is the only river that discharges perennially. Flow in the other rivers is limited by infiltration, evaporation and extraction [Schneider, 1998]. Almost 2000 $hm^3$ [Chambouleyron, 2000] of storage capacity was created by dams, used for both irrigation regulation and to generate hydroelectric energy.

The Northern groundwater catchment covers an area of 22800 $km^2$. It consists of sediments mentioned above. The grain size distribution within the area correlates with the surface slope that decreases from NE to SW [Hernández, 2006a]. The groundwater flow is consequently rectangular to this direction. The Andes pediment is dominated by coarse material; it constitutes the main GW recharge zone and the aquifer is unconfined. Surface slope lowers with increasing distance from the mountain range and with that grain size gets smaller and the substratum is less permeable. In a transition zone resurgence occurs. Further southwest clay lenses are found that partly cause semi-confined aquifer comportment. The groundwater resources along the rivers Mendoza and Tunuyan have been estimated at around 490 000 $hm^3$ but only 13 500 $hm^3/a$ or 3 % are recharged annually [Zambrano, 1999]. In contrast [Hernández, 2006a] gives 275 000 $hm^3$ of stored recourses and only 7000 $hm^3$ as recharge rate. [Forster, 2005] estimates that in average 8 500 $hm^3/a$ are recharged by the river courses and another 4 000 $hm^3/a$ by reinfiltration of irrigation water. The strongly varying numbers denote the uncertainty about this resource.

### 1.1.4 Socioeconomic Conditions

Population growth and urbanization determine the population dynamics in Mendoza province. The number of inhabitants in the city of Mendoza and the surrounding agglomeration Gran Mendoza, raised between 1981 and 2001 from 613 000 to 849 000 corresponding to 39% increase [INDEC, 2002]. Until 2015 a further growth by 15 % is expected on the provincial scale [INDEC, 2005]. Within this total increase of population an additional concentration in urban settlements is registered, accelerating the population growth in Gran Mendoza. As mentioned above the distribution of population is extremely heterogeneous, within the oasis population density is with 300 capt./km$^2$, the actual urbanization degree is 80 % [DEIE, 2007].

The most dynamic population growth took place at the beginning of 20$^{th}$ century. Immigrants from Spain, Italy and the Eastern Mediterranean region, mostly farmers and cultivators, adapted the existing social and economic structures and favored traditions from their home countries [Chambouleyron, 1992].

Until today formative agricultural activities that are also characteristic for the province, are viniculture with 56% of the cultivated land participation, followed by fruit cultivation, horticulture and olive plantations. 25% of the manufacturing industry is connected to wine making and the elaboration of fruit and vegetables. Another important activity is the extraction and refinement of petroleum contributing in 14% to the total national production. [DEIE, 2007]

Water consumption in Argentina accounts to 300 – 500 l/(d capt) [Mendieta, 2007], in Mendoza it is estimated to be 400 l/(d capt) [Montaña, 2008] or even 600 l/d [OSM, 1996].Due to increasing standard of living and economic development this number still tends to rise, although environmental awareness and sustainability concepts are developing [Chambouleyron, 2003]. Hence wastewater amounts increase in the private as well as industrial sector.

### 1.1.5 Irrigation system and silviculture

Mendoza’s irrigation system creates the largest oasis in Latin America [Peyke, 1989]. Origins of irrigation along Río Mendoza date back to the pre-Columbian time. The indigenous Huarpes used the river for the irrigation of the cultivation of corn [Schneider, 1998]. The

Spanish colonialist basically relied on this existing system and expanded it. Not until the end of the 19th century the irrigation system was conceptualized and managed using the waters of Mendoza and Tunuyán rivers jointly and thus creating the Oasis Norte. With the great immigration wave around 1900 agriculture was adapted to the Mediterranean model emphasizing wine, olives, drupaceous fruit and vegetables in the cultivation schemes at the same time the predominance for viticulture rises [Chambouleyron, 1990].

DGI is a state agency that manages the administration of water bodies in Mendoza province. It controls supervision, evaluation and development of the valorisation of hydrological resources as well as their use and protection. Water use rights for irrigation, hydroelectricity and industrial and domestic water supply are given as temporary concessions. The share of the water amount depends on actually available yield.

Specifications about the surface actually irrigated vary considerably between 2964 km² [DEIE, 2001a] and 3400 km² [DGI, 2005]. The system consists of 8000km of primary and secondary canal system [Chambouleyron, 1990]. Of these, only 500 km are concrete-lined; the others are earth-lined. In the lower parts of the irrigation systems, there is also an extensive network of drainage collectors, with a length of 2 500 km approximately. [Querner, 2008] found that great part of the groundwater recharge in the plain, that causes locally elevated phreatic levels is caused by infiltration from the irrigation channels. By comparison of irrigated area and available water resources, overall efficiency accounts to only 38 % [Chambouleyron, 1990]. [Marre, 1998] proposes a reformation of cost distribution and claims the need for higher shares for system maintenance, especially in for the distribution system.

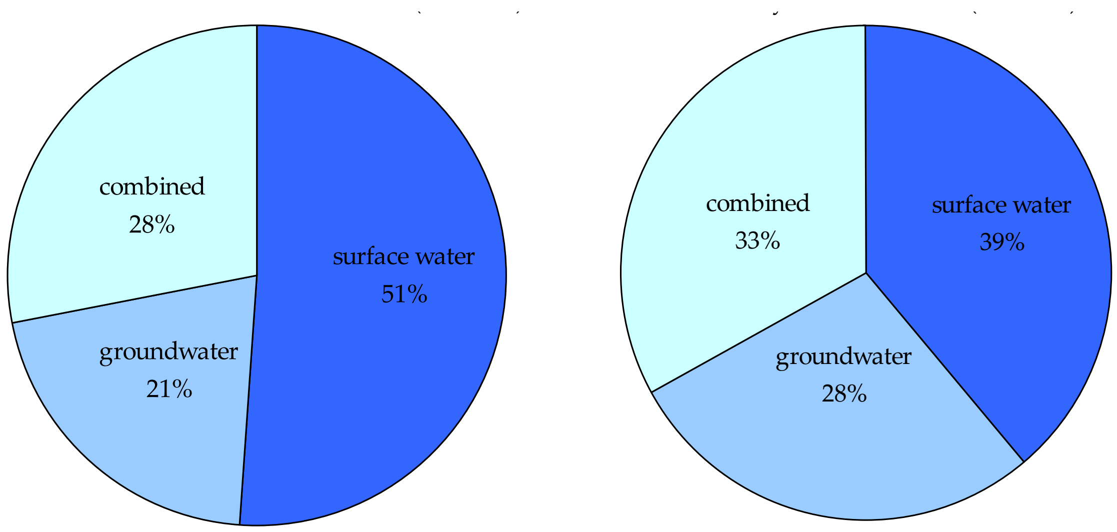


**Fig. 6 Portions of water sources in irrigation for Río Mendoza (left) and Tunuyán Inferior (right)**

In the Oasis Norte 40000hm³ of groundwater recourses are available. They are mostly exploited between 100m – 300m depth from more than 25000 wells registered at DGI [DGI, 2005]. About 50 % of Mendozas irrigation area relies at least partly on groundwater (compare Fig. 6) [Foster, 2005]. In 1990 50m³/s were pumped from groundwater wells [Thomas, 1998], although the rate strongly depends on annual river discharge [Hernandez, 2006a]. They tap three aquifer levels. The surface aquifer (0 – 80 m below surface level) provides water of 1 to 2.2 dS/m conductivity, in some zones the value reaches up to 5.5 dS/m, indicating stronger influence of salinity. For this reason the 2nd (100 – 180 m bsl) and 3rd (below 200 m bsl) are harvested, where salinity levels are generally lower [Hernandez, 2006a]. Excess water in irrigation evaporates or contributes to groundwater recharge. Drainage is applied mainly in the Llanura, where soil texture is finer and Halosols are more common. There are 1800km of drainage collectors installed [Chambouleyron, 1990].

Forestry does not count to the classical industries present in Mendoza. Natural conditions do not favor the growth of trees and timber is not among the crops historically grown by the developers of Mendozas irrigation system [Chambouleyron, 1990]. It accounts with 178 km² [DEIE, 2001a] for about 5 % of the total cultivated area. Nevertheless, due to the intensive form of cultivation Mendoza contributes to 3 % of total wood production and 43 % of production of poplars and willows in Argentina [SAGPyA, 2007]. The poplar is by far the most important cultivated tree; it covers 95 % of all silvicultural area [Calderon, 2006]. In the period of 1971 to 2001 the forestry plantations almost doubled their extension, indicating a rising importance of this resource. Especially the production of high quality wood is a recent focus [Calderón, 2006]. The growth of trees for biomass harvesting is in a state of research [Bustamante, 2008].

## 1.2 Problems and Vulnerability related to Water Use

"Historically, both growth and progress of the population of Mendoza have been made possible by irrigated agriculture. The expansion of irrigated land has reached a critical stage from both, economical and physical point of view. A wealth of problems has emerged" [Menenti, 1988].

The proceeding quote emphasizes the importance of irrigation for Mendoza and concludes the motivation to create this work. Irrigation and the concerted use of water are more than just a major branch of local business; they are the vital base for all human activity in the zone. But due to contrasting focuses conflicts occur about water use. [Montaña, 2008] concludes the following:

- natural scarcity of water is exacerbated by steady increase of demand and diversification; deficits in the coverage of water supply and sewer networks
- low level in water use efficiency, overall efficiency of between 30 and 40 % in the agriculture, in urban water supply a consume of some 400 l/(d*capt) are reported of which 75 % return as domestic effluents
- deficit in the coordinated management of superficial and subterranean water resources
- notable increase of contamination as well of surface water bodies as of aquifers (due to urban waste disposals, urban and industrial waste waters , hydrocarbons, salinization)
- split institutional competences in water management and lag of public participation
- insufficient credible information and lag of qualified human resources
- lag of incentives for efficient water use in all consumption

[Hernández, 2006a] concludes the main problems of Mendozas water recources as: contamination from petrol industry; salinization of the aquifers by agriculture and sediment deficit problems related to Potrerillos reservoir.

### 1.2.1 Salinization and hydro-saline balance

The productivity of one third of all irrigated land is negatively affected to some degree by salinity [Boyer, 1982]. This number tends to increase as more and more unsuitable land is applied for irrigation and irrigation projects fail due to salt accumulation in the ground [Tanji, 1990].

[Aragüés, 1990] points out that sustainable irrigation systems in arid regions are difficult to maintain as waterborne salt tends to accumulate in the rooting zone. Salt accumulation has negative effects on soil structure e. g. reduced infiltration, poor aeration and poor water retention but also on plant physiology e. g. due to toxic effects of sodium ions. The osmotic component of water potential is linearly proportional to the electric conductivity, e. g. if the

EC in the soil solution increases from 1 dS/m to 3 dS/m, osmotic potential decreases from -300 cm to -1000 cm [Neumann, 1996], or according to [Borg, 2001][1] from -430 to -1100 cm.

A lot of investigation is done to trigger this subject. Monitoring of salinity in groundwater [Hernandez, 2006a], phreatic water [Mirábile, 1997], [Ortíz Maldonado, 2005] and soil [Mirábile, 2003], [Morábito, 2005], [Mastrantonio, 2006] are conducted.

Surface water of 0.3 – 1.8 dS/m deteriorates downstream of Río Mendoza, within a range that does not affect irrigation purposes [Chambouleyron, 1990]. Before entering the irrigation distribution system electric conductivity of the Río Mendoza is less than 1 dS/m [Ortíz Maldonado, 2005] corresponding to roughly 0.3 mg/l NaCl.

Groundwater quality varies considerably, depending on area and depth of exploitation [Chambouleyron, 1990]. 80% of the groundwater cannot be used, because of poor water quality [Querner, 1997], basically because of salinity problems.

### 1.2.2 Excess exploitation of the groundwater

In Mendoza, groundwater is exploited in an area of 5300 km². The level of the water table generally varies between 10 and 30 m. But in large areas, especially under intensive agricultural use, depths are more shallow [Querner, 1997].

Assuming the figures mentioned in section 1.1.5, an irrigational water consumption of 1500 mm/a and a total irrigation efficiency of 40 %, an area of 720 km² could be supplied sustainably with groundwater only[2]; if the groundwater recharge rate stated by [Hernandez, 2006a] is correct of only 400 km². While [Querner, 1997] mentions that 800 km² are irrigated with groundwater only and another 300 km² applies both, ground- and surface water. The numbers given by [Hernandez, 2006a] suggest much higher proportions. In areas with surface water irrigation, there is in principle no need to use supplementary groundwater.

[1] [Borg, 2001] proposes the relation that osmotic potential in centimeters is proportional to salt concentration in grams per liter by factor 760.

[2] Equation is: recharge volume divided by irrigation volume per area multiplied with irrigation efficiency and 20 % usable groundwater.

However, because of the misallocation of surface water, the need for groundwater exists, especially when vegetables are grown [Baars, 1993]

DGI registered in 1994 about 18 200 wells in Mendoza province, of which only 8 900 are in use. The mean discharge of a well is about 50 l/s [Querner, 1997] and its use depends on the water need of the crop according to the farmer's criteria. About three quarters of these wells penetrate the Northern Aquifer [DGI, 1994]. Assuming these figures a mean global extraction rate would be 445 $m^3/s$ although it is not clear if this refers only to irrigation season or if it is an annual mean. In comparison with the value of 50 $m^3/s$ mentioned by [Thomas, 1998] again big uncertainty is revealed. The costs of using groundwater are about 3 to 4 times higher than for surface water and depend on the costs of electricity and the efficiency of the pumping equipment.

### 1.2.3 Oil production and industry

Mendoza accounts for 13 % of the Argentinean oil dwelling and 3 %of natural gas production. In 2002 Mendoza was the province with the fastest growing production rates, with 11 % annual growth [Sivera, 2003]. At the same time it’s a mayor center of refinement and processing of petroleum products and has Argentines biggest refinement complex [Scheimberg, 2007].

Petroleum hydrocarbons (PHC) consist of alkanes, aromatics (BTEX – benzene, toluol, ethylbenzene and xylene) and polycyclic hydrocarbons (PAH) [Cummins, 2001]. BTEX and PAH’s are declared pollutants. BTEX are volatile organic compounds found in petroleum derivatives, they have harmful effects on the central nervous system and benzene is carcinogenic and effects the blood circulation. PAH’s consist of fused aromatics, nautrally they occur in oil, coal and tar deposits. PAH’s are of concern because some compounds have been identified as carcinogenic, mutagenic, and teratogenic. The petroleum deposits in the Mendoza area generally produce heavy oils [Ercoli, 2001], they are a main source of PAH’s.

Due to neglectable natural groundwater recharge rate, the threat for the aquifer is not urgent. Nevertheless this problem may increase if climatic boundary conditions change. Another path of contamination may occur throughout the spatial vicinity of Río Mendoza to the Oil production fields. 28 cases of petroleum contamination were reported between 1996 and 2003 to the Direction of Sanitation and Environment[3].

### 1.2.4 Unmonitored reuse of waste water

In Mendoza wastewater treatment is conducted with stabilization lagoons. They represent an uncontrolled physical-biological treatment method. In the lagoons mainly organic and hygienic contamination is reduced by solar UV-radiation and the activity of heterotrophic organisms. The output discharge is, under regular operation conditions, hygienically safe and rich in nutrients, making it a valuable water source for irrigation purposes [FAO, 1995].

The use of wastewater for agriculture in Mendoza is limited to especially registered areas, the ACRE (Area de Cultivos Restringidos Especiales). The uncontrolled nutrient content causes a main thread for the reuse of pretreated wastewater. It may exceed the actual demand of plants. Especially during the winter, when irrigation water demand is much lower while supply is rather constant throughout the year, a mayor fraction of the irrigation water passes the ground without reduction of nutrient load. Nitrate is of special importance as it is not retarded a lot in the soil and is under certain circumstances toxic for human health In Mendoza elevated concentrations of nitrate were monitored in shallow groundwater layers in the vicinity of the ACRE [Fasciolo, 2006] but no transport to the profound aquifer could be proved.

[Masotta, 1992] did some work on the evolution of soils under irrigation with pretreated waste water in the environment of "Campo Espejo" treatment facility. In an comparison of virgin soil and soils after 5 years of irrigation he found increases of heavy metals (namely Cadmium, Zinc and Lead) and nutrients (total N and total P) that varied considerably between different observation points. The increases could by partly explained with the different soil types occurring. Salinity de- or increased on different

The use of viticultural effluents for irrigation purposes is common practice in Mendoza. These waters have usually high organic charges but may also contain plant treatment

[3] Information from http://www.saneamiento.mendoza.gov.ar (site of the sanitation direction, visited 19.12.2008

products and other substances. The treatment of these effluents is still uncommon [Bloch, 2000] and an impact study of the effects on soil and water recourses not available.

## 1.3 Previous Works

### 1.3.1 State of science in water and mass transport dynamics

[Perry, 2001] describes a similar methodology for water balance modeling to the one applied in this project. He calibrates a hydrologic model for runoff prediction using soil moisture data measured on a roughly biweekly basis.

[Maddock, 1998] proposes a measurement setup that permits the integral registration of the water cycle on basin scale. By coordinated measurement of groundwater, stream flow and near stream soil moisture and a coupling with LIDAR-determined evaporation, each in the process relevant resolution, a closed balance can be set up.

[Kavazanjian, 2006] highlights the problems of unsaturated flow models to represent arid conditions. Under arid conditions and extremely dry top soils he concludes that difficulties in accurately measuring small values of percolation on one side and the inability of unsaturated flow models to accurately predict surface runoff prevent a consistent possibility to calibrate coupled surface – unsaturated zone models. Although flux values predicted using models calibrated solely upon internal soil moisture content data are of questionable reliability, they represent the “lesser of two evils”

### 1.3.2 Projects related to agricultural water use in Mendoza

Literature was reviewed extensively in order to sort the present work into a regional context as well as into the state of science. Especially projects carried out in Mendoza and / or by local institutions were focused. A lot of the relevant works were already mentioned in the preceding two sections thus this chapter aims to give some structural analysis on research focus in Mendoza.

Due to the importance of water management tasks for Mendoza oasis, a widespread range of investigation projects is carried out in the region. Basically themes of agricultural as well as industrial water management practices and related contamination processes were focused. Certain tendencies in the thematic orientation of the investigation projects can be appointed, namely:

- large-scale measurement campaigns rather than localized works
- taking of an inventory rather than process-orientated measurement
- single task projects rather than integrated cycle-orientated approaches

Due to the large extensions of Mendoza's irrigation area, investigation projects often head to give an overview on a present state or the evolution of certain tendencies e. g. [Mirábile, 2003], [Mastrantonio, 2006]. These projects often compare states of a delimited area throughout several years. The two mentioned works compare changes in soil salinity distribution in a period of six or 17 years respectively. But, as working capacities are limited, there are hardly any projects that reach an adequate temporal resolution which allows estimating the dynamics of hydrological processes.

[Morábito, 2004] states the lag of coordinated and systematized measurements of information related to integral determination of water resources and irrigation efficiency. This problem can't be triggered only on a technical level. [Foster, 2005] proposes institutional and administrative measures for integrated groundwater resource conservation in the Mendoza aquifers.

Modeling is still not a common practice in the scientific community engaged in water resource management. Although this field of work is strongly emerging. Some projects have been conducted to represent aquifer [Hernández, 2006b], channel system [Menenti, 1995], irrigated fields [Salomon, 2007], [Mirábile, 2006]. [Querner, 1997] emphasizes the importance of a stronger focus on coupling of different subsystems and integrated projection for the irrigation system of Mendoza and suggests an approach for lower Tunuyán River. [Menenti, 1995] showed in a conclusion the application of different surface runoff models at Mendoza. A conceptual approach to the integral representation of surface flow, unsaturated zone and groundwater is given by [Querner, 2008].

### 1.3.3 Poplars and their interaction with the environment

Poplars are capable to adapt to a broad range of climatic conditions and changing environments [Gilen, 2001]. They are therefore grown for wood and biomass production in Mendoza region, often on sites where other crops appear unsuitable. [Shannon, 1998] mentions the capability of some poplar clones to cope with conditions of elevated salinity, he states that some hybrid poplars are able to cope with salinities as high as 14 g/l NaCl, corresponding to a conductivity of more than 50 dS/m. This additionally raises the value of this crop for Mendoza area, e.g. on halosol-sites or for drainage- and wastewater recycling. In contrast [Neumann, 1996] describes poplars as more sensitive to elevated salinity than other irrigated tree species but also variability of salt resistance is high, values between 1 – 5 dS/m are mentioned, to compare for eucalyptus resistance range is 10 – 25 dS/m.

Water demand of poplars is elevated. Some figures are given in section 2.2.7 below. Compared with the listing given in [Chambouleyron, 1991] they belong to the crops with the highest water demand in Mendoza. [Neumann, 1996] names poplars as silvicultural crop with the highest potential water demand. In the context of Phytoremediation poplars are called "solar pumps" for their high capacity of water suction from the phreatic water table

The combination of elevated irrigation volumes and high salinity potential of as well of the irrigation water as of the plant site indicate the risk of poplar plantations for groundwater salinization. Due to badly managed irrigation schemes or leaching at these plantations, salt is washed into the soil zone below capillary rise. Possible consequences are an elevation of the water table and following salinization of the surface or constant salt washout into the aquifer.

Roots functionally transmit water from the soil to the metabolically active parts of the plant. [Thomas, 2008] shows the importance of transpiration rate for the water balance of soils. He compares soil water dynamics between a hedgerow and surrounding bare areas and reveals that water dynamics differ importantly as well temporally as spatially. Under the hedges he generally finds more amplitude in total water consumption and a less pronounced reduction of amplitude with depth.

[Mulia, 2005] found that poplar roots are highly sensitive for heterogeneous environmental conditions. In his research, conducted in southern France, he found that regularly root distribution decreased with depth and distance from the stem but in situations of growth concurrence by intercrops or unfavorable soil conditions in the upper layer, root distribution was reverted. [Tschaplinski, 1998] shows that higher seasonal irrigation volumes have a slight effect on denser root distribution and considerable effect on lower root to stem weight ratios. These two factors indicate that, while root growth is weakly effected by different irrigation regimes, stems show more growth when watered more intensely. Conductance tests indicate that water uptake of poplar roots is strongly reduced under flooded soil conditions [Pregitzer, 1996]. Distribution and performance of poplars roots were so far not in the focus of research in the Mendoza region. Hence only scarce information is available about root distribution and water uptake at root level. [Riu, 1993] captured this relation conceptually by level-wise determining water storage change in the soil.

[Li, 2006] states that straightforward coupling of water uptake to root distribution, as realized by the SiWaPro implemented [Feddes, 1978] model, does not reproduce adequately, processes especially in dry periods. Upper soil layers are densely rooted and they dry fastest, hence in these drought periods water uptake is realized more intense by lower roots. [Hopmans, 1998] presents a tool for the coupled modeling of soil water and root dynamics. He concludes that integrated parameter estimation for the water movement in soil and uptake by roots as well as root growth corresponds basically to a gray box approach of model calibration. At the actual state of knowledge spatial resolution of data acquisition and measurement of fine root water flow are the bottleneck for enhanced system understanding.

It is worth mentioning that root dynamics and root water uptake modeling is carried out at the moment on three different spatial scales: plant e.g. [Tschaplinski, 1998], [Durso, 2004] site [Abrahamson, 2005], [Verstraeten, 2005] and regional to global scale [Kalma, 1999]. [Feddes, 2001] points out the problems in scale transition and [Li, 2006] confirms that modeling results o different spatial levels are often not consistent. It is thus valuable to compare modeling results on different scales in order to enhance system comprehension.

## 1.4 Model Description

The mathematical model behind SiWaPro [Kemmesies 1999] is based on the computational core used in SWMS 2D [Šimunek 1994]. The model core was developed to simulate water and solute movement in variably saturated media. The software consists of the SiWaPro computer program, a graphical - and a database interface, soil, climate and contaminant databases, a weather generator and subroutines for the estimation of hydraulic and mass transport parameters. The SiWaPro program numerically solves the Richards equation for variably-saturated water flow and the convection-dispersion type equations for solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. Hysteresis can be represented by a scaling parameter. Adsorption and decomposition may be considered as substance transformation processes.

Main parts of this section refer to SiWaPro [Blankenburg, 2008] and SWMS 2D [Šimunek 1994] and HYDRUS-2D [Šimunek 1999] handbooks in their most recent available version.

### 1.4.1 Physical base of flow and mass transport

SiWaPro computes water and mass transport physically based. Elementary laws of dynamics and mass conservation are combined in Richards Equation in order to flow in porous media. Convection-Dispersion-Equation (CDE) computes mass transport process but is equally apt to describe heat transport in the ground.

**Description of flow in porous media**

Flow conditions of fluids in partly saturated media can be described by combining the fundamental law of dynamics with the corresponding balance equation. Governing forces for the flow in porous media are gravity, pressure and friction. Darcy's Law (F. 2) concludes the balance of forces as given in F. 1. Friction, viscosity and density are concluded in a material specific constant- the coefficient of permeability of saturated conductivity k.

$$\frac{\partial p}{\partial x} + \rho g \frac{\partial x}{\partial z} + C_x \eta v_x = 0 \qquad \text{F. 1}$$

$$\text{with:} \quad k_x = \frac{\rho g}{C_x \eta}$$

$$\text{follows:} \ v_x = k_x \left( \frac{1}{\rho g} \frac{\partial p}{\partial x} + \frac{\partial z}{\partial x} \right) \qquad \text{F. 2}$$

with:

| | |
|---|---|
| $p$ | pressure [M/L²] |
| $x$ | coordinate of direction [L] |
| $\rho$ | density of the fluid [M/L³] |
| $g$ | acceleration of gravity [L/T²] |
| $z$ | coordinate of direction of gravity [L] |
| $C_x$ | coefficient of friction [1/M²] |
| $\eta$ | dynamic viscosity [M²/LT] |
| $v_x$ | velocity of flow in direction of x [L/T] |
| $k_x$ | coefficient of permeability in direction of x [L/T] |

Mass balance continuity for the observation volume is an expression of the law of mass conservation. It states that water content of the volume is completely defined by in- and outflow to the volume, storage change within the volume and sinks and sources.

**Flow under unsaturated conditions**

$$\frac{\partial}{\partial x_i}\left(k(h)\cdot\left(K_{ij}\frac{\partial h}{\partial x_j}+K_{iz}\right)\right)=\frac{\partial\theta}{\partial t}-w_0 \qquad \text{F. 3}$$

with:

| | |
|---|---|
| $x_i$ | coordinate of direction (indexes i and j represent directions of a transformed cartesian coordinate system [L] |
| $k(h)$ | unsaturated hydraulic conductivity (function of pressure head) [L/T] |
| $K_{ij}$ | components of a dimensionless anisotropy tensor [-] |
| $h$ | water pressure / suction head [L] |
| $\theta$ | water content [-] |
| $t$ | variable in time [T] |
| $w_0$ | source/sink term [$L^3$] |

The central equation of the flow model combines the two terms of water flow and mass balance; it describes unsaturated water flow in the unsaturated zone. F. 3 displays Richards Equation in its two dimensional formulation. The equation represents unsaturated and saturated flow using the assumptions that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected. For planar horizontal flow conditions indexes i and j can be replaced by x and z.

The unsaturated soil hydraulic properties, $\theta$(h) and K(h), (compare F. 3) are nonlinear functions of the pressure head. SiWaPro applies the physically based approach of [Luckner, 1989] for the empirical relation found by [van Genuchten, 1980].

$$\theta_b=\theta_r+\frac{\phi-\theta_s-\theta_r}{(1+(\alpha * p_c)^n)} \quad \text{if } p_c>0$$
$$\theta_b=\phi-\theta_r \quad \text{if } p_c\le 0 \qquad \text{F. 4}$$

with:

| | |
|---|---|
| $\theta_b$ | actual water content [$L^3/L^3$] |
| $\theta_s$ | saturated water content [$L^3/L^3$] |
| $\theta_r$ | residual water content [$L^3/L^3$] |
| $\phi$ | porosity [$L^3/L^3$] |
| $\alpha$ | scaling parameter [-] |
| $n$ | increase parameter [-] |
| $p_c$ | capillary pressure head [$M/L^2$] |

$\theta_r$ is the residual water content of the wetted phase under different courses of soil dehydration. In contrary $\theta_s$ is the saturated water content, which describes the volumetric water fraction if all pores are filled. Scaling parameter $\alpha$ represents the magnitude of order if the water pressure at the inflection point of the retention curve; it is thus adapting capillary pressure of equation F. 4. Increase parameter n describes the increment of the retention curve at the inflection point. It can be interpreted as a measure for the homogeneity of soil grain size distribution and is therefore largely independent from phases and hysteresis.

Relative saturation (F. 5) is introduced as a normalized measure of water content. It describes the ratio of actual- to saturated wc. Relative saturation can occupy values between zero and one, corresponding to 0 – 100 % disposable mobile water.

$$S_e = \frac{\theta_e - \theta_r}{\theta_s - \theta_r} \qquad \text{F. 5}$$

with: $S_e$ relative saturation

Permeability is dependent on the water content. For saturated permeability as characteristic parameter it is supposed that all pores are water filled. In the case of partial saturation only a part of the pores bear water. The pores with the biggest diameter are the ones that show highest flow velocity and drain fastest. Hence with increasing dehydration, the flow active surface (as sum of water filled pore surfaces) and mean flow velocity (as integral average of velocities in the water filled pores) diminish. Accounting for both factors in the law of mass conservation discharge decreases non-linearly.

Fig. 7 shows the relation between relative saturation, relative permeability and water content. Relative permeability expresses the ratio of actual to saturated permeability. Saturation is directly proportional to water content conduct (compare F. 5). For low saturation values relative permeability increases slowly but monotonously. Strongest increase occurs for saturation values higher than 80 %. Vice versa for the initial drying phase conductivity lowers fast. For the example given in the figure below, at 80 % saturation permeability is only 40 % of the potential value, for 60 % as low as 15 %. It is thus crucial to consider soil moisture condition when computing water movement under unsaturated conditions.

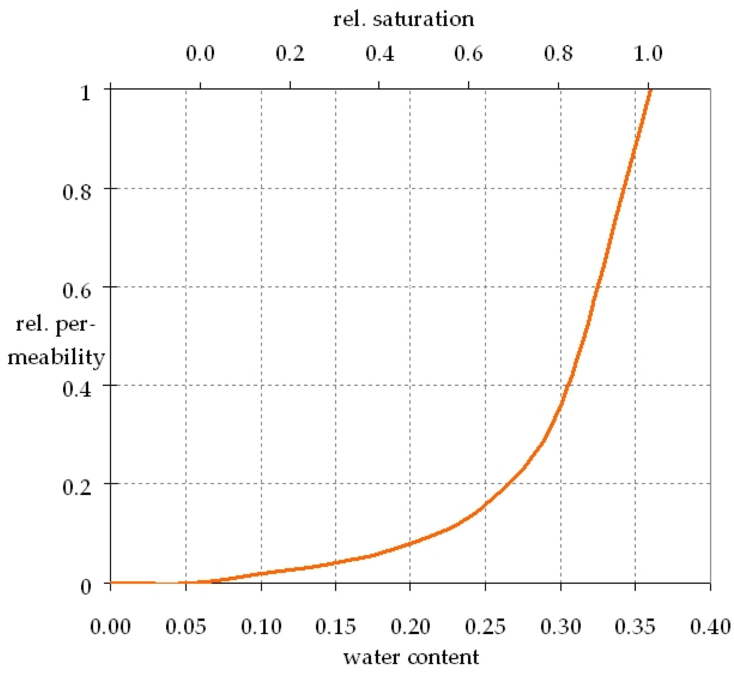


**Fig. 7 Water content, relative saturation and relative permeability for a model loam**

A physically based relation between permeability and saturation was defined by [Mualem, 1976] and adapted by [Luckner, 1989]. Its formulation is given in F. 6.

$$k(\theta_e) = k_0 * S_e^{\lambda} * \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad \text{F. 6}$$

with: λ tortuosity parameter [-]

m transformation parameter [-]

Tortuosity describes the "windiness" of a pore geometry. Parameter $\lambda$ is the product of a pore connectivity determinant and a tortuosity factor. [Mualem, 1976] defines no limits of range for lambda but recommends a value of 0.5 as default. [Nielsen, 1992] showed that physically reasonable ranges of the parameter are $0 < \lambda \leq 1$. [Schaap, 2000a] found that best fits were achieved for values $\lambda \leq 0$. Transformation parameter m is an empirical material constant. [van Genuchten, 1980] showed that numerical integration of the retention function is possible if $m = 1 - (1/n)$ and $0 < m \leq 1$. But a functional connection between m and n can not be proven [Nielsen, 1992]. [Blankenburg, 2008] recommends values of $0.1 < m \leq 1$ and to consider the parameter as free.

The water flow component of the model considers prescribed head (first type) and flux (second type) and combined (third type) boundary conditions, boundaries controlled by atmospheric conditions, free and determined as well as groundwater tables below model limits.

### Estimation of soil hydraulic parameters

SiWaPro comes with two tools that allow an appraisal of soil hydraulic parameters. DIN 4220 of the German Institute for Standardization [DIN 4220, 2007] gives single value estimates based on texture class properties. Some of the values given are not physically consistent e.g. clayish soils are supposed to have no residual water content although the soil score generally with values of more than 10 % for this parameter. The second method implemented is a pedotransfer function (PTF) developed by [Vereecken, 1989]. PTFs are used to estimate soil parameters from properties that are measured easily. In the given case Vereecken investigated 40 Belgian soils from 182 undisturbed samples. Soil hydraulic properties were correlated to texture properties (clay and sand content), organic content and bulk density. Regressive equations are used to relate the soil parameters to Van Genuchten Parameters. As a special restriction the transformation parameter is defined with the value one.

### Plant water uptake

The sink term $w_0$ in F. 3 describes a volume of water removed in a unit of time from a unit of soil. It may be interpreted as water uptake by plants. In the model equation $w_0$ is represented by a water stress function [Feddes, 1978].

$$w_0(h) = a(h) * w_P \qquad \text{F. 7}$$

with:

| | | |
|---|---|---|
| with: | $w_0(h)$ | water uptake rate (function of pressure head) [$L^3/T$] |
| | $a(h)$ | uptake scaling parameter (function of pressure head) [-] |
| | $w_P$ | potential water uptake rate |

$a(h)$ is a dimensionless function that occupies values between $0 < a(h) < 1$. It is defined by four pressure heads.

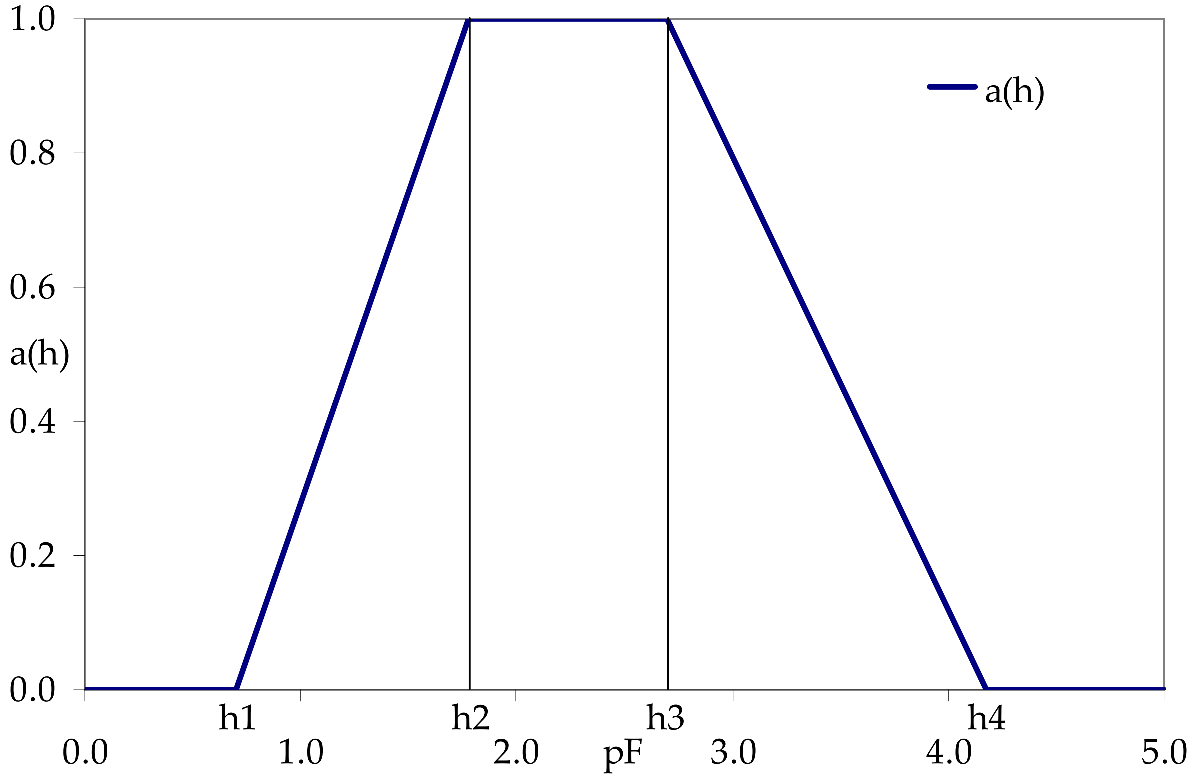


**Fig. 8 Course of the water uptake scaling function a(h), estimate for poplars**

Fig. 8 displays the course of water uptake scaling function. On the x-axis the values occupied by a(h) are given, while the y-axis represents the negative common logarithm of water pressure (pF-value). The four pressure heads labelled in the diagram define the course of a(h). At h1 water uptake by the plant begins, in the example at a pF value of 0.7, corresponding to a pressure head of -5 cm, for pressures higher than h1 an anaerobiosis point is surpassed and no water uptake is assumed. Between pressure values h2 and h3 optimum water supply is assumed and actual water uptake equals the potential value, in the diagraph this range lies between -60 cm and -500 cm water pressure. h4 characterizes the permanent wilting point (PWP) at which root water take-up diminishes to zero.

$$w_P = b(x,z) * L_S T_P \qquad \text{F. 8}$$

with: b(x,z) water uptake distribution function [-]

$L_s$ transpiration active surface width

$T_P$ potential transpiration rate [L/T]

Equation F. 8 represents the distribution of roots in the soil zone. The water uptake distribution function can be interpreted as a weighting factor that defines the spatial variation of $w_P$ over the root zone. The transpiration active surface expresses what extension of the soil surface contributes to the transpiration process. Accordingly the potential transpiration rate expresses the metabolic water output of plant as a flux normalized over the cultivated surface.

### Mass transport description

The program uses Convection-Dispersion-Equation to compute mass transport processes. F. 9 gives the equation for the two dimensional case under the same conventions of direction as in F. 3. The joint consideration of mobile and immobile phase is only feasible for the assumption that concentrations in both phases are related linearly.

$$\frac{\partial s_m}{\partial t} = \frac{\partial}{\partial x_i}(\theta D_{ij}\frac{\partial c}{\partial x_i}) - \frac{\partial q_i c}{\partial x_i} + \mu_m s_m + \gamma_w \theta + \gamma_s \rho - c_w w_0 \qquad \text{F. 9}$$

with:

| | | |
|---|---|---|
| | $s_m$ | substance mass (combining mobile and immobile phase) |
| | $D_{ij}$ | dispersion coefficient tensor [$L^2/T$] |
| | $c$ | concentration in the mobile phase [$M/L^3$] |
| | $q_i$ | water flux towards i (normalized by volume) [M/L] |
| | $\mu_m$ | first order decomposition constant (mobile and immobile) [1/T] |
| | $\gamma_w$ | zeroth order decomposition constant for mobile phase [$M/L^3T$] |
| | $\gamma_s$ | zeroth order decomposition constant for immobile phase [1/T] |
| | $\rho$ | solid phase bulk density [$M/L^3$] |
| | $c_w$ | source / sink concentration [$M/L^3$] |

Equation F. 9 can be solved if water content and flux through the volume are known. Both values are computed by Richardson Equation as given in F. 3.

Mass transport parameters are user specified. A data base of currently more than 100 substances is incorporated. Transport parameters of dispersion, decomposition and adsorption are estimated based on organic content, soil pH and clay content.

### 1.4.2 Numerical solution of the governing equations

Flow and transport equations are solved numerically using Galerkin-type linear finite element schemes. The observation area (2D case) is discretized into an irregular triangular network. The corner points of the adjacent triangles serve as nodal points for the computations.

#### Discretization

For each nodal point the dependent variables of the governing equations F. 3 and F. 9 are approximated by a finite series of linear basis functions. They are required to meet the condition of a minimum deviation between linearized and exact solution. The linear approaches are introduced into the governing equations and integrated over all elements and boundaries of the observation area. This leads to a system of ordinary differential equations. The solution for the triangular elements is realized by a weighting of permeability and storage volume over the corner nodes.

Temporal derivates are represented by finite time differences. For water dynamics modeling an implicit scheme is used for the solution under saturated and unsaturated conditions. That means that the solution of the previous time step is used to solve the equation of the actual one. Initial conditions feed the first time step. For mass transport computation the scheme can be defined by a time weighting factor that allows solutions to by completely explicit, implicit or of any weighted scheme in between (e.g. Crank-Nicholson that accounts explicit and implicit solution with same weights).

#### Solution strategies

The non-linear equations that evolve from the combination of spatial and temporal discretization matrices are solved by iteration. The boundary conditions for every time step allow determining the variables matrix values by Gaussian Elimination, where values from the previous iteration loop are used to calculate variables of the actual one. If the difference of the calculated pressure heads of two subsequent time steps falls below a predefined threshold, the result is accepted. The initial estimate of the actual time step is estimated by an extrapolation from the two previous steps. Besides from iteration threshold mass balance is controlled for every time step. Time step control is managed dynamically where numerical stability, dates of changing boundary conditions and output dates are considered. Numerical stability is ensured by adapting time step length to the iteration process of the previous time step. If the number of iterations surpasses a predefined value, time step length is lowered by a predefined factor smaller than one. If the number of iterations is smaller than a predefined number, time step length is raised by a predefined factor. If the number of iterative loops surpasses a predefined maximum number, computation is interrupted and continued in the following time step, an error is reported to the operator. For mass transport computation the solved matrix of water transport is inserted into the mass transport term (compare F. 9 and corresponding explanation) resulting in a set of linear equations. Depending on the solution scheme (see above) the equation has to be solved for the actual, previous or both time steps. Upstream weighting is included in order to minimize numerical oscillation, for further explanation compare [Yeh, 1990]. Peclet numer and courant number are included for the control of numeric stability. Courant numbers are communicated program-internally for the control of time step lengths.

### 1.4.3 Input data

SiWaPro requires basically a geometrically defined section of the underground that allows delimiting influences from the surrounding. Soil information is used to describe the water and mass transport properties. Hydrological boundary conditions drive the model computation, with climatic influence being usually the upper condition and groundwater table determining the lower limit. Mass transport properties are regarded and the temporal variation of mass sources is taken into account. Optionally source and sink terms, e. g. plant consumption may be defined.

As climatic data time series of precipitation, evaporation and eventually transpiration are used. If this data is not available, time series may be generated with a weather generator. For agricultural drainage cases time series of drainage rates may be defined. Groundwater table may be considered statically or as a series of time.

For the water uptake by plants root distribution and distributed water consumption are included.

Resolution of input data may be chosen freely, typical values range from meters to kilometers in space and minutes to years in time. The operator should keep in mind that the resolution of input data delimits model purposes. Temporal and spatial resolution should correspond to the velocity of the processes represented.

### 1.4.4 Limits and possibilities

Spatial and temporal resolution may be defined freely. Time steps are managed adaptively by the program within defined limits. The finite element discretization allows distributing model resolution heterogeneously, sections of high dynamics or special interest may be considered more exactly.

SiWaPro model allows representing heterogeneous soil conditions. Soil properties may be defined section-wise or layer-wise. In the same way anisotropy is considered Due to the finite element structure different soil properties may be taken into account in the spatial resolution as well, e.g. soils of higher transport dynamics can be represented with higher discretization.

The program includes a routine for inverse parameter optimization. Starting from an initial estimation of soil hydraulic parameters and observed values of water or mass flux at model boundaries; pressure head or water content at defined points of the model or specific mass content at a defined point of time.

A weather generator is included into the program. Based on a internal database of German CSs it is possible to generate series of climate data for any point situated within the extensions of the database stations. The series are based on the interpolated statistical values of the CSs.

Often there is a lag of mass transport parameters measured for the investigation site. These parameters are laborious to determine or samples for the experimental determination are not available. To solve this gap SiWaPro comes with a data base of mass transport properties. More than 90 organic and 10 inorganic substances are integrated and PTFs allow considering site specific soil conditions.

# 2 MATERIAL AND METHODS

The section gives a short overview on the site where the investigation project was carried out. A measurement campaign was conducted in June 2008 and the analyses undertaken are concluded. Data that was available or acquired is characterized and analyzing methods are presented. The data was used for the development and setup of a computer model. Calibration and validation were conducted and on their base a method for model quality evaluation is proposed. The calibrated water dynamics model serves as foundation for the development of scenarios on mass transport.

## 2.1 Investigated site


**Fig. 9 Satellite image of the investigated site (from: google earth virtual globe program)**

The area that was chosen for the survey is situated at La Libertad, Rivadavia Department of Mendoza, about 60 km from the capital. In an investigation of Universidad Nacional de Cuyo, Faculty of Agricultural Sciences poplars were planted at the site. The project triggered the relation between irrigation frequency and wood production of the trees.

### 2.1.1 Environmental Conditions at the site

The investigated site is situated at the former Instituto Forestal Nacional (National Forest Institute) that belongs now to the INTA (Instituto Nacional de Tecnología Agropecuaria). The site itself is abandoned and neighbouring parcels are vineyards and mixed tree stands (Fig. 9). The surface is flat with a slight decline in north-western direction towards Río Tunuyán.

**Soil and Underground**

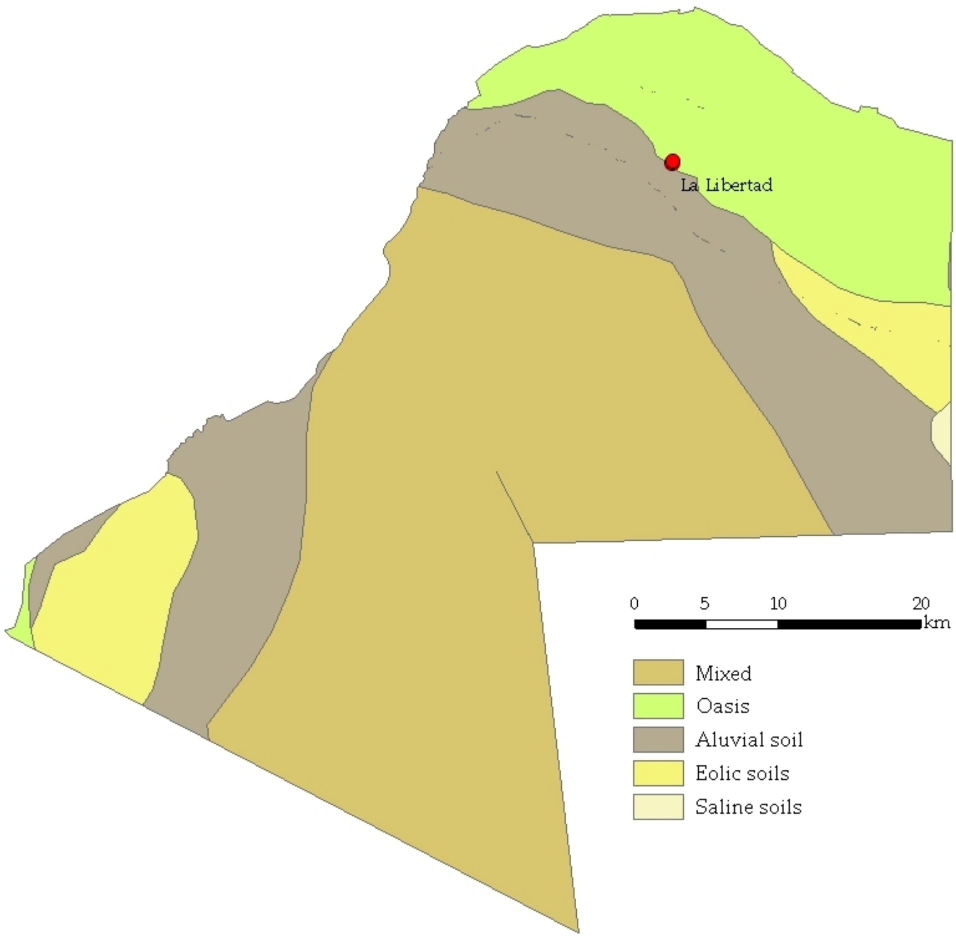


**Fig. 10 Map of soils according to soil genesis in the department of Rivadavia [MdR; 2008]**

The department of Rivadavia is situated partly on a quaternary alluvial fan and partly in the downstream alluvial plain. Both cover a postglacial fluvio-lacustrine plain that is exposed in some parts [Abraham, 1999].

Great pedologic groups occurring are Torripsaments, Torrifluvents and Torriortents, all three belong to the entisol group Entisols are defined as soils that do not show any profile development more than an A horizon. An Entisol has no diagnostic horizons, and most are basically unaltered from their parent material. Although no horizons are determinable, sedimented soils may well show stratification, due to different deposition periods. [Torre, 2006] mentions those groups as typical for the arid Chaco region.

The soils that are irrigated in the area are mainly alluvial. They are heterogeneous and show different texture layers. Eolic soils are also fertile but lag organic matter and nitrogen [Chambouleyron, 1990] and often have a very fine texture. The ground at the site is within an alluvial zone at the boundary of an extended irrigation region (Fig. 10). Soils typically have relatively high pH values between 7.2 and 8.5 and organic matter contents of less than 1 % [Chambouleyron, 2002].

The soil at the site was characterized as sandy loam; measured sedimentation volumes indicated small heterogeneity. Permanent wilting point and field capacity indicate sandy loam as well although available water content is with about 11 % more in the range of sand. Bulk density is medium and soil salinity low.

**Tab. 1 Soil properties at La Libertad**

| SV [ml/g] | fc [%] | pwp [%] | $D_B$ [g/cm³] | $EC_e$ [dS/m] |
|---|---|---|---|---|
| 0.85 | 16 - 19.5 | 6 - 8 | 1.5 | 1.56 |

La Libertad lies in a zone where the groundwater level is 2.5 m or more meters below surface (state of 2002) [DGI, 2003]. Local workers from former Estación Forestal Nacional stated that groundwater was not reachable for the tree roots and irrigation is vivid for the parkscape with a mature mixed tree population.

## Climate and Vegetation

Climate basically matches the conditions described for the Llanura in section 1.1.2. The site has naturally arid climate although oasis effect is likely to occur over irrigated surfaces. [Riu, 2003] gives the values concluded in Tab. 2. It is mentioned that rainfall is concentrated in the period November to March.

**Tab. 2 Climate characteristics at La Libertad**

| Tm [°C] | Tmin [°C] | Tmax [°C] | rh [%] | u [m/s] | P [mm/a] |
|---|---|---|---|---|---|
| 15.8 | 32.1 | 1.2 | 60 | 1.67 | 204 |

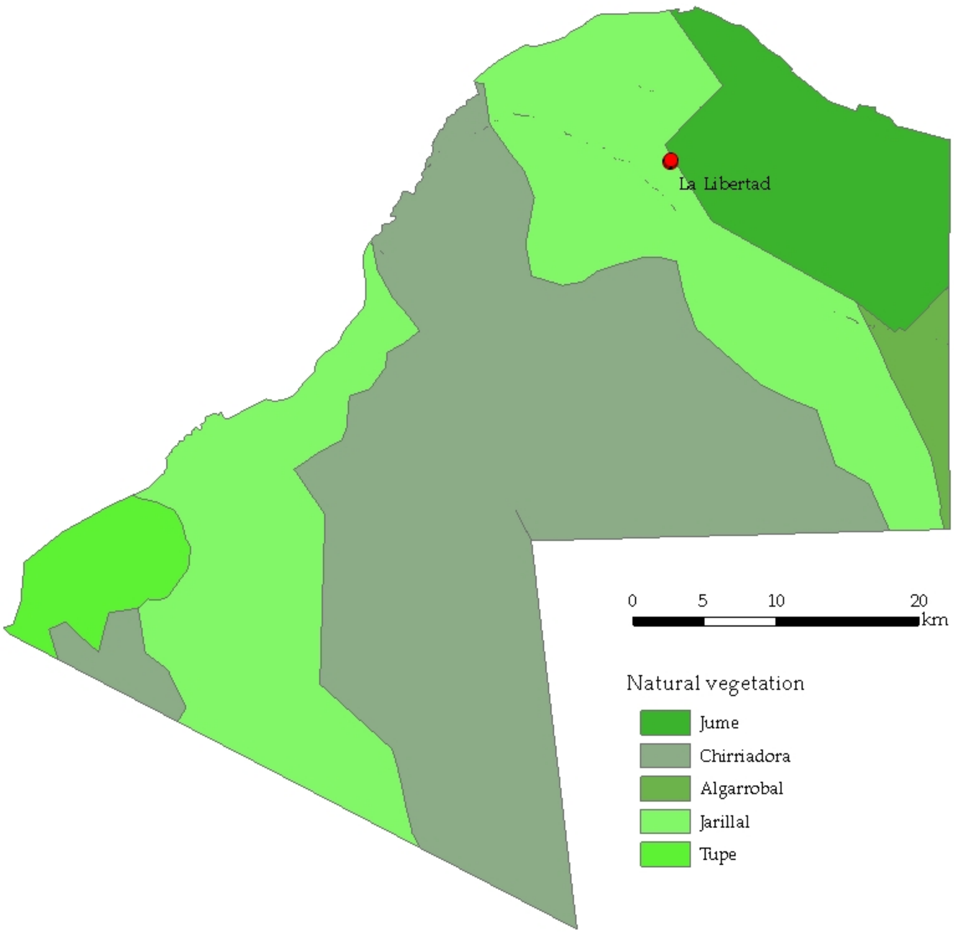


**Fig. 11 Natural vegetation in the surrounding of the investigated site**

The natural vegetation in Rivadavia department consists of xerophytic plant communities and belongs to the Monte ecoregion. [Roig, 1999] mentions the presence of psilophytic and halophytic plant communities, a finding that is supported by the presence of saline soils in the region (see above). The Jarillal is a community of shrub plants (Larrea speciemen) of low biodiversity. In more humid zones it passes into the Algarrobal community a pre-form of dry forests, dominated by Prosopsis specimen [Roig, 1972].

## 2.2 Situation and Data at the site

### 2.2.1 Previous projects

From 1986 – 1997 the site was used for a research project on irrigation schemes and plant growth of irrigated poplars (Populus x Euroamericana). As part of the project extensive determinations of soil water content were accomplished. It was measured with the gravimetric method directly before and two days after each irrigation application. Four diagnostic layers: 0 – 30 cm, 30 – 60 cm, 60 – 90 cm and 90 – 150 cm were considered, that were suspected to contain root biomass. Climate data, including evaporation was measured daily.

Soil (see above) and irrigation water were characterized according to agricultural needs at the beginning of the poplar project. In 2008 a revision of soil properties was executed with spatially referenced sample taking and special focus on water retention properties.

**Configuration of the site**

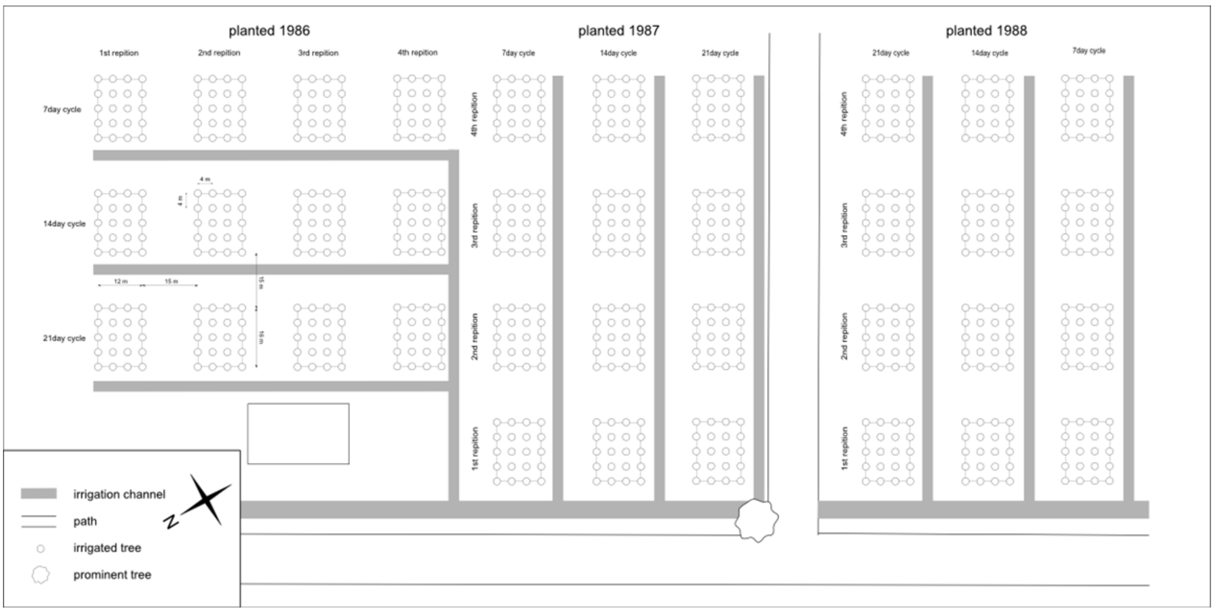


**Fig. 12 Schematization of the investigated site during irrigation – plant growth project**

The distribution of irrigation parcels is seen in Fig. 12. Roughly from north to south the different plantation years are arranged. There are three irrigation regimes for each year and four statistical repetitions for each regime. The site comprises a total of nine different configurations with four repetitions each.

### Irrigation

Water was applied by basin irrigation. The parcels were levelled before the investigation started and channels were impermeabilized, so that neither uncontrolled losses nor sources should occur. The irrigation depth was described [Riu, 2004] as "until field capacity within the diagnostic layer", which would correspond to approximately 150 mm if soil was previously at wilting point. One of the field hands, who was in charge of irrigation at the site stated that about 100 – 150 mm of water were applied. It consisted basically of surface water from lower Río Tunuyán section and was only in cases of shortage supplemented by conveyed groundwater. Surface water of this section shows salinity values of about 1.2 dS/m or 0.57 mg/l NaCl, while groundwater accounts for values about 1.7 dS/m (0.95 mg/l) [Mirábile, 2003]

## 2.2.2 Sample taking

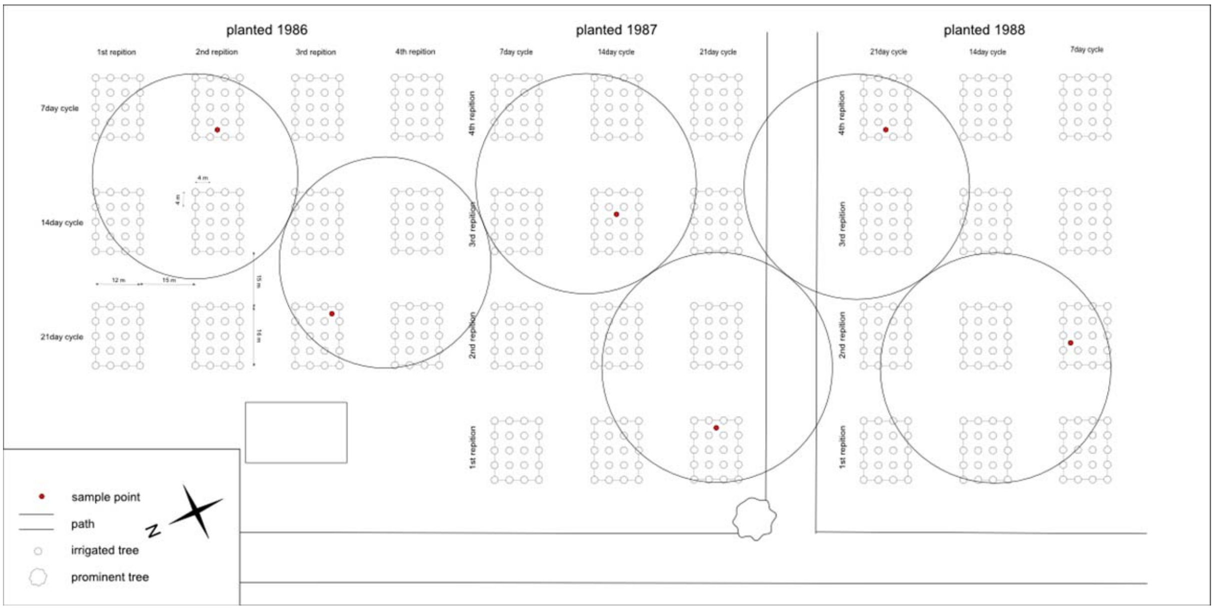


**Fig. 13 Distribution of sample points at the site**

On July 23rd 2008 soil samples were taken at the former plantation site. Physical and chemical soil parameters were determined from the samples. Furthermore they were deployed to determine water- and mass transport characteristics in the soil zone. During the campaign, sample points and site geometry were geo-referenced, using a GPS handheld.

The distribution of the sample points was optimized graphically with the objectives of reaching a homogeneous distance between the points and a maximum coverage of site by adjacent circles (Fig. 13).

The derived points were displaced within a radius of 15 m, in order to reach a maximum variation of the plant configuration. By that the six sample points could be reallocated that represent each plantation year and irrigation cycle with two points (Fig. 14).

At each point samples were taken at 15 cm, 45 cm, 75 cm and 120 cm below soil surface, corresponding to the observation horizons mentioned above. In the following, denotation refers to sample point with the first count and depth with the second count, e.g. soil 5.2 is the sample taken from the 21d irrigation cycle parcel of the 1986 planted part at 45 cm below surface.

| plantation year →<br>irrigation cycle↓ | 1986 | 1987 | 1988 |
|---|---|---|---|
| 7d | MP 6 | | MP 2 |
| 14d | | MP 4 | MP 1 |
| 21d | MP 5 | MP 3 | |

**Fig. 14 Configuration of sample points (MP = measurement point)**

### 2.2.3 Available Data

As mentioned above, the project can be seen in continuation of the works done by the Faculty of Agrarian Sciences, Universidad Nacional de Cuyo [Riu, 1993], [Riu, 2004] and others. Hence great parts of the data obtained in these studies could be used.

Soil moisture data was measured directly before and two days after each irrigation donation. Relative humidity was measured from soil samples with a gravimetric method as proposed by [ISO 11461, 2001]. Values are available from four depths. Potential evaporation was detected from a Class A evaporation pan and precipitation with a gauge. Both values were registered with daily resolution. Plants actual transpiration was calculated from evaporation data and soil humidity dynamics with a resolution with Grassi method (F. 15, below) of each irrigation cycle and normalized in 15-day periods.

Estimates for irrigation volumes were available concluding the fact that it was irrigated until field capacity in the diagnostic layer [Riu, 2003]. The local workers that were responsible for the application of irrigation water estimated that irrigation depths reached 100-150 mm. Irrigation water was analyzed before the plant growth project began.

Evaporation, Transpiration and Precipitation are direct climatic boundary conditions of SiWaPro program. Resolution requirements should match process dynamics. They determine possible modeling purposes. For the present work a consistent set of climate and plant data was elaborated, applying competition and regionalization strategies. The climate data for the climate stations (CSs) was delivered by Servicio Meteorológico Nacional (SMN, Argentine National Meteorological Service) and cover the period 01.01.1990 until 31.10.2007.

### 2.2.4 Preprocessing

The data from the investigation site was on hand in written form. It was digitized partly using optical character recognition and partly by manual transcription. During this process data was verified using the plausibility ranges given in Tab. 3

**Tab. 3 Plausibility ranges of measured parameters**

| Parameter | Minimum range | Maximum range |
|---|---|---|
| Evaporation [mm/d] | 0 | 30 |
| Wind Speed [m/s] | 0 | - |
| Sunshine duration [h] | 0 | 18 |
| Mean Temperature [°C] | -30 | 60 |
| Precipitation [mm/d] | 0 | - |
| Relative air humidity [%] | 0 | 100 |
| Relative soil humidity [%] | 0 | 50 |

Climate data that ranged out of these values was completed with data from neighboring CSs (see below). Soil moisture dates were not considered if values exceeded the limits.

### 2.2.5 Completion and Regionalization of climate data

Climate data was available from three principle sources. During the irrigation period, pan evaporation and precipitation were measured directly on site. Information from four CSs was used to calculate evaporation. Additionally reference pan evaporation was measured at the CS at Agricultural Sciences Faculty in Chacras de Coria. The variables from the CSs were applied to validate the data and to fill the gaps. Fig. 15 shows the position of the CSs in relation to the investigation site.

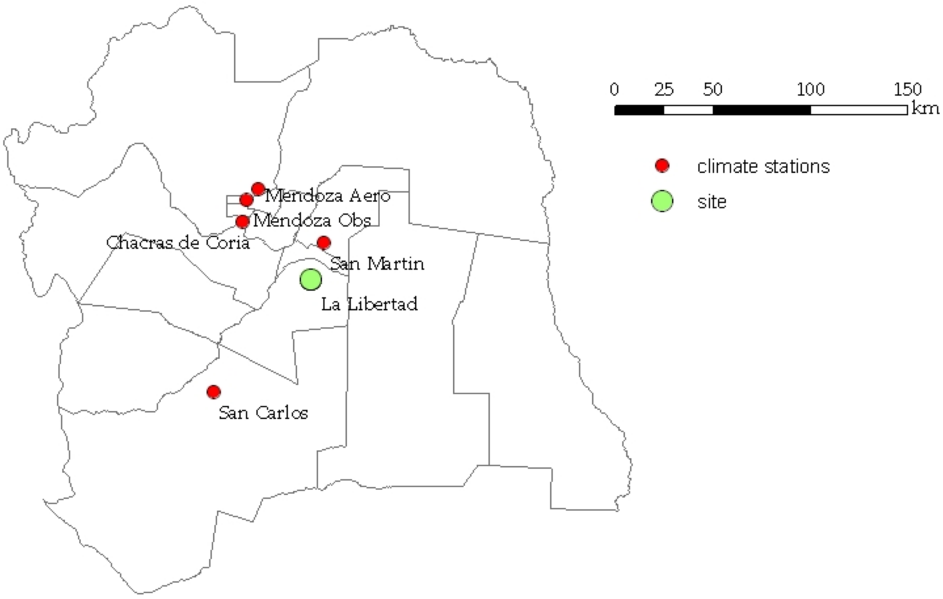


**Fig. 15 Position of climate stations and investigation site in the northern part of Mendoza province**

Data of the CSs at Mendoza airport (Mendoza Aero), Mendoza Observatory (Mendoza Obs), Chacras de Coria and San Martin was available. The properties of the CSs are displayed in Tab. 4.

**Tab. 4 Properties of the climate stations considered for Evaporation calculation**

| Name | Altitude [m asl] | Dist. from site [km] | Characteristics |
|---|---|---|---|
| Mendoza Aero | 704 | 53.5 | semiarid, wasteland, plain |
| Mendoza Obs | 827 | 52.7 | irrigated, park, hilly |
| Chacras de Coria | 921 | 43.8 | irrigated, cultivated / park, plain |
| San Martin | 653 | 17.7 | irrigated, cultivated, plain |

Penman-Monteith (PM) equation was used to calculate potential evaporation. The equation takes into account latitude, sunshine duration, mean daily air temperature, relative humidity and wind speed at 2 m height as input data. Data gaps in the input data were closed using a best regression model (see below). Correlation between the stations time series was calculated and a linear regression for the best correlated series applied.

For PM equation various forms were developed, contributing to different levels of available input data and purpose of application [Howell, 2004]. Comparatively the FAO form [Allen, 1998] (F. 10) and the form proposed by [Jensen, 1990] (F. 11) were computed with daily resolution.

$$ETP = \frac{0.408 s R_n + y \frac{900}{T} u_2 (e_s - e_a)}{s + y(1 + 0.34 u_2)} \qquad \text{F. 10}$$

$$ETP = \frac{s R_n + 90 y u_2 \frac{e_s}{T} (1 - rH)}{s + y(1 + 0.34 u_2)} \qquad \text{F. 11}$$

| | | |
|---|---|---|
| with: | ETP | potential evapotranspiration |
| | s | slope vapour pressure curve [kPa $K^1$] |
| | $R_n$ | net radiation at the crop surface [$mm^{-2}$ $day^{-1}$] |
| | $\gamma$ | psychrometric constant [kPa $K^1$] |
| | T | mean daily air temperature at 2 m height [K] |
| | $u_2$ | wind speed at 2 m height [m $s^{-1}$] |
| | $e_s$ | saturation vapour pressure [kPa] |
| | $e_a$ | actual vapour pressure [kPa] |
| | rH | relative humidity [-] |

Climate data at the investigation site was measured only during irrigation periods. It also shows during those periods some gaps. For both evaporation and precipitation data different models of data completion were considered. A Kriging could not be applied, as the site was not surrounded in all directions by stations (compare Fig. 15). Linear inverse distance weighting (IDW) was computed withF. 12.

$$Z_0 = \sum_i^n \frac{Z_i}{d_i} \Big/ \sum_i^n \frac{1}{d_i}$$ F. 12

with:

| | | |
|---|---|---|
| with: | $Z_0$ | interpolated value |
| | $Z_i$ | value at reference station i |
| | $d_i$ | distance between reference station i and interpolation point |
| | n | number of stations considered |

IDW does not include information from the interpolation point. In contrast regression methods set variables from the interpolation point into a relation, e. g. linear regression with variables from other points. For the study best regression (F. 13) and multiple regression (MReg) methods (F. 14) were tested and interpolation quality compared. Weighting coefficients for the MReg were determined with a least squares method.

$$X_A(t) = \vee(m_i * X_{Bi}(t) + n_i)$$ F. 13

$$X_A(t) = \sum_i (m_i * X_{Bi}(t)) + n$$ F. 14

| | | |
|---|---|---|
| with: | $X_A(t)$ | time series value at station A |
| | $X_B(t)$ | time series value at station B (best correlated to A, in order of i) |
| | $m_i$ | scaling / weighting coefficient |
| | n | residual term |

## 2.2.6 Roots and water uptake

[Pregitzer, 1996] describes poplar root systems as wide ranging and extensive. Poplars have strong horizontal surface roots from which sinker roots develop. In poplar hybrids, horizontal roots have been measured at 15 m for a 10-year-old tree growing in sandy soil and 20 m for an old tree. The development of sinker roots is limited by the level of the water table or by the soil conditions [Burns, 1990].

According to [Mulia, 2005] roots of poplar explore soil volumes up to 10 m in radius and more than 3 m in depth. In contrast [Trapp, 2001] mentions that this species roots are distributed within the upper two meters of the soil layer and 90 % of the roots are found in the first 60 cm. These rather contrary findings emphasize the flexibility of root systems to interact with their environment. [Pregitzer, 1996] describes the coarse structural root system of poplars to have typically some 5 m radial horizontal extension. Roots concentrate in the first 60 cm although sinkers can reach down as far as some meters. It is also reported that roots grow preferentially into constantly humid soil regions.

Water uptake by roots is driven by the tension gradient within the plant within a soil plant atmosphere continuum [Phillip, 1966]. The extraction from the ground is in equilibrium between soil water tension and root tension. Low soil tensions limit the uptake. According to the model presented in F. 8, water uptake is characterized by four tension heads. Tab. 5 concludes literature values from different sources.

**Tab. 5 Parameters on root water uptake for deciduous trees**

| h [cm] | h1 | h2 | h3 | h4 | source |
|---|---|---|---|---|---|
| apple | 0 | -10 | -1000 | -15000 | [Green, 2003] |
| citrus | -10 | -25 | -400 | -8000 | [Gärdenäs, 2005] |
| grape | -1 | -10 | -1000 | -8000 | [Gärdenäs, 2005] |
| poplar | -0.00001 | | | -10000 | [Iskandar, 2001] |
| poplar | | -30 | -700 | -13000* | [Neumann, 1996] |

* the value was given as permanent wilting point of drought resistant poplars

### 2.2.7 Actual transpiration of the trees

Grassi Method [Grassi, 1978] calculates ET rate by means of measured soil moisture values. In the investigated case soil relative humidity was determined directly before and two days after each application of irrigation water, using gravimetric method. It is supposed that two days after the application water is available to a maximum extent but excess water is percolated or evaporated. The reduction of humidity over time is then used to calculate the integral effects of evaporation from soil surface and transpiration (F. 15).

$$ET_a = \frac{\sum_i s_i * (rh_{1,i} - rh_{2,i})}{\Delta t} \qquad \text{F. 15}$$

with: s thickness of the soil layer [mm]

i number of soil layers

$rh_{1/2}$ relative soil humidity two days after / before irrigation

$\Delta t$ time difference between soil humidity determinations [d]

In agricultural sciences it is common to express actual ET of a crop as ratio to potential ET with a crop coefficient (kc), e.g. as proposed in [Allen, 1998].

$$ET_a = k_c * ET_0 \qquad \text{F. 16}$$

with: $ET_a$ actual evapotranspiration

$k_c$ crop coefficient

The investigation team used two different methods to calculate crop coefficients. On the one hand the ratio was calculated from pan-evaporation data on the other hand Blayney-Criddle method [Bouwer, 1986] was used to calculate ET in 15 day cycles.

The ratio between actual and potential evaporation of poplar stands depends on water availability but also on soil conditions. [Verstraeten, 2005] found that actual evaporation varied about 30% for sites with different soil conditions and similar water yield. Crop coefficients varied during the growth season between 0.9 and 1.2. Silvicultural grown poplars under irrigation consume up to 2100 mm/a [Riu, 2004], [Giraud, 2001]. The trees are resistant and thus often planted under poor water or soil conditions [Zhang, 2005], [Leguizamón, 2007].

[Chappell, 1997] gives some figures on the transpiration of poplars on a tree-wise base:

- 100 to 200 l/(d*tree) as optimum transpiration rate for 5 year old trees under different climatic environments
- 50 l/(d*tree) (estimated annual mean) when trees extract their water directly from the groundwater table
- up to 40 l/(d*tree) as observed sap flow rates for young hybrid poplars at the Aberdeen Proving grounds in Maryland

The value determined by [Riu, 2004] for poplars irrigated every seven days corresponds to an annual mean of 90 l/(d*tree) and is integrating the effects of evaporation and transpiration.

## 2.3 Soil properties

Soil samples were taken in a field campaign that was carried out on July 23rd 2008. The sample distribution was configured in order to retrieve maximum spatial distribution as well as high representation of the different plant configurations during the growing period.

### 2.3.1 Physical soil properties

To capture the texture properties at first the sedimentation volume (SV) was appraised for all samples. SV [Nijensohn, 1962a] is a parameter that was developed in Mendoza. It shows good correlation to clay content and is hence used to estimate soil texture classes. Based on this, the grading curve was determined for six probes that showed the maximum variation in SV. 2 mm and 0.5 mm fractions were determined by sieving, finer fractions obtained by densimetry, as proposed by [ISO 11277, 1998]. Bulk density was determined from undisturbed samples with a volumetric method [ISO 11272, 1998] and particle density with picnometer method. Porosity was calculated as ratio of the densities, given by F. 17 and in comparison from saturated water content (see below) of disturbed samples.

$$\phi = 1 - \frac{D_B}{D_P} \qquad \text{F. 17}$$

with: $\phi$ porosity [-]

$D_B$ bulk density [g/cm³]

$D_P$ particle density [g/cm³]

Texture classification was derived from three classification standards. The simplest one refers to SV and was defined by [Nijensohn, 1962a]. ISSS [FAO, 2006] and DIN [DIN 4220, 2007] approaches both take into account grain size distribution.

### 2.3.2 Water Dynamics

**Qualitative rank analysis**

In a first step heterogeneity of soil water retention properties was analyzed qualitatively from variation of soil humidity data. A rank analysis was carried out, as proposed e.g. by [Ogg, 2000]. Hypothesis was that, if soil properties are spatially heterogeneous, variability has to be higher between different points of the site than between different dates at the same point.

As variables of water retention characteristics water content before and after irrigation as well as water content variation were considered. In order to limit the influence of external factors (irrigation frequency, climatic conditions in different years) the values were not analyzed directly but their rank within a group of same external factors, e.g. for all probes taken in 1991/92 with an irrigation frequency of seven days water contents before irrigation application were compared. The rank was distributed from highest to lowest variable value. Analysis was carried out for every investigated soil layer separately. The ranks of the different depths and soil parameters were than averaged over every parcel, this procedure created the mean rank (F. 18).

$$\overline{r_{i,j}} = \frac{1}{n} \sum_{p,d} r_{i,j} \qquad \text{F. 18}$$

with: $\overline{r_{i,j}}$ mean rank (specific in time and space)

i control variable of time

j control variable of irrigation regime

p control variable of retention parameter

j control variable of soil depth

$\overline{r_{i,j}}$ mean rank (specific in time and space)

Variation coefficient (F. 19) was than calculated from the deviation of ranks between different years (interannual covariation), where measurements have taken place on the same configuration parcel and irrigation configuration (interconfigurational covariation), where parcels change and comparison refers to the same year.

$$cov_i = \frac{SD_i(\overline{r_{i,j}})}{mean_i(\overline{r_{i,j}})} \qquad \text{F. 19}$$

with: $cov_i$ interannual variation coefficient

SD standard deviation of ranks

mean arithmetic mean of ranks

The rank parameters mean and SD were than compared with Wilcoxon test of equal distributions, stating hypothesis F. 20 that the parameters belong to the same distribution.

$$H : p(ia) = p(ic) \qquad \text{F. 20}$$

with: p(ia) probability distribution of interannual ranks

p(ic) probability distribution of interconfigurational ranks

The hypothesis is fulfilled, for the case that testing variable T (F. 21) is higher than z-quantile for normal dstributions.

$$T = \frac{\text{mean}(r_{i,1}) - \text{mean}(r_{i,2})}{\text{sdev}(r_{i,1} + r_{i,2})} \qquad \text{F. 21}$$

with: p(ia) probability distribution of interannual ranks

p(ic) probability distribution of interconfigurational ranks

### Retention properties

Retention curve was determined for suction heads between 5 - 1500 cm; saturated water content, with 0 cm suction head, with double ring method. At each suction head, water content was determined gravimetrically. The determinations were carried out for the same samples, for which grain size distribution were investigated.

Van Genuchten parameters were estimated in two different ways. Physical soil properties were used to drive two different estimation models and a fitting tool was applied to measured data. Norm DIN 4220 proposes tabulated values for soil texture classes as given in [AG Boden, 1994]. ROSETTA software [Schaap, 2000b] was developed by US Soil Salinity Service (USSS). It implements pedotransfer functions based on artificial neural networks. Data base for the pedotransfer functions were 2085 soil samples from US territory. Texture classes, texture distribution, bulk density and single value suction head information can be incorporated to apply the most exact model possible. Predicted parameters and their uncertainty ranges are given as output.

In contrast to the estimation approaches presented above, RETC (van Genuchten, 2002) fits van Genuchten parameters to a given retention curve. It applies a model that fits the parameters employing a nonlinear least squares optimization approach.

### Saturated hydraulic conductivity

Saturated hydraulic conductivity was researched in static pressure head columns under different pressure heads. The column has a diameter of 2.7 cm and 5 cm height. Pressure heads were varied between 20 and 50 cm but restricted by the condition that flow rate was less than two powers higher than permeability [DIN 18130, 1998]. As these experiments are relatively time consuming, only the four samples that showed maximum variation in retention properties were considered. Flow rate was measured every 10 – 30 min, with five to ten repetitions for each pressure head. For statistical validity experiments were repeated 4-6 times for each soil at different pressure heads.

ROSETTA allows also the estimation of saturated and unsaturated hydraulic conductivity. The same principles as mentioned above are used but data base is more limited (1306 samples for saturated and 285 samples for unsaturated conductivity). Measured saturated conductivity was validated and unsaturated relations estimated with the program. In SiWaPro texture classes according to [AG Boden, 1994] may be combined with bulk density classes to equip [Vereecken, 1989] PTF in order to determine saturated hydraulic conductivity.

Dispersion properties were retrieved from tracer experiments in the same static pressure head column as hydraulic conductivity. Salt solution (0.1 M NaCl) was used as conservative tracer. Breakthrough curves were measured from a step input concentration change (Fig. 16).

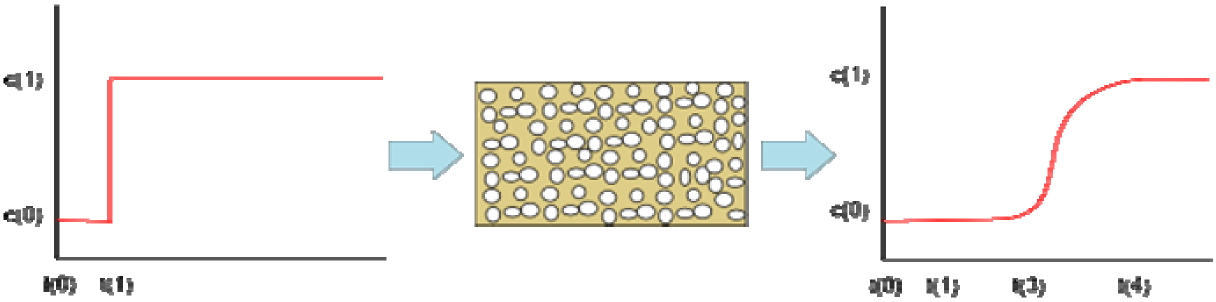


**Fig. 16 Change of concentration course due to hydromechanic dispersion**

Electric conductivity can be presumed as an equivalent of salt concentration. It was supposed that only sodium and chloride ions contribute to electric conductivity. A linear relation between both variables can be assumed for the value ranges considered. The upper equation given in F. 22 describes the relation as given by [LUBW, 2002] for pure NaCl-solutions. [Bergemann, 2005] gives the ratio for different river and brackish waters of German ecosystems. He states that the relation between EC and salt concentration depends on the mineral composition of the salts. A good mean approximation is given with the two lower equations in F. 22.

$$c(NaCl) = 3.08\ EC \qquad (EC < 2\ dS/m)$$
$$c(S) = 1.93\ EC \qquad (EC < 3\ dS/m) \qquad \text{F. 22}$$
$$c(S) = 1.49\ EC + 1.23 \qquad (EC > 3\ dS/m)$$

with: c(NaCl) salt concentration [g/l]

EC electric conductivity [dS/m]

Water density rises with salt concentration and measurement equipment allowed only determining elevated concentrations. Hence the dispersion experiment was preceded each time with an upside-down and downside-up flow direction, in order to avoid the influence of density layering due to the experimental setup.

STANMOD toolbox (Simunek, 1998) is applied to retrieve dispersion coefficient from the measured data using a nonlinear least-squares parameter optimization method. It is supposed that salt acts as ideal tracer. For the description of dispersion process equation F. 23 is applied.

$$I_c = D_D \frac{\partial c}{\partial x} \qquad \text{F. 23}$$

with: $I_c$ mass flux [g/d]

$D_D$ dispersivity [$m^2$/d]

### 2.3.3 Mass Transport

SiWaPro is able to model adsorption and decomposition, therefore a broad variety of substances can be considered. In the program structure a database for the estimation of transport properties is implemented. PTFs for mass transport are included take account into local soil properties. Organic matter, pH-value and clay content are direct input data for the deduction of mass transport properties.

Clay content was derived from texture analysis and describes the particle fraction smaller 2 µm. A regression between clay content measured and SV was established. For the soils, for which only SV was measured, clay content values were interpolated. The pH-values were determined in the saturated soil solution. In order to inhibit coagulation of clay minerals, 0.01 M CaCl solution was used to solve to soil. The procedure was applied according to [ISO 10390, 1994]. Loss on ignition method was applied with a combustion temperature of 550°C. Organic matter content was determined as difference of weight before and after ignition. It represents a simplified method as described in [DIN 18128, 2002]. The combination of the three parameters allows giving an appraisal for the transport characteristics of organic and inorganic substances.

## 2.4 Modeling

As already mentioned SiWaPro software program [Blankenburg, 2007] was applied to compute water and substance transport in the soil zone. Physical and modeling principles were introduced in section 1.4.

A data requirement scheme (Tab. 6) was developed in order to give an overview on the capabilities and requirements of the SiWaPro program and to provide users assistance on the decision which modeling objective is in focus. Different levels of data quality were defined and the corresponding modeling purpose evaluated.

**Tab. 6 Levels of data requirements and modelling objective**

| data level | low | medium | high |
|---|---|---|---|
| soil | texture class | grain size distribution | retention curve |
| climate | ETP from climate zone | ETP from phys. based models | cont. measurement |
| mass transport | occurring substances → database | packing density, organic matter, dispersivity | absorption and decomposition coefficients |
| plants | type of vegetation for monthly estimation | plant density and ecol. water demand | root density and macropores |
| modeling objective | water and mass transport balance | continuous modeling of present state | continuous modeling of varying boundary conditions |

### 2.4.1 Conceptual Model

The model to be built describes the upper part of the soil layer of an irrigated pattern. It is delimited by the ground surface as upper limit where infiltration and interaction with the atmosphere takes place. The lower limit is defined below the root zone at a level at which no capillary rise occurs In Fig. 17 possible processes represented by SiWaPro are visualized. Not all of them may actually be relevant for the concrete modeling study.

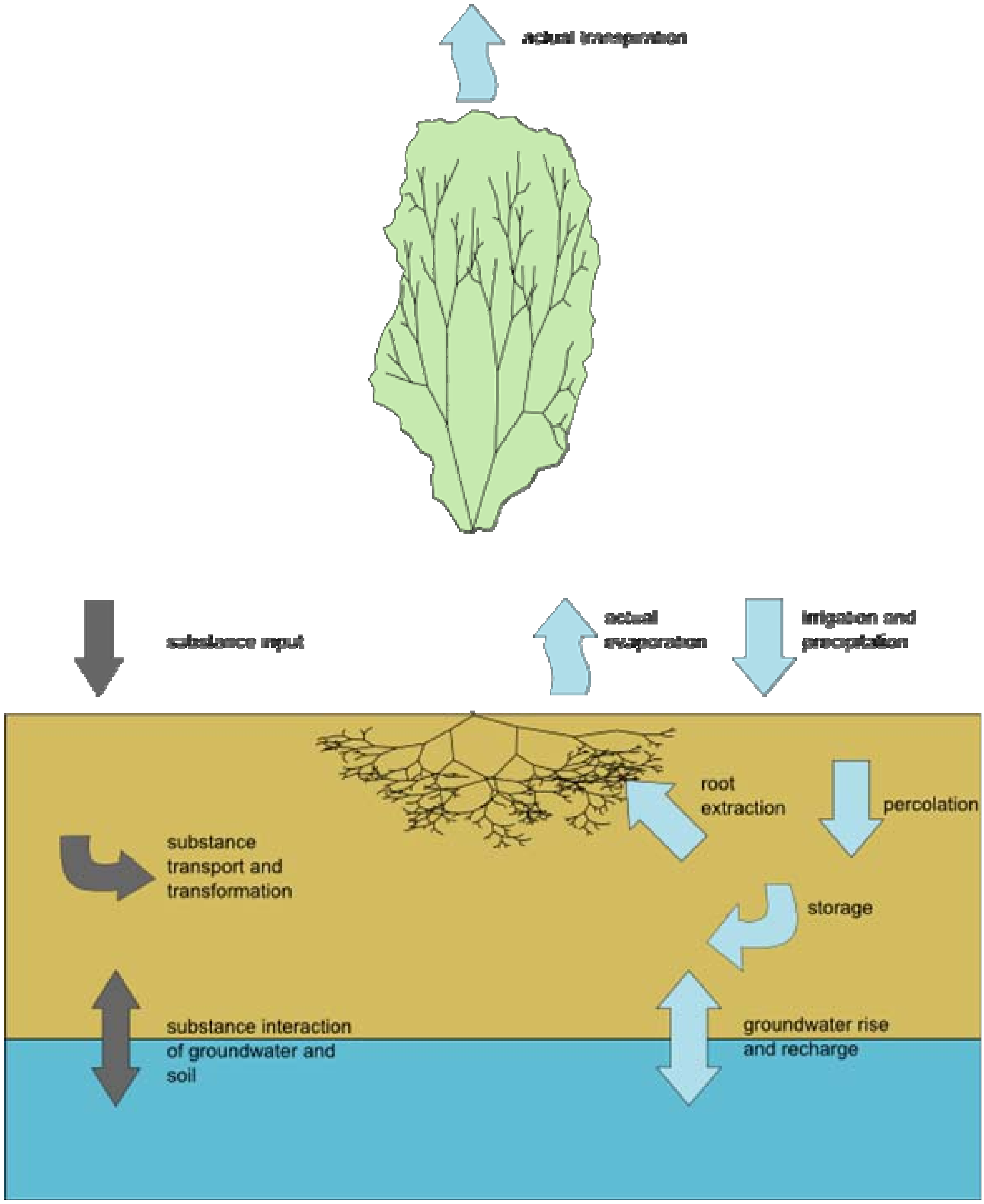


**Fig. 17** **Scheme of relevant processes of water and mass transport dynamics in SiWaPro**

Driving forces of water movement are gravity and matrix tension for infiltration and percolation as components of the downwards movement and plant and atmospheric vapor deficit tension for upwards movement. For the water balance on finite element as well as model scale water either enters the observation unit, is stored, taken up by plants or leaves observation unit.

### 2.4.2 Model Setup

Due to the arrangement of the investigation site, the total area consists of 36 geometrically equal parcels of 12 x 16 m² (compare Fig. 12). As the program structure only permits a limited number of equal type boundary conditions (e.g. for water flux at surface under differing irrigation schemes) parcels were modeled separately.

**Resolution**

The purpose of the model determines its spatial and temporal resolution. Data availability suggested a daily resolution of input data. A test of a fourteen day period in a downscaled hourly resolution was conducted but rejected as generation of input data was laborious and could only be realized conceptually. With regards to the modelling purpose output did not differ a lot from results of daily input values.

Several configurations of finite element resolution were tested in order to represent process dynamics adequately but at the same time guarantee model efficiency and limit computation time. The configuration finally established was five centimetres mesh size in the upper 30 cm and a linear vertical increase from 5 – 20 cm between 30 and 200 cm. This resulted in a mesh of 4091 nodes and 7748 elements.

**Model boundaries**

Groundwater level is at greater distance from the surface thus it was considered up to which depth capillary rise might occur. A pre model test was carried out in order to estimate the height of capillary rise. The test conditions did not take into account the influence of roots. Soil parameters were adapted for typical loamy sand. Potential gradient is greatest between saturated conditions and dry surface. To simulate this extreme case, a virtual groundwater level was lowered 20 cm each time and the model ran for a period of one month without irrigation or precipitation events. From a depth of groundwater level lower that 1.8 m no capillary rise was observed (no water flux at surface). Thus it can be assumed, that water that passes the two meter lower boundary eventually contributes to groundwater recharge.

The lateral component of flow was tested to evaluate in case a significant proportion of water leave the observation cell that way. For that case the parcel-wise recognition of the site would not be adequate. For this pre model boundaries were defined five meters away from the parcel border. The model was run during one month with four irrigation cycles and three precipitation events. A maximum distribution of wetting front (more than 15 % soil humidity) outside of the parcel borders was observed. The maximum extension reached 1.5 m, for an irrigation event with shortly antecedent rainfall. It is therefore concluded that lateral flow is negligible and parcel borders were defined as “no-flow” boundaries.

### Plant configuration

In order to keep the number of calibration parameters on a reasonable level and as quantifiable information for the site was not available, root distribution and density were treated conceptually. As described by [Riu, 2008a], already the roots of young poplar trees reach diameters of more than two meters and are most dense within the uppermost 60 cm. Literature values were discussed in the review above( section 1.3.3). The layerwise analysis of [Riu, 1993] indicated, that water extraction was similar in all layers (compare Tab. 11 below) hence all roots were expected to have the same potential of water extraction.

As indicated by [Tschaplinski, 1998] and described in (2.2.6) root distribution develops fairly independent from irrigation regime, if no severe water stress occurs. It was therefore assumed that for all trees roots were spread out equally. As root distribution can not be represented by a time series, it was regarded as stable during the calculation time.

Potential transpiration was obtained by scaling the potential evaporation with the crop coefficients given in Fig. 23. Uptake scaling parameter was adjusted with the pressure levels stated by [Neumann, 1996] that are concluded in Tab. 5.

### Boundary conditions

The upper boundaries are third type conditions; a climate balance calculated as precipipitation and irrigation minus evapotranspiration. Time series of flow rates are used within critical limits: in case water potential head passes an upper or lower threshold, this value is considered instead. This condition is introduced in order to stabilize computation in very dry conditions or under water pressure.

The lateral boundaries were described as “no-flow” condition according to the findings mentioned above. The lower boundary is defined as a third type condition and represents a distant groundwater level. Flow is calculated with empirical relation F. 24 that was introduced by [Hopmans, 1989] for soil water modelling.

$$q = -A_{qh} e^{B_{qh} * (h - OL)}$$ F. 24

with: q nodal flow [m²/s]

$A_{qh}$ scaling factor [m²/s]

$B_{qh}$ scaling factor [1/m]

h water pressure / tension head [m]

OL surface level [m]

## 2.5 Representation of present state

In a first step a sensitivity analysis was carried out to enhance system comprehension. Calibration is conducted based on this knowledge and the experiences from the model setup.

### 2.5.1 Sensitivity analysis

Starting from the estimated parameters a sensitivity analysis was conducted. The variability of the input parameters was calculated presuming a normal distribution, as proposed by [Schaap, 2000b]. Focus of the sensitivity analysis (SA) was to:

- enhance system comprehension
- test the system influences in order to facilitate calibration process
- identify system stability limits in order to avoid model instability

SAs provide a possibility to detect and quantify the relation between input variables, system parameters and results of a model. Parameters are changed univariantly within sensible ranges and are set into relation to the response of an output variable.

**Parameter ranges**

As the model is calibrated with soil moisture data and target variable is the discharge at the lower model boundary, these two variables were considered in the SA. Van Genuchten parameters were varied within their normally distributed probability; they were calculated from the measured values. Boundaries were defined as ten and ninety percent non-exceedence probability (quantile).

$$x_q = \frac{SD_x * z}{\bar{x}}$$ F. 25

with:
- $x_q$ quantile value of x
- q non-exceedence probability percentile
- $SD_x$ standard deviation of x
- z probability value (tabled) of quantile q for ND
- $\bar{x}$ mean value of x

**Execution**

The initial "standard" model matched the findings from the model setup routine but without plants. Soil water content, accumulated discharge and maximum discharge were chosen as target variables, as they are most representative for system reaction on changes. The model was run for a period of 30 days with two irrigation pulses at 10 and 20 days. An accumulated discharge at the lower boundary and water content one meter below surface six days after irrigation were registered for each parameter combination. The single parameters were permuted univariantly with the others staying on the standard configuration.

The sensitivity index is a parameter that allows capturing the sensitivity of a target variable for changes of a certain parameter, if the relation is linear. It describes the increment of one the target variable over the parameter by differential approximation (F. 26).

$$SI = \frac{dTV}{dSP} \cong \frac{\Delta TV}{\Delta SP}$$ F. 26

with:
- SI sensitivity index
- TV target variable
- SP system parameter

Nonlinear relations might be described with polynomial or exponential equations [Blair, 2002] but the informative value is much less apparent when compared to the linear approach.

### 2.5.2 Calibration and Validation

After model setup calibration is a crucial step to obtain a functional model. In order to fit a model objectively, optimization needs a measure of agreement between measured data and simulation results. As already presented for the sensitivity analysis, the basic principle of a calibration is the univariant adaptation of parameters in order to optimize a target function. Relative humidity was used as target variable. This state variable was measured with high frequency and is a measure directly related to water dynamics. According to [Riu, 2008a] the values were examined for each diagnostic layer and at 50 cm distance from a tree. For the calibration water content values were readout in daily resolution at 6.5 m from the model border, corresponding to 50 cm distance from the position of the second tree.

### Performance parameters

Various measures were tested to assess calibration quality. The formulas in the following are exemplarily set up for the relative soil humidity that served as calibration target variable. They serve with some adaptations for many other environmental measures. They are also used for the evaluation of interpolation quality of input data (sections 3.1.1, 3.1.3). If not mentioned differently a more detailed description of the indexes can be found in [Willmot, 1985].

The bias describes the difference between mean measured and simulated value. The higher the difference the less confident is the estimate (F. 27). Bias is applied to detect systematic differences between measured and simulated data and is base for a further statistical analysis e. g. of frequency distributions.

$$\text{bias} = (\overline{rh_m} - \overline{rh_s})^2 \qquad \text{F. 27}$$

with: $\overline{rh_m}$ mean measured relative soil humidity

$\overline{rh_s}$ mean simulated relative soil humidity

The bias is integrating the dynamics of measured data so that e. g. differences in the variability are not captured. This problem is addressed by mean error (ME) based indexes. The simplest form is given in F. 28.

$$ME = \frac{1}{n}\sum_{i}^{n}(rh_{mi} - rh_{si}) \qquad \text{F. 28}$$

with: ME mean error

n number of observations

$rh_{mi}$ measured relative humidity at date i

$rh_{si}$ simulated relative humidity at date i

A disadvantage of mean error evaluation is that single value deviations of different signs compensate each other so that the absolute deviation is underestimated. This is avoided by using the root mean square error (RMSE) as given in F. 29. Absolute values of the single value deviations are considered and the effect of exceptionally high single deviations is buffered. Relative root mean square error (rRMSE) is the RMSE divided by mean measured value. It sets the deviation into a relation with the expectancy index and allows estimating the magnitude of the error.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i}^{n}(\mathrm{rh}_{mi} - \mathrm{rh}_{si})^2} \qquad \text{F. 29}$$

$$\mathrm{rRMSE} = \frac{\mathrm{RMSE}}{\overline{\mathrm{rh}_m}} \qquad \text{F. 30}$$

with: RMSE mean error

n number of observations

Nash-Sutcliffe efficiency (NSE) was introduced by [Nash, 1970] for the evaluation of hydrologic modeling results (F. 31). Values can range from -∞ to 1. An efficiency of 1 (NSE=1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of zero indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (-∞<NSE<0) occurs if the observed mean is a better predictor than the model.

$$\mathrm{NSE} = \frac{\sum(\overline{\mathrm{rh}_m} - \mathrm{rh}_m)^2 - \sum(\mathrm{rh}_m - \mathrm{rh}_s)^2}{\sum(\overline{\mathrm{rh}_m} - \mathrm{rh}_m)^2} \qquad \text{F. 31}$$

with: NSE Nash-Sutcliffe efficiency

Index of agreement is a measure for the difference between simulation and measured data. In contrast to standard mean square error based measures it allows additionally to evaluate relative size of the average difference and is stable for a broad range of comparison data. Big relative differences in small comparison pairs are considered as strong as those in big comparison pairs. The IoA can be interpreted as extend with that the simulated values are able to explain the deviation of measured values. That means the value expresses what portion of the predictions are error free.

$$IoA = 1 - \frac{\sum (rh_m - rh_s)^2}{\sum \left( \left| rh_m - \overline{rh_m} \right| + \left| rh_s - \overline{rh_s} \right| \right)^2}$$ F. 32

with: IoA index of agreement

Correlation coefficient (R) is not a direct index for the evaluation of fitting quality but it is a measure how strong the dynamic of a variable depends on another. R describes the efficiency of a predictive function to reproduce a series of data. In its simplest form a linear regression is used. Coefficient of determination ($R^2$) is the squared correlation coefficient. It can be interpreted as proportion of the variance of measured data in the variance of the estimation function. Spearman rank significance test allows the assessment of correlation reliability.

F. 33

$$R = \frac{\sum_i^n (rh_{mi} - \overline{rh_m})(rh_{si} - \overline{rh_s})}{n * SD_{rh_m} * SD_{rh_s}}$$

F. 34

with: R correlation coefficient

$SD_{rh_m}$ standard deviation of measured values

$SD_{rh_s}$ standard deviation of simulated values

### Multi-objective performance evaluation

The use of multiple parameters causes the problem of a ranking between their importance. For this work an approach similar to utility analysis is proposed. The method is widely applied in the field of scenario evaluation in the water management sector [DVWK, 1993]. A detailed introduction is given in [Eisenführ, 1993]. Adapted on the field of performance evaluation the idea is to:

- define utility functions for every performance parameter (PP) that scale the parameter to a value between zero and one
- define weights for the different PPs that scale their contribution to the integral "performance utility" (PU)

$$PU = \sum_{i}^{PP} w_i * uv_i(PP)$$
$$\text{with: } 0 < uv_i(PP) < 1 \qquad \text{F. 35}$$
$$\text{and: } \sum_{i}^{PP} w_i = 1$$

with:

| | | |
|---|---|---|
| with: | PU | performance utility |
| | PP | performance parameter |
| | uv(PP) | utility value, function of PP |
| | w | weighting coefficient |

The PU is an integrated parameter that allows the objective evaluation of performance quality based on multiple evaluation criteria. Weighting coefficients might be defined according to the prevalent modeling objective and utility functions can be adapted to specific requirements e. g. as a function of input data quality or significant parameter moments.

## 2.6 Scenario Setup

Based on the working and calibrated water dynamics model, scenarios of water application and mass transport are developed. The scenarios try to approach problems of overexploitation of water and contamination of soil and groundwater due to irrigation.

### 2.6.1 Salinization due to irrigation

Probably the principle and most widespread source of contamination in Mendoza area is salt in the irrigation water. Threads and measures were broadly discussed in 1.2.1.

SiWaPro can provide a physically based representation of the unsaturated soil zone. It is thus a possible link between surface- and groundwater compartments and may be used to validate other more conceptual models.

**Motivation**

The background and importance of salt as a source of contamination was already introduced above in sections 1.2.1 and 1.3.2. The idea to set up this scenario was to validate the balance orientated approaches, e.g. presented by [Mirábile, 2006]. As sodium chloride represents a conservative constituent the balance is rather easy to draw: the amount of salt that enters is accumulated in the soil zone or convectively passed to the groundwater. But, as transport processes depend on water distribution, the physical based representation allows detecting distribution patterns and transporting dynamics.

**Assumptions**

Configuration and boundary conditions are the same as in the calibrated model. Irrigation water is charged with a conductivity of 1.5 dS/m, corresponding to 0.49 g/l NaCl. Precipitation water is assumed to not contain any salt. Initial soil conductivity is 2.5 dS/m corresponding to 0.81 g/l. Irrigation is applied with a seven day frequency and observation period is one year. Salt is assumed to be a conservative constituent of water, thus neither adsorption nor decomposition is considered. Dispersion coefficient and dispersivity are adopted from experiments. The incorporation of salt by the poplars as e.g. mentioned by [Shannon, 1998] is also neglected.

### 2.6.2 Irrigation with alternative irrigation methods

**Motivation**

Basin irrigation is considered as one of the most ineffective methods with regard to water consumption [FAO, 1995]. Some reasons are:

- water has an extended contact surface with the atmosphere so that evaporation rate is elevated
- water is distributed equally within the irrigation basin without regard to position of the plants
- irrigations depths within the field are difficult to control due to surface asperities, making the method vulnerable to over- rather then undersupply of water

Furrow irrigation is another common irrigation method in Mendoza. Generally furrow irrigation reaches better irrigation efficiencies than basin irrigation [FAO, 1995], which was also confirmed for Mendoza [Bos, 1997] but application needs more skills and water is distributed unequal along the furrows. [Schmitz, 2007] proposes a coupled 1D surface – 2D soil model to describe the flow process along the furrow. Drip irrigation belongs to the micro irrigation methods that allow providing water adequately in space and time to the plant. [Riu, 2008b] has done research on the application of drip irrigation for the fertirrigation of poplars.

**Assumptions**

A cross section profile of the furrow irrigation is considered. The furrows are estimated to have a contact surface of 0.5 m and trees are situated in the middle of the furrows, as it is common practice in Mendoza. Irrigation frequency is seven days. Two sub-cases of irrigation are considered irrigation with 50 % and 100 % of the water applied in basin irrigation, which results in irrigation depths of 260 mm or 520 mm respectively within the furrows or 65 mm or 130 mm per square meter. Over the irrigation season this accumulates to 1300 mm or 2600 mm.

The configuration of the drip irrigation scheme was adapted from [Riu, 2008b]. During the growth period 48 l/d were applied on every tree corresponding to 320 mm per square meter in one irrigation season. Two sub-cases are considered: with and without leaching after the irrigation season. In the leaching case a pulse of 200 mm is applied on the total irrigation surface.

As flow processes are supposed to be unaffected by mass transport, salinization is investigated with the same scenarios.

### 2.6.3 Phytoremediation of petroleum contamination

**Motivation**

Just recently a case of uncontrolled petroleum waste disposal was reported for the Piedras Coloradas oil production [Rojas, 2008] area that affects the investigation site through downstream El Carrizal reservoir. Various petroleum fields, e.g. at Vicacheras and La Ventana deposits are found in Rivadavia, the same department as the investigation site. Also in groundwater wells cases of hydrocarbon contamination were reported in the vicinity of extraction areas [Rojas, 2003].

Phytoremediation methods are comparatively cheap, accepted by the public and ecologically advantageous, compared to common technological approaches. The presence of a microflora in the rhizosphere and the discharge of root exudates [Moormann, 2002] may accelerate the degradation of contaminants. [Hoffmann, 1998] also mentions the possibility of incorporation of certain contaminants by certain plants. Furthermore plants have an influence on the water balance of a site; they change redox potential and pH, and stimulate microbial activity of the soil [Doty, 2007]. These indirect influences may accelerate degradation in the root zone or reduce the leaching of compounds into the groundwater. Phytoremediation represents an attractive treatment option for halosols [Ventosa, 2008] and arid soils [Gómez-Silva, 2008], where natural activity of micro-organisms is strongly reduced.

In spite of the advantages mentioned phytotoxicity and pollutants mass balance have rarely been documented carefully. Often the success of the projects is not controlled, and only estimates can be made about the applicability and the potential of Phytoremediation [Trapp, 2000]. Main requirements for further investigation are concluded by [Collins, 2007]:

- species that tolerate the presence- or support the degradation of specific pollutants
- reaction of phytoremediation systems on different ages of contamination
- influence and interrelation with environmental boundary conditions
- combination with other treatment options
- possibilities of phytoremediation in ecological restoration

This lack of experience about possibilities and limitations seems to be a hindrance for a broader use of these techniques. The preliminary modelling of a project allows the effective design of Phytoremediation, an accompanying control of monitoring results based on the model supports strategic decisions.

Phytoremediation is an innovative practice for the treatment of petroleum sites. It enhances the effects of bioremediation especially for potentially toxic petroleum components [Fiorenza, 1999]. As already introduced above, BTEX are common pollutants in petroleum contamination. For benzene [Austenat, 1986] gives decomposition half-lives of 8-18 months in soil and up to 4 years in the groundwater. SiWaPro contaminant database gives 720 days as estimate. Although [BMZ, 1995] mentions that the substance is highly volatile in the upper soil layer.

Mainly willows, poplars and grasses are applied for the degradation of petroleum products, aromatic hydrocarbons (BTEX), chlorinated solvents, explosives and cyanides [Frick, 1999]. [Stuwort, 2003] names poplars and alfalfa as most efficient plants for the removal of BTEX without giving quantifiable information. [Rydberg, 2003] and [Pilipovych, 2006] mention poplars as suitable crop for the removal of volatile organic carbons. In general, BTEX compounds are relatively easy to remediate because they are rapidly degraded in the presence of oxygen, relatively soluble, thus making them bioavailable. Additionally it can serve as the primary electron donor for many bacteria widely distributed in nature [Frick, 1999]. [Schnoor, 1995] describes the ability of poplars to incorporate moderately hydrophobic organics, including BTEX species.

Poplars are an established crop in the field of phytoremediation [Collins, 2007].The species contains many varieties that are well suited for phytoremediation because of their rapid growth, extensive root systems, high water uptake, and amenability to transformation [Doty, 2007]. [Calderon, 2006] mentions poplars as possible crop for phytoremediation in Mendoza region. [Jordahl 1997] reported that hybrid poplar trees had 5 times more BTEX degraders in the rhizosphere compared to bulk soil, indicating the potential for phytoremediation by these species.

## Assumptions

Two cases are set up for the schenario: during a five year period phytoremediation is applied and compared to an untreated site. Initial concentration of benzene is 10 ppm (7.29 g/m$^3$), the limit for industrial use of an area [Ercoli, 2005b] and a value commonly found in PHC contaminated sites. The assumptions are concluded in Tab. 7 below. Climate conditions are equal for both scenarios and correspond to the 1991 – 1995 period generated for La Libertad. The treatment site has the same plant configuration as the calibrated model, for the untreated site no plant growth is assumed. Irrigation is provided every seven day with 50 mm in growth season and 20 mm in the rest of the year in order to maintain soil humid for microbial activity. Transpiration rate is set as for the 14 day irrigated poplars because irrigation depths are smaller. The values given in SiWaPro database were considered for mass transport.

**Tab. 7 Assumptions for benzene transport scenarios.**

| scenario | phytoremediation | no treatment |
|---|---|---|
| model geometry | cm | cm |
| soil | cm | cm |
| boundary conditions | cm | cm |
| irrigation | 20-50 mm/7d | no |
| climate | '91-'95 LL | '91-'95 LL |
| plants | cm | no |
| transpiration | 14d transpiration rate | no |
| mass transport | database, decomp. rate x5 | database, decomp. rate x0.5 |
| mass boundaries | no | no |

Adaptations were made where measured values were available. The dispersivities and organic content (Tab. 20) were taken from the experiment; compactness was adapted to the soil bulk density (Tab. 12). The decomposition rate is assumed to be five times higher than default value for phytoremediation and half as high without treatment, due to the reduced microbiological activity in arid soils [Gómez-Silva, 2008]. Scenario assumptions are concluded in Tab. 7, "cm" means that the value was taken from the calibrated model, "no" means that the aspect was not considered. Estimates for the mass parameters are given in Tab. 8.

**Tab. 8 Mass transport parameters for the benzene transport scenarios**

| scenario | phytoremediation | no treatment |
|---|---|---|
| compactness | 1.33 $g/cm^3$ | 1.33 $g/cm^3$ |
| diffusion coefficient | 0.685 $cm^2/d$ | 0.685 $cm^2/d$ |
| long. Dispersivity | 0.12 m | 0.12 m |
| trans. Dispersivity | 0.012 m | 0.012 m |
| half-live | 144 d | 1440 d |
| organic content | 0.80% | 0.80% |
| Henry coefficient | 0.898 $cm^3/g$ | 0.898 $cm^3/g$ |

# 3 RESULTS AND DISCUSSION

In the following results of the project are concluded. Special attention is drawn on the part of input data preparation. To the author this part appears of special interest as data situation in many arid regions in the world is sparse and efforts have to be focused on the most relevant factors. As there are not many references available for modeling the vadose zone, this evaluation might be valuable for future projects. As a consequence the section 3.1 Processing and evaluation of input data occupies considerable space within the work. As a consequence soil data section is divided into analysis (3.1.2) and parameter estimation (3.1.3).

## 3.1 Processing and evaluation of input data

The need and strategy of data enhancement were presented in sections **Fehler! Verweisquelle konnte nicht gefunden werden.** to 2.4. In the following results of data processing are concluded, interpreted and their use in vadose zone modeling is described.

### 3.1.1 Climate data and plant data

#### Data consistency

A main drawback of data from the site is that it was only available during the irrigation periods. Only this time segment was of interest for the antecedent investigation. Hence reference data for the neighboring stations was obtained and evaporation was calculated in daily resolution. During the processing of the data some irregularities were identified.

Fig. 18 shows the accumulated tank evaporation data for the measurement period 1991 – 1996. As data was only collected during the irrigation season, corresponding to more or less 120 days per year, the total amount is circa 730 dates. Around the 360$^{th}$ day, corresponding to January 1994, a clear change in the gradient of the accumulation curve takes place. The periods before and after this date are approximated satisfyingly with linear trend, coefficients of determination ($R^2$) are in both cases greater 0.99. Nevertheless gradient slope, corresponding to mean daily evaporation is reduced after this changing point by more than half of the initial value, from 8.1 mm/d to 3.9 mm/d.

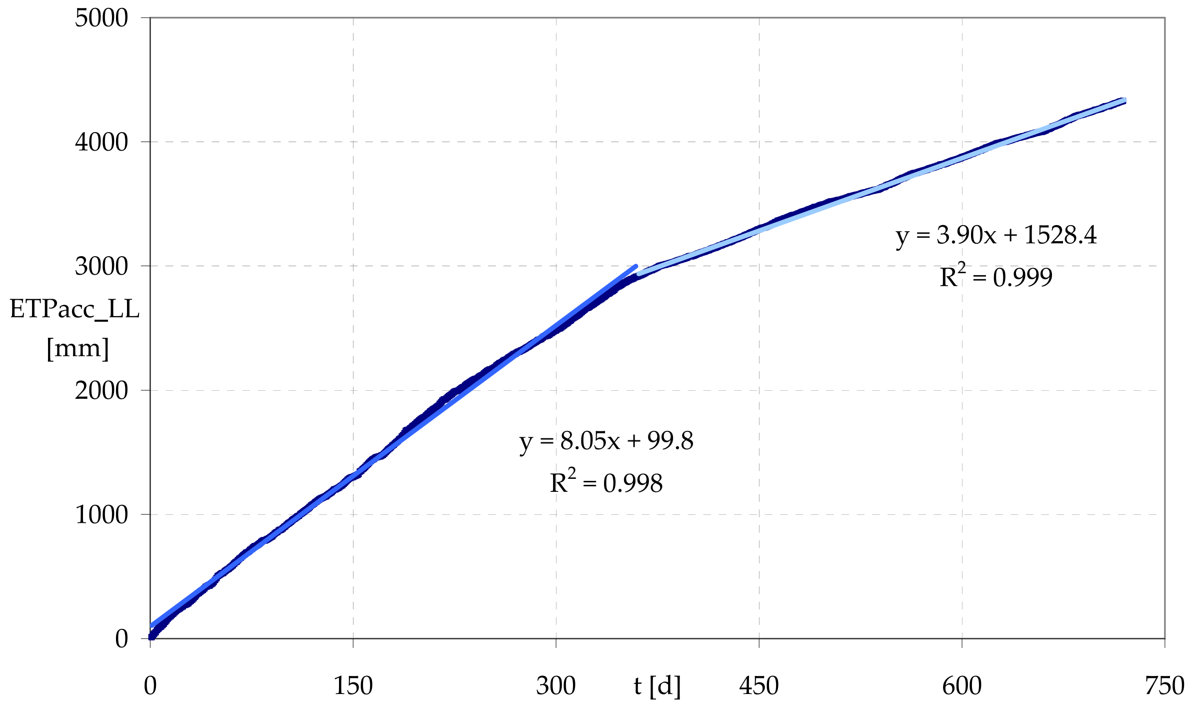


**Fig. 18 Accumulated evapotransiration rates and fitted trends**

The findings from the accumulated evaporation are confirmed by a comparison of mean daily values during the irrigation season (Tab. 9). Evaporation at La Libertad is in '91 – '92 and '92 – '93 clearly higher than CS values; in '94 – '95 and '95 – '96 lower. For season '93 – '94, values are intermediate, because it integrates the overestimation before and the underestimation after January. In contrast calculated evaporation and measured pan evaporation from Chacras de Coria are stable throughout the years.

**Tab. 9 Mean evaporation rates during irrigation seasons**

| ETP [mm/d] | ETP_LL | ETP_SM | ETP_MA | ETP_MO | CdC_PM | CdC_T |
|---|---|---|---|---|---|---|
| 91 - 92 | 8.81 | 4.61 | 5.37 | 5.06 | 4.45 | 6.43 |
| 92 - 93 | 8.07 | 4.35 | 5.02 | 4.63 | 3.90 | 6.18 |
| 93 - 94 | 6.43 | 4.73 | 5.00 | 4.45 | 4.67 | 6.91 |
| 94 - 95 | 3.86 | 5.21 | 6.08 | 5.40 | 5.12 | 7.17 |
| 95 - 96 | 3.96 | 5.02 | 5.77 | 4.50 | 5.05 | 5.81 |

## Completition and regionalization of climate data

The time series delivered by SMN consisted of minimum mean and maximum temperature, relative air humidity, wind speed, sunshine duration and precipitation. The series were not complete, single dates were missing or not the complete series was available. Missing values were supplemented by best correlation with other variables from the same station or same variables from other stations. Correlation was calculated from the existent data. For the best correlated value the linear regression parameters were determined and the missing value replaced by the regression estimate.

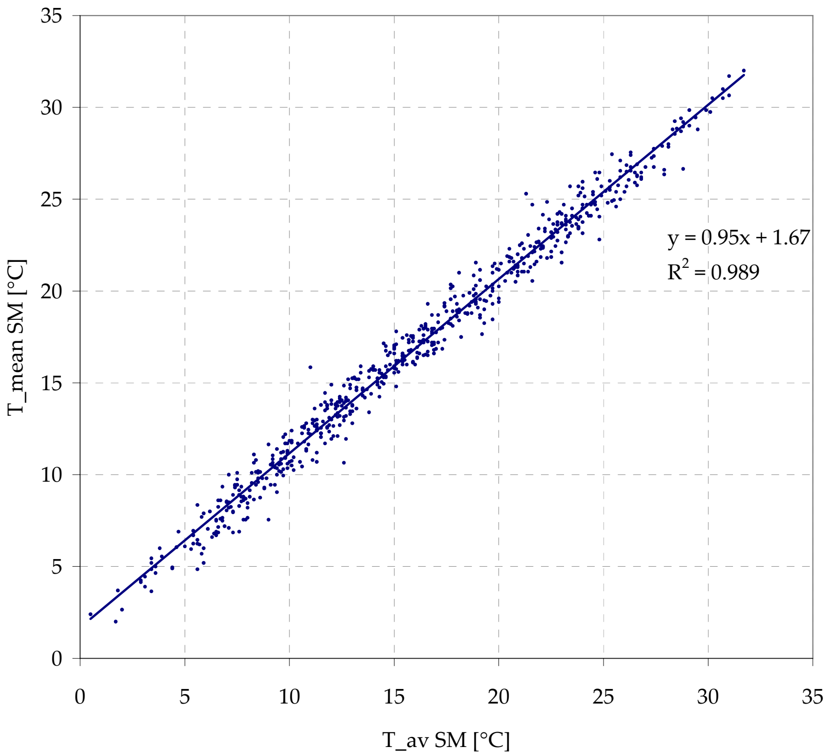


**Fig. 19 Correlation between mean temperature and average temperature at San Martin CS**

Fig. 19 gives an example for the correlation between mean temperature and the average value of minimum and maximum temperature value. With a $R^2$ of 0.989 the estimation confidence is high. Regression equation indicates that average value is 1.67°C higher at 0°C but increases slower with higher mean temperatures, so that for 30°C values are equal.

If no value was available at the best correlated station for the missing date, second, third or fourth best correlated value were considered. In this way a coherent data set of all stations was obtained. Statistical analysis showed a convincing completition quality. The difference between mean values was for all stations smaller than one percent, for SD smaller than three percent.

Comparison on a daily scale between calculated and measured evaporation on a daily resolution resulted in low accordance. Fig. 20 visualizes that the correlation between single day values (light blue) is poor, with a $R^2$ of 0.2 (significance of 75 %). As a reference: the $R^2$ between Chacras de Coria pan and PM calculated daily values is 0.79 For the five day moving average the dependence between both variables gets much more apparent, $R^2$ suggests a confidence of correlation with a significance of 95 %.

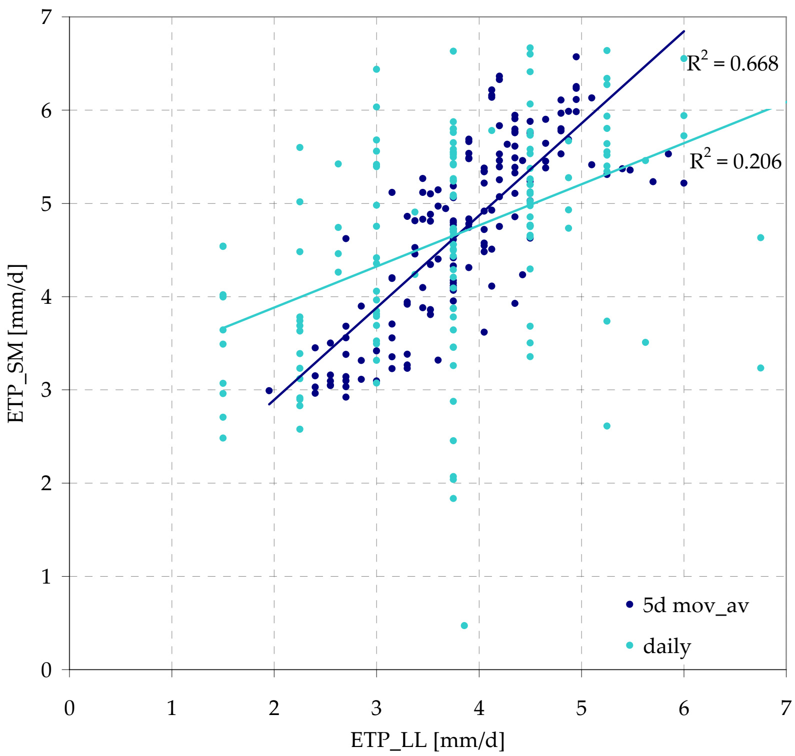


**Fig. 20 Correlation between evaporation from San Martin and La Libertad**

If the values of measured and PM evaporation are compared in their temporal course some additional differences are revealed. In Fig. 21 the courses for precipitation and evaporation at LL and SM are given for the irrigation season '93 – '94. Light blue lines are from SM dark blue ones from LL, Fine lines are daily values, bold lines the five day moving average. For the daily data two aspects are obvious: data from LL shows a much greater variability not only throughout the whole observation period but also from day to day. This strong movement could not be related to any other climatic variable from the site or the other CS; it is thus unclear how it can be explained. The year displayed is the one with the change in evaporation regime (see above) from January on measured daily values decrease much faster than computed ones. With regard to the precipitation data patterns of occurrence for rainfall events are similar but neither date nor dynamics are related directly. The only statistical hypothesis that could be confirmed was that if rainfall occurs at the climate stations CdC or SM it is likely to occur also at LL.

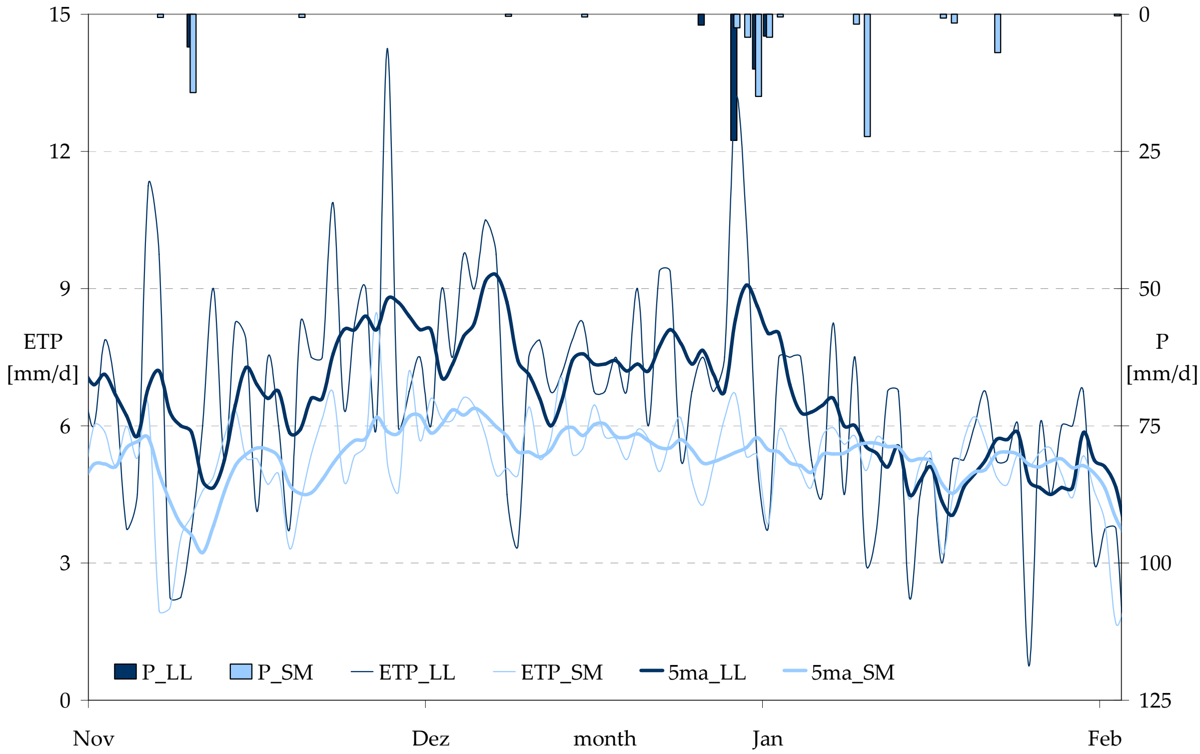


**Fig. 21 Courses of evaporation and precipitation from San Martin and La Libertad**

For the regionalization of evaporation and precipitation different approaches were applied. The simple best regression models turned out to give bad fits with coefficients of determination of generally less than 0.3. Mean values were predicted correctly, as inherent for the method. In a next step IDW was applied. Different combinations were tested and the combination of CdC pan, CdC PM and SM PM gave the best estimate. Correlation quality was slightly better with a $R^2$ of 0.33 but mean value was biased with 28 %: interpolated mean was 6.12 instead of 8.39 for 1993 to 1995 irrigation seasons. MReg was conducted with between two and five CSs considered. The more information included the more improved coefficients of determination. With all five CSs included $R^2$ was 0.59, which corresponds to a significance level of more than 95 % according to Spearman rank analysis. Bias matched the input data. As disadvantage it turned out, that evaporation during the no irrigation seasons was estimated very high. This observation could not be validated statistically as no measured data was available but it was judged as unrealistic because none of the observed stations had values nearly that high. Due to that a combination of IDW and MReg was chosen. For the irrigation seasons, when measured data was available, it was used for the estimation of evaporation for the periods of time without reference measured data IDW was applied SM PM, CdC PM and CdC pan were used as weighting stations. In that way a coherent, consistent and statistical valid set of evaporation data was generated.

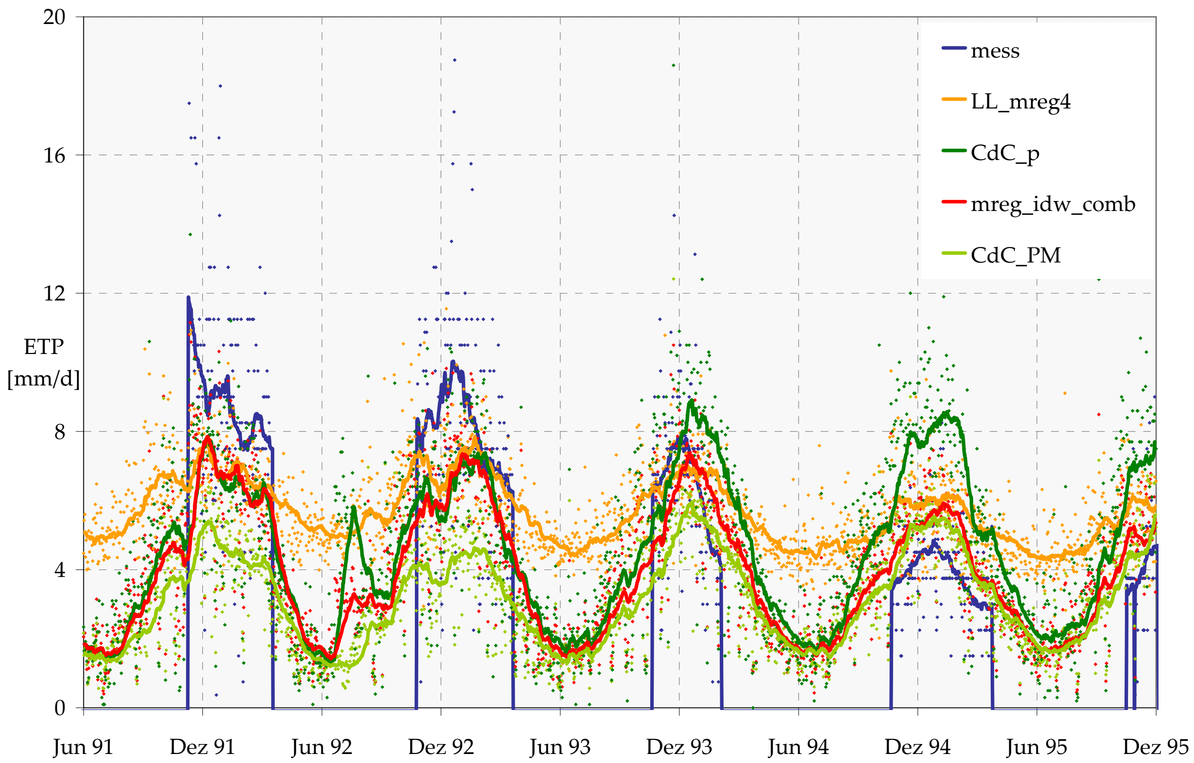


**Fig. 22 Measured, calculated and interpolated courses of evaporation**

In Fig. 22 the comparison of measured data (blue) with CdC PM and pan data (green shades) and generated time series is given for the whole period during that evaporation data was available. Bold lines stand for the thirty day moving average, dots represent daily values. The orange line represents the MReg with four CS series (MO PM, SM PM, CdC PM and CdC pan). During the irrigation seasons predicted values are acceptable: the general course is reproduced and the regime change is at least detectable, although not as pronounced as in the measured data. During winter the evaporation is strongly increased in comparison with the other courses. Because the fit was optimized with summer data winter values are overestimated. The red line represents the combined approximation with IDW in non-irrigation period (April to October) and MReg with all five CS series during irrigation season

(November to March). The advantages of regression takes effect: mean value is conserved during the irrigation season and principle course at the station is reproduced. Additionally winter values are in better accordance with the other stations.

Precipitation is not a continuous process and spatial and temporal patterns are much more dynamic than for evaporation. The data obtained from LL did not contain information of "no data" periods. It could thus not be evaluated if rainfall did not occur or if it was not registered. E. g. when comparing the rainfall events displayed in Fig. 21 is remarkable that during January no rainfall was detected while in nearby SM two events with more than 10 mm are registered. Summer rainfall events in the Mendoza Llanura have often convective genesis and are spatially limited and intense [Thomas, 1998]. Correlation of daily precipitation depths was calculated during the irrigation seasons. Tab. 10 concludes the $R^2$s for all CSs. Only for the three stations with that are closest together (SM, MA and CdC) $R^2$ is significant. For LL also the closest station (SM) has the highest $R^2$. It can thus be concluded that summer precipitation events occur rather independently at each CS but closest stations show biggest accordance. For the completition of precipitation data it was assumed that during the irrigation season data is coherent and for periods without records the precipitation course of SM was taken over.

**Tab. 10 Coefficients of determination for the correlation of precipitation depths**

| $R^2$ | SM | MA | MO | CdC |
|---|---|---|---|---|
| LL | 0.141 | 0.049 | 0.079 | 0.065 |
| CdC | 0.242 | 0.319 | 0.495 | |
| MO | 0.230 | 0.539 | | |
| MA | 0.111 | | | |

The fitting of data as presented here should be evaluated critically. The considerable uncertainties about the validity of the measured data might be detrimental for the estimation procedure. On the other hand especially if the availability of local data is limited, the ones at hand should be considered. Local changes of land use (cultivation in the surrounding) or surface morphology (construction, growing trees) might affect the driving forces of evaporation. Such local effects are not represented in regionalized or interpolated data that does not take to account local data.

## Plant water uptake and actual evapotranspiration

As already mentioned for plant water consumption no additional investigations were undertaken. Assumptions rely on the results obtained in the previous project. The analysis presented in this section are based on unpublished [Riu, 1993] and published [Riu, 2003], [Riu, 2004] data.

**Tab. 11 Actual water consumption (transpiration) from different soil depths**

| layer | 0-30 cm | 30-60 cm | 60-90 cm | 90-120 cm | total |
|---|---|---|---|---|---|
| T (6 y, 21d) [mm] | 236.7 | 216.0 | 164.7 | 170.1 | 788 |
| rel. T (6y, 21d) [%] | 30.1 | 27.4 | 20.9 | 21.6 | |
| T (6y, 14d) [mm] | 343.8 | 295.2 | 313.2 | 269.1 | 1221 |
| rel. T (6y, 14d) [%] | 28.2 | 24.2 | 25.6 | 22.0 | |
| T (6y, 7d) [mm] | 521.1 | 438.3 | 472.5 | 557.1 | 1989 |
| rel. T (6y, 7d) [%] | 26.2 | 22.0 | 23.8 | 28.0 | |
| mean rel. T | 28.1 | 24.5 | 23.4 | 23.9 | |

From the pedological point of view transpiration can be seen as a sink for water in the soil zone. Applying Grassi Method (compare F. 15) water consumption in the soil was calculated. The results are concluded in Tab. 11 as integrated annual (irrigation seasonal) values in an average of the three subsequent irrigation seasons 1991 to 1994. For six year poplars water consumption depends largely on irrigation frequency. Poplars irrigated every 21 days (first two lines) consume 788 mm annually, less than half of the water consumed by poplars irrigated every week (last two lines). With respect to the consumption per soil horizon it appears that uptake is distributed rather equal over the whole diagnostic depth. Roughly 25 % of the total consumption takes place in the four layers investigated. For the 14 day and 21 day irrigated trees consumption in the upper layers is slightly higher than in the lower layers. For the seven day irrigated trees uppermost and deepest layer consume most. It can't be excluded that this might be related to deep percolation from this zone or different retention properties in the lower part (compare section 3.1.2 below).

The kc is the actual evapotranspiration normalized over the potential evapotranspiration. For the antecedent irrigation project actual evaporation and kc's were calculated for a reference period of 15 days. The potential ET was taken from pan values and comparatively calculated with Blayney-Criddle (BC) method. The average results for irrigation seasons 1991 – 1994 are concluded in Fig. 23 below. The sections on the x-axis refer to one of these reference periods each. It is noticeable that the course of kc's is strongly determined by the course of the actual ET, this indicates that potential ET is fairly stable over this period of time. The values themselves and differences between BC and pan based kc's are bigger for higher irrigation frequencies and also the seasonal course is more pronounced. The peak in November can be interpreted as elevated consumption in the sprouting phase and the peak in February as period of maximum energy incorporation.

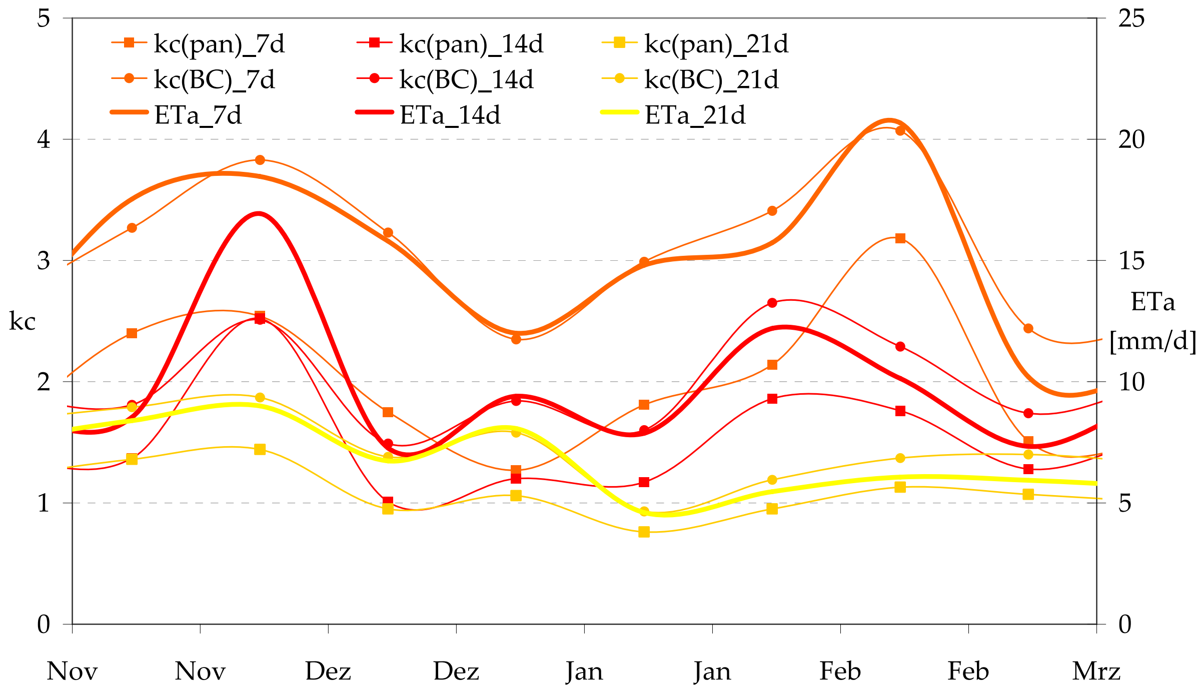


**Fig. 23Actual evapotranspiration and crop coefficients for six year poplars**

## 3.1.2 Soil data analysis

Special attention was spent on soil data evaluation. The initial research of the irrigation – growth project indicated that soil was quite homogeneous and visual appraisal on site seemed to confirm this. Nevertheless, as La Libertad is situated at the border of genetically different soils (Fig. 10) and surrounding is highly variable considering salinization and potential vegetation, it seemed valuable to gather more detailed information. Hence a sampling campaign was carried out on July 23rd 2008. Soil was sampled at six points and at each point in four depths. The points and extensions of the investigation site were georeferenced with a GPS handheld. Distribution of sampling points and configuration of the site is displayed in Fig. 24

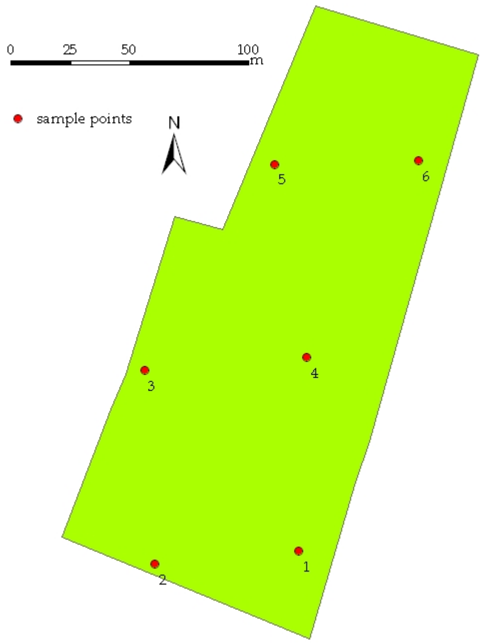


**Fig. 24 Georeferenced distribution of sample points**

### Physical soil properties

The understanding and evaluation of water movement in the subsurface is directly based on a proper estimation of soil properties, they indicate evolution, behavior and threads of a soil. With respect to modeling, soil parameters can be divided into three groups: porosity is a direct input parameter that drives model equations. Bulk density and grain size distribution are used to equip sub-models to parameterize retention models. Finally particle density and sedimentation volume are applied in "sub-sub-models" (section 2.3.2) to estimate other soil properties as the ones mentioned above.

**Tab. 12 Bulk densities at different sample points and sample layers**

| **Bulk density [g/cm³]** | | | | | |
|---|---|---|---|---|---|
| MP | mean MP | SD MP | depth | mean depth | SD depth |
| 1 | 1.32 | 0.07 | 0 - 30 cm | 1.39 | 0.06 |
| 2 | 1.39 | 0.10 | 30 - 60 cm | 1.37 | 0.04 |
| 3 | 1.38 | 0.13 | 60 - 90 cm | 1.34 | 0.04 |
| 4 | 1.38 | 0.15 | 90 - 150 cm | 1.39 | 0.09 |
| 5 | 1.37 | 0.01 | | | |
| 6 | 1.37 | 0.13 | | | |
| mean | 1.37 | 0.10 | mean | 1.37 | 0.06 |
| SD | 0.02 | | SD | 0.02 | |
| VC | 0.02 | | VC | 0.02 | |

Bulk density describes the ratio of weight to volume of an undisturbed soil package. The parameter could be determined for 20 of the soil sample, the other four showed problems during sampling procedure. In Tab. 12 comparison of bulk density values is displayed for the different sample points and diagnostic layers. For both comparison dimensions values are pretty homogeneous and don’t show trends in direction or with depth. SDs are higher for sample points than for depth comparison, indicating that soils layers are more heterogeneous than locations.

**Tab. 13 Particle densities at different sample points and sample layers**

| **Particle density [g/cm³]** | | | | | |
|---|---|---|---|---|---|
| MP | mean MP | SD MP | depth | mean depth | SD depth |
| 1 | 2.61 | 0.15 | 0 - 30 cm | 2.54 | 0.10 |
| 2 | 2.60 | 0.08 | 30 - 60 cm | 2.62 | 0.04 |
| 3 | 2.64 | 0.08 | 60 - 90 cm | 2.63 | 0.06 |
| 4 | 2.66 | 0.04 | 90 - 150 cm | 2.69 | 0.03 |
| 5 | 2.60 | 0.08 | | | |
| 6 | 2.63 | 0.06 | | | |
| mean | 2.62 | 0.08 | mean | 2.62 | 0.06 |
| SD | 0.02 | | SD | 0.06 | |
| VC | 0.01 | | VC | 0.02 | |

Particle density describes the specific weight of grains that make up the soil. Values were determined for the complete population of 24 samples. Tab. 13 shows the values of particle density in a comparison along the different sample sites and sample layers. Generally values are rather high, quartz soils commonly have particle densities around 2.4 g/cm³. This might indicate basaltic rocks or feldspar as geological source of the material as these formations have higher material densities. In the table mean values and SDs of each group are given. For the different sample points no clear tendency can be identified, values range from 2.60 to 2.66 and show relatively low and with the exception of point MP1 even SD. A trend in direction can’t be identified. In contrast to that particle density increases continuously with depth. Values range from 2.54 in the uppermost layer to 2.69 in the lowest layer. SD in the layers is lower that between sample points, confirming the assumption that heterogeneity is higher in vertical direction. An explanation might be that, due to the alluvial genesis of the soil, particle composition varies throughout the time of sedimentation and development of the soil. Geological and geochemical investigations could reveal this instance.

**Tab. 14 Soil porosities at different sample points and sample layers and according to different determination methods**

| **Porosity [-]** | | | | | |
|---|---|---|---|---|---|
| MP | mean MP | SD MP | MP | PV_d [%] | PV_r [%] |
| 1 | 0.47 | 0.04 | 3.1 | 0.47 | 0.372 |
| 2 | 0.46 | 0.05 | 3.4 | 0.46 | 0.312 |
| 3 | 0.48 | 0.02 | 5.2 | 0.46 | 0.367 |
| 4 | 0.49 | 0.01 | 6.1 | 0.45 | 0.395 |
| 5 | 0.47 | 0.02 | 6.4 | 0.51 | 0.329 |
| 6 | 0.48 | 0.03 | | | |
| mean | 0.47 | 0.03 | mean | 0.47 | 0.36 |
| SD | 0.01 | | SD | 0.02 | 0.03 |
| VC | 0.02 | | VC | 0.05 | 0.10 |
| depth | mean depth | SD depth | | | |
| 0 - 30 cm | 0.44 | 0.02 | | | |
| 30 - 60 cm | 0.48 | 0.02 | | | |
| 60 - 90 cm | 0.50 | 0.01 | | | |
| 90 - 150 cm | 0.49 | 0.03 | | | |
| mean | 0.47 | 0.02 | | | |
| SD | 0.02 | | | | |
| VC | 0.05 | | | | |

Porosity was determined in two ways. One possibility is defined by the ratio of bulk to particle density, as given in F. 17. Column PV_d represents these density-computed values in Tab. 14. The second method to evaluate porosity is by saturated water content; values are given in column PV_r. There is a remarkable difference between the two values that can not be fully explained by methodical differences. Only two factors might be mentioned: saturated water content was determined in a disturbed, compacted sample and, as mentioned above, certain problems occurred during sample taking of the bulk density samples. The PV_d values are very high and uncommon for soils with a low organic content in contrast PV_r values are to low for most soils. For loamy sands, the group to which the soils belong according to a first visual estimation, porosities typically range around 0.4.

**Tab. 15 Sedimentation volumes at different sample points and sample layers**

| **Sedimentation volume [ml/100g]** | | | | | |
|---|---|---|---|---|---|
| MP | mean MP | SD MP | depth | mean depth | SD depth |
| 1 | 89 | 2.00 | 0 - 30 cm | 92 | 6.20 |
| 2 | 88 | 4.12 | 30 - 60 cm | 85 | 6.53 |
| 3 | 78 | 5.16 | 60 - 90 cm | 86 | 3.67 |
| 4 | 84 | 8.00 | 90 - 150 cm | 81 | 6.53 |
| 5 | 88 | 8.64 | | | |
| 6 | 91 | 3.83 | | | |
| mean | 86.25 | 5.29 | mean | 86.25 | 5.73 |
| SD | 4.64 | | SD | 4.40 | |
| VC | 0.05 | | VC | 0.05 | |

Sedimentation volume is a parameter that allows estimation of texture properties. [Nijensohn, 1962b] states a strong correlation between clay content and SV. In Mendoza it is used for a general texture classification. For the project all samples were analyzed, mainly to identify most heterogeneous samples for a more detailed view. SVs vary considerably between the different sample points. Lowest mean values occur for the central sample points "3" and "4". No tendencies can be identified for a change with direction. Mean values of SV augment with smaller distance to surface, indicating that material gets sandier in deeper layers. This finding may correspond to different soil composition as described for particle density. Absolute highest SV amounts to 96, it occurs at point six in the uppermost layer. The lowest value was examined for the lowest layer of point 3.

Grain size distributions (Fig. 25) were determined for the six soils that showed biggest variability in SV, namely 2-4, 3-1, 3-4, 5-2, 6-1 and 6-4. Hence all sample points, aside from MP1 and all depths aside from 75 cm were considered. All soils examined show the whole range of texture classes. Skeletal fraction accounted in all samples with less than 1 %, hence soil can be defined as stone free. Biggest variation between the samples results for silt fraction, between 0.01 - 0.1 mm. In clay and silt fractions soils 6-1 as finest and 3-4 as coarsest soil define the ranges. This corresponds to the findings of SV determination 6-1 ranged highest and 3-4 lowest. For medium sand fraction and coarser soils 6-4 and 2-4 are limiting.

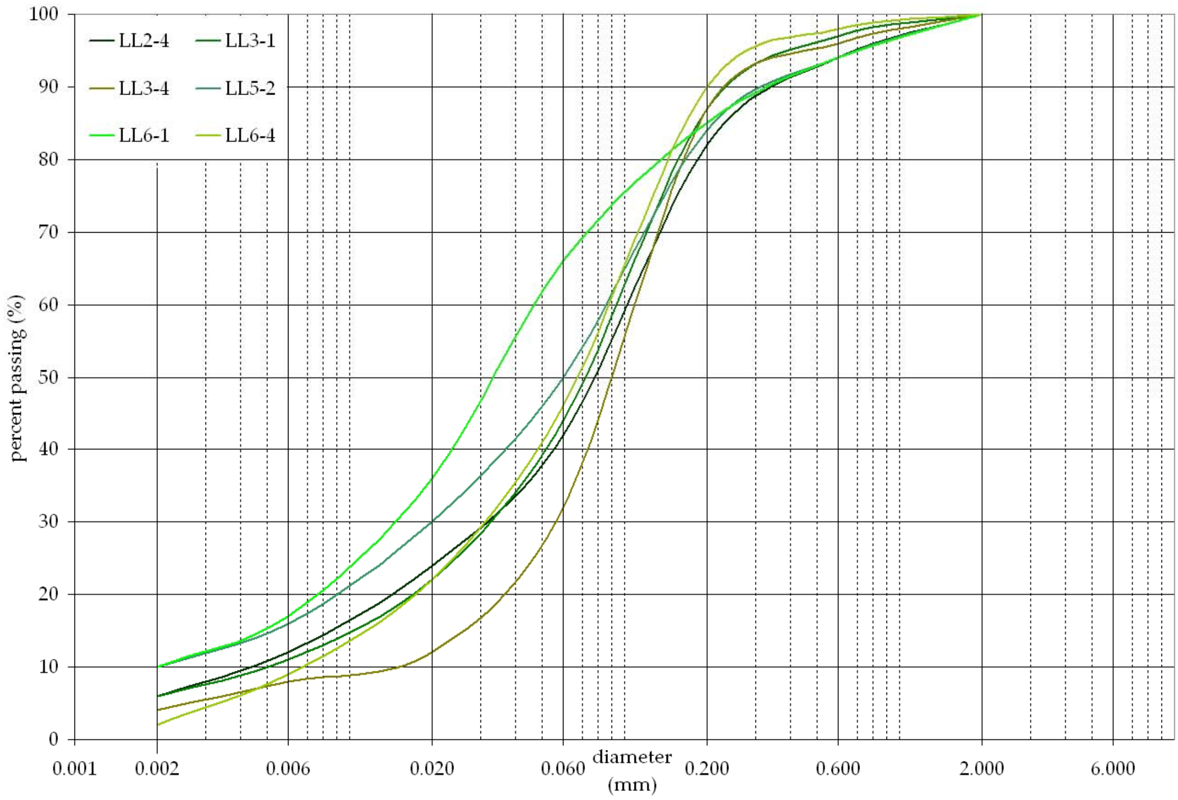


**Fig. 25** **Grain size distribution of six soils at the investigation site**

Texture properties are concluded in Tab. 16. Texture class portions refer to the texture class ranges as defined by [AG Boden, 1994]. Sand and silt represent are biggest fractions of all soils with portions roughly between 30 – 60 %. Absolute variance is most pronounced for sand, where fraction ranges between 34 – 68 %. Clay shows highest relative variability but absolute fractions are generally lowest (2 – 10 %). For classification, texture ranges were applied as proposed by US Natural Recourses Conversation Service (NRSC) [USDA, 1999] and by Manual of Soil Mapping (KA4, Bodenkundliche Kartieranleitung) [AG Boden, 1994] respectively. According to NRSC soils are sandy loams (Ls), loams (L) and silty loams (Lu). While KA4 classifies medium silty sand (Su3), very silty sand (Su4), loamy silty sand (Slu) and loamy sandy silt (Uls). SV categories, as defined in [Nijensohn, 1962a] correspond fairly to KA4 classification, especially as silt is not considered separately from loam, soils are identified as sand, loamy sand and loam. Nevertheless texture categories are coarser than NRSC and KA4 categories. Generally NRSC gives classifications with a shift towards finer soils.

**Tab. 16 Texture porperties and classification for sampled soils**

| Texture properties | | | | | | |
|---|---|---|---|---|---|---|
| sample point | LL2-4 | LL3-1 | LL3-4 | LL5-2 | LL6-1 | LL6-4 |
| portion of texture class [%] | | | | | | |
| clay | 6 | 6 | 4 | 10 | 10 | 2 |
| silt | 36 | 38 | 28 | 40 | 56 | 44 |
| sand | 58 | 56 | 68 | 50 | 34 | 54 |
| clasification | | | | | | |
| NRSC | Ls | Ls | Ls | L | Lu | Ls |
| KA4 | Su3 | Su3 | Su3 | Slu | Uls | Su4 |
| SV-categories | Sl | Sl | S | Sl | L | Sl |
| SV [ml/100g] | 84 | 80 | 72 | 92 | 96 | 88 |

The correlation between clay content and SV as stated above could not be confirmed for the dominion of samples taken. Sand and silt content show much stronger dependency from SV, as to be seen in Fig. 26. Constrictively may be stated that relative variation and portion were lowest for clay fraction and soils were quite coarse. Hence clay fraction has probably only a minor influence on the SV determined.

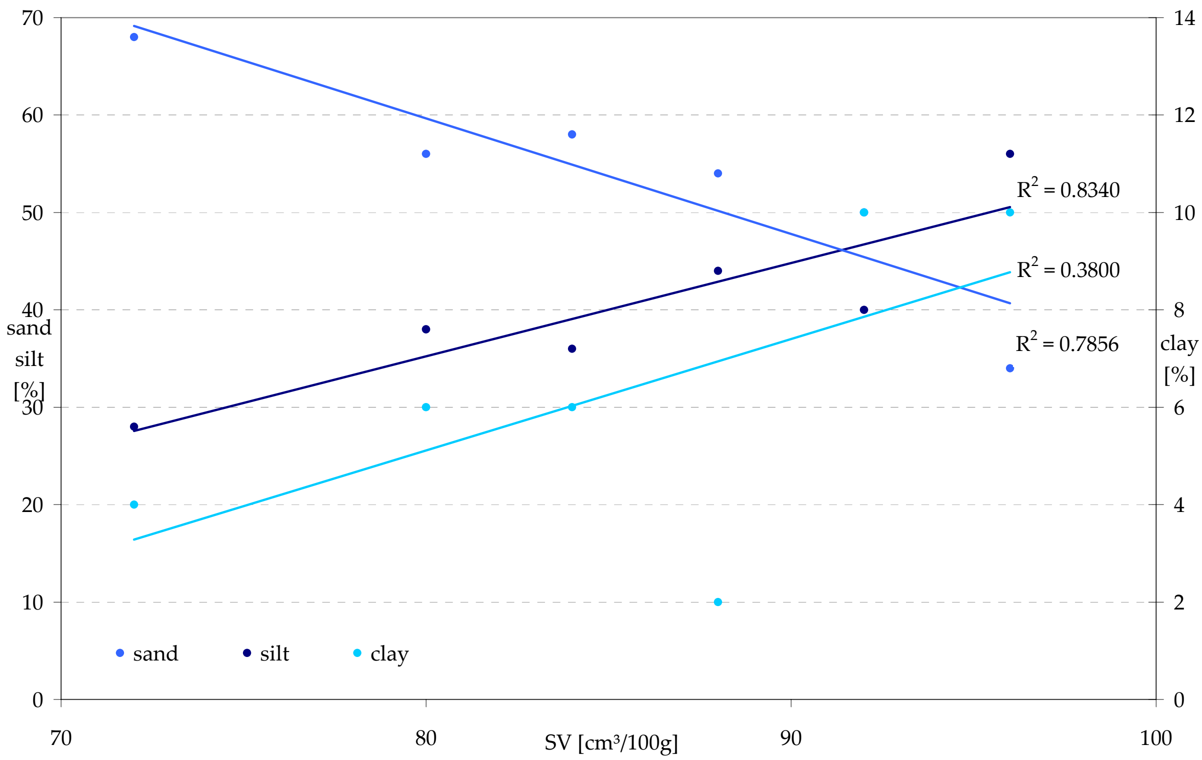


**Fig. 26** **Correlation between texture class portion and sedimentation volume**

## Interpolation of soil properties

In order to discover patterns in the distribution of the soil properties grids were interpolated applying a linear Kriging method. Grids were generated for each sampling layer, and three cross sections, as given in Fig. 27. The actual sample points can be seen in Fig. 13. The lines within the map mark position of the cross sections, they correspond to northing coordinates 6321700 and 6321800 and easting coordinate 2546900. Interpolation was carried out in a 5 m resolution. The coordinates refer to the Universal Transverse Mercator projection.

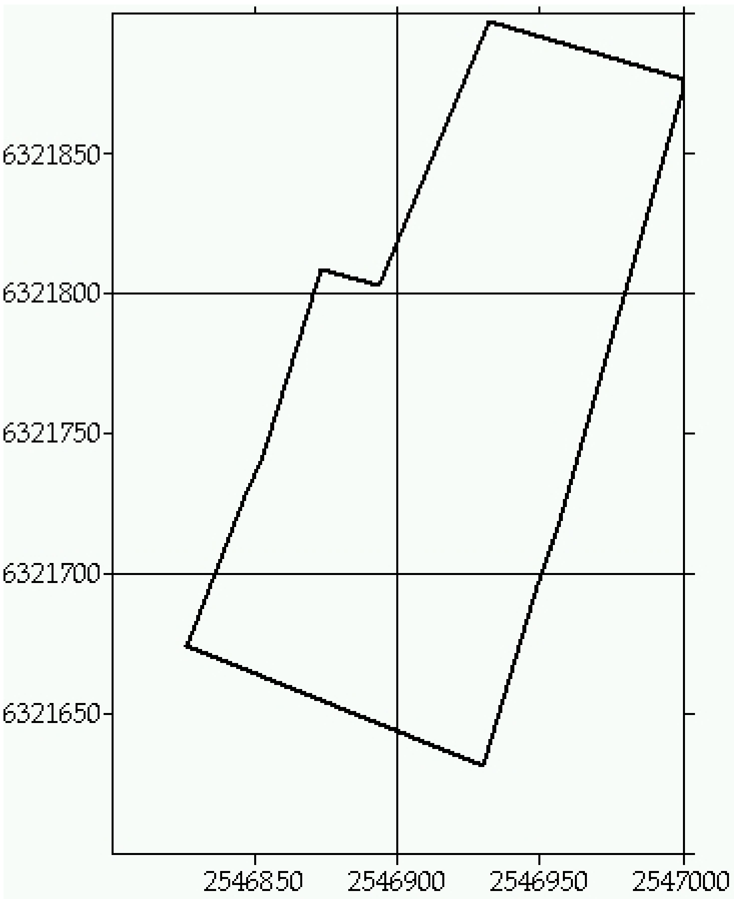


**Fig. 27 Position of the cross sections (lines) for the interpolation of soil properties**

In Fig. 28 four maps of the sedimentation volume are given. The layers are arranged as 0.15 mbsl upper left, 0.45 mbsl upper right, 0.75 mbsl lower left and 1.20 mbsl lower right. The findings from the statistical analysis (Tab. 15) are confirmed, SV decreases with depth, indicating more pervious soil in deeper layers. Additionally the horizontal distribution of the values can be captured easily. Generally SVs are higher in the eastern (right) part of the area. A bay of material with lower SVs enters the site from the west; this material bay seems to expand with depth, with the only exception at 75 cm below surface. The material in the eastern part is more homogeneous, apart from a more elevated SV in the top layer, the deeper strata range all with SVs of 80 – 85.

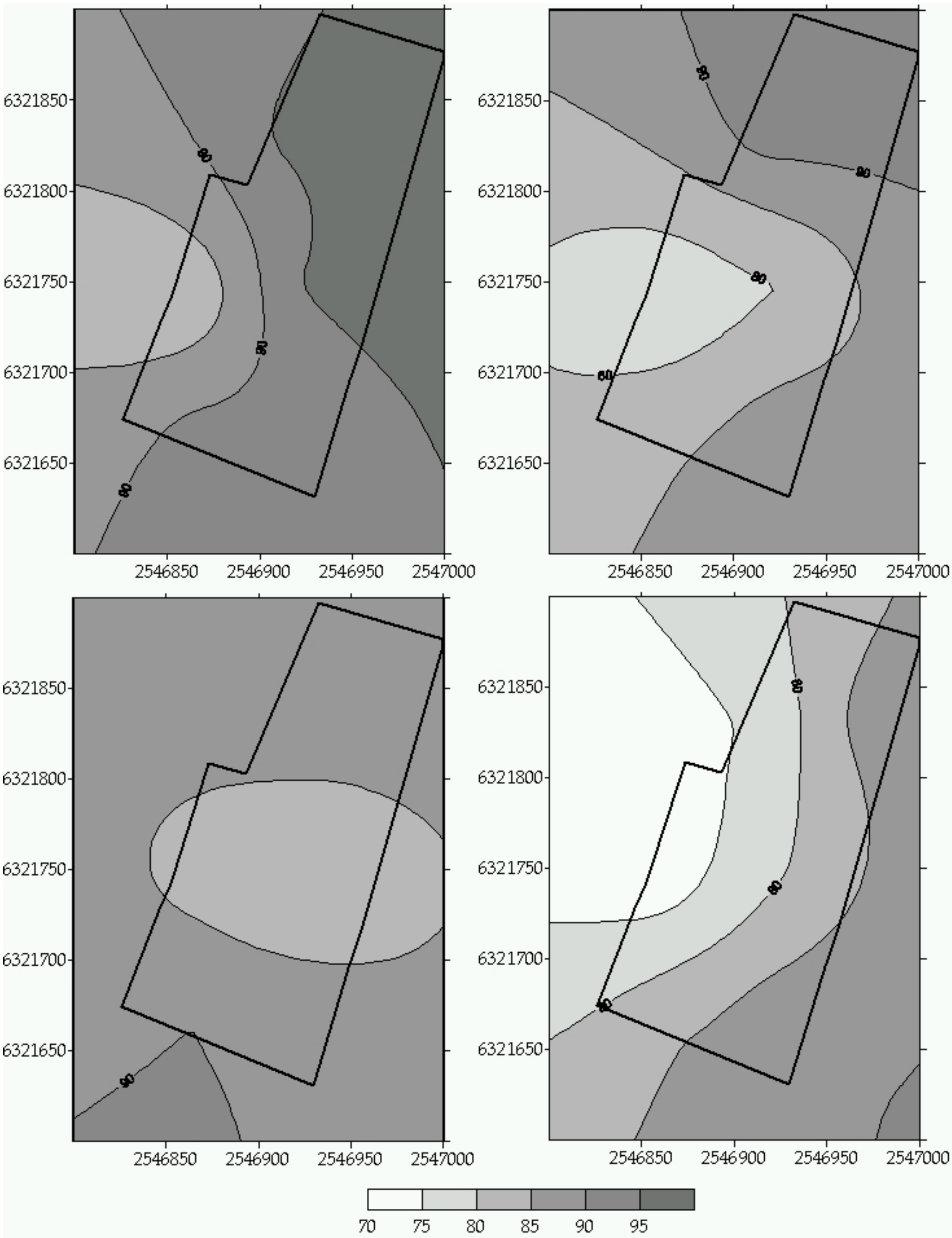


**Fig. 28 Distribution of sedimentation volumes within the four sampling layers**

For the cross section grids the lines along from the coordinates of the horizontal grids were extracted, recombined and again interpolated. Results, also for the SV, are given in Fig. 29. Mark that horizontal scale is in meters and vertical scale in centimetres. The upper plot is the cross section along the northing line. The image suggests that the bay of higher SVs identified above is more pronounced in the northern part of the area (right) while in the southern part the profile is more homogeneous. The two lower images are the cross sections along the easting lines. They support the finding of the bay in the West of the area. The more homogeneous profiles in the East are also confirmed.

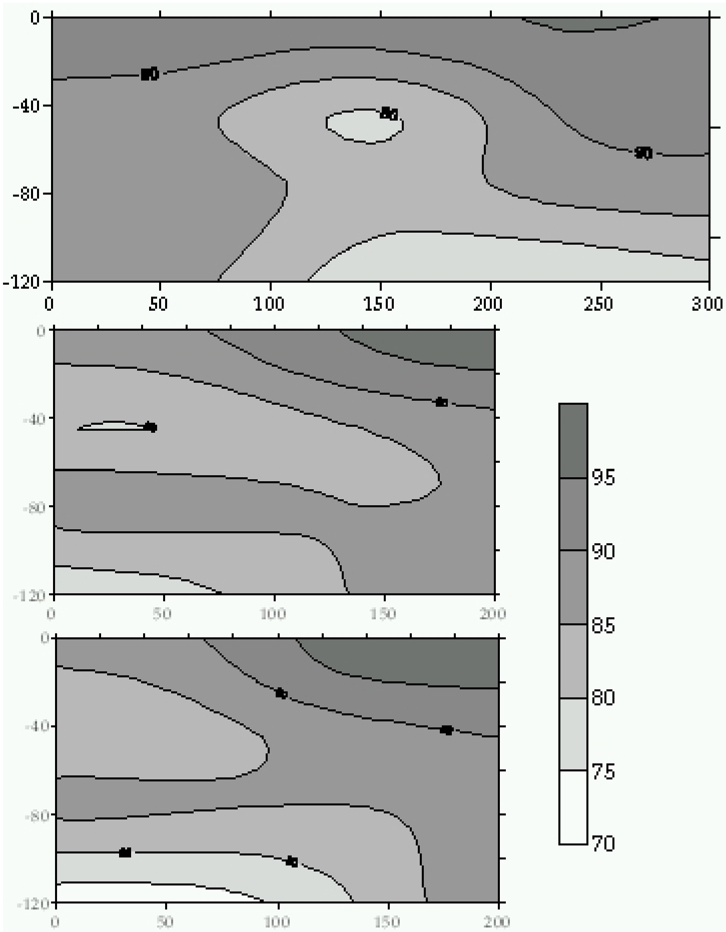


**Fig. 29 Distribution of sedimentation volumes along three cross sections**

## Hydraulic properties

Retention curves were determined at INTA (Instituto Nacional de Tecnología Agropecuaria) laboratories. The water content – suction head relation was measured for saturated condition and six suction heads, at 5, 10, 30, 100, 300 and 1500 cm WC. Fig. 30 shows measured data in green shades and estimates of two prediction models (ROSETTA, DIN4220) and a fitting model (RETC) are given in blue shades. Axis of ordinates shows pF value, that represents the decadal logarithm of suction head. As in the experiments above, soils 3.4 and 6.1 define the range of values, with approximately 10% difference in water content for equal suction heads. On the other hand for the range of suction heads considered same water contents correspond to differences in suction head of more than 1000 cm WC. Soil 6.1, that has the finest texture stores highest water contents, while coarsest soil 3.4 stores fewest water. Generally measured curves progress flatter that prediction curves, corresponding to higher loss of water with increasing suction head, the effect will be discussed in 3.1.3, further below.

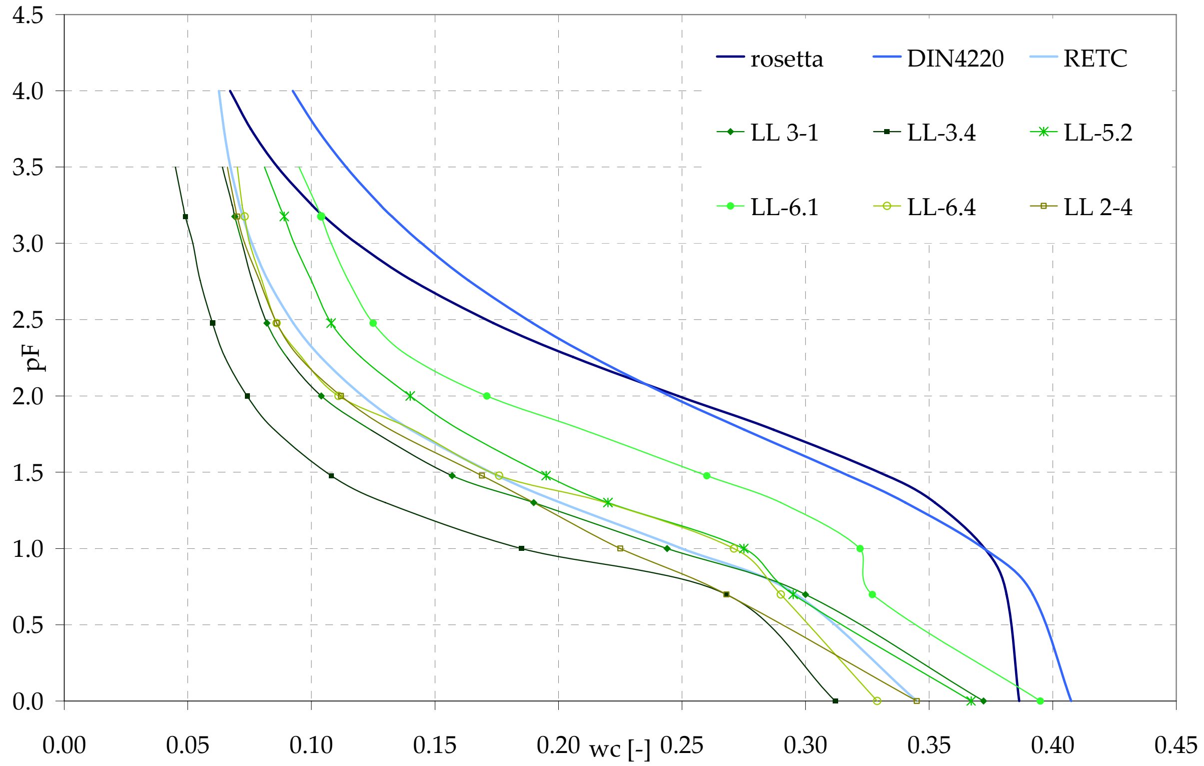


**Fig. 30** **Measured retention curves in comparison to estimation models**

Saturated hydraulic conductivity was determined in laboratory with disturbed soil samples of sample points 3.1, 3.4, 5.2 and 6.4 in a constant head column. Experiments were repeated four to six times with different pressure heads. The values for the repetitions are given in Tab. 17. They represent the average of seven to ten realizations obtained under equal pressure heads. From the average of the realizations, the average of the repetitions was calculated. Additionally SD and variation coefficient of repetitions allow estimating the uncertainty of the determination procedure. Soil 3.4 shows highest conductivity, it is with 5.96 E-06 m/s about eight times higher than soil 6.4’s conductivity that has the lowest value with 7.23 E-07 m/s. Hence the same soils as in the previous experiments defined the range of occurring values. The conductivities of soils 3.1 and 5.2 rank between the extremes with values between 1 E-06 m/s and 2 E-06 m/s. The SDs are generally more than one order of magnitude smaller than mean values, resulting in variation coefficients smaller than 0.10. This narrow distribution indicates a confident estimation of mean value as representative.

**Tab. 17 Saturated hydraulic conductivity of four soil samples**

| Saturated hydraulic conductivity [m/s] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| repetition | 1. | 2. | 3. | 4. | 5. | 6. | mean | sdev | vcov |
| 3.1 | 2.08E-06 | 2.13E-06 | 1.83E-06 | 2.00E-06 | 1.91E-06 | | 1.99E-06 | 1.20E-07 | 0.06 |
| 3.4 | 6.08E-06 | 6.15E-06 | 5.71E-06 | 5.59E-06 | 6.34E-06 | 5.91E-06 | 5.96E-06 | 2.82E-07 | 0.05 |
| 5.2 | 1.21E-06 | 1.13E-06 | 9.66E-07 | 9.82E-07 | 1.01E-06 | 1.11E-06 | 1.07E-06 | 9.98E-08 | 0.09 |
| 6.1 | 7.07E-07 | 7.34E-07 | 6.94E-07 | 7.58E-07 | | | 7.23E-07 | 2.86E-08 | 0.04 |

Dispersion was determined in the same experimental setup as hydraulic conductivity. As the experimental procedure is quite elaborate only the soils that promised to define the range of possible values were examined. The column was charged with a step impulse of 0.01 M sodium chloride solution. Dispersion coefficients were estimated to be 0.053 m²/d for soil 3.1 and 0.097 m²/d for soil 6.4. Dispersivities result in 0.11 m and 0.38 m respectively.

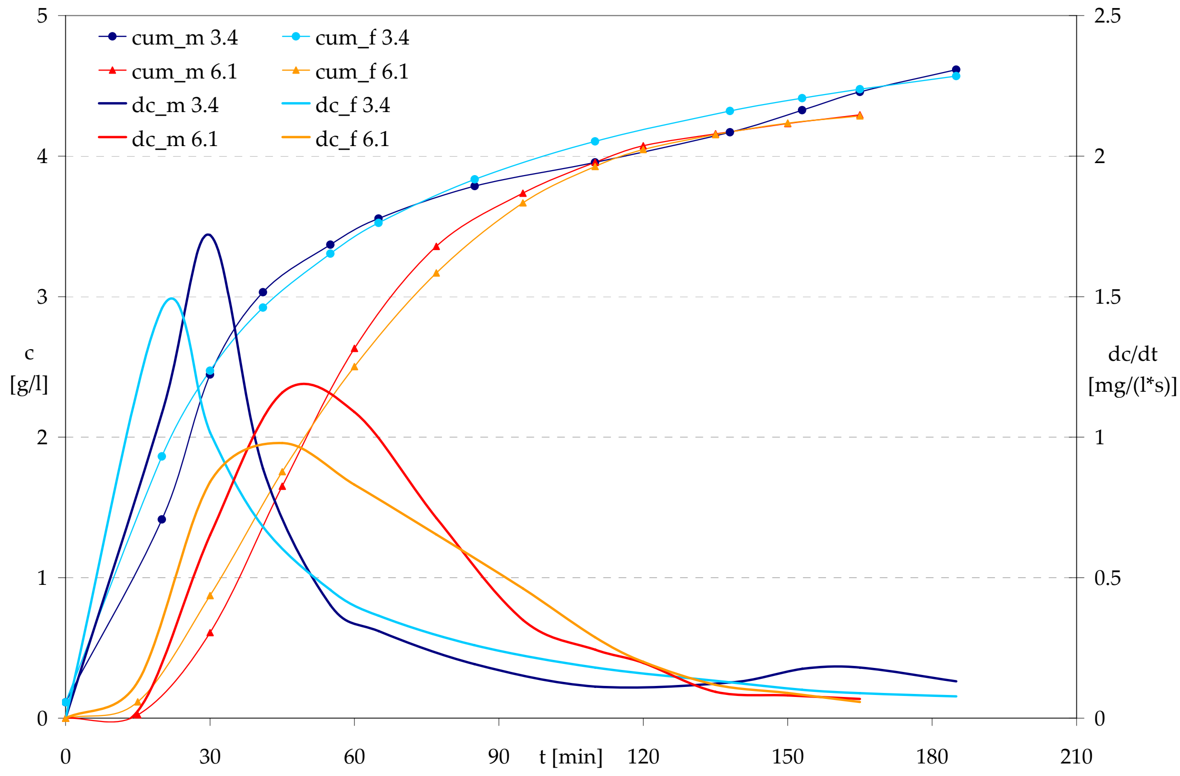


**Fig. 31 Measured and fitted curve progression for concentration breakthrough of two soils**

Fig. 31 visualizes the results of the experiments. Red/ orange lines show the breakthrough curve for soil 6.1, blue lines for soil 3.4. The dotted lines represent the measurements of cumulated concentration progression. Bold lines stand for the differentiated cumulated concentration with respect to time. They describe distribution of travel time. The lines indicated with _m show measured values; the ones indicated with _f are fitted with STANMOD tool. It appears that soil 3.4 has a much steeper breakthrough curve than soil 6.1. Hence the peak of the differentiated curve is much more pronounced. This corresponds to less dispersivity for sample 3.4, as to be expected for a coarser, more permeable soil.

## Rank analysis of retention properties

As described in section 2.3.2 soil retention properties were evaluated qualitatively applying a rank analysis. Tab. 18 gives an example for the rank analysis of interannual variation for seven day irrigation configuration.

**Tab. 18 Qualitative retention parameters and ranks for seven day irrigation**

| | 7d | mean_bi | mean_ai | sdev_bi | sdev_ai | mean_diff | |
|---|---|---|---|---|---|---|---|
| 91-'92 | 0 - 30 cm | 15.17 | 22.46 | 2.52 | 3.32 | 7.81 | |
| | 30 - 60 cm | 14.63 | 20.80 | 2.25 | 2.52 | 6.51 | |
| | 60 - 90 cm | 14.93 | 21.10 | 2.39 | 3.11 | 6.38 | |
| | 90 - 150 cm | 14.52 | 19.83 | 2.66 | 5.06 | 5.97 | |
| 92-'93 | 0 - 30 cm | 14.34 | 20.32 | 4.29 | 2.85 | 6.02 | |
| | 30 - 60 cm | 14.33 | 18.40 | 3.84 | 4.83 | 5.11 | |
| | 60 - 90 cm | 12.30 | 16.71 | 4.02 | 2.27 | 4.51 | |
| | 90 - 150 cm | 13.25 | 17.29 | 6.00 | 2.61 | 5.75 | |
| 93-'94 | 0 - 30 cm | 15.08 | 20.65 | 3.32 | 1.93 | 6.01 | |
| | 30 - 60 cm | 13.38 | 18.52 | 4.03 | 2.41 | 5.97 | |
| | 60 - 90 cm | 15.12 | 21.80 | 3.99 | 3.04 | 6.78 | |
| | 90 - 150 cm | 11.11 | 14.59 | 4.39 | 3.73 | 5.30 | |
| | 7d | r_mean_bi | r_mean_ai | r_sdev_bi | r_sdev_ai | r_mean_diff | r_mean |
| 91-'92 | 0 - 30 cm | 1 | 1 | 3 | 1 | 1 | 1.4 |
| | 30 - 60 cm | 1 | 1 | 3 | 2 | 1 | 1.6 |
| | 60 - 90 cm | 2 | 2 | 3 | 1 | 2 | 2.0 |
| | 90 - 150 cm | 1 | 1 | 3 | 1 | 1 | 1.4 |
| | total | | | | | | 1.6 |
| 92-'93 | 0 - 30 cm | 3 | 3 | 1 | 2 | 2 | 2.2 |
| | 30 - 60 cm | 2 | 3 | 2 | 1 | 3 | 2.2 |
| | 60 - 90 cm | 3 | 3 | 1 | 3 | 3 | 2.6 |
| | 90 - 150 cm | 2 | 2 | 1 | 3 | 2 | 2.0 |
| | total | | | | | | 2.3 |
| 93-'94 | 0 - 30 cm | 2 | 2 | 2 | 3 | 3 | 2.4 |
| | 30 - 60 cm | 3 | 2 | 1 | 3 | 2 | 2.2 |
| | 60 - 90 cm | 1 | 1 | 2 | 2 | 1 | 1.4 |
| | 90 - 150 cm | 3 | 3 | 2 | 2 | 3 | 2.6 |
| | total | | | | | | 2.2 |

In the upper part the water retentions characteristics are displayed. Listed parameters are: mean water content before (mean_bi) and after (mean_ai) SD of the water contents before (sdev_bi) and after (sdev_ai) irrigation and mean difference of water content after irrigation and subsequent value before irrigation (mean_diff). Values are given in percent and refer to each irrigation season and observation layer corresponding to each block and line. The lower part of the table displays the rank corresponding to each value in cross comparison of different years, e.g. SD of water content before irrigation at 30 -60cm below surface was highest in '93-'94 and lowest in '91-'92. The same tables were drawn for the other irrigation configurations and for the interconfigurational comparison of irrigation years.

Ranks of each site-time-configuration combination were averaged over all retention parameters. These mean values were used to calculate interannual and interconfigurational variation coefficient as described in F. 19. Interconfigurational coefficient accounts 0.09 while interannual coefficient is 0.22. Hence the influence of changed environmental boundary conditions at the same spot causes more variation than potentially differing soil properties of different spots under equal environmental conditions. Wilcoxon test of equal distribution was applied, evaluating rank distribution of both cross comparisons. With a T-value of 4.18 hypothesis F. 20 is rejected with a confidence of 99% ($z_{99}$ = 4.09).

## Mass transport properties

Mass transport properties were not determined directly. The parameters clay content, organic matter and pH-value are applied in a SiWaPro-internal sub-model to estimate contaminant properties from an implemented data base and PTFs.

Clay content as given in Tab. 19 shows considerable differences between the different sample points, as indicated by the relatively high variation coefficient. Especially for sample point 3 values range lower than for the other points. Besides of that no trend in direction is detected. SDs are slightly higher within sample points than between them, the mean of SDs of the points (SD MP) is higher than the deviation over sample point means (mean MP). With depth again there is a trend of decreasing clay content values that corresponds to decreasing SV (Tab. 15) and increasing particle density (Tab. 13). This finding is confirmed by a bigger mean variation within the diagnostic layers (SD depth) than between layers.

**Tab. 19 Clay content values at different sample points and sample layers**

| Clay content [%] | | | | | |
|---|---|---|---|---|---|
| MP | mean MP | SD MP | depth | mean depth | SD depth |
| 1 | 7.17 | 0.46 | 0 - 30 cm | 7.86 | 1.42 |
| 2 | 6.83 | 0.94 | 30 - 60 cm | 6.34 | 1.49 |
| 3 | 4.66 | 1.18 | 60 - 90 cm | 6.56 | 0.84 |
| 4 | 6.03 | 1.83 | 90 - 150 cm | 5.42 | 1.49 |
| 5 | 6.95 | 1.98 | | | |
| 6 | 7.63 | 0.88 | | | |
| mean | 6.55 | 1.21 | mean | 6.55 | 1.31 |
| SD | 1.06 | | SD | 1.01 | |
| VC | 0.16 | | VC | 0.15 | |

The distribution of organic matter is summarized in Tab. 20. In general organic matter is relatively low for a cultivated soil. The differences between sample points are again rather high, resulting in the highest VC of all parameters investigated. Sample point 1 has by far the highest organic matter content of all positions although variation within the point is relatively low. Again there is no trend of direction detected; rather surprisingly central points 3 and 4 show slightly lower values than the ones closer to the border. Organic matter content decreases with depth. Although mean OM decreases, variation between the points increases. This may indicate that biologic activity, e.g. root depth varies for the different sample points.

**Tab. 20 Organic matter contents at different sample points and sample layers**

| Organic matter [%] | | | | | |
|---|---|---|---|---|---|
| MP | mean MP | SD MP | depth | mean depth | SD depth |
| 1 | 1.05 | 0.13 | 0 - 30 cm | 0.94 | 0.18 |
| 2 | 0.61 | 0.26 | 30 - 60 cm | 0.71 | 0.15 |
| 3 | 0.58 | 0.16 | 60 - 90 cm | 0.57 | 0.22 |
| 4 | 0.59 | 0.23 | 90 - 150 cm | 0.59 | 0.26 |
| 5 | 0.64 | 0.23 | | | |
| 6 | 0.67 | 0.14 | | | |
| mean | 0.69 | 0.19 | mean | 0.70 | 0.20 |
| SD | 0.18 | | SD | 0.17 | |
| VC | 0.26 | | VC | 0.24 | |

Observed pH values are the measurements with least variation between the different samples. VC is has lowest values compared to the other measures as well for comparison of positions as of layers. Sample point 1 has slightly lower values than the other positions and for all points values increase with depth. But both findings are not significant and below the range of uncertainty of the measurement.

**Tab. 21 pH values at different sample points and sample layers**

| **pH** | | | | | |
|---|---|---|---|---|---|
| MP | mean MP | SD MP | depth | mean depth | SD depth |
| 1 | 7.70 | 0.03 | 0 - 30 cm | 7.79 | 0.10 |
| 2 | 7.79 | 0.08 | 30 - 60 cm | 7.83 | 0.07 |
| 3 | 7.89 | 0.07 | 60 - 90 cm | 7.83 | 0.07 |
| 4 | 7.91 | 0.03 | 90 - 150 cm | 7.88 | 0.10 |
| 5 | 7.84 | 0.06 | | | |
| 6 | 7.85 | 0.03 | | | |
| mean | 7.83 | 0.05 | mean | 7.83 | 0.09 |
| SD | 0.08 | | SD | 0.04 | |
| VC | 0.01 | | VC | 0.00 | |

### 3.1.3 Estimation of soil hydraulic and transport parameters

#### Retention properties

Fig. 32 shows the estimation quality and probability range for the parameterization with ROSETTA model. Exemplarily data is given for soil sample 2.4. The colours are arranged from light to dark blue for increasing input data quality. For each quality level mean (bold line), minimum and maximum probable ranges (fine lines) are given. The suffix _tex corresponds to the estimate if only texture class of the soil is given, _SSC for given sand, silt and clay portions, _SSCBC as before and bulk density and _th1 as before and water content at field capacity (330 cm WC). Uncertainty ranges get notably smaller with increasing data quality. If only texture class is known the range for probable water content values under saturated conditions (pF0) is 0.30 - 0.46, for the best estimation model the range diminishes to 0.33 – 0.37. Nevertheless it gets clear that the measured retention curve is represented badly by all estimated parameter sets. Especially the fast decrease of water content for low suction heads can’t be reproduced satisfyingly. Still _th1 allows the closest approximation to the measured curve. Hence it is indicated to determine at least some characteristic points of the retention curve in order to validate estimation quality and enhance estimation models. An explanation for the bad estimation quality might be that alluvial soils under arid conditions of pedogenesis are not very common and hence contribute only to a small part to the domain that was used to calibrate the pedotransfer functions.

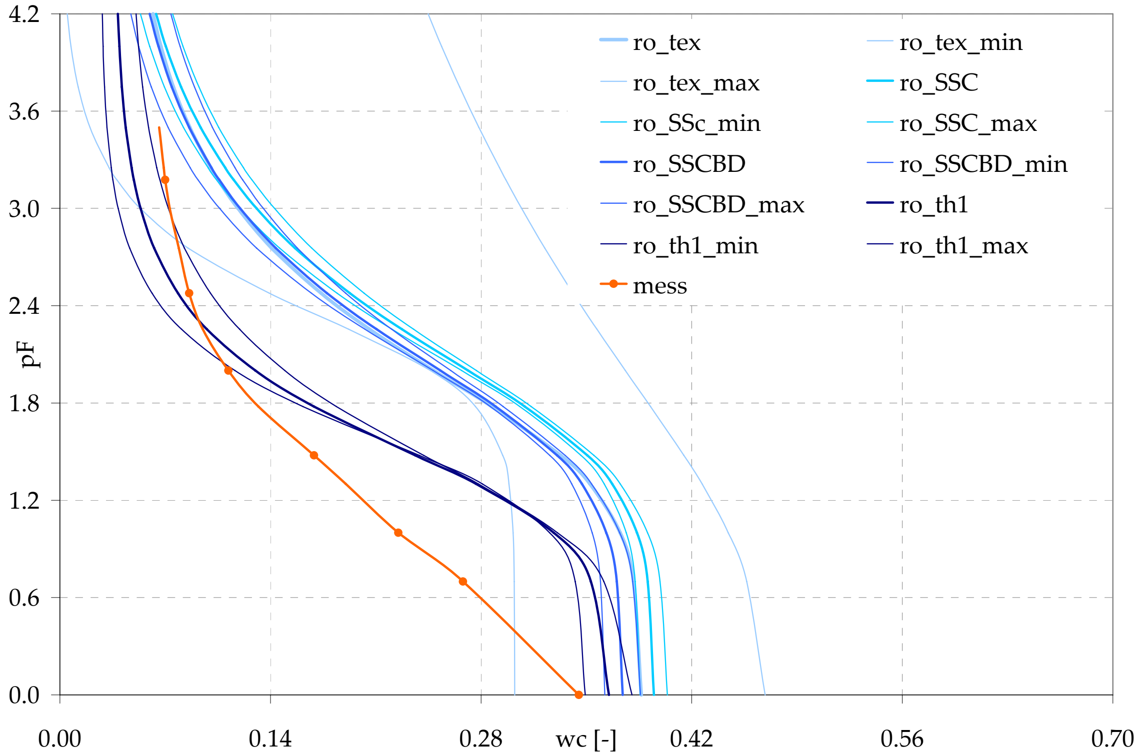


**Fig. 32 Estimation of retention properties with ROSETTA model and measured values for sample 2.4**

Basically the same problem of unsatisfying curve fits appears for DIN 4220 model. In Fig. 33 a range of curves that correspond to the determined texture classes is given. Just as ROSETTA curves DIN 4220 curves overestimate generally water content compared to measured values. Closest curves are given by Ss (pure sand) and St2 (slightly clayish sand).

It should be mentioned that retention curves were determined with disturbed, compacted soil samples. Due to the compaction, porosity is also reduced. This may explain the gap between measured and modelled curves for very low suction heads. On the other hand as pores are smaller water is held back stronger for medium suction heads. Both effects can not explain consistently the difference in the courses of measured and estimated retention curves.

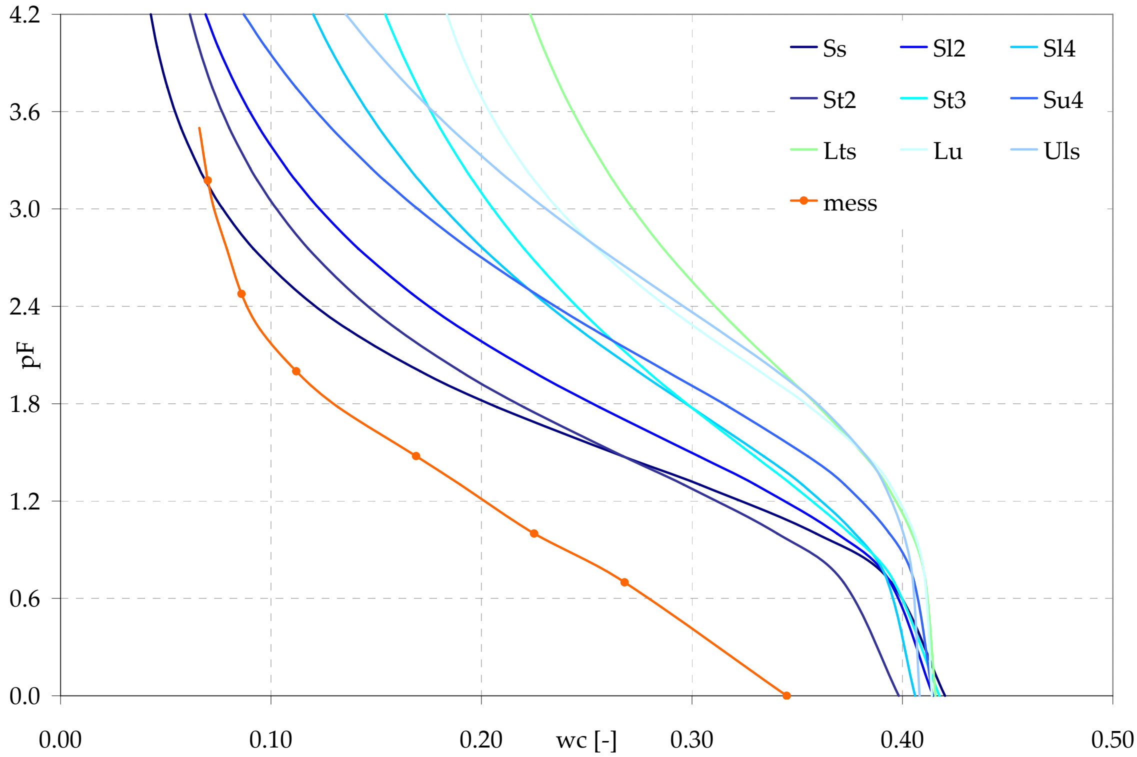


**Fig. 33** **Estimation of retention properties with DIN 4220 parameter sets for sample 2.4**

## Parameter fitting with RETC

**Tab. 22 RETC estimates of van Genuchten parameters and statistical analysis**

| | 2.4 | 3.1 | 3.4 | 5.2 | 6.1 | 6.4 |
|---|---|---|---|---|---|---|
| α [1/cm] | 0.279 | 0.187 | 0.154 | 0.206 | 0.136 | 0.091 |
| n | 1.431 | 1.668 | 1.997 | 1.432 | 1.353 | 1.772 |
| m | 0.301 | 0.400 | 0.499 | 0.301 | 0.261 | 0.436 |
| θ(r) | 0.045 | 0.061 | 0.048 | 0.060 | 0.043 | 0.066 |
| θ(s) | 0.345 | 0.372 | 0.315 | 0.365 | 0.387 | 0.324 |
| kf [m/d] | 1.373 | 1.457 | 1.743 | 1.234 | 0.629 | 1.317 |
| | min | mean | max | STD | VC | all |
| α [1/cm] | 0.091 | 0.175 | 0.279 | 0.065 | 0.369 | 0.177 |
| n | 1.353 | 1.609 | 1.997 | 0.249 | 0.155 | 1.532 |
| m | 0.261 | 0.366 | 0.499 | 0.093 | 0.254 | 0.347 |
| θ(r) | 0.043 | 0.054 | 0.066 | 0.010 | 0.181 | 0.057 |
| θ(s) | 0.315 | 0.351 | 0.387 | 0.028 | 0.080 | 0.352 |
| kf [m/d] | 0.720 | 1.292 | 1.743 | 0.369 | 0.285 | |

Van Genuchten parameters were fitted to the determined retention curves. In contrast to the methods above, not correlated information is applied to estimate the unknown retention characteristics but measured van Genuchten parameters are optimized to reproduce the measured water content – water tension relation.

Tab. 22 concludes the results of the parameter fitting with RETC. Conductivity values are given as estimated by ROSETTA from the RETC-fitted van Genuchten parameters. The upper part gives the van Genuchten values and saturated conductivity for every soil sample, the lower part gives a statistical evaluation of the findings. The single values correspond roughly to sands (scaling parameter, residual water content) or loamy sand (increase parameter, saturated conductivity). Saturated water contents are slightly lower than literature values, probably a consequence of the determination for disturbed samples. The statistical analysis shows that the heterogeneity of the different parameters varies considerably. The variation coefficient is biggest for the scaling parameter and smallest for the saturated conductivity. The mean values correspond satisfyingly with the "all" values that were obtained by fitting the parameters to all samples at the same time. Fitting quality was generally high, rRMSE was less than 2 % for all samples, less than 5 % for the all parameter set. The fitting quality is visualized in Fig. 34. Generally the curves are well fitted. There is no systematic tendency detectable, that higher or lower suction heads are reproduced worse. The curves of generally higher or water content at same pressure head also do not give worse approximations. Irregularities in the measured curve are not reproduced by the program, e. g. the step of curve LL 6.1 is not found in the fitted course. This is mainly because of the limited flexibility of van Genuchten model.

A trail to reduce the number of estimation points was carried out. With four points it was still possible to reproduce the retention curve satisfyingly (rRMSE < 10 %). The fitting was generally better if the input values covered a broad range of water tensions.

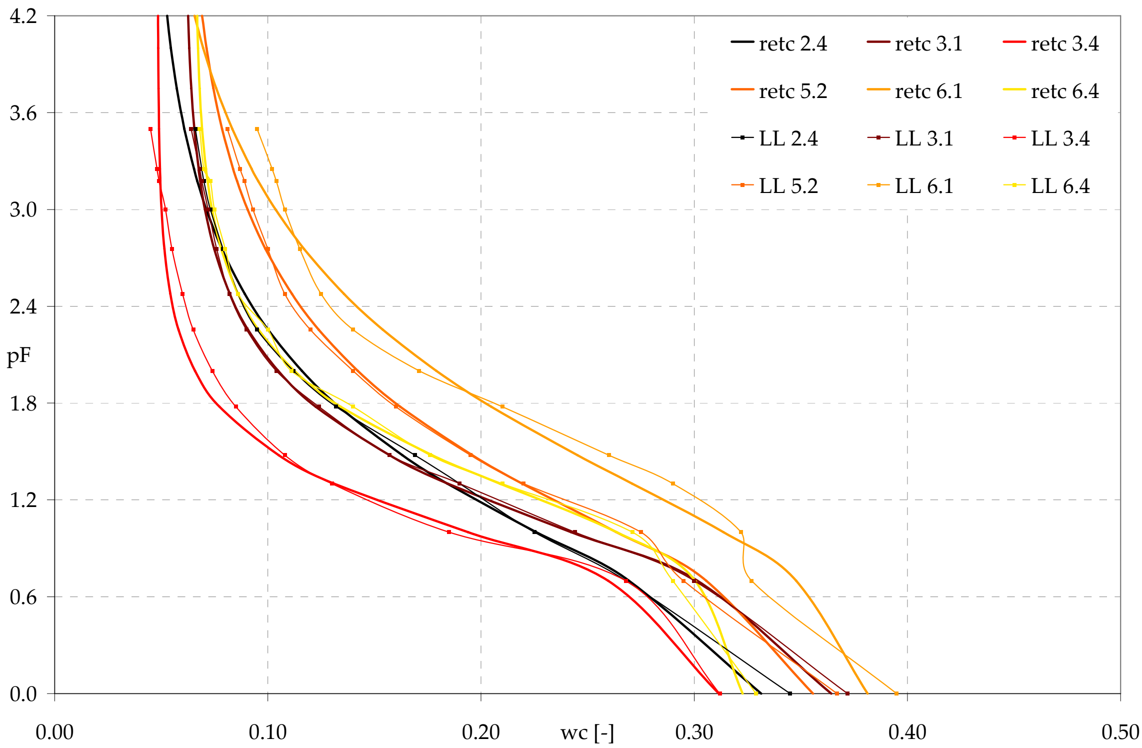


**Fig. 34 Measured and fitted retention curves**

## Unsaturated hydraulic conductivity

For unsaturated hydraulic conductivity no actually measured data was collected. ROSETTA software offers an estimation routine based on the parameter estimation routines applied for the determination of soil hydraulic conductivity. In RETC code the Corey-Brooks model is used to retrieve conductivity parameters form the measured retention curve.

In Fig. 35 the estimates of unsaturated conductivity functions are visualized. Orange graph is the estimate given by RETC as determined based on all measured retention data. The red lines are based on van Genuchten parameters and represent the maximum variability defined for sandy loams according to DIN 4220. The blue lines cover the uncertainty ranges given by ROSETTA parameter estimation. Thin lines define the ranges while bold lines are the central estimate. Considering consistency it might be remarked that all estimates show similar tendencies although the ranges are very broad. For saturated conductivities the range is most extended for DIN 4220 estimates from $4x10^{-5}$ m/s to $2x10^{-7}$ m/s while more than two orders of magnitude are covered, this uncertainty is more or less stable over the considered range of suction heads. ROSETTA gives an uncertainty range of roughly one order of magnitude for saturated conductivity between $1x10^{-5}$ m/s and $1x10^{-6}$ m/s, but the variability increases fast for unsaturated conditions. When comparing the bold lines only the models different models give quite similar estimates. From saturation to PWP (pF 4.2) conductivity decreases from $1x10^{-5}$ m/s to $1x10^{-7}$ m/s and difference between the estimates is always less than one order of magnitude. Critically it has to be stated that the predicted courses cover a very broad range of possible values. The RETC estimate that is based on the measured retention curve data is placed fairly in the center of the estimates. The range given by ROSETTA appear to be both rather unrealistic, neither is it probable that conductivity stays basically constant for such an advanced state of dryness nor is it expectable that soil gets quasi-impermeable ($1x10^{-11}$ m/s) at less than 10 000 cm suction head.

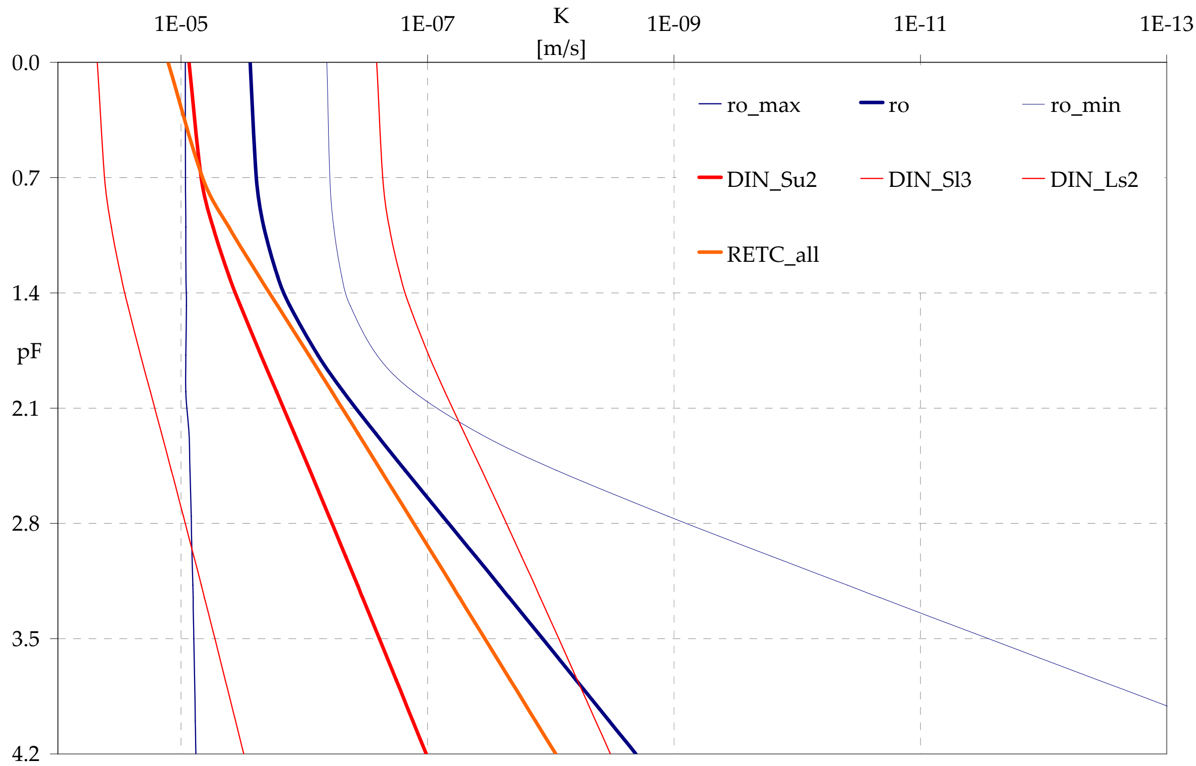


**Fig. 35 Unsaturated hydraulic conductivities as a function of water tension head**

Tab. 23 gives the comparison for estimation parameters determined with ROSETTA. The denotation is similar as for Fig. 32. Some tendencies of the findings may be concluded in the following. Hydraulic conductivity is in the range for sandy loams, generally estimated values rise with rising data quality, uncertainty levels are quite stable with rising data quality. For the tortuosity parameter almost for all soils negative values are found, exception is soil 6.1, one of the soils with the lowest conductivity among the researched ones. As already mentioned above (section 1.4.1) negative values for this parameter have no physical base but were found to give best estimations, especially for permeable soils. A statistical evaluation of the determined values is given below, in section 3.2.

**Tab. 23 Unsaturated hydraulic conductivity parameters, ROSETTA estimate**

| Code | kf_min | kf [m/d] | kf_max | λ_min | λ [–] | λ_max |
|---|---|---|---|---|---|---|
| 2.4_tex | 0.929 | 1.122 | 1.315 | 0.047 | -0.674 | -1.394 |
| 2.4_SSC | 0.893 | 1.101 | 1.308 | -0.003 | -0.748 | -1.493 |
| 2.4_SSCBD | 0.994 | 1.212 | 1.429 | -0.124 | -0.940 | -1.756 |
| 2.4_th1 | 1.161 | 1.373 | 1.584 | -0.212 | -1.190 | -2.168 |
| 3.1_tex | 0.865 | 1.055 | 1.245 | 0.151 | -0.546 | -1.243 |
| 3.1_SSC | 0.835 | 1.042 | 1.249 | 0.061 | -0.678 | -1.416 |
| 3.1_SSCBD | 1.043 | 1.267 | 1.491 | -0.149 | -0.989 | -1.829 |
| 3.1_th1 | 1.234 | 1.457 | 1.679 | -0.239 | -1.241 | -2.244 |
| 3.4_tex | 1.228 | 1.438 | 1.649 | -0.166 | -1.012 | -1.858 |
| 3.4_SSC | 1.183 | 1.402 | 1.620 | -0.179 | -0.973 | -1.767 |
| 3.4_SSCBD | 1.359 | 1.606 | 1.854 | -0.220 | -0.965 | -1.710 |
| 3.4_th1 | 1.497 | 1.743 | 1.989 | -0.112 | -1.072 | -2.032 |
| 5.2_tex | 0.581 | 0.780 | 0.979 | 0.433 | -0.298 | -1.029 |
| 5.2_SSC | 0.582 | 0.787 | 0.993 | 0.347 | -0.386 | -1.119 |
| 5.2_SSCBD | 0.833 | 1.042 | 1.251 | -0.025 | -0.792 | -1.559 |
| 5.2_th1 | 1.027 | 1.234 | 1.441 | -0.214 | -1.120 | -2.027 |
| 6.1_tex | 0.063 | 0.314 | 0.565 | 1.878 | 0.501 | -0.876 |
| 6.1_SSC | 0.168 | 0.388 | 0.609 | 1.191 | 0.113 | -0.965 |
| 6.1_SSCBD | 0.204 | 0.417 | 0.630 | 1.176 | 0.133 | -0.910 |
| 6.1_th1 | 0.439 | 0.629 | 0.820 | 0.831 | -0.044 | -0.919 |
| 6.4_tex | 0.894 | 1.081 | 1.268 | 0.465 | -0.258 | -0.981 |
| 6.4_SSC | 0.860 | 1.074 | 1.288 | 0.094 | -0.715 | -1.525 |
| 6.4_SSCBD | 0.830 | 1.044 | 1.259 | 0.102 | -0.729 | -1.561 |
| 6.4_th1 | 1.102 | 1.317 | 1.533 | -0.172 | -1.162 | -2.152 |

## Dispersivity

In Fig. 31 curves of STANMOD fitted and measured data were given. Systematically for both curves peak concentrations are underestimated by the fitted values. Thus dispersivity is overestimated by the fitting routine. This might be due to the retarded initial phase of the measured breakthrough curve, an effect that can’t be explained with the dispersivity kinetics if salt is assumed to be a conservative constituent.

## 3.2 Sensitivity Analysis

The analyses undertaken are exemplarily and could be extended for a better system comprehension. Only soil parameters were investigated as they determine the governing equations, a similar proceeding would be valuable for plant parameters and the groundwater boundary condition parameters as well.

In Tab. 24 the probability quantiles of the tested parameters are given. Numbers p10 to p90 refer to the 10 to 90 percent non-exceedence quantile, 50 percent quantile corresponds to the mean value. The quantiles were calculated based on the RETC estimates of van Genuchten parameters for the experimentally determined retention curves. Ranges vary according to the statistical deviation between the parameters.

**Tab. 24 Probability quantiles for van Genuchten parameters**

| | p10 | p20 | p30 | p50 | p70 | p80 | p90 |
|---|---|---|---|---|---|---|---|
| $\alpha$ [1/cm] | 0.092 | 0.121 | 0.141 | 0.175 | 0.209 | 0.230 | 0.258 |
| n | 1.290 | 1.399 | 1.478 | 1.609 | 1.739 | 1.818 | 1.927 |
| m | 0.247 | 0.288 | 0.318 | 0.366 | 0.415 | 0.445 | 0.486 |
| $\theta(r)$ | 0.041 | 0.046 | 0.049 | 0.054 | 0.059 | 0.062 | 0.066 |
| $\theta(s)$ | 0.315 | 0.327 | 0.336 | 0.351 | 0.366 | 0.375 | 0.387 |
| kf [m/d] | 0.819 | 0.982 | 1.099 | 1.292 | 1.485 | 1.602 | 1.765 |

Parameters were adapted univariantly according to the standard values given by the p50 column of Tab. 24. An example for the effect of this variation is given in Fig. 35. The effect of the adaptation of the values is shown for different values of the saturated hydraulic conductivity. The discharge course at the lower model boundary is compared for the cases that conductivity corresponds to the 25 % (brown line), 50 % (red line) or 90 % (orange line) quantile. For conductivities lower than the 25 % quantile model run was not stable, so these values were not considered. In the comparison it can be seen, that for higher conductivities maximum discharge is more pronounced and after the peak drying is faster. A shift in the time of maximum discharge is also observed that causes later peak discharges for lower conductivities. Discharge volume, as integration over time, appears highest for the highest conductivity and vice versa, basically because more or less water is stored during the longer transition time or is evaporated at the upper model boundary.

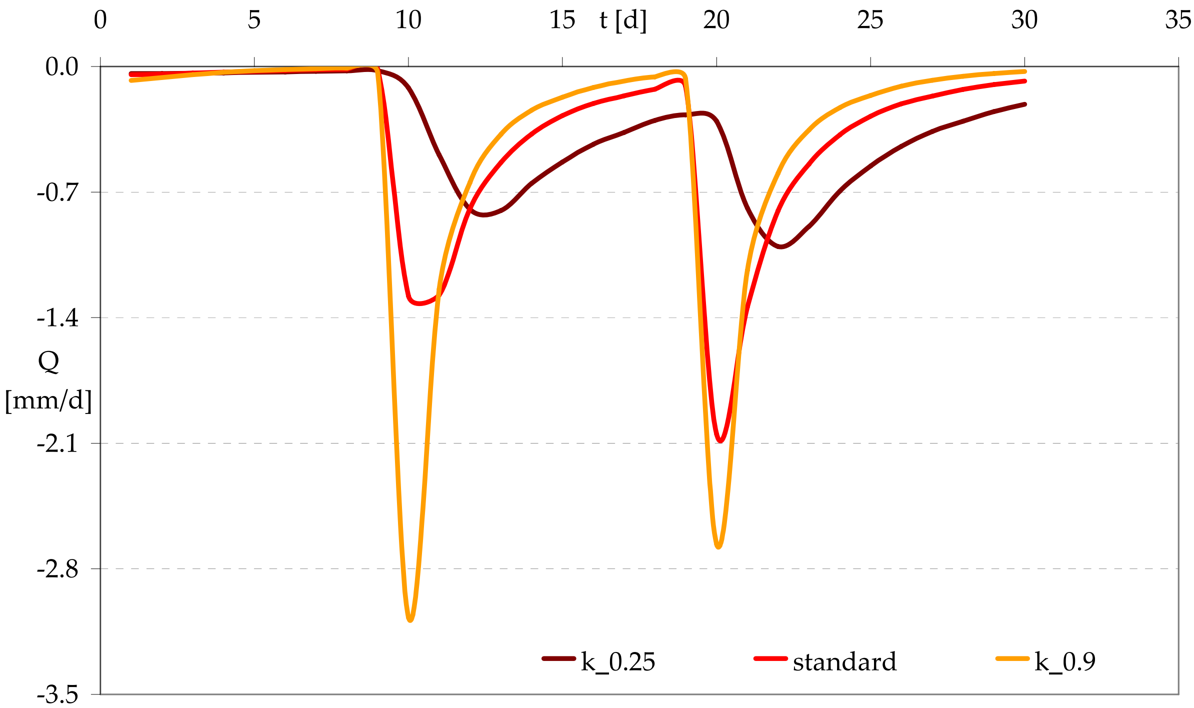


**Fig. 36 Discharge courses for different hydraulic conductivities**

Fig. 37 displays the relative change of water content six days after irrigation in relation to the water content of the "standard" case. Lines that are shorter than the 0.1 – 0.9 range did not perform stable beyond the displayed range and were thus not considered completely. The courses of transformation parameter, hydraulic conductivity and residual water content conduct a fairly linear. For example with increasing m the water content decreases after six days proportionally. The increase parameter has a negative sensitivity from 0.3 – 0.5 quantile and becomes insensitive for further increase. Saturated water content and scaling parameter are both not monotonous. While for the scaling parameter minimum point is at the 0.5 quantile, saturated water content decreases for quantiles smaller than 0.3 and than increases to 0.7 non-exceedence probability.

Similar sensitivity courses are found for maximum discharge and accumulated discharge although parameters may show different courses. The findings confirm that the processes of water transport and storage in the unsaturated soil zone are highly non-linear and great care has to be spent on parameter definition and calibration.

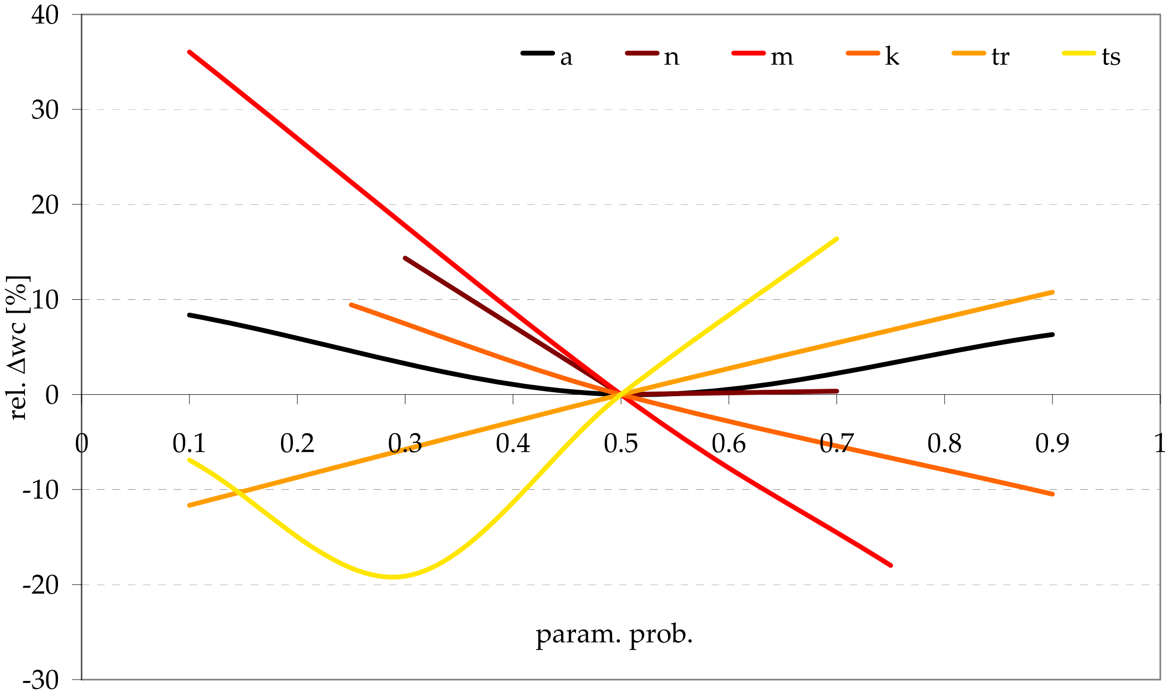


**Fig. 37 Sensitivities of water content to van-Genuchten parameters**

In Tab. 25 the sensitivity indexes of the parameters that showed linear behaviour are concluded. Parameter – target variable combinations with non-linear behaviour are labelled "nl". It is apparent that for the different target values parameters conduct different. The by far highest sensitivity is found for maximum discharge and hydraulic conductivity. Other important relations exist between water content and transformation parameter as well as maximum discharge and residual water content. The generally lower sensitivities of accumulated discharge might be explained with the integrative character of this parameter, after a certain amount of time all water that goes in goes out again and differences in the course are compensated by the accumulation.

**Tab. 25 Sensitivity indexes for the different soil parameters and target variables**

| | SI(Q_acc) | SI(Qmax) | SI(wc) |
|---|---|---|---|
| α | -0.203 | -0.334 | nl |
| n | -0.077 | -0.125 | nl |
| m | nl | 0.244 | -0.451 |
| k | nl | 1.803 | -0.306 |
| θr | 0.023 | 0.405 | 0.280 |
| θs | nl | nl | nl |

## 3.3 Calibration and Validation

Calibration was carried out for ’93 – ’94 irrigation season with seven days irrigation frequency. Validation was conducted with 14 and 21 days irrigation frequency as well as with ’91 – ’92 and ’92 – ’93 irrigation seasons each with seven day frequency. The aim was to determine if climate driving forces or flow boundaries have a bigger influence on model performance.

Relative water content was used as target variable for the calibration. When left to the choice it is disadvantageous compared to flow information because it is only an indirect measure of water movement. Percolation at the lower model boundary is difficult to determine, especially where no drainage is installed. In comparison soil water content monitoring is easily set up. Another advantage is the higher resolution with that it can be determined. Both factors make soil water content an interesting target variable for the description of soil water movement.

SiWaPro also includes a parameter optimization algorithm for inverse estimation of soil hydraulic parameters from measured transient or steady-state flow. The inverse estimation was not tested successfully probably because boundary conditions were too dynamic respectively the repeated water application did not permit to identify an optimum parameter configuration.

### 3.3.1 Calibration parameters and model performance

**Tab. 26 Parameters addressed during the calibration**

| | initial value | final value |
|---|---|---|
| $\alpha$ [1/m] | 17.7 | 14.3 |
| n | 1.53 | 1.61 |
| m | 0.347 | 0.347 |
| k [m/d] | 1.29 | 2.13 |
| $\lambda$ | -1.92 | -1.32* |
| $A_{qh}$ | -0.169 | -0.113 |
| $B_{qh}$ | -0.027 | -0.081 |
| $\theta r$ | 0.057 | 0.057 |
| $\theta s$ | 0.352 | 0.398 |

*tortuosity parameter had to be adapted afterwards again in order to enhance model stability

Calibration was focused on soil and groundwater boundary condition parameters. The initial estimates and final values are concluded in Tab. 26. Initial values were basically obtained from the parameter configuration determined by RETC under consideration of all determined retention data values. Biggest adaptations had to be undertaken on saturated conductivity, tortuosity parameter and saturated water content. Transformation parameter and residual water content could be left unchanged.

### Visual fitting quality

Relative water content in the four diagnostic layers was the target variable for the calibration. The values were collected by defined observation points at the specific coordinates. A visualization of the comparison between some calibration alternatives is given in Fig. 38. Varied parameter is the scaling factor $B_{qh}$ of the [Hopmans, 1989] groundwater approach. The upper diagraph shows the modeled development of water content dynamics over the irrigation period. All alternatives perform fairly well with regard to the reproduction of measured values. _b0.08 and _b0.06 alternatives have the constraint, that not all irrigation cycles are reproduced. The image suggests that the measurement of field capacity after 48 hours was too late, soil was already in the drying phase at this point of time and maximum moisture contents are not covered by the measurements. The differences in the performance of the alternatives are more pronounced at 120 cm depth (lower diagraph). Alternatives _b0.08 and _b0.04 overestimate the average water content, which is expressed by a high bias for these alternatives. Amplitude of the water content course is overestimated by _b0.08 and reproduced sufficiently for alternatives _b0.06 and _b0.04. Deviation for single values is better for _0.04 while overall performance accounts for _0.06.

Generally it must be stated that soil and groundwater parameters where more sensitive in the lower soil layers, probably because the predominant influence of climate drivers over the water movement drivers diminishes. As a consequence, if a choice is necessary and possible, it would be preferable to measure water content dynamics in a more profound soil layer in order to be more certain about determining processes.

Besides from the quantitative and objective performance quality parameters (evaluation below), the visualization of water content development is valuable because determinant effects are identified more easily. E.g. in Fig. 38 at 120 cm depth the PPs for alternatives _b0.06 and _b0.04 were similar but the visualization reveals that drying phase is reproduced to slow so that the movement in the course can’t be explained.

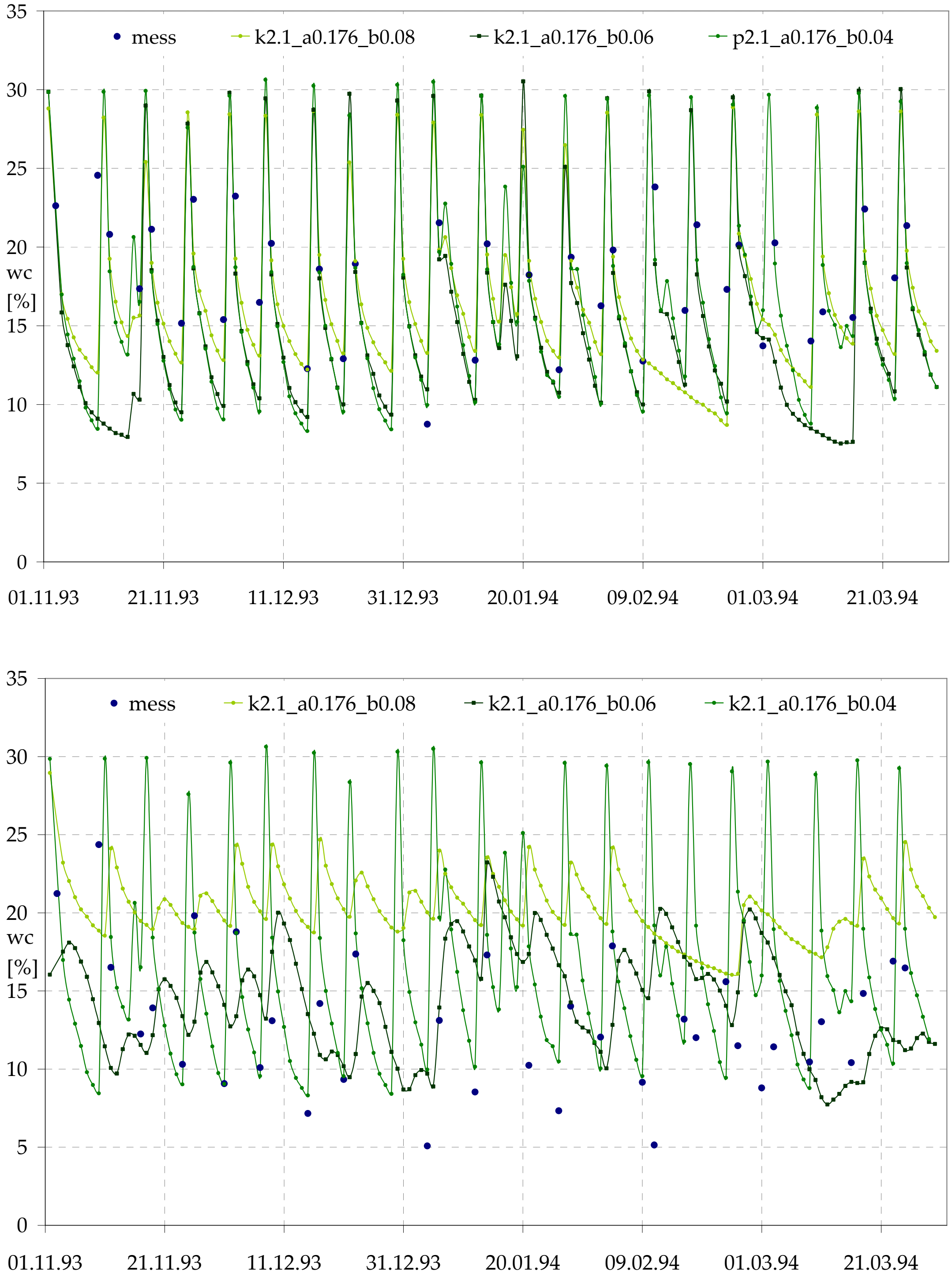


**Fig. 38 Calibration performance for water contents at 15 cm and 120 cm depth**

For some events the general assumption of 130 mm irrigation depth proved inconvenient and does probably not correspond to reality. E. g. the pronounced period of lower humidity values as well for "before irrigation" as for "after irrigation" events indicates that during that time not the same amount of water reached the lower soil zone. No calibration configuration allowed representing as well this period of low values as the regular regime during the rest of the irrigation season. This drawback underlines that it is important to capture the water balance in order to explain model - or measured value irregularities.

## Performance quality parameters

A part of the determination of performance evaluation was conducted automatized, an example is given in Fig. 39. A MATLAB script provided by F. Blumensaat was adapted to the specific situation. Similar to Fig. 38 the upper plot shows the courses of measured and simulated data. For every calibration run bias, NSE and IoA were determined. Lower plot shows accumulated values taken for the measurement dates. Increase coefficients are specified for both accumulation curves and deviation determined as ratio of simulated to measured increase coefficient. The plot of accumulated values determined in order to identify possible changes in the regime or systematic errors that are not detected by the bias.

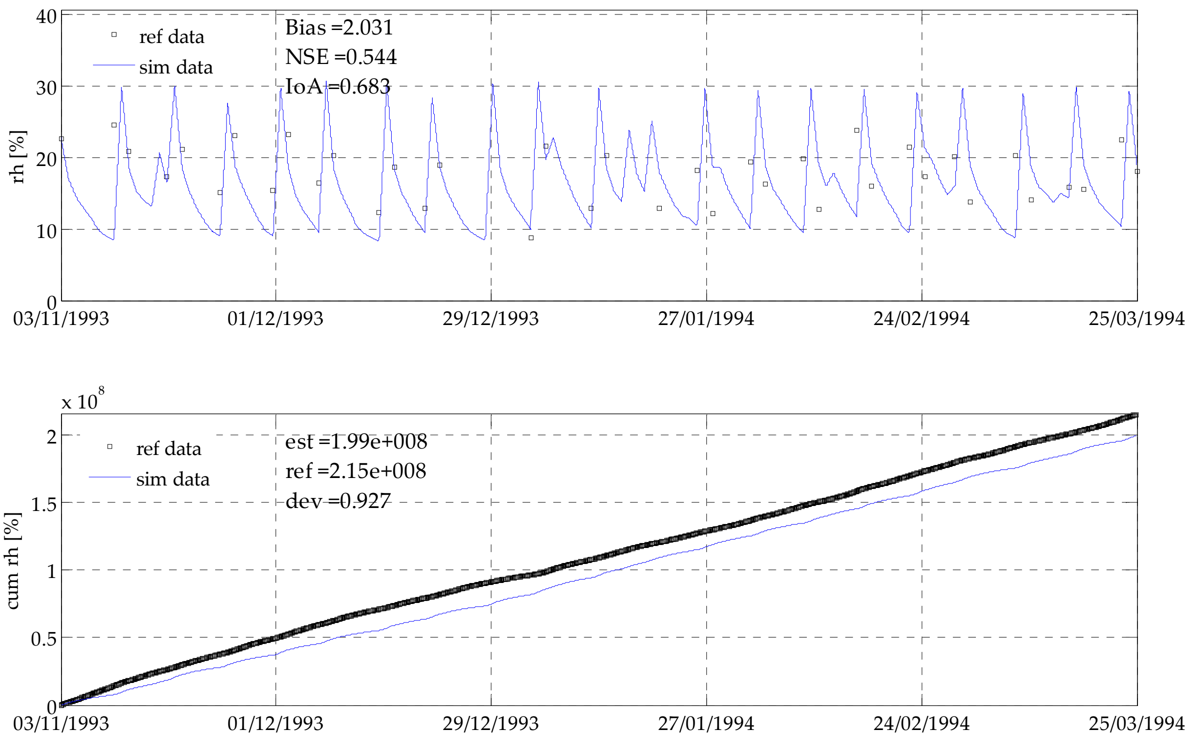


**Fig. 39 Quality assessment of a calibration version**

**Tab. 27 Fitting quality parameters of calibration and validation**

| 93 - '94 7d | 0 - 30 cm | 30 - 60 cm | 60 - 90 cm | 90 - 120 cm | mean |
|---|---|---|---|---|---|
| bias | 0.026 | 0.032 | 0.029 | 0.047 | 0.034 |
| RMSE | 0.031 | 0.039 | 0.042 | 0.065 | 0.044 |
| rRMSE | 0.065 | 0.082 | 0.088 | 0.137 | 0.093 |
| NSE | 0.79 | 0.65 | 0.68 | 0.55 | 0.67 |
| IoA | 0.81 | 0.77 | 0.69 | 0.64 | 0.73 |
| $R^2$ | 0.87 | 0.83 | 0.69 | 0.61 | 0.75 |
| | | | | | |
| 93 - '94 14d | 0 - 30 cm | 30 - 60 cm | 60 - 90 cm | 90 - 120 cm | mean |
| bias | 0.054 | 0.058 | 0.062 | 0.047 | 0.063 |
| RMSE | 0.063 | 0.071 | 0.084 | 0.107 | 0.081 |
| rRMSE | 0.132 | 0.149 | 0.177 | 0.225 | 0.171 |
| NSE | 0.74 | 0.69 | 0.65 | 0.53 | 0.66 |
| IoA | 0.78 | 0.73 | 0.66 | 0.61 | 0.70 |
| $R^2$ | 0.77 | 0.74 | 0.62 | 0.59 | 0.68 |
| 93 - '94 21d | 0 - 30 cm | 30 - 60 cm | 60 - 90 cm | 90 - 120 cm | mean |
| bias | 0.060 | 0.067 | 0.083 | 0.075 | 0.071 |
| RMSE | 0.068 | 0.089 | 0.093 | 0.097 | 0.087 |
| rRMSE | 0.142 | 0.186 | 0.195 | 0.204 | 0.182 |
| NSE | 0.66 | 0.61 | 0.58 | 0.51 | 0.67 |
| IoA | 0.74 | 0.72 | 0.66 | 0.61 | 0.68 |
| $R^2$ | 0.68 | 0.65 | 0.53 | 0.57 | 0.61 |
| | | | | | |
| 91 - '92 7d | 0 - 30 cm | 30 - 60 cm | 60 - 90 cm | 90 - 120 cm | mean |
| bias | 0.023 | 0.040 | 0.017 | 0.050 | 0.030 |
| RMSE | 0.037 | 0.037 | 0.050 | 0.065 | 0.045 |
| rRMSE | 0.079 | 0.078 | 0.106 | 0.146 | 0.102 |
| NSE | 0.83 | 0.66 | 0.69 | 0.55 | 0.68 |
| IoA | 0.81 | 0.79 | 0.74 | 0.67 | 0.75 |
| $R^2$ | 0.83 | 0.79 | 0.64 | 0.59 | 0.71 |
| 92 - '93 7d | 0 - 30 cm | 30 - 60 cm | 60 - 90 cm | 90 - 120 cm | mean |
| bias | 0.036 | 0.043 | 0.040 | 0.052 | 0.042 |
| RMSE | 0.050 | 0.047 | 0.057 | 0.080 | 0.076 |
| rRMSE | 0.105 | 0.098 | 0.120 | 0.106 | 0.107 |
| NSE | 0.79 | 0.67 | 0.70 | 0.58 | 0.68 |
| IoA | 0.85 | 0.78 | 0.73 | 0.66 | 0.75 |
| $R^2$ | 0.79 | 0.77 | 0.67 | 0.58 | 0.70 |
| | | | | | |
| mean | 0 - 30 cm | 30 - 60 cm | 60 - 90 cm | 90 - 120 cm | mean |
| bias | 0.040 | 0.048 | 0.046 | 0.054 | |
| RMSE | 0.050 | 0.056 | 0.065 | 0.083 | |
| rRMSE | 0.104 | 0.119 | 0.137 | 0.164 | |
| NSE | 0.76 | 0.66 | 0.66 | 0.54 | |
| IoA | 0.80 | 0.76 | 0.70 | 0.64 | |
| $R^2$ | 0.79 | 0.76 | 0.63 | 0.59 | |

Tab. 27 concludes the results of the calibration and validation process. The considerations given for the visual evaluation are confirmed by the PPs. Lower soil layers are generally represented worse by the calibrated as well as the validated model. If the model quality was enhanced for the lower layers it was on the cost of an over-proportionally stronger deterioration of fitting quality in the upper layers. As a reason the effect previously mentioned might be stated. For arid climates evaporation is the predominant driver for water movement in the upper layer while further down percolation increases in importance. Both processes have to be represented sufficiently.

For the validation four configurations were considered, two with different irrigation regime ('93 – '94 14d and 21d) and two with different climatic boundaries ('91 – '92 7d and '92 – '93 7d). It is apparent that validation quality for different irrigation regime was globally worse than for different climatic boundaries. All performance indicators range lower for the irrigation cases than for the climate cases. In comparison between the two irrigation cases the one that is "further away" from the calibration case performs worse. Hence model performance is less sensitive towards climatic boundaries than towards anthropogenic water regime. It should be thus intended that the probable range of water donations is considered during the calibration phase. Nevertheless, even for the 21 day validation period performance quality is satisfying.

Each performance quality parameter has advantages and disadvantages. Only the proper combination of different parameters permits an integral evaluation of model performance. The choice which parameters should be applied depends on modelling purpose and the type of target variable that is considered.

Bias allows detecting systematic errors; it is especially relevant for water balance considerations. A drawback is that systematic errors of deviation compensate each other. E. g. if highest and lowest water contents are over- respectively underestimated by the same extend no bias is predicted. In the application bias performs generally well, it is for all cases less than ten percent of mean humidity values. Highest bias values are found for 21 d irrigation case and for the two deeper soil layers. Still differences are not very pronounced.

RMSE is avoiding the deviation insensitivity of bias and buffers the influence of outliers is buffered. RMSE values are globally slightly higher than bias. This advocates a certain influence of systematic deviation misestimation although the effect can't be to strong, as mean difference is less than 20 % between the values. With regards to performance tendencies again in greater depths and with minor irrigation frequency estimation quality is worse. But for RMSE depth is a stronger influence on deterioration.

The parameter rRMSE expresses the ratio between RMSE and mean rh, tendencies are thus the same as for RMSE but differences are more pronounced.

NSE is an illustrative parameter as it delivers two prominent points of reference for NSE = 0 model performance is worse than mean value. For NSE = 1 the model matches perfectly measured values. For the calibration and validation NSEs are generally higher than 0.5 with lowest values for the deepest soil layer. The mean performance of the irrigation frequency validation cases is only slightly worse than for the calibration. For climate boundary validation it is even slightly better. A clear tendency is found for soil depth, model performance gets worse in the lower soil layers. This indicates that the course of water content is reproduced for the validation with a high confidence but within the distinct cases performance quality is heterogeneous.

The capability of IoA to consider relative differences between comparison pairs (see section 2.5) proved valuable in order to estimate lower "before irrigation" values as well as higher "after irrigation" values. For the IoA variability again is more driven by depth than by configuration. Lowest IoAs are found in the deepest soil layer, indicating that there the dynamic of either low or high soil moisture values is reproduced worse than in average. IoA is especially valuable in combination with the visual assessment as it supports to focus on certain performance aspects.

$R^2$s describe the proportion of the variance of measured data in the variance of the estimation function. As NSE it is a parameter that supports the evaluation of the modeling course. The $R^2$ values found partly affirm the findings of NSE. Variability is bigger for soil depths than for validation cases. Nevertheless heterogeneity between the validation cases is bigger than for NSE.

Model performance assessment with respect to both spatial distribution of the performance and model configuration proved to be an efficient tool for the identification of systematic weaknesses and gives a quantifiable background for model enhancement and vulnerability for model application.

## Integrated performance quality

Performance utility was calculated for the calibration and validation cases. The motivation was rather to introduce the method and test applicability as no convenient method was found. In Tab. 28 the thresholds of the utility function and weighting coefficients for the PPs are concluded. Assumptions are somewhat conceptual but serve to demonstrate the performance of the method.

**Tab. 28 utility function thresholds and weighting coefficients for performance utility analysis**

| 93 - '94 7d | min. threshold | max. threshold | weight |
|---|---|---|---|
| bias | 0.1 | 0 | 0.2 |
| RMSE | 0.2 | 0 | 0.2 |
| rRMSE | - | - | - |
| NSE | 0 | 1 | 0.2 |
| IoA | 0 | 1 | 0.2 |
| $R^2$ | 0 | 1 | 0.2 |

Utility functions are assumed to be linear between the thresholds defined. For values not more than minimum threshold utility value is assumed to be zero, for values not less than maximum threshold they equal one. For bias and RMSE minimum thresholds were defined according to calibration cases that performed "bad". rRMSE was not considered as it is directly dependent form RMSE. The thresholds for NSE, IoA and $R^2$ are defined by characteristic values of these parameters. Weighting coefficients were distributed equal between the PPs as no special modeling aspect was favored specifically.

A comparison of performance utilities is given in Fig. 40. Denotation refers to the cases discussed above; "optium" represents a virtual perfect model. As to be seen calibration and validation with '91 – '92 climate reach highest performance qualities. Both climate validation score better than the irrigation validations. Bias was in average the hardest performance criterion with lowest partial utility values. IoA generally contributes the biggest portion.

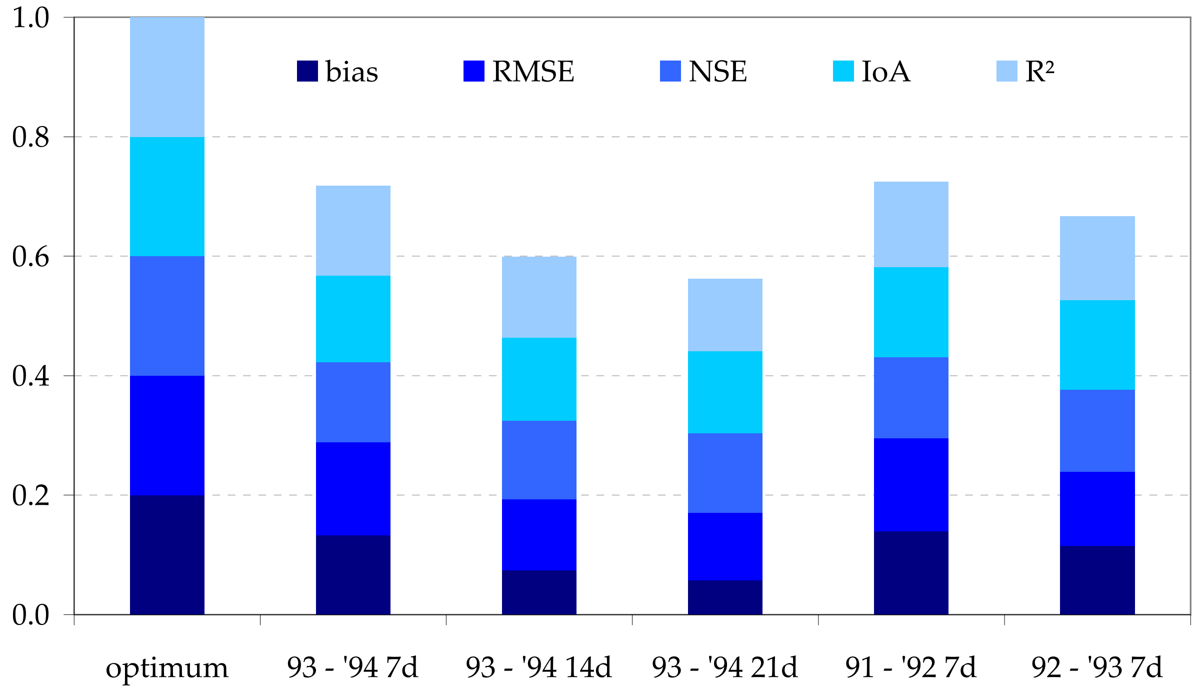


**Fig. 40 Performance utilities for an virtual optimum model, calibration and validation cases**

## 3.4 Modeling results

In the following some findings on model performance and evaluation methods are concluded. The section is somewhat brief because the evaluation of scenarios below refers to some aspects similarly.

### 3.4.1 Numerical stability and mass balance

Mass balance problems were inherent for the model runs that could not be solved neither by refinement of the temporal or spatial resolution nor by increase of expense in the simulation control. The sharp changes between extreme dry climate out of irrigation season and the highly dynamic water fluxes during irrigation caused mass imbalances for the first few irrigation cycles but over all mass balance error, calculated as difference between inflow and outflow was controlled to not to exceeded five percent.

Some parameter combinations proved to cause numerical instabilities that caused oscillating solutions and / or a breaking off of the simulation. Although it is hard to define a physical base for these phenomena they shall be mentioned in order to allow further research. Under extremely dry conditions, when small amounts of water faced big potential gradients mass balance problems are observed. The “climate-type” boundary condition that allowed defining thresholds as minimum pressure head at which water flow takes place proved as very useful to avoid instable conditions.

Especially the tortuosity parameter earns further attention. While the parameter estimation tools almost exclusively predicted negative values; default recommendation for modeling is a value of 0.5. Negative values between -1 and -2 increased model stability for steep frontlines of water movement, as they frequently appeared for the irrigation pulses. On the other hand especially for the interannual cases the parameter raised mass balance and stability problems during and after extremely dry soil conditions. For the parameter no final calibration value was obtained and it had to be readjusted several times for the scenario runs.

### 3.4.2 Heterogeneity of soil moisture distribution

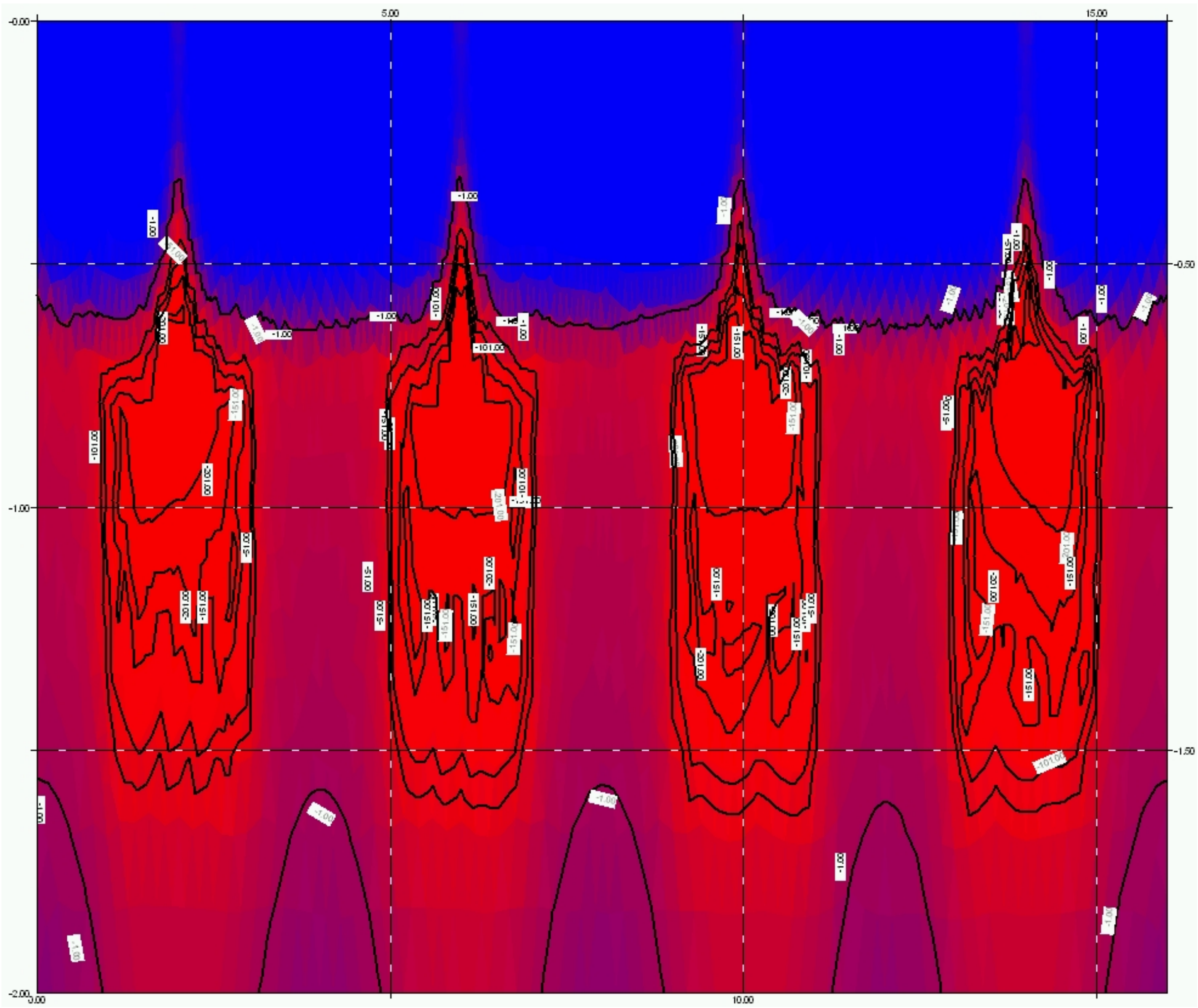

**Fig. 41 Spatially heterogeneous distribution of soil humidity during an irrigation pulse**

Fig. 41 is a screenshot from a model run. The image shows the distribution of soil water content during an irrigation event. Red colors represent low water contents blue colors show contents close to saturation. Some interesting aspects might be highlighted:

- tree stems cause a slipstream directly below their position with an reduced water content
- water content in root zones and non-root zones varies considerably at the same depth
- while in non-root zones water content increases constantly with depth, due to diminishing influence of evaporation, root zones have low water contents in their whole vertical extension
- below the root zones "leeward" patterns develop, irrigation water is consumed in the root zone and does not percolate

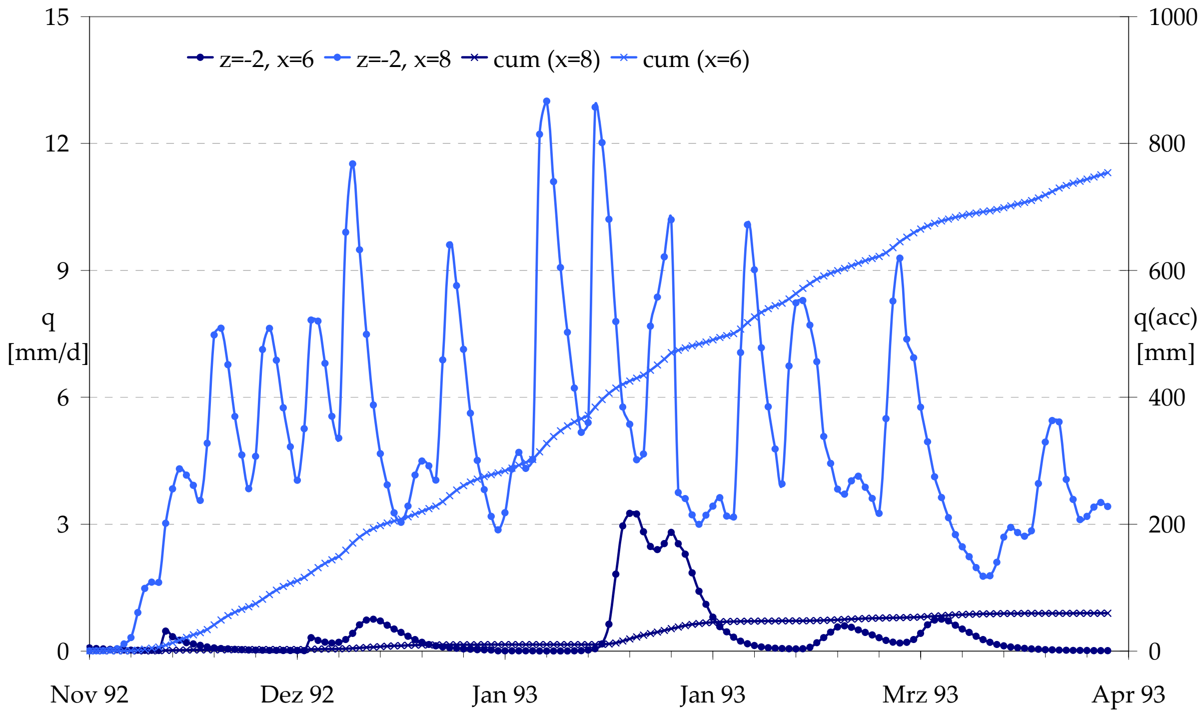


**Fig. 42 Percolation at the lower model boundary, under a plant and between plants**

As a consequence groundwater recharge is highly variable when compared under plants and between the stands. Fig. 42 visualizes the effect for seven day irrigation configuration in '92 – '93 irrigation season. The dark blue line (x=6) shows discharge under a poplar, the light blue line. Dotted lines represent the course while dashed lines stand for accumulated values. Differences in groundwater recharge between the two profiles are tremendous. For the between plants profile almost every irrigation donation causes deep percolation for some donations (the two maximum peaks in January) it accumulates to 65 mm or half of the total irrigation depth. The total amount accumulates to 754 mm of percolating water or 29 % of the total irrigation depth. In contrast below the plant stand deep percolation occurs only occasionally. Only one “mayor” event in January with 40 mm over two irrigation cycles accounts for more than half of the total percolation. Only 70 mm or 3 % of the total seasonal irrigation volume are lost by deep percolation. If the balance is drawn for the total irrigation parcel, where only 8.3 % of the soil is occupied by deep root zones[4], under this assumption effective percolation is 711 mm.

### 3.4.3 Groundwater recharge and salt balance

Tab. 29 concludes the results of the water balance as drawn above, irrigation and precipitation are either evaporated / transpired or percolated, the portions of storage change in the soil and incorporation by plants are neglected as inferior compared to the other balance components. It is apparent that percolation portion is more than proportionally increased with higher irrigations frequencies. While percolation coefficient (as ratio of percolation to irrigation plus precipitation) is 0.27 for the seven day irrigation case it diminishes to 0.17 for the 21 day case, values are given as c_per in Tab. 29. The coefficients are rather stable for the different seasons although precipitation depths vary considerably between 320 mm in ’92 – ’93 and 45 mm in ’93 – ’94.

The salt balance considerations are based on the simplified concentration – leaching - model proposed by [Ayers, 1985]. He defines a concentration factor as dependent variable of percolation coefficient and assumes that in average soil salinity increases multiplied by concentration factor and irrigation water salinity. Ayers proposes the model for calculation with ECs but as conductivity is directly dependent from concentration (see section 2.3.3), the model is adapted to a load-based balance. Assumptions are that initial salt concentration in soil and irrigation water are equally at 0.49 g/l (1.5 dS/m). Precipitation water is considered as salt free. Complete mixture of irrigation water and residual soil water is guaranteed at every time. The balance components given in Tab. 29 are determined as following (F. 36):

[4] 16 squares of 1 m x 1 m out of an parcel of 12 m x 16 m

$$l_{per} = l_I - l_{res}$$
$$l_{per} = c_I * q_I - (1 - c_c) * q_{ET}$$ F. 36

with:

| | | |
|---|---|---|
| with: | $l_{per}$ | percolation load [M/L²] |
| | $l_I$ | irrigation water load [M/L²] |
| | $l_{res}$ | residual load [M/L²] |
| | $c_I$ | irrigation water concentration [M/L³] |
| | $q_I$ | depth of irrigation [L³/L²] |
| | $c_c$ | concentration coefficient [-] |
| | $q_{ET}$ | depth of evapotranspiration [L³/L²] |

The results of the mass transport balance given by F. 36 are concluded in Tab. 29. Water balance indicates that the water is applied inefficiently at higher irrigation depths. Parameter c_per expresses the ratio of applied water to percolated water with 0.27 the values for seven day irrigation is almost 40 % higher than for 21 day configuration. But also ET is reduced which confirms the finding of [Riu, 2004] that trees with more frequent irrigation grow stronger. Restrictively it has to be mentioned that evaporation and transpiration can't be evaluated separately. Climate seems to have a minor role on groundwater recharge from irrigation excess. The c_per values hardly change for the different years, as a slight tendency the c_per for seven day irrigation increases with higher precipitation rates.

For all cases a mayor portion of the salt is transferred to the lower soil zone and contributes sooner or later to groundwater salinization. As salt load is proportional to irrigation depth (biased by precipitation), seven day alternative shows highest salt input rates (NaCl_in). For the residual content the tendency is reverted. As to be expected with higher irrigation excess leaching portion is bigger and less salt accumulates in the soil zone. The difference between percolated salt load is much more pronounced than for residual loads. While percolated load in average of seven day irrigation is four times higher than for 21 day irrigation, the residual content is about 1.5 times higher for 21 day irrigation than for seven day regime.

**Tab. 29 Water balance and balance based salt load**

| | | 7d | 14d | 21d |
|---|---|---|---|---|
| 91 - '92 | I+P [mm] | 2734 | 1564 | 1044 |
| | ET [mm] | 1996 | 1198 | 857 |
| | perc [mm] | 738 | 366 | 187 |
| | c_per | 0.27 | 0.23 | 0.18 |
| | NaCl_in [g/m²] | 1219.6 | 646.3 | 391.5 |
| | NaCl_res [g/m²] | 85.8 | 116.7 | 134.9 |
| | NaCl_perc [g/m²] | 1133.8 | 529.6 | 256.6 |
| 92 - '93 | I+P [mm] | 3050 | 1750 | 1230 |
| | ET [mm] | 2339 | 1367 | 1037 |
| | perc [mm] | 711 | 383 | 193 |
| | c_per | 0.28 | 0.22 | 0.16 |
| | NaCl_in [g/m²] | 1337.7 | 700.7 | 445.9 |
| | NaCl_res [g/m²] | 98.9 | 128.2 | 158.1 |
| | NaCl_perc [g/m²] | 1238.8 | 572.5 | 287.8 |
| 93 - '94 | I+P [mm] | 2775 | 1475 | 955 |
| | ET [mm] | 1437 | 774 | 509 |
| | perc [mm] | 657 | 340 | 152 |
| | c_per | 0.24 | 0.23 | 0.16 |
| | NaCl_in [g/m²] | 1337.7 | 700.7 | 445.9 |
| | NaCl_res [g/m²] | 68.2 | 89.3 | 102.3 |
| | NaCl_perc [g/m²] | 1269.5 | 611.4 | 343.6 |

## 3.5 Scenarios Analysis

In the following main results of the scenarios are presented. As mentioned above irrigation and salinization scenarios are combined as the salt transport was considered in addition to water balance aspects under the general assumptions for salt mass transport defined in 2.6.1.

### 3.5.1 Salinization and irrigation with alternative methods

A main advantage of the modelling is that output resolution can be fitted to the users needs and to process relevant scale. In Fig. 43 the distribution of salt in two soil profiles is seen for the basin irrigation case. Y-Axis indicates depth, x-axis refers to salt concentration in the soil solution directly six days after irrigation application. The profile x=6 (light blue) corresponds to the stand of the second tree, x=8 refers to a profile between two stands. Diferences between the two positions are considerable. For x=8 the concentration gradient is clearly evaporation driven. Close to surface, where most of the water evaporates and soil is driest, salt concentration in the remaining water is highest. In contrary for the profile at the tree stand a superposition of two influences can be assumed in the directly below surface evaporation also dominates but water extraction by roots additionally increases the effect and depletion with depth is much less pronounced. Also below the plant stand water has a higher salt concentration than in the between stand zone. The differences between the two profiles indicate the spatial heterogeneity of salt distributions. Main drivers are concentration by evaporation and roots. Thus for the determination in field it would be recommendable to gather samples as a qualified mixture of different points or to recognize small scale heterogeneity in the sampling procedure by a dual scale approach.

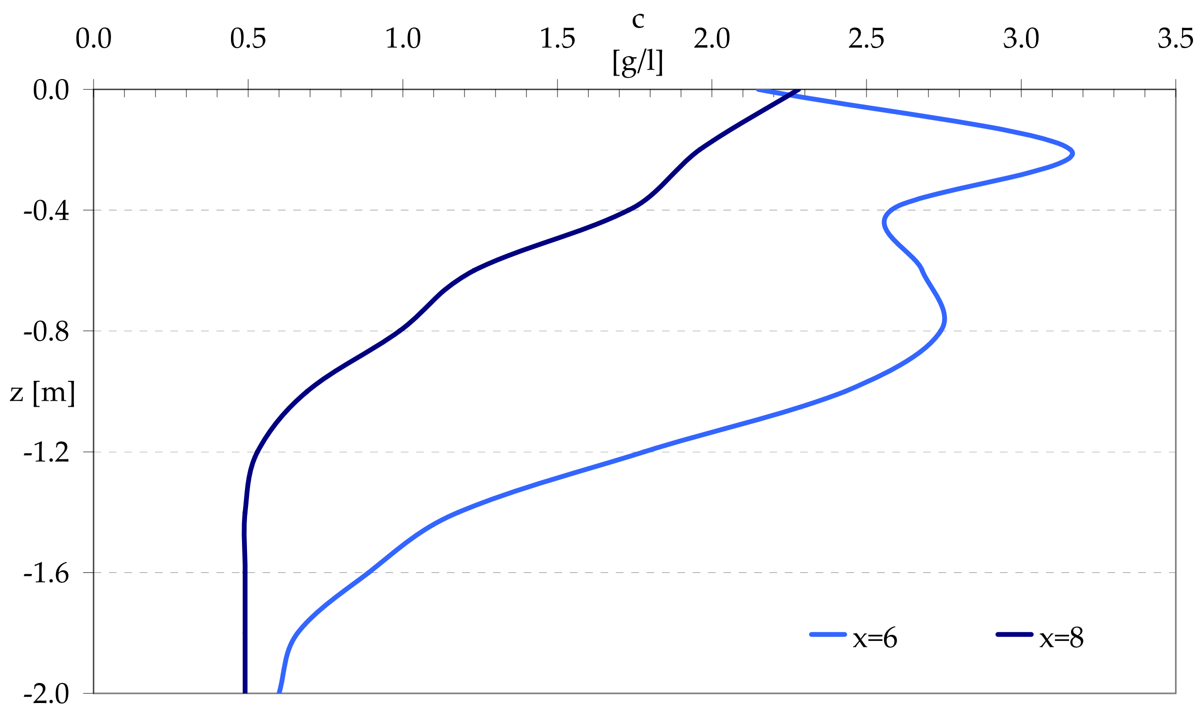


**Fig. 43 Distribution of NaCl concentration at a plant (x=6m) and between two stands (x=8m)**

Fig. 44 concludes the results of modeling of the alternative irrigation cases. Denotation refers to _fur furrow irrigation with furh (dark green) being the high variant and furl (light green) the low variant. _drip scenarios refer to drip irrigation, the light blue curves show the normal case, the dark blue curve (dripl) refers to the alternative combined with leaching at the end of irrigation season. Orange _bas curves are the reference basin irrigation alternative. For each irrigation case actual concentration (bold lines) and accumulated load (squared thin lines) are displayed, integration for the load is over the model width.

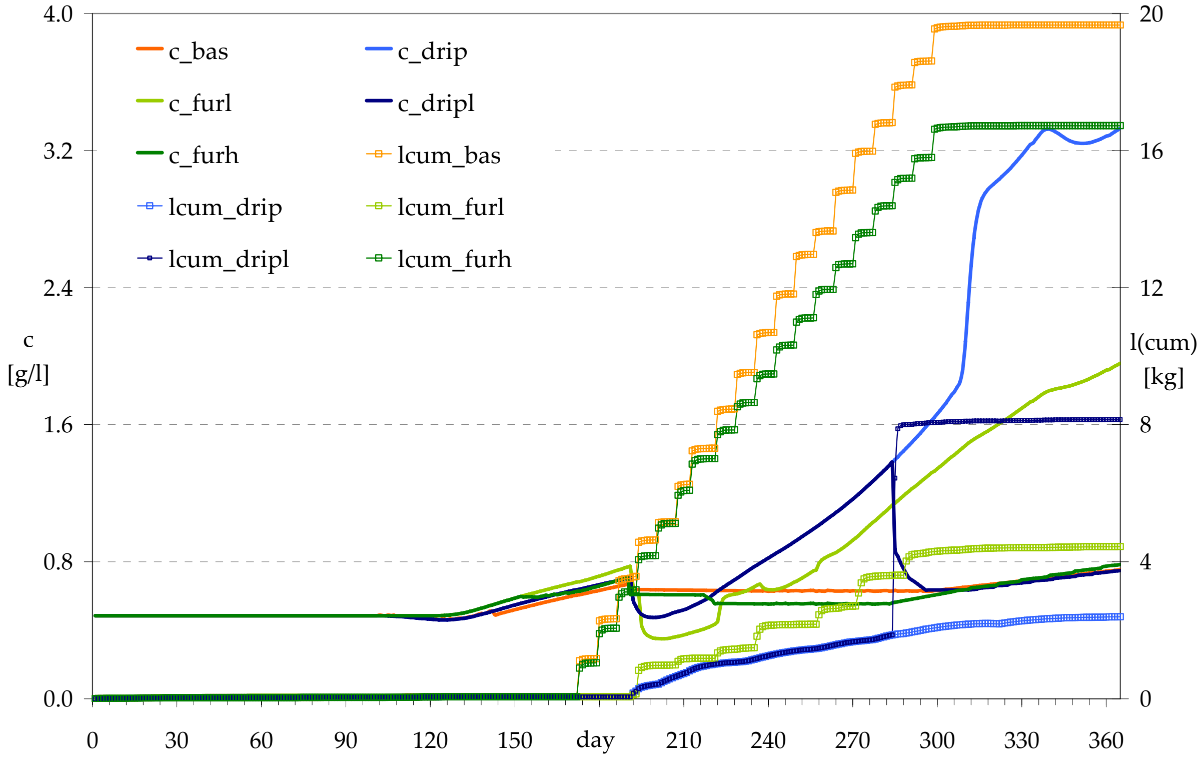


**Fig. 44 Drainage water salt concentration and accumulated load at lower boundary**

For the basin alternative show concentration course is rather stable. During the pre-irrigation phase no water pulses reach the lower model boundary and thus concentration is constant. At the initiation of irrigation a heavier rainfall event occurs and drainage water is diluted slightly. during the irrigation phase concentration is rather constant and elevated in comparison with pre-irrigation. after the end of irrigation season the residual salt is concentrated in the outflowing water and concentration again raises slightly. The accumulated salt load is step-shaped. With every irrigation impulse the load increases, indicating that each time water percolates below the lower boundary. At the end of the season salt load accounts with some 20 kg over the whole model width. The high furrow irrigation alternative shows concentration and load courses quite similar to the ones for basin irrigation although dynamic is somewhat changed, e. g. the step function during irrigation phase shows a different increase and post-irrigation concentration increases faster. On the first view surprising is that low furrow alternative comports completely different. The impact of precipitation event in early irrigation season is more pronounced and the step function is much less predominant, the smaller number of steps indicates that not every irrigation pulse leads to groundwater recharge and recharge rates are smaller. In contrast to the previous alternatives the salt concentration in the drainage water constantly rises throughout and after the irrigation season. Maximum value at the end of the observation period is 1.9 g/l, corresponding to an $EC_e$ of 5.8 dS/m. For the drip irrigation scenarios the courses are similar to the low furrow alternative although the concentration effect is much more pronounced. at the end of the observation period salt concentration reaches 3.3 g/l or 10.2 dS/m. The step function can't be detected for the drip irrigation alternatives as water was applied continuously. The leaching (dark blue) application at the end of the irrigation season shows a clear effect. Accumulated load instantaneously increases while leachate concentration decreases.

**Tab. 30 Water balance and modelled salt load**

| | basin | furrow low | furrow high | drip | drip+leach |
|---|---|---|---|---|---|
| I+P [mm] | 2734 | 1564 | 2864 | 584 | 784 |
| ET [mm] | 1996 | 1380 | 2180 | 541 | 583 |
| perc [mm] | 738 | 184 | 684 | 43 | 201 |
| c_per | 0.270 | 0.118 | 0.239 | 0.074 | 0.257 |
| NaCl_in [g/m²] | 1219.6 | 646.3 | 1283.3 | 166.1 | 264.1 |
| NaCl_res [g/m²] | 73.3 | 243.0 | 195.6 | 120.1 | 65.7 |
| NaCl_perc [g/m²] | 1146.3 | 403.3 | 1087.7 | 46.0 | 198.4 |
| c_res | 0.060 | 0.376 | 0.152 | 0.723 | 0.249 |
| plant_stress | 0.137 | 0.228 | 0.178 | 0.326 | 0.326 |

Tab. 30 concludes the modeling results of water balance and salt transport. Aditionally to the features given in Tab. 29 the proportion of residual salt content in the observation domain and a plant stress value are specified. Plant stress was determined as portion of nodes with a salt concentration greater than, integrated over all nodes and the irrigation time. The value represents the portion of soil where this value is exceeded. As a simplification it is assumed that all nodes represent an equal surface. As nodes in the upper layer are smaller this leads to an overestimation of these nodes and because these nodes tend to have higher salt concentrations (see above) the proportional value is overestimated.

The different irrigation alternatives show remarkable differences in irrigation performance. For the high furrow alternative four times more water is applied than for drip irrigation, in consequence high furrow and basin irrigation cause 15 times more percolation. With regard to salt transport, basin and high furrow irrigation have an initial salt load nine times higher than drip irrigation. While for basin irrigation only six percent of this salt stay in the observation zone, for drip irrigation 72 % are stored. With a leaching application at the end of the irrigation season this portion can be reduced by 50 % but to the cost of 20 % more water application. with regard to plant stress it might have been more reasonable to apply the leaching during the irrigation season. Plant stress value is by far highest for both drip irrigation alternatives. Drip irrigation proves to be a really water saving alternative irrigation volume per season corresponds to 380 mm if normalized for cultivation area. But salt accumulation within and below the central root zone is tremendous. Maximum values of 25 g/l concentration were calculated. At values that high the aspects of crystallization become relevant. As another limitation neither the influence of osmotic tension due to the ion concentration nor the plant response on salinity or sodium stress were taken into account. The findings of the balance based analysis in 3.4.3 were verified with convenient accordance. For an annual or seasonal evaluation the balance approach is sufficient but modeling offers the possibility for more detailed and better resolved analyses.

### 3.5.2 Phytoremediation of petroleum contamination

For phytoremediation an observation period of five years was considered. Alternatives compared are the treatment of a benzene contaminated site with phytoremediation vs. without treatment.

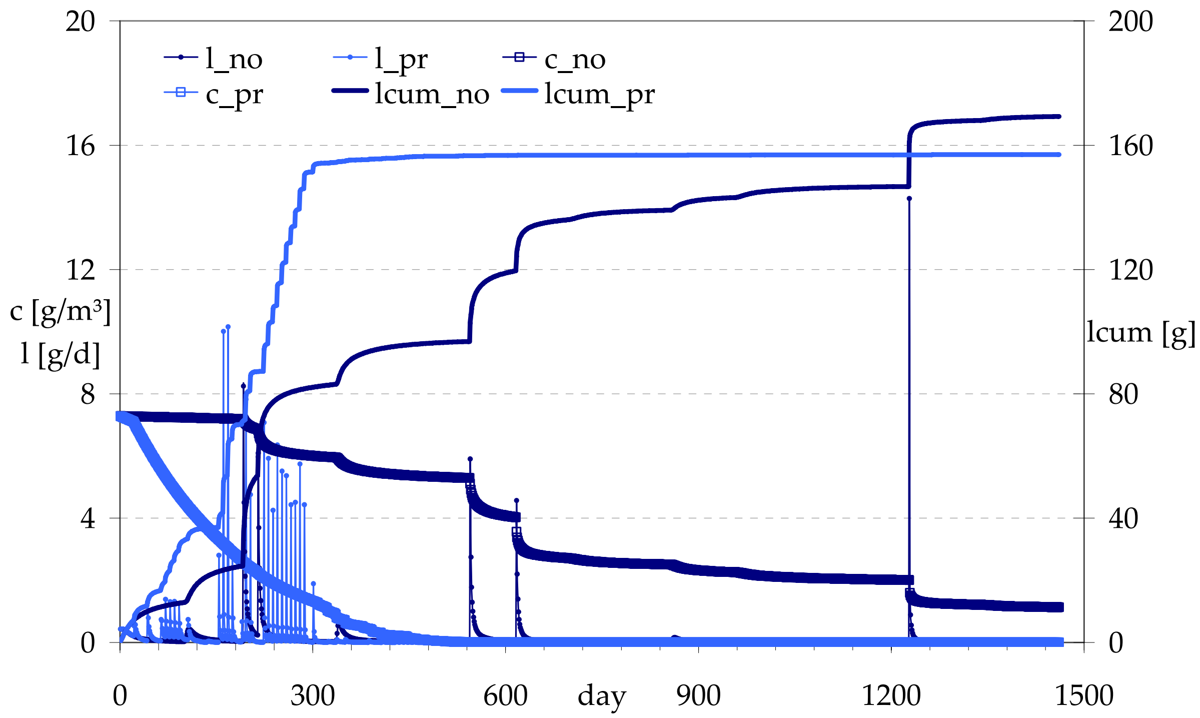


**Fig. 45 Concentrations and loads for benzene scenario alternatives.**

Fig. 45 visualizes the results of the mass transport modelling. Concentration (thin squared line), load (thin dotted line) and accumulated load (bold line) are displayed for phytoremediation (_pr) and no treatment scenarios (_no).

The phytoremediation site shows a continuous decrease of benzene content. Both decomposition and washout contribute to the effect. After approximately 500 days concentration falls below the 0.035 g/m$^3$ concentration value, that corresponds to the limit for agricultural use in Mendoza [Ercoli, 2001]. Accumulated load over the five year period is 158 g. For the untreated site washout clearly dominates over decomposition. For the few drainage significant events steps as well in the load as in the concentration curves are visible, they represent a decline of contaminant content due to losses rather than decomposition. After the five year period the leachate of the untreated site still has a concentration of 1.3 g/m$^3$ and continues contaminating the subjacent zone.

Residual concentration over the whole observation domain was calculated as accumulated water content multiplied by concentration for each node, assuming the same simplification as above. For phytoremediation alternative residual concentration was 0.2 g while for no treatment alternative it accounted to 17.8 g or 0.74 ppm. As a conclusion, if no measure is applied

As management recommendation poplars should not be planted in squares but in order to provide a homogeneous root distribution throughout the soil zone. High density cultivation as applied for biomass growth would be a feasible alternative. Additionally the high density of plants prevents eolic soil erosion and dry deposition of the contaminant. In spite of the percolation thread basin irrigation is recommended for phytoremediation because it distributes water over the whole affected area. Soil humidity control should be foreseen in order to prevent excess application and leaching of the contaminants, especially if they a well soluble in water. Alternatively sprinkler irrigation systems could be applied.

# 4 CONCLUSIONS

This section aims to give a brief recapitulation of limitations and findings obtained throughout the project. Results are rearranged and set into a synthesizing context so that, without working through all the details, the central statements are at hand. Additionally some of limitations are concluded that were not discussed within the main part as their influence is not retraceable. Some of those factors are at the focus of fundamental research at the moment. They are mentioned rather than discussed to put the results into a perspective and to allow relativization for the use in other contexts.

One central point that was not emphasized in this thesis might be mentioned here: It was quite laborious to get and keep the model running. A lot of time was spent in the configuration of parameters that were both, exact in representation and stable in computation. A figure might illustrate that: after all 32852 days or 90 years of time variable boundary conditions and 125 cases were registered during the elaboration of the project, excluding re-runs of the same case.

## 4.1 Limitations

### 4.1.1 Data base

A lot of effort was spent on the correction, completition and interpolation of input data on both regional and site-scale. For many arid regions, where human activity is spread over large extends, the lag of quantifiable information inhibits efficient solution of environmental problems. Aside from the value for the actual project the proposal of possibilities for data enhancement might be useful for the elaboration in similar situations of future projects. Nevertheless the possibilities of recapitulation of lagging information were limited, especially as the project was based on investigation done more than ten years ago.

As a clear constraint of the project it has to be marked out that neither inflow volumes nor deep percolation rates were determined. Hence it was not possible to validate the quality of the water balance fit. Although moisture content is a representative variable for soil water dynamics, it integrates different effects of water movement. If e. g. moisture change at a point is seemingly reproduced correctly it is not straightforward apparent if this is due to a correct description of the underlying processes or due to a combination of incorrect descriptions. Still results for the reproduction of soil moisture dynamics are satisfying in calibration as well as validation. So that at least within the range of tested boundary conditions the model can be applied as functional

The development of poplar root system for the specific varieties and site conditions of Mendoza were not considered within this investigation. The estimates taken were basically supported by local knowledge, however some uncertainty remains. Especially the possibility of a hydraulic lift caused by deep sinker roots that would change completely the distribution of roots and consequently water uptake can not be excluded.

### 4.1.2 Modeling

As the assumptions indicate and as it is intrinsic for modeling, simplifications had to be applied. Some processes were not considered by the model, for some no data foundation was available. Some main uncertainties may be concluded in the following

**Boundary conditions**

For the edition of boundary freedom of definition is limited. For most types of conditions only one time series or constant value can be designated. This reduces the options to consider a bigger model scale, e.g. for the parallel consideration of various irrigation parcels. On a bigger scale the consideration of different climatic drivers is not possible at the moment.

The climate type boundary condition proved very valuable to stabilize computation procedure but the assumptions for the definition of limit values is rather conceptual than physically based.

**Water flow**

For the influence of macropores and preferential flow paths is not included in the model. These processes are occasionally important in order to represent soil moisture distribution and infiltration properties adequately on local scale.

Surface water flow is not considered, time series may be defined to account for water levels courses, e. g. to describe flooding but there is no interaction assumed between surface and subsurface flow.

## Plan growth

Although transpiration rate can be considered as a time series, the root distribution is regarded as a steady state. Especially if long simulation periods for perennial plants are computed this leads to unrealistic assumptions.

Interaction of plant and environment is limited. Conceptually roots are a simple sink term. The scaling function for water uptake that is applied is widely discussed in related literature. Especially the no continuous course and the difficulties for defining the static characteristic suction heads are criticized. The response of roots to variable soil moisture is considered by a single relation, this is imprecise where roots with different functionality occur. Substance interaction between root and environment e.g. reduced consumption due to salinity stress or the exudation of substances that support decomposition can't be taken into account.

Analogous to the limitations for boundary conditions only a single set of root extraction parameters can be defined. This obstructs the representation of different cultivation types or mixed plant populations. Although to some extend the parameters can be equipped integrally e.g. by weighting the portions of the different species, the resulting consequences for the single species can't be derived.

## Mass transport

As already mentioned salt concentration influences via osmotic potential the total soil water tension. The changes in water tension – water content relation for the salinity scenarios can't be taken into account.

At concentrations as high as the ones found for the salinization scenarios, salt crystallizes and blocks soil pores. When rewetting the solving salts absorb water that does not contribute to flow. The crystallization-solution-kinetics is a fundamental problem and influence on water movement is not fully investigated.

Especially if the decomposition of substance mixtures, e.g. PAHs is considered the influence of concurrence, selective decomposition, cometabolism and related effects is not fully investigated and very case specific. For these cases the zeroth or first order decomposition kinetics is not able to describe decomposition behavior.

### 4.1.3 Scenarios

The scenarios were set up for two purposes to validate model performance for the site specific circumstances and to demonstrate capabilities of the application.

For all scenarios it has to be stated that it would have been desirable to incorporate more measured data for a more adequate representation of governing processes and validation of the results. The scenarios are set up somewhat on the merits. Especially for the phytoremediation local experiences could not be taken into account so that the assumptions are conceptual. Due to that the significance for actual planning is limited but the results may raise the awareness for basic drivers and enhance system comprehension.

## 4.2 Findings

In this section some of the central perceptions of the work are concludes, they are not so much oriented on the working scheme but more on different aspects of modeling and concrete results.

### 4.2.1 Treatment and assessment of input data

**Climate data**

A strategy for the completition and regionalization of climate data was presented under incorporation of a maximum extend of available data. Although the values measured at the investigation site bear some uncertainties and inconsistencies they provide valuable information about local climate effects. Especially as additional information is spatially sparse it should be intended to account for their contribution.

**Soil data**

The sampling of soil was valuable for two main reasons: seemingly homogeny of the soil was not completely confirmed. Especially grain size distribution and particle density showed considerable variation. As a second aspect the models for the prediction of retention and permeability properties were set into a perspective and measured data served as initial estimate for the model calibration.

**Soil hydraulic parameters**

Both tools for the estimation of soil hydraulic parameters implemented in SiWaPro, DIN 4220 table as well as Vereecken PTF, were not able to reproduce the measured data. For the estimation with ROSETTA only with the highest level of input data quality acceptable results were obtained. The divergence between modeled and measured values may be partly explained by the use of disturbed soil probes for the determination of the retention curves. Nevertheless the systematic error does not suggest this. Generally measured water content at equal pressure levels was lower for measured than for modeled curves although compaction of the soil decreases the portion of big pores that drain fast at low pressure levels. Another explanation may be that the tools implemented in SiWaPro are based on data that does not refer to soil that evolved under arid conditions. Hence the specific properties of aridic soils are not within the range. It should be remarked critically that the classification offered by DIN 4220 may only serve as an orientation. The classification based only on texture classes is not detailed enough to allow an attribution of single values for the hydraulic parameters. For the application of ROSETTA it is recommendable to invest effort into input quality as estimation results improved remarkably with better input data.

RETC program proved useful for the fitting of van Genuchten parameters to the measured curve. Generally fits had small difference from measured data. Six measured points allowed decreasing rRMSE values to less than 5 % while three measured points resulted in rRMSE values of up to 12 %.

### 4.2.2 Model performance

Model performance was evaluated with a multi-objective parameter set. The parameters were applied for calibration and validation and allowed a comprehensive assessment on different aspects of model performance. Additionally with the performance utility a flexible and adaptive "metaparameter" was introduced. Its application was tested successfully.

### 4.2.3 Model Verification for an Arid Climate

The application of SiWaPro for an arid climate was conducted successfully. Nevertheless the setup and calibration were laborious and readjustments were frequent in order to avoid instabilities.

The combination of a soil with poor water retention, the elevated evaporation rates and highly variable irrigation / precipitation dynamics, especially in the interannual consideration of irrigation – non-irrigation regimes was a challenge for the simulation tool. Although the model configuration is not very complex, "only" a cross section of 16 x 2 m with four trees was considered, the program proved sensitive to the elevated water dynamics of irrigation in an arid site. The climate-type boundary condition proved as valuable stabilizing feature.

### 4.2.4 Water Balance of Poplars

It was found that in presence of trees basin irrigation induced heterogeneous patterns of soil moisture distribution and consequently of drainage and groundwater recharge. As the method is plane (2D) oriented water between the plant stands is applied inefficiently. Groundwater recharge rates were high, accounting for 700 mm/a or 27 % of the irrigation volume for seven day irrigation cycles and about 200 mm/a or 17 % for the 21 day cycle.

### 4.2.5 Scenarios and Best Management Recommendations

Basin irrigation is not the method of choice as irrigation practice, especially for crops where root domain does not cover the whole irrigated subsurface. In the present case, the effect of deep percolation is fortified by the low retention potential of the soil and the corresponding relatively low traversal component. Irrigation water is applied efficiently if the maximum proportion of water reaches the maximum extend of roots. As a consequence it might be stated that "irrigation dimension" should match "crop dimension". If trees are considered as point crops (0D) water should correspondingly be applied on point, while for row crops (most vegetables) should be provided by linear irrigation methods. For crops that grow distributed over surface 2D irrigation meets plants requirements.

Furrow and drip irrigation permit to allow water much more localized and in the case of drip irrigation timely. The problem of salt accumulation in the soil cannot be solved by these measures but as less water is applied, also less salt is distributed. Salt accumulation for drip irrigation exceeded tolerable values and a regular leaching has to be provided.

The plantation of hybrid poplar species that tolerate high salinity of even incorporate salt as mentioned by [Shannon, 1998] can give a valuable contribution to cope with the salinity thread. Although for this further investigation is necessary e. g. in order to estimate the actual incorporation rates. From the present point of view drainage on field scale and a more restrictive management of land use rights on regional scale seem to provide the most efficient tools to reduce salinization.

## 4.3 Outlook

With the present work questions arose and not all aspects could be validated to a satisfying extend. Some of the suggestions made here may stimulate interest in further projects or raise awareness for deficits.

### 4.3.1 Data situation

With the emerging technologies of satellite detection for climate data and regional climate modeling new tools for the generation and validation of measured data get available. Although they are not yet disposable for the local scale they could at least serve as a reference.

The base of knowledge on problems and threads for the water resources in Mendoza is advanced. In a further step it would be relevant to take steps towards a more process description rather than monitoring focus. This is not only a matter of will as financial possibilities are limited but for a sustainable development and efficient decisions the extension of coordinated and conceptual knowledge is crucial. Especially the use of remote sensed as well as continually measured, automatically registered data could be applied to contribute to this aspect. With regards to data acquisition concepts a water cycle oriented approach could be favored, in a first step on local scale. E. g. the coordinated measurement of irrigation, soil moisture, transpiration (sap flow) and drainage could contribute largely to a better understanding of irrigation water dynamics.

### 4.3.2 Suggestions for model development

Many of the aspects mentioned here meet the deficits concluded in 4.1.2. They are mentioned reviewed in order to give a more constructive feedback. The proposals from this section are divided into two lines, some of the points focus more on additional features; others propose adaptations in the model performance.

For the application of SiWaPro program in an agricultural context a greater flexibility in the definition of boundary conditions would be needed. If the model is applied on a bigger scale different cultivation schemes, crops and irrigation regimes occur each requiring adapted boundary conditions. On a regional scale this option would be also interesting in order to represent different climatic conditions. The data base approach that is used in SiWaPro for information management favors the implementation of freely configurational boundary condition time series but it has to be evaluated if this obstructs the intuitive use of the model setup assistant.

Interfaces to surface runoff and groundwater models could be incorporated in order to make SiWaPro more apt for the working field of integrated modeling. This is especially relevant for interactive processes as the infiltration from water courses or groundwater dynamics.

Root distribution and water uptake have big influence on water movement in the soil. At the same time the dynamics of root growth are dependent on parameters of their environment and water availability [Mulia, 2005]. For an adequate estimation of water transport processes it would be thus advantageous to implement time series of root parameters e. g. to represent growth in long term simulations. In a more advanced state a root sub-model would be desirable that represents a growth function in interrelation with environmental boundary conditions.

With regard to salt transport a representation of the osmotic potential would be relevant. The connection between ion concentration and osmotic potential are described conceptually with linear relations. For the description of crystallization-solution-kinetics no modeling approaches are at hand at the moment.

### 4.3.3 Possible continuation

Based on the existent data an investigation on the influences of soil heterogeneity could follow up. Soil data analysis showed a certain layering and this may lead to retaining horizons that influence subsurface flow paths. Further data acquisition would contribute to an enhanced accuracy as described above.

A validation under similar conditions but with measured irrigation and drainage volumes would trigger uncertainties about the adequate process description. Especially as irregularities in the calibration process (compare 3.3.1) were explained with uneven water application.

It would be interesting to consider the drainage heterogeneity on a bigger scale. The differences between plant – no plant points should buffer on a bigger scale but it is likely that configuration of plant positions, crop types and soil properties do have a mentionable influence.

For the phytoremediation a feasibility study would be valuable. Although a lot of investigation is done in the field of bioremediation, this technique is not considered yet. Based on local knowledge experience design, management and control could be supported by an accompanying model approach.

# 5 QUELLENVERZEICHNIS


Abihaggle C. E., Day J. A.: Agua y sociedad: un ensayo económico sobre la política hídrica; EDIUNC; Mendoza; 2004

Abraham M. E.: Mapa Geomorphologico de Mendoza Sector Norte; Catálogo de Recursos Humanos e Información Relacionada con la Temática Ambiental en la Región Andina Agrentina; Abraham E. M., Martínez F. R. (Edt.); C-Bra Systematics; Buenos Aires; 1999

Abrahamson D. A. et al.: Calibration of the Root Zone Water Quality Model for Simulating Tile Drainage and Leached Nitrate in the Georgia Piedmont; Agronomy Journal; Vol. 97 (2005); p. 1584–1602.; American Society of Agronomy

AG Boden: Bodenkundliche Kartieranleitung; Publ.: Bundesanstalt für Geowissenschaften und Rohstoffe und Geologische Landesämter; 4. Edt.; Hannover; 1994.

Allen R. et al.: Crop evapotranspiration - Guidelines for computing crop water requirements; FAO Irrigation and drainage paper 56; FAO (Food and Agriculture Organization of the United Nations); Rome; 1998

Aragüés R. et al.: Conceptual irrigation return flow hydrosalinity model; in: Agricultural salinity assessment and management; Tanji K. K. (Edt.); ASCE Manuals and Reports on Engineering Practices No. 71; American Society of Civil Engineers; New York; 1990

Austenat L., Zink C.: Handbuch Stoffdaten zur Störfall-Verordnung : Zusammenstellung von Informationen zu Stoffeigenschaften und zum Reaktionsverhalten gefährlicher Chemikalien; Umweltbundesamt (Edt.); Schmidt; Berlin; 1986

Ayers R. S., Westcot D. W.: Water quality for agriculture;. Irrigation and Drainage Paper; No. 29, Rev. 1; FAO (Food and Agriculture Organization of the United Nations) (Edt.); Rome; 1985

Baars E., van Logchem B.P.: A client-oriented and quantifiable approach to irrigation design, a case-study in Mendoza, Argentina; DLO Winand Staring Centre; Report 75.1; Wageningen; 1993

Becerra L. C. G. et al.: Ciencias Sociales Mendoza; Santillana; 1st Edt.; Buenos Aires; 2007

Bergemann M.: Berechnung des Salzgehalts der Elbe; Arbeitsgemeinschaft Reinhaltung der Elbe, Wassergütestelle Elbe (Edt.); Hamburg; 2005

Benson C. H.: Springer Proceedings in Physics; Theoretical and Numerical Unsaturated Soil Mechanics; Vol. 113; Springer; Berlin, Heidelberg; 2007

Blankenburg R. et. al: SiWaPro DSS software program;

Blankenburg R. et al.: Programmdokumentation SiWaPro; KP Ingenieurges. für Wasser und Boden mbH, TU Dresden; 2007

Bloch G.: Irrigación distiguió a otra empresa que preserva el ambiente; B&T Gerencia Vitivinícola; No. 4, Mendoza; 2000

Borg H: The Relationship Between the Concentration of Total Soluble Salts and Osmotic Potential in Soil, Ground and Surface Waters for Several Regions of Western Australia; Resource Management Technical Report No.83; Department of Agriculture Western Australia; Perth;2001

BMZ (Bundesministerium für Zusammenarbeit) (Edt.): Environmental Handbook Volume III: Compendium of Environmental Standards; Vieweg; Eschborn; 1995

Borsdorf A. C., Hofert H.: Naturräume Lateinamerikas: Von Feuerland bis in die Karibik.; LAS-Online; Österreichisches Lateinamerika-Institut (www.lateinamerika-studien.at/ content/natur/natur/natur-titel.html); Wien; 2003

Bos M. G., Chambouleyron J. L. (Edts.): Parámetros de Desempeño de la Agricultura de Riego de Mendoza, Argentina; Internacional Water Managment Institute, Latin America Series; Vol. 5; Battaramulla; 1997

Bouwer C., Heibloem M: Irrigation Water Needs; FAO Irrigation Water Management Training Manual no. 3; FAO (Food and Agriculture Organization of the United Nations); Rome; 1986

Boyer J. S.: Plant Productivity and Environment; Science; Vol. 218. No. 4571; p. 443 – 448; American Association for the Advancement of Science; New York; 1982

Burns R. M. et al. (Edts.): Silvics of North America: Vol. 2. Hardwoods; Agriculture Handbook 654; U.S. Department of Agriculture; Forest Service; Washington DC; 1990

Bustamante J. A.: Proyecto – Cultivo de forestales en cortas rotaciones para la producción de biomasa; Programa Jornada Cultivos energéticos en la región de Cuyo; Facultad de Ciencias Agrarias, UNCuyo; Mendoza; 09.05.2008

Calderón A. D.: Silvicultura y situación de álamos en Cuyo; Actas Jornadas de Salicáceas 2006; p. 71-79; Buenos Aires; 2006

Chambouleyron L. J.: Irrigation and Remote Sensing in the Province of Mendoza, Argentina; in Menenti M. (Ed.): Remote Sensing and Management of Irrigation; Centro Regional Andino (INCYTH); Mendoza; 1990

Chambouleyron L. J. et al.: Descripción y balance hídrico salino; in: Conflictos ambientales en tierras regadías: Evacuación de impactos en la cuenca del río Tunuyán Mendoza, Argentina; Chambouleyron J. et al. (Edts.); UNCuyo; Mendoza, 2002

Chappell J.: Phytoremediation of TCE using Populus; Status Report; U.S. EPA Technology Innovation Office; Washington D.C.; 1997

Collins C. D.: Implenting Phytoremediation of Petroleum Hydrocarbons; in: Phytoremediation – Methods and Reviews; Neil Willey (Edt.); Humana Press; Totowa, (NJ); 2007

Corripio J. et al.: Modeling climate-change impacts on mountain glaciers and water resources in the Central Dry Andes; in: Darkening Peaks: Glacier Retreta; Orlove B. et al. (Edts.); p. 126-135; Science and Society; University of California Press; San Diego; 2007

DEIE (Dirección de Estadísticas e Investigaciones Económicas) (Edt.): Estadísticas agropecuarias. Uso de la tierra.; Gobierno de Mendoza; Mendoza, 2001a

DEIE (Dirección de Estadísticas e Investigaciones Económicas) (Edt.): Censo de Población y Vivienda; Gobierno de Mendoza; Mendoza, 2001b

DEIE (Dirección de Estadísticas e Investigaciones Económicas) (Edt.): Síntesis Estadística Social y Económica de la Provincia de Mendoza; Gobierno de Mendoza; Mendoza, 2007

DGI (Departamento General de Irrigación) (Edt.): Presupuestos de Gastos y Cálculo de Recursos de las Inspecciones de Cauce de la Provincia; DGI; Mendoza; 1994

DGI (Edt.): Proyecto PNUD-FAO-ARG-00/08 Informe General – Unidad de SIG y Teledetección; DGI; Mendoza; 2003

DGI (Departamento General de Irrigación) (Edt.): Política provincial de riego – Marco legal e institucional; DGI; Mendoza; 2005

DGI (Departamento General de Irrigación) (Edt.):Pronóstico de escurrimiento periodo Octubre 2006 - Septiembre 2007; DGI; Mendoza; 2007a

DGI (Departamento General de Irrigación) (Edt.): Plan de Recursos Hídricos; Proceedings of Taller Provincial - Plan de Recursos Hídricos; DGI; Mendoza; 27.02.2007b

DIN (Deutsches Institut für Normierung) (Edt.): DIN 4220 – Kennzeichnung, Klassifizierung und Ableitung von Bodenkennwerten (normative und nominale Skalierungen); Beuth Verlag GmbH; Berlin; 2007

DIN (Deutsches Institut für Normierung) (Edt.): DIN 18128 – Baugrund - Untersuchung von Bodenproben - Bestimmung des Glühverlustes; Beuth Verlag GmbH; Berlin; 2007

DIN (Deutsches Institut für Normierung) (Edt.): DIN 18130 – Baugrund - Untersuchung von Bodenproben; Bestimmung des Wasserdurchlässigkeitsbeiwerts - Teil 1: Laborversuche; Beuth Verlag GmbH; Berlin; 1998

Dixon J.: An Evaluation of Unsaturated Flow Models in an Arid Climate; Thesis Master of Science Degree; Howard R. Hughes College of Engineering; Las Vegas; 1999

Dogan A., Motz L. H.: Saturated-Unsaturated 3D Groundwater Model; Journal of Hydrologic Engineering; Vol. 10 (2005) No. 6; p. 505-515; ASCE (American Society of Civil Engineers); Reston (VA)

Doty S. et al.: Enhanced phytoremediation of volatile environmental pollutants with transgenic trees; Proceedings of the National Academy of Sciences of the United States of America; p.16816–16821; National Academy Press; Washington; 2007

DVWK (Deutscher Verband für Wasserwirtschaft und Kulturbau): Fallbeispiel zur Nutzwertanalyse – Wasserwirtschaftliche Planung Emstal; Mittelungen; Vol. 23;Köln; 1993

Dyck S., Peschke G.: Grundlagen der Hydrologie; Verlag für Bauwesen; 3rd. Edition; Berlin; 1995

Eisenführ F, Weber M.: Rationales Entscheiden; Springer; Berlin, Heidelberg; 1993

Ercoli E. et al.: Analisis sobre la aplicabilidad de tecnicas biologicas en tratamiento de suelos contaminados con hidrocarburos pesados; technical report; unpublished, 2001

Ercoli E.: Problemática ambiental generada por el uso de emulsión inversa en perforación petrolera; 6tas Jornadas de Preservación de Agua, Aire y Suelo en la Industria del Petroleo y del Gas; Instituto Argentino deletroleo y del Gas; Neuquen; 31.10 – 02.11.2005a

Ercoli, Eduardo et al.: Clean up practical limits on full scale bioremediation processes for hydrocarbon contaminated soils; Proceedings of the 20$^{th}$ International Conference on Solid Waste Technology and Management; Department of Civil Engineering, Widener University; Chester (PA); 3.–6.04.2005b

FAO (Food and Agriculture Organization): Reforming Water Resources Policy. A Guide to Methods, Processes and Practices; FAO Irrigation and Drainage Paper; No. 52.; Rome; 1995

FAO (Food and Agriculture Organization): World Reference Base for Soil Recourses; World Soil Recourses Report; International Soil Science Service; Rome; 2006

Fasciolo G. et al.: Evaluación del impacto ambiental en acuíferos: contaminación producida por actividades de saneamiento y disposición de efluentes; Proyecto; Taller sobre hidrología de áreas regadías; Instituto Nacional de Agua Centro Regional Andino; Mendoza; 17.11.2006

Feddes R. A. et al.: Simulation of Field Water Use and Crop Yield; John Wiley & Sons; New York; 1978

Feddes R. A. et al.: Modeling Root Water Uptake in Hydrological and Climate Models; Bulletin of the American Meteorological Society; American Meteorological Society; Vol. 78 (2001); p. 2797 – 2809; Redwood

Fiorenza S. et al.: Phytoremediation of Hydrocarbon-Contaminated Soils; CRC; Boca Raton (Fl); 1999

Foster S., Garduño H.: Argentina – Integrated Approaches to Groundwater Resource Conservation in the Mendoza Aquifers; Sustainable Groundwater Management: Concepts and Tools ; World Bank Global Water Partnership Associate Program; No. 6; New York, 2005

Frick C. M. wt al.: Assessment of Phytoremediation as an In-Situ Technique for Cleaning Oil-Contaminated Sites; Project Report; Department of Soil Science, University of Saskatchewan; Saskatoon; 1999

Friend L. A. et al.: Quantification of two-year-old hybrid poplar root systems: morphology, biomass, and 14C distribution; Tree Physiology; p. 109-119; Heron Publishing; 1991

Gerbi B. et al.: Geology and structural history of the southwest Precordillera margin, northern Mendoza Province, Argentina; Journal of South American Earth Sciences; Vol. 14; p. 821 – 835; Pergamon; Oxford; 2001

Gielen B., Ceulemans R.: The likely impact of rising $CO_2$ on natural and managed Populus: a literature review; Environmental Pollution; Vol. 115 (2001); p. 335-358; Elsevier; Amsterdam

Giraud Billou C.: Informe final sobre Estudios de Distribución del Agua – Proyecto Constitución y Montecaseros; Departamento General de Irrigación; Mendoza; 2001

Gómez-Silva B. et al.: Atacama Desert Soil Microbiology; in: Microbiology of Extreme Soils; Dion P., Nautiyal C. S. (Edts.); Springer; Berlin, Heidelberg; 2008

Grassi J. C.: Aspectos metodológicos, para la determinación experimental de la evaporación y la frecuencia de riego; CIDIAT (Centro Interamericano de Desarrollo e Investigación Ambiental y Territorial); Material Didáctico de Riego y Drenaje No. 26; Merida; 1978

Gudiño de Muñoz M. E.: Problemática de la agricultura periurbana: caso oasis del Río Mendoza; Boletín de Estudios Geográficos; No. 24/87; Universidad Nacional de Cuyo; Mendoza; 1991

Hernández J. u. Martinis M.: Particularidades de las Cuencas Hidrogeologicas explotadas con fines de Riego en la Provincia de Mendoza; III Jornadas de Actualización en Riego y Fertirriego; Instituto Nacional de Tecnología Agropecuaria ;Mendoza; 10.-11.08.2006a

Hernández, J. et al: Aplicación del modelo de flujo de aguas subterraneas MODFLOW al acuífero de la subcuenca El Carrizal y su extensión al oasis norte; Taller sobre hidrología de áreas regadías; Mendoza; 17.11.2006b

Hoffmann J., Viedt H.: Biologische Bodenreinigung; Springer; Berlin, Heidelberg; 1998

Hopmans J. W., Stricker J. N. M.: Stochastic analysis of soil water regime in a watershed; Journal of Hydrology; Vol. 105 (1989); p.57-84; Elsevier; Amsterdam

Howell R. A., Evett S. R.: The Penman-Monteith Method; USDA Agricultural Research Service; Bushland; 2004

Hsieh P. A. et al. (Edts.): Conceptual Models of Flow and Transport in the Fractured Vadose Zone; Panel on Conceptual Models of Flow and Transport in the Fractured Vadose Zone; National Academy Press; Washington; 2001

INDEC (Instituto Nacional de Estadísticas y Censos): Censo Nacional de Población, Hogares y Viviendas del año 2001; INDEC; Buenos Aires, 2002

INDEC (Instituto Nacional de Estadísticas y Censos): Proyecciones provinciales de población por sexo y grupos de edad. 2001-2015; Serie Análisis Demográfico; No. 31; INDEC; Buenos Aires, 2005

ISO (International Standardization Organisation) 10390: Soil quality - Determination of Determination of pH; International Organization for Standardization; Geneva; 1994

ISO (International Standardization Organisation) 11272: Soil quality - Determination of dry bulk density; International Organization for Standardization; Geneva; 1998

ISO (International Standardization Organisation) 11277: Soil quality - Determination of particle size distribution in mineral soil material -- Method by sieving and sedimentation; International Organization for Standardization; Geneva; 1998

ISO (International Standardization Organisation) 11461: Soil quality - Determination of soil water content as a volume fraction using coring sleeves - Gravimetric method; International Organization for Standardization; Geneva; 2001

Jensen M.E. et al.: Evaporation and irrigation water requirements; ASCE Manuals and Reports on Eng. Practices No. 70; Am. Soc. of Civil Eng., New York; 1990

Jordahl J. L. et al.: Effect of hybrid poplar trees on microbial populations important to hazardous waste bioremediation; Environmental Toxicology and Chemistry; Vol. 16 No.6; p. 1318-1321; Allen Press; Lawrence (KS); 1997

Kavazanjian E. et al.: Unsaturated Flow Flux Assessment for Evapotranspirative Cover Compliance; in: Unsaturated Soils 2006 - Proceedings of the Fourth International Conference on Unsaturated Soils; Miller G. A. et al. (Edts.); Carefree; 02.–06.04.2006

Keese K. E. et al.: Assessing controls on diffuse groundwater recharge using unsaturated flow modeling, Water Resources Research; Vol. 41; American Geophysical Union; Washington; 2005

Kemmesies O.: Darstellung des Sachstandes, Umsetzung im Programm SiWaPro/HYDRUS; BWK-AG 6.2 „Instrumente zur Sickerwasserprognose“; BWK-Materialien; 1999

Klinka K. et al.: Distribution and Synopsis of Ecological and Silvical Characteristics of Tree Species of British Columbia’s Forests; Forest Sciences Department, University of British Columbia; Coquitlam BC: Canadian Cartographics Ltd; Vancouver; 2000

Leiva J. C. et al.: 20 years of mass balances on the Piloto glacier, Las Cuevas river basin, Mendoza, Argentina; Global and Planetary Change; Vol. 59; p. 10–16; Elsevier; Amsterdam; 2007

Leguizamón G. et al.: Sistemas productivos agroforestales adaptados a pequeños productores del área de riego salinizada de Santiago del Estero; in: Cáceres, Daniel M.: Catálogo de tecnologías para pequeños productores agropecuarios 2; Secretaría Agricultura, Ganadería, Pesca y Alimentación; Buenos Aires ; 2007

Li Y. et al.: Root-Water-Uptake Based upon a New Water Stress Reduction and an Asymptotic Root Distribution Function; Earth Interactions; Vol. 10 (2006) No. 14 ; p 1-22; http://EarthInteractions.org; Wisconsin

LUBW (Landesanstalt für Umweltschutz Baden-Württemberg)(Hrsg.): Arbeitsanleitung Pegel und Datendienst – Durchflussermittlung mit der Salzverdünnungsmethode; Karlsruhe; 2002

Luckner, L., van Genuchten, M.Th., Nielsen, D.R.: A Consistent Set of Parametric Models for the Two-Phase Flow of Immiscible Fluids in the Subsurface; Water Resources Research; Vol. 25(10), 1989; p. 2187-2193; Elsevier; Amsterdam

Maddock T. et al.: The overview of atmospheric and surface water coupling to regional groundwater models in semi-arid basins; American Meteorological Society - Special Symposium on Hydrology; Phoenix; 1998

Marre M. et al.: Irrigation water rates in Mendoza's decentralized irrigation administration; Irrigation and Drainage Systems 12: 67–83, Kluwer; Amsterdam; 1998

Mastrantonio L. et al.: Variación espacio-temporal de características edáficas y paisajísticas en un sistema bajo riego; Presentación Facultad Ciencias Agrarias Universidad Nacional de Cuyo; Mednoza; 2006

MdR (Municipalidad de Rivadavia): Sistema de Información Geográfica Municipal; MdR; Rivadavia; 2008

Mendieta M: En LatAm, incluida la Argentina consumimos el doble de agua que en Europa o Estados Unidos; El Informatorio; 21.03.2007; Madrid

Menenti M. (Edt.): Mecanismos de aprovechamiento hídrico en la región andina – Modelos de simulación e imágenes satelitarias; Centro Regional Andino-Instituto Nacional de Ciencia y Técnicas Hídricas; Mendoza; 1988

Menenti M.: Analysis of regional water resources and their management by means of numerical simulation models and satellites in Mendoza, Argentina; Modelling and Management of Sustainable Basin-scale Water Resource Systems; International Association of Hydrological Sciences; Publication No. 231; Boulder; 1995

Mirábile C.: Estudio Zonal de Drenaje del Río Tunuyán Medio. Diez Anos de Control Freatimétrico; INA-CRA (Instituto Nacional de Agua-Centro Regional Andino; Mendoza; 1997

Mirábile C. et al.: Dinámica de la salinidad del Suelo en el Oasis del Río Tunuyán Inferior Comparación 1985 – 2002; INA-CRA (Instituto Nacional de Agua-Centro Regional Andino; Mendoza; 2003

Mirábile C. et al.: Validación del modelo hídrico-salino "Balansal" en suelos cultivados de la Pampa Húmeda cultivados con riego complementario; Presentation; Proyecto de Investigación y Desarrollo; Ministerio de Planificación Federal, Inversión Publica y Servicios, Subsecretaría de Recursos Hídricos; Buenos Aires; 2006

Montes T. A.: El proyecto Potrerillos; Diario Uno; Mendoza; 29.10.1995

Montaña E. et al.: Coming Down the Mountain: Understanding the Vulnerability of Andean Communities to Hydroclimatologic Variability and Global Environmental Change; Inter-American Institute for Global Change Research; Sao Paolo; 2008

Moormann H.: Einfluss der Rhizodeposition von Helophyten auf den mikrobiellen Schadstoffabbau; UFZ-Bericht; No. 1/2002; Halle, Leipzig; 2002

Morábito J. et al.: Salinidad de Suelos Regadíos e Incultos en el Oasis Norte de Mendoza – Argentina; INA-CRA (Instituto Nacional de Agua-Centro Regional Andino; Mendoza; 2005

Morábito J. et al.: Determinación de escenarios de la demanda de riego en el área dominada por el Río Mendoza; Convenio Instituto Nacional del Agua y Ministerio de Ambiente y Obras Públicas del Gobierno de la Provincia de Mendoza (Resolución Nº 1984/00), Informe Final; INA-CRA (Instituto Nacional de Agua-Centro Regional Andino; Mendoza; 2004

Morábito J. et al.: Using performance indicators for the analysis of water use in the Mendoza irrigated area; in: Sustainabiltiy of Groundwate recouses and its indicators – Proceedings of the Seventh IAHS Scientific Assembly at Foz do Iguaçu; IAHS Publishing; 2006

Mualem Y.: A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media; Water Resources Research; Vol. 12 1976(3); p. 513-522; Elsevier; Amsterdam

Mulia R., Dupraz C.: Unusual 3D fine root distributions of two deciduous tree species observed in Southern France: what consequences for root dynamics modelling?; INRA Montpellier; unpublished; 2005

Neumann R. et al.: Stress physiology of poplars – abiotic factors; in: Biology of Populus and its Implications for Management and Conservation; Stettler R. et al. (Edts.); NRC Research Press; Ottawa; 1996

Nielsen D. R., Luckner L.: Theoretical aspects to estimate reasonable initial parameters and range limits in identification procedures for soil hydraulic properties; Proceedings of the International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils (M. Th van Genuchten et al.); University of California; Riverside; 1992

Nijensohn L.: Curso de Edafología V-1 "El suelo como sistema polifásico heterogéneo", Edición C.E.F.C.A., Mendoza; 1962a

Nijensohn L., Pilasi H.: Correlación entre contenido de agua a pF0, volumen de sedimentación y porcentaje de arcilla; Resúmenes de Trabajos y Comunicaciones, 2da Reunión Argentina y 1er Congreso Latinoamericano de la Ciencia del Suelo, Mendoza; 1962b

Ongay O., Bourget M.: Curso de educación ambiental – 10 flora; Gobierno de Mendoza, Ministerio de Ambiente y Obras Públicas, Subsecretaría de Medio Ambiente, Programa Provincial de Educación Ambiental; Mendoza; 2006

Ogg C. M. et al.: Statistical Verification of Soil Discontinuities in Virginia; Soil Science; Lippincott, Williams & Wilkins; Philadelphia, 2000

Ortíz Maldonado G. et al.: Salinidad en el agua freática regadía en el área del Río Mendoza; Revista de la Facultad Ciencias Agrarias Universidad Nacional de Cuyo; Vol. 37 (2005), Nr. 2; p. 51 – 64; Mendoza

OSM (Obras Sanitarias de Mendoza): Consumo de agua en el área de la ciudad de Mendoza; OSM; Mendoza; 1996

Peyke G., Schneider T.: Mendoza – Stadt und Oase am Fuße der Anden: Beiträge zur regionalen Geographie des argentinischen Westens; Geographisches Institut der Humboldt Universität Berlin; Berliner Geographische Arbeiten; No. 85; Berlin; 1998

Pilipovych A. et al.: Investigating potential of some poplar clones for phytoremediation of nitrates through biomass production; International Poplar Commission; Conference: Environmental Applications of Poplar and Willow Working Party; Northern Ireland; 18-20.05.2006

Pregitzer K. S., Friend A.L.: The Structure and Function of Populus Root Systems; in: Biology of Populus and its Implications for Management and Conservation; Stettler R. et al. (Edts.); NRC Research Press; Ottawa; 1996

Querner E. P., Bakel v. P.: Description of the regional groundwater flow model SIMGRO; Report 72 DLO; The Winland Staring Centre; Wangeningen; 1988

Querner E. P. et al.: The use of hydrological models in the irrigated areas of Mendoza, Argentina; Agriculutral Water Management; Vol. 35 (1997); p. 11-28; Elsevier; Amsterdam

Querner E. P. et al.: SIMGRO, a GIS-Supported Regional Hydrologic Model in Irrigated Areas: Casa Study in Mendoza, Argentina; Journal of Irrigation and Drainage Engineering; Vol. 134 (2008); Nr. 1; p. 43 – 48; ASCE (American Society of Civil Engineers); Reston (VA)

Riu N.: Evaporación actual por capa diagnostica en álamos de 5 años edad; unpublished data; Mendoza; 1993

Riu N., Settepani V.: Requerimiento hídrico en álamos de 6 años Rivadavia, Mendoza (Argentina); Revista de la Facultad Ciencias Agrarias Universidad Nacional de Cuyo; Vol. 36 No. 1; p. 63 – 68; Mendoza; 2004

Riu N., Settepani V.: Requerimiento hídrico en álamos de 5 años Rivadavia, Mendoza (Argentina); Revista de la Facultad Ciencias Agrarias Universidad Nacional de Cuyo; Vol. 35 No. 1; p. 52 – 57; Mendoza; 2003

Riu N: personal correspondence, May – Sept. 2008a

Riu N: Fertirrigación en álamos de 6 años de edad; Revista de la Facultad Ciencias Agrarias Universidad Nacional de Cuyo; submitted; Mendoza; 2008b

Rodríguez Aguilera P. et al.: Estudio para el control de inundaciones en el área de afectación del canal cacique Guaymallen; Departamento General de Irrigación; Mendoza; 2006

Roig F. A. et al..: Mapa de Vegetación de la Provincia Mendoza; Catálogo de Recursos Humanos e Información Relacionada con la Temática Ambiental en la Región Andina Agrentina; Abraham E. M., Mertinez F. R. (Edt.); C-Bra Systematics; Buenos Aires; 1999

Roig F. A.: Bosquejo fisionómico de la vegetación de la provincia de Mendoza; ECOSUR; Vol. 3; p. 1 – 45; Rosario; 1972

Rojas J. F.: La Justicia investiga una contaminación petrolera próxima a El Carrizal; http://www.argenpress.info/2008/11/argentina-mendoza-la-justicia-investiga.html; visited 10.12.2008; 05.11.2008

Rydberg Z: Course on Phytoremediation; Department of Biology, Colorado State University; http://rydberg.biology.colostate.edu/CourseCatalog/syllabus/FA03.pdf; visited 08.12.2008; 2003

SAGPyA (Secretaria de Agricultura, Ganadería, Pesca y Alimentos): Sector Forestal – Año 2006; Dirección de Producción Forestal, SAGPyA; Buenos Aires; 2007

Salomon M. A. et al.: Estimación del Balance Hídrico mediante aplicación des modelo ISAREG en el canal Segundo Visalba Lujan de Cuyo. Mendoza (Argentina); Taller "Modernización de riegos y uso de tecnologías de la información" La Paz; 17-19.09.2007

Schaap M., Leij F. J.: Improved Prediction of Unsaturated Hydraulic Conductivity with the Mualem-van Genuchten Model; Soil Science Society of America Journal; Vol. 64; p. 843-851; Soil Science Society of America; Stanford; 2000a

Schaap M.: ROSETTA model for estimation of unsaturated hydraulic soil properties; version 1.2; US Salinity Service, Riverside; 2000b

Scheimberg S.: Petroleo y Gas sus Aportes a la Argentina; Instituto Universitario 'Escuela Superior de Economía y Administración de Empresas'; Concurso de ensayos en conmemoración a los 100 anos del descubrimiento de petróleo en Argentina; Buenos Aires, 2007

Schmitz G. et al: Irrigation control: towards a new solution of an old problem; IHP/HWRP-Berichte; No. 5; Hydrology and Water Resources Programme of WMO; Koblenz; 2007

Schnoor, J. et al.: Phytoremediation of organic and nutrient contaminants; Environmental Science and Technology; Vol. 29 No. 7; p. 318-323; American Chemical Society Publications; Washington D.C.;1995

Šimunek J. et al.: The SWMS_2D code for Simulating the Two-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, Version 1.1.; Research Report No.132; US. Sa1inity Service; Riverside; 1994;

Šimunek J. et al.: STANMOD Studio of Analytic Models for Solving Convection Dispersion Equation; version 2.2; US Salinity Service, Riverside; 1998

Šimunek J. et al.: The HYDRUS-2D Software Package for Simulating the Two-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, Version 2.0; Research Report No.132; US. Sa1inity Service; Riverside; 1994;

Sivera M: Petróleo y Gas: Petróleo: La mitad de la industria de Mendoza; Diario de los Andes; Mendoza; 24.03.2003

Shannon M. C., Banuelos G. S.: Poplars that cope with salty water, Agricultural Research; Volume 28 ; p. 19; USDA; Washington; 1998

Stuwort M.: Suck it up – also known as Phytoremediation; in: Our garden gang – In the garden; online-publication www.ourgardengang.com/pubs/inthegarden.html; 2003

Thomas P. Oasenbewässerung in Trockenräumen: Ansichten zum Problem des Managements von Bewässerungswasser und Einzugsgebieten am Beispiel der äprovinz Mendoza – Argentinien; in: Mendoza – Stadt und Oase am Fuße der Anden: Geographie des argentinischen Westens; Peyke G, Schneider T. (Edts.); Geographisches Institut der Humboldt Universität Berlin; Berliner Geographische Arbeiten; Vol. 85; Berlin; 1998

Thomas Z. et al.: Simulating soil-water movement under a hedgerow surrounding a bottomland reveals the importance of transpiration in water balance; Hydrological Processes; Volume 22 (2008), Nr. 5, p. 577 – 585

Torre V.: El Algarrobo; Editorial Dunken; Buenos Aires; 2006.

Trapp S. Phytoremediation organischer Schadstoffe; Umweltwissenschaften und Schadstoffforschung; Vol. 12, No. 5; p. 246-255; 2000

Trapp S., Karlson U.: The effect of Phytoremediation of Organic Pollutants; Journal of Soil and Sediments; Vol. 1; p. 1-7; Ecomod; Landsberg; 2001

Tschaplinski T. J. et al.: Drought resistance of two hybrid populus clones in a large scale plantation ; Tree Physiology ; Volume 18 (1998) ; p. 653-658

USDA (United States Department of Agriculture) (Edt.): Soil Taxonomy; 2nd Edition; Agriculture Handbook No. 436; USDA; Washington; 1999

van Genuchten, T. M. (1980): A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils; Soil Scientific Society of America (ASSS) Journal; 44 (1980); p. 892-898; ASSS

van Genuchten T. M. et al.: RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils; version 6.0; US Salinity Service, Riverside; 2002

Velasco M. I.: Los aprovechamientos de agua para riego en la región árida argentina; Boletín de Estudios Geográficos; Vol. 7; UN Cuyo; Mendoza; 1963

Ventosa A. et al.: Halophytic and Halotolerant Micro-Organisms from soils; in: Microbiology of Extreme Soils; Dion P., Nautiyal C. S. (Edts.); Springer; Berlin, Heidelberg; 2008

Vereecken H. et al.: Estimating the soil moisture retention characteristics from texture, bulk density and carbon content; Soil Science; Vol.148 ((1989), p. 389-403; USDA; Washington D.C.

Verstraeten W. W. et al: Comparative analysis of the actual evapotranspiration of Flemish forest and cropland, using the soil water balance model WAVE; Hydrology and Earth Sciences; No. 2 (2005); p. 761-799;

Willmott C.J. et al.: Statistics for the evaluation and comparison of models; Journal of Geophysical Research; Vol. 90; p. 8995-9005; Elsevier; Amstedam; 1985

Yeh, G. T. Tripathi, V. S.: HYDROGEOCHEM- A coupled model of hydrologic transport and geochemical equilibria in reactive multicomponent systems; Environs Science Division, Publ. No.3170; Oak Ridge National Lab.; Oak Ridge; 1990

Zhang J. et al.: Effects of salinity stress on poplars seedling growth and soil enzyme activity; Silviculture and Forestry; 16(2005), Nr. 3; p. 426-30; Beijing