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Modeling water and salt dynamics under irrigated cotton with shallow groundwater in the Khorezm region of Uzbekistan

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ABSTRACT

In the Khorezm region of Uzbekistan, the main problems during cotton production remain poor management of irrigation water and the absence of efficient drainage, which causes a change in the local and regional hydrology and can lead to secondary soil salinization. This study aims at providing insights into how the different parts of the soil-plant-atmosphere system interact and where improvements could be implemented. Therefore, the soil water and salt balance of two cotton fields in the semi-arid region of Khorezm were examined. The one-dimensional, soil water model HYDRUS-1D based on the Richards equation was applied. During the 2002 and 2003 vegetation seasons, the research focused on three locations in a sandy loam field (field #1) and on two locations in a sandy field (field #2). For model calibration, the groundwater table and its salinity, the soil salinity (EC_e), and the gravimetric soil water content and soil water pressure head was repeatedly determined across the survey fields. Using on-site meteorological measurements, the FAO-56 potential evapotranspiration (ET_0) was calculated and separated into soil evaporation (E_0) and transpiration (T_0). The latter was fine-tuned with measurements on the development of the cotton leaf area index. Water applied during leaching and irrigation events was quantified.

The simulated soil moisture data at four depths agreed well with the measured values ($RMSE$ = 0.026 to 0.068 $cm^3\ cm^{-3}$), whereas deviations between simulated and observed soil water potential could not be fully eliminated during model calibration ($RMSE$ = 182 to 193 cm). Annual ET_0 was estimated to be 994 mm in 2003. Simulated actual transpiration (T_a) was lower than potential transpiration (T_0) due to the prevalence of water stress during the initial growth stage of cotton. On field #2, the simulated reduction in T was 45 % (~ 100 mm), which was caused by a rapidly desiccating top-soil layer in combination with a shallow groundwater, resulting in poor cotton establishment under these waterlogged conditions. As expected, on field #1, the most severe water stress (81 % of T_0) occurred at the location where least water was applied, highlighting the general problem related to a non-uniform water distribution along the field during irrigation. For all locations, the actual ET during the vegetation season 2003 was greater than the total amount of applied irrigation water. Overall, the soil was depleted by 32 mm of water on field #1 (0-90 cm soil depth) and by 60 mm on field #2 (0-28 cm soil depth).

A capillary rise of 277 mm, 129 mm and 92 mm on field #1, beginning, mid and end, respectively, and 142 mm on field #2 in 2003 indicated that there was considerable groundwater contribution to ET. Moreover, the great heterogeneity of the results demonstrated that this contribution heavily depended upon the imposed irrigation management scheme.

The simulated EC_e for all locations was in a good agreement with the observed data at 20 cm soil depth. At 50, 80 and 105 cm depth, simulation results only poorly reflect the observed rapid salt fluctuations in 2003 ($RMSE$ = 0.39 to 3.23 dS m^{-1}), although the seasonal trend – desalination in response to leaching and slow re-salinization during the vegetation season – was correctly predicted by the model. Thus, the simulation results of solute transport provide reasonable insight into the seasonal salt balance of the monitored fields over the cotton root zone. At the beginning and middle of field #1, about 18 t salts per hectare were leached at the end of the simulation period 2003, while at the end of the field, 9 t of salts per hectare were leached due to the lowest amount of applied irrigation water. In field #2, no irrigation water was applied, and at the end of the simulated period there was a minor salt accumulation of 0.3 t per hectare.

In general, the study allowed assessing the direct and indirect consequences of irrigation and basic agronomic mismanagement (field preparation and cultivation) on the soil water and salt regime. Furthermore, the model could precisely quantify the groundwater contribution and the (de-)salinization process. Based on the results, decisions can be made on how to improve the irrigation scheduling at the field level and how to prevent salt accumulation.

Modellierung der Wasser- und Salzdynamik bewässerter Baumwolle bei niedrigem Grundwasserspiegel in der Region Khorezm in Usbekistan

KURZFASSUNG

Die Hauptprobleme beim Anbau von Baumwolle in der Region Khorezm in Usbekistan betreffen das unzureichende Bewässerungsmanagement und das Fehlen von effizienter Drainage. Beides hat weitreichende Folgen für die regionale Hydrologie und kann sekundäre Bodenversalzung nach sich ziehen. Die vorliegende Arbeit hat zum Ziel, die Interaktionen der verschiedenen Komponenten im Systemverbund Boden-Pflanze-Atmosphäre zu beschreiben, sowie aufzuzeigen, wo Verbesserungen realisiert werden könnten. Dazu wurde die Wasser- und Salzbilanz von zwei Baumwollfeldern in der semiariden Region Khorezm untersucht. Das eindimensionale Bodenwassermodell HYDRUS-1D, das auf der Richards-Gleichung basiert, wurde eingesetzt. Die Studie fand im Anbauzeitraum der Jahre 2002 und 2003 statt und konzentrierte sich auf drei Messpunkte eines Feld mit sandig-lehmigem Boden (Fläche #1) und zwei Messpunkte eines Feld mit sandigem Boden (Fläche #2). Für die Modellkalibrierung wurde auf den Untersuchungsflächen regelmäßig der Grundwasserspiegel, die Grundwassersalinität, die Bodensalinilät (EC_e), der Bodenwassergehalt und das Bodenwasserpotenzial bestimmt. Anhand von meteorologischen Messungen wurden die potenzielle Bestandsverdunstung (ET_0), aufgeteilt in Bodenevaporation (E_0) und Transpiration (T_0), nach FAO-56 Standards bestimmt. T_0 wurde mit Messungen zur Entwicklung des Baumwollblattflächenindex präzisiert. Die applizierten Wassermengen für Salzauswaschung und für Bewässerung wurden quantifiziert.

Die simulierten Bodenfeuchten stimmte mit den in vier Bodentiefen gemessen Werten gut überein (*RMSE* = 0.026 bis 0.068 $cm^3\ cm^{-3}$), während im Zuge der Modellkalibrierung die Abweichungen zwischen den gemessenen und simulierten Bodenwasserpotenzialen nicht vollständig beseitigt werden konnten (*RMSE* = 182 bis 193 cm). In 2003 erreichte die jährliche potentielle Verdunstung 994 mm. Aufgrund von Wasserstress im ersten Wachstumsstadium von Baumwolle war die simulierte Transpiration (T_a) geringer als die potentielle (T_0). Die Verringerung belief sich auf Fläche #2 auf 45 % (~100 mm); ausgelöst wurde sie durch eine rasche Austrocknung des Oberbodens in Verbindung mit einem flach anstehendem Grundwasser, das zu einem schlechten Auflaufen der Baumwollpflanzen unter diesen staunassen Bedingungen führte. Wie erwartet trat auf Fläche #1 dort der größte Wasserstress auf (T_a 81 % von T_0), wo am wenigsten bewässert worden war. Dies unterstreicht die Relevanz der unzureichend homogenen Verteilung von Bewässerungswasser auf dem Feld. Auf beiden Flächen und an allen Messpunkten war die aktuelle Verdunstung im Anbauzeitraum 2003 größer als die Menge des applizierten Bewässerungswassers. Auf Fläche #1 reduzierte sich der Bodenwasservorrat (0-90 cm Bodentiefe) in diesem Zeitraum um 32 mm. Auf Fläche #2 waren dies 60 mm (0-28 cm Bodentiefe).

Kapillar aufsteigendes Grundwasser trug am Anfang der Fläche #1 mit 277 mm, in der Mitte mit 129 mm und am Ende mit 92 mm zur aktuellen Verdunstung in 2003 bei; ein beachtlicher Anteil. Darüber hinaus verdeutlicht die große Spannbreite der Werte, dass dieser Anteil stark vom auferlegten Bewässerungsmanagement abhing.

Die simulierte Bodensalinität in 20 cm Tiefe stimmte an allen Messpunkten gut mit den gemessenen Werten überein. In 50, 80 und 105 cm Bodentiefe reflektierten die simulierten Salinitäten die gemessene starke zeitliche Dynamik in 2003 nur mäßig (*RMSE* = 0.39 bis 3.23 $dS\ m^{-1}$), wobei allerdings der saisonale Trend – Entsalzung durch Auswaschung und anschließende erneute graduelle Versalzung in der Vegetationsperiode – korrekt simuliert wurde. Folglich boten die Simulationsergebnisse zum Salztransport einen guten Einblick in die saisonale Salzbilanz der Untersuchungsflächen. Am Anfang der Fläche #1 wurden im Simulationszeitraum 2003 rund 18 Tonnen Salz pro Hektar aus dem Boden ausgewaschen. Am

Ende dieser Fläche waren dies aufgrund geringerer Mengen applizierten Bewässerungswassers nur noch 9 Tonnen. Auf Fläche #2 wurde nicht bewässert, so dass am Ende des Simulationszeitraums 0.3 Tonnen mehr Salz im Boden vorgefunden wurden.

Im Allgemeinen ermöglichte die Studie es, die direkten und indirekten Konsequenzen von bewässerungstechnischem und generellem landwirtschaftlichem Missmanagement (Feldvorbereitung und -bewirtschaftung) auf das Bodenwasser- und Salzregime zu evaluieren. Weiterhin konnte der Grundwasserbeitrag und die Ent-/Versalzungsprozesse mit dem Modell präzise quantifiziert werden. Auf Grundlage dieser Ergebnisse können Entscheidungen für eine verbesserte Bewässerungsplanung auf Feldebene und für das Verhindern von Bodenversalzung getroffen werden.

Моделирование динамики влажности и транспорта солей в условиях близкозалегающих грунтовых вод при возделывании хлопчатника в Хорезмской области Узбекистана

АБСТРАКТ

В Хорезмской области Узбекистана главными проблемами при возделывании хлопчатника являются плохое управление водой при поливах и отсутствие эффективного дренажа, которое ведет к изменению местной и региональной гидрологии и возникновению проблем вторичного засоления земель. Целью данного исследования является изучение взаимодействия различных составляющих системы почва-растение-атмосфера и определение областей, в которых возможно достичь улучшения. В рамках работы был изучен водно-солевой баланс двух хлопковых полей в Хорезмском регионе. Для выполнения задачи была использована одно-пространственная почвенно-водная модель HYDRUS-1D, базирующаяся на решении уравнения Ричардса. В течение вегетационного сезона 2002 и 2003 исследование было сфокусировано на трех точках супесчаного поля (поле 1) и на двух точках песчаного поля (поле 2). Для калибровки модели с обоих полей были собраны данные по уровню и минерализации грунтовых вод, засолению почв, гравиметрическая влажность почвы и давление почвенной влаги. Используя метеорологические данные, полученные с установленной в хозяйстве мини-метеостанции, определена потенциальная эвапотранспирация (ET_0) по методике ФАО-56. Далее, ET_0 была разделена на испарение с поверхности почвы (E_0) и транспирацию (T_0), используя данные по индексу листовой поверхности хлопчатника. Кроме того, были замерены объемы подаваемой воды при промывках и вегетационных поливах.

Смоделированная влажность почвы для различных глубин относительно хорошо «предсказывает» влажность, определенную во время полевых работ (среднеквадратичная ошибка (*СКО*) между 0.026 и 0.068 $см^3 см^{-3}$). Однако достичь минимального расхождения между смоделированным и измеренным в поле почвенно-водным потенциалом в течение оптимизации модели не удалось (*СКО* между 182 и 193 см). Годовая потенциальная *ET* в 2003 составила 994 мм. Фактическая транспирация (T_a), определенная моделью, была ниже потенциальной (T_0). Это объясняется водным стрессом в течение начальной фазы развития хлопчатника. На поле 2 смоделированная транспирация была ниже потенциальной на 45 % (~100 мм). Это снижение обусловлено быстрым высыханием верхних слоев почвы в комбинации с близкорасположенными грунтовыми водами, которые послужили причиной плохих всходов и развития хлопчатника в условиях подтопления. Как и ожидалось, на поле 1 наибольший водный стресс (81 % от T_0) наблюдался на точке, где наименьшее количество воды было подано в течение вегетации, что еще раз подчеркивает общую проблему, связанную с неравномерным распределением воды вдоль поля во время полива. На всех точках фактическая *ET* в течение вегетационного периода 2003 была больше, чем общее количество поданной воды за вегетацию. В целом, в конце вегетационного сезона, запасы воды в почве на поле 1 были истощены на 32 мм (корневая зона 0−90 см) и на 60 мм на поле 2 (корневая зона 0−28 см).

В 2003 году вклад грунтовых вод в *ET* был значительным и составил 277 мм, 129 мм и 92 мм в начале, середине и конце поля 1 соответственно, и 142 мм на поле 2. Результаты подтверждают, что вклад грунтовых вод в *ET* в большой степени зависит от того, как осуществляется управление водными ресурсами.

Смоделированное засоление почвы в корневой зоне хлопчатника по всем точкам сходится с фактическими данными наблюдений только для верхнего (20 см) горизонта почв. Для 50, 80 и 105 см результаты по засолению почвы, представленные

моделью, лишь слабо отражают резко изменяющиеся данные фактических наблюдений в 2003 году (*СКО* между 0.39 и 3.23 dS m^{-1}). В целом, сезонная тенденция – рассоление почв после промывки и слабая аккумуляция солей в течение вегетационного периода – была правильно предсказана моделью. Следовательно, результаты моделирования транспорта солей позволили корректно установить сезонный солевой баланс в корневой зоне хлопчатника на наблюдаемых полях. Таким образом, в начале и середине поля 1 около 18 т солей на гектар были вымыты к концу 2003 года, тогда как в конце поля 1 из корневой зоны хлопчатника было вымыто 9 т солей на гектар вследствие наименьшего количества поданной воды за сезон. На наблюдаемую точку на поле 2 не было подачи воды в течение вегетации, вследствие этого произошло слабое накопление солей в количестве 0.3 т $га^{-1}$.

В целом, результаты исследования позволили установить прямые и косвенные последствия для водно-солевого режима почв вследствие неграмотного орошения и неправильного управления агротехническим процессом (подготовка полей и культивация). Более того, с использованием модели стало возможным определить вклад грунтовых вод в *ET* хлопчатника и оценить процессы рассоления и накопления солей. Основываясь на результатах моделирования, можно принять решения об улучшении режима орошения хлопчатника, не допуская накопления солей.

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1 INTRODUCTION

Uzbekistan comprises an area of around 447,400 square kilometers with potentially fertile soils and sufficient irrigation water resources, where various types and varieties of agricultural crops could be grown. Almost 85 % of Uzbekistan's territory is covered by desert and semi-desert, including the largest desert in Central Asia, the Kyzylkum. Due to the agro-climatic conditions, agricultural production fully relies on irrigation. In the early 1950s, a substantial development and improvement of Uzbekistan's agricultural sector was initiated. This went in line with an expansion of the arable land and an increase in productivity. Until the end of the last century, the total irrigated land increased from 1.2 million ha to 4.2 million ha (Abdullaev, 2003). Agriculture in Uzbekistan is one of the most important sectors of the economy providing 22.5 % of the GNP in 1996 (BPSP, 2000). Moreover it constitutes the main income for the rural population.

One of the most important crops in Uzbekistan is cotton, also referred to as "white gold". In the mid-1990s, Uzbekistan was the world's fifth cotton producer and second largest cotton exporter, exporting annually almost 80 % of the cotton harvest (Spectrum Commodities, 2004). Today, Uzbekistan is the fourth largest producer of cotton in the world, with 20 % of the total world production (Petr et al., 2003).

Growing cotton in the semi-arid climate conditions and on saline soils requires intensive irrigation. The cultivation of cotton consumes about 50 % of the total irrigation needs in the region (Tsutsui and Hatcho, 1995). Through intensive irrigation, the achieved crop yields are relatively high. According to the Regional Department of Statistics (OblStat), the average yield of raw-cotton in 1991-2001 in Uzbekistan was 2.4 t ha^{-1}, but in the intervention zone Khorezm it constituted 2.7 t ha^{-1} (OblStat, 2004). Although mature cotton plants are salt tolerant, they are very sensitive to soil salinity during germination and at the juvenile stage. Therefore, in order to wash salts from the surface horizons, high water amounts are applied during the winter-spring leaching period. On average, 4300 m^3 ha^{-1} of water is applied for leaching on 85 % of the irrigated land in Khorezm (Djanibekov, 2005).

The ambitious plans during Soviet times for agricultural development in Uzbekistan led to the environmental degradation of the Aral Sea region and the desiccation of the Aral Sea itself. This has had drastic impacts on agricultural production and the livelihood of the rural population, as about 56 % of the total irrigated area of the country is concentrated in the basin of the Amu-Darya River, the largest of the Aral Sea's tributaries (Abdullaev, 2003). High water amounts were and still are applied for cotton and rice production, while water management at the field level is poor and efficient drainage lacking. This is all leading to a rising groundwater table, drastically changing the local and regional hydrology and causing problems of secondary soil salinization. Abdullaev (2003) mentioned that the entire irrigated area in the Khorezm region has secondary salinization problems.

The Amu-Darya River is also the main water source in the Khorezm region, which is located at the southern edge of the Aral Sea Basin in northwest Uzbekistan. The region encompasses a complicated network of irrigation systems and drainage water collection canals, which have been constructed since the early 1950s. There is a need to maintain the irrigation and drainage systems in good shape by yearly removal of sedimentation and weeds from the bed and sides of the canals. Irrigation water quality is degrading due to partial disposal of the polluted drainage waters into the river system. This also imposes a risk for the human health of the local population, which also has to cope with a range of serious problems, such as water scarcity and salinization in response to unsustainable agricultural management. It has been reported that the region regularly experiences shortages of water resources (e.g., a severe shortage during 2000-2001). Soil salinity is often reported to have increased in the past decades. For instance, according to Shirokova (2003, *unpublished*), at least 94 % of the irrigated areas are saline. However, for a profitable crop production in semi-arid regions avoiding plant water stress and soil salinity are two important aspects (Homaee et al., 2002). Effective water management practices are supposed to cover these aspects by maintaining favorable soil moisture and omitting salinity stress by reducing the salt content in the root zone during leaching (Vrugt et al., 2001).

Many studies have been conducted by national and international organizations and researchers to restore the Aral Sea and to rehabilitate the degraded environments (Micklin and Williams, 1994). However, the Khorezm region, which is also a part of Aral Sea Basin, has not received special attention in those studies. Thus ZEF, in collaboration with national and international partners (among others UNESCO, DLR, University of Urgench and Tashkent Institute for Irrigation and Mechanization in Uzbekistan), initiated a bilateral German-Uzbek research program on the "Ecological and Economical Restructuring of Land and Water Use in the Khorezm Region of Uzbekistan – a Pilot Project for Development Research" that aims at providing options for a regional development based on sustainable and efficient land and water use (Vlek et al., 2003).

Field studies are included to increase the understanding on how farmers deal with and manage irrigation water, water deficits and soil salinity during and outside the vegetation periods. However, field studies alone are insufficient to gain insight into how the different parts of the soil-plant-atmosphere system interact (Evett and Lascano, 1993). Here the model application is one of the options of research.

A generally shallow groundwater table is on the one hand the consequence of excessive application of irrigation water. On the other hand, it is a result of imperfect drainage, which in Khorezm is caused by several factors. Since, due to institutional shortcomings, irrigation water is sometimes not available when needed, farmers in Khorezm tend on such occasions to manually block drains and irrigation canals and maintain high soil moisture prior to and after the planting of cotton. Furthermore, the general drainage system is also dysfunctioning and consequently about 34 % of the area of Khorezm has a saline and shallow (<1.0 m) groundwater table (MAWR, 2004).

Shallow groundwater not only advances secondary salinization, but also contributes significantly to crop water demand (Kiseliova and Jumaniyazov, 1975). Yet little is documented on the quantification of the groundwater contribution to meeting the crop water demands, mainly because a precise quantification of capillary rise into the rooting zone of the crop *in situ* implies cost- and labor-intensive experimental setups (e.g., construction of lysimeters). Modeling in this regard provides an effective alternative, as it can help to understand temporal as well as spatial aspects of soil water and solute fluxes. It also is a cheap alternative, since it does not require expensive and laborious lysimeters installations.

Short-term experiments (less than 10 years) are considered appropriate for testing and parameterizing simulation models, which further can be applied for water balance studies based on long-term climate data (Keating et al., 2002). Pereira et al. (2003) argued that experiments in combination with simulation models offer the possibility to gain detailed insights into the system behavior, both in space and in time. Such a combination would also bypass the constraint that field experiments are often site-specific and time consuming to conduct. Despite the fact that by now numerous models exist, the need to test and upgrade them is still high (Xu and Singh, 1996).

One of the existing models, the HYDRUS-1D, was selected and applied in the current study and adapted to local conditions. The HYDRUS-1D software package is a finite-element numerical model for simulating the one-dimensional movement of water, heat and multiple solutes in variably saturated media (Simunek et al., 1998a).

Many studies in Uzbekistan have been carried out to establish water and salt balances for different crops and groundwater regimes under conditions of furrow irrigation with a shallow groundwater (Abdullaev, 1995; Faizullaev, 1980; Isabaev, 1986; Jabbarov et al., 1977; Rysbekov, 1986; Yusupov et al., 1979). However, the reports of modeling results are poorly introduced in the literature. In some cases, the different general implications of these models cannot be assessed because of differing system parameters and input variables, and hence various research institutes worked with their own independently elaborated or modified models. Usually the capillary rise from groundwater can not be modeled, and this has been merely estimated by additional lysimeters studies. For these reasons, existing models have not become widely used, also due to the existence of unfriendly user interfaces. Therefore, the well known HYDRUS-1D model was applied for the first time in Uzbekistan.

Besides application of the model, the agricultural management carried out by the farmers on the cotton fields was monitored to evaluate the consequences with regard to the established water and salt balances and subsoil water fluxes. Thus, this study was undertaken to:

- establish a water and salt balance of the irrigated fields under cotton;
- estimate capillary rise from the groundwater table during the non-vegetation and vegetation seasons;
- assess the agricultural management of cotton growing.

The current regional conditions of soil, irrigation and drainage networks, problems of water management in Khorezm and the arising needs as well as the state-of-the-art of soil water and salt modeling are reviewed and discussed in Chapter 2. After a general introduction to the study region given in Chapter 3, Chapter 4 is dedicated to the description of the field-data collection methodology and description of the model used in the study. In Chapter 5, the analyses of water and salt balances are performed and discussed. Simulation of water and solute transport for different locations in the fields will be presented, and the effect of the soil properties variability on the water and salt balance will be examined. Special attention is given to a quantification of the subsoil water fluxes and leaching requirements. The findings of the comparison of two vegetation seasons are also reported in this section. Chapter 6 discusses the results of the study, comparing the findings with previously conducted studies in the region, while Chapter 7 closes with conclusions.

By describing and quantifying the actual water and solute fluxes as well as seasonal salt dynamics in the soil, the results of the modeling contribute to identifying the problems of water management. Moreover, the model can be used in combination with models on irrigation scheduling and management as well as crop-growth analysis within the framework of an integrated modeling and decision support system.

2 LITERATURE REVIEW

The Aral Sea Basin is a region with water scarcity problems due to an arid climate and poor water management (Micklin, 1991). To solve the water scarcity in the region, crop irrigation management has to be improved, including the management of salinity in the region (Horst et al., 2004). In this regard, it is necessary to understand how water can be used efficiently for agricultural needs. The agricultural production in the region, as well as in entire Central Asia, largely depends on irrigation using water from the two main rivers, Amu-Darya and Syr-Darya. Due to the large-scale irrigation systems constructed since the 1950s, less water from both rivers flows into the Aral Sea, causing it to shrink in size. Between 1960 and 1994, the surface area of the Aral Sea shrunk by more than 50 %, and the “salinity risen by more than three-fold to near that of the ocean” (Micklin and Williams, 1994). At the same time, water losses in agriculture are notoriously high. For more than 30 years, the infrastructure of the irrigation and drainage has operated without rehabilitation and modernization (Abdullaev, 2003). Hence, by 1994, about 63 % of the diverted river water for irrigation was lost before it reached the fields (FAO, 1997). The crop water needs for the two major crops, cotton and winter wheat, produced in Uzbekistan are not well known to the present farming population, which has led in most cases to over-irrigation, high groundwater tables and an increase in soil and groundwater salinity (Evett et al., 2002). Crucial questions such as “How much water is enough to grow crops?” and “What is the level of seasonal salt accumulation in the crop rooting zone?” or “How efficiently do crops use the applied water?” are difficult to answer. However, a successful water management scheme for irrigated crops requires knowledge on the relationship of different key factors in the soil-water-plant-atmosphere system.

2.1 Soil properties of the Khorezm region

The Khorezm region is an irrigated oasis with a history of more than 2000 years (Ablyazov, 1973). Long-term settlement practices caused changes in soil structure and influenced soil salinity. Medium and heavy loam soil textures prevail in the region, while clayey, light loam and sandy loam soils are less widespread and often located either in the lower parts of lake sedimentation or in former riverbeds and adjacent sites.

Faizullaev (1980) determined four groups of soils in the region according to permeability and hydraulic conductivity:

1. Soils of light texture, usually homogeneous with high permeability during the first hour of 70 mm hour^{-1}, and a coefficient of filtration of 0.52 m d^{-1}. These are so-called newly irrigated meadow sandy loams.
2. Soils of medium and heavy loamy texture, homogeneous and heterogeneous, lightening to the bottom with a good permeability of 50-70 mm during the first hour and a coefficient of filtration of 0.45 m d^{-1}. These are both old and newly irrigated meadow soils, usually slightly saline.
3. Soils of different soil textures with clayey layers having a satisfactory permeability of 30-50 mm hour^{-1} and a coefficient of filtration of 0.36 m d^{-1}. These are both old and newly irrigated meadow and bog-meadow soils of medium and high salinity, as well as solonchaks.
4. Soils of different soil textures becoming heavier downward with a low permeability of less than 30 mm per first hour and a coefficient of filtration of 0.2 m d^{-1}. These are solonchaks and soils with compacted top layers.

Abdullaev (1995) summarized the basic water and physical soil properties depending on soil texture: The water permeability of sandy soils is 230-360 cm d^{-1} and in sandy loam soils between 12 and 230 cm d^{-1}. Data on saturated hydraulic conductivity for soils in the Khorezm region were not found in the literature. There is a general lack of data in available soil hydraulic databases for application in model simulations on soils in the Khorezm region.

2.2 Water management and problems of soil salinization in the Khorezm region

Worldwide, soil salinity is a latent threat within irrigated agriculture. Improper irrigation can lead to a rising groundwater table in particular when the drainage system is not working properly. Hence, this directly changes the local and regional groundwater movements. Salt accumulation in the crop root zone is a logical consequence of raising saline groundwater tables under conditions of potentially high evapotranspiration as prevailing in an arid environment such as in Khorezm.

Kaurichev et al. (1989) noted that the soil water regime is an aggregate of events of water infiltration into the soil, its movement, retention in the soil layers and loss from the soil profile. Quantitatively it is expressed through a water balance, which characterizes the water influx into the soil profile and discharge out of it. A soil water balance allows judging the reserves of the soil water available to crops. Ratliff et al. (1983) pointed out that an accurate calculation of the soil water balance is important because of the need to manage water as efficiently as possible. The amount of irrigation water required for crops can be calculated considering the water balance of the crop root zone, taking into account crop water requirements.

Over the past centuries, people have gained knowledge and experience on how to use saline soils and water to produce crops. One of the commonly applied remedies is applying high water amounts to remove harmful salts by downward percolation beyond the crop rooting zone (Hillel, 2004) during special leaching periods or irrigation. Unless the salts are leached out, they poison the root zone. Hence, the necessary amount of water for leaching highly depends on the salt content of soils, drainage system conditions, irrigation and groundwater salinity (Ferrer and Stockle, 1996). The crop salt tolerance, climate, soil and water management should be taken into consideration as well as economic aspects for determining the frequency and total amount of leaching water.

However, not only leaching *per se* plays an important role within irrigated agriculture, but also the timing for leaching. This is usually determined on the basis of climatic factors such as first frosts in autumn or air and soil temperatures above a certain threshold in spring. Kiseliova and Lifshits (1971b) concluded that in Khorezm the first soil freezing occurs in mid November in 50 % of all years based on monitoring from 1953 onwards. Since early frosts complicate the autumn to spring field activities, such as leaching and ploughing, leaching activities in Khorezm are conducted in February-April, when climatic conditions are more favorable.

Cotton is considered as a salt tolerant crop (Allen et al., 1998), although during the germination period it is sensitive to salinity. Thus, in order to achieve acceptable plant establishment rates and ultimately yields, leaching is necessary if the electrical conductivity of the soil solution before planting is greater than 7.7 dS m^{-1} (Rhoades et al., 1992). At the same time after leaching, the soil moisture content is high to secure seed germination. The timing of the first irrigation, especially under saline conditions, is crucial for unrestricted crop growth and rooting system development (Kruse and Ayars, 1996). Already in the early 19th century, farmers used groundwater as sub-surface irrigation by blocking the drains after the leaching. They kept them closed for a few weeks, thus maintaining soil moisture at favorable levels for crop germination.

Naturally, soil salinity is not constant and uniform in time and space. Depending on leaching and/or irrigation rates and the height of the groundwater table and its salinity, the salt distribution may be uniform along the soil profile with slow changes with depth, or may be irregular, with high concentrations on top or at the bottom of the root zone (Hutson et al., 1996). Numerous factors such as soil physical and chemical properties, crop water and solute uptake, and water and solute application rates affect solute transport in the vadose zone (Dudley and Shani, 2003; Rose, 2004). In arid environments with shallow groundwater tables, the capillary rise of water and solutes from the groundwater into the rooting zone has to be taken into account. Thus, water and solute uptake by plant roots greatly affects rootzone concentration and fluxes of salts from or towards the groundwater.

Abdullaev (1995) pointed out that at the lower reaches of the Amu-Darya River, the groundwater under the irrigated soils is mainly evaporates and transpires, while a minor part is discharged to the collectors and deep percolation. Therefore, the groundwater flow contributes to the vertical water exchange, i.e., it is hydrostatically connected to the surface water. Kats (1976) mentioned that in the Khorezm region the vertical movements of groundwater prevail over horizontal movements in large areas. Thus, the groundwater table changes very fast in response to changes in the water level in the irrigation and drainage systems. Under such circumstances, difficulties arise with regard to a precise determination of groundwater depth. Moreover, Yusupov et al. (1979) mentioned that the actual groundwater table is 20-30 cm lower than the water table measured with observation wells. They attributed these deviations to the hydrostatic pressure building up in the observation wells due to a sandy groundwater aquifer overlaid by a less-permeable loamy soil layer. They finally concluded that the height and rate of groundwater table rise depends on soil texture. The existence of a hydro-dynamical connection between groundwater and filtration fluxes from the irrigation canals and collectors in stratified soil structures creates a low positive groundwater pressure head almost everywhere. The size of this head depends on the water level difference in the canals and the distance from the canal. This means that for the conditions in Khorezm the groundwater tables measured with observation wells need to be cross-checked and, if necessary, corrected for deviations from real levels based on established site-specific relationships.

Yusupov et al. (1979) stated that even where changes in soil texture are not significant, sudden changes in soil moisture within one soil layer often is observed in Khorezm. In the case where the overlaid soil layer is heavier due to its texture, the capillary rise and capillary moisture here is higher. If the thickness of this layer is less than the height of the capillary rise, then the next layers will also be in the capillary zone. In contrast, if the thickness of this layer is larger than the capillary rise height, then the capillary fringe will break. This is more evident in sandy layers, especially in those with coarse textures. An inevitable consequence of shallow groundwater tables and capillary rise of water is that salts dissolved in the groundwater also rise and remain in the top-soil layer, thus increasing soil salinity.

The impact of blocked drains is generally strongest in light and shallow soil layers with good filtration properties and decreases as the soil texture becomes heavier. An important ameliorative aspect of the Khorezm region is that the soils there are fine-grained silty sands located at different depths. Sandy soils with shallow groundwater tables are free from salts more quickly during leaching periods and salt restoration is slow (Jabbarov et al., 1977). Additionally, in sandy soils a decrease in the groundwater table may completely stop the salt accumulation processes in the upper layers (Yusupov et al., 1979). Furthermore, the under-laying sandy layers facilitate groundwater flow-out at natural degree of drainage and help to wash out the salts. Consequently, the blocking of irrigation canals and drains is considered to be a feasible activity for slightly saline soils with shallow sandy soil layers (Yusupov et al., 1979).

According to official data from the Ministry of Agriculture and Water Management of Uzbekistan for autumn 2004 (MAWR, 2004), on 34 % of the irrigated lands in Khorezm the groundwater table varied from 0 to 1 m below the surface and on 59 % it ranged between 1 and 1.5 m depth. Under these conditions, 55 % of the irrigated lands were classified as slightly saline (2-4 dS m^{-1}), 33 % as medium saline (4-8 dS m^{-1}) and 12 % as highly saline (8-16 dS m^{-1}). The percentage of saline soils in 2004 is comparable to the situation in 1990, when the share of slightly, medium and highly saline lands was 50 %, 33 % and 10 %, respectively. In 2000, a year of notable water shortage, the percentage of medium and highly saline soils increased (43 % and 13 %, respectively), whereas slightly saline soils decreased to 45 %. Although the Khorezm region is characterized as an area with clearly expressed continuous secondary salinization (Abdullaev, 2003), the rapid change in area, e.g., of medium saline soils in 1990, 2000 and 2004, suggests that with sufficiently available water resources the secondary salinity problem in the region can be handled by appropriate leaching practices.

Transpiration is the main mechanism of salt accumulation in irrigated lands (Schoups and Hopmans, 2002). Thus, the salt accumulation is influenced not only by the groundwater table depth and its salinity, but also by climate, soil physical and chemical properties, plant water and solute uptake rates, and the quality of irrigation water and management practice (Schoups and Hopmans, 2002). Results of a study conducted by the Central Asian Scientific Research Institute of Irrigation (SANIIRI) in Khorezm on soils with shallow groundwater and properly working drainage show that it is possible to desalinize soils completely by the application of 700-800 mm of irrigation water during the vegetation season and 400-500 mm at leaching (Ikramov, 2001).

Summarizing the above said, irrigated agriculture in arid and semi-arid regions may lead to salt accumulation in the soil and deterioration of productivity. Salts are brought to the field with irrigation water where, under evapotranspiration processes, they are accumulated and stored in the profile. To avoid crop damage, the level of salt content has to be decreased by appropriate management practices (Ayers and Westcot, 1985). To leach the salts below the rooting zone of the crop, a sufficient amount of water must be applied. However, the control of soil salinity by applying excess water is limited under conditions of poor drainage and shallow groundwater tables. Therefore, management practices should include the use of different irrigation scheduling while taking into account agricultural water demand, leaching fraction and frequency of leaching, and selecting salt tolerant crops and reusing drainage water.

Ibrakhimov (2004) concluded that one way to decrease the shallow groundwater in the southern part (including Khiva district) of the Khorezm region would be to reduce the areas under high water demanding crops. The appropriate practices for salinity control should be selected based on the quantification of water and salt movement in the soil, how crops respond to water and salinity stress and how environmental conditions and management influence these interactions. In this regard, mathematical models as mentioned by Feere and Stockle (1996) can help to integrate all interactions and define the best management for crop production under saline conditions.

2.3 Water flow and solute transport models and their peculiarities

Water flow

Models applied in natural science to simulate processes of the real system are able to predict state variables at any stage during the simulation (Ines et al., 2001). The more complex the model is, the larger the number of processes it describes, and consequently more information about the described system is needed. The accurate simulation of water and solute fluxes in the unsaturated zone is necessary in many environmental studies (van Dam et al., 2004). Existing models (Table 2.1) are applied to address practical problems in assessment of water and solute transport (Costantini et al., 2002; Hammel et al., 2000; Mandal et al., 2002; Srinivasulu et al., 2004; Vanderborght et al., 2005; Vrugt and Bouten, 2002), water infiltration (Hermsmeyer et al., 2002; Hernandez, 2001; van Dam and Feddes, 2000), leaching (Logsdon et al., 2002), water uptake by roots (Li et al., 2001; Vrugt et al., 2001), specific irrigation system (Horst et al., 2004; Liu, 1999; Pereira et al., 2003; Ragab, 2002) or a combination of the processes (Abbasi et al., 2004; Dorji, 2001; Ma et al., 2000; Nielsen et al., 2002; Sarwar and Feddes, 2000; Wu et al., 1999).

A predictive model should include all processes and properties of the system that impact on the system's behavior and functioning (Vanderborght et al., 2005; Zavattaro and Grignani, 2001). Comparing different models highlights the way the models solve the underlying processes and indicates the weaknesses and strengths of each model. The accuracy of the model results depends on the assumptions and simplifications made in the model and their relation to site-specific conditions (Zavattaro and Grignani, 2001). Besides these assumptions, the model parameterization and the use by different modelers also may lead to differences in the model results (Vanclooster et al., 2000). When selecting a model, it should be ensured that adequate inputs can be derived. Following model selection, all required input parameters should be compared and validated with reliable and accessible data for a given situation.

Table 2.1 Some soil water and solute movement models

Model	Purpose
ISAREG (Teixeira and Pereira, 1992)	ISAREG is a soil-water balance simulation model aiming at establishing irrigation scheduling programs for a given soil-crop combination, or at the evaluation of selected irrigation schedules.
CROPWAT (Smith, 1992)	CROPWAT is meant as a practical tool to help agro-meteorologists, agronomists and irrigation engineers to carry out standard calculations for evapotranspiration and crop water use studies, and more specifically the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rainfed conditions or deficit irrigation.
UNSATCHEM (Simunek et al., 1996)	UNSATCHEM is a software package for simulating water, heat, carbon dioxide and solute movement in one-dimensional variably saturated media.
HYDRUS-1D (Simunek et al., 1998a)	The HYDRUS-1D program is a finite element model for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated media.
SWAP (van Dam et al., 1997)	SWAP is a computer model that simulates transport of water, solutes and heat in variably saturated top soils. The program is designed for integrated modeling of the Soil-Atmosphere-Plant System.
VLEACH (Ravi and Johnson, 1997)	The Vadose zone LEACHing model (VLEACH) is a one-dimensional finite difference model for simulating the vertical mobilization and migration of dissolved organic contaminants through the vadose zone.
LEACHM (Hutson and Wagenet, 1992)	LEACHM (Leaching Estimation and Chemistry Model) refers to a suite of simulation models describing the water and chemical regime in the soil root zone.
CHAIN-2D (Simunek and van Genuchten, 1994)	CHAIN-2D is a computer program for simulating two-dimensional variably saturated water flow, heat transport, and the movement of solutes involved in sequential first-order decay reactions.
HYDRUS-2D (Rassam et al., 2003)	HYDRUS-2D is a numerical modeling environment for simulating one- and two-dimensional variably saturated fluid flow and heat, and multiple solute transport in porous media.
SWMS-2D (Simunek et al., 1994)	SWMS-2D is a computer program for simulating water and solute movement in two-dimensional variably saturated media.
RZWQM (Ahuja et al., 1999)	The RZWQM (Root Zone Water Quality Model) is a process-oriented simulation model. The purpose of the model is to simulate water, chemical and biological processes in and on top of the root zone. The model also examines solute movement from the bottom of the root zone to the water table. It also includes crop-growth routines for some major crops.

Several models were developed for simulating water flow and solute transport. Among them are one-dimensional flow models, which allow accounting for the soil heterogeneity and preferential flow. The reliability of model results can be evaluated by comparing results from different models, or comparing modeled and empirical data or by comparing modeled results with analytical solutions. Scanlon et al. (2002) compared seven codes to simulate the water balance of non-vegetated engineered covers in semi-arid regions in warm and cold deserts. In general, the results of the compared codes were similar, but there were also some differences. These deviations were due to differences in modeling approaches (e.g., Richards equation versus storage routine), definition of upper and lower boundary conditions (seepage face versus unit gradient), and water retention function (van Genuchten versus Brooks and Corey). Vanderborght et al. (2005) evaluated five numerical models that use different numerical methods to solve the flow and transport equations. The accuracy of the tested models was compared with existing analytical solutions for the simple initial and boundary conditions. Differences of water flow simulations at limited evaporation were attributed to the spatial discretization and internode averaging of the hydraulic conductivity in the surface grid layers. It is clear that the accurate determination of water flow and solute transport at the field scale requires reliable estimates of soil hydraulic properties.

Richards et al. (1956) were the first to use the unsteady drainage-flux method to determine unsaturated soil hydraulic properties in the field. Their method was based on Darcian analysis of soil water redistribution and hydraulic head profiles during vertical drainage after saturating (Zhang et al., 2003). The unsteady drainage-flux method assumes that during the whole observation period there will be no evaporation at the soil surface. Kelleners et al. (2005) mentioned that the flow in the soil cannot be fully described by the Richards equation, as the modeled preferential flow and vapor transport deviate from the data measured in the field. They also pointed out that the soil-hydraulic properties might not fit the Mualem-van Genuchten model. However, Russo (1988) compared models of Gardner (1956), Brooks and Corey (1966) and Mualem-van Genuchten (Mualem, 1976; van Genuchten, 1980) and concluded that the latter model predicted the outflow data from a silty loam most accurately and consistently.

Depending on the flow regime, i.e., unsaturated or saturated, three main forms of the Richards equation are possible: saturation based, pressure based, or mixed. Many direct laboratory and field methods exist to determine soil-hydraulic properties (Dirksen, 2001). Besides, they can be identified indirectly by so-called transient models. They include one-step outflow (Parker et al., 1985), multi-step outflow (Minasny et al., 2004; van Dam et al., 1994) and evaporation experiments (Simunek et al., 1998b).

Parameter estimation by inverse simulation (optimization) was first reported in the early 1980s, and since then the use of that method has continually expanded. The advantages of the inverse simulation procedure are that any available information, such as measured water content, matric potential, and the measured water retention curve, can be used. Thus, this approach is very useful when laboratory analyses are not possible but soil-hydraulic properties have to be determined.

Boundary and initial conditions

In any model, the initial and boundary conditions have to be determined to describe the water movements in the soil. Aside from physical boundaries, hydraulic boundaries that are represented by three types of mathematical condition exist: (1) specified head boundaries (Dirichlet conditions), when the pressure head is given; (2) specified flow boundaries (Neumann conditions), when derivative pressure heads or fluxes across the boundary are given; and (3) head-dependent flow boundaries (Cauchy or mixed boundary conditions), when fluxes across the boundary are calculated from the given boundary head values. The upper boundary conditions include the applied water and precipitation input into the soil profile and water output via evaporation. When crop growth and water movement in the field are considered, the upper boundary conditions of the soil normally comprise precipitation and/or irrigation and soil evaporation (E_{pot}).

Evaporation from the soil surface is the dominant component of evapotranspiration (*ET*) over bare soils, meaning during the off-season and in the early stages of crop development (Burt et al., 2002a). In general, *ET* is the largest component in most hydrological water balances (Xu and Singh, 1996). A number of complex models were developed to determine *ET,* among which the Penman-Monteith method is one of the most accepted. Hence, the FAO adopted this method for agricultural crops although suggesting various generalizations and simplifications with regard to the original equations. This resulted in the so-called FAO-56 version (Allen et al., 1998), which is accompanied by a comprehensive handbook that explains in detail how the so-called crop coefficients are derived to determine crop evapotranspiration (ET_c) and how ET_c can be partitioned into *E* and *T*. For soil water models, the proper determination and subsequent partitioning of evapotranspiration is necessary. Transpiration, as one of the major components of the field water balance (Feddes et al., 1978; Raats, 1974), enters soil models via the so-called sink term as part of the Richards equation.

Meiwirth and Mermoud (2004), while simulating herbicide transport in south-west Switzerland, found that shallow groundwater and a high evaporation rate greatly influenced the soil water conditions in the unsaturated zone. The authors concluded that in such environments the lower boundary conditions should be selected carefully, because they strongly influence the outcome results of water content and solute concentration. Depending on the conditions for which simulations are to be carried out, in one-dimensional models the lower boundary can be defined by the constant pressure head, constant flux, variable pressure head, variable flux, free drainage, deep drainage, seepage face, and horizontal drains. In case of deep groundwater tables, the free drainage (driven by gravity only) conditions are usually applied. When the groundwater table during the whole season is shallow and an upward movement (capillary rise) of water (into the rooting zones of the crops) is taking place, monitored groundwater table depths can be converted into pressure heads (where the soil surface is used as the reference point) and used as lower boundary conditions.

Initial conditions are normally derived from the observed soil moisture or pressure head and groundwater table and salinity data (Simunek et al., 1998a).

Solute transport

To describe and quantify the subsoil solute fluxes in the unsaturated zone, three physically based solute-transport concepts have been developed: (1) the stochastic-convective model (SCM); (2) the convection-dispersion equation (CDE); (3) the fractional advection-dispersion equation (FADE) (van Dam et al., 2004). The CDE represents mass continuity for solute movement by dispersion and convection under specified boundary and initial conditions. It relates to deterministic-mechanistic models, which are the largest group of models for describing solute transport. Those models are easy to understand, describe the relationships between different processes, and what is most important, can be directly combined with models for water movement (Wang, 2002).

According to Kelleners et al. (2005), modeling of solute transport demands accurate definition of solute dispersion. Khamraev et al. (1984) noted that the soil salt regime determines the necessity of studying anion diffusion and dispersion processes and capillary movement of solutes. The structural form of the soil and its water content causes dispersion of the nonreactive solutes (Bejat et al., 2000). Lateral movement and redistribution of irrigation water on the soil surface and the movement of the solutes through macro-pores are two processes mentioned by Poletika and Jury (1994) by which solutes and water become spatially variable. A number of experiments was conducted to fit the transport parameters to tracer experiments to find the relationships between transport parameters and flow rates (for details see Bejat et al., 2000; Simunek et al., 2002). Some argued that dispersivity is independent of water content and only determined by pore space geometry, while others noted that dispersivity depends on the soil saturation degree. Analyzing the solute transport data from undisturbed, unsaturated soil blocks, Bejat et al. (2000) concluded that the structural controls on solute dispersion in unsaturated soils were indirect and rather caused by variations in water content produced by differences in pore-size distribution.

Interactions between the solution and adsorbed concentrations can be described either by equilibrium or by non-equilibrium models (Simunek et al., 2002). In case of equilibrium adsorption, the relationships between solution and adsorbed concentrations can be described by a generalized nonlinear equation. Special cases of this equation are Freundlich, Langmuir and linear isotherms (Simunek et al., 1998a). In contrast, non-equilibrium models are described by a mass transfer reaction. In this reaction, the transfer between solutes in solution and sorbed phases is determined by the concentration differences and a mass transfer coefficient (Simunek et al., 2002).

According to the classification by Kaurichev (see Appendix 9.1), the soils of the monitored fields in the present study are very highly saline, with a chloride and chloride-sulphate type of salinity. Akramkhanov (2005) in his study also mentioned that the soil salinization type on the research farm of the Urgench State University is predominantly chloride-sulphate. Although many researches have been conducted to study Cl^- transport in the soil under unsaturated/saturated conditions (Akhtar et al., 2003; Gee et al., 2005; Scanlon, 2000; Scanlon et al., 2003; Schick, 2005; Ventrella et al., 2000), the values for dispersivity and isotherm adsorption coefficients for Cl^- were not cited in these studies. Normally, these coefficients are determined in the laboratory by so-called sequential batch experiments, but for chloride no such publications could be found.

One-dimensional models

To simulate the timing of irrigation, irrigation depths, drain spacing, drain depth, or the system behavior and response to irrigation, unsaturated-zone models in combination with mechanistic crop growth models or saturated zone models are suggested (Bastiaanssen et al., 2004; Simunek et al., 1998a; van Dam, 2000). Nowadays, the understanding of irrigation and drainage with respect to the soil-water-plant-atmosphere system allowed the development of models for soil moisture and solute transport in the unsaturated zone (see Table 2.1). Yet, because of the numerous models, it is obvious that no universal model exists that can be applied in all situations, but rather that each model has its weaknesses and strengths. Bastiaanssen et al. (2004) emphasized that model selection criteria should follow the objectives of the study.

Among many developed models that are based on the Richards equation, the HYDRUS-1D model (Simunek et al., 1998a) was selected and applied in the current research. The HYDRUS-1D model includes relatively easy and useful tools to simulate soil water content, and on the other hand predicts soil hydraulic conductivity, root water uptake and root growth and solute concentration in the soil profile. HYDRUS-1D is one of the various numerical codes that has been developed for identifying the soil hydraulic and solute transport parameters from unsaturated flow and transport data of one-dimensional porous media and that has been frequently applied in the recent past (Bitterlich et al., 2004; Hernandez, 2001; Meiwirth and Mermoud, 2004; Sommer et al., 2003; van der Grift et al., 2004; Vanderborght et al., 2005; Ventrella et al., 2000).

In the HYDRUS-1D model, the soil water fluxes are calculated by the standard Richards equation, whereas the solute flow is described by the convective-dispersion equation. Data input includes simulation parameters, time-step parameters, parameters defining the geometry, soil hydraulic properties, solute transport parameters, initial and boundary conditions, output times and observation point location. After a successful simulation, the model output includes pressure head, soil water content and solute concentrations for user-specified times.

Despite the obvious advantages of one–dimensional (1-D) models, which mainly lie in their simplicity, van Dam et al. (2004) concluded that if the soil profile is not homogeneous horizontally and boundary conditions are not uniform, a 1-D model may fail to mimic reality. In contrast, 1-D models have proven their validity not only with laboratory experiments with uniform soil cores, but also in the field in the case of deep groundwater tables (Ventrella et al., 2000) or in layered lysimeters (Hermsmeyer et al., 2002; Kelleners et al., 2005). One–dimensional models were also used successfully in the case of vertically heterogeneous soils but only when the soil hydraulic properties were known for every soil layer (van Dam et al., 2004). In case a lateral water flow is prevailing and not a vertical flow, it is recommended to apply 2-D and 3-D models instead. If there is no dominant lateral flow, 1-D models are preferable (for details see van Dam et al., 2004).

One–dimensional models are simpler than 2-D and 3-D models. Yet in unsaturated soils, the water flow is predominantly vertical, i.e., one-dimensional (Hillel, 2004; Meiwirth and Mermoud, 2004; van Dam and Malik, 2003). One–dimensional models nevertheless solve the Richards equation accurately and efficiently. Also, the crude soil-hydraulic properties are accessible in databases. One–dimensional models can be combined with GIS (Geographical Information Systems) to analyze water flow in a hydrological system at the regional scale. The disadvantage of the HYDRUS-1D model is that for the determination of the net precipitation, which infiltrates the soil, evaporation is overestimated (Scanlon et al., 2002). The model assumes that during precipitation and irrigation events, soil evaporation is at a maximum (potential rate), which is true only if the respective precipitation/irrigation was homogenously distributed over a given day, which however is rarely the case. Thus, HYDRUS-1D tends to overestimate *E* and underestimate water storage in the soil profile. More studies are necessary to prove the above-mentioned disadvantages of the model.

Soil water and salinity regime studies conducted in Uzbekistan

In arid and semi-arid regions, a high evaporation and concurrent lack of precipitation as prevailing in the study region can contribute to overall soil salinization (Kloetzli, 1995). Soil salinization occurs not only because of the presence of salts in the soil (the so-called primary salinization), but also due to upward movements of the groundwater with the salts, which results in salt accumulation in the upper soil horizons. This so-called secondary salinization recurrently occurs predominantly under conditions of high evaporation. Jorenuch and Sepaskhah (2003) emphasized that secondary salinization is prone to occur under arid and semi-arid conditions such as in the study region Khorezm, where the potential evapotranspiration (ET_0) ranges from 1300 to 2000 mm per year (Micklin, 1991; Tursunov, 1981). The process of soil salinization is even enhanced on the alluvial soils of Khorezm, since these soil types have good physical properties, meaning that when groundwater tables are shallow, these soils tend to accumulate salts, particularly at the end of the vegetation season. On the other hand, such soil types can be easily leached (Ablyazov, 1973).

To counterbalance the process of soil salinization in arid and semi-arid regions, several remedies are recommended to the farming population (Morozov, 2004a). Aside from leaching with adequate amounts of water with minimum salt concentration, an appropriate discharge from the fields is compulsory. Consequently, soil water and salt regimes in arid/semi-arid zones can be managed through optimization of the irrigation schedules and in particular under the conditions of a well functioning irrigation system.

Many models for optimizing irrigation schedules have been developed for Central Asian conditions by various institutes, such as the Russian Scientific Research Institute of Hydro-technique and Melioration (VNIIGIM), the Central Scientific Research Institute of Complex Water Use (CNIIKIVR), SANIIRI and others. Most of those models are based on the earlier work of Horst (1960) or Yaron et al. (1980), which are elaborations of a rootzone balance model. In these models, the soil moisture conditions are taken into account and stress thresholds are defined when modeling crop yield. In a recent overview of these simulation models, Morozov (2004b) described for which tasks and conditions they are appropriate. Imitation models, which are based on the solution of the hydraulic conductivity equation and convective salt transfer in a soil, allow prognoses of soil moisture and solute dynamics by soil horizon under changing groundwater tables (Morozov, 2004c). The parameters to be included in the model are well described (Morozov, 2004d) and finally provide prognoses of the water and salt regime and yield for a given irrigation schedule on a daily basis, and the irrigation scheduling for a given critical soil moisture and for different crop phases with the aim of stabilizing the long-term salt regime. In addition, the model output provides data on changes in irrigation water salinity, groundwater flow and salinity and drainage conditions and finally prognoses drainage water salinity. Despite these useful outputs, this model is not widely known or used in Uzbekistan. One of the reasons may be the user-unfriendly interface of the model and the absence of a version that runs under the Microsoft Windows operating system.

Various studies on soil water and salinity regimes in Uzbekistan were combined with the elaboration of models to solve specific tasks. But surprisingly enough, they were used exclusively in the scientific institutes where they were created. The introduction of the HYDRUS-1D model, which is well known worldwide, well documented and freely available for download, may provide an opportunity to use the outcomes of this model and concurrently may improve and support the modification of local models for irrigation scheduling and other related tasks.

3 STUDY REGION

3.1 Geographical setting

The Khorezm region is situated in the northwest of Uzbekistan, on the left bank of the Amu-Darya River, within the transition zone of the Karakum and Kyzylkum deserts and in the center of the Turan plain (Figure 3.1). The Khorezm region covers an area of 6800 km^2 bordered by the Amu-Darya River to the northeast, the Autonomous Republic of Karakalpakstan to the north, the Karakum desert to the south and southeast, the Kyzylkum desert to the east, and the Republic of Turkmenistan to the southwest. The population is about 1.2 million, i.e., 190 persons per square kilometer, with about 80 % living in rural areas (Dickens, 2002). Khorezm is divided into 10 administrative districts. The capital is Urgench, with a population of 135,000. Another major town is Khiva, which is located in the south-western part of the Khorezm (35 km from Urgench) and is very close to the Karakum desert.

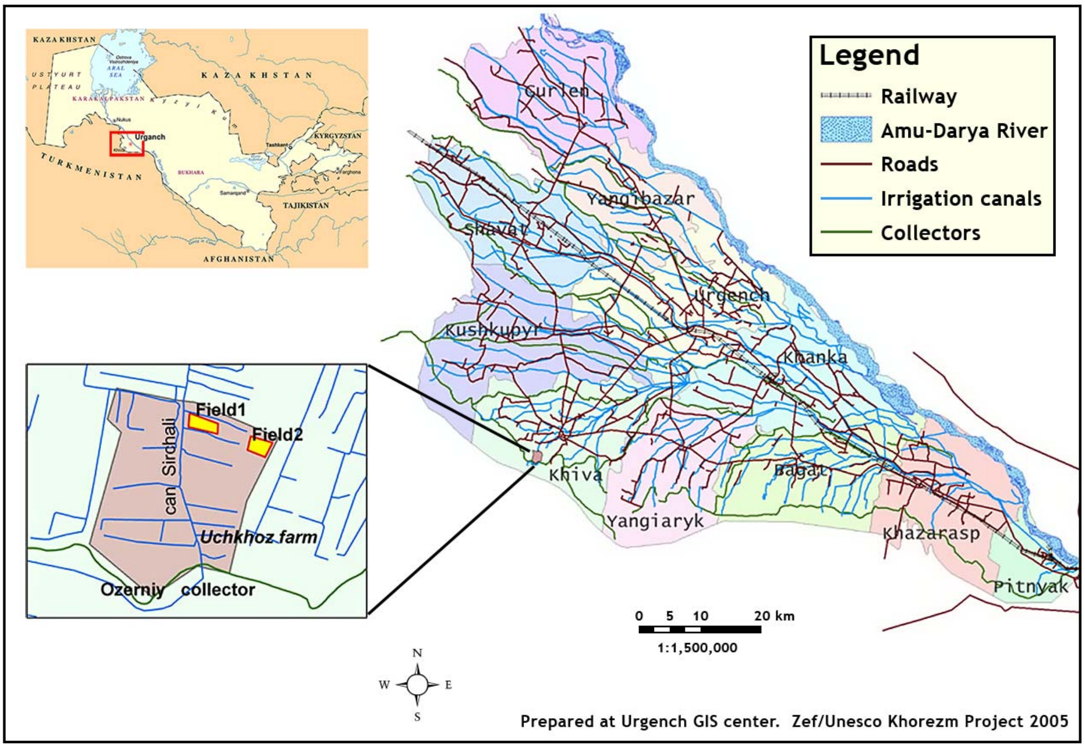


Figure 3.1 The Khorezm region in the northwest of Uzbekistan and the location of the study farm

The study was conducted at two fields in the Khiva district (area: 463 km^2) within the bounds of the former University of Urgench research farm (Uchkhoz) (41°20′ N 60°18′ E, altitude 92 m a.s.l.; Figure 3.1). The research station comprises an area of 270 ha with cotton as the primary cultivated crop, followed by winter wheat, rice and various other crops. The area contains a network of irrigation canals, drains and collectors. Water for irrigation of fertile land in the suburbs of the Khiva district comes from the ancient Palvan-Gazavat canal, which flows through the entire southern part of the district. Water for on-farm irrigation is exclusively supplied by the Sirchali irrigation canal, which branches off from the XX canal in Khiva city. Drainage water is collected by on-farm drains and diverted into the inter-farm collectors and further into the Ozerniy collector, which drains the whole Khorezm region.

3.2 Climate

According to Koeppen's Climate Classification System (Koeppen, 1936; Pidwirny, 2004), the Khorezm oasis is characterized as *BWh,* which is a dry climate: potential evaporation and transpiration exceed precipitation during most of the year. The study region appertains to the semi-desert climatic zone (Abdullaev, 2003). The climate can also be described as “typically arid continental” with considerable seasonal and daily temperature fluctuations: long hot dry summers, sporadic rains or snow in autumn-spring and very cold temperatures in winter (Abdullaev, 2003; Bogushevskiy et al., 1981). Due to its ongoing desiccation, the capacity of the Aral Sea to act as a regional buffer, protecting the area from severe Siberian winter winds and high summer temperatures, now is strongly reduced. As a consequence, the frost-free period has shortened to 170 days a year from the 200 frost-free days needed to grow cotton (Vinogradov and Langford, 2001).

The Khorezm region is characterized by low precipitation and relative humidity, and high air temperatures, radiation and wind velocity. Precipitation usually occurs in the winter-spring period and, in the long-term average does not exceed 80-90 mm annually (Kiseliova and Lifshits, 1971a). About 73 % of the annual precipitation occurs in the winter-spring period, 19 % in autumn and 8 % in summer (Figure 3.2). According to Kiseliova and Lifshits (1971a), neither summer nor winter precipitation plays any role in the water balance of the region.

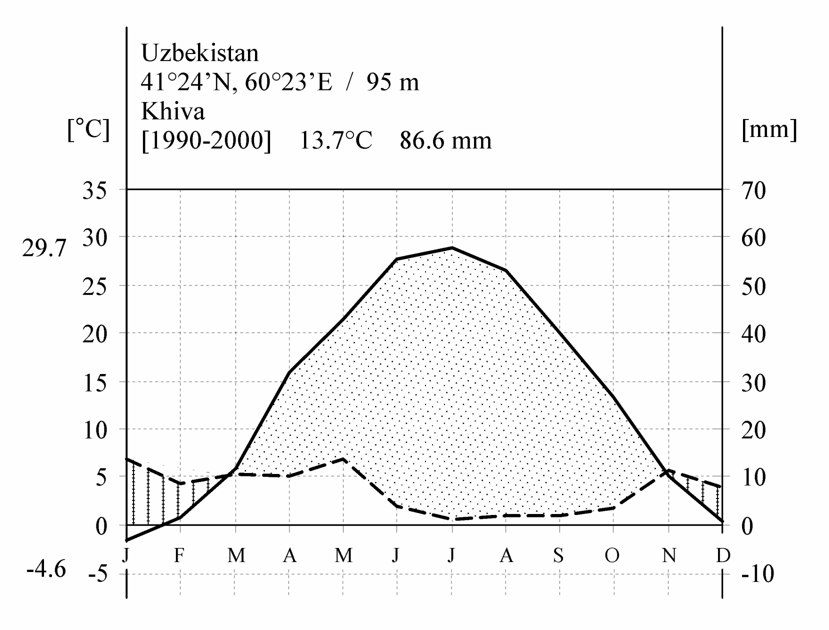


Figure 3.2 Mean monthly air temperature and precipitation (diagram according to Walter) of the Khiva meteorological station (Glavgidromet, 2003)

The situation has not changed considerably in recent years in this region. For the period from 1980 till 2000, the average long-term precipitation amounted to 93 mm (Figure 3.3). However, it can be observed that deviations from the average long-term precipitation starting from 1990 have become more severe and the years 1995 and 2000 were extremely dry, with annual precipitation of only 40 mm and 37 mm, respectively.

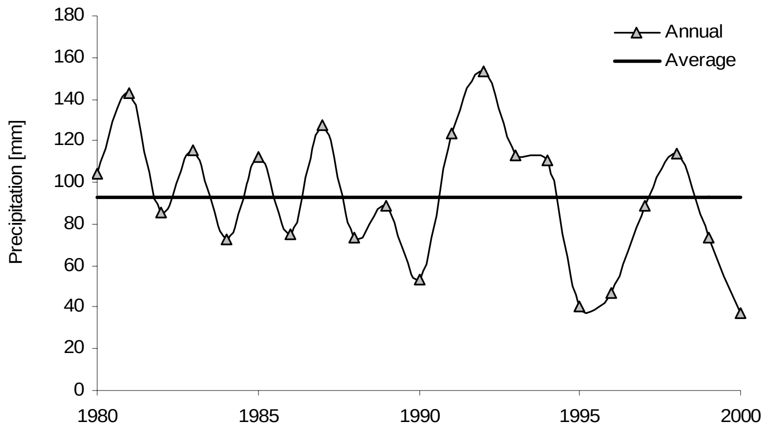


Figure 3.3 Long-term precipitation measurements (Glavgidromet, 2003; Kiseliova and Lifshits, 1971a)

According to data from the Main Administration on Hydrometeorology (Glavgidromet) of the Republic of Uzbekistan, during the period from 1982 to 2000 the average precipitation in the Khiva district was less than 100 mm per year, and the mean annual temperature was 13.6ºC (Glavgidromet, 2003).

The coldest month was January, with an average temperature of –1.5°C (Figure 3.2) with the exception of 2002, when the coldest month was December. The hottest month was July, with an average of 28.8°C. A characteristic of the region is the north-easterly wind during the vegetation season (from April until October) with an average wind velocity of 1.4 to 5.5 m s^{-1} with maximum velocities reaching 7-10 m s^{-1} (Glavgidromet, 2003; Jabbarov et al., 1977; Tupitsa, 2005, *personal communication*). Actual sunshine hours range from 2700 to 3000 per year (Meteo-infospace, 2004).

3.3 Soil

With respect to agro-climatic divisions, the Khorezm region comprises the first sub-zone of the northern climatic zone within Uzbekistan (Jabbarov et al., 1977). Soils have been irrigated for centuries and have a very complicated lithological profile (Faizullaev, 1980). Faizullaev (1980) notes that in most cases the thickness of the alluvial sediments in or close to the river bed consists of 35-70 m thick sands, while former lake locations are represented by loam and clay. Felitsiant (1964) states that the old irrigated soils are characterized by a large amount of melkozem (soil particles with a diameter of <1 mm), that have low average water penetration. The soils of the study site consist of rock debris (alluvial deposits) (Figure 3.4), which are fine layered and very deep (FAO, 2003). The soil structure undoubtedly affects the ameliorative potential as well as agro-physical and other soil properties.

The research farm is located within the subtropical zone on meadow and serozemic soils. According to Tursunov and Abdullaev (1987), these soils have developed in the former valleys and floodplains of the Amu-Darya River. The main chemical and physical properties of the soils in the study site are presented in Appendix 9.1 and Appendix 9.2. The infiltration rate in field #1 is between 0.23-0.3 m day^{-1} and in field #2 amounts to 0.5 m day^{-1}. Myagkov (1995) points out that the upper soil layer in the Khorezm region is thin: fractional alluvial deposits show a thickness varying from 0.5 to 1.5 m and filtration coefficients between 0.5 and 1.0 m per day.

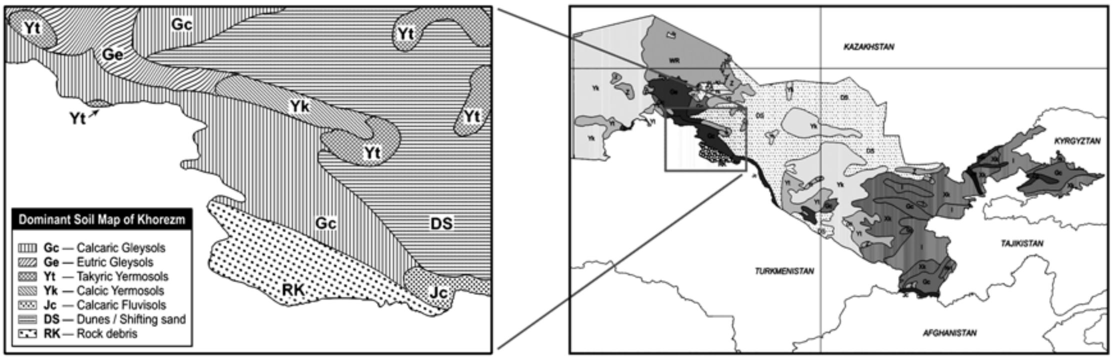


Figure 3.4 Predominant soils of Khorezm (FAO, 2003)

Soil salinity is a major issue in the irrigated areas of Uzbekistan, and the study area is no exception. According to official government data (1999-2001), the entire (100 %) irrigated area in the Khorezm region shows secondary salinization problems, and 81 % of the area has problems with waterlogging (Abdullaev, 2003). The processes governing secondary soil salinization and waterlogging are caused by a shallow groundwater table (between 0.5 m and 2.0 m).

To wash salts from the soil, huge amounts of irrigation water are generally applied to all fields in spring. This water is used to leach the salts from the topsoil, and this water percolates quickly and causes the groundwater table to rise. The high groundwater tables remain, as an efficient drainage system is either not in place or sometimes artificially blocked by the farmers in order to raise groundwater contribution to meet the crop water requirements, especially in areas and/or periods with insufficient water availability in the irrigation system. This strategy increases the risk of re-salinization in the root zone. As a result, the leaching process has to be repeated every cropping season in order to avoid build-up of high salt concentrations.

3.4 Irrigation and drainage system

An intensive and complicated network of irrigation systems with different drainage water collection facilities in the region mostly originates from the Soviet era, i.e., from 1950 to 1970 (Sinnott, 1990). Since this period, however, the reliability of the irrigation and drainage systems has been significantly reduced due to a lack of maintenance and to age (Ibrakhimov et al., 2004), and thus water insecurity has increased (Mueller, 2005). There has been no further irrigation-system development in Uzbekistan since independence, and the management of water resources has concentrated on the operation and infrequent maintenance of existing systems. Nowadays, due to the lack of governmental financial investment, about 2500 km of canals and collectors/drains in Uzbekistan require reconstruction (Glavgidromet, 2002). Furthermore, due to the fact that most of the canals are not lined, the rate of seepage is very high. It has been estimated that only about 45-50 % of the water reaches the farmers' fields (Glavgidromet, 2002; Schieder and Wehrheim, 2004).

The irrigation infrastructure in the region comprises an interconnected system of irrigation canals and drainage collectors. The main irrigation network is oriented in an east-west direction. In Khorezm, the most common method of irrigation is furrow irrigation (Abdullaev, 2003).

3.5 Land use

The Amu-Darya delta has been inhabited for millennia, e.g., the ancient Khorezmian civilization was established in the fourth century B.C. Millet, wheat, barley, watermelons, honey melons, and gourds have been grown in the oasis since historical times. Following the creation of sophisticated irrigation systems, agriculture began to bloom. The extensive development of irrigated agriculture in the mid 20th century resulted in the establishment of large-scale irrigation and drainage infrastructure in the region. Discharge from the collector-drainage system to the river has led to the deterioration of the river water quality and a worsening of the wider environment. The quality and quantity of water available for agriculture are very important. The increase in salt concentrations in water and soil leads to a species-specific decrease in crop production (Petr et al., 2003).

In 2001, the plant producing sector in Khorezm contributed 44 % of the value of all agricultural commodities (Ruzmetov et al., 2003). Currently, 240,000 out of 605,000 ha of agricultural lands are suitable for irrigation in the Khorezm region, whereas the presently irrigated area covers about 270,000 hectares (Abdullaev, 2003). The quality[1] of land suitable for irrigation is presented in Figure 3.5. This figure indicates that about 40 % of the irrigated land is very good and capable of producing 81-100 % of the potential yield.

[1] "The main factor in the qualitative assessment of land is its fertility and this is determined by "bonitation". The "bonitation" of land is the comparative assessment of the land quality and productivity with a representative level of agricultural activity" (FAO, 2003).

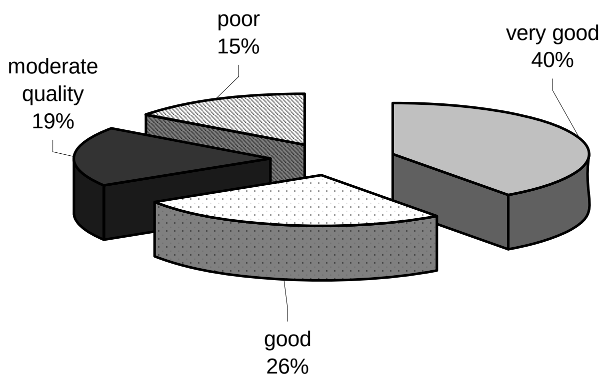


Figure 3.5 Bonitation ("bonitet") or quality of land suitable for irrigation (% irrigated land) in the Khorezm region (Abdullaev, 2003)

Irrigated agriculture and agro-processing are the most important sources for employment and income. Around 40 % of the labor force is officially employed in agriculture, while more are in fact actually dependent on it (Mueller, 2005). Agricultural production focuses mainly on cotton, wheat, rice and fodder.

There are three main types of farming enterprises in Uzbekistan (Ruzmetov et al., 2003): shirkats (former state and collective farms), so-called private farms, and dekhan farms (or household plots). Shirkats have an average farm size of 1850 ha, private farms generally range between 10 and 100 ha, while dekhan farms are limited by law to 0.25 ha of land. At the end of 2003, the area under crops in private farms, households and shirkats constituted 30 %, 16 % and 50 %, respectively, of the total cultivated area in Khorezm (OblStat, 2003).

4 MATERIALS AND METHODS

4.1 Experimental conditions

The research was conducted on two cotton fields with sandy loam and sandy soil textures within the research farm. Information about previous land cultivation activities was collected from the management and supporting staff of the research farm. The cultivation of cotton, however, was managed by local farmers. They decided about the amount and timing of irrigation and all other cultivation activities ranging from land preparation to harvest.

Field size and topography

The size and micro-topography of the fields was investigated in spring 2002. The area of the sandy loamy field (field #1) was 3.5 ha and the sandy field (field #2) 3.7 ha. A geodetic survey was conducted to determine micro-relief and the slope of the fields using a leveling instrument. To be able to accurately monitor the water and salt distribution during irrigation events, it was decided to focus the study on one selected sub-area in each field. In these areas, 2-3 locations (Figure 4.1) were observed in detail during the vegetation seasons of 2002 and 2003. Consequently, the geodetic survey addressed only these sub-areas.

Agricultural practice

In mid-February 2002, in preparation for the leaching of salts out of the soil profile, both fields were divided by the farmers into micro-basins and roughly leveled with a leveling bar connected to a tractor. The fields were leached twice in 2002 (at the beginning and the end of March) and three times in 2003 (twice in March and once in April). In mid-April of both years, the land was ploughed to a depth of 40 cm followed by leveling and chiseling. After this, the upland cotton (*Gossypium hirsutum*) of local variety (*IF-175*) was planted in April in rows 0.6 m apart at a depth of 5-6 cm. The plant population after thinning on the sandy loamy field was 3 plants m^{-2} in 2002 and 3.3 plants m^{-2} in 2003. On the sandy field, plant-thinning was carried out in 2002 only. Thus, plant density was 4.9 plants m^{-2} in 2002 and 7.8 plants m^{-2} in 2003 (Coppi, 2004). The cotton phenology was studied in collaboration with the M.Sc. student Luca Coppi.

In mid-May 2002, a total of 250 kg ha^{-1} of ammonium was applied. At the beginning of June, a second dose consisting of ammonium-nitrate and ammonium-sulphate was applied at a rate of 300 kg ha^{-1}. At the same time, furrows for irrigation were made. In 2003, fertilizer was only applied once, before the first irrigation event (14-16 July). The total amounts of applied N and P_2O_5 were 250 kg ha^{-1} and 150 kg ha^{-1}, respectively. Potassium was not applied.

After this, a ditch with a depth of 40 cm was ploughed around field #1 by a tractor. Farmers, together with members of their family, divided the field into 10-11 micro-plots with areas varying from 0.1 ha to 0.3 ha. During the 2002 and 2003 growing seasons, continual manual weeding was carried out. There were five irrigation events each season. Cotton was harvested manually by farmers and members of their families.

4.2 Soil characterization

Soil profiles

Following the geodetic survey, four soil pits (1.5 m depth and 2 m length) were established at the end of May 2002 to describe the soil by genetic layers (Figure 4.1, Appendix 9.3). Three 1.5 m deep pits were located in field #1, representing both ends and the middle of the experimental site, and one 0.8 m deep pit was dug in field #2.

Two replicates of undisturbed soil cores were sampled with sampling rings (Eijkelkamp) at each genetic horizon for the later analysis of soil hydraulic properties in the Soil Laboratory of the Scientific Research Institute of Irrigation (SANIIRI, Tashkent). Soil bulk density was determined according to Blake and Hartge (1986) and soil water retention characteristics by the pressure membrane method (Klute, 1986b). Sub-samples were used to determine soil textures gravimetrically (Loveland and Whalley, 2001) and to assess electrical conductivity with a portable EC-meter (Chernishov and Shirokova, 1999). A short description of the methods is given in Appendix 9.4.

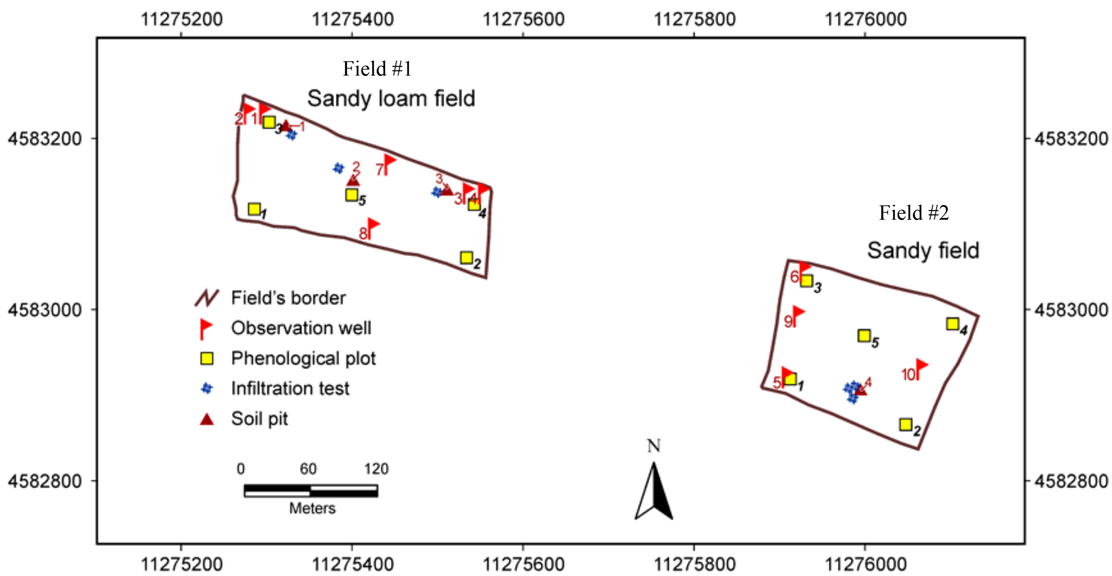


Figure 4.1 Scheme of main installations in the monitored fields

4.2.1 Infiltration test

The permeability of the soil at both fields was determined using standard double ring infiltrometers with an outer ring of 40 cm and inner ring of 20 cm (Clothier, 2001). The test was conducted in the vicinity of the locations used for the soil profile description. Three infiltrometers were placed about 1.5 m apart at each location.

4.2.2 Soil-water retention

For a better soil water balance assessment, the soil-water pressure head was measured in the middle of field #1 with tensiometers (Eijkelkamp, 2002). Two pairs of tensiometers (Figure 4.2) were installed vertically at 0.3 m and 0.5 m soil depth and 0.5 m apart from each other in the center of field #1. Tensiometers were installed prior to the first irrigation event (16 July, 2003) and were kept in field #1 until the end of the vegetation season (30 September, 2003). In the period of no irrigation, readings were taken manually on selected days every hour. Directly after irrigation, the interval between readings was 10-15 minutes. The values of the soil-water pressure head for unsaturated soils are negative (below zero) and expressed in centimeters or meters.

Figure 4.2 Tensiometers installed in field #1

4.2.3 Dissolved salts versus electrical conductivity of the saturated extract

Salinity is a measure of the amount of salts dissolved in water. There are two ways of measuring salinity: total dissolved solids (*TDS*) and electrical conductivity (*EC*). In the first method, the salts remaining after the water has been evaporated are weighed and expressed in milligrams of total dissolved solids per liter of water. The second method consists of measuring the electrical conductivity of the water recorded as dS m^{-1}. The electrical conductivity of water linearly correlates with the concentration of dissolved salts. Usually, to convert *EC* (dS m^{-1}) into *TDS* (mg l^{-1}) a standard factor of 640 is used (Abrol et al., 1988). Based on the independent determination of *TDS* and *EC*, an adjusted factor for local conditions was calculated that accounts for deviations, caused by different composition of the salts, from the standard factor.

4.3 Field studies

4.3.1 Meteorological measurements

Meteorological data are necessary to estimate the evapotranspiration and the effective part of rainfall. Therefore, in the beginning of September 2002 a meteorological station was set up on the research farm about 3 km from the experimental site. The area of the meteorological station comprised 71.4 m^2 (8.4 m EW direction and 8.5 m SN direction).

Figure 4.3 The micro-meteorological station at the research farm

Air temperature and relative humidity were measured with an accuracy of ±0.2ºC and 2 % by Eijkelkamp sensors. The net short- and long-wave energy balance (0.2-100 μm) and incoming short-wave radiation (0.4-1.1 μm) were measured with a Kipp en Zonen NR-light radiometer and SP-light pyranometer, respectively. Wind speed and direction at 2 m above the ground surface were measured with an anemometer and anemoscope (accuracy for wind speed sensor is 1 % within the range of 0.25-75 m sec^{-1}). The amount of precipitation was measured at 1 m above the ground surface with a rain gauge. Parameters were recorded automatically from 16 September 2002 every 30 minutes with a solar energy powered data logger system (Micromec Multisens - Technetics 2000). The Glavgidromet provided additional meteorological data for the January 2002 to April 2003 period and monthly data for the 1990-2002 period (Glavgidromet, 2003).

4.3.2 Leaching and irrigation (frequency, quantity and salinity)

To measure the water supply to the field, two Cipoletti (or trapezoidal) weirs were installed before each irrigation event (Figure 4.4). Discharge over the Cipoletti weir can be formulated as a function of the upstream water depth referenced to the weir crest (*H*), where *H* is called "head" (Equation 4.1). The side slopes have a vertical to horizontal ratio of 4:1. The accuracy of the measurements obtained with Cipoletti weir is about ±5 % (Bos, 1989; USBR, 1997). The measurements of field application discharge were taken every minute during the irrigation events at the two field input points.

Figure 4.4 Cipoletti weir on field #1

The Cipoletti weir equation is (USBR, 1997):

$$Q = 1.86 \cdot b1 \cdot H\sqrt{H} \tag{4.1}$$

where Q is discharge [m^3 sec^{-1}], $b1$=0.5 is weir length [m], H is head [m].

Throughout the 2002 vegetation season, field #1 was irrigated five times, while field #2 was not irrigated at all by the farmers. In March and April 2003, large amounts of water were applied to the micro-basins three times (4-5 March, 14-15 March and 3 April) to leach salts out of the rooting zone (Figure 4.5).

Figure 4.5 Leaching event on micro-plots of field #1

After the last leaching event on 3 April 2003, both fields were ploughed and planted with cotton. Prior to the first irrigation event (16 July), field #1 was once again divided manually by farmers into micro-plots (30 m by 30 m squares separated by small ridges), and furrows were made. The size of the subdivided parts of field #1 was approximately the same as during leaching. During the vegetation season 2003, five irrigation events were carried out at field #1. At every event, water input was measured for the whole field and independently for the three plots where location measurements for the subsequent simulation were done. Field #2 was not intended to be irrigated and was, therefore, not subdivided into micro-plots, but was nevertheless irrigated in the middle of the season. There was no surface water runoff during irrigation from the four plots; however, this took place during leaching in some parts of the fields that were not monitored.

Spatial differences of relevant irrigation parameters, soil moisture and salinity can be expected in the direction of water distribution in the field rather than perpendicular to that direction. Therefore, spatial differentiation by three locations was applied in the water flow direction. Three weirs were installed separately for each of the three locations in field #1, as irrigation water was applied consecutively to the subdivided parts of the field. These locations represent the beginning (location 1), middle (location 2) and end (location 3) of field #1, where measurements of groundwater table and salinity as well as soil moisture and crop phenology monitoring were conducted (Figure 4.6).

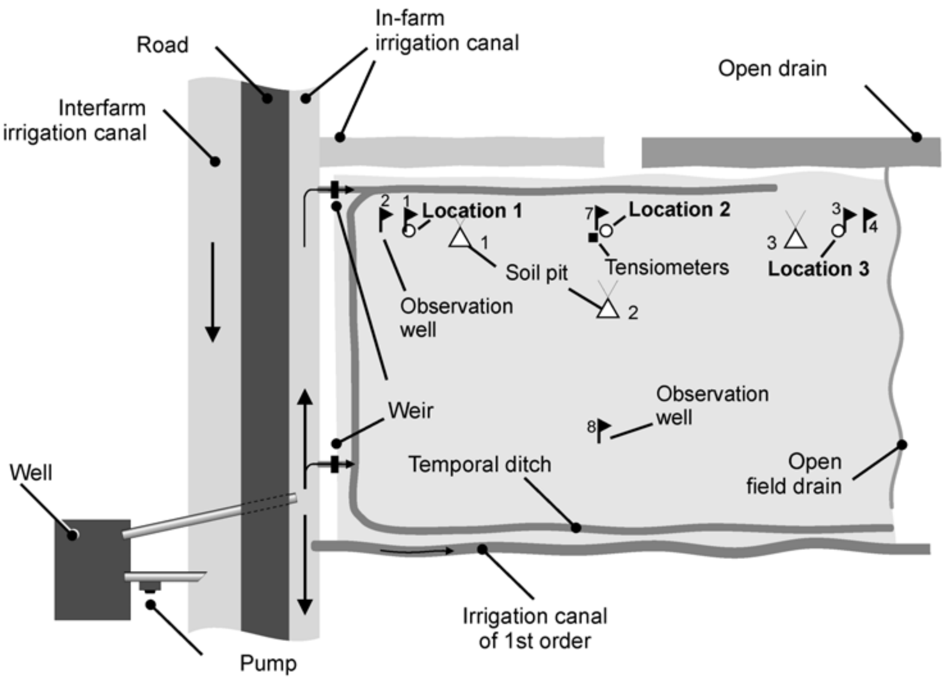


Figure 4.6 Scheme of irrigated field #1

4.3.3 Soil moisture and salinity

As soil moisture is the main parameter of the water balance, the model calibration requires repeated measurements of soil moisture in time and space. The samples were taken with a soil auger (Eijkelkamp, 2002) at 20, 50, 80 and 105 cm depths (Figure 4.7) on the ridge and in the furrow at four locations in field #1 and two locations in field #2.

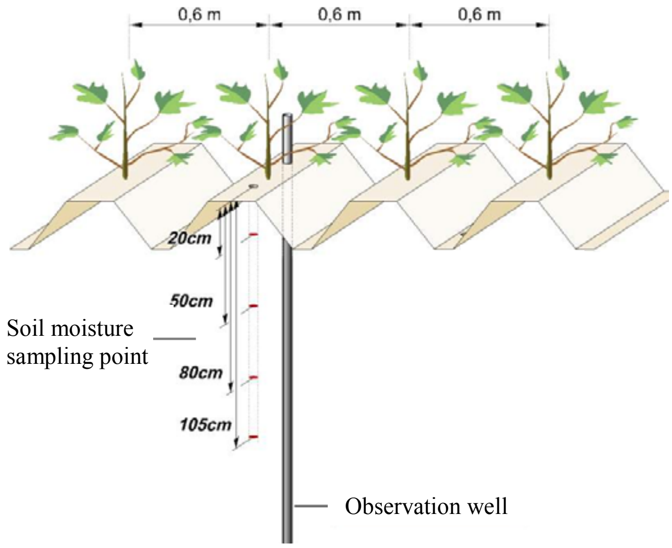


Figure 4.7 Scheme of field soil sampling and observation well location

To assess the effect of irrigation, soil samples were taken one day before and two days after irrigation events. Reliable calibration of the water balance requires information on the time-dependent change in soil moisture between irrigation events. This was realized by additional measurements conducted between two irrigation events. Soil samples were collected in tin cans to determine the gravimetrical soil moisture content. The weight of the soil was determined before and after oven-drying. The soil moisture content based on the dry weight was calculated as follows (Gardner et al., 2001):

$$\theta_d = \frac{\text{wet weight - dry weight}}{\text{dry weight}} \tag{4.2}$$

Subsequently, θ_d was converted into the soil moisture content on a volume basis by considering the bulk density of the respective soil layers (determined in the soil pits). Soil salinity was measured as electric conductivity (*EC*) in a 1:1 soil-water mixture (method described in Appendix 9.5) with a portable electrical conductivity meter developed at SANIIRI (Chernishov and Shirokova, 1999). The soil samples taken before and after the irrigation events were also analyzed for *TDS* and salt ion composition (Na^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}) at the SANIIRI laboratory (method see Appendix 9.4).

4.3.4 Soil-water pressure head

A soil-water retention curve (also called *pF*-curve) describes the relationship between the volumetric soil water content θ (cm^3 cm^{-3}) and the soil matric potential h (cm). For each soil type in 2002, the characteristic *pF*-curve was established in the laboratory at SANIIRI (see Appendix 9.6).

4.3.5 Groundwater

The groundwater table was monitored to assess the irrigation performance and its impact on groundwater as well as, in case of shallow groundwater, the contribution to crop soil-water use. To monitor the groundwater table, 10 shallow observation wells were installed: 6 in field #1 and 4 in field #2 (Figure 4.1). The observation wells consisted of poly-plastic pipes with a diameter of 4 cm, closed at the bottom with a metal lid. Pipes were perforated on one side starting 50 cm above the lower end and were wrapped in gauze to protect the perforations from silt build-up. Pipes were installed next to the soil-moisture sampling locations. Concurrently with soil-moisture sampling, the groundwater table was measured with a hand-operated sounding apparatus with acoustic and light signals (Eijkelkamp, 2002).

The *EC* of sampled irrigation and drainage water and groundwater was measured with a portable *EC*-meter. The salt content (Na^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}), and *pH* of drainage water and groundwater was analyzed at SANIIRI at the beginning and the end of the 2002 and 2003 irrigation seasons and after selected irrigation events throughout the two years (Appendix 9.7).

4.3.6 Cotton development

Phenological measurements were carried out in both fields throughout the 2002 and 2003 seasons. In both fields, five sample plots 2 m x 2 m in size were chosen. Four plots were placed at each corner of each field and the fifth plot was located in the center of the field. In each plot, ten cotton plants were monitored twice per month to determine the plant height (by measuring stick), rooting depth (dug and measured), number of flowers, closed and open cotton bolls, plant density at sowing and after thinning, number of weeds per square meter, and leaf area index (*LAI*) for the stage of full cotton establishment. At the end of each season, the cotton yield was quantified on the experimental plots in addition to that of the complete fields.

4.4 HYDRUS-1D model

4.4.1 General description

The model HYDRUS-1D (version 2.02) (Simunek et al., 1998a) was selected for application in the study, because it is able to simulate and estimate water and salt balances under conditions of shallow groundwater, and it is frequently updated and well documented. Besides, in this model one can include not only groundwater tables but also their salinity as well as soil salinity, which is a very important issue in the research area. This program was developed by the U.S. Salinity Laboratory, U.S. Department of Agriculture and Agriculture Research Service. HYDRUS-1D solves for the one-dimensional movement of water, heat and multiple solutes in unsaturated, partially saturated or fully saturated soils (Simunek et al., 1998a). The capability of the model to simulate heat transport was not used in this study.

The governing equation in the model is the well known Richards equation (Richards, 1931):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] - S(h) \tag{4.3}$$

where θ is the volumetric soil water content [$cm^3\ cm^{-3}$]; t is time [d]; h is the soil-water pressure head [cm]; z is the gravitational head as well as the vertical coordinate [cm] (upwards is positive); *K(h)* is the unsaturated hydraulic conductivity [$cm\ d^{-1}$]; S is the soil water extraction rate by plant roots [$cm^3\ cm^{-3}\ d^{-1}$].

4.4.2 Input parameters

Most of the parameters required in the model could be measured directly in the field or laboratory. Also, the initial soil moisture content and soil salinity for the simulation were derived from field measurements. Boundary conditions for the top (soil surface) and bottom layer of the soil profile have to be set to start simulations in HYDRUS-1D.

Top boundary conditions

The soil surface boundary conditions are defined by the potential evapotranspiration (ET_0) as well as irrigation and precipitation. For this study, ET_0 was estimated with the Penman-Monteith equation (Allen et al., 1998) using recorded meteorological data (more details in section 4.5.1). For a crop that partly covers the ground, ET_0 can be split into potential transpiration T_p (cm d^{-1}) and potential soil evaporation E_p (cm d^{-1}). If the soil is wet, the actual soil evaporation E_a will be equal to E_p, while in dry conditions E_a is governed by the maximum soil-water flux in the topsoil. Due to a low slope and unequal soil leveling in the field, there was no runoff during the monitored years. Surface water build-up was allowed to take place. This condition allows water to build up on the surface and participate in the next modeling step without being removed immediately.

Bottom boundary conditions

The groundwater tables in both fields were not deep enough to exclude their influence on water movement in the rooting zone. Therefore, the measured groundwater depths were specified to describe the bottom boundary of the soil profile.

Soil hydraulic properties

In HYDRUS-1D, the Richards equation (4.3) is solved numerically by applying a finite difference scheme for given boundary conditions and with specified relations between the soil hydraulic variables (θ, h and K). The model contains the soil-water retention characteristics as described by van Genuchten (1980):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(1 + \alpha_r \left|h\right|^n\right)^{-m} \tag{4.4}$$

where S_e is effective saturation [-]; θ_r and θ_s are residual and saturated water contents [cm^3 cm^{-3}], respectively; α_r [cm^{-1}], m [-] and n [-] are shape parameters.

The soil hydraulic conductivity function in the model is described by the statistical, Mualem-van Genuchten, pore-size distribution model (Mualem, 1976; van Genuchten, 1980):

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m \right]^2 \tag{4.5}$$

where K_s is the saturated hydraulic conductivity [cm d^{-1}]; l [-] is a pore connectivity parameter; $m=1-1/n,$ when $n>1$.

For the finite difference scheme, a vertical grid with a total length of 200 cm was defined. The soil profile was divided into 200 numerical compartments and grouped into the soil layers determined during the soil pit description. Soil hydraulic properties were specified for each layer and described by the Mualem-van Genuchten parameters (Equations 4.4 and 4.5).

Root water uptake and root growth

For the determination of the root water uptake (transpiration), the method proposed by Feddes (1978) and modified by van Genuchten (1987) to include osmotic stress was applied:

$$S(h,h_\phi) = \alpha(h,h_\phi) S_{\max} \tag{4.6}$$

where S_{max} is the maximum water uptake rate [cm^3 cm^{-3} d^{-1}]; $\alpha(h,h_\phi)$ is a function of pressure and osmotic head [-].

The reduction in crop yields due to salinity stress is linearly related to the soil-water electrical conductivity EC (Maas and Hoffman, 1977). Van Genuchten (1987) suggested that the reduction from the osmotic head can be additive or multiplicative. In the current study, the multiplicative threshold model was used:

$$\alpha(h,h_\phi)=\frac{1}{1+\left(h/h_{50}\right)^{p_1}}\frac{1}{1+\left(h_\phi/h_{\phi_{50}}\right)^{p_2}} \tag{4.7}$$

where p_1,p_2 are experimental constants; h_{50} is the pressure head at which the water extraction rate is reduced by 50 % during conditions of negligible osmotic stress; $h_{\phi 50}$ is the osmotic head at which the water extraction rate is reduced by 50 % during conditions of negligible water stress.

The critical pressure head values for root water uptake were derived from three published studies (Gidrometioizdat, 1976; Ryjov, 1973; Ryjov and Zimina, 1971) and are discussed in detail in Chapter 6.

4.4.3 Inverse modeling of soil hydraulic properties

So-called inverse estimation methods are now increasingly used to determine the hydraulic properties of unsaturated soils (Bitterlich et al., 2004). As mentioned by Singh et al. (2003), water flow and salt transport are very sensitive to the soil hydraulic functions $\theta(h)$ and $K(\theta)$. In the current research, the Rosetta DLL (Dynamically Linked Library; Schaap et al., 2001) was applied as part of HYDRUS-1D to predict the van Genuchten (1980) water retention parameters and the saturated hydraulic conductivity from soil texture and bulk density using pedotransfer functions (PTFs). These estimates can be refined by including one or two water retention points as input data. The resulting hydraulic properties were calibrated to site-specific conditions by inverse estimation. For this calibration, data on soil moisture, tension and salinity, measured every fifth day and especially before and after irrigation, were used. The water retention curve derived in the laboratory was not used for a model calibration (see Chapter 6). The minimization of the objective function was done by the Levenberg-Marquardt nonlinear minimization method (Marquardt, 1963).

4.5 Water balance

Principle equation

The water balance of the vertical soil domain covered by vegetation for a given period (Burt et al., 2002a; Singh et al., 2003) is:

$$\Delta W = P + I - R - P_i - T_a - E_a - E_w + Q_{bot} \qquad (4.8)$$

where ΔW is the change in soil water storage [mm]; P is precipitation [mm]; I is irrigation [mm]; R is surface runoff [mm]; P_i is interception by vegetation [mm]; T_a is actual transpiration [mm]; E_a is actual evaporation [mm]; E_w is evaporation of ponding water [mm]; Q_{bot} is water percolation at the soil column bottom (positive upward) [mm].

As mentioned above, there was no runoff during irrigation, therefore R equals zero. Interception of rainwater by the cotton plants was also neglected, as it was of minor importance given the low amounts of rainfall during the vegetation period.

4.5.1 Evapotranspiration

Reference evapotranspiration

Evapotranspiration (ET) governs the consumptive use of irrigation water and rainfall for agriculture. The potential evapotranspiration (ET_0) was calculated using the Penman-Monteith method according to the FAO-56 standards (Allen et al., 1998). In order to solve this equation, data on the solar radiation, air humidity, and wind speed and air temperature are needed:

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \qquad (4.9)$$

where ET_0 is the reference evapotranspiration [mm day^{-1}]; Δ is the slope of the vapor pressure curve [kPa ºC^{-1}]; R_n is the net radiation at the crop surface [MJ m^{-2} d^{-1}]; G is the soil heat flux density [MJm^{-2}d^{-1}]; γ is the psychrometric constant [kPa ºC^{-1}]; T is the mean daily air temperature at 2 m height [ºC]; u_2 is the wind speed at 2 m height [m s^{-1}]; *(es-ea)* is the saturation vapor pressure deficit [kPa].

Crop evapotranspiration

To start the computation of crop evapotranspiration (ET_c), the regional crop coefficients (K_c) should be defined. The crop coefficient is a ratio of the crop ET_c to the reference

ET_0 (Allen et al., 1998). Characteristics such as crop height, crop-soil surface resistance and albedo of the crop-soil resistance distinguish the crop from the reference. A complete description of how crop coefficients are used to define crop ET_c is provided in the FAO-56 paper on crop evapotranspiration (Allen et al., 1998). The so-called dual approach was used to determine the K_c-values. Here ET is split into the two components: transpiration (T) and evaporation (E), and a basal crop (K_{cb}) and soil evaporation (K_e) coefficient are used. Although a dual coefficient approach requires more numerical calculations than the procedure of a single K_c coefficient, it is known to be the best approach to soil water computations and for research studies where day-to-day soil surface wetness, soil water profile and deep percolation fluxes are important (Allen et al., 1998). The equation reads:

$$ET_c = \left(K_{cb} + K_e\right) \cdot ET_0 \tag{4.10}$$

Due to basic energy limitations, the sum of K_{cb} and K_e should not exceed the maximum value for a crop, which is determined during calculations.

In the dual approach, the basal crop coefficient (K_{cb}) is the ratio of ET_c to ET_0 under conditions of a dry soil layer but when the root zone contains enough water to sustain full plant transpiration (Allen et al., 1998). Thus, $K_{cb} \cdot ET_0$ is the transpiration component of ET_c. After soil wetting (by precipitation or irrigation), the evaporation occurs at the maximum rate and $K_e \cdot ET_0$ represents the evaporation component of ET_c.

Crop coefficient

The methodology of FAO-56 divides the K_{cb}-curve into four periods: the initial phase, the crop development phase, the midseason and the late season phase. To produce the K_{cb}-curve, three values of K_{cb} must be known: $K_{cb\,ini}$ (the initial period), $K_{cb\,mid}$ (midseason) and $K_{cb\,end}$ (late season, usually time of harvest). The initial and middle phases are characterized by horizontal line segments, while development and late phases are described by rising and falling segments, respectively (Figure 4.8).

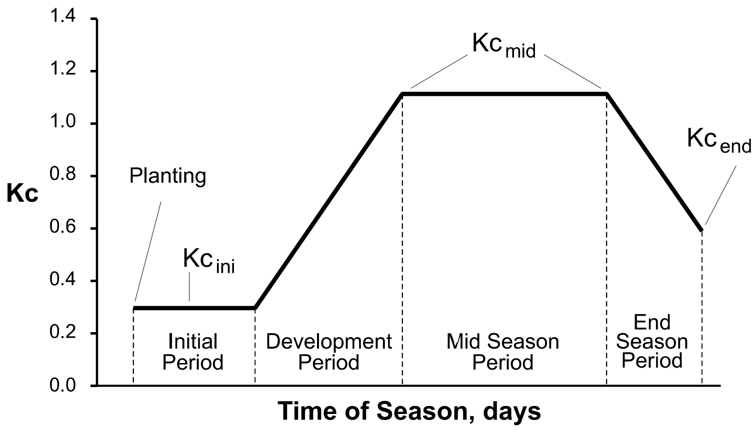


Figure 4.8 Generalized crop coefficient (K_{cb}) curve (Allen et al., 1998)

The $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ values were adjusted for the local conditions taking into account minimum daily relative humidity (RH_{min}) and wind speed (u_2) measured at 2 m height. The *LAI* data were used to adjust the crop coefficient for local conditions following the proposed FAO-56 procedure (Allen et al., 1998):

$$K_{cb\ mid\ adj} = K_{c\ \min} + \left(K_{cb\ mid} - K_{c\ \min}\right) \cdot \left(1 - \exp\left[-0.7 LAI\right]\right) \tag{4.11}$$

where $K_{cb\ mid\ adj}$ is estimated basal K_{cb} during mid-phase when plant leaf area is lower than for full cover conditions; $K_{cb\ mid}$ is the value for K_{cb} during a mid-phase for cotton plants having full ground cover; $K_{c\ min}$ is the minimum K_c for bare soil; *LAI* is actual leaf area index [$m^2\ m^{-2}$].

Burt and coworkers (2002a) point out that it is necessary to understand that the initial stage of crop growth starts at the planting date, but that no transpiration occurs on the day of planting, and that the crop cannot reach its potential transpiration rate until some point in the developmental stage. For this study, this day was set as the day when 50 % of the emergences had occurred (8 May, 2003). When the crop approaches the middle stage in the development, most *ET* is transpired and only little contributed via evaporation. Based on expert visual estimation and collected information about the number of plants and weeds per square meter it was decided to double (field #1) and triple (field #2) *LAI* values for every location, since weed biomass was equal and in some cases even higher than cotton biomass. The implications of this measure are discussed in section 5.2.3.

Evaporation from soil

Evaporation from the soil is predicted by the estimation of energy available at the soil surface. When the soil is wet due to precipitation or irrigation, evaporation occurs at some maximum rate $K_{c\,max}$. Reduction in evaporation occurs when the soil layer dries out. Then K_e values might even become zero, because no water in the soil layer is available for evaporation:

$$K_e = K_r \left(K_{c\,\max} - K_{cb} \right) \leq f_{ew} K_{c\,\max} \quad (4.12)$$

where K_e is the soil evaporation coefficient; K_{cb} is the basal crop coefficient; $K_{c\,\max}$ is the maximum K_c value, following irrigation or precipitation; K_r is a dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the top soil; f_{ew} is the fraction of the soil not covered by vegetation and that is wetted by irrigation or precipitation.

It is obvious that evaporation from the soil does not occur uniformly over the surface due to incomplete ground cover, and that it is higher between plants where exposure to sunlight occurs and where, due to improved ventilation, more vapor is transported from the soil surface to above the canopy. Some authors (Burt et al., 2002b; Raats, 1974) point out that even when the crop has reached full ground cover, evaporation may correspond to 10-20 %. When the complete soil surface is wetted, then the fraction of soil surface from which most evaporation occurs, f_{ew}, is defined as ($1-f_c$), where f_c is an average fraction of soil surface covered by vegetation and ($1-f_c$) is the approximate fraction of soil surface that is exposed. For irrigation methods where only a fraction of the ground surface is wetted, f_{ew} should be limited to the fraction of the soil surface wetted by irrigation (f_w):

$$f_{ew} = \min\left(1 - f_c, f_w\right) \quad (4.13)$$

where *(1-fc)* is the average exposed fraction not covered or shaded by vegetation and has limits of [0.01-1]; f_w is the average fraction of soil surface wetted by precipitation or irrigation and has limits of [0.01-1].

For this study, f_w was taken from Table 20 of FAO-56 as being equal to 0.6 (furrow irrigation and narrow beds); f_c was estimated from the following equation:

$$f_c = \left(\frac{K_{cb} - K_{c\,\min}}{K_{c\,\max} - K_{c\,\min}} \right)^{(1+0.5h)} \tag{4.14}$$

where f_c is the effective fraction of soil surface covered by vegetation and is limited to [0-0.99]; K_{cb} is the basal crop coefficient for the particular day or period; $K_{c\,min}$ is the minimum K_c for dry bare soil with no ground cover ($\approx$0.15-0.20); $K_{c\,max}$ is the maximum K_c immediately following wetting; *h* is the mean plant height [m]. For numerical stability, the difference ($K_{cb} - K_{c\,min}$) should be limited to $\geq$0.01.

4.6 Salt balance

Principle equation

The salt balance of the soil profile over a certain time interval can be written as:

$$\Delta C = PC_p + IC_i + Q_{bot}C_{bot} \tag{4.15}$$

where ΔC is the change in salt storage [g cm^{-2}]; *C* is solute concentration [g cm^{-3}]; subscripts $_p$, $_i$, and $_{bot}$ refer to precipitation, irrigation and bottom flux, respectively.

4.6.1 Soil-salt dynamics

Solutes in the soil profile are transported by convection and dispersion in the liquid phase as well as by diffusion in the gas phase (Simunek et al., 1998a). In irrigated fields, the total salt flux density can be described as the sum of the convection and dispersion fluxes, neglecting the diffusion (Sarwar et al., 2000; Singh et al., 2003):

$$J = J_{con} + J_{dis} \tag{4.16}$$

where J is the total salt flux density [g cm^{-2} d^{-1}]; J_{con} is the convection dispersion flux density [g cm^{-2} d^{-1}]; J_{dis} is the dispersion flux density [g cm^{-2} d^{-1}]; when $J_{con}=qC$ and $J_{dis} = -qL_{dis}\frac{\partial C}{\partial z}$.

The convection-dispersion equation in HYDRUS-1D is solved numerically, using specified initial irrigation and groundwater concentrations (Simunek et al., 1998a):

$$\frac{\partial \theta C}{\partial t} = \frac{\partial}{\partial z}\left[qL_{dis}\frac{\partial C}{\partial z}\right] - \frac{\partial qC}{\partial z} \tag{4.17}$$

where L_{dis} is the dispersion length [cm].

In HYDRUS-1D, the interactions between the solution and adsorbed concentrations are not in equilibrium, while those between the solution and the gas concentration of the solute in the soil are. The adsorption isotherm that describes the relationship between adsorbed concentration and solutes reads as:

$$s_k = \frac{k_{d,k} c_k^{\beta^k}}{1 + \eta_k c_k^{\beta^k}} \tag{4.18}$$

where s_k is adsorbed solute concentration at k-th chain number [-]; $k_{d,k}$ [cm^3 mg^{-1}], β^k [-] and η_k [cm^3 mg^{-1}] are empirical coefficients.

In this study, β_k=1 and η_k=0, and therefore Equation 4.18 becomes a linear adsorption isotherm equation. The values for dispersivity (L_{dis}) and adsorption isotherm coefficient (k_d) are determined inversely and discussed in Chapter 5. Diffusion values (D_{dif}) were fixed at 2 cm^2 d^{-1} (Simunek, 2004, *personal communication*).

4.7 Leaching requirements

The fraction of irrigation water that must be leached through the root zone to control the salt content in the soil profile at a specific level, the so-called leaching requirement (*LR*) was calculated as the ratio of the irrigation water salt content (EC_{iw}) and the salt tolerance of the crop (EC_e) according to Ayers and Westcot (1985) and Tanji and Kielen (2002):

$$LR = \frac{EC_{iw}}{5\left(EC_e\right) - EC_{iw}} \tag{4.19}$$

where *LR* is the minimum leaching requirement needed to control salts within the tolerance of the crop with ordinary surface methods of irrigation [-]; EC_w is the salinity of the applied irrigation water [dS m^{-1}]; EC_e is the average soil salinity tolerated by the crop as measured on a soil saturation extract [dS m^{-1}].

The equation for estimation of total annual irrigation water to be applied to meet crop ET_c and *LR* reads as (Ayers and Westcot, 1985; Tanji and Kielen, 2002):

$$AW = \frac{ET_c}{1 - LR} \tag{4.20}$$

where AW is the amount of applied water [mm year^{-1}]; *LR* is the leaching requirement expressed as a leaching fraction [-]; ET_c is the total annual crop demand [mm year^{-1}].

In 2003, leaching was carried out by flooding the bare soil with varying depths of water three times in spring. The quantity of water discharged by the drainage system was impossible to measure because of inter-linkages between the surrounding experimental site fields. However, the quantity and quality of applied water was recorded.

4.8 Statistical analyses

Regression analyses were carried out with the statistical program SigmaStat for Windows (version 3.11).

The goodness-of-fit between observed and modeled parameters was assessed by calculating the Root Mean Square Error (*RMSE*) according to:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left[M\left(t_i\right) - S\left(t_i, b\right) \right]^2}{n}} \tag{4.21}$$

where $M(t_i)$ is measured value at time t_i; $S(t_i,b)$ is predicted value at time t_i; n is the total number of parameters.

5 RESULTS AND DISCUSSION

5.1 Site description: pre-conditions for modeling

Micro-topography

The trial plot in field #1 was 45 m wide and 300 m long, in field #2 120 m wide and 90 m long (Figure 5.1). According to the geodetic survey, the micro relief of field #1 was not uniform but showed a pattern of micro heights and dips, with a main slope of 0.15 % from west to east. Also, the micro-topography of field #2 was irregular, but there was no general slope.

Field #1 is located close to the Sirchali irrigation canal. Field #2 is in the vicinity of an inter-farm collector. Both fields are drained by a smaller (inner-farm) canal, which starts in the middle of field #1 and discharges into the inter-farm collector after field #2. Water to field #2 is distributed from the in-farm irrigation canal located on the southern part of the field.

Soil physical properties

The soil profile investigation revealed that the soils are partly stratified (Figure 5.2). According to Kachinsky's classification (Handbook on soil science, 1980) the topsoil layer of field #1 was a sandy loam (Appendix 9.2). At location 2 of field #1, the subsoil layer (85-200 cm) contained more clay and silt and thus was classified as a loam. Field #2 had a lighter texture (loamy sandy topsoil followed by sandy subsoil).

Bulk density increased with depth from 1.27 to 1.77 g cm^{-3}. Using a particle density of 2.66 g cm^{-3} on field #1, porosity was determined to range between 0.395 and 0.401 cm^3 cm^{-3} in the 0-150 cm layer. In field #2, a particle density of 2.5 g cm^{-3} (sand) was used and determined porosity varied between 0.33 and 0.47 cm^3 cm^{-3} in the 0-70 cm layer (Table 5.1; Appendix 9.2). The subsoil layers in all cases had a rather low porosity compared to the top soil layers.

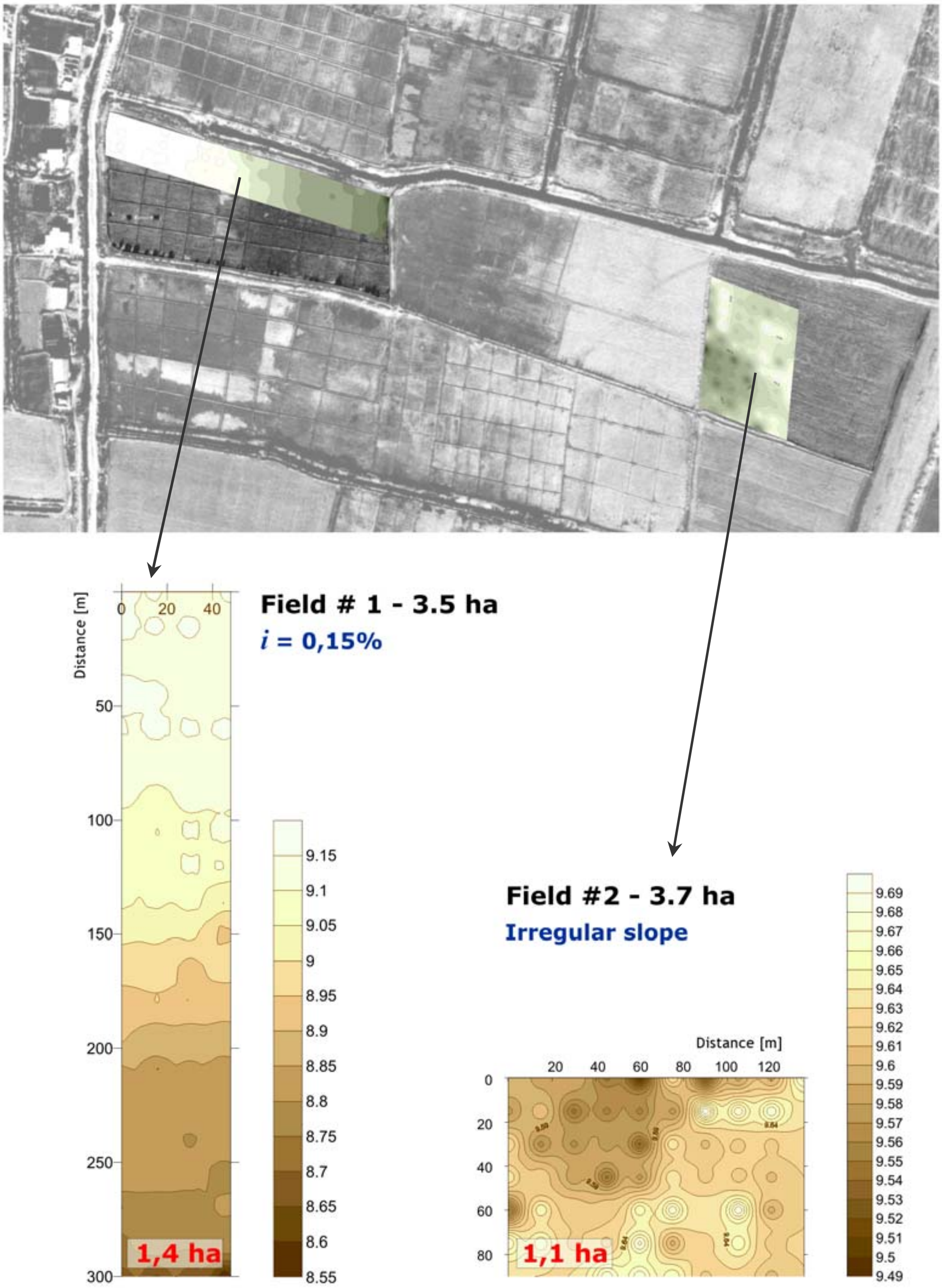


Figure 5.1 Location and micro-relief of the monitored fields

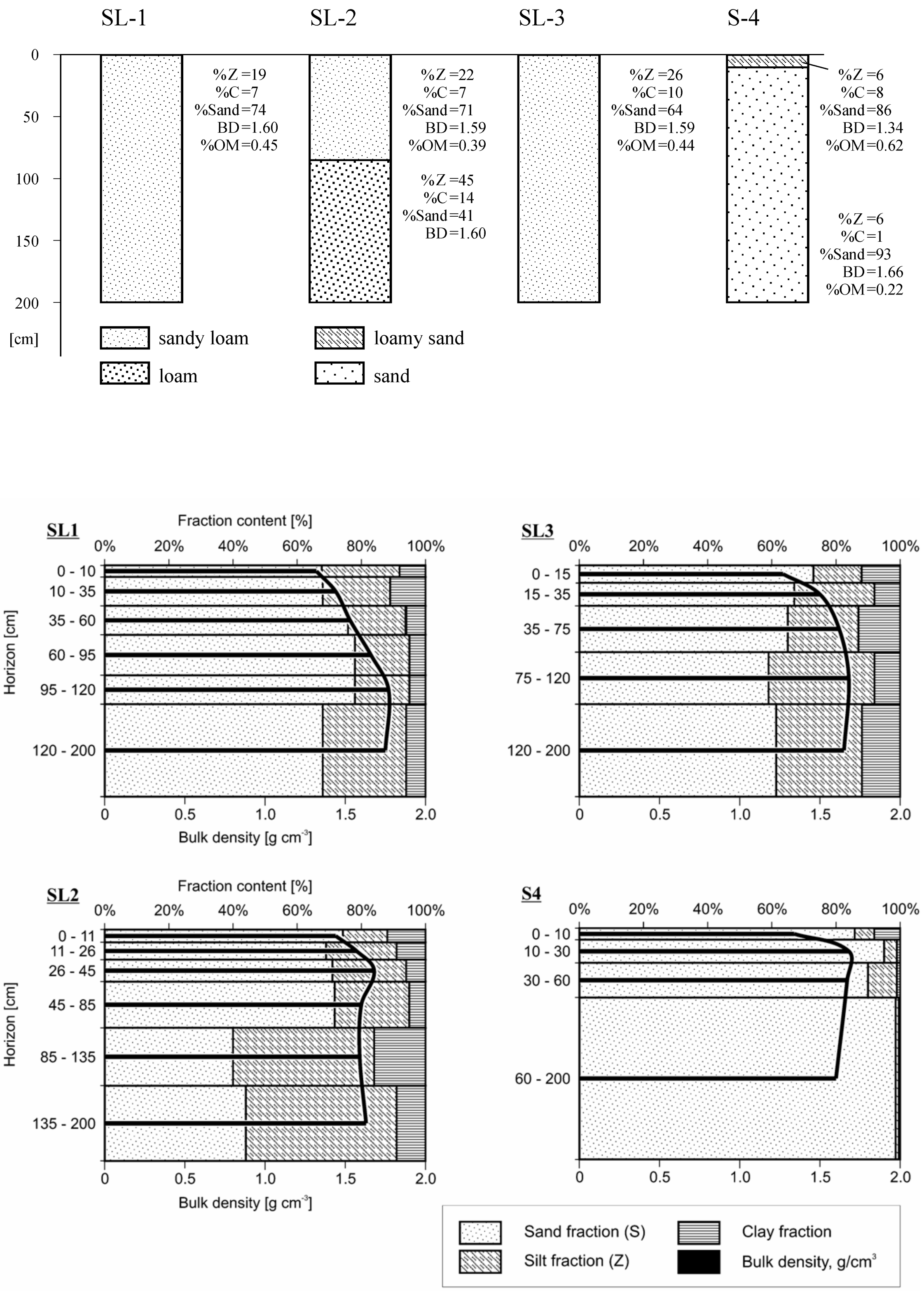


Figure 5.2 Soil texture, bulk density (BD) [g cm^{-3}] and soil organic matter (OM) [%]. C = clay, Z = silt, SL = sandy loam field (field #1), S = sandy field (field #2)

Table 5.1 Soil water retention (soil samples collected in 2002 on the monitored fields)

Field No.	Pit No.	Horizon [cm]	Volumetric soil moisture [cm^3 cm^{-3}] of a sample at different pressure (*pF*)					Bulk density [g cm^{-3}]	Porosity [cm^3 cm^{-3}]
			2.0 (FC)	2.7	3.0	3.5	4.2 (PWP)		
1	1	0-10	0.151	0.133	0.127	0.109	0.043	1.32	0.500
		10-35	0.255	0.247	0.239	0.227	0.157	1.44	0.460
		35-60	0.149	0.136	0.127	0.115	0.054	1.53	0.420
		60-95	0.169	0.154	0.148	0.134	0.056	1.66	0.380
		95-120	0.174	0.159	0.154	0.139	0.041	1.77	0.330
		120-140	0.216	0.198	0.190	0.172	0.034	1.75	0.340
1	2	0-11	0.170	0.137	0.120	0.103	0.047	1.44	0.460
		11-26	0.183	0.143	0.125	0.097	0.052	1.57	0.410
		26-45	0.173	0.137	0.121	0.099	0.056	1.68	0.370
		45-85	0.158	0.130	0.118	0.108	0.027	1.60	0.400
		85-135	0.294	0.268	0.242	0.217	0.086	1.59	0.400
		135-150	0.290	0.254	0.234	0.209	0.049	1.63	0.390
1	3	0-15	0.158	0.130	0.108	0.098	0.064	1.27	0.520
		15-35	0.184	0.161	0.144	0.136	0.094	1.50	0.430
		35-75	0.189	0.172	0.156	0.136	0.102	1.62	0.390
		75-120	0.248	0.232	0.206	0.182	0.114	1.68	0.370
		120-148	0.226	0.212	0.191	0.157	0.048	1.65	0.380
2	4	0-10	0.053	0.050	0.042	0.033	0.010	1.34	0.470
		10-30	0.088	0.084	0.076	0.058	0.012	1.68	0.330
		30-60	0.092	0.085	0.072	0.057	0.014	1.67	0.330
		60-70	0.061	0.048	0.032	0.020	0.006	1.60	0.360

Based on laboratory soil water retention characteristics (Table 5.1), the available water holding capacity (AWHC) was determined as the difference between Field Capacity (FC) and Permanent Wilting Point (PWP). The AWHC values differed between the two fields: on field #1, AWHC varied from 87-131 mm m^{-1} in the 0-60 cm soil profile and reached 114 – 241 mm m^{-1} in lower layers; on field #2, AWHC was 43-78 mm m^{-1} in the plough layer and 54 mm m^{-1} in lower layers.

Soil chemical properties

Sulphate, sodium and potassium prevailed in the top 0-15 cm layer of field #1 and constituted 4.7-9.4, 0.2-0.25 and 2.6-8.2 $cmol_c$ kg^{-1}, respectively. In the lower layers, *Cl* dominated (0.4-6.5 cmol(-) kg^{-1}). In both fields, the *Ca* content was 2-5 cmol(+) kg^{-1}, the *Mg* content was from 1.2 to 2.96 cmol(+) kg^{-1}, and HCO_3 was 0.15-0.25 cmol(-) kg^{-1} (see Appendix 9.1). Figure 5.3 also visualizes that the soils were relatively homogeneous, except the soil pit #2, where the ion content was higher.

The chemistry of soil salinity is generally defined by the chloride to sulphate ratio (Cl^- : SO_4^{2-}) (Kaurichev et al., 1989). According to the classification (Appendix

9.1), there were chloride, sulphate-chloride, chloride-sulphate, sulphate, and carbonate-sulphate and sulphate-soda types of salinity. The soils of both fields were medium saline with a chloride-sulphate type of salinity (FAO classification, Abrol et al., 1988).

According to the soil organic matter (SOM) content (0.51-0.79 %) in the plough layer, the soils could be classified as "poor". The SOM content at deeper layers even decreased to a “very poor” level of 0.14 % (Appendix 9.8).

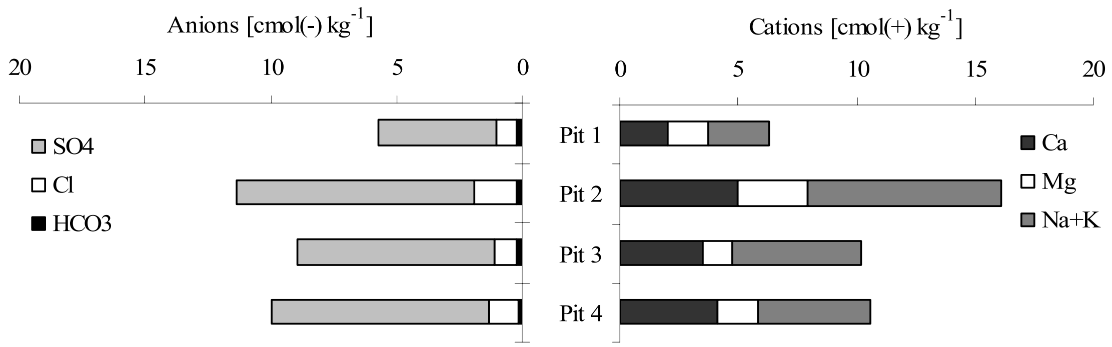


Figure 5.3 Ion content in soil profiles (field #1: pit 1 - pit 3, field #2: pit 4)

The mineral nitrogen (N) content in form of ammonium was 73.6-82.4 mg kg^{-1} in the upper horizon and decreased to 15.6-25 mg kg^{-1} in underlying layers. Plant-available phosphorus (expressed as P_2O_5) changed with depth from 45.5-50 mg kg^{-1} to 18.6-27 mg kg^{-1}. The potassium content was around 207 mg (K_2O) kg^{-1}, except for the 0-15 cm horizon in pit #3, where the content was 458 mg kg^{-1}, and thus assessed as “very high” (Appendix 9.8).

5.2 Water balance

5.2.1 Precipitation

In 2002, the amount of precipitation was below the long-term average (93 mm) and amounted to only 75 mm, while for 2003 season with 172 mm it was almost twice the long-term average. Daily precipitation, average air temperature, and average relative humidity and wind speed for 2003 are presented in Figure 5.4. Distribution of precipitation throughout the year 2003 deviated from the norm, where most of the precipitation occurs from February to March. As much as 31 % of the yearly precipitation occurred in May 2003, whereas in February and March this was only 13 % and 15 %.

It is known from the literature (Muhitdinova et al., 1988) that for optimal cotton development, the air temperature should be 25-30ºC and relative humidity 40-60 %. In 2003, the average temperature from April till July did not exceed 25ºC and caused delay in cotton development and led to a yield decrease.

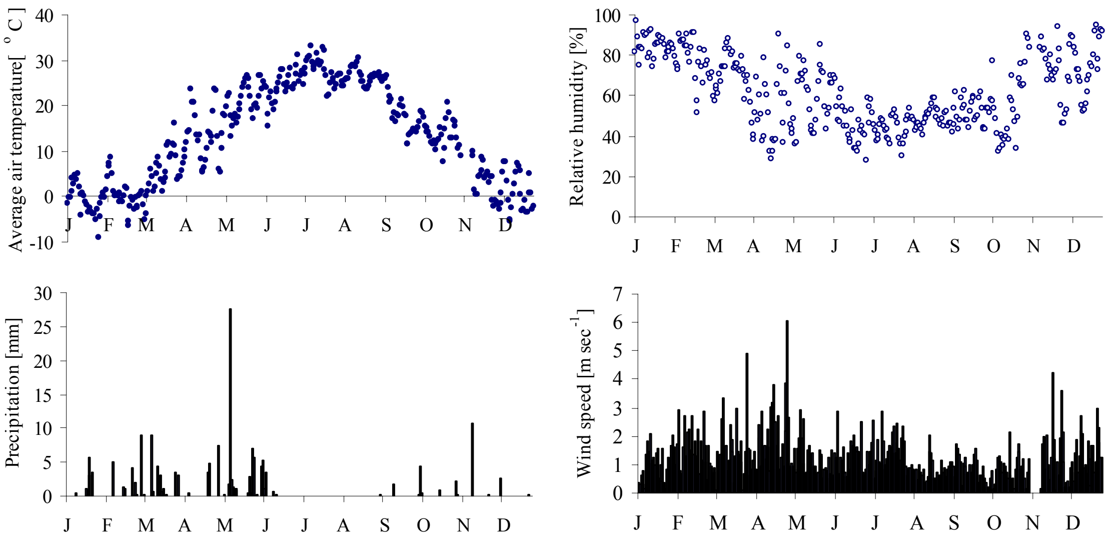


Figure 5.4 Mean daily air temperature, relative humidity, wind speed and precipitation at the research farm of Urgench State University in 2003

5.2.2 Irrigation and groundwater

The monitoring in 2003 started with the measurements of applied water for salt leaching on both fields. Due to surface irregularities (poor field leveling) and the large size of the fields, the farmers divided the fields before leaching into micro-plots (30 m by 30 m; Figure 5.1) to achieve water distribution during irrigation as uniformly as possible. Cipoletti weirs were installed at two water input points at both fields. Total applied water to wash the salts out of the rooting zone in March-April 2003 for the whole field #1 was measured. In total, 300 mm of water was applied during leaching (Table 5.2) with an average water salinity of 1.7 dS m^{-1}. Water application during the leaching period to field #2 was not recorded, as the farmers applied water to the field or discharged water out of the field without informing the researcher. Therefore, the simulations for field #2 were only started after the leaching event; the results are discussed in section 5.2.4 below.

Table 5.2 Applied water [mm] and its salinity [EC_w] during leaching season 2003 in field #1

Date of irrigation	4-5 March	14-15 March	3 April	**TOTAL:**	**AVERAGE:**
Amount [mm]	120	78	102	**300**	
EC_w [dS m^{-1}]	1.55	1.50	1.92		**1.7**

In 2002 for field #1 in total 236 mm of irrigation water with an average salinity of 0.91 dS m^{-1} was applied (Table 5.3 a), while field #2 was not irrigated at all. The amount of applied water in 2003 differed between the locations (Table 5.3 b) on field #1. The average irrigation water salinity in 2003 was 1.16 dS m^{-1} on field #1 and 0.99 dS m^{-1} on field #2.

Table 5.3 Applied water [mm] and its salinity [EC_w] during (a) 2002 irrigation season at field #1 and (b) 2003 irrigation season at both monitored fields

(a)

2002	Total amount	EC_w [dS m^{-1}]
6-7 July	43	0.89
16 July	36	0.90
25 July	35	0.94
12 August	65	0.90
27 August	57	0.90
TOTAL:	**236**	
AVERAGE:		**0.91**

(b)

2003	Field #1					Field #2	
	Location 1	Location 2	Location 3	Total amount	EC_w [dS m^{-1}]	Total amount	EC_w [dS m^{-1}]
16-17 July	66	73	77	66	1.02		
23 July	68	118	49	57	0.96		
29-31 July						85	0.99
5 August	97	90	64	103	0.99		
23-25 August	130	64	45	78	1.24		
9-13 September	46	42	33	68	1.57		
TOTAL:	**407**	**387**	**268**	**372**		**85**	
AVERAGE:					**1.16**		**0.99**

In the middle of field #1 (location 2), the farmer decided to apply more water than in other locations when the 2003 irrigation season started. This decision was made based on the farmer's visual impression that this location was more saline. This issue will be discussed in more detail in section 5.3.

Thus, during the first two irrigations, the highest amount of water was applied in the middle of field #1 (Table 5.3 b). Nevertheless, for the whole year most of the water was applied in the beginning of the field (location 1), where the water entered the field from the main irrigation canal during the water application. The amounts of applied water also differed because the field was not uniformly leveled and because it was impossibile to apply water equally at all locations[2].

Field #2 was not prepared for irrigation in 2003. Nonetheless, the farmers spontaneously decided to irrigate from 29-31 July, when there was water in the irrigation canal. However, they only succeeded in irrigating 1.4 ha of the whole area due to the irregular micro-topography of the field. The farmers stopped irrigation when the groundwater table had risen to 20 cm below the soil surface. Irrigation water did not reach the monitored location during these days.

On both fields, the relationship between applied water (irrigation and precipitation) and groundwater table dynamics was examined (Figure 5.5). During the 2003 leaching period on field #1, the influence of the application of high amounts of water was evident when the groundwater table increased, though only for a short time. On the other hand, in spite of (second) leaching activities on 14-15 March, the

[2] To assess the irrigation water application in the field, the field application efficiency (E_a) is a commonly used criterion. Relating the water stored in the root zone by the irrigation to the total amount of irrigation water directed to the field, E_a describes the quality of the water application as a technical process. For every irrigation event and at all locations in field #1, E_a for the cotton root zone was calculated as the difference in volumetric soil moisture content after and before the irrigation divided by total applied irrigation water to this location. The values of E_a were irregular and varied between irrigation events and along the field. In average, E_a values for location 1, 2 and 3 were 54 %, 42 % and 92 %, respectively. The variation of E_a between irrigation events were in the range of 9 % to 100 %. Practically, E_a mainly depends on irrigation method, field conditions (i.e., degree of leveling, field size), soil texture, irrigation depth, application discharge and on farmers' skills. Hillel (1997) states that even with the best irrigation practices, the field application efficiency cannot be as high as 100 %, but is usually less than 50 % and often about 30 %. Application efficiency as an averaged value from worldwide surveys is in the range of 57 % (Doorenbos and Pruitt, 1984). The calculated E_a values for furrow irrigation in the present study indicate the efficiency of water application as a technical process for the selected locations and considered irrigation events. In order to assess the water management on field level regarding water use, especially in the case of shallow groundwater and regarding the whole vegetation period, further considerations are necessary. In a situation of shallow groundwater, the water percolating from the root zone (which is considered to be a loss by the above-applied standard definition of application efficiency) can partly be used by the crops as capillary rise from groundwater. Using the E_a as an indicator related to the technical process of irrigation, the overall assessment of field-water management needs to take into account the appropriate timing of the irrigation events and the fulfillment of crop-specific soil moisture levels as well as soil salinity limits (in order to avoid yield reduction). However, from the field experience and especially the spatial distribution of the calculated application efficiency values, it was evident, that water application inside the micro-plot was not uniform, mainly because of poor leveling and insufficient discharge control.

groundwater table dropped considerably due to the proper functioning of (unblocked) drains. Yet immediately after the third leaching event (3 April), the groundwater table rose again, highlighting the fact that no reliable estimates on the influence of leaching practices on the table of groundwater can be made without knowledge of the state of the drainage system. The latter can easily be manipulated by farmers.

After leaching and before the irrigation season, there was a slow drop in groundwater tables with some intermediate local rises and drops. In response to the first irrigation event, the groundwater table rose again.

On field #2, after the beginning of irrigation at the end of July 2003 the groundwater table rose up to 20-30 cm below the soil surface (Figure 5.5).

Again, there were some unforeseeable changes in groundwater table dynamics during the 2003 vegetation season in field #1: After the application of high water amounts on 5 August, the groundwater table did not rise, but even decreased. Disturbing influences could be: (1) irrigation of the neighboring fields and water level change in the Sirchali canal (see Figure 3.1), (2) management activities regarding drainage discharge and water levels, and/or (3) relative height of groundwater table compared to the drainage system level.

In conclusion, the relationship between surface water input and groundwater dynamics remained poorly understood and more research is needed on groundwater table dynamics on the regional scale rather than monitoring single fields.

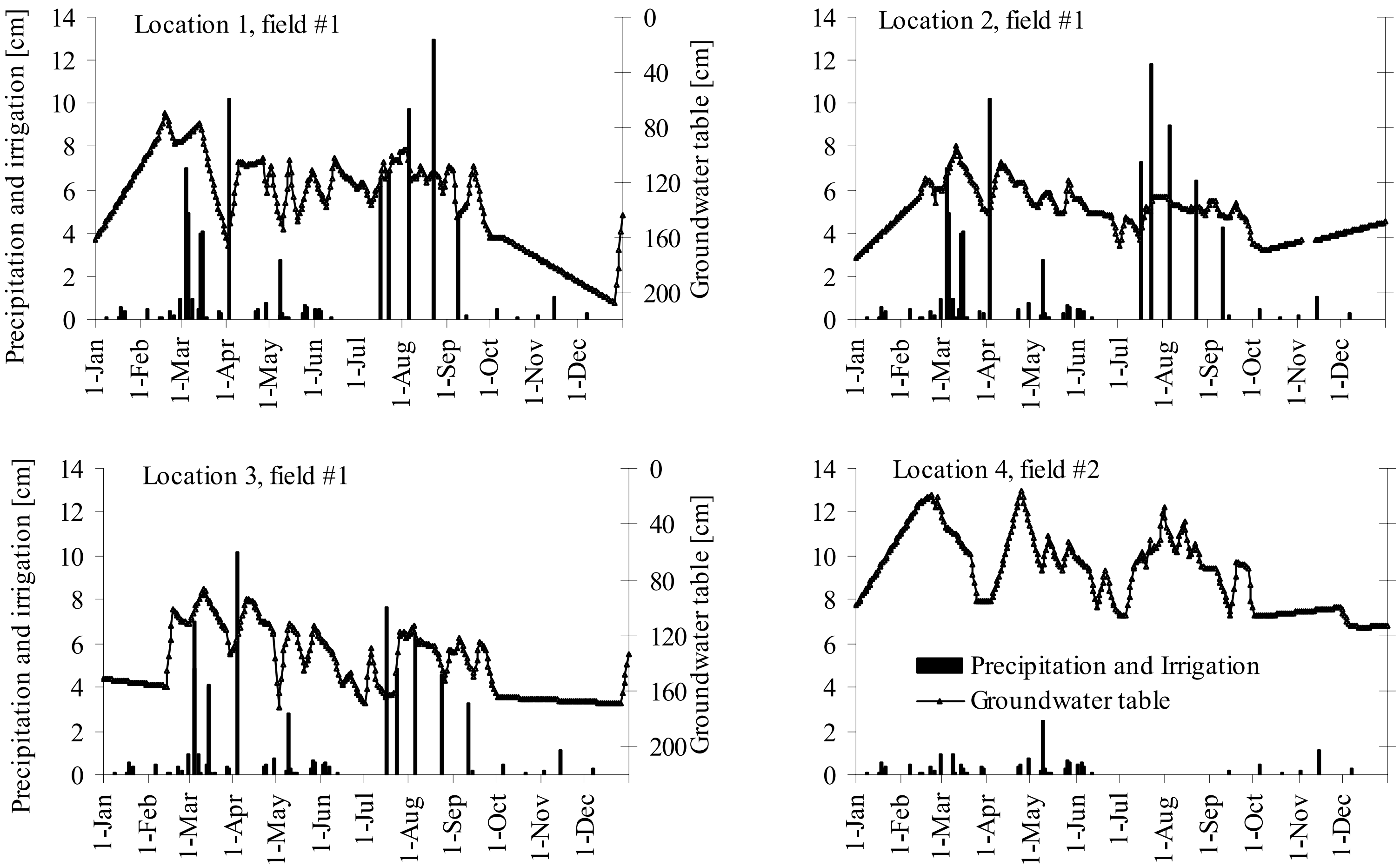


Figure 5.5 Groundwater table dynamics and applied water for leaching and irrigation, including precipitation (for field #2 only precipitation is considered) on the monitored fields (2003)

5.2.3 Potential and actual evapotranspiration

Reference crop evapotranspiration was calculated according to the FAO-56 approach using daily meteorological data. Annual ET_0 was estimated to be 994 mm (Table 5.4). This is relatively low compared to values cited elsewhere (Froebrich, 2003; Micklin, 1991; Tursunov, 1981), which are based on long-term averages of meteo/climatic parameters. However, data on temperature and wind speed show that in 2003 temperatures and wind speed are lower than average, and this explains the low ET_0.

Table 5.4 Monthly mean temperature (T), relative humidity (RH_{mean}), wind speed (u_2) and short wave radiation (R_s) as well as potential evapotranspiration (ET_0) and precipitation (P) per month at the research farm in 2003

	T [ºC]			RH [%]			u_2 [m sec^{-1}]			R_s [MJ m^{-2}day^{-1}]	ET_0	P
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	[mm month^{-1}]	[mm month^{-1}]
Jan	-0.8	3.3	-4.4	85	97	74	1.0	2.1	0.2	5.5	13	14.6
Feb	0.5	3.9	-2.3	78	91	51	1.5	2.9	0.1	6.9	21	23.0
Mar	5.1	10.0	1.0	72	88	57	1.5	4.9	0.1	12.2	46	25.8
Apr	13.2	18.8	7.8	53	90	28	2.0	6.0	0.5	16.1	95	16.0
May	20.0	25.7	14.2	58	85	36	1.2	2.9	0.5	21.3	129	53.0
Jun	24.2	30.5	17.3	48	70	28	1.2	2.9	0.5	22.5	150	15.2
Jul	27.8	33.9	21.5	44	59	30	1.6	2.9	0.5	24.7	188	0
Aug	26.5	33.6	18.8	49	59	40	0.8	2.0	0.4	24.3	153	0
Sept	19.4	26.8	12.5	51	62	42	0.9	1.8	0.3	19.8	102	2.0
Oct	14.5	22.4	7.7	51	77	32	0.8	2.1	0.1	13.3	60	5.8
Nov	5.4	9.5	2.1	77	94	46	1.3	4.2	0.1	5.5	21	13.4
Dec	0.6	5.7	-3.3	73	95	46	1.2	3.0	0.2	6.0	16	2.8
										TOTAL:	**994**	**172**

Crop coefficient

The so-called dual approach was implemented in the current research. Cotton was planted in April 2003 and harvested throughout September-November. Table 5.5 gives an overview of the dates of some management activities and phenological stages.

Table 5.5 Management activities and phenological stages of cotton in 2003

Planting	25 April	Flowering*	4 July
Emergence*	8 May	Boll development*	10 July
Squaring*	21 June	First picking	24 September

**50 % of all plants*

For the estimation of the crop coefficient-curve (K_{cb}-curve), the vegetation season (2003) was divided into four periods: initial (25 April – 18 May), crop development (19 May – 04 July), midseason (05 July – 30 August) and late season (31 August – 4 October).

First, basal crop coefficients were adjusted to the local climatic conditions using data on wind speed, mean relative humidity, observed cotton height and basal crop coefficients for non-stressed, well-managed cotton (Table 17 in the FAO-56 handbook). In semi-arid and arid regions under water- or salt-stressed conditions, crops often do not reach full ground cover. In such a case, the basal crop coefficients need to be adjusted to natural (local) conditions. Allen et al. (1998) suggested reducing mid-stage K_{cb} (see Equation 4.11) in case the plant density or *LAI* is lower than for full-cover conditions. This was the case in this study: cotton experienced water and salt stress and the crop development along field #1 (by the three locations) and field #2 was not uniform as was monitored in detail by Coppi (2004). Some places in the fields remained completely without cotton plants, but instead showed a high abundance of weeds (Figure 5.6).

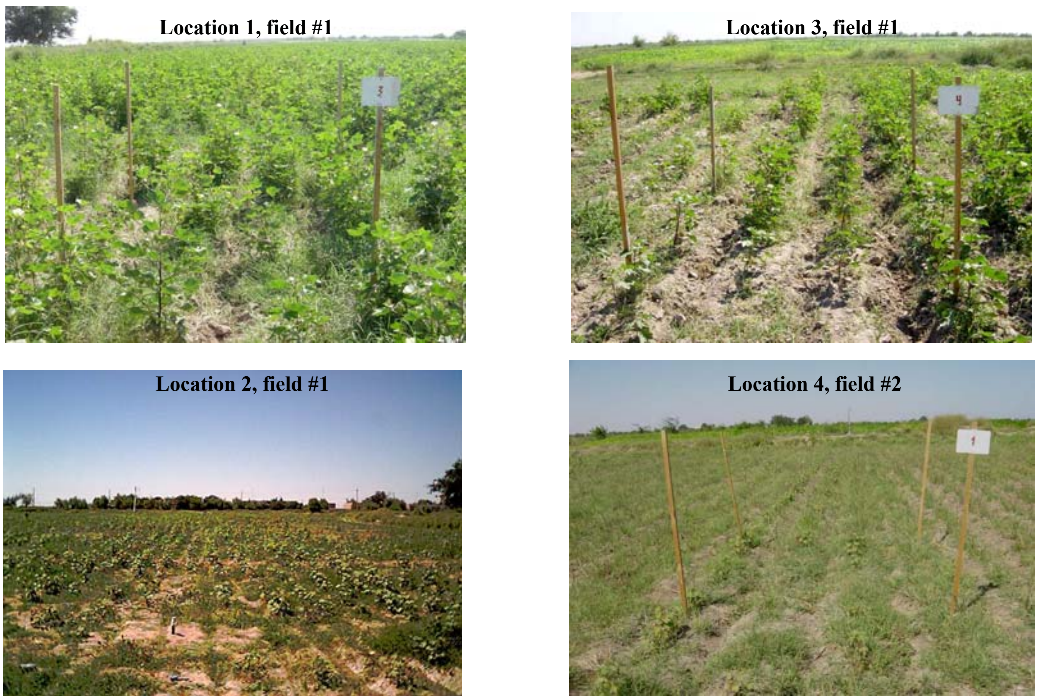


Figure 5.6 Cotton condition and weeds on the monitored fields in 2003

In general, the biomass of weeds was equal or in some cases (especially field #2) even higher than the cotton biomass (Figure 5.7).

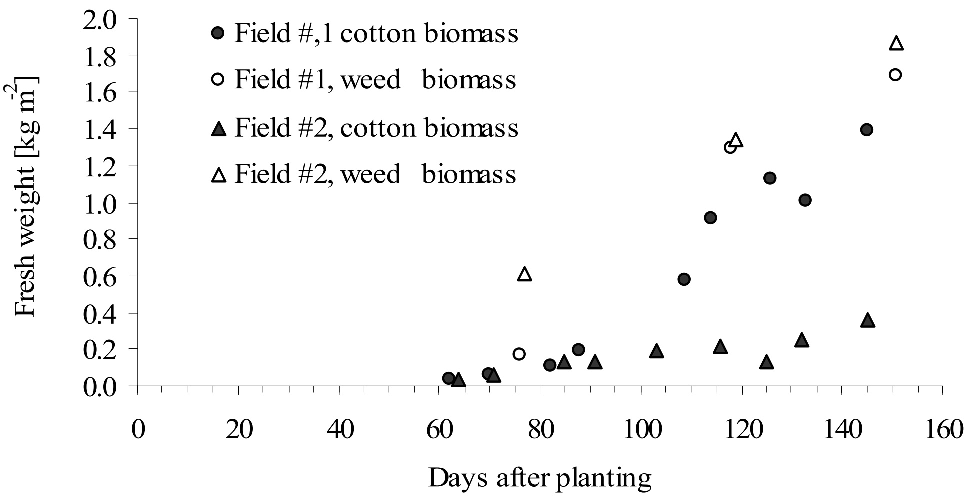


Figure 5.7 Cotton and weed biomass on the monitored fields in 2003

Detailed information about the *LAI* and root distribution of weeds, however, was not collected during the study. Consequently, to account for the (extra) transpiration of weeds and a reduction of evaporation due to weed ground cover, the *LAI* of cotton, as an input parameter to adjust K_{cb} to local conditions, was doubled (tripled on field #2) to comprise both cotton and weed leaf area. Thus, the maximum *LAI* values used for field #1 were 1.62, 1.24 and 0.88 for location 1, 2 and 3, respectively; the *LAI* for field #2 was 0.27. Furthermore, it was assumed that the root system (maximum rooting depth and root growth) of weeds would be the same as for cotton. The resulting adjusted crop coefficients during crop-development and midseason stage were on average 26-46 % lower than basal unadjusted values (Figure 5.8).

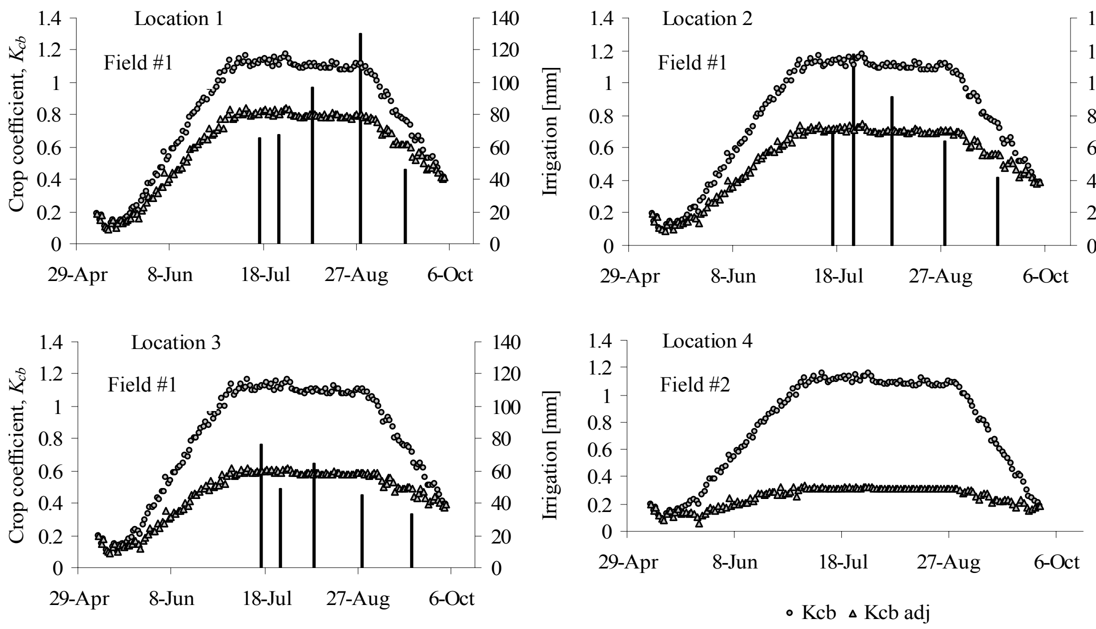


Figure 5.8 Crop coefficient adjusted to meteorological conditions and local cotton development on the monitored fields (2003). Here K_{cb} = crop coefficient for "ideal" conditions; K_{cb} *adj* = crop coefficient adjusted to local climate and *LAI* during cotton mid-stage development accounting weeds

Root water uptake

In the current study, the multiplicative threshold model of root water uptake (Equation 4.7) proposed by van Genuchten (1980) was applied. Under optimal water conditions, the maximum root water uptake in the rooting zone is equal to the potential transpiration rate, while under non-optimal (too dry or too wet) conditions, the root water uptake reduces by means of the factor *α(h).* The water stress (Figure 5.9) may be described by the function proposed by Feddes et al. (1978). The maximum water uptake occurs between h_2=-25 [cm] and h_3, while below h_1=-10 [cm] (oxygen deficiency) and above h_4=-15000 [cm] (wilting point) it is set to zero. The linear variation is assumed between h_1 and h_2 and between h_3 and h_4. The h_3 values depend on the water demand of the atmosphere, therefore vary with potential transpiration. Thus, h_3^l=-6000 [cm] and h_3^h=-200 [cm] are soil-water pressure heads below which water uptake reduction starts at low (T_{low}=0.1 cm d^{-1}) and at high (T_{high}=0.5 cm d^{-1}) levels of atmospheric demand, respectively.

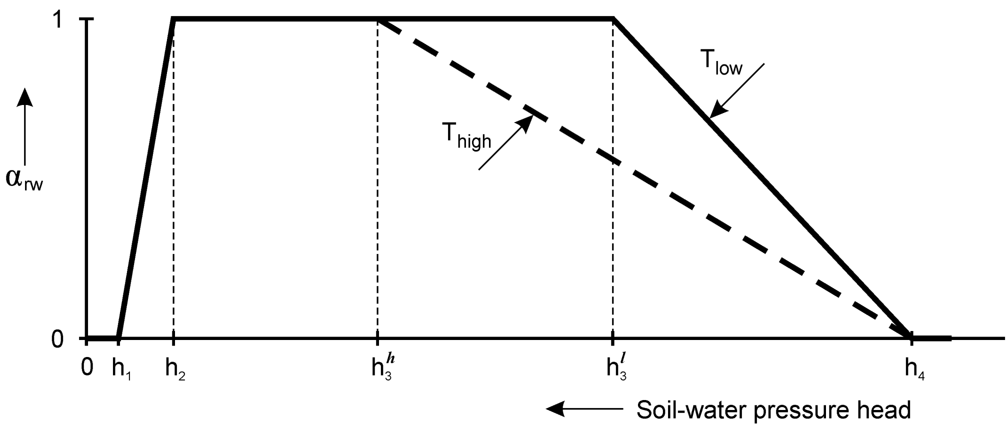


Figure 5.9 Reduction coefficient for root water uptake, α_{rw}, as a function of the soil-water pressure head and potential transpiration rate (Feddes et al., 1978)

The response function of water uptake reduction due to salinity stress (after Maas and Hoffman, 1977) can be presented according to Feddes and Raats (2004) as the soil-water pressure head and concentration, or electrical conductivity of the soil saturation extract, or osmotic pressure head (Figure 5.10).

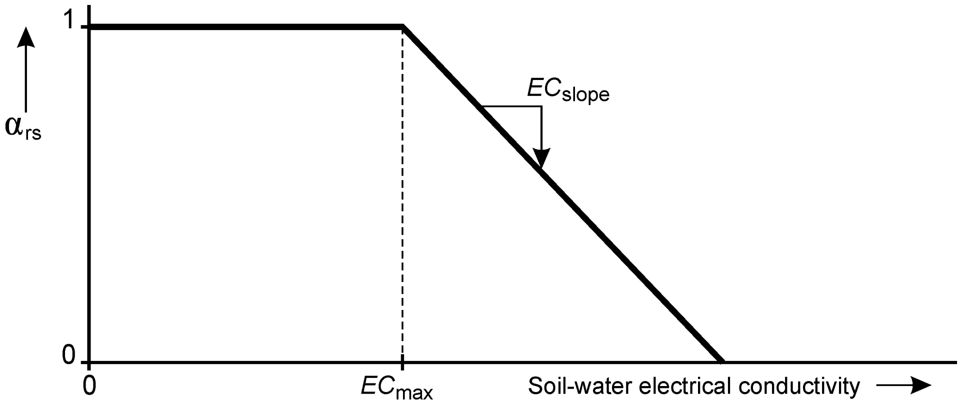


Figure 5.10 Reduction coefficient for root water uptake, α_{rs}, as a function of the electrical conductivity of the saturation extract (Rhoades et al., 1992)

It is known from the literature (Rhoades et al., 1992) that cotton is a salt tolerant crop, being sensitive to soil salinity in the planting-germinating period. The level at which salt stress starts for cotton is 7.7 dS m^{-1} (EC_{max}) and the decline of root water uptake above EC_{max} is 5.2 % per dS m^{-1}. According to Richards (1954), a factor 360 can be used to convert electrical conductivity values into osmotic pressure heads. Soil-water electrical conductivity was converted into salt concentration based on the relationship between electrical conductivity of the saturated extract (EC_e) and total dissolved salts derived from the laboratory data (see section 5.2.4).

The evapotranspiration (*ET*) calculated by the FAO-56 Penman-Monteith approach separated into evaporation and transpiration was fed into the model. Prior to separation, *ET* values were multiplied by crop coefficients and approximated to local conditions with the *LAI*. Following imposed restrictions and in case of water scarcity, HYDRUS-1D reduces *ET* (to actual transpiration and evaporation). Results on potential and actual transpiration (2003) are depicted in Figure 5.11. Discrepancies between potential and actual transpiration indicate the prevalence of water stress during the initial stage of cotton establishment. The most severe water stress on field #1 occurred at the end of the field (location 3), which highlighted the general problems related to a non-uniform water distribution along the field during irrigation. Actual transpiration equaled potential with the first irrigation on 16 July; the further discrepancies between actual and potential transpiration are due to quick desiccation of the top (0-10 cm) layer in response to continuous evaporation.

At location 4 (field #2), the actual transpiration was lower than potential transpiration most times during May to October 2003. This was not only because of a desiccated top soil layer. A poor cotton establishment with a maximum cotton root length of 28 cm was due to a shallow groundwater table (rising up to 20 and 30 cm in May and July). From 23 May till 6 June, 31 mm of precipitation occurred in the field and triggered actual transpiration to reach potential levels during this period. Later at the beginning of August, there again was a match between potential and actual transpiration. From 29-31 July, the field was irrigated and groundwater table was 25-30 cm below the surface. Thus, matching was due to shallow groundwater and significant capillary rise from its surface into the top soil layer.

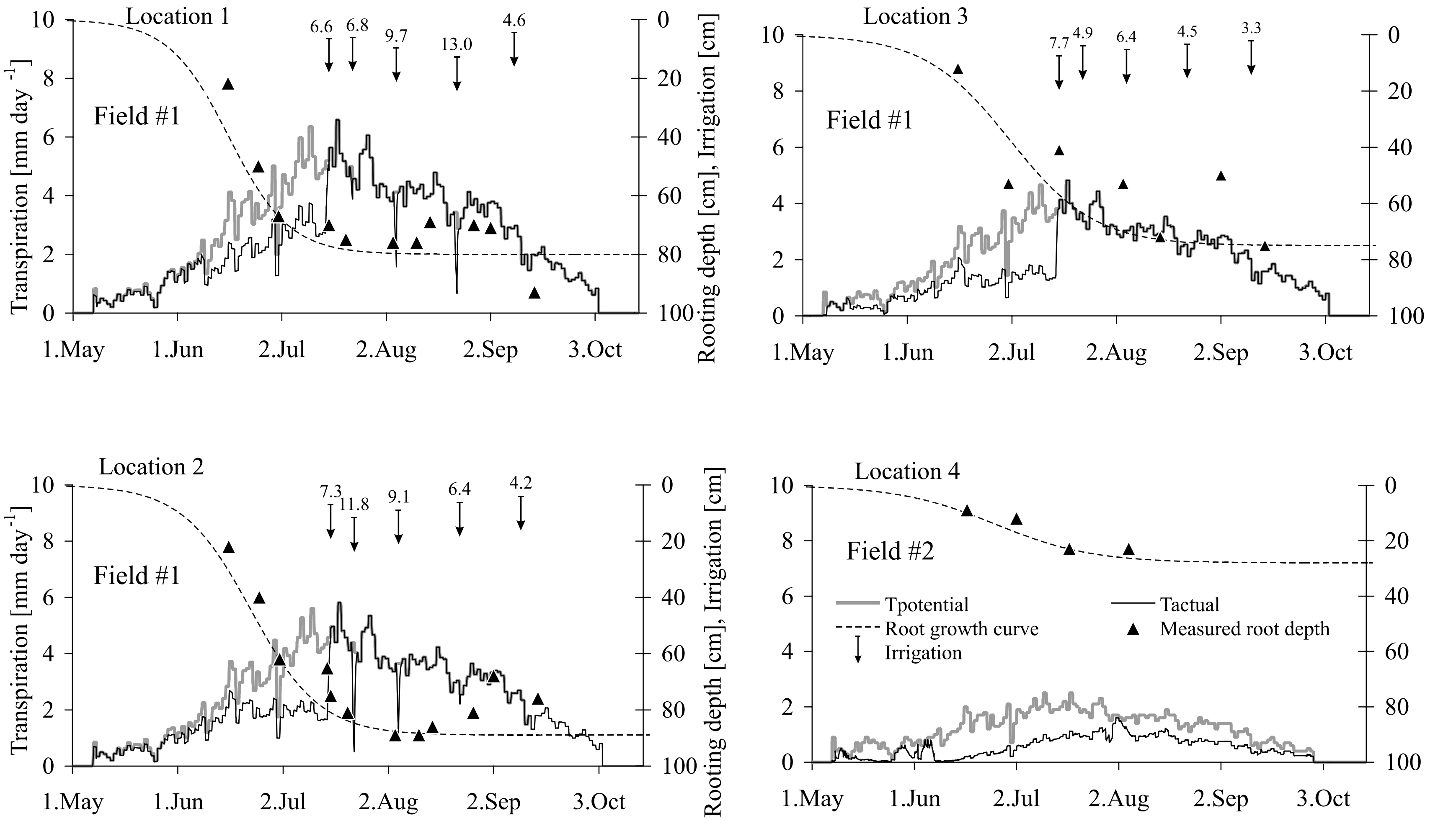


Figure 5.11 Potential and actual transpiration (left y-axis) as well as root growth and applied irrigation water (right y-axis) on the monitored fields during vegetation season 2003

Soil water evaporation is controlled by the availability of energy and the rate of water conduction to the soil surface (Ziemer, 1979). In the absence of favorable topsoil moisture conditions, e.g., during a dry summer, actual evaporation rates fall below the corresponding potential evaporation rates. Figure 5.12 presents the cumulative potential and actual evaporation rate of both fields during the vegetation season 2003.

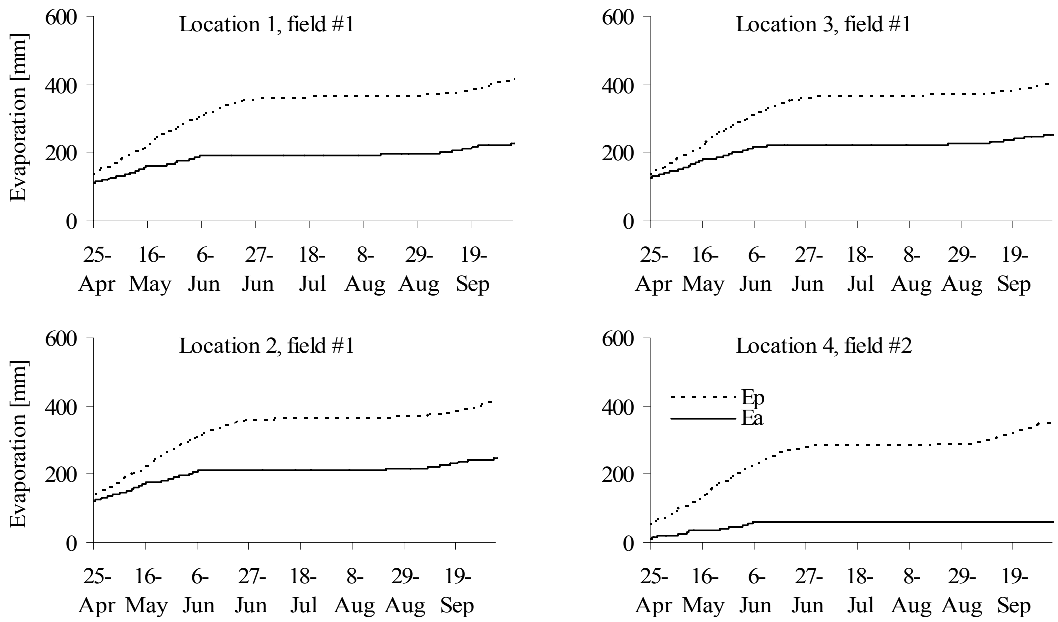


Figure 5.12 Cumulative potential (FAO-56) and actual (simulated) evaporation over the vegetation season in 2003 of the monitored fields

The actual evaporation reached 40 %, 44 % and 47 % of potential evaporation at the beginning, middle and end of field #1 and 18 % in field #2. Cotton performed best at the beginning of field #1 and gradually lesswell towards the end of the field, while it was very poor in field #2. The big difference between potential (298 mm) and actual (53 mm) evaporation on field #2 is explained mainly by the sandy soil texture, which dry out quickly, thus reducing evaporation.

For all locations, actual evapotranspiration during the vegetation season was greater than the total amount of applied irrigation water (Figure 5.13).

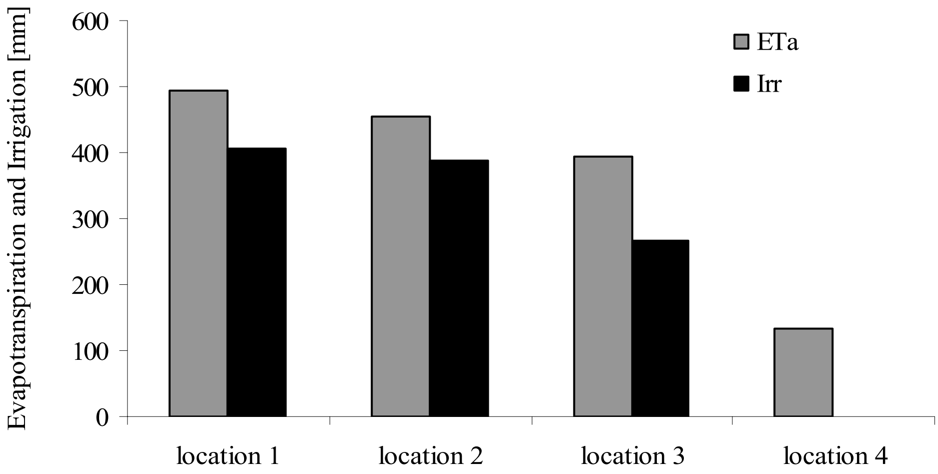


Figure 5.13 Actual evapotranspiration (ET_a) and applied irrigation water (I_{rr}) during 2003 vegetation season for locations 1 to 3 (field #1) and location 4 (field #2)

Root growth parameters are presented in Table 5.6. The actual root depth in HYDRUS-1D is the product of maximum rooting length (L_m) and a root growth coefficient ($f_r(t)$). The growth rate was adjusted in accordance with the duration of crop growth periods in the fields. Therewith, the beginning and end of root growth as well as intermediate and maximum rooting depth were matched with those values measured in the fields (Figure 5.11).

Table 5.6 Cotton root growth parameter on the monitored fields in 2003 determined from the Verhulst-Perl logistic growth function

Date		Location	Initial rooting length [cm]	Max. rooting length [cm]	Growth rate [d^{-1}]
Start root growth	End root growth				
25 April	4 October	1	1	80	0.111
25 April	4 October	2	1	89	0.098
25 April	4 October	3	1	75	0.079
25 April	30 September	4	1	28	0.068

5.2.4 Soil water movement and moisture regime

Model adjustment

The water content-pressure head relationship, $\theta(h)$, and the conductivity-pressure head relationship, $K(h)$, constitute the main soil hydraulic properties. Accurate determination of soil hydraulic properties is necessary for receiving reliable information on the water flow and solute transport simulated with mathematical models (Wang et al., 2002).

The simulated soil profile of 2-m depth was divided into genetic layers representing the different materials according to soil profile description (Appendix 9.3). A total of 200 nodes were used to represent the profile with a nodal spacing of 1.0 cm. The simulation period for field #1 and field #2 started on 12 February 2003 and 10 April 2003, respectively. The initial and boundary conditions, as well as time step, were set up as described in Chapter 4 (see also Appendix 9.9). The model calibration was based on volumetric soil moisture and pressure head by time series using the inverse modeling approach in HYDRUS-1D. Because there were no direct measurements of soil hydraulic functions in the current study, their initial shape was estimated with the Rosetta DLL (Schaap et al., 2001).

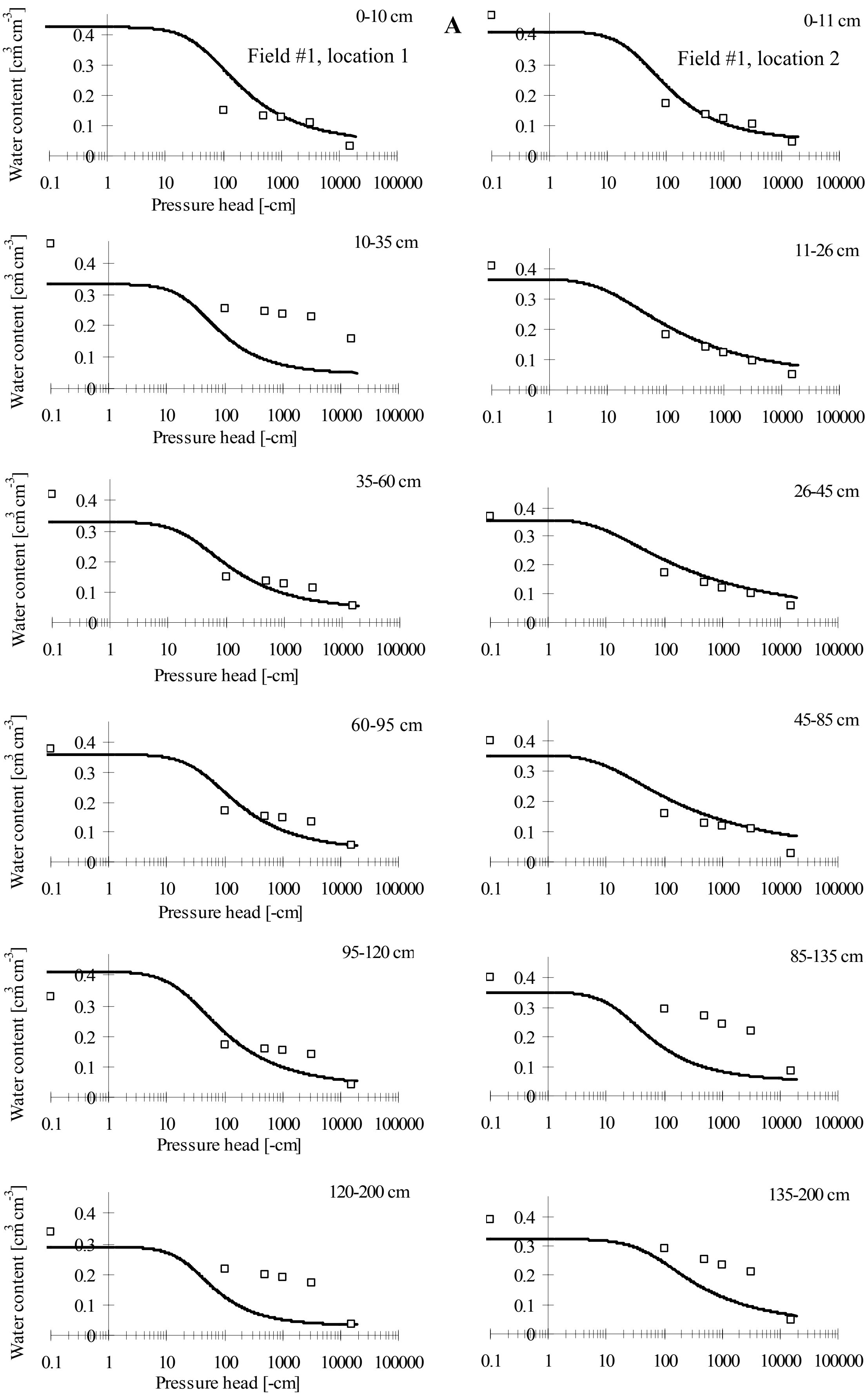
For calibration, pressure heads measured with tensiometers installed at 30 cm and 50 cm depth from the soil surface were used. During calibration, it was not possible to optimize 24 soil hydraulic parameters and 6 solute transport parameters simultaneously, since the Levenberg-Marquardt method used in HYDRUS-1D can only identify a limited number of unique parameters. To achieve unique and stable estimates, the number of fitting parameters was always not more than one for each layer following the suggestions given by Simunek and van Genuchten (1996), Gribb (1996) and Rassam et al. (2003). The residual and saturated water content was kept as determined by Rosetta, the other parameters (α, n, K_s and l) were fitted during inverse optimization (Table 5.7) one by one for every soil horizon where gravimetrical soil moisture sampling had been conducted, namely at 20 cm, 50 cm, 80 cm and 105 cm.

Soil hydraulic properties for horizons with no soil moisture sampling are kept as predicted by the Rosetta program based on known texture and bulk density. Although some soil horizons were identical by texture and similar regarding bulk density, it was decided not to combine horizons, but to go one by one and include all the soil layers examined during the soil profile description. To avoid unrealistically high or low values during the inverse optimization process, the following constraints were imposed: $0.0001<\alpha<1.000$ [cm^{-1}]; $1.0001<n<10$ [-], $1.000<K_s<1000$ [cm day^{-1}], $-1.6<l<1.6$ [-]. The pore connectivity parameter l for horizons where soil moisture had not been measured was kept at 0.5 as proposed by Mualem (1976) and discussed widely in the literature by van Genuchten (1980), Kool et al. (1987) and Sommer et al. (2003).

Table 5.7 Calibrated Mualem-van Genuchten parameters to describe the soil hydraulic properties (SL=sandy loam, L=loam, LS=loamy sand, S=sand). Here θ_{res} and θ_{sat} are residual and saturated soil water content, α and n are parameters in the soil water retention function, K_s is the saturated hydraulic conductivity and l is the pore connectivity parameter

	θ_{res} [cm^3 cm^{-3}]	θ_{sat} [cm^3 cm^{-3}]	a [-]	n [-]	K_s [cm d^{-1}]	l [-]	Texture
Field #1, location 1							
0-10 cm	0.043	0.427	0.021	1.47	23	0.500	SL
10-35 cm	0.046	0.332	0.035	1.64	41	1.510	SL
35-60 cm	0.040	0.329	0.039	1.45	82	0.001	SL
60-95 cm	0.038	0.360	0.024	1.49	75	0.100	SL
95-120 cm	0.036	0.410	0.049	1.46	38	0.213	SL
120-200 cm	0.032	0.290	0.040	1.70	22	0.500	SL
Field #1, location 2							
0-11 cm	0.049	0.408	0.033	1.52	75	0.500	SL
11-26 cm	0.040	0.363	0.093	1.28	156	0.001	SL
26-45 cm	0.036	0.356	0.112	1.24	81	0.004	SL
45-85 cm	0.036	0.351	0.099	1.25	65	0.001	SL
85-135 cm	0.049	0.349	0.060	1.54	59	1.202	L
135-200 cm	0.035	0.324	0.018	1.40	14	0.500	L
Field #1, location 3							
0-15 cm	0.052	0.453	0.033	1.63	103	0.500	SL
15-35 cm	0.039	0.375	0.045	1.53	51	0.346	SL
35-75 cm	0.044	0.356	0.030	1.59	25	0.102	SL
75-120 cm	0.033	0.380	0.054	1.44	18	0.024	SL
120-200 cm	0.040	0.343	0.034	1.35	19	0.500	SL
Field #2, location 4							
0-10 cm	0.055	0.443	0.073	3.52	29	0.426	LS
10-30 cm	0.048	0.331	0.029	2.46	92	0.256	S
30-60 cm	0.043	0.333	0.016	1.57	282	0.604	S
60-200 cm	0.052	0.353	0.022	5.44	851	0.000	S

As mentioned in Chapter 4, for each soil layer *pF*-curves (soil-water retention curve) were derived in the laboratory within a *pF* range of 2.0-4.2 (0.1-15 bar). However, they were not used to derive the Mualem-van Genuchten parameters. Though, in general, the laboratory water retention curves matched the inversely simulated ones, there were some cases where both curves deviated drastically (Figure 5.14 A and B). In these cases, the laboratory-derived curves showed a rather unrealistic shape. Moreover, test runs using these curves instead of the inversely simulated ones would not reproduce in-situ soil moisture regimes. Saturated soil moisture was adapted from the Rosetta program, because in the laboratory the soil water content at saturation or close to saturation was not determined.


A
Field #1, location 1
Field #1, location 2
0-10 cm
10-35 cm
35-60 cm
60-95 cm
95-120 cm
120-200 cm
0-11 cm
11-26 cm
26-45 cm
45-85 cm
85-135 cm
135-200 cm
Water content [cm3 cm-3]
Pressure head [-cm]
0.1 1 10 100 1000 10000 100000
0 0.1 0.2 0.3 0.4

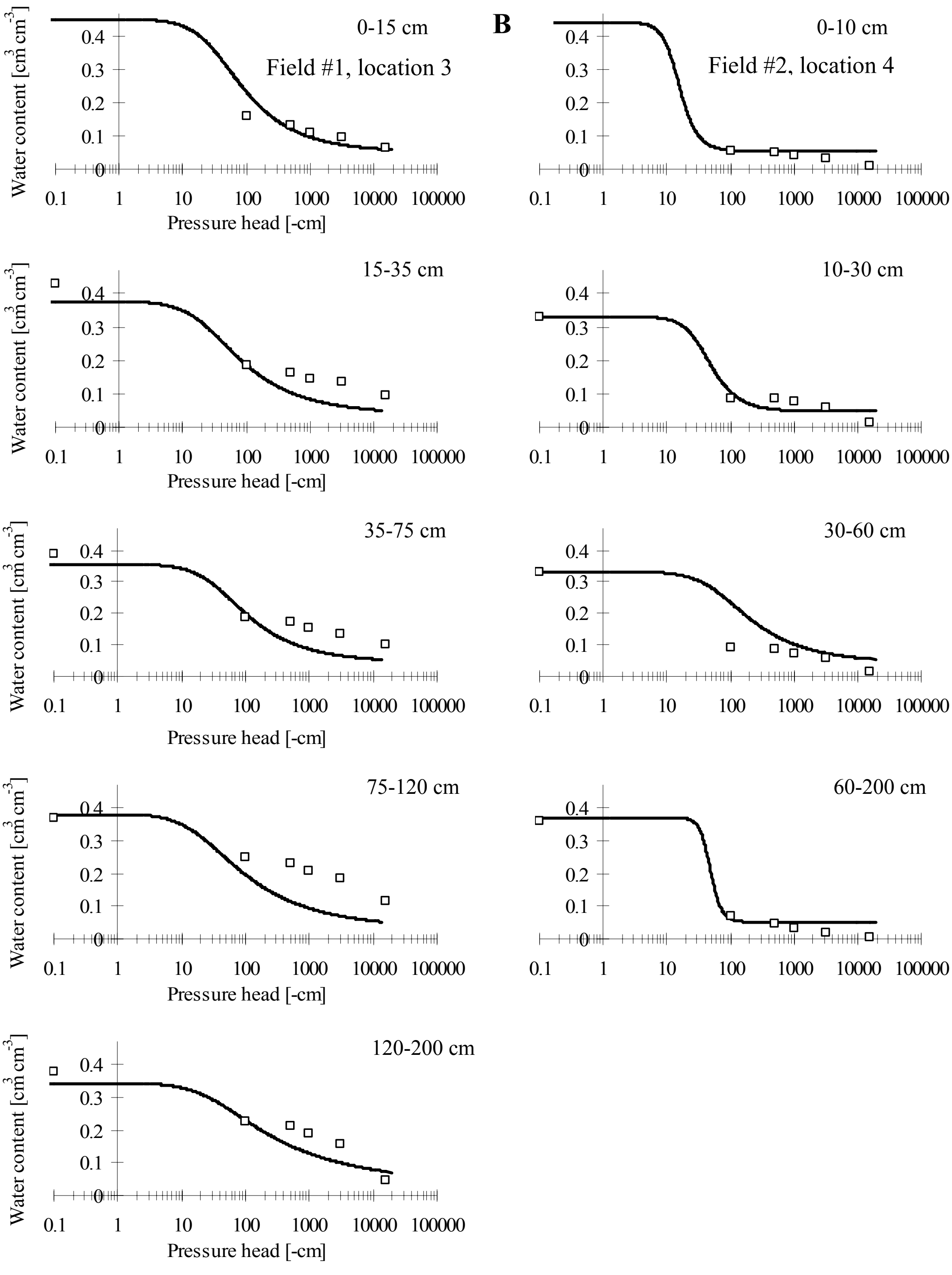


Figure 5.14 Laboratory-derived (dots) versus inversely optimized (solid line) water retention curves for selected soil horizons on the monitored fields

There was no measurement on saturated hydraulic conductivity (K_s) in the laboratory; therefore the K_s-values were those received from Rosetta program based on soil texture and bulk density information for every soil layer. Figure 5.15 shows the *K-h* relationships using these K_s-values.

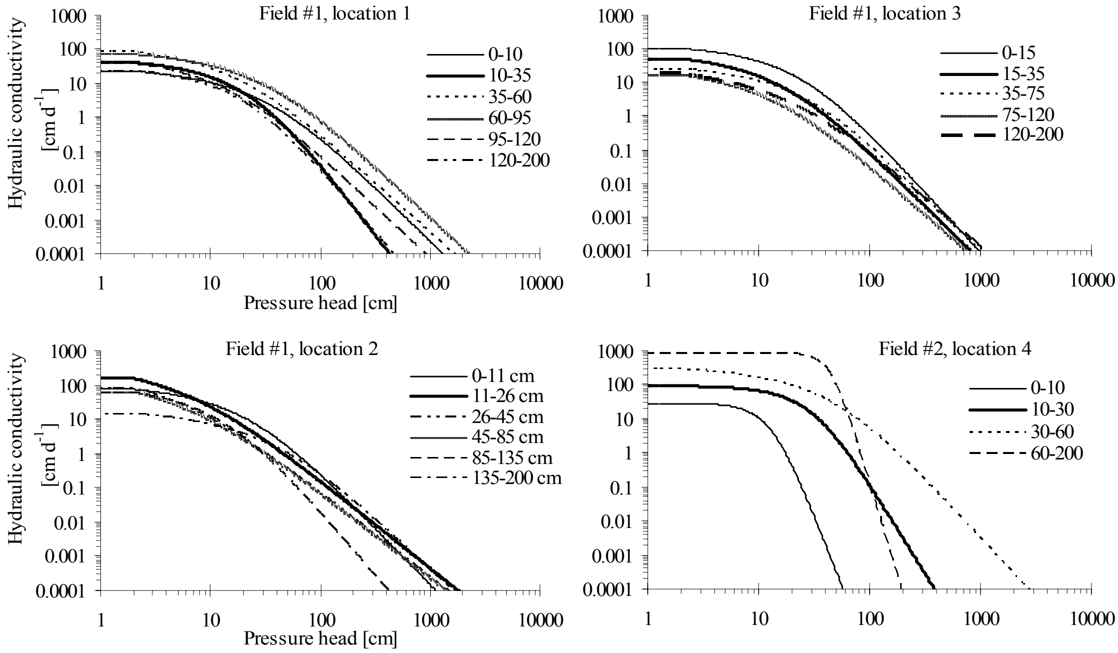


Figure 5.15 Relationship between hydraulic conductivity and pressure head of the monitored fields

In Figure 5.16 the pressure heads before and after the optimization procedure are presented. Without parameter optimization, the modeled pressure head values were far below the measured pressure heads and could not follow the day to day dynamic particularly at 50 cm depth. After the parameter optimization procedure, the modeled pressure head values became closer to the measured values, with some remaining discrepancies, especially at the 50 cm-depth horizon. This was due to obviously imprecise in-situ measurements of pressure head against soil moisture that did not describe a unique *pF*-curve (Figure 5.17).

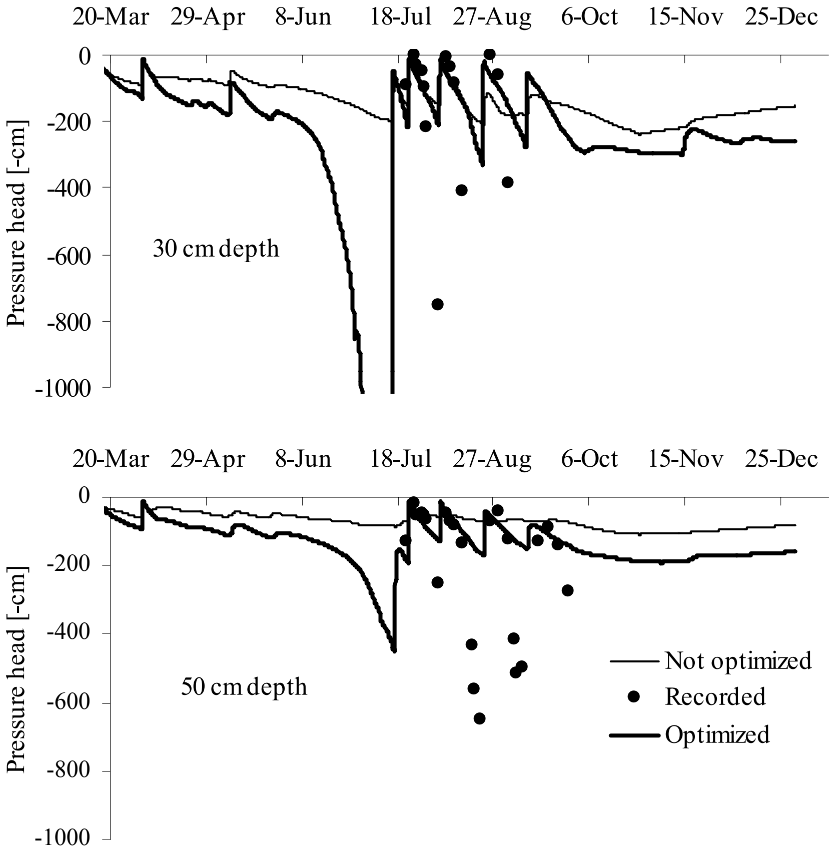


Figure 5.16 Measured and modeled pressure head at 30 and 50 cm depth over two months in 2003 at field #1 (location 2)

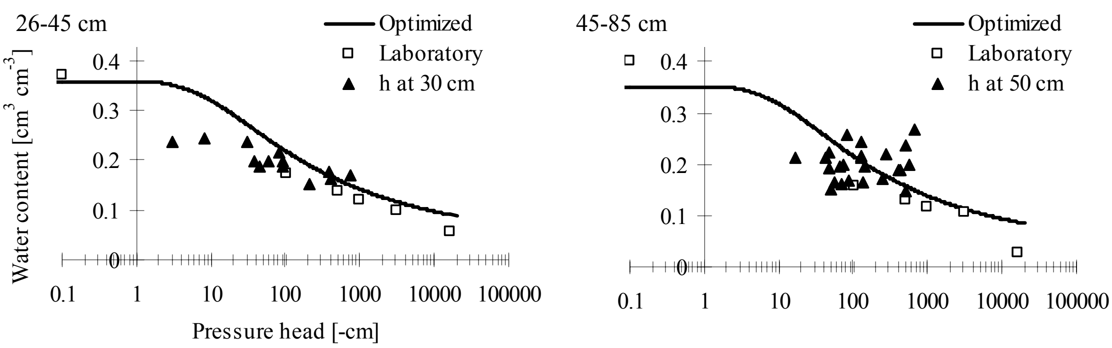


Figure 5.17 Laboratory-determined and inversely optimized soil water retention curves, and in-situ parallel measurement of pressure head (*h*) and soil moisture at 30 and 50 cm depth at field #1 (location 2) in 2003

The measured and simulated soil moisture data at different depths were compared. As is depicted in Figure 5.18 and Figure 5.19, the simulated soil moisture content agreed well with the measured values during the simulation period. As expected, the effect of leaching and irrigation on soil moisture content was most evident on field #1 at 20 cm and 50 cm depth. As for field #2, the simulated soil moisture at the deep layers (80 cm and 105 cm) was always at saturation, because the groundwater table was at these depths or even higher during the same time period (Figure 5.19). The upper layers of both fields (20 cm and 50 cm) were mostly under the influence of evapotranspiration processes, rather than precipitation. No tensiometers were installed in field #2, therefore a precise model calibration was not possible.

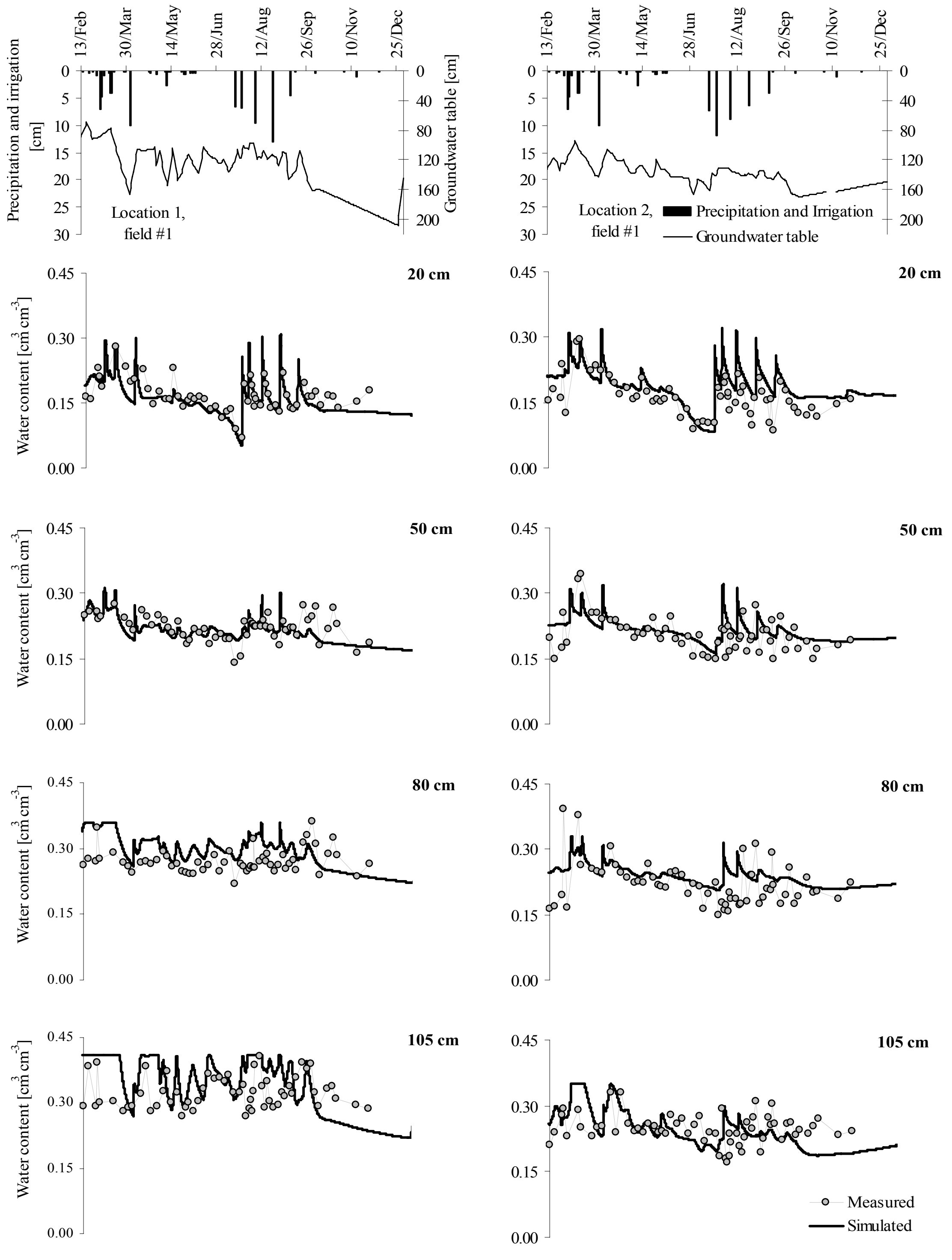


Figure 5.18 Comparison of measured and simulated soil moisture content at different depths of field #1 (locations 1 and 2) in 2003 under the given applied water (irrigation plus precipitation) and groundwater tables (upper two graphs)

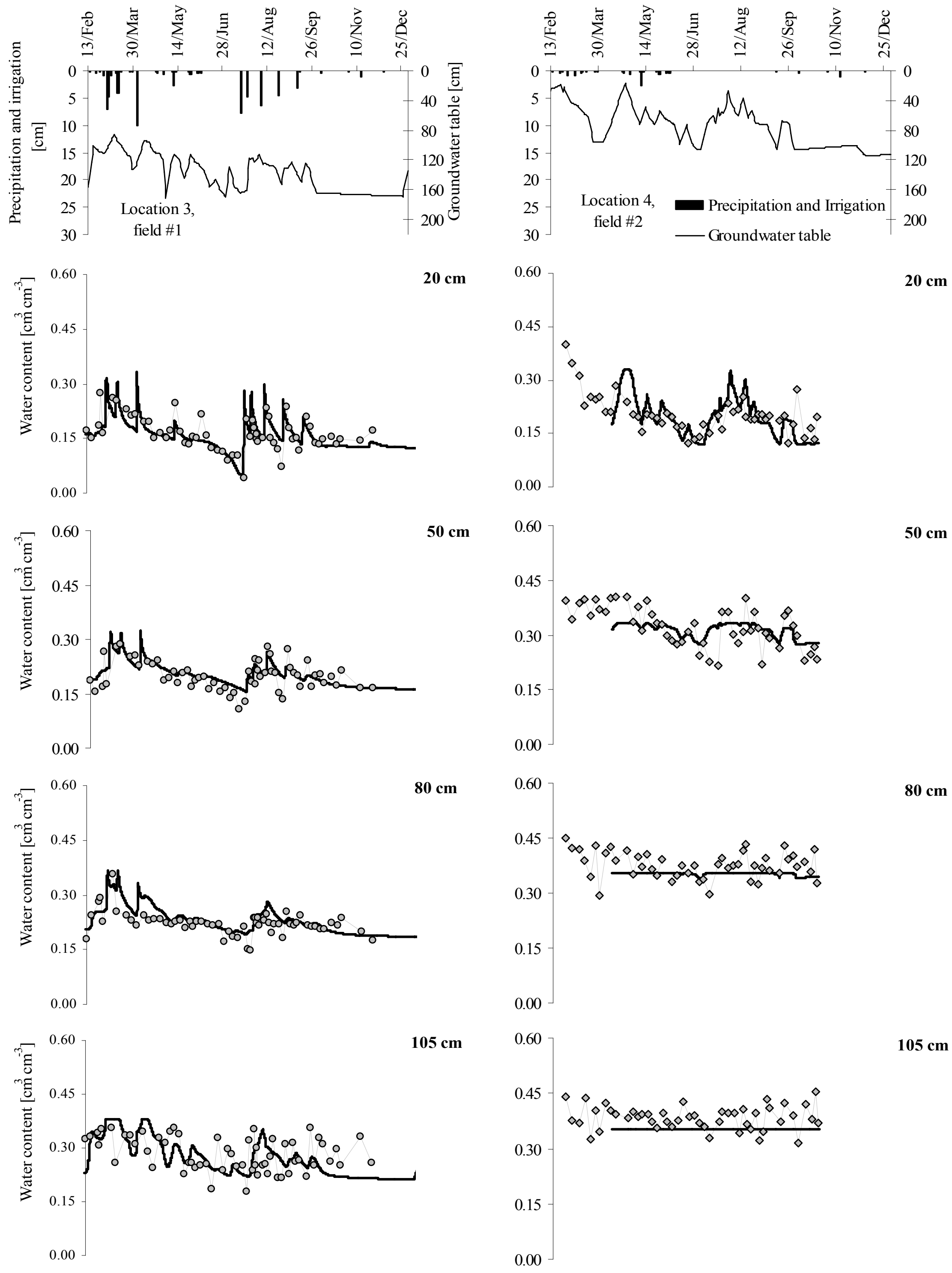


Figure 5.19 Comparison of measured and simulated soil moisture content at different depths of field #1 (location 3) and field #2 (location 4) in 2003 under given precipitations, applied water (not for field #2) and groundwater tables

To evaluate the differences between measured and simulated data, the *RMSE* was calculated (Table 5.8). It ranged between 0.026 and 0.068 $cm^3\ cm^{-3}$ with no clear influence of location or depth. The calibration results show that soil hydraulic properties and crop input parameters were determined accurately enough to simulate the water fluxes in the rooting zone of both cotton fields.

Table 5.8 Number of observations (N) and Root Mean Square Error (*RMSE*) of measured and simulated soil moisture θ [$cm^3\ cm^{-3}$] on the monitored fields in 2003

Horizon [cm]	Field #1, location 1 (beginning) (*Max. root length = 80 cm*)		Field #1, location 2 (middle) (*Max. root length =89 cm*)		Field #1, location 3 (end) (*Max. root length =75 cm*)		Field #2, location 4 (*Max. root length = 28 cm*)	
	N	*RMSE*	N	*RMSE*	N	*RMSE*	N	*RMSE*
20	59	0.035	62	0.043	60	0.042	21	0.042
50	59	0.026	62	0.035	60	0.026	21	0.035
80	59	0.047	62	0.050	60	0.028	21	0.044
105	59	0.068	62	0.045	60	0.056	21	0.034

Conversion factor for soil salinity

Shirokova et al. (2000) estimated the factor for converting soil salinity ($EC_{1:1}$) into electrical conductivity of the saturated soil extract (EC_e) for the whole Syr-Darya region to be 3.6. For the Khorezm region this coefficient was estimated as 3.5 (Shirokova, 2002), thus EC_e=3.5·$EC_{1:1}$ [$dS\ m^{-1}$]. To convert EC_e [$dS\ m^{-1}$] into *TDS* [$g\ l^{-1}$], a standard factor of 0.64 is generally used (Abrol et al., 1988). However, based on the laboratory data for this study, this factor is rather on average 0.82 for water salinity (Figure 5.20).

As for the soil, the factor 0.042 is used to convert EC_e [$dS\ m^{-1}$] into *TDS* [$g\ 100\ g^{-1}$ soil or %] (Figure 5.20). Further, knowing the bulk density and soil moisture content for a given date, *TDS* is converted into salt concentration (in $mg\ cm^{-3}$ water) and the latter data fed into the model.

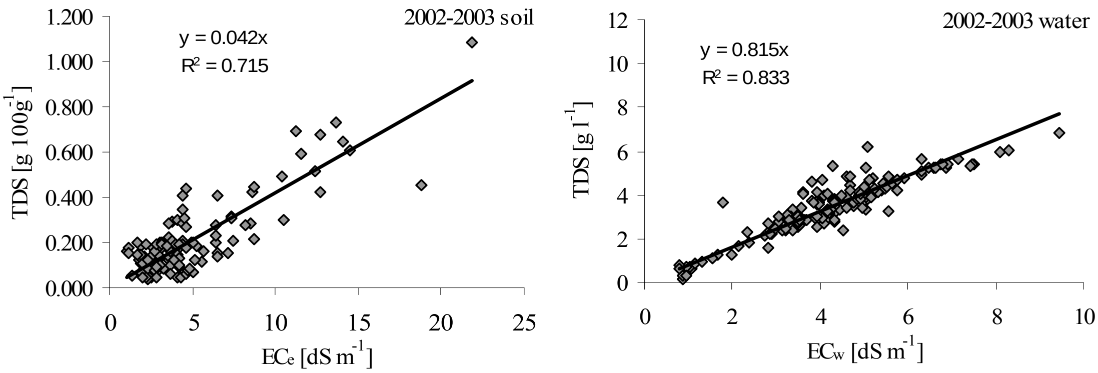


Figure 5.20 Plotting total dissolved solids *TDS* [g 100 g^{-1}] against electrical conductivity of the saturated extract EC_e [dS m^{-1}] and *TDS* [g l^{-1}] against *EC* of water EC_w [dS m^{-1}]

Components of water balance

Actual transpiration and actual evaporation, soil water storage in the rooting zone and water fluxes at maximum rooting depth were derived from the model results (Table 5.9). There was no runoff from the field surface during the simulation period, neither observed nor modeled.

During the vegetation season 2003 (25 April – 4 October) the amount of water applied to the different locations of field #1 was not equal. Total water inflow (P+I_{rr}) was highest at the beginning of the field (485 mm) and lowest at the end (364 mm), being 465 mm in the middle of the field. The actual evapotranspiration (sum of E_a and T_a) was higher than total water input (P+I_{rr}) at every location in the field, except location 2. On average 32 mm of water was depleted from the soil profile.

At the beginning and middle of field #1, 28 mm and 39 mm of water were lost via percolation out of the root zone, while at the end of the field there was an upward water movement of 16 mm from 25 April to 4 October. These variations are explained by the differences in the amounts and timing of applied irrigation water. At the beginning and middle of the field there was a slight over irrigation, which caused percolation, while at the end of the field under irrigation caused an upward movement of water.

Table 5.9 Seasonal and annual water balance (13 February to 31 December 2003 for field #1 and 10 April to 20 October 2003 for field #2). *P*=gross rainfall, I_{rr}=irrigation, T_a=actual crop transpiration, E_a=actual soil evaporation, ΔW=change in moisture storage (zero till maximum rooting depth), and Q_{bot}=fluxes at maximum rooting depth (positive values denote an upward movement of water)

Period	P [mm]	I_{rr} [mm]	Q_{bot} [mm]	T_a [mm]	E_a [mm]	ΔW [mm]
Field #1, location 1 (beginning), maximum rooting depth = 80 cm						
13 Feb–25 Apr, 2003	52	299	-272	0	113	-33
25 Apr – 4 Oct, 2003*	78	407	-28	382	111	-36
13 Feb–31 Dec, 2003	152	706	-298	382	259	-82
Field #1, location 2 (middle), maximum rooting depth = 89 cm						
13 Feb–25 Apr, 2003	52	299	-240	0	123	-12
25 Apr – 4 Oct, 2003*	78	387	-39	333	121	-29
13 Feb–31 Dec, 2003	152	686	-245	333	296	-36
Field #1, location 3 (end), maximum rooting depth = 75 cm						
13 Feb–25 Apr, 2003	52	299	-215	0	126	11
25 Apr – 4 Oct, 2003*	78	268	16	270	124	-33
13 Feb–31 Dec, 2003	152	567	-182	270	298	-31
Field #2, location 4, maximum rooting depth = 28 cm						
10 Apr –25 Apr, 2003	8	0	-51	0	10	49
25 Apr – 30 Sept, 2003*	78	0	4	81	53	-60
10 Apr –20 Oct, 2003**	108	0	-44	81	64	-9

* *planting till harvest of cotton;* ** *the beginning of winter wheat season is from 21 October*

In field #2, the soil water depletion during the vegetation period from 25 April to 30 September over the rooting zone of 28 cm was 60 mm. On this field, the reduction in transpiration (T_a versus T_{pot}) was 45 %, i.e., 100 mm, which was caused by a rapidly desiccating top-soil layer in combination with a shallow groundwater table, resulting in a poor cotton establishment under these unfavorable (waterlogged) conditions.

5.2.5 Subsoil water fluxes

One of the benefits of the model is that it is possibile to quantify the soil water fluxes at any defined depth and time. Figure 5.21 shows the time-depth domain of the water fluxes. The y-axis of the graph depicts the depth below the soil surface; the horizontal coordinate represents the time.

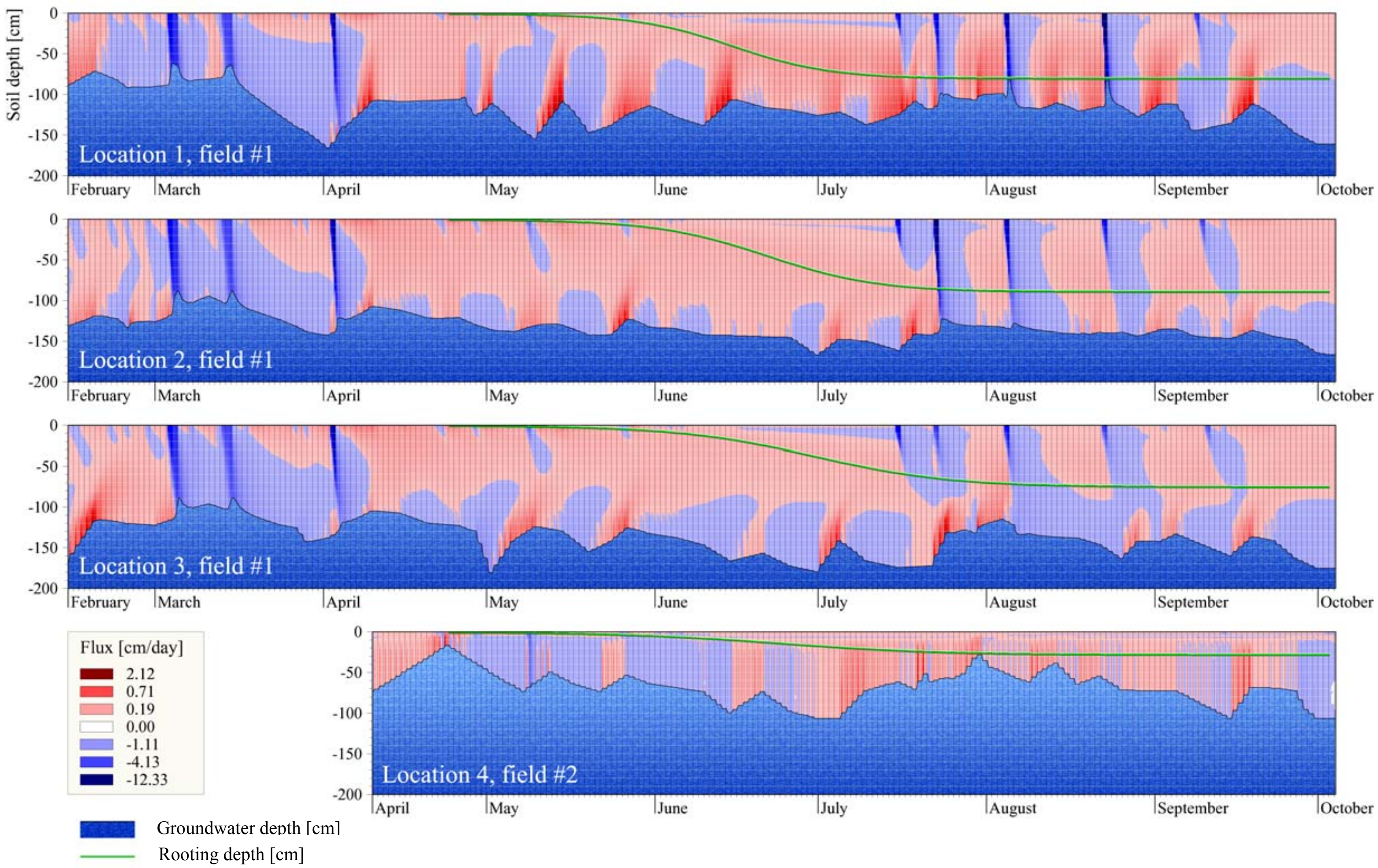


Figure 5.21 Vertical soil water fluxes in unsaturated-saturated zone at the monitored fields (2003). The x-axis represents time and the y-axis depth

On this graph, the days with high percolation fluxes and their variation with depth, as well as groundwater table fluctuations, can be identified. The negative values of fluxes represent downward water movements and the positive fluxes denote upward soil water flow. The soil water fluxes are typical for irrigated cotton fields, when the effect of leaching and irrigation events is evident with downward soil water movement. During periods of no water application, under high evaporative demands the direction of the water fluxes changes to an upward orientation, therefore, the fluxes sometimes become zero. The downward fluxes from the soil surface on field #2 refer to precipitation only.

Capillary rise and groundwater contribution to crop water consumption

The capillary rise of 277 mm, 129 mm and 92 mm in field #1 and 142 mm in field #2 indicate that there was considerable groundwater contribution to crop transpiration (Table 5.10).

Table 5.10 Sum of monthly soil water fluxes [mm] at maximum rooting depth on field #1 (simulation period from 13 February till 31 December 2003) and field #2 (simulation period from 10 April till 20 October 2003). Here q↓ and q↑ denote downward and upward water fluxes, respectively

Month	Field #1						Field #2	
	Location 1 (beginning) at 81 cm		Location 2 (middle) at 90 cm		Location 3 (end) at 76 cm		Location 4 at 29 cm	
	q↓	q↑	q↓	q↑	q↓	q↑	q↓	q↑
February	-16.6	20.0	-1.9	5.4	0.0	17.1		
March	-233.1	2.9	-195.9	1.5	-182.4	2.5		
April	-73.6	27.6	-61.7	12.2	-59.6	8.3	-11.5	28.5
May	-23.2	35.6	-0.4	15.8	-1.4	9.8	-40.0	8.0
June	-4.8	39.8	0.0	15.6	0.0	8.5	-13.5	8.1
July	-30.7	65.6	-58.7	18.4	-6.3	8.0	-4.9	50.6
August	-170.2	49.6	-55.6	10.3	-25.1	9.7	-13.4	29.2
September	-19.2	33.9	-0.2	14.0	-0.2	10.6	-11.4	17.4
October	-0.4	1.2	0.0	8.6	0.0	5.6	-3.0	0.3
November	-0.1	0.0	0.0	11.6	0.0	5.7		
December	-0.2	0.6	0.0	15.2	0.0	5.9		
ANNUAL	**-572**	**277**	**-374**	**129**	**-275**	**92**	**-98**	**142**

Moreover, the great heterogeneity of the results demonstrates that this contribution heavily depended upon the imposed irrigation management scheme. For the vegetation period (25 April–4 October) on field #1, the capillary rise constituted 229 mm, 77 mm and 49 mm at the beginning, middle and end of the field, respectively, and

115 mm on field #2. On field #2, observations showed that due to a shallow groundwater table cotton root growth was inhibited (maximum rooting depth of 28 cm) and yield was depressed due to reduced soil aeration.

The resulting groundwater contribution was compared to estimates based on the four different approaches most commonly applied in Uzbekistan (Table 5.11). The underlying equations are listed in Appendix 9.10. The difference among the proposed estimates of capillary rise from groundwater was sometime very large. One of the weaknesses of the empirical methods evidently is that they cannot provide a clear answer to the question of how much groundwater contributes to crop water demand. However, the modeled values for groundwater contribution are comparable with those from studies cited in the literature (Abdullaev, 1995; Yusupov et al., 1979).

Table 5.11 Groundwater contribution [mm] for crop growth during the vegetation season 2003 on the monitored fields according to Kats (1967), Kvan (1997), Harchenko (1975) and Harchenko-Laktaev-Horst (Djurabekov and Laktaev, 1983; Horst, 2001) and estimated with the HYDRUS-1D

		25 April – 4 October			25 April – 30 September
		Field #1, location 1	Field #1, location 2	Field #1, location 3	Field #2, location 4
This study		229	77	49	115
Kats		78	71	69	116
Kvan		115	105	90	64
Harchenko	E_p	48	41	38	-*
Harchenko-Laktaev-Horst					
	ET_a	347	287	193	-*
	ET_p	401	296	204	-*

* *no data on coefficients for sandy soil texture available in the literature*

5.3 Salt balance

Salt balance is the sum of all incoming and outgoing salts in a certain soil volume at a specified time (Hillel, 2004).

Solute transport

The solute transport and reaction parameters dispersivity (L_{dis}) and adsorption isotherm coefficient (k_d) were constraint to $1<L_{dis}\leq1000$ and $0<k_d<0.35$ following ranges given by the GSF- Forschungszentrum für Umwelt und Gesundheit (1982). The maximum k_d-values were taken for chloride ions, because the laboratory analysis revealed that they are dominating in the monitored soils. Optimized data for the solute transport simulation are presented in Table 5.12.

Table 5.12 Optimized dispersivity L_{dis} [cm] and adsorption isotherm coefficient k_d [$cm^3\ g^{-1}$] for the different soil layers of the monitored fields

	L_{dis}	k_d		L_{dis}	k_d
Field #1, location 1 (beginning)			**Field #1, location 3 (end)**		
0-10	414.6	0.2470	0-15	1.5	5.2E-005
10-35	15.1	6.9E-006	15-35	25.7	0.0064
35-60	92.1	0.0191	35-75	552.1	0.3200
60-95	70.8	0.0270	75-120	1.1	0.0282
95-120	49.5	0.1040	120-200	1.0	0.0194
120-200	1.0	0.1170			
Field #1, location 2 (middle)			**Field #2, location 4**		
0-11	274.5	0.0002	0-10	1.0	0.2009
11-26	643.7	0.3400	10-30	4.0	0.0058
26-45	349.5	0.1800	30-60	41.5	0.0283
45-85	805.6	0.0004	60-200	416.5	0.0506
85-135	2.0	0.0008			
135-200	430.5	0.3270			

The simulated soil salinity over the rooting zone for all four locations was in good agreement with the observed data for the first 20 cm soil depth (Figure 5.22 and Figure 5.23). At 50 cm, 80 cm and 105 cm depth, simulation results only poorly reflect the observed rapid salt fluctuations (*RMSE* equal to 0.39 to 3.23 dS m^{-1} for both fields), though the seasonal trend – desalination in response to leaching and slow re-salinization during the vegetation season – was correctly predicted by the model (Table 5.13). At the beginning of field #1, the highest amount of water was applied throughout the season. Consequently, at the end of the simulated period 18 t salts per hectare were leached from the rooting zone. Nevertheless, in the middle of the field (location 2), though in total less water was applied, also 18 t salts per hectare were leached. At the end of field #1, only 9 t of salts per hectare were leached due to lowest amount of applied irrigation water. In field #2, no irrigation water was applied, and at the end of the simulation period there was a slight salt accumulation of 0.3 t per hectare.

The farmer complained about the apparent highly saline middle part of field #1. The collected soil samples before leaching (13 February, 2003) confirmed this estimation. The mean electrical conductivity over the first 1-m profile in the middle of field #1 was equal to 5.8 dS m^{-1}, which corresponds to a medium saline soil, while at the beginning and at the end of the field it was 4.5 dS m^{-1} and 4.2 dS m^{-1} (medium saline soils), respectively. Based on his visual estimation during the leaching period, the farmer paid more attention to the middle part of field #1. Consequently, leaching the soil in the middle part of field #1 removed 17 t ha^{-1} of salts from the rooting zone of cotton, while at the beginning and end of the field this was 17 t ha^{-1} and 10 t ha^{-1}, respectively.

The soils of field #2 were not saline and thus, before planting, the average EC_e of the top 1-m soil profile was 1 dS m^{-1}. Although no water was applied to location 4, 1.0 t ha^{-1} of salts was leached from the cotton rooting zone during the vegetation season. The average EC_e for this period did not exceed 1.6 dS m^{-1}, and the soils can be classified as not saline according to the FAO-39 standards (Abrol et al., 1988).

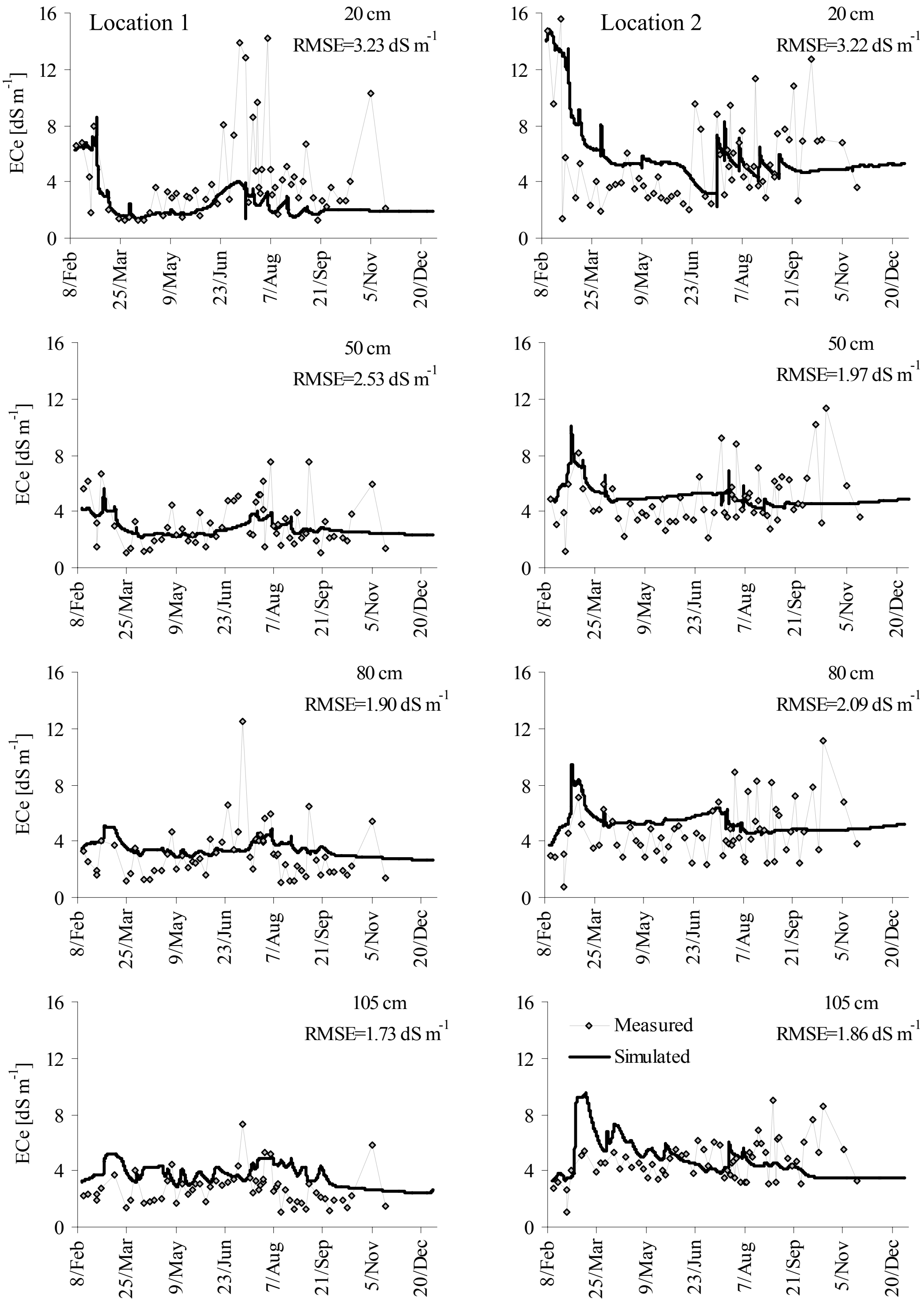


Figure 5.22 Comparison of measured and simulated soil salinity expressed as electrical conductivity of saturated extract (EC_e) at different depths of field #1 in 2003

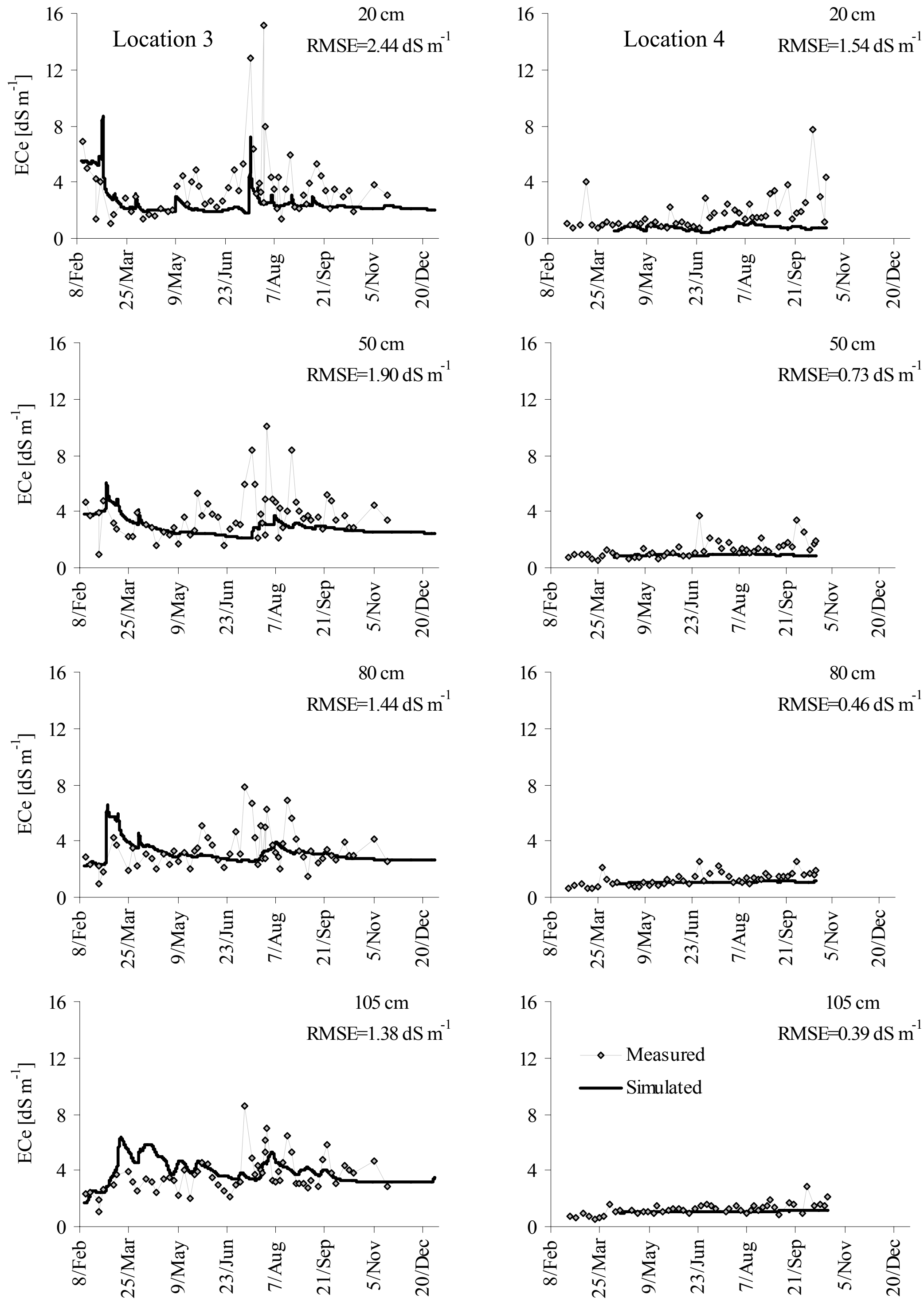


Figure 5.23 Comparison of measured and simulated soil salinity expressed as electrical conductivity of saturated extract (EC_e) at different depths in 2003 for field #1 (left side) and field #2 (right side)

Table 5.13 Computed seasonal salt balance [t ha^{-1}] considering the soil to maximum rooting depth on the monitored fields in 2003

Location	Time period	Input (via irrigation)	Output (via drainage)	Salt content in the profile*
Field #1, location 1	13 Feb – 25 Apr	3.9	-21.0	-17.1
Root depth=80 cm	25 Apr – 4 Oct	3.7	-3.5	+0.2
	13 Feb – 31 Dec	7.6	-25.4	-17.8
Field #1, location 2	13 Feb – 25 Apr	3.9	-21.1	-17.2
Root depth=89 cm	25 Apr – 4 Oct	3.3	-6.6	-3.3
	13 Feb – 31 Dec	7.3	-25.1	-17.8
Field #1, location 3	13 Feb – 25 Apr	3.9	-14.2	-10.3
Root depth=75 cm	25 Apr – 4 Oct	2.4	-3.5	-1.1
	13 Feb – 31 Dec	6.3	-15.6	-9.3
Field #2, location 4	10 Apr – 25 Apr	0.0	+1.3	+1.3
Root depth=28 cm	25 Apr – 30 Sept	0.0	-1.0	-1.0
	10 Apr – 20 Oct	0.0	+0.3	+0.3

* *- is leached; + is accumulated*

5.4 Model robustness

Water balance

After having simulated every location of both fields individually, the question was raised whether one could apply the model for the entire field based on calibration of one location. To answer this question, some additional simulations were carried out for field #1. Therefore, the soil hydraulic properties and solute transport and reaction parameters determined for the middle location of field #1 were used for the beginning and end locations. The applied water during leaching and irrigation, cotton *LAI* and maximum rooting depth, groundwater tables and their salinity, and initial conditions were kept location-specific. The resulting water balance did not differ significantly from the previous, location-specific water balance (Table 5.14).

Two fluxes are noteworthy: Firstly, the fluxes at the bottom of the rooting zone during the vegetation season of location 1 changed from slightly negative (-28 mm) to a slightly positive, i.e., upward movement (+7.5 mm). Secondly, at location 3 during the pre-planting period, more water drained, and thus overall the water content in the profile was now slightly depleted (-0.6 mm). The deviation between location-specific and generalized actual evapotranspiration (ET_a) constituted 6 % and 1 % for location 1 and location 3, respectively, over the vegetation period, while for the complete simulation period it was 9 % and 1 %, respectively.

Table 5.14 Water balance of locations 1 and 3 (field #1) based on location-specific soil hydraulic properties and generalized location 2 properties (2003)

	P [mm]	I_{rr} [mm]	Q_{bot} [mm]	T_a [mm]	E_a [mm]	ΔW [mm]	Q_{bot} [mm]	T_a [mm]	E_a [mm]	ΔW [mm]
Field #1, location 1			location-specific				generalized			
13.02-25.04	52	299	-272	0	113	-33	-257	0	123	-29
25.04-04.10	78	407	-28	382	111	-36	+7.5	390	132	-30
13.02-31.12	152	706	-298	382	259	-82	-229	390	309	-71
Field #1, location 3			location-specific				generalized			
13.02-25.04	52	299	-215	0	126	+11	-228	0	124	-0.6
25.04-04.10	78	268	+16	270	124	-33	+28	280	117	-24
13.02-31.12	152	567	-182	270	298	-31	-177	280	291	-29

The average groundwater contribution during the vegetation season for field #1 was estimated at 118 mm. Generalizing soil properties this was 113 mm (-4 %).

Salt balance

Differences in the salt content in the rooting zone of the cotton during the whole year determined with location-specific and generalized properties were in the range of 2-23 % (Table 5.15).

Table 5.15 Comparison of salt content in the rooting zone for field #1 based on location-specific soil hydraulic properties and on generalized location 2 properties (2003)

Period	Field #1, location 1		Field #1, location 3	
	location-specific	generalized	location-specific	generalized
13 Feb-25 Apr	-17.1	-13.3	-10.3	-10.9
25 Apr–4 Oct	+0.2	-0.5	-1.1	+0.8
13 Feb–31 Dec	-17.8	-13.7	-9.3	-9.5

Summarizing the above results: A rough estimation of the water and salt balance as well as groundwater contribution could be done by generalizing soil hydraulic properties. However, for precise estimation, location-specific soil hydraulic properties and solute transport parameters are needed.

Solute transport parameters

Typically, the longitudinal dispersivity, L_{dis}, under normal field conditions is supposed to range between 5 cm and 20 cm (Simunek, 2005, *personal communication*). Perrson et al. (2005) noted that L_{dis} is a difficult parameter to estimate and considerable research has been conducted to describe it for different soils under different conditions (see

Perrson et al., 2005 for details). The data on L_{dis} presented in the Table 5.12 were obtained by (inverse) parameter optimization, but the fitting procedure resulted in sometimes higher values than considered reasonable. However, these artificially high dispersivity values did not change the absolute level of simulated solute concentrations, but only shifted concentration peaks slightly in time (i.e., the lower the L_{dis} the faster the appearance of such peaks).

The adsorption isotherm coefficients, k_d, were also estimated by inverse simulation. As a result, the k_d-values changed considerably with depth (especially at location 2), despite any significant change in soil texture or bulk density that could trigger such changes. This seems implausible and therefore has to be seen as an optimization artifact. Since no laboratory studies have been done or were available on the estimation of k_d, for instance by so-called sequential batch experiments, parameter optimization by inverse modeling was the only viable alternative. The adsorbed and non-adsorbed fraction of salts in the profile for all locations at the beginning and end of the simulation run is shown in Table 5.16.

Table 5.16 Adsorbed and non-adsorbed fraction of salts [t ha^{-1}] in the cotton root zone on the monitored fields in 2003

Date	Field #1						Field #2	
	Location 1 (beginning) *Max. root depth 80 cm*		Location 2 (middle) *Max. root depth 89 cm*		Location 3 (end) *Max. root depth 75 cm*		Location 4 (field 2)* *Max. root depth 28 cm*	
	Adsorbed	Non-adsorbed	Adsorbed	Non-adsorbed	Adsorbed	Non-adsorbed	Adsorbed	Non-adsorbed
13 Feb	39.5	29.3	89.9	46.3	50.8	24.3	2.7	1.1
25 Apr	15.6	12.3	50.4	29.2	31.2	14.0	3.8	2.3
4 Oct	16.2	12.4	48.3	25.9	34.6	12.8	2.6	1.3
31 Dec	16.3	11.6	52.8	28.6	36.4	15.0	2.5	1.4

* *for this location: 10 April; 25 April; 30 September; 20 October*

Table 5.16 shows that the adsorbed fraction of salts is as dynamic as the soluble (non-adsorbed) fraction and also the decrease of adsorbed and non-adsorbed salts in the cotton root zone after the leaching activities (held in March 2003). Thus, the amount of adsorbed salts after leaching in field #1 decreased to about 40 %, 56 % and 61 % of the initial value at the locations 1, 2 and 3, respectively, while the decrease of non-adsorbed salts constituted 42 %, 63 % and 58 % for the same locations. For field #2 there is no information about soil salinity before leaching, and no measurements of applied water for leaching were available, therefore these results are not discussed here.

After planting till harvesting, the amounts of adsorbed and non-adsorbed salts did not change significantly and remained almost constant during this period. In general, there is a clear trend of soil desalinization from April till December 2003.

Generally, in simulations of salt balances, a mass balance error of less than 5 % is a reasonable target, when there are no inconsistencies or sudden change in initial and boundary conditions (Alberta Environment, 2003). A comparison of mass balance errors given for the simulated 200 cm domain show that the simulations matched this target (Table 5.17).

Table 5.17 Overall mass balance [t ha^{-1}] for simulated domain of 200 cm of the monitored fields (2003)

Period	Mass		Difference	Solute flux "in"	Solute flux "out"	Difference	Mass balance error [%]
	beginning of simulation	end of simulation					
Field #1, location 1 (beginning)							
13 Feb – 25 Apr	73.8	60.5	13.3	4.0	17.5	13.5	2.0
25 Apr – 4 Oct	60.5	59.1	1.4	3.7	5.3	1.6	2.0
13 Feb – 31 Dec	73.8	56.7	17.1	7.7	25.3	17.6	5.0
Field #1, location 2 (middle)							
13 Feb – 25 Apr	151.5	130.5	21.0	4.0	25.2	21.2	2.0
25 Apr – 4 Oct	130.5	115.8	14.7	3.4	18.4	15.0	3.0
13 Feb – 31 Dec	151.5	116.1	35.4	7.4	43.2	35.8	4.0
Field #1, location 3 (end)							
13 Feb – 25 Apr	70.8	66.7	4.1	4.0	8.2	4.2	1.0
25 Apr – 4 Oct	66.7	66.5	0.2	2.4	2.6	0.2	0.0
13 Feb – 31 Dec	70.8	66.5	4.3	6.4	10.8	4.4	1.0
Field #2, location 4							
10 Apr – 25 Apr	16.1	17.5	-1.4	0.0	-1.4	-1.4	0.0
25 Apr – 30 Sept	17.5	17.9	-0.4	0.0	-0.4	-0.4	0.0
10 Apr – 20 Oct	16.1	17.7	-1.6	0.0	-1.6	-1.6	0.0

The mass balance error for the rooting zone at each location for the vegetation season was also below 5 % with exception of location 2 where this was 8 %. However, in the mass balance error, all salts, comprising those in the sorbed as well as soluble phase, are included. Yet for the comparison of simulated and observed salts (Figure 5.22 and Figure 5.23) and for salt balance estimation only soluble salts were considered, because the EC_e was measured in a 1:1 soil-water paste and correlated with *TDS* measurements, which do not cover adsorbed salts.

5.5 Leaching

In Figure 5.24, soil salinity in the upper 60 cm soil profile before and after leaching is presented. Before leaching on 28 February 2003, the average soil salinity in field #1 was 4.6 dS m^{-1}, which is classified as medium saline according to Abrol et al. (1988), while after leaching activities the salinity decreased to 2 dS m^{-1}. Thus, just before planting, the soil was classified as slightly saline, i.e., reasonably suitable for cotton germination.

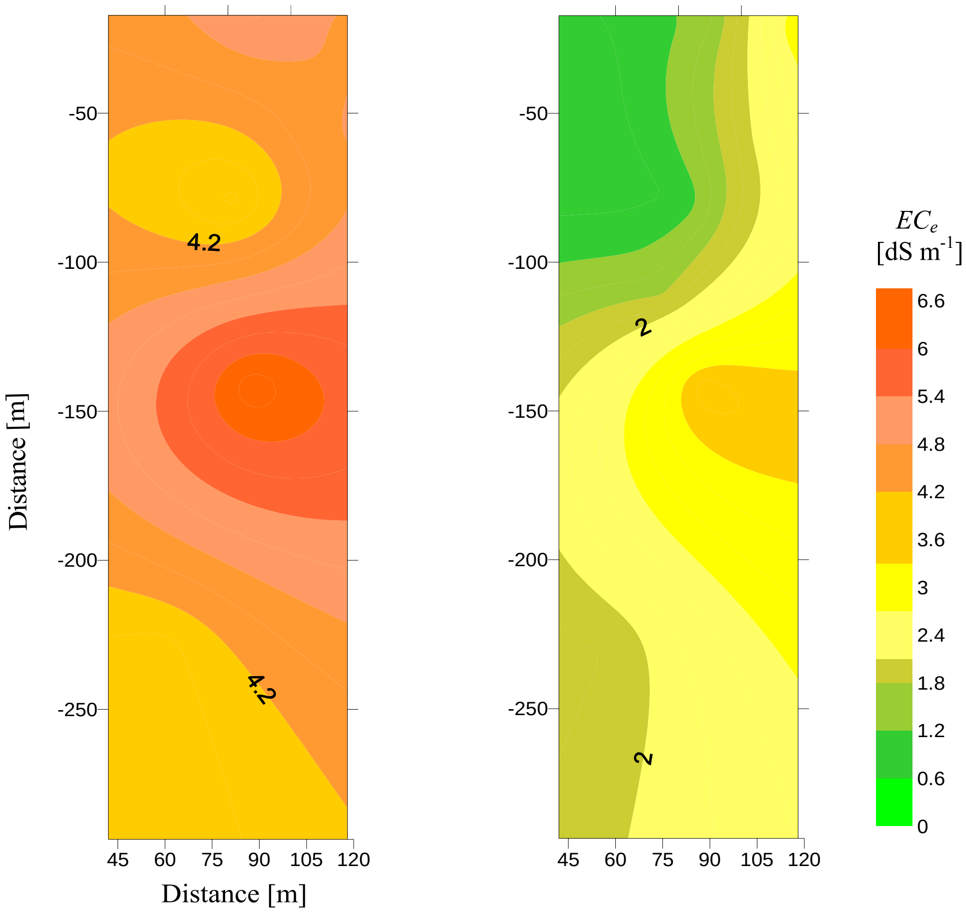


Figure 5.24 Soil salinity in the top 60 cm soil layer of field #1 before leaching, 28 February 2003 (left), and after leaching, 11 April 2003 (right) (based on 26 sampling points)

To manage the soil salinity, it is important to understand the relationship between leaching fraction and root zone salinity. The leaching requirement (*LR*) (Equation 4.19) is the minimum leaching fraction at which a crop can develop without yield losses (Hoffman and Hall, 1996). The *LR* must be satisfied to prevent salt accumulation (Ayers and Westcot, 1985). In the monitored fields, applied irrigation water had an average electrical conductivity of 1.04 dS m^{-1}. According to the quality ranking of Bauder et al. (2005), this refers to Class 3 and is classified as "permissible" for irrigation, but leaching is compulsory. The *LR* for the local conditions is 0.03. This means that 3 % more irrigation water has to be applied to achieve a yield potential of 100 %. As mentioned by Ayers and Wescot (1985), when LR<0.10 and water quality is good, "inefficiencies in irrigation water application will almost always apply sufficient extra water to accomplish leaching". In other cases, when the water salinity is higher, meeting the *LR* might be difficult, as it requires large amounts of water and, in case of poor drainage, will lead to water outflow problems. According to some authors, an appreciable portion of water might be lost by deep percolation during normal irrigation to control salinity in the rooting zone (Ayers and Westcot, 1985; Tanji and Kielen, 2002).

The actual amount of water (*AW*) to be applied in the field to supply crop evapotranspiration (ET_c) and leaching can be determined by Equation 4.20. For field #1, potential ET_c=662 mm (average of 3 locations) and, therefore, at least 679 mm of irrigation water should be applied. However, during the vegetation season on average 354 mm of irrigation water was applied, which does not satisfy the before-mentioned demand, even considering that ET_c was *actually* 215 mm lower than the potential ET_c. The required irrigation water in this case would be 460 mm. However, in the proposed equations the capillary rise of groundwater is not taken into account.

The groundwater contribution in field #1 was on average 118 mm. With this water, additional salts were moved into the root zone, which had to be leached. Assuming the same salt concentration as for irrigation water, an additional 121 mm of leaching water would be needed to satisfy the leaching requirements as stated above. On the other hand, during the pre-season leaching of the field in spring, an additional 300 mm of water was applied. As such, the applied water (in total: 654 mm) lies above the necessary amounts (581 mm) for maintaining an acceptable soil salinity regime for cotton.

5.6 2002 versus 2003

The model was applied only for 2003 data due to an incomplete data set in 2002. The 2002 year was more a period of getting to know the local conditions, collecting general information about fields, soil texture and soil chemical composition. However, in 2002 some limited information about applied irrigation water, groundwater dynamics and salinity, as well as soil salinity and cotton yields was collected. Below, some measurements for the two years were compared to identify what and to which extent changes during the two years of monitoring had occurred.

The average air temperature during the vegetation season was higher in 2002 and precipitation lower than in 2003 (23.2ºC vs 21.9ºC and 75 mm vs 172 mm). After cotton planting, there was heavy rainfall (53 mm) in May 2003, and air temperature decreased, which entailed serious consequences for cotton development and yield. May 2002 was exceptionally dry.

On field #1 during the vegetation season 2003, on average both the groundwater table and salinity were lower than in 2002. On field #2, the average groundwater table and salinity were equal in both years, except for July and August 2003. During these two months, the groundwater table on average was at 70 cm and 55 cm, respectively (Table 5.18).

Table 5.18 Average groundwater table (*GWT*) and salinity (EC_{gw}), and average soil salinity (EC_e) measured in 1m-depth soil profile in 2002 and 2003 on the monitored fields

	June	July	August	September	October
Field #1					
GWT [cm]					
2002	126	127	110	121	147
2003	142	137	129	136	170
EC_{gw} [dS m^{-1}]					
2002	5.6	5.6	5.5	5.3	5.1
2003	5.3	4.5	4.7	5.3	5.1
EC_e [dS m^{-1}]					
2002	3.9	3.9	6.7	8.7	-
2003	3.6	5.0	4.0	3.9	4.4
Field #2					
GWT [cm]					
2002	58	75	100	84	101
2003	93	70	55	82	104
EC_{gw} [dS m^{-1}]					
2002	3.4	3.4	3.0	2.9	-
2003	2.6	3.2	3.0	3.3	3.0
EC_e [dS m^{-1}]					
2002	1.7	1.4	1.6	2.6	-
2003	1.1	1.8	1.4	1.7	2.4

In response to irrigation on field #2 on 29 July 2003, the groundwater table raised temporarily to a minimum of 30 cm below the surface. During the same period in 2002, the groundwater table was at about 100 cm depth. The salinity of the groundwater (Table 5.18) for both fields did not differ significantly in 2002 and 2003, except for July-August 2003 on field #1. On both fields, the average soil salinity during the vegetation period was higher in 2002 than in 2003. The comparison of soil salinity in the rooting zone during the vegetation period in 2002 and 2003 (Figure 5.25) revealed higher soil salinity in 2002.

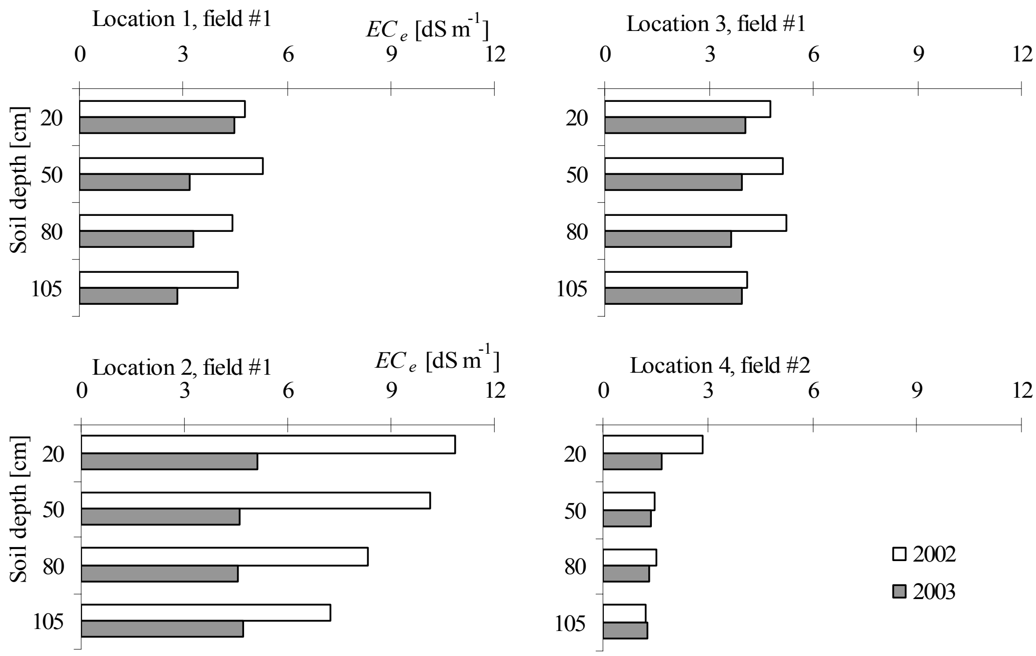


Figure 5.25 Observed electrical conductivity of soil saturated extract [dS m^{-1}] from the monitored fields in 2002 and 2003 (average for period April-October)

At location 2 (field #1), the average soil salinity in the 1-m soil profile was 9.1 dS m^{-1} (highly saline) in 2002 and 4.8 dS m^{-1} (medium saline) in 2003. At locations 1 and 3, the soil salinity changed from medium saline in 2002 to slightly saline in 2003. In field #2, the soil was not saline (average EC_e of 1.7 dS m^{-1} in 2002 and 1.8 dS m^{-1} in 2003). The high soil salinity in field #1 in 2002 as compared to 2003 is explained by less applied irrigation water (236 mm in 2002 versus 372 mm in 2003) coupled with a higher groundwater table and groundwater salinity. The average air temperature was also higher, while the amount of precipitation was lower in 2002 than in 2003. Table

5.19 compares the soil salinity changes at the beginning and in the end of each vegetation season.

Table 5.19 Observed electrical conductivity of soil saturated extract (EC_e) [dS m^{-1}] for the beginning and end of the vegetation season in 2002-2004 on the monitored fields

Date	Field #1			Field #2
	Location 1	Location 2	Location 3	Location 4
2002				
12 June	4.3	4.2	4.1	1.8
21 September	6.0	14.8	12.1	3.5
2003				
10 June	3.2	4.6	3.4	1.0
23 September	2.7	6.8	4.4	1.7
2004*				
1 June	1.9	3.5	2.1	-

* *Soil salinity data for 2004 were collected by the field team two times per month as requested by researcher*

According to the observed data, there is a seasonal salt accumulation in the 1-m soil profile at all locations except location 1 in 2003, where the soil salinity decreased by the end of the vegetation season. However, in 2003 at locations 2, 3 and 4, due to precipitation in autumn-winter, by the end of the year the salt content in 1-m soil profile decreased (see Chapter 5). Soil salinity in the early stages (e.g., June) of cotton development tended to decrease from year to year, i.e., there was a desalinization of the soil profile.

In spite of the fact that more water was applied in the 2003 vegetation season, and soil salinity was lower in the 1-m profile for this year, the cotton yield decreased from 3 t ha^{-1} in 2002 to 1.7 t ha^{-1} in 2003 on field #1 and from 1.6 t ha^{-1} to 0.08 t ha^{-1} on field #2, respectively. Consequently, neither did water application by irrigation nor groundwater and soil salinity significantly influence yields. Therefore, other factors were obviously influencing yields. These could have been: lower temperatures in 2003 than in 2002 during the cotton growth season, heavy precipitation in May 2003, the lower groundwater table and consequently lower groundwater contribution to the crop water demands, and no mechanical weeding (by tractor) after irrigation in 2003. Interestingly, in field #2 (sandy soil) in 2002 without any irrigation the cotton yield was 1.6 t ha^{-1}. But this is not a new phenomena. According to research conducted by the Uzbek Scientific Cotton Research Institute in Khorezm (Kurambaev, 1969), without irrigation cotton yields still might reach 2.7-3.7 t ha^{-1} when the groundwater table is at 1-1.2 m depth and only slightly saline. In 2002, farmers reported that due to a shortage of irrigation water in 2000 and 2001, field #2 was used as a pasture for cattle and sheep. The input of manure from these animals might have positively influenced the 2002 cotton yield. On the other hand, in 2003 fertilization was not done effectively, i.e., fertilizer was applied but the field was not irrigated. Also, the groundwater table was shallower than in 2002, which caused anaerobic conditions and hampered the development and function of the cotton root system.

6 GENERAL DISCUSSION

6.1 General methodology

A number of authors indicate that a precise knowledge of soil hydraulic properties is necessary for many soil-water related studies such as the determination of plant-available water, infiltration, drainage, irrigation, plant water stress, and water and solute transport (Butters and Duchateau, 2002; Kern, 1995; Rajkai et al., 2004; Saxton et al., 1986; van Dam et al., 2004).

HYDRUS-1D is one of the various numerical codes that has been developed for identifying the soil hydraulic and solute transport parameters from unsaturated flow and transport data in one-dimensional porous media. The soil water fluxes are calculated by the standard Richards equation. There are several descriptions of the relationship between soil-water potential and water content: Brooks and Corey (1964), van Genuchten (1980) and Vogel and Cislerová (1988). In the present study, the standard Mualem-van Genuchten hydraulic model (see Equations 4.4 and 4.5) with an air entry value of -2 cm was applied, but no attempt was made to use the extended, so-called "modified van Genuchten model". This seems justifiable, as Butters and Duchateau (2002) pointed out that there are only slight differences between the two models. To describe the solute flow in the unsaturated zone, the convection-dispersion equation (CDE) was used. Therewith, as mentioned by Hopmans et al. (2002), depending and relying on soil water retention and unsaturated hydraulic conductivity data, an adequate hydrological description of water flow and solute transport in the vadose zone can be derived. Besides, selected boundary conditions and the root water uptake function effect the results. The influences of the above-mentioned parameters on the results of the conducted research are discussed below.

6.2 Direct and inverse optimization of soil hydraulic properties and solute transport parameters

Several methods exist for directly measuring soil water retention curves and hydraulic conductivity functions. Unfortunately, it is generally concluded that direct measurement of $K(h)$ and $\theta(h)$ is typically time consuming, expensive, difficult and impractical (Dirksen, 2001; Klute, 1986a). Thus, for many purposes general estimates based on easily available information such as soil texture and bulk density (Saxton et al., 1986) will suffice. In order to indirectly estimate the hydraulic properties from more easily obtainable data, many authors rely on pedotransfer functions (PTF; Kern, 1995; Schaap et al., 1998). The term "pedotransfer function" was introduced by Bouma (1989). In some models, such as the RETC (RETention Curve) model by van Genuchten et al. (1991), measured water retention data are used to predict the entire soil moisture curve.

In this study, soil hydraulic parameters were predicted from basic soil data (texture and bulk density) for every soil layer using Rosetta Lite Version 1.1 (Schaap et al., 2001), which implements PTFs. Then the soil hydraulic properties were optimized based on the pressure head readings and soil moisture measurements. Gijsman et al. (2002) reviewed eight methods for estimating water retention parameters and concluded that precise texture data for each soil layer are needed to parameterize a model. They also found that for very sandy soils there was no well performing method for estimation of water retention parameters. In the present study, water retention curves were determined in the laboratory, but not used in the inverse procedure. It is well known that the "field capacity" and "wilting point" determined in the laboratory may be very different from what the plants experience in the field (Gijsman et al., 2002; Hopmans et al., 2002; Ratliff et al., 1983). Ratliff et al. (1983) suggest that in order to insure accuracy of water balance calculations, to use field-measured soil water limits rather than lab-measured.

Although the inverse modeling approach is good for estimating unsaturated hydraulic conductivity functions (Hopmans et al., 2002), there is a problematic limitation of this approach, as mention by Butters and Duchateau (2002). This limitation is the lack of reliability near saturation, particularly with respect to fitting values for the saturated hydraulic conductivity (K_s). In addition, the authors point out that differences between a set of inversely estimated $K(h)$ and $\theta(h)$ might occur in response to the measured range of soil water pressure and the hydraulic property function selected for the soil. Nevertheless, the inverse approach is becoming popular because it is a powerful tool for estimation of unsaturated flow properties that can be applied instead of laborious direct measurements. Successful application of the inverse modeling improves the speed and accuracy of the estimated parameters (Butters and Duchateau, 2002; Hopmans et al., 2002; Kodesova, 2003; Simunek et al., 1998b).

In the current research, it was essential to be able to inversely estimate the soil hydraulic properties, because direct field and laboratory experiments could not be conducted due to a lack of (automatic) equipment. Furthermore, the laboratory-determined soil water retention curves could not be used, because in some cases they showed highly unrealistic patterns (see Figure 5.14 A and B), which questioned the reliability of the entire laboratory data set. Furthermore, an initial model test run with the laboratory-determined *pF*-curves completely failed to mimic the observed soil moisture (results not shown).

In most studies, the adsorption isotherm coefficient k_d is set equal to zero (Tischbein, 2005, *personal communication*). In the present study, these values were inversely optimized in the model and restricted to a maximum value of 0.35 [cm^3 g^{-1}] based on information from GSF (1982), because no other information for chloride adsorption isotherm coefficients was found in the literature. Results of inverse optimization showed that for some soil layers the values of k_d were surprisingly close to the maximum value of 0.35 (Table 5.12) with only slight changes in soil texture and bulk density (Table 5.1 and Figure 5.2). In general, one can assume that k_d values that are set to zero and artificially high values computed by inverse simulation cannot be correct. Because the first case (k_d=0) is applicable for tracer experiments (Simunek, 2004, *personal communication*), the second case (high k_d) influences the value of the adsorbed salts fraction (Table 5.16). However, in the present study no experiments were conducted to estimate the adsorption isotherm coefficient, therefore even high values of inversely simulated k_d were accepted for further simulations. It is worthwhile to conduct sequential batch experiments for estimating solute transport parameters for the soils of the region with chloride and chloride-sulphate types of salinity for further improvement of solute transport simulations.

6.3 Boundary conditions

Lower boundaries

Meiwirth and Mermoud (2004) showed that a correct simulation of water flow highly depends on a realistic definition of the lower boundary conditions. The soil moisture in the lower layers, for instance, is highly driven by the lower boundary conditions.

The groundwater table was used as the lower boundary condition throughout present study. It greatly influenced the soil pressure head values at 105 cm depth, which were underestimated by the model. The attempt to manually increase the values of K_s resulted in increased simulated soil pressure heads, while at the same time increasing soil moisture at the respective depths, which mismatched observations. Lowering the groundwater table in the simulations allowed matching the observed and modeled pressure heads, which, however, lead to an underestimation of soil moisture. Nevertheless, all those changes were done manually and no simultaneous measurements of soil moisture and pressure head in the field were taken for verification. Also, the effect of soil hysteresis was not considered in the simulations as no data could be measured to underpin subsequently necessary calibrations. In view of these restrictions, no further attempts were made to improve the simulated pressure heads for the benefit of keeping well-matching soil moisture simulation.

There were some discrepancies of simulated and observed soil moisture in the lower layers. This was probably the consequence of temporarily unrealistic lower boundary values due to an improper functioning of the observation wells. These would not mark out the rapid changes in groundwater tables during days of strong influence of lateral groundwater movement triggered by the neighboring, frequently irrigated, winter wheat and sunflower fields. Yusupov et al. (1979) in their work also mentioned that the groundwater table changed rapidly with the change of the water level in the irrigation canal or drain that generated a hydrodynamic pressure.

It is generally difficult to avoid artificial groundwater tables when observation wells are used. Rather than digging a ~10 cm-diameter hole and thus allowing a hydrodynamic pressure to build up (as outlined above), one could using tensiometers, which are much smaller in diameter and thus could prevent these disturbances. Another option is to install a network of observation wells of various depths and thus provide information about different layers with large differences with respect to hydraulic conductivity. More detailed analysis is necessary to come to final conclusions and recommendations in this regard.

Upper boundaries

The atmospheric boundary conditions with a potential surface layer were selected as the upper boundary in the present study. These conditions allow water to build up on the surface in response to precipitation or irrigation. Subsequently, this water layer reduces due to infiltration or evaporation. To calculate the net precipitation infiltrating the soil, in HYDRUS-1D the potential evaporation is subtracted from precipitation. HYDRUS-1D evapotranspires the full amount of E and T as provided in the input file and lowers ET in case of water scarcity according to the Feddes function. By doing so, Scanlon et al. (2002) found out that HYDRUS-1D overestimated evaporation and underestimated soil water storage as compared to other models. In fact, none of the numerical codes could accurately predict the field-measured fluxes. Since there were no direct measurements of actual evapotranspiration of cotton throughout the study, the above-mentioned conclusions were neither justified nor rejected.

Problems with ET_c calculation

In this study, the actual transpiration was calculated by the methodology proposed in the FAO-56 paper, using the cotton LAI data to adapt ET to local conditions. Due to a high number of weeds in both fields (with biomass equal or sometimes even exceeding cotton biomass), it was decided to account for this extra (weed) transpiration via the LAI of cotton. For this, the LAI of cotton was doubled (on field #1) and tripled (on field #2) to comprise the cotton and weed leaf area. It remains unclear to what extent this approximation reflects real conditions due to a lack of data on weed phenology and rooting depth. On the other hand, weed growth started together with cotton growth implying a certain phenological synchronization of both weed and cotton. Nevertheless, in future modeling either detailed phenological observations of both species have to be included or weeds have to be extinguished by herbicides or repeated weeding. The latter, however, does not fully reflect reality, as weed-free cotton fields are not the norm in Khorezm.

The current study revealed discrepancies between potential and actual transpiration (T), especially in the initial phase of cotton development, which were caused by water stress. Immediately after the first irrigation (field #1), actual T approached potential T (Figure 5.11). Further slight discrepancies during the vegetation season were caused by minor water stress because of rapid desiccation in the top 10-cm soil. Measured and calculated topsoil (~20 cm) water contents compare reasonably well with some discrepancies (Figure 5.18 and Figure 5.19), which could be due to several reasons: as it dried, the soil of field #1 after heavy rain or water application became very hard, formed a crust and finally partly cracked. Subsequent irrigation water by-passed the first centimeters of the soil via these cracks and infiltrated immediately into the subsequent soil layer. Bypassing flow is not considered in the HYDRUS-1D code, which might lead to differences between observed and modeled topsoil moisture. Furthermore, it is clear that the "wetting" soil hydraulic properties may be different from "drying" properties due to the effect of hysteresis, which was not included during the simulations. Kelleners et al. (2005) note that the vapor flow is not included in HYDRUS-1D, which they assumed "could be the main driving force behind the drying of the topsoil".

6.4 Root water uptake in saline soils

In the current research, the measured rooting depth changed along the fields. Thus, at the beginning, middle and end of field #1 it was 80 cm, 89 cm and 75 cm, respectively. In field #2 it was only 28 cm. Calibrating the root growth routine of HYDRUS-1D, it was possible to match observed root depth. Root distribution plays an important role in soil moisture redistribution in the profile, as plant root systems can adapt to a great extent to changes in availability of water and nutrients and chemical properties in soils (Feddes et al., 2001). Root water uptake representing the sink term in the Richards equation (see section 4.4) is a key component for analyzing the changes in soil moisture. It depends on soil water availability and salinity. The extraction rate by roots is smaller near the top of the soil profile and increases downward to a certain maximum rate and decreases to zero at the bottom of the rooting zone (Feddes and Raats, 2004). Root water uptake decreases if the concentration of the soluble salts exceeds plant-specific threshold values, especially in periods of water stress (Homaee, 2004; Homaee et al., 2002; Sheldon et al., 2004). Cotton is a salt tolerant crop, being sensitive only during the early growth stages (Rhoades et al., 1992). Therefore, pre-planting irrigation plays an important role in maintaining low soil salinity during the early stages of crop development (Coelho et al., 2003).

Influence of soil water and salinity stress on cotton yield

Many studies have been conducted for different crops and climates, which have identified that under conditions of soil water deficit as well as salt stress, there is a linear dependence of relative yield ($Y_{actual} / Y_{potential}$) on relative transpiration ($T_{actual} / T_{potential}$). Shani and Dudley (2001), for instance, attempted to quantify the effect of simultaneously imposed water and salinity stress on yields of corn, melon and alfalfa grown in Israel and USA. Their findings demonstrated that under deficit irrigation, even when salt accumulation is noticeable, there is no salinity effect on crop yield. Dudley and Shani (2003) hypothesized that the effects of water and salt are not equal or additive and that joint stresses are best computed by multiplication of water stress with salinity stress. However, Homaee (2002) concluded from his experiments on root water uptake that the multiplicative solute stress model underestimated the actual transpiration and, moreover, that neither the multiplicative nor the additive reduction functions could accurately reproduce the experimental data. In the current research, the model output using the additive reduction function showed 1 % lower values for actual transpiration than the multiplicative reduction function. Thus, differences were negligible under the given moderately saline soil conditions. When extending simulation with the current model settings to conditions of high salinity, however, a new cross checking of both methods is inevitable.

Also, in Uzbekistan some authors (Gidrometioizdat, 1976; Ryjov, 1973; Ryjov and Zimina, 1971) attempted to establish a relationship between salinity stress and cotton growth and yields and cotton yield reduction in response to different soil solution salinity. Shirokova and Morozov (2002) estimated the effect of a combined osmotic and matric pressure on cotton yield (Figure 6.1). They found that for the period from cotton planting till budding, cotton yield decreased due to the combined soil matric and osmotic pressure starting from 0.6 MPa. Above 1.0 MPa, cotton yields were close to zero. A similar trend was observed for the period from budding till harvest, whereas yield decreased less drastically and approached zero only above 1.5 MPa. In the current research, high pressure heads (h) of 10.6-14.9 MPa were simulated to occur in the top 20 cm soil layer before first irrigation on 16 July 2003, gradually decreasing with increasing soil depth to 0.07-0.09 MPa at 105 cm. By 16 July, the cotton roots already had reached 55-70 cm and water stress in the top 20 cm could not restrict the overall root water uptake by cotton plants. According to the simulated soil salinity for the 1-m profile, there was no salinity stress for cotton (EC_e always smaller than 7.7 dS m^{-1}), with the exception of the middle location on field #1, when during two days (22-23 July 2003) at 20 cm depth the EC_e was slightly higher (up to 8.3 dS m^{-1}) than the salinity threshold level of cotton (Figure 5.22).

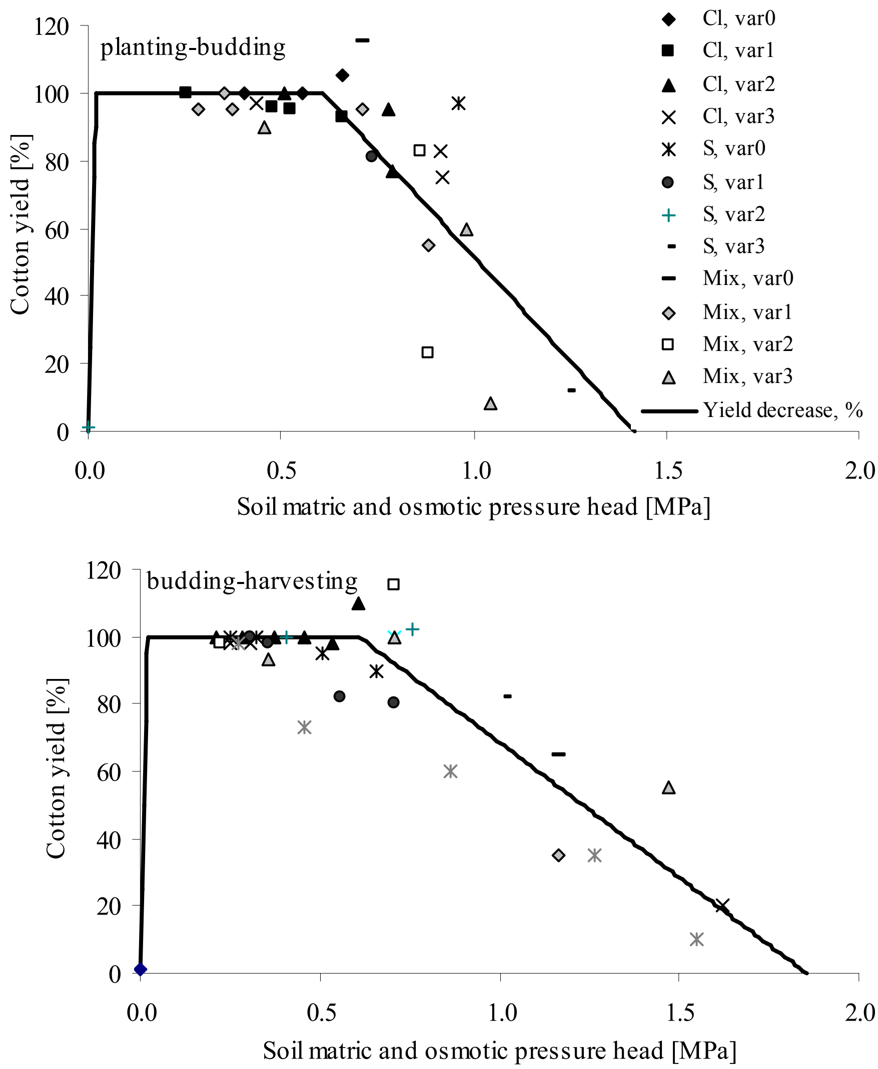


Figure 6.1 Cotton yield decrease as a function of soil salinity in the Tashkent region on medium loam soils (1968-1970). Here *Cl* = chloride type of soil salinity, *S* = sulphate, Mix = mixed *Cl-S* and *S-Cl*; var0: variant with no fertilization, var1: $N = 3$, $P_2O_5 = 2$, $K_2O = 1.5$ g/container; var1: $N = 5$, $P_2O_5 = 3$, $K_2O = 2.5$ g/container; var2: $N = 7$, $P_2O_5 = 5$, $K_2O = 3.5$ g/container (for more details see Gidrometioizdat, 1976; Ryjov, 1973; Ryjov and Zimina, 1971; Shirokova and Morozov, 2002)

However, the model did not follow the rapid change in soil salinity dynamics. When judging soil salinity in the soil profile based on field measurements, it can be seen that soil salinity at the middle location of field #1 is higher than at the beginning and end of the field (see Figure 5.22 and Figure 5.23). There were some days when soil salinity was above the cotton salinity threshold, but on average, the soil salinity of the two summer months (July-August) with highest ET_c, over the top 80 cm did not exceed 5 dS m^{-1}.

6.5 Capillary rise from groundwater

Rakhimbaev (cited in Felitsiant, 1964) stated that cotton can use slightly saline groundwater. According to his studies, cotton could take up as much as 45.5 % of the total water consumption from the groundwater when the average level is at 1 m below the surface. This contribution reduced to 26.8 % and 20.6 % when the groundwater table had dropped to 2 m and 2.5 m, respectively. Atashev et al. (1966) found that in Khorezm, cotton acquired 25-49 % of total consumed water from shallow groundwater with a salinity of 2-3 g l^{-1} (~1.6-2.4 dS m^{-1}). Based on lysimeters studies in sandy loam soils according to Hoffman and Hall (1996), cotton received 57 %, 38 % and 28 % of the transpired water from groundwater when the levels were at 0.9 m, 1.8 m and 2.8 m, respectively. The groundwater had a salinity of 6 to 8 dS m^{-1}. They also reviewed several studies conducted in the San Joaquin Valley, California, and found that the cotton water uptake of groundwater did not reduce considerably until EC_{gw} exceeded 12 dS m^{-1}; a value that was never reach in this study, underpinning model results that salt stress should not have affected root water uptake.

To monitor the process of capillary rise from the groundwater into the rooting zone, a set of specific parameters has to be determined. The transient solution for the Richards equation can be used to estimate capillary rise from a groundwater table (Jorenush and Sepaskhah, 2003). In the HYDRUS-1D model, the Richards equation and the diffusive and convective solute transport equation were solved simultaneously to estimate capillary rise and unsaturated soil profile salinity. The rate of salinization can be approximated by multiplying the nodal soil moisture by the nodal soil salt concentration and summarized for the depth of the rooting zone. For the calculation of salt mass in the node, the bulk density, distribution coefficient k_d and soil moisture and concentration for this node should be considered. Comparison of mass balance estimation from different output files of the model showed that the code calculates it precisely (see section 5.4).

Horst (2000) reviewed a number of research studies that estimated the groundwater contribution to crop water demand. He mentioned that all equations used in this respect included groundwater table and soil texture. However, the peculiarities of root development were often not included or taken into account only indirectly. The latter was only considered by Harchenko (1975), Dukhovny (1984), Harchenko-Laktaev-Horst (discussed in WUFMAS, 1999; WUFMAS, 2000) and by Horst (2001). This, on the one hand, highlights the arbitrariness involved in the process of developing empirical approaches to quantify groundwater contribution to crop water consumption. On the other hand, it highlights the need for a more sophisticated approach in this regard as was done in the current study.

Many studies used lysimeters to estimate the groundwater contribution to crop water consumption. Only some studies provide full information about the water balance and percentage groundwater contribution, while the others just provide the latter (Table 6.1). The calculated percentage of groundwater contribution to crop water consumption in this study is within the range of values from earlier research. However, HYDRUS-1D provides complete information on all components of the water balance, while the way the percentage of groundwater contribution was calculated in the other studies remains unclear due to missing information.

In the present study, in field #2 no water was applied to the monitored location in 2003; however, part of the field was irrigated with 85 mm of water. Thus, groundwater contribution on this part would constitute 86 % to actual *ET* (Table 6.1). It was noticed that at the beginning of field #1, the highest water amount was applied (407 mm versus 387 mm in the middle and 268 mm at the end of the field) and the highest groundwater contribution was during the vegetation (229 mm versus 77 mm and 49 mm for the middle and end location, respectively). However, the average groundwater table was different: 1.2 m at the beginning, 1.4 m in the middle and 1.5 m at the end of field #1.

Table 6.1 Groundwater contribution to crop water consumption in relation to groundwater table (*GWT*) and applied irrigation water for different soil textures according to different studies

Author	Region	Soil texture	GWT [m]	EC_{gw} [dS m^{-1}]	Applied water [mm]	Total actual *ET* [mm]	Ground-water contribution [mm]	Percentage of ground-water contribution [%]
Faizullaev (1980)	Khorezm	meadow old irri-gated*	1.1 - 2.2	4.5 - 6.1	914	n/a	256*	n/a
Rysbekov (1986)	Tashkent	medium loam	1-1.2	n/a	n/a	900 - 1175	n/a	61 - 89
Hamidov (1993) cited by Abdullaev (1995)	Khorezm	medium loam**	1.0 1.5 2.5	n/a n/a n/a	n/a n/a n/a	791 691 538	586 434 235	74 63 17
Hoffman and Hall (1996)	San Joaquin Valley	loam	2-2.5	6	603	n/a	362	60
Nerozin cited in Yusupov (1979)	Khorezm	n/a	1-2	n/a	300-380	n/a	n/a	25-49
This study	Khorezm	sandy loam sandy	1.4 0.7	5 3	372 85	394 - 493 134	49 - 229 115	12 - 47 86

* *different soil texture;* ** *lightening to the bottom*

Thus, although several experiments were conducted to understand the relationship between groundwater table and root water uptake, the conclusions are difficult to generalize. An advantage of a model such as HYDRUS-1D to identify subsoil fluxes including groundwater contribution to crop water consumption is that expensive and time consuming lysimeter setups are not required. Lysimeters additionally bear the risk that measurements do not fully reflect real conditions, as installations mostly lead to a complete disturbance of the soil profile.

6.6 Soil salinity

The soil solution of irrigated fields is often more saline than the applied irrigation water, because under predominating evaporative processes salts slowly accumulate in the soil. Additionally, a shallow groundwater table and capillary rise may add to the salt balance (secondary salinization). Hoffman and Hall (1996) noted that the relationship between water use by crops and groundwater depth and salinity is not well understood.

Faizullaev (1980) discussed the results of a salt balance for 1974-1975 under cotton on the highly saline meadow soils in the Khiva district of Khorezm. The author compared the salt content in the upper 1-m soil in 1974 and 1975 and found that the salt content decreased from 1974 to 1975 by 21 %. Intermediately after leaching in 1975, it had decreased by 34 %. Faizullaev (1980) attributes the decreasing salt content to high water amounts (10011 m^3 ha^{-1} yr^{-1}) applied during the vegetation season. He continued monitoring of the soil salinity at the selected area till 1977. After 3-4 years of monitoring, the ameliorative soil conditions significantly improved, because at the end of each year the salt content in the 1-m profile had decreased. He concluded that soil desalinization is prevailing in the Khorezm region. The author also mentioned that during the vegetation period, the cotton field was heavily irrigated (8483 m^3 ha^{-1}) creating the meadow type of irrigation. The cotton condition was good and the yield was 2.8-3 t ha^{-1} (in 1977). Based on experiments conducted by SANIIRI on soils with shallow groundwater and good drainage options, Ikramov (2001) stated that in Khorezm in 2-3 years it is possible to desalinize the soils when 7000-8000 m^3 ha^{-1} of water are applied during the vegetation season and 4000-5000 m^3 ha^{-1} during leaching periods. However, the author also stated that salt restoration is unavoidable even with slight deviations from the established amounts of leaching water even if the drainage system is working properly.

The salt content decrease after leaching in the present study was in the same range. Leaching in 2003 was carried from 4 March till 3 April and 3000 m^3 ha^{-1} of water was applied on field #1. During this time, the amount of salts leached out of the upper 1-m soil differed between the three locations of field #1. According to the model, the amount of salts before leaching (1 March) at the locations 1, 2 and 3 were 34, 52 and 29 t ha^{-1}, respectively. After leaching on 10 April, 16, 33 and 20 t ha^{-1} of salts remained in the profile, respectively. On average, about 15 t ha^{-1} or 39 % salts were leached out of the upper 1-m soil of field #1.

According to Faizullaev (1980), the main source of salts in the soils is from the irrigation water (up to 13 t ha^{-1}), less is introduced by groundwater (up to 1.5 t ha^{-1}). Yusupov et al. (1979) established a salt balance for two sites in the Khanka district of Khorezm. The authors found that during the vegetation season on the first site 46 t ha^{-1} of salts were received with irrigation water, while 55 t ha^{-1} were discharged into drains.

On the second site, this was 43 t ha^{-1} added and 62 t ha^{-1} discharged. Thus, the process of desalinization was prevailing in the research area, where about 9 to 19 t of salts per hectare were leached. However, data on the amount of applied irrigation water and its salinity were not found in this work. Only the groundwater salinity is discussed; at 2.5-3 m it was 2.9-3.1 dS m^{-1} and at 10 m it was 3.3 dS m^{-1}. The salinity of groundwater seeping to the nearest drain was higher and constituted 3.3-3.8 dS m^{-1}.

According to own investigations in 2003 on field #1, 8 t ha^{-1} of salts were added with irrigation water, groundwater contributed 10 t ha^{-1} at the beginning, 5 t ha^{-1} in the middle and 4 t ha^{-1} at the end of the field. On field #2, the amount of salts added to the soil from the groundwater table was about 3 t ha^{-1}; no other salt was added at the monitored location, as this field was only partly irrigated in 2003. The reason for the high salt amounts, in the study conducted by Yusupov et al. (1979), added with irrigation water (~4.5 times higher than in this study) and discharged into drains (~6 times higher) remains unclear. It might be because of higher irrigation water salinity and higher amounts of applied water for irrigation. HYDRUS-1D output files provide all input and output information for checking.

6.7 Poor irrigation management and/or problem of secondary salinity?

To prevent salt accumulation in the crop rooting zone, the irrigation must be adequate and consistent over a long term (Kruse and Ayars, 1996). This means that the amount of applied water must not be excessive in order to prevent a groundwater table rise or excessive deep percolation and surface runoff. At the same time, the amount of applied water should not be too low to guarantee that salts will be leached out of the rooting zone. According to Ochs and Smedema (1996), in the Aral Sea Basin, water applied for leaching of seriously saline land is about 5000 to 10000 m^3 ha^{-1} yr^{-1}. However, previous work in the region (Ramazanov and Yakubov, 1988; Shirokova and Ramazanov, 1989) showed that with efficient drainage systems these amounts can be reduced to about 2000 m^3 ha^{-1} yr^{-1}, considering the degree of salinity, soil texture and the leaching depth. The 0-60 cm soil layer of field #1 before leaching was classified as moderately saline (EC_e=5 dS m^{-1}), therefore the amount of applied water was 3000 m^3 ha^{-1} during leaching in 2003, which is far below 10000 m^3 ha^{-1} yr^{-1}.

During 2002-2003, farmers irrigated cotton by furrows. However, the leveling of field #1 was poor, therefore farmers divided the field manually into micro-plots of 30 m by 30 m and irrigated the cotton by furrows inside the micro-plot. Due to the irregularities in the field, the water application was not uniform; therefore some parts of the field were over irrigated while others were left without water. In this situation, the observed salinity pattern was different along the field. The salt contribution from the groundwater further increased spatial differences. Thus, at the beginning of field #1 with the highest amount of applied irrigation water on the one hand and the highest groundwater contribution on the other, 0.2 t ha^{-1} salts accumulated over the vegetation season 2003 (see Table 5.13), which made the soil slightly saline. The groundwater table during 2003 was on average 1-1.5 m below the soil surface. A high groundwater table is often intentionally created by farmers. Already in 1977, Jabbarov et al. (1977) mentioned that to prevent top-soil layer desiccation, farmers in the Khorezm region block the inter- and inner-farm drainage system. Farmers have found that this method facilitates cotton germination and sustains good crop development under conditions of insecure availability irrigation water.

According to Rysbekov (1986), the shallow groundwater table plays a negative role in cotton development due to high soil moisture in the aeration zone. He compared cotton yield in response to different groundwater tables in a lysimeter study and found that the first flowers appeared 3-5 days later and first open cotton bolls 12-14 days later when the soil moisture in the aeration zone was high due to shallow groundwater tables, as compared to a lower moisture regime when the groundwater table was at 2.8 m depth. Kahlown and Azam (2002) also found that cotton is more sensitive to a shallow groundwater table than wheat and sugarcane. From their results they also concluded that cotton was very sensitive to salinity under high groundwater tables. Adequate oxygen amounts are required for root respiration and for metabolic functions of the root and plant in general (Bhattarai and Midmore, 2004). Cotton yield decreased about 11-60 % with the rising of the groundwater table from 2-3 m to less than 1 m. Thus, the blocking of the drainage system has both positive and negative consequences. On the one hand, it increases the soil moisture content during germination phase and on the other, it causes a change in groundwater chemistry and an increase in soil salinity in the aeration zone.

Concluding from the results of the conducted study and from experiments carried out elsewhere it becomes obvious that with a shallow groundwater table less irrigation water is needed. Yusupov et al. (1979), for instance, in a cotton experiment in the Khorezm region had to apply only 1900-2000 m^3 ha^{-1} when the groundwater was at 0.5-1 m. This increased to 3000-3800 m^3 ha^{-1} with a groundwater table at 1-1.5 m. The latter amount is similar to that applied on field #1 (groundwater table at ~1.4 m depth; applied water 3720 m^3 ha^{-1}).

The results of the present study show a high variability of soil moisture, soil salinity, groundwater tables and groundwater salinity during the two years of monitoring. There was a seasonal salt accumulation under cotton, most noticeable in 2002 (Table 5.19). This was due to different water application rates and times. In 2002, farmers applied less water during the vegetation season and the last irrigation was conducted at the end of August, while in 2003 the whole irrigation schedule was delayed (Table 5.3). Also, the amount of irrigation water applied in 2003 was 136 mm higher than in 2002. In spite of salt accumulation at the end of the 2002-vegetation season, at the beginning of 2003, due to autumn-winter precipitation, the amount of salt already had decreased. After leaching in 2003, even more salts were removed, turning the soils to non-saline or slightly saline. The salt balance during both the vegetation and non-vegetation period has proved that salt removal prevails over salt accumulation (Table 5.13). From that it can be seen that the farmers in the region can manage the problem of seasonal salt accumulation when there is enough water during the leaching period and vegetation season. In case of water shortage, salt accumulation takes place, and under these conditions the proper management of the field becomes difficult. This is also reported by Ikramov (2001) in studies conducted in Khorezm.

The soil salinity levels of the last decades in the region (MAWR, 2004) show that in years of water shortage, the areas with moderately and highly saline soils increased, but as soon as enough water was available these areas decreased, sometimes turning into moderately to sometimes even only slightly saline soils. From 1990 till 2004, the degree of soil salinity did not change much in these areas. One of the main reasons is water availability for leaching and irrigation. Therefore it is necessary and very important to improve irrigation management on the fields, especially in the years when water availability is reduced. Verplancke (1992) stated that limited water is often considered the cause of low crop yields, and inadequate water supply is one of the major problems in the semi-arid regions, resulting in a decrease in land productivity. Besides, a shallow saline groundwater table cannot be neglected in arid regions with high evaporation. In general, successful agriculture depends on the combination and interaction of human- and nature-controlled elements to achieve beneficial results (Verplancke, 1992). Ablyazov (1973) concluded that the soils of the Khorezm region from the ameliorative point of view are some of the best in Central Asia. It is only necessary here to control and regulate the groundwater regime taking into account the soil lithological structure.

6.8 Beyond water and salt management

It was observed during two years of monitoring that farmers experienced problems with getting tractors on their fields in time, and therefore fields were not ploughed in time, that the leveling was not done on the whole field and was also not properly done. Farmers also complained that fertilizer application was not timely, because the fertilizers were not bought by the farm or the tractors were not working. The high number of weeds in both fields in 2003 made it difficult for cotton cultivation through tractors, and for the same reason no single harrowing was carried out. Instead, farmers did cultivation and weeding manually. Neither herbicide nor insecticides were applied in the two years. Only biological control (*pheromone traps*) was used to combat the insects. Furthermore, farmers were not interested in growing cotton in 2003, because the money for the 2002-yield had not been paid when the 2003 season started. Therefore, field management was done slackly. This all emphasizes that suboptimal water distribution/management is not the only problem, but several inter-related issues threaten the productivity and sustainability of irrigated agriculture: the lack of incentives for farmers to improve production and productivity, low reliability of water provided by the irrigation canal, waterlogging, soil salinization, lack of drainage, and the deteriorating infrastructure for irrigation and drainage.

7 CONCLUSIONS AND RECOMMENDATIONS

The water flow model HYDRUS-1D was successfully applied for the estimation of the soil water and salt balance of a sandy loam and sandy soil in the Khorezm region. There were some discrepancies between observed and simulated soil moisture and solute concentration in the profile, but the model predictions may be further improved if water retention data combined with basic soil properties are available. Laboratory-determined $\theta(h)$ relationships for some soil layers were found to be non-representative for field conditions, therefore more effort should be addressed to the determination of these parameters in-situ. Also, it should be realized that in regions with strong lateral water flow, one-dimensional models may fail.

The results of the parameter estimation show that consistent sets of soil hydraulic parameters should be determined for both soil types. There were difficulties in finding data on saturated hydraulic conductivity for soils in the region in the literature; therefore, in this study they were inversely estimated. For accurately studying the capillary rise from the groundwater, optimized location-specific soil hydraulic properties rather than generalized (e.g., region-specific) parameters should be used. Nevertheless, the results discussed in section 5.4 show that the soil hydraulic properties and solute transport parameters determined for one soil profile in field #1 (location 2) can be extrapolated to other locations (1 and 3) to roughly estimate water flow, salt transport, and capillary rise. The deviation in the salt balance was within 2-23 %.

The model allows calculating subsoil water fluxes for a specific time frame and node. The simulated rates of capillary rise under cotton were in the range of research conducted earlier in the region, whereas rates in this case were calculated with empirical equations. However, for a precise estimation of the capillary rise, lysimeter studies on the selected fields should be conducted, because they allow completely controlled experiments (e.g., to control boundary conditions) under field conditions.

Only few measurements of the soil pressure head in the current study were taken (two pairs of tensiometers installed at 30 cm and 50 cm depth). The model reproduced observed pressure head values only poorly. Due to lack of data, no further conclusions are warranted.

The actual groundwater table measured in the observation wells appears to be imprecise. To measure the actual groundwater table and soil moisture at levels close to the groundwater, longer observation periods are needed. Additionally, it is advisable to install tensiometers below the groundwater table. Data from the tensiometers can be used to determine the temporal variation, maximum height and spatial geometry of the water table.

The modeling revealed that the actual transpiration was lower than the potential before the first irrigation event due to water stress at the beginning of the 2003 vegetation season. Farmers themselves complained about the delay of the first irrigation event, and data on the high pressure head before the first irrigation prove this. Consequently, by applying a soil water model like HYDRUS-1D, irrigation-water mismanagement could be clearly shown.

The high groundwater tables favor salt accumulation in the top soil layers. However, high water amounts applied during the leaching and irrigation seasons lead to flushing of salts that most likely had accumulated in the deeper soil layers because of insufficient drainage due to manual blocking of drains. At the end of the vegetation season, the amount of salts in the 1-m soil profile increased to the level of soil salinity observed before the planting. At all locations in field #1, except location 1, the salt balance of the rooting zone for the vegetation period and also for the whole year was negative. At location 1, salt accumulation was caused by a high capillary rise from the groundwater. In field #2, the salt balance was negative considering merely the vegetation season but positive for the whole year. Farmers are aware of soil salinity problems and therefore generally pay more attention to those parts of the fields where they assume higher soil salinity. However, the cotton yield decreased from 2002 to 2003 due to overall mismanagement of the fields, like late first irrigation, no weeding, no pesticide and insecticide application, etc. Sustainable land use, rational soil and water management requires continuous activities to prevent undesirable processes in soil and their environmental and economical consequences. It is advisable to continue studies in the area that tackle the water and salt dynamics and underlying causes. Given the potentially significant influences of laterally moving shallow groundwater on these balances, it seems a worthwhile exercise to extend the one-dimensional modeling by a two-dimensional approach. Furthermore, as the study shows that crop growth (and yield) was mostly affected by (poor) management and not by water or salt stress, it seems appropriate to combine a two-dimensional soil model with a fully fledged crop growth model.

The results of two years of soil salinity monitoring show that slight secondary soil salinization occurred. Whether salinization or desalinization was observed or not depended to a large extent on the timing and amounts of water applied during the vegetation season. Thus, in 2003, due to higher water application and a late last irrigation event, the amount of salts accumulated in the 1-m soil profile at the end of the vegetation season was less compared to 2002. Besides, farmers conduct leaching every spring, and thus regulate soil salinity before planting. In general, according to Uzbek scientists, in Khorezm the processes of soil desalinization prevail. However, it should be remembered that without leaching and adequate amounts of water during the vegetation season, a decrease in salt levels is not possible in a region that is characterized by high evapotranspiration due to shallow groundwater and poorly working drainage.

In the present study, field application efficiency was estimated, and the analysis showed that the field application efficiency in field #1 was in about the same range as mentioned in the literature. However, evapotranspiration and groundwater contribution were not taken into account in the calculations. In addition, these results are relevant only to one location in the monitored micro-plot. Therefore, more research should be conducted to estimate field application efficiency as well as irrigation efficiency on the field level in general.

The study emphasizes the need for monitoring soil salinity on the same date every year, as it is done in the region by the Hydrogeologic Melioration Expedition (GME) staff. This is necessary because the processes of (de-) salinization are very dynamic and depend very much on the groundwater table and the change in salinity, the amounts of water applied during leaching and irrigation seasons, and the water levels in the irrigation and drainage canals.

Uzbek scientists have been working for years in the region and have developed several models to estimate water and salt balances in the crop root zone; however, these models have not become widely used in Uzbekistan. This is at least partly due to the fact that the models had/have unfriendly user interfaces or to a poor interaction between institutes. Under these conditions, using the HYDRUS-1D model has several advantages: all equations used in the model are well known and scientifically sound, the model has a user-friendly interface, and allows estimation of water and solute fluxes for every node in the simulated profile. Although soil water modeling requires a great deal of input information, which sometimes is difficult to obtain, there is the option of inverse simulation (optimization) to optimize missing data on water retention curves, longitudinal dispersivity, and adsorption isotherm coefficients. In general, the HYDRUS-1D model proved to be a successful tool for estimating water and salt dynamics under conditions of shallow saline groundwater and is recommended for further studies in the region.

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9 APPENDICES

Appendix 9.1 Chemical soil properties of the study site in the Khiva district

Date	Field Id	Pit Id	Horizon [cm]	Water extract 1:5, content in:													$EC_{1:1}$ [dSm^{-1}]
				TDS [%]	[%]						[cmol kg^{-1}]						
					HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^++K^+	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^++K^+	
31.05.02	1	1	0-10	0.420	0.012	0.050	0.226	0.040	0.021	0.059	0.197	1.410	4.700	2.000	1.726	2.566	2.45
31.05.02	1	1	10-35	0.140		0.025						0.705					0.60
31.05.02	1	1	35-60	0.094		0.025						0.705					0.71
31.05.02	1	1	60-95	0.105	traces	0.025		traces			traces	0.705		traces			0.84
31.05.02	1	1	95-120	0.120		0.030						0.846					0.81
31.05.02	1	1	120-149	0.085		0.020						0.564					0.80
01.06.02	1	2	0-11	1.085	0.015	0.023	0.454	0.100	0.036	0.188	0.246	6.486	9.443	5.000	2.959	8.178	6.25
01.06.02	1	2	11-26	0.120		0.025						0.705					1.02
01.06.02	1	2	26-45	0.125		0.020						0.564					0.83
01.06.02	1	2	45-85	0.108	traces	0.025		traces			traces	0.705		traces			0.80
01.06.02	1	2	85-135	0.141		0.030						0.846					1.03
01.06.02	1	2	135-150	0.140		0.030						0.846					0.86
02.06.02	1	3	0-15	0.690	0.012	0.050	0.378	0.070	0.015	0.125	0.197	2.115	7.862	3.500	1.233	5.437	3.20
02.06.02	1	3	15-35	0.135		0.020						0.564					1.02
02.06.02	1	3	35-75	0.048	traces	0.015		traces			traces	0.423		traces			0.72
02.06.02	1	3	75-120	0.180		0.025						0.705					0.74
02.06.02	1	3	120-148	0.900		0.025						0.705					0.78
05.06.02	2	4	0-10	0.995	0.012	0.115	0.548	0.110	0.027	0.168	0.197	3.243	11.398	5.500	2.219	7.308	0.65
05.06.02	2	4	10-30	0.440	0.009	0.020	0.278	0.055	0.015	0.050	0.147	0.564	5.803	2.750	1.233	2.175	1.33
05.06.02	2	4	30-60	0.070	traces		0.015	traces			traces		0.423	traces			0.81
05.06.02	2	4	60-70	0.060	traces		0.015	traces			traces		0.423	traces			0.54

Appendix 9.1 (cont.) Qualitative salinity content and soil classification by salinity degree according to Kaurichev et al. (1989)

By anions [cmol kg^{-1}]			By cations [cmol kg^{-1}]		
Salinity type	Cl^- / SO_4^{2-}	HCO_3^- / (Cl^- + SO_4^{2-})	Salinity type	(Na^+ + K^+) / (Ca^{2+}+Mg^{2+})	Mg^{2+} / Ca^{2+}
Chloride	>2	-	Sodium	>2	-
Sulphate-chloride	2-1	-	Magnesium-sodium	2-1	>1
Chloride-sulphate	1-0.2	-	Calcium-sodium	1-2	<1
Sulphate	<0.2	-	Calcium-magnesium	<1	<1
Carbonate-sulphate	<0.2	>1	Magnesium-calcium	<1	>1
Sulphate-soda	-	>2			

Salinity	Salinity type, total dissolved salts [%]			
	Sulphate-Chloride	Chloride-Sulphate	Chloride	Sulphate
Non saline	<0.2	<0.25	<0.15	<0.3
Slightly saline	0.2-0.3	0.25-0.4	0.15-0.3	0.3-0.6
Moderately saline	0.3-0.6	0.4-0.7	0.3-0.5	0.6-1.0
Highly saline	0.6-1.0	0.7-1.2	0.5-0.8	1.0-2.0
Solonchak	>1.0	>1.2	>0.8	>2.0

Salinity	Salinity type, total dissolved salts [%]			
	Chloride-Sodium	Sulphate-Sodium	Sodium-Chloride	Sodium-Sulphate
Non saline	<0.15	<0.15	<0.15	<0.15
Slightly saline	0.15-0.25	0.15-0.3	0.15-0.25	0.15-0.25
Moderately saline	0.25-0.4	0.3-0.5	0.25-0.4	0.25-0.5
Highly saline	0.4-0.6	0.5-0.7	0.4-0.6	0.5-0.7
Solonchak	>0.6	>0.7	>0.6	>0.7

Appendix 9.2 Physical soil properties of the study site in the Khiva district

Date	Field Id	Pit Id	Horizon, cm	Sample moisture with pressure pF [bar], % of volume		AWC [mm]*	Bulk density [g cm^{-3}]	Porosity [cm^3 cm^{-3}]	EC_e [dS m^{-1}] [EC_e=$EC_{1:1}$x3.5]	Fraction weight [mm] in %								Kachinsky classification	Fraction content by triangle USA [mm]			FAO classifica-tion**
				2	4.2					>0.25	0.25-0.1	0.1-0.05	0.05-0.01	0.1-0.005	0.005-0.001	<0.001	Physi-cal clay		Sand 0.05-2.0	Silt 0.002-0.05	Clay <0.002	
31.05.02	1	1	0-10.	13.97	3.27	107	1.32	0.50	8.58	9.1	29.1	27.8	14.1	10.4	0.9	8.6	19.9	Sandy Loam	67	24	8	SL
31.05.02	1	1	10-35.	25.49	15.68	98	1.44	0.46	2.10	10.1	25.6	30.7	14.0	4.1	5.3	10.2	19.6	Sandy Loam	68	21	11	SL
31.05.02	1	1	35-60	14.94	5.37	96	1.53	0.42	2.49	10.0	28.9	35.7	7.4	3.6	11.5	2.9	18.0	Sandy Loam	76	18	6	SL
31.05.02	1	1	60-95	16.92	5.56	114	1.66	0.38	2.94	10.2	23.5	43.7	5.1	4.2	11.0	2.3	17.5	Sandy Loam	78	16	5	SL
31.05.02	1	1	95-120	17.36	4.12	132	1.77	0.33	2.84	9.0	32.5	35.8	6.6	3.3	11.1	2.0	16.4	Sandy Loam	78	17	5	SL
31.05.02	1	1	120-140	21.61	3.39	182	1.75	0.34	2.80	7.3	21.0	38.5	13.9	4.2	12.0	3.1	19.3	Sandy Loam	68	26	6	SL
01.06.02	1	2	0-11	17.01	4.70	123	1.44	0.46	0.88	10.4	25.9	37.0	6.6	4.3	5.2	10.6	20.1	Light loam	75	14	12	SL
01.06.02	1	2	11-26.	18.32	5.20	131	1.57	0.41	3.57	11.6	29.1	26.1	12.3	10.4	1.1	9.4	20.9	Light loam	69	22	9	SL
01.06.02	1	2	26-45	17.29	5.61	117	1.68	0.37	2.91	9.7	25.2	34.9	13.1	2.8	11.7	2.6	17.1	Sandy Loam	71	23	6	SL
01.06.02	1	2	45-85	15.82	2.69	131	1.60	0.40	2.80	5.2	27.0	38.4	12.7	3.3	11.1	2.3	16.7	Sandy Loam	71	23	5	SL
01.06.02	1	2	85-135	29.35	8.57	208	1.59	0.40	3.61	0.9	7.7	31.2	30.6	5.8	11.2	12.6	29.6	Light loam	40	44	16	L
01.06.02	1	2	135-150	29.04	4.93	241	1.63	0.39	3.01	1.5	11.9	30.3	30.3	7.1	14.1	4.8	26.0	Light loam	44	47	9	L
02.06.02	1	3	0-15.	15.82	6.39	94	1.27	0.52	11.20	9.7	25.5	36.4	7.2	3.9	6.8	10.5	21.2	Light loam	73	15	12	SL
02.06.02	1	3	15-35	18.41	9.42	90	1.50	0.43	3.57	9.7	24.0	31.8	12.2	5.4	12.8	4.1	22.3	Light loam	67	25	8	SL
02.06.02	1	3	35-75	18.94	10.22	87	1.62	0.39	2.52	8.7	25.2	30.0	12.7	4.5	7.9	11.0	23.4	Light loam	65	22	13	SL
02.06.02	1	3	75-120	24.77	11.37	134	1.68	0.37	2.59	2.4	17.4	38.4	11.7	12.3	13.4	4.4	30.1	Medium loam	59	33	8	SL
02.06.02	1	3	120-148	22.55	4.79	178	1.65	0.38	2.73	4.0	23.7	33.2	16.6	6.5	5.7	10.3	22.5	Light loam	62	27	12	SL
05.06.02	2	4	0-10.	5.29	0.95	43	1.34	0.47	2.28	14.5	46.9	23.0	1.7	1.2	5.3	7.4	13.9	Sandy Loam	85	6	8	LS
05.06.02	2	4	10-30.	8.81	1.18	76	1.68	0.33	4.66	17.6	37.5	39.5	1.7	1.6	1.3	0.8	3.7	Loose sand	95	4	1	S
05.06.02	2	4	30-60	9.21	1.39	78	1.67	0.33	2.84	17.2	36.4	35.7	2.2	4.9	3.4	0.2	8.5	Cohesive sand	90	9	1	S
05.06.02	2	4	60-70	6.07	0.64	54	1.60	0.36	1.89	21.4	41.4	26.3	0.4	0.3	0.2	0.0	0.5	Loose sand	99	1	0	S

* *AWC is theoretically related to 1 m depth;* ** *SL – Sandy Loam; L – Loam; LS – Loamy Sand; S - Sand*

Appendix 9.3 Description of soil genetic layers

Characteristics of soil profiles

Field #1 (Sandy loam), Pit # 1

Date:	31/05/2002
Researcher:	I.Forkutsa, A.Akramkhanov, M.Ibrakhimov
Location:	Research Farm of Urgench State University, field #1
Longitude:	60°18'515" E
Latitude:	41°21'068" N
Land form:	valley, fairly even surface
Land use/vegetation:	irrigated field / cotton upland, shoots 5-7 cm, 2-3 "not real" leaves; cotton condition is satisfactory
Micro-relief and soil top:	relatively leveled field, shallow furrows with 60 cm row spacing
Salinity:	salt spots along the profile
Humus:	0-35 cm poor- moderate humus layer, >35 cm – grey tint along the profile
Carbonate:	Morphologically not shown
Gypsum:	Morphologically not shown
Root system:	Filiform weed roots down to 35 cm; down to 95 cm root hairs are met
Moisture:	0-5 cm is dry soil; 5-35 cm is moist soil; 35-120 cm – from moist to damp; >120 cm from damp to wet
Groundwater table and salinity:	groundwater disclosed at 180 cm depth; after 24 hrs GWT = 149 cm
Parent material:	alluvial deposition of the river
Soil name:	irrigated sandy loam - light loamy meadow alluvial soils
Soil samples depth, cm:	0-10 cm, 10-35 cm, 35-60 cm, 60-95 cm, 95-120 cm, 120-149 cm
Notes:	10-60 cm – compacted layer; light grey spots starting at 95 cm

Field #1 (Sandy loam), Pit # 2

Date:	01.06.2002
Researcher:	I.Forkutsa, A.Akramkhanov, M.Ibrakhimov
Location:	Research Farm of Urgench State University, field #1
Longitude:	60°18'55" E
Latitude:	41°21'05" N
Land form:	valley, fairly even surface
Land use/vegetation:	irrigated field / cotton upland, shoots 3-6 cm very poor, 3-4 "real" leaves; cotton condition is not satisfactory, rushy
Micro-relief and soil top:	relatively well-leveled field, shallow furrows with 60 cm row spacing
Salinity:	salt spots along the profile under 85 cm
Humus:	0-48 cm poor humus layer, >48 cm – grey tint along the profile
Carbonate:	Morphologically not shown
Gypsum:	Morphologically not shown
Root system:	Filiform plant roots down to 80 cm; under 120 cm

	root hairs are met
Moisture:	0-8 cm – dry soil; 8-45 cm – moist soil; 45-140 cm from moist to damp; >140 cm from damp to wet
Groundwater table and salinity:	groundwater disclosed at 170 cm depth; after 24 hrs GWT = 150 cm
Parent material:	alluvial deposition of the river
Soil name:	irrigated sandy loam - light loamy meadow alluvial soils
Soil samples depth, cm:	0-11 cm, 11-26 cm, 26-45 cm, 45-85 cm, 85-135 cm, 135-150 cm
Notes:	8-45 cm – compacted layer; rush roots are met at 85 cm

Field #1 (Sandy loam), Pit # 3

Date:	01.06.2002
Researcher:	I.Forkutsa, A.Akramkhanov, M.Ibrakhimov
Location:	Research Farm of Urgench State University, field #1
Longitude:	$60^{o}19'00''$ E
Latitude:	$41^{o}21'045''$ N
Land form:	valley, fairly even surface
Land use/vegetation:	Irrigated field / cotton upland, shoots 3-5 cm are poor, 3-5 leaves; cotton condition is satisfactory, bare soil spots
Micro-relief and soil top:	relatively good-levelled field, shallow furrows with 60 cm row spacing
Salinity:	salt spots along the profile down to 120 cm
Humus:	0-40 cm moderately humus layer, >40 cm – grey tint along the profile
Carbonate:	Morphologically not shown
Gypsum:	Morphologically not shown
Root system:	0-35 cm – a lot of plant roots are met, filiform weed roots down to 110 cm; weed roots are met at 120-125 cm
Moisture:	0-12 cm is dry soil; 12-75 cm is moist soil; 75-120 cm is moist to damp; >120 cm from damp to wet
Groundwater table and salinity:	groundwater disclosed at 175 cm depth; after 24 hrs GWT = 148 cm
Parent material:	alluvial deposition of the river
Soil name:	irrigated sandy loam - light loamy meadow alluvial soils
Soil samples depth, cm:	0-15 cm, 15-35 cm, 35-75 cm, 75-120 cm, 120-148 cm
Notes:	5-60 cm – compacted layer

Field #2 (Sand), Pit # 4

Date:	05.06.2002
Researcher:	I.Forkutsa, A.Akramkhanov
Location:	Research Farm of Urgench State University, field #2
Longitude:	$60^{o}19'211''$ E
Latitude:	$41^{o}20'575''$ N
Land form:	Valley, fairly even surface

Land use/vegetation:	Irrigated field / cotton upland, shoots 5-12 cm, 2-8 leaves; cotton condition is good
Micro-relief and soil top:	relatively well-leveled field, shallow furrows with 60 cm row spacing
Salinity:	Morphologically not shown
Humus:	spots (about 40%) along the profile down to 70 cm, poor- moderate humus content
Carbonate:	Morphologically not shown
Gypsum:	Morphologically not shown
Root system:	0-40 cm filiform weed roots in a good condition; >40 cm roots are rarely met (1 root in 100 sq.cm.)
Moisture:	0-5 cm is dry soil; 5-25 cm is moist soil; 25-60 cm from moist to damp; 60-90 from damp to wet, >90 cm is wet
Groundwater table and salinity:	groundwater disclosed at 109 cm depth; after 24 hrs GWT = 97 cm
Parent material:	alluvial deposition of the river
Soil name:	irrigated sandy soil with light loam impurities, meadow or swampy-meadow alluvial soils
Soil samples depth, cm:	0-10 cm, 10-35 cm, 35-60 cm, 60-95 cm, 95-120 cm, 120-149 cm
Notes:	- Before 1975 on the field, a garbage deposit with a depth down to 1 m was located. Later garbage was removed and area was filled up with soil. Before 2000, maize was cultivated, in 2000 cotton planted (without yield), in 2001 nothing was planted in the field; - At 40 cm depth, big larva (species not known) was found. - The work was delayed for 1 day after rain.

Field #1, Pit #1	
Ap **0-10 cm**	Gray, dry loose, powder-like and lumpy-nut structure, loamy sand, close to light loam, plant debris in different stages of decomposition, gradual soil density changes.
A2 **10-35 cm**	Gray, including yellow-white impurities, moist, packed, residual soil, silty loam, sporadic small nests of yellow sand, fairly often black spots occur in lower part of horizon, noticeable color changes.
B1 **35-60 cm**	Gray with pale-yellow tone, moist, more packed, compared to previous horizon, clayey silt, often white dice (probably salts) are met, sporadic small black spots (organic origin) with diameter under 1 mm occur, seldom worm-holes, gradual horizon changes.
B2 **60-95 cm**	Gray-pale-yellow, from moist to damp, same compaction as previous layer, sandy clay loam, mostly thinly-porous, in upper part sporadic little white dice (probably salts) occur, rather often black greasy impurities of organic origin are met, noticeable density and composition changes.
B3 **95-120 cm**	Gray-pale-yellow, damp, dense, low-grade constitution, thinly-porous, sandy loam, close to light loam, rarely with root hairs, black greasy impurities (diameter under 5 mm) of organic origin are met, often small impurities with ceramic ware remains occur, noticeable density and color changes.
B4 **120-149 cm**	Pale-yellow with faint gray tint, rare light dove-colored spots and often ochre-brown spots (Fe), wet, less dense than previous layer, from light to medium loam, mostly thinly-porous, laminated, with signs of clay formation.

Field #1, Pit #2	
Ap **0-11 cm**	Gray, dry, friable soil, granular-crumbly structure, light loam, plant residuals in different stages of decomposition are met; changes are gradual.
A_2 **11-26cm**	Grayish, with yellow-white impurities and white dice (shining under sun), moist, not very dense, light loam, without structure, thinly-porous, down to the profile black spots occur, along the profile inclusions of half decayed and decayed roots, noticeable color and density changes.
A/B **26-45 cm**	Grayish pale-yellow, moist, denser than previous layer, silty loam, with humus, porous (interstice with diameter under 5 mm), often small white spots (probably salts) as dice are met, sporadic black greasy inclusions (diameter under 3 mm) of organic origin can be met, a lot of fresh roots, noticeable density changes.
B_1 **45-85 cm**	Grayish pale-yellow, moist, less denser than previous layer, more silty loam with sand nests (d<2 cm), with humus content, thinly-porous, sporadic white dice (may be salts) can be met, fairly often black greasy inclusions (d<3 mm) of organic origin can be met, worm holes are rare, noticeable moisture and density changes.
B_2 **85-135 cm**	Grayish pale-yellow, damp, less dense than previous layer, light loam, sand nests with d<3 cm can be met, porous (interstice with d<2 mm), do not break out into component units, roots are rarely met, noticeable color and moisture changes.
B_3 **135-150 cm**	Pale-yellow, wet, same density as a previous layer, from light to medium loam with sand inclusions (20-30%), thinly-porous, poorly noticeable ochre spots (Fe) occur, signs of clay formation.

Field #1, Pit #3	
Ap 0-15 cm	Gray, dry loose, granular-crumbly structure, sandy loam, half-decayed plants can be met, changes are gradual.
A2 15-35 cm	Grayish, from fresh to moist, more dense than previous layer, weakly structural, silty loam, with humus, often thinly-porous, rare black impregnations (under 5%) and white dice (shining under sun), half-decayed plants, noticeable density and color changes.
B1 35-75 cm	Pale-yellow and gray tone, moist, denser than previous layer, light loam with yellow sand nests (under 40%), thinly-porous, often small white spots (probably salt dice) and small black greasy inclusions (d<5 mm) of organic origin are met, noticeable density changes.
B2 75-120 cm	Grayish pale-yellow, from moist to damp, less dense than previous layer, medium loam with sand spots (d<3 cm), sporadic white dice (might be salt) as well as black greasy inclusions (d<3 mm) of organic origin are met, noticeable density and moisture changes.
B3 120-148 cm	Grayish pale-yellow, from damp to wet, less dense, light loam, thinly-porous, small white shining dice look like sand (d=2-7 mm), and black greasy inclusions of organic origin as well as ochre-brown spots (Fe) are met, good plant roots, with signs of clay formation.

Field #2, Pit #4	
Ap 0-10 cm	Gray, dry, friable soil, sandy, no structure, plant residuer half decayed, noticeable color, density and structure changes.
A_2 10-30 cm	Heterogeneous by color, yellow-grayish, with rare dark humus spots, moist, more dense than previous layer, sandy with rare inclusions of medium loam (under 30%) and nests of pure yellow sand (d<5 cm), thinly-porous, easy fall apart, white fragments (d<1 cm) of root residues as well as rare dark firm inclusions (under 5%) are met, noticeable moisture changes.
B_1 30-60 cm	Yellow-grayish, damp, mixed by density (depending on inclusions of loam), sandy with medium loam (under 50%) inclusions, humus, thinly-porous, decayed as well as fresh roots are met, black greasy spots (under 10%) occur, noticeable texture and moisture changes.
B_2 60-70 cm	Yellow, damp, sand without loamy inclusions, rarely decayed roots.
B/C >70 cm	Running yellow sand, without inclusions, rarely filiform plant roots.

Appendix 9.4 Methods of the analysis in the Soil Laboratory of SANIIRI

Analysis	Method	Note
Soil-water physics		
Texture (gradation)	Sedimentation	Differentiating of 7 fractions and convertion to the FAO classification
Permanent wilting point (*PWP*)	Richards pressure membrane (by loose samples)	Soil moisture at pressure 15 atmosphere (*pF* 4.2)
Field moisture capacity (*FC*)	Richards pressure membrane (by loose samples)	Soil moisture at pressure 2.7 atmosphere (*pF* 2)
Full soil-water retention curve	Richards pressure membrane (by loose samples)	
Agrochemical properties		
Humus	By Tyurin method	In sulfurous extract
Mobile nitrogen ($N\text{-}NH_4$)	Colorimeter	Ammonium carbonate extract
Mobile phosphorus (P_2O_5) plant available	Colorimeter	Ammonium carbonate extract
Exchange potassium	Flame- photometer	
Chemical properties		
Full saturation extract analysis (1:5 ratio)	Classical method	Total dissolved salts, salt ion composition: HCO_3^- Cl^-; SO_4^{2-};Ca^{2+}; Mg^{2+}; Na^+; K^+
Electrical conductivity of paste (1:1 ratio)	Electrical conductivity meter	Converting to EC_e – evaluation index by FAO method

Appendix 9.5 Portable conductometer: the model "X-Express"

Electrical conductivity (*EC*) is measured in dS m^{-1} (=mmhos cm^{-1}), using electrodes, with automatic temperature compensation. In 1995, at SANIIRI a portable instrument was designed by Chernishov A.K. (Chernishov and Shirokova, 1999).

For determination of soil salinity, the electrical conductivity of soil suspensions was measured with the ratio soil:water (distilled) as 1:1 in weight ($EC_{1:1}$).

The method for evaluation of soil salinity through measurement of electrical conductivity in suspension is widely accepted in international practice because of its simplicity. However, under local conditions it has not been widely applied to date. The coefficient K=3.5 for local conditions (Shirokova, 2002) permits evaluation of the soil salinity degree using the FAO classification on the basis of measurement in suspension ($EC_{1:1}$).

Table 9.1 Evaluation of soil salinity according to Abrol et al. (1988)

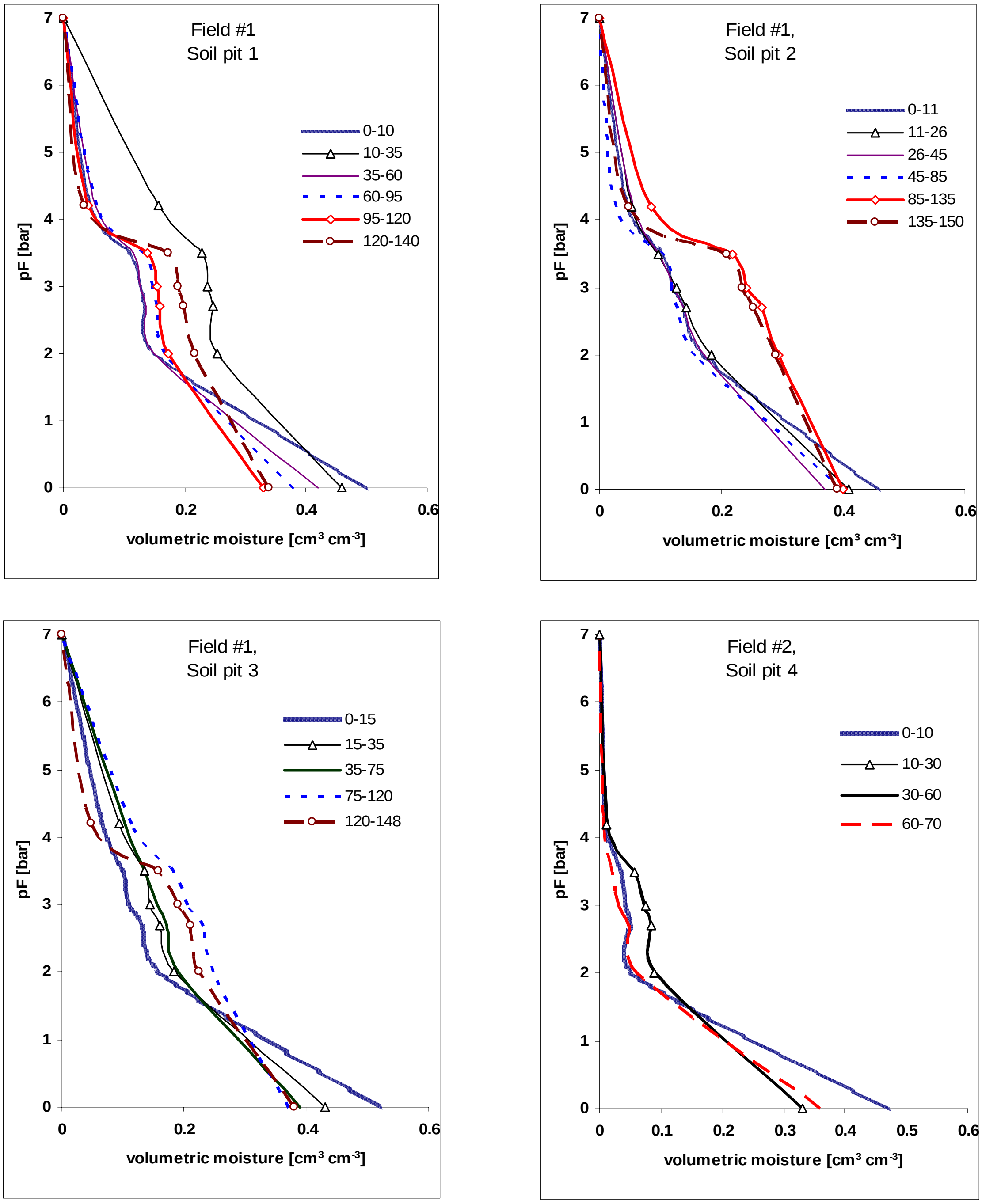
Degree of salinity	EC_e [dS m^{-1}]
Non saline	0-2
Slightly saline	2-4
Medium saline	4-8
Strongly saline	8-16
Very strongly saline	>16

To determine the salinity of the water (irrigation, drainage or groundwater), a water sample of 30 mm was poured into a glass (with 70 mm volume or more), and then the electrodes were submerged in the center of the glass to a 1-cm depth and readings taken. The *EC* values can be translated into the total quantity of dissolved salts with the following conversions:

$$TDS = K_w \cdot EC_w \tag{9.1}$$

where *TDS* is total dissolved salts [g l^{-1}]; K_w=0.8 for water in the Khorezm region (see section 5.2.4); EC_w is electrical conductivity of water [dS m^{-1}]

Appendix 9.6 Water retention curve (*pF*-curve) of four soil profiles established in the laboratory (SANIIRI)



Appendix 9.7 Chemical irrigation, drainage and groundwater content

Water	Date	EC_w [dS m^{-1}]	TDS [g l^{-1}]	g l^{-1}						cmol kg^{-1}						pH
				HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	$Mg^{2+.}$	$Na^- + K^-$	HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	$Mg^{2+.}$	$Na^- + K^-$	
Irrigation	06.07.02	0.81	0.765	0.146	0.140	0.263	0.080	0.060	0.065	2.394	3.948	5.470	3.992	4.932	2.827	
Irrigation	16.07.02	0.89	0.185	traces	0.060	traces	traces	traces	traces	traces	1.692	traces	traces	traces	traces	6.5
Irrigation	25.07.02	0.94	0.298	0.036	0.100	0.080	0.040	0.012	0.047	0.607	2.820	1.664	1.996	0.986	2.044	7.4
Irrigation	12.08.02	0.89	0.307	0.036	0.100	0.084	0.040	0.024	0.028	0.607	2.820	1.740	1.996	1.973	1.218	6.4
Irrigation	13.02.03	1.53	1.125	0.146	0.100	0.558	0.120	0.060	0.123	2.394	2.820	11.606	5.988	4.932	5.350	8.3
Irrigation	16.07.03	1.02	0.730	0.159	0.140	0.220	0.100	0.036	0.072	2.608	3.948	4.576	4.990	2.959	3.132	
Irrigation	05.08.03	0.94	0.680	0.048	0.080	0.331	0.080	0.036	0.082	0.804	2.256	6.884	3.992	2.959	3.567	8.4
Irrigation	22.08.03	1.16	0.860	0.110	0.100	0.398	0.080	0.048	0.112	1.804	2.820	8.278	3.992	3.946	4.872	8.3
Irrigation	10.09.03	1.31	0.930	0.072	0.100	0.466	0.100	0.048	0.114	1.197	2.820	9.692	4.990	3.946	4.959	8.2
Drainage	05.07.02	1.89	1.607	0.183	0.320	0.617	0.160	0.108	0.186	3.001	9.024	12.835	7.984	8.878	8.091	
Drainage	09.07.02	1.74	1.485	0.220	0.280	0.607	0.160	0.192	0.026	3.608	7.896	12.625	7.984	15.78	1.131	
Drainage	14.07.02	2.45	1.310	0.084	0.400	0.470	0.120	0.084	0.215	1.394	11.280	9.760	5.988	6.905	9.352	7.4
Drainage	24.07.02	2.14	1.178	0.134	0.300	0.418	0.140	0.096	0.104	2.198	8.460	8.694	6.986	7.891	4.524	6.50
Drainage	11.08.02	1.90	1.385	0.159	0.260	0.611	0.140	0.072	0.220	2.608	7.332	12.708	6.986	5.918	9.570	7.40
Drainage	26.08.02	2.22	1.725	0.342	0.320	0.508	0.180	0.096	0.192	5.609	9.024	10.566	8.982	7.891	8.352	
Drainage	02.09.02	2.28	1.620	0.220	0.340	0.517	0.140	0.084	0.220	3.608	9.588	10.753	6.986	6.905	9.570	
Drainage	21.09.02	2.38	1.700	0.220	0.320	0.617	0.180	0.084	0.217	3.608	9.024	12.833	8.982	6.905	9.439	
Drainage	18.02.03	1.86	2.040	0.415	0.380	0.633	0.220	0.120	0.231	6.806	10.716	13.166	10.978	9.864	10.048	
Drainage	10.04.03	2.19	1.665	0.200	0.340	0.573	0.200	0.024	0.301	3.395	9.588	11.918	9.980	1.973	13.093	
Drainage	19.07.03	2.3	1.655	0.183	0.340	0.580	0.160	0.060	0.269	3.001	9.588	12.064	7.984	4.932	11.701	
Drainage	25.07.03	2.52	1.805	0.220	0.340	0.675	0.200	0.072	0.255	3.608	9.588	14.040	9.980	5.918	11.092	
Drainage	22.08.03	1.86	8.500	1.375	0.183	0.120	0.670	0.140	0.096	0.122	3.001	3.384	13.936	6.986	7.891	5.3
Drainage	04.08.03	1.99	8.500	1.605	0.207	0.180	0.749	0.140	0.096	0.196	3.395	5.076	15.579	6.986	7.891	8.5
Drainage	07.08.03	2.07	8.500	1.595	0.183	0.160	0.874	0.160	0.132	0.163	3.001	4.512	18.179	7.984	10.850	7.1
Drainage	08.09.03	1.7	8.600	1.400	0.220	0.140	0.675	0.180	0.084	0.127	3.608	3.948	14.040	8.982	6.905	5.5
Drainage	26.08.03	1.71	8.500	1.415	0.122	0.160	0.716	0.100	0.108	0.170	2.001	4.512	14.892	4.990	8.898	7.4

Appendix 9.7 (cont.)

Well Id	GWT [cm]	Date	EC_w [dS m^{-1}]	TDS [g l^{-1}]	g l^{-1}						cmol kg^{-1}						pH
					HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	$Mg^{2+.}$	Na^-+K^-	HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	$Mg^{2+.}$	Na^-+K^-	
Pit1	149.0	31.05.02	3.96	2.971	0.378	0.620	0.987	0.280	0.156	0.395	6.199	17.484	20.529	13.972	12.823	17.182	
Pit2	155.0	31.05.02	4.33	2.745	0.305	0.740	0.896	0.360	0.144	0.334	5.002	20.868	18.636	17.964	11.837	14.529	
Pit3	148.0	31.05.02	5.02	3.345	0.268	0.860	1.102	0.420	0.180	0.381	4.395	24.252	22.921	20.958	14.796	16.573	
Pit4	90.0	31.05.02	4.00	3.045	0.232	0.640	1.215	0.240	0.084	0.642	3.805	18.048	25.272	11.976	6.905	27.927	
1	118.0	15.06.02	5.54	3.280	0.305	1.060	0.913	0.340	0.024	0.388	5.002	29.892	18.990	16.966	19.728	16.878	
1	123.5	05.07.02	5.20	4.735	0.415	1.040	1.864	0.380	0.228	0.848	6.806	29.328	38.771	18.962	18.742	36.888	
1	106.5	15.07.02	5.75	4.660	0.329	0.920	2.042	0.360	0.204	0.891	5.369	25.944	42.473	17.964	16.769	38.758	7.5
1	112.5	24.07.02	5.51	4.371	0.342	0.920	1.714	0.280	0.192	0.851	5.609	25.944	35.651	13.972	15.782	37.018	7.3
1	96.5	11.08.02	5.08	3.825	0.354	0.780	1.637	0.320	0.192	0.680	5.806	21.996	34.049	15.968	15.782	29.580	7.8
1	94.5	26.08.02	4.98	4.035	0.342	0.780	1.586	0.320	0.180	0.680	5.609	21.996	32.988	15.968	14.796	29.580	
1	100.0	02.09.02	5.39	4.195	0.366	0.820	1.590	0.360	0.192	0.650	6.002	23.124	33.072	17.964	15.782	28.275	
1	131.5	21.09.02	5.40	4.295	0.366	0.840	1.636	0.340	0.180	0.717	6.002	23.688	34.028	16.966	14.796	31.624	
1	66.8	04.08.03	4.32	3.805	0.451	0.400	1.763	0.400	0.168	0.480	7.396	11.280	36.670	19.960	13.810	20.880	8.3
1	82.8	22.08.03	3.92	3.610	0.390	0.380	1.776	0.380	0.168	0.478	6.396	10.716	36.940	18.962	13.810	20.793	8.3
1	115.8	08.09.03	3.56	3.380	0.342	0.360	1.683	0.360	0.180	0.401	5.609	10.152	35.006	17.964	14.796	17.443	8.4
1	130.8	01.10.03	3.36	3.300	0.329	0.340	1.659	0.280	0.240	0.379	5.396	9.588	34.507	13.972	19.728	16.486	8.4
1		18.11.03	3.81	4.602	0.589	0.501	2.158	0.400	0.270	0.614	9.660	14.100	44.886	19.960	22.194	26.709	.
2	113.0	15.06.02	3.92	2.575	0.317	0.680	0.814	0.280	0.144	0.352	5.199	19.176	16.931	13.972	11.837	15.312	
2	122.0	09.07.02	3.24	2.850	0.342	0.620	1.028	0.240	0.120	0.516	5.609	17.484	21.392	11.976	9.864	22.446	
2	105.0	15.07.02	3.52	3.021	0.195	0.560	1.387	0.260	0.108	0.610	3.198	15.792	28.849	12.974	8.878	26.535	7.1
2	110.0	24.07.02	3.55	2.980	0.305	0.540	1.220	0.240	0.144	0.496	5.002	15.228	25.376	11.976	11.837	21.576	6.6
2	94.0	11.08.02	3.09	2.450	0.342	0.460	0.969	0.220	0.084	0.472	5.609	12.972	20.155	10.978	6.905	20.532	7.5
2	93.5	26.08.02	3.40	2.930	0.354	0.520	1.241	0.260	0.120	0.535	5.806	14.664	25.812	12.974	9.864	23.272	
2	99.0	02.09.02	3.36	2.370	0.317	0.520	0.865	0.240	0.120	0.364	5.199	14.664	17.992	11.976	9.864	15.834	
2	133.0	21.09.02	3.53	2.660	0.183	0.560	0.980	0.260	0.108	0.399	3.001	15.792	20.384	12.974	8.878	17.356	
2	71.5	04.08.03	3.35	3.040	0.354	0.340	1.363	0.340	0.132	0.352	5.806	9.588	28.350	16.966	10.850	15.312	8.4
2	87.5	22.08.03	3.29	2.865	0.354	0.300	1.414	0.300	0.156	0.340	5.806	8.460	29.411	14.970	12.823	14.790	8.5

Appendix 9.7 (cont.)

Well Id	GWT [cm]	Date	EC_w [dS m^{-1}]	TDS [g l^{-1}]	g l^{-1}						cmol kg^{-1}						pH
					HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	Mg^{2+}	Na^-+K^-	HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	Mg^{2+}	Na^-+K^-	
2	121.5	08.09.03	3.25	3.070	0.305	0.320	1.516	0.340	0.132	0.403	5.002	9.024	31.532	16.966	10.850	17.530	8.5
2	136.5	01.10.03	2.35	2.285	0.244	0.200	1.098	0.260	0.132	0.206	4.002	5.640	22.838	12.974	10.850	8.961	8.6
2		18.11.03	2.83	2.741	0.281	0.240	1.346	0.360	0.120	0.271	4.608	6.768	27.996	17.964	9.864	11.788	8.4
3	130.0	15.06.02	4.33	3.185	0.293	0.780	1.068	0.300	0.192	0.421	4.805	21.996	22.214	14.970	15.782	18.313	
3	124.0	05.07.02	3.95	3.650	0.256	0.760	1.440	0.380	0.180	0.516	4.198	21.432	29.949	18.962	14.796	22.446	
3	123.0	15.07.02	4.78	3.486	0.268	0.780	1.457	0.440	0.156	0.496	4.395	21.996	30.305	21.956	12.823	21.560	7.1
3	123.0	24.07.02	5.01	3.960	0.366	0.780	1.620	0.460	0.264	0.384	6.002	21.996	33.696	22.954	21.701	16.704	6.7
3	115.0	11.08.02	5.45	4.545	0.378	0.840	2.004	0.460	0.192	0.744	6.199	23.688	41.683	22.954	15.782	32.364	7.6
3	107.5	26.08.02	5.04	4.145	0.354	0.800	1.642	0.420	0.168	0.688	5.806	22.560	34.153	20.958	13.810	29.928	
3	110.0	02.09.02	5.30	4.135	0.317	0.840	1.597	0.460	0.156	0.607	5.199	23.688	33.217	22.954	12.823	26.404	
3	135.0	21.09.02	5.24	4.300	0.342	0.820	1.710	0.460	0.204	0.570	5.609	23.124	35.568	22.954	16.769	24.795	
3	112.8	04.08.03	3.98	3.825	0.342	0.420	1.888	0.460	0.168	0.455	5.609	11.844	39.270	22.954	13.810	19.792	8.3
3	135.8	22.08.03	4.17	4.015	0.342	0.420	2.117	0.440	0.204	0.506	5.609	11.840	44.033	21.956	16.769	22.011	8.4
3	130.8	08.09.03	3.60	4.130	0.122	0.520	2.225	0.480	0.216	0.496	2.001	14.664	46.280	33.952	17.755	21.576	8.4
4	128.0	15.06.02	4.21	3.275	0.268	0.680	1.415	0.260	0.264	0.418	4.395	19.176	29.432	12.974	21.701	18.183	
4	119.0	05.07.02	3.82	3.720	0.293	0.720	1.489	0.420	0.180	0.498	4.805	20.304	30.971	20.958	14.796	21.663	
4	119.0	14.07.02	4.61	3.865	0.134	0.700	1.707	0.400	0.132	0.650	2.198	19.740	35.505	19.960	10.850	28.275	7.6
4	113.0	19.07.02	4.75	3.630	0.293	0.700	1.555	0.420	0.252	0.346	4.805	19.740	32.344	20.958	20.140	15.051	7.2
4	117.0	24.07.02	4.50	3.990	0.293	0.700	1.653	0.340	0.240	0.540	4.805	20.304	34.382	16.966	19.728	23.490	6.8
4	110.0	11.08.02	4.96	4.000	0.342	0.720	1.618	0.440	0.204	0.468	5.609	20.304	33.654	21.956	16.769	20.378	6.7
4	102.0	26.08.02	4.95	4.000	0.293	0.820	1.556	0.400	0.168	0.688	4.805	23.124	32.364	19.960	13.810	29.928	
4	106.0	02.09.02	4.90	4.120	0.329	0.760	1.597	0.420	0.168	0.585	5.396	21.432	33.217	20.958	13.810	25.447	
4	132.0	21.09.02	4.89	3.970	0.256	0.780	1.588	0.420	0.180	0.566	4.198	21.996	33.030	20.958	14.769	24.621	
4	113.0	04.08.03	4.60	4.845	0.427	0.560	2.307	0.640	0.264	0.414	7.003	15.792	47.985	31.936	21.701	18.009	8.3
4	121.0	22.08.03	4.70	4.840	0.366	0.480	2.563	0.580	0.204	0.617	6.002	13.536	53.310	28.942	16.769	26.839	8.2
4	135.0	08.09.03	4.30	5.345	0.244	0.520	2.944	0.580	0.204	0.739	4.002	14.664	61.235	28.942	16.769	32.146	8.4
4	147.0	01.10.03	3.61	4.015	0.342	0.420	2.107	0.420	0.216	0.535	5.609	11.844	43.825	20.958	17.755	23.272	8.2

Appendix 9.7 (cont.)

Well Id	GWT [cm]	Date	EC_w [dS m^{-1}]	TDS [g l^{-1}]	g l^{-1}						cmol kg^{-1}						pH
					HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	Mg^{2+}	Na^-+K^-	HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	Mg^{2+}	Na^-+K^-	
4		18.11.03	3.94	4.160	0.476	0.420	2.111	0.440	0.192	0.566	7.806	11.844	43.908	21.956	15.782	24.621	8.5
7	154.0	05.07.02	4.68	4.460	0.354	0.960	1.785	0.420	0.216	0.712	5.806	27.072	37.128	20.958	17.755	30.920	
7	155.0	14.07.02	5.63	4.725	0.207	0.940	2.027	0.440	0.156	0.848	3.395	26.508	42.161	21.956	12.823	36.888	7.5
7	136.0	19.07.02	7.51	5.440	0.366	1.320	2.180	0.600	0.300	0.760	6.002	37.224	45.344	29.940	24.660	33.060	7.3
7	156.0	24.07.02	6.85	5.270	0.354	1.220	1.986	0.520	0.420	0.515	5.806	34.424	41.308	25.948	34.524	22.402	7.1
7	124.0	11.08.02	6.90	5.365	0.390	1.200	2.082	0.460	0.240	0.931	6.396	33.840	43.305	22.954	19.728	40.498	8.0
7	119.0	26.08.02	5.90	4.760	0.403	1.080	1.811	0.460	0.180	0.844	6.609	30.456	37.668	22.954	14.796	36.714	
7	120.0	02.09.02	5.53	4.390	0.415	0.960	1.631	0.440	0.168	0.731	6.806	27.072	33.924	21.956	13.810	31.798	
7	136.0	21.09.02	5.64	4.520	0.329	0.960	1.661	0.400	0.192	0.713	5.396	27.072	34.548	19.960	15.782	31.015	
7	122.3	04.08.03	3.97	3.625	0.378	0.400	1.874	0.380	0.192	0.451	6.199	11.280	38.979	18.962	15.782	19.618	8.3
7	128.3	22.08.03	3.83	3.620	0.378	0.400	1.757	0.320	0.180	0.521	6.199	11.280	36.545	15.968	14.796	22.663	8.2
7	133.3	08.09.03	1.80	3.675	0.281	0.420	1.870	0.320	0.168	0.580	4.608	11.844	38.896	15.968	13.810	25.230	8.4
7	154.3	01.10.03	-	11.12	-	2.050	-	-	-	-	-	57.810	-	-	-	-	-
8	133.0	05.07.02	6.30	5.670	0.244	1.280	2.246	0.540	0.240	0.921	4.002	36.096	46.716	26.946	19.728	40.063	
8	128.0	14.07.02	7.48	5.370	0.232	1.400	2.015	0.540	0.300	0.763	3.805	39.480	41.912	26.946	24.660	33.190	8.0
8	124.0	19.07.02	2.82	1.626	0.134	0.400	0.715	0.220	0.096	0.215	2.198	11.280	14.872	10.980	7.891	9.352	6.4
8	128.0	24.07.02	4.09	2.675	0.281	0.640	1.060	0.320	0.216	0.246	4.608	18.048	22.048	15.968	17.755	10.701	7.8
8	118.0	11.08.02	7.13	5.645	0.366	1.220	2.188	0.500	0.204	1.009	6.002	34.404	45.510	24.950	16.769	43.891	6.9
8	115.0	26.08.02	6.58	5.275	0.244	1.160	2.141	0.480	0.228	0.880	4.002	32.712	44.532	23.952	18.742	38.280	
8	118.0	02.09.02	5.75	4.715	0.354	0.960	1.788	0.480	0.192	0.702	5.806	27.072	37.192	23.952	15.782	30.537	
8	142.0	21.09.02	6.31	5.080	0.427	1.060	1.940	0.460	0.264	0.744	7.003	29.892	40.352	22.954	21.701	32.364	
8		18.11.03	4.05	4.820	0.268	0.520	2.645	0.480	0.240	0.704	4.395	14.664	55.016	23.952	19.728	30.624	8.4
5	54.0	14.06.02	3.02	2.400	0.256	0.520	0.888	0.220	0.108	0.401	4.198	14.664	18.470	10.978	8.878	17.443	
5	25.0	12.02.03	2.78	2.205	0.366	0.160	1.005	0.300	0.108	0.165	6.002	4.512	20.904	14.970	8.878	7.177	8.5
5	94.7	29.09.03	-	1.915	0.134	0.200	0.998	0.120	0.168	0.208	2.198	5.640	20.758	5.988	13.810	9.048	
5		06.11.03	4.99	6.780	0.256	0.820	3.570	0.540	0.300	1.139	4.198	23.124	74.256	26.946	24.660	49.546	8.5

Appendix 9.7 (cont.)

Well Id	GWT [cm]	Date	EC_w [dS m^{-1}]	TDS [g l^{-1}]	g l^{-1}						cmol kg^{-1}						pH
					HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	$Mg^{2+.}$	Na^-+K^-	HCO_3^-	Cl^-	SO_4^{2+}	Ca^{2+}	$Mg^{2+.}$	Na^-+K^-	
6	69.0	14.06.02	2.41	1.389	0.183	0.360	0.485	0.200	0.072	0.170	3.001	10.152	10.088	9.980	5.918	7.395	
6	63.0	12.02.03	1.74	1.340	0.354	0.140	0.517	0.200	0.060	0.126	5.806	3.948	10.753	9.980	4.932	5.481	8.4
6	64.0	29.09.03	2.48	2.255	0.268	0.200	1.175	0.140	0.108	0.417	4.395	5.640	24.440	6.986	8.878	18.139	8.4
6		06.11.03	3.57	4.110	0.342	0.400	2.288	0.320	0.204	0.705	5.609	11.280	47.590	15.968	16.769	30.667	8.6
9	87.5	14.10.03	3.08	3.335	0.281	0.280	1.818	0.280	0.204	0.467	4.608	7.896	37.814	13.972	16.769	20.314	8.6
9		06.11.03	2.58	2.030	0.256	0.220	0.987	0.180	0.084	0.338	4.198	6.204	20.529	8.982	6.905	14.703	8.7

Appendix 9.8 Humus and nutrient content of soil in the study site in the Khiva district

Date	Field Id	Pit Id	Horizon [cm]	Humus		$N\text{-}NH_4$		P_2O_5		K_2O	
				[%]	Evaluation	[mg kg^{-1}]	Evaluation	[mg kg^{-1}]	Evaluation	[mg kg^{-1}]	Evaluation
31.05.06	1	1	0-10	0.79	poor	73.6	high	36.4	moderate	202	moderate
31.05.06	1	1	10-35	0.72	poor	19.8	very low	39.8	moderate	142	low
31.05.06	1	1	35-60	0.48	poor	16.8	very low	44.3	moderate	111	low
31.05.06	1	1	60-95	0.15	very poor	15.6	very low	27.0	low	101	low
01.06.02	1	2	0-11	0.55	poor	14.3	very low	33.4	moderate	198	low
01.06.02	1	2	11-26	0.51	poor	16.3	very low	30.7	moderate	154	low
01.06.02	1	2	26-45	0.38	very poor	18.1	very low	25.0	low	101	low
01.06.02	1	2	45-85	0.31	very poor	14.9	very low	18.6	low	96	very low
02.06.02	1	3	0-15	0.69	poor	82.4	high	45.5	increased	458	high
02.06.02	1	3	15-35	0.51	poor	18.7	very low	42.0	moderate	207	moderate
02.06.02	1	3	35-75	0.45	poor	18.1	very low	39.8	moderate	176	low
02.06.02	1	3	75-120	0.31	very poor	16.3	very low	26.0	low	142	low
05.06.02	2	4	0-10	0.62	poor	76.4	high	39.8	moderate	207	moderate
05.06.02	2	4	10-30	0.34	very poor	25.0	low	47.7	increased	159	low
05.06.02	2	4	30-60	0.14	very poor	21.8	low	50.0	increased	133	low
05.06.02	2	4	60-70	0.24	very poor	17.4	very low	30.2	moderate	137	low

Appendix 9.8 (cont.) Evaluation of soil fertility according to different authors

(a) Musaev (2001)

Evaluation	*Available* P_2O_5 [mg kg^{-1}]	*Exchangeable* K_2O [mg kg^{-1}]
Very low	0-15	0-100
Low	16-30	101-200
Moderate	31-45	201-300
Increased	46-60	301-400
High	>60	>400

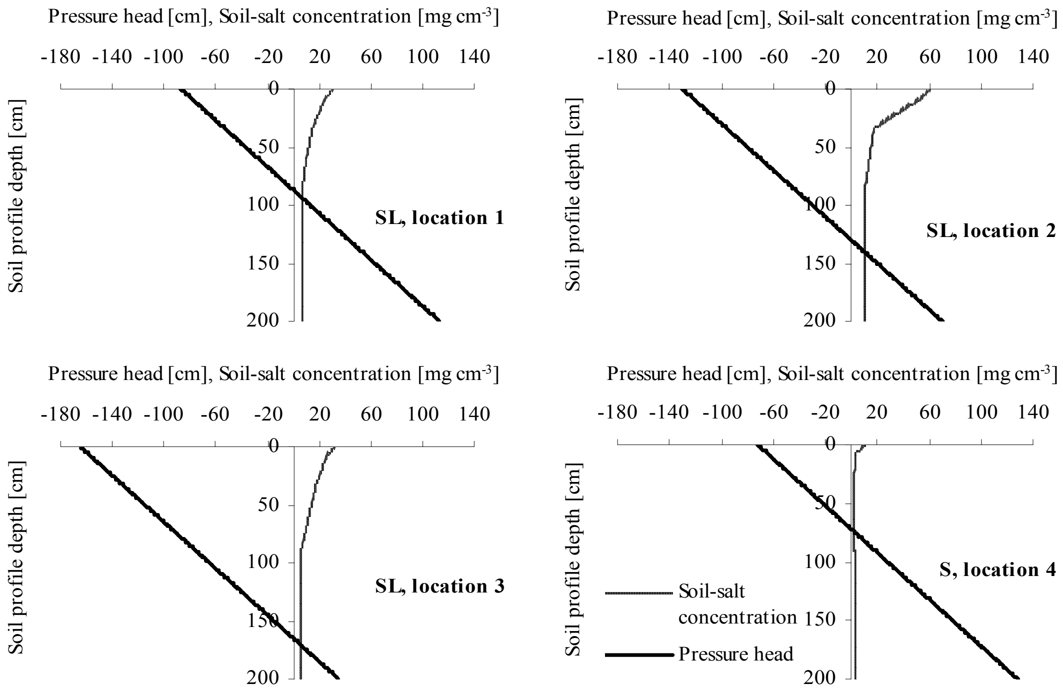
Evaluation	*N-*NH_4 [mg kg^{-1}]
Very low	<20
Low	20-30
Moderate	30-50
Increased	50-60
High	>60

(b) Krasnouhova et al. (1988)

Evaluation	Humus [%]
Very poor	<0.4
Poor	0.4-0.8
Moderate	0.8-1.2
Increased	1.2-1.6
Rich	1.6-2.0
Very rich	>2.0

Appendix 9.9 Initial and boundary conditions

(a) Initial conditions (SL=field #1, S=field #2)



Appendix 9.9 (cont.)

(b) Boundary conditions: Groundwater table [cm] (here GWT is measured from the bottom of simulated profile) and concentration of groundwater [mg cm^{-3}] (cBot)

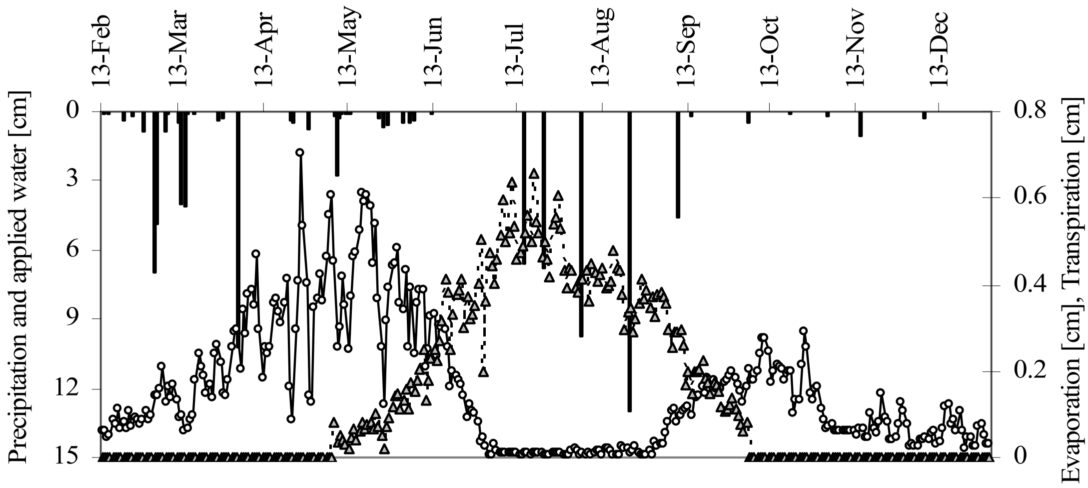
Date	Field #1, location 1		Field #1, location 2		Field #1, location 3		Field #2, location 4	
	GWT [cm]	cBot [mg cm^{-3}]	GWT [cm]	cBot [mg cm^{-3}]	GWT [cm]	cBot [mg cm^{-3}]	GWT [cm]	cBot [mg cm^{-3}]
13-Feb-03	112.5	2.9	69	3.784	33.6	4.61		
18-Feb-03	130.5	2.5	83	3.448	88.6	4		
22-Feb-03	117.5	2.53	78	3.528	83.6	4.18		
24-Feb-03	107.5	2.5	65	3.51733	80.6	4.18		
25-Feb-03	109.5	2.49	75	3.512	80.6	4.18		
1-Mar-03	109.5	2.58	74	3.456	78.6	4.16		
11-Mar-03			106	2.84	103.6	2.53		
14-Mar-03	122.5	2.78	95	3.152	96.6	3.62		
24-Mar-03	73.5	2.55	76	4.84	77.6	4.59		
27-Mar-03	60	2.75	68	4.0672	74.5	4.58		
29-Mar-03	54	2.88	61	3.552	56.5	4.57		
2-Apr-03	34	3.12	58	3.952	62.5	3.44		
10-Apr-03	95	2.31	95	2.832	96.5	2.38		
13-Apr-03							138	2.32
15-Apr-03	92	2.66	89	3.584	93.5	2.8		
20-Apr-03					80.5	3.33		
24-Apr-03							184	2.2
26-Apr-03	95	4.03	80	4.624	78	5.54		
27-Apr-03	98	4.06			75	5.42		
28-Apr-03	81	4.09			72	5.29		
29-Apr-03	72	4.11			71	5.16		
30-Apr-03	78	4.14						
2-May-03	92	4.19	64	4.04	19	4.78		
4-May-03							142	2.1
6-May-03	64	4.46	62	3.68	60	4.52		
8-May-03							127	2.23
10-May-03	45	4.38	71	3.904	78	5.39		
13-May-03							151	2.28
15-May-03	96	3.62	70	3.76667	71	5.09		
17-May-03							137	2.57
20-May-03	52	3.73	57	3.6	45	4.88		
22-May-03							127	2.54
24-May-03	63	3.8	59	3.568	59	4.63		
27-May-03	78	4	81	3.984	77	5.55	147	2.56
31-May-03	88	3.9	67	3.744	68	6.03	137	2.81
5-Jun-03	72	3.39	66	3.504	63	5.54	132	2.61
10-Jun-03	62	3.49	58	3.368	54	5.74	127	2.54
15-Jun-03	97	3.66	58	3.304	34	5.5	101	2.4
21-Jun-03	85	3.35	56	3	44	4.33	127	2.14
26-Jun-03	82	3.26	55	3.56	28	4.96	103	2.42
1-Jul-03	75	3.23	33	3.44889	21	4.96	94	1.6
5-Jul-03	80.2	3.26	54	3.36	61.2	4.97	94	2.06
10-Jul-03	63.2	3.4	51	3.544	34.2	5.42	128	2.62

Appendix 9.9 (cont.)

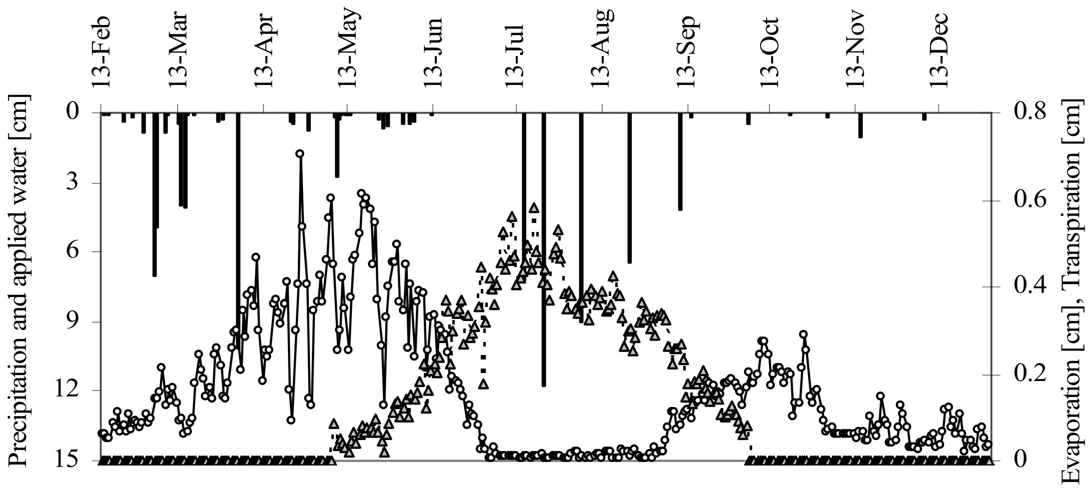
Date	Field #1, location 1 GWT [cm]	Field #1, location 1 cBot [mg cm^{-3}]	Field #1, location 2 GWT [cm]	Field #1, location 2 cBot [mg cm^{-3}]	Field #1, location 3 GWT [cm]	Field #1, location 3 cBot [mg cm^{-3}]	Field #2, location 4 GWT [cm]	Field #2, location 4 cBot [mg cm^{-3}]
16-Jul-03	78.2	3.5	39	2.456	26.2	4.44	139	2.65
19-Jul-03	94.2	3.55	62	1.912			130	2.66
21-Jul-03	82.2	3.82	59	2.72267	28.2	3.62	149	2.74
22-Jul-03	83.2	3.95	59	3.128	28.2	3.46	139	2.78
25-Jul-03	99.2	3.33	70	3.336	73.2	2.97	144	2.57
26-Jul-03	96.2	3.54	69	3.408	70.2	3.11	143	2.5
27-Jul-03			69	3.48				
28-Jul-03	96.2	3.98	69	3.552	73.2	3.4	149	2.36
29-Jul-03	96.2	4.33	69	4.128	71.2	3.99	158	2.35
30-Jul-03	94.2	4.22	69	4.072	68.2	4.31	168	2.34
31-Jul-03	102.2	4.22	70	4.0384	79.2	4.28	172	2.32
2-Aug-03							157	2.3
4-Aug-03	103.2	4.23	68	3.904	87.2	4.14		
7-Aug-03	81.2	1.82	64	3.968	64.2	4.02	143	2.24
9-Aug-03	84.2	2.66	64	3.936	66.2	4.32	139	2.26
11-Aug-03	83.2	3.24	63	3.912	64.2	4.27	151	2.2
14-Aug-03	92.2	4.18	61	3.864	63.2	4.35	162	1.74
18-Aug-03	80.2	4.25	59	3.752	62.2	4.26	136	2.38
19-Aug-03			61	3.8				
20-Aug-03			59	3.848				
22-Aug-03	87.2	3.91	62	3.944	54.2	4.36	146	2.55
26-Aug-03	84.2	1.6	61	3.192	36.8	4.78	129	2.57
29-Aug-03	72.2	2.51	56	3.464	59.2	4.82	128	2.65
2-Sep-03	91.2	3.63	66	3.704	58.2	4.8	128	2.73
5-Sep-03	89.2	3.94	66	3.784	68.2	4.7	128	2.72
8-Sep-03	54.2	3.93	57	3.944	59.2	4.98		
15-Sep-03	65.2	4.01	54	3.664	40.2	5.17	94	2.64
19-Sep-03	92.2	3.91	65	3.824	65.2	4.81	132	2.61
23-Sep-03	73.2	4.1	56	3.992	59.2	4.96	131	2.46
27-Sep-03	51.7	4.27	52	3.968	37.2	5.07	128	2.54
1-Oct-03	39.2	4.05	36	3.93382	25.2	5.02	94	2.51
9-Oct-03	40.2	3.83	30	3.86545	25.4	4.91		
26-Dec-03	0	2.8	49	3.26727	21.2	3.85		

Appendix 9.9 (cont.)

(c) Boundary conditions: Precipitation [cm], applied water for leaching and irrigation [cm], evaporation [cm] and transpiration [cm] (SL=field #1, S=field #2)

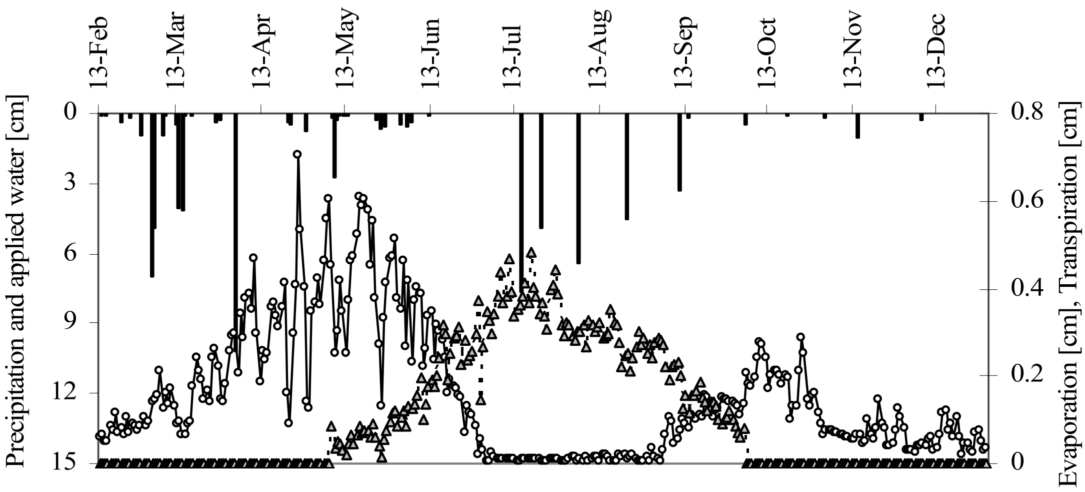


SL, location 1

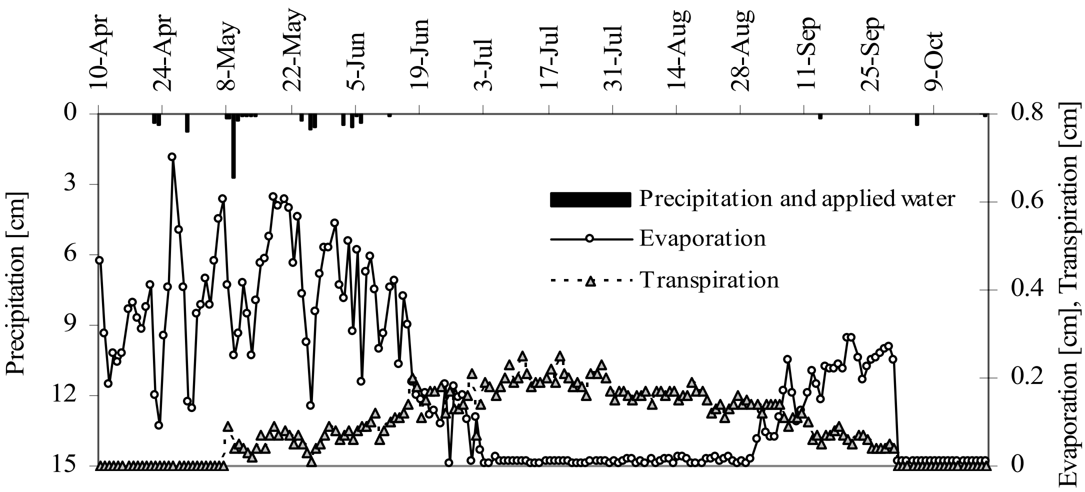


SL, location 2

Appendix 9.9 (cont.)



SL, location 3



S, location 4

Appendix 9.10 Groundwater contribution

Kats (1967) on the base of lysimeters data of cotton grown on loamy soils in the Khorezm region found that:

$$G_e = \frac{K}{H^n} \tag{9.2}$$

where G_e is groundwater contribution to ET [mm]; H is groundwater table [m]; K=0.541 and n=0.66 are empirical coefficients for the Khorezm region.

In the Kazakh Scientific Research Institute of Water Economy, Kvan (1997) established relationships between groundwater contribution and evapotranspiration and groundwater tables on the base of lysimeter studies for different climatic zones of Kazakhstan on light soil textures:

$$G_e = \left(0.086 - 0.019 \cdot H\right) \cdot ET_{crop}^{1.323+0.189 \cdot H+0.034 \cdot H^2} \tag{9.3}$$

where G_e is groundwater contribution to ET [mm]; ET_{crop} is crop evapotranspiration [mm]; H is groundwater table [m].

The Harchenko (1975) formula for a stable water exchange, which is correct for irrigated lands located not higher than 1500 m a.s.l. with groundwater tables from 0.1 m to 6 m, reads:

$$G_e = E_0 \cdot e^{-mH} \tag{9.4}$$

where G_e is groundwater contribution to ET [mm]; E_0 is evaporation [mm]; e is base of logarithm; m is coefficient which depends on soil texture and crop development stage; H is groundwater table [m].

For sandy loam soils, "m"-coefficients according to Harchenko (1975) are:

Planting to 1st decade after planting	2.0
2nd decade after planting	1.6
Decade of active vegetation	1.1
Next to last decade of full crop development	1.6
Last decade and harvesting	2.0

For approximate evaluation of groundwater contribution, the formula of Harchenko (1975) and Laktaev (1983) modified by Horst (2001), can be used:

$$G_e = \frac{\alpha \cdot ET_0}{e^{b \cdot (H-h)}} \tag{9.5}$$

where G_e is groundwater contribution [mm d^{-1}]; ET_0 is potential evapotranspiration [mm d^{-1}]; H is groundwater table [m]; h is rooting depth [m]; α=1.19 and b=1.23 are coefficients for sandy loam soil texture.

Note, that the above-given formula gives adequate estimation of G_e when (H-h) < 0.5 m.

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