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Spatial and temporal dynamics of groundwater table and salinity in Khorezm (Aral Sea Basin), Uzbekistan

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ABSTRACT

Agriculture is a major economic activity in the countries of the Aral Sea Basin, employing about 60% of the rural population. The countries in the region depend on water resources, the majority of which comes from the rivers Amu-Darya and Syr-Darya, for irrigation. In recent years, water shortages have become more frequent and are especially acute in the downstream areas of the two rivers. The Khorezm region is located in the lower Amu-Darya River delta. Despite the water shortages, the irrigated areas in the region are experiencing a rapid rise in the groundwater (GW) table after applications of water for irrigation and leaching. The shallow saline GW leads to soil waterlogging and salinization, which reduce crop yields. The GW table rises in conditions of flat topography and extremely slow lateral subsurface water flow and exceeds the critical threshold, which was defined for the conditions of Khorezm to be 1.2 – 1.5 m below the ground surface depending on several factors, such as soil properties, soil and GW salinity, precipitation and evapotranspiration (ET), methods of irrigation and agro-techniques, and crops grown. To maintain crop yields sustainably, it is important to be able to estimate the causes of spatiotemporal changes in shallow saline GW, location and magnitude of the areas at risk of waterlogging and salinization and to develop management measures aimed at remediation or alleviation.

This study investigates the long-term sustainability of irrigated agriculture in Khorezm through an analysis of the temporal and spatial changes of GW table and salinity. Due to the nature of the analysis, secondary data collected by government agencies in Uzbekistan were extensively used in this study. The following objectives were defined to achieve the main goal: 1) to estimate seasonal and long-term temporal and spatial dynamics of GW table and salinity, 2) to identify the areas of potential risk from shallow saline GW, 3) to estimate the accuracy of different interpolation methods in delineating areas with high GW table and salinity, 4) to establish the factors influencing the spatial and temporal distribution of GW table and salinity, and 5) to identify areas characterized by rapid temporal changes in GW salinity (hotspots).

The temporal and spatial dynamics of GW table and salinity in the region were assessed in April, July and October during the period 1990 to 2000 from the 1987 monitoring wells that belong to the Hydrogeologic Melioration Expedition of the Khorezmian Department of Agriculture and Water Resources of Uzbekistan. The hydrograph of the Amu-Darya River, drainage discharge, drainage and irrigation water salinity as well as areas sown with winter wheat were used to explain the causes of the negative changes in the GW table and salinity. After benchmark years, when the statistically significant temporal changes in the average GW table and salinity occurred, had been identified, the study concentrated on the analysis of the spatial distribution and causes of the spatial changes in the selected measurement periods.

Four interpolation methods were employed for the estimation of the spatial distribution of GW table and salinity, namely ordinary and universal kriging, inverse distance weighted (IDW), spline, and triangulated irregular networks (TIN). Soil lithology, irrigation and drainage networks and topography were used to explain the causes of the spatial changes in GW table and salinity. Analysis of the spatial changes over time resulted in the establishment of 'hotspot' areas in the Khorezm region during the study period.

Temporal analysis revealed that the GW tables were unacceptably shallow throughout the region in the three measurement periods. The average values of the GW

table were 1.36 m below the ground surface in April, 1.25 m in July and 1.82 m in October. The critical threshold for risk of waterlogging and salinization was exceeded in all the measurement periods. The rise of the GW table occurred in the period 1990 to 1994 in April, and 1996 in October. After that, GW tables declined until 2000. July readings were constant despite the years with lower and higher river runoff during the study period. Both the GW table rise in April and shallow levels in July were explained by the increased water diversion and use in Khorezm during the period from 1990 to 1994. The hydrograph of the drainage discharge was used as a proxy to the water use in Khorezm. The introduction of winter wheat appeared to have led to a considerable increase in the GW table outside the growing periods in October by 73 cm.

The rise in the GW table shows that irrigation water is diverted from the river in greatly increased amounts and is not used efficiently. Non-efficiency is clear from the GW recharge and the shallow GW levels, which potentially could result in waterlogging and salinization. The observed GW table rise in October as a result of the introduction of winter wheat allows concluding that cropping patterns in Khorezm must be set up with care in order to avoid adverse soil conditions.

GW salinity was low, being 1.81 g L^{-1} in April, 1.77 g L^{-1} in July and 1.68 g L^{-1} in October. There was a decreasing pattern of GW salinity in April from 1.98 g L^{-1} in 1990 to 1.62 g L^{-1} in 1994 with a subsequent rise to 1.85 g L^{-1} in 2000. In July, a salinity decrease was observed until 1996 – 97 with a subsequent rise until 2000. For October, a decrease from 1.81 g L^{-1} in 1990 to 1.55 g L^{-1} in 1996 was followed by an increase to 1.75 g L^{-1} in 2000. The salinity of irrigation water played an important role in salt accumulation in the GW in April and October, which was not the case in July. The changes in water diversion significantly influenced GW salinity changes only in October.

Given the apparent low salinity levels in the GW, and provided the GW tables in the region are sufficiently deep, there seems to be no or little threat of soil salinization from GW. However, upper GW layers were not captured by the monitoring wells. More detailed investigation is necessary to identify the actual levels and origin of the GW salinity.

Analysis of the spatial distribution of GW table and salinity was performed using the kriging interpolation method, because with this method the estimation errors were the lowest among the four compared interpolation methods. Shallower GW table and higher salinity occurred in the southern and western parts of the region. Soil lithology was found to have a significantly strong influence on the spatial distribution of GW table and salinity. Because of the soil lithology and the influence of the Turkmen Canal (subsurface inflow) the drainage network in the southern part of the region was not efficient in lowering the GW tables to acceptable levels.

The areas at risk from shallow saline GW during the study period were assessed to be ca. 65-70% in April and July. In October, the areas at risk of waterlogging and salinization varied from ca. 1% in 1990 to ca. 36-43% in 1996, and to ca. 6% in 2000. Extremely large areas appear to be jeopardized from the shallow saline GW tables and it is likely that only large amounts of water for leaching and increased irrigation providing downward percolation for salt removal prevent the soils in Khorezm from becoming extremely saline. However, this leads to excess surface water, which creates a still higher GW table rise and salinity increase.

Analysis of the spatial changes in GW salinity that occurred during the study period showed an occurrence of hotspot areas (Figure 5.32). A hotspot area is defined as an area where soil conditions are jeopardized by the increasing long-term seasonal GW salinity, the dynamics of which are higher than in the other areas. These areas occurred in all lithological soil types and probably under different cropping patterns and irrigation intensity. A detailed analysis of the occurrence of such hotspots in Khorezm would allow an estimation of the role of natural conditions and management factors, further allowing the definition of actions to be taken for remediation or alleviation not only in these areas but also in the entire irrigated areas of the Khorezm region to assure sustainable agriculture.

To assure sustainable agricultural practices in the Khorezm region, the following recommendations are made. As the IDW interpolation method performed better than the TIN method in estimating the distribution of the areas with shallow and saline GW tables based on the existing number of the monitoring wells, and since it does not require special training, this method should be implemented for a clearer spatial estimation and further alleviation measures when necessary. Spatial assessment revealed shallower and more saline GW in the southern and western parts of the region, which was not clear in the maps produced by the TIN method. These are the priority intervention areas in Khorezm in terms of better drainage solutions and cropping patterns. A detailed investigation of the causes for the occurrence of hotspots and associated natural conditions/management factors will enable an assessment of the most sustainable long-term agricultural practices. On unproductive (marginal) land, resources should be reallocated to better areas, while additional measures might be necessary in the hotspot areas (e.g., growing of salt-tolerant commercial trees or halophytes).

Räumliche und zeitliche Dynamik von Grundwasserspiegel und -salinität in Khorezm (Aralseebecken), Usbekistan.

KURZFASSUNG

Die Landwirtschaft beschäftigt etwa 60% der ländlichen Bevölkerung in den Ländern des Aralseebeckens und ist damit einer der größten Wirtschaftszweige. All diese Länder hängen von Wasserressourcen ab, die zum überwiegenden Teil aus den Flüssen Amu-Darya und Syr-Darya stammen. In neuerer Zeit sind Jahre mit Wasserknappheit häufiger geworden, und diese ist in den unteren Flussläufen dieser beiden Flüsse besonders stark ausgeprägt. Die Region Khorezm liegt am unteren Amu-Darya-Delta. Trotz der Wasserknappheit wird in den bewässerten Gebieten dieser Region ein schneller Anstieg des Grundwasserspiegels infolge Bewässerung und Auswaschung von Salzen (leaching) beobachtet. Das hoch anstehende, saline Grundwasser (GW) führt zu Problemen mit Staunässe und Salinisierung, beides Faktoren, welche die Anbauerträge vermindern. Das GW steigt unter den vorherrschenden Bedingungen einer flachen Topographie und extrem langsamer lateraler unterirdischer Wasserbewegungen an und erreicht schnell den kritischen Grenzwert, der für Khorezm bei 1.2-1.5 m unter der Bodenoberfläche definiert wurde, und der von verschiedenen Faktoren abhängt wie z.B. Bodeneigenschaften, Boden- und GW-Salinität, den Niederschlägen und Evapotranspiration (ET), den Bewässerungs- und Anbaumethoden, und den angebauten Feldfrüchten. Damit die Erträge nachhaltig hoch bleiben, ist es wichtig, die Ursachen für die räumlich-zeitlichen Änderungen des flachen und salinen GW, sowie die Lage und Ausdehnung der Flächen mit Staunässe- und Salinitätsrisiko zu erfassen, und Management-Ansätze zu einer Verbesserung der Situation zu entwickeln.

Diese Studie hatte zum Ziel, die langfristige Nachhaltigkeit des Bewässerungsanbaus in Khorezm mit Hilfe einer Analyse der zeitlich-räumlichen Änderungen von GW und Salinität zu analysieren. Die Natur dieser Analyse brachte es mit sich, dass umfangreiche, durch Regierungsorganisationen in Usbekistan gesammelte sekundäre Datensätze herangezogen wurden. Die folgenden Ziele wurden definiert: (1) die Bestimmung der saisonalen und langzeitlichen zeitlichen und räumlichen Dynamik des GW-Niveaus und seiner Salinität; (2) die Identifizierung der Regionen unter potentiellen Risiko durch hoch anstehendes, salzhaltiges GW; (3) die Bestimmung der Genauigkeit verschiedener Interpolationsmethoden zur Erfassung von Flächen mit hohem GW-Stand und hoher Salinität; (4) die Erfassung der Faktoren, die die zeitliche und räumliche Verteilung des GW und der GW-Salinität bestimmen; und (5) die Identifizierung der durch schnelle zeitliche Veränderungen der GW-Salinität gekennzeichneten Flächen (sog. „hot spots“).

Die zeitliche und räumliche Dynamik von GW-Spiegel und -Salinität in der Region wurden jeweils im April, Juli und Oktober im Zeitraum 1990-2000 in 1987 GW-Messstationen erfasst, die von der „Hydrogeologic Melioration Expedition of the Khorezmian Department of Agriculture and Water Resources of Uzbekistan“ betrieben werden.

Die Hydrographie (Jahres-Abflußganglinie) des Amu-Darya, Drainagewasserabfluß, Drainage- und Bewässerungswasser-Salinität sowie die mit Winterweizen bebaute Fläche wurden herangezogen, um die Gründe für die negativen

Veränderungen in GW-Stand und –Salinität zu erklären. Nachdem Bezugsjahre, in denen statistisch signifikante zeitliche Veränderungen in GW-Spiegel und -Salinität erfolgen, identifiziert wurden, konzentrierte sich die weitere Analyse auf die räumliche Verteilung und die Gründe für die räumlichen Veränderungen in den ausgewählten Erfassungsperioden.

Vier Interpolationsmethoden wurden für die Abschätzung der räumlichen Verteilung von GW-Ständen und –Salinität herangezogen (ordinary and universal kriging; inverse distance weighted (IDW); spline; triangulated irregular networks (TIN)). Bodenlithologie, Bewässerungs- und Drainage-Netzwerke, und Topography wurden herangezogen, um die Gründe für die räumlichen Veränderungen in GW-Stand und – Salinität zu erklären. Die Analyse der räumlichen Veränderungen in der Zeit führte zu einer Festlegung von 'Hotspot'-Bereichen in Khorezm in der Untersuchungsperiode.

Die zeitliche Analyse ergab, dass die GW-Spiegel in den 3 Erfassungsperioden in der gesamten Region inakzeptabel flach waren. Die Durchschnittlichswerte der GW-Stände waren 1.36 m unter Bodenoberfläche im April, 1.25 m im Juli und 1.82 m im Oktober. Der kritische Grenzwert, der ein erhöhtes Risiko von Staunässe und Salinität anzeigt, wurde in allen Erfassungsperioden überschritten. Der Anstieg des GW-Spiegels erfolgte in den Jahren 1990-1994 im April, und in 1996 im Oktober. Danach gingen die Werte bis zum Jahr 2000 wieder zurück. Juliwerte waren konstant, obwohl Jahresabflussganglinien höher oder niedriger waren. Sowohl GW-Anstieg im April als auch flache GW-Stände im Juli wurden durch die erhöhte Wasserentnahme in Khorezm in der Periode 1990-1994 erklärt. Der Jahresabflussgang wurde als Näherungswert für die Wasserentnahme in Khorezm herangezogen. Die Einführung von Winterweizen führte zu einem deutlichen Anstieg des GW-Spiegels außerhalb der Anbauperioden im Oktober um 73 cm.

Ein Anstieg des GW-Spiegels zeigt, dass aus dem Fluss Bewässerungswasser in großen Mengen entnommen und ineffizient genutzt wird. Die Ineffizienz ergibt sich deutlich aus dem Nachfluss an Grundwasser und den flachen GW-Ständen, welche potentiell zu Problemen mit Staunässe und Salinität in der Region führen können. Der beobachtete GW-Anstieg im Oktober als Folge der Einführung von Winterweizen zeigt dass Feldfrucht-Rotationen in Khorezm behutsam eingeführt werden müssen, um die Bodenfruchtbarkeit nicht zu beeinträchtigen.

Die GW-Salinität war gering, mit 1.81 g L^{-1} im April, 1.77 g L^{-1} im Juli und 1.68 g L^{-1} im Oktober. Auf einen Abfall der GW-Salinität im April von 1.98 g L^{-1} in 1990 auf 1.62 g L^{-1} in 1994 folgte ein Anstieg auf 1.85 g L^{-1} im 2000. Im Juli, ein Abfall der Salinität wurde bis 1996 – 97 beobachtet, gefolgt von einem Anstieg bis 2000. Im Oktober, folgte dem Abfall von 1.81 g L^{-1} in 1990 auf 1.55 g L^{-1} in 1996 ein Anstieg auf 1.75 g L^{-1} in 2000. Die Salinität des Bewässerungswassers spielte eine wichtige Rolle bei der Salzakkumulation im April und Oktober, aber nicht im Juli. Die Unterschiede in der Wasserentnahme beeinflussten die Veränderungen der GW-Salinität in signifikanter Weise nur im Oktober.

Niedrige GW-Ständer in der Region vorausgesetzt, gibt es bei diesen niedrigen Salzgehalten kein oder nur ein geringes Risiko einer Bodenversalzung durch Grundwasser. vorausgesetzt, Allerdings wurden höhere GW-Lagen durch die GW-Messstationen nicht adäquat erfasst. Genauere Untersuchungen sind notwendig, um die tatsächlichen Werte der GW-Salinität und die Ursachen ihrer Entstehung zu erfassen.

Eine Analyse der räumlichen Verteilung von GW-Stand und –Salinität wurde mit der Kriging-Methode durchgeführt, denn der Abschätzungsfehler war mit Kriging am niedrigsten im Vergleich der vier Interpolationsmethoden. Flachere GW-Stände und höhere Salinität zeigten sich in den südlichen und westlichen Teilen der Region Khorezm. Die Bodenlithologie wurde als ein signifikanter Faktor für die räumliche Verteilung von GW-Stand und –Salinität erkannt. Wegen der Lithologie und dem Einfluss des Turkmen-Kanals (unteriridische Zuflüsse) war das Drainagenetzwerk in den südlichen Teilen der Region nicht effizient genug, um die GW-Stände auf akzeptable Niveaus zu drücken.

Die von flachem, salinen GW bedrohten Risikoflächen umfassten in der Untersuchungsperiode im April und Juli ca. 65-70% des Landes. Im Oktober variierten die entsprechenden Flächen zwischen ca. 1% in 1990 bis auf ca. 36-43% in 1996, zu ca. 6% in 2000. Weite Flächen scheinen durch flache, saline GW-Stände ungünstig beeinflusst zu sein, und vermutlich sind es nur die großen Wassermengen, die für die Salz-Auswaschung und Bewässerung eingesetzt werden, und die eine vertikale Abwärtsbewegung der Salze ermöglichen, die die Böden in Khorezm vor extremer Versalzung bewahren. Allerdings führen diese zu einem Überfluss an oberflächennahem Wasser, welches wiederum die GW-Stände und –Salinität ansteigen lässt.

Die Analyse der räumlichen Veränderungen in der GW-Salinität zeigten das Vorhandensein von “Hotspot”-Bereichen (Abb. 5.32). Ein solcher Bereich ist definiert als eine Region, in der sich die Bodenbedingungen durch eine langfristig ansteigende saisonale GW-Salinität verschlechtern. Diese Flächen gibt es in allen lithologischen Bodentypen und vermutlich unter verschiedenen Anbaupflanzen und unterschiedlicher Bewässerungsintensität. Eine detaillierte Analyse dieser Hotspots würde es erlauben, die Rolle der natürlichen Gegebenheiten und der Bewirtschaftungsfaktoren abzuschätzen, und es damit ermöglichen, Vorschläge für Maßnahmen zu einer Bodenverbesserung nicht nur in diesen, sondern in der gesamten Bewässerungsfläche Khorezms zu definieren, um damit eine nachhaltige Landwirtschaft zu garantieren.

Um eine nachhaltige Landwirtschaft in Khorezm zu ermöglichen, werden die folgenden Maßnahmen vorgeschlagen. Da bei der gegebenen Zahl der GW-Beobachtungsstationen die IDW-Methode zur Abschätzung der GW-Verteilung besser als die TIN-Methode geeignet ist, und da kein spezifisches Training zur Anwendung dieses Verfahrens erforderlich ist, sollte dieser Methode der Vorzug gegeben werden, um eine bessere räumliche Abschätzung der GW-Verteilung und bessere Vorhersagen zu ermöglichen. Die räumliche Analyse zeigte flacheres und stärker salines GW in den südlichen und westlichen Teilen der Region, was aus den mit TIN erstellten Karten nicht ersichtlich wurde. Dieses sind die Regionen in Khorezm, für die proritär eine bessere Drainage und optimierte Feldfrucht-Rotationen gefunden werden müssen. Eine detaillierte Analyse der Gründe für das Auftreten von „Hotspots“ und der diese begleitenden natürlichen Gegebenheiten und Managementfaktoren wird es erlauben, die langfristig nachhaltigsten landwirtschaftlichen Praktiken zu finden. Ressourcen sollten von unproduktivem (marginalen) Land auf bessere Standorte umgewidmet werden, während für „Hotspots“ zusätzliche Maßnahmen wie z.B. der Anbau salztoleranter Bäume oder von Halophyten notwendig werden können.

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1 INTRODUCTION

1.1 Background

The Government of Uzbekistan maintains an intensive groundwater (GW) monitoring system throughout the country, including the Khorezm region, one of the smallest administrative districts of the country. Continuous records are provided for both GW depth and salinity. More than 240,000 ha out of the total of 275,000 ha of irrigated land in Khorezm are under the control of a large number of staff in each district. Every year, substantial financing is directed to the maintenance and operation of a large number of monitoring wells (2300 units in 1990) from the state budget given to water management agencies. This great attention paid to GW is due to the fact that GW is one of the important components of the agricultural system in the region (Kats 1976; Nurmanov 1966).

As in other regions with similar (semi)arid climates, GW provides additional sources of water for irrigation through pumping. However, the peculiarity of GW in Khorezm is its rapid rise after irrigations and shallow position throughout the growing period from April till September, extremely slow lateral flow due to low hydraulic conductivity in the upper part of the soil and small slopes and intensive accumulation of salts (Kats 1976). Shallow saline GW and a constant capillary rise due to evaporation is one of the main mechanisms of soil salinization processes, resulting in reduced land productivity. Therefore, an intensive irrigation and drainage network is maintained to leach the salts from the soil and GW and remove them out of the area. This network is apparently not efficient, because the areas with moderately and strongly saline soils covering ca. 50% of the region did not significantly differ between 1990 and 2000 (GME report, 2001).

Despite the importance and relatively large investments into GW monitoring, data analysis is under-developed. It takes weeks, if not months, to manually draw paper maps of the GW table (or salinity) after the data have been processed. The base paper maps were prepared more than 10 years ago (personal communication with GME staff) and are extremely outdated, because the irrigation and drainage networks have undergone (re-) construction changes, new irrigated areas have appeared or been reallocated, and some lakes disappeared in the periphery of the region (Dzhabarov

1990). The readings are usually recorded on paper. The transfer of the readings to the maps is subject to errors and the controlling opportunities are reduced. Local specialists have drawn maps based on the linear interpolation between data values utilizing the interpolation method of triangulated irregular networks. Apart from many errors, these maps become rapidly outdated, as GW fluctuations are very dynamic. Computerized data processing approaches are not yet introduced aside from a data coding procedure. This restricts data analysis to a simply static comparison of the readings of previous with those of current years. The use of modern (geo)-statistical methods of analysis and mapping would allow a statistically-based identification of cause-effect relationship of the irrigation and drainage resources.

This study forms one component of a multidisciplinary research development project on the current situation in the areas of the lower Amu-Darya River reach. It is well known that enormous diversions and water use from the Amu-Darya River have caused serious environmental problems in the Aral Sea Basin, thereby deteriorating rather than improving, as was anticipated, the economic and social welfare of the people in the region (UNESCO 2000; Vlek et al. 2001). Especially the population in the regions of the lower Amu-Darya River area face acute socio-economic, environmental and particularly health problems. These problems have been attracting the increasing attention of the world research community as they have grown from a local to a global scale. The extent of the problems demands a radical solution, as the former gradual intervention has not led to any success. The research community has been tasked and mandated to investigate the situation in the lower Amu-Darya River Basin. The ZEF/UNESCO research project "Economic and Ecological Restructuring of Land and Water Use in the Khorezm Region (Uzbekistan): A Pilot Project in Development Research" affiliated with the university of Bonn, was initiated to identify economically and ecologically sustainable land and water-use strategies in Khorezm, Uzbekistan, and to encourage local scientific and technological capacity-building (Vlek et al. 2001).

Although the focus of this study is on the GW component, because of the complexity and interlinkage of GW dynamics with other factors it could not be restricted to GW analyses alone. An understanding of the GW dynamics is needed as well as basic intelligence of the efficiency of land- and water-resources use, irrigation and drainage network and the influence of the environmental factors in the region. The cause-effect relationships of the various interlinked components indicate that changes in one could immediately affect the others and thus, the whole system. Therefore, environmental factors and agricultural management practices have been analyzed concurrently to explain the changes in GW.

1.2 Objectives

The main objective of this study is to analyze the long-run sustainability of irrigated agriculture in Khorezm through an analysis of the spatial and temporal changes of GW table and salinity. The following specific objectives/research questions were defined to achieve the main goal of this study:

- To estimate seasonal and long-run temporal and spatial groundwater table and salinity,
- To identify the areas of potential risk from shallow saline groundwater,
- To estimate the accuracy of different interpolation methods in delineating areas with high groundwater table and salinity,
- To establish the factors influencing the spatial and temporal distribution of GW table and salinity, and
- To identify areas characterized by rapid temporal changes in GW salinity (hotspots).

The following are the research questions:

1) To characterize the ameliorative conditions in the region through an analysis of the level and salinity of GW,
2) To analyze the causes for temporal changes in GW table and its salinity,
3) To analyze the causes for the spatial changes in GW table and its salinity,
4) To determine potentially unsustainable irrigated areas based on established patterns of the GW table/salinity dynamics, and
5) To recommend proper management actions in the potentially non-sustainable irrigated areas.

1.3 Outline of the study

Following this introduction, Chapter 2 describes the general aspects and current knowledge of GW flow and salinity dynamics, their peculiarities in Khorezm and existing methods of (geo)-statistical analyses and interpolation methods. The area description and materials and methods are explained in Chapter 3. Data collection and methods used in the analysis are briefly discussed. The area description includes the geographic location, as well as the predominant features of the climate, soils, geology and hydrogeology, irrigation and drainage network and crops grown. Chapters 4 and 5 contain the results of the spatio-temporal analyses of GW table and salinity in Khorezm. The general discussion is given in Chapter 6. Finally in Chapter 7, recommendations for necessary actions to improve agricultural management practices in the Khorezm region are presented.

2 LITERATURE REVIEW

2.1 Characteristics of groundwater with emphasis on (semi-)arid zones

Studies of different aspects of hydrological processes are a special concern of research in the scientific community. Many problems related to water resources exist such as proper allocation of scarce water among competing users, agriculture and environment, its over-exploitation, lack of freshwater and point- and non-point source deterioration of quality. Solving them requires understanding of the processes and improved knowledge of relations among watershed components like rivers, irrigation and GW, hydrology and topography, climate, vegetation, and soil parameters, analysis of their interactions and prediction of possible adverse changes (Wilson et al. 2000).

Groundwater studies have received wide attention, as 97% of the freshwater worldwide is stored underground (UNEP 1996). Groundwater plays an important role as a source for drinking water and for irrigation purposes. In most arid areas where precipitation is low, GW is the only source of water. With population growth, over-exploitation and pollution of GW resources is becoming an increasingly evolving process, which requires urgent intervention and protection.

GW is defined as subsurface water storage. The dynamics of GW depend to a great extent on climate, geology and topography (UNEP 1996; Sophocleous 2002), which are considered as the three main factors in the hydrologic landscape that control subsurface water flow (Sanford 2001). In arid/semiarid climates, natural GW changes occur mainly due to evaporation from the soil surface and transpiration by vegetation, while precipitation and upslope flow determine recharge. In irrigated areas, where the rate and/or spatiotemporal distribution of precipitation are frequently inadequate for farming, recharge occurs mainly through irrigation.

In arid/semiarid regions, GW influences the soil formation processes, moisture and solute transport dynamics and is one of the important factors ameliorating soil conditions (Kats 1976). Irrigation changes the surface and subsurface hydrology causing GW table fluctuation (Bos 1996) and mobilizes salts that are naturally present in the rock and soil (Ghassemi et al. 1995; Hillel 1998, 2000). Rising GW eventually comes close to the soil root zone (ca. top 1 meter), which, with improper management, may lead to waterlogging and salinization through capillary rise (FAO 1996 a; Bos 1996;

Hillel 2000). An excessive net recharge triggers processes of soil salinity (Salama et al. 1999). A high water table also makes the soil difficult to cultivate (FAO 1996 b). Most food and cash crops grown are glycophytes, which are to a certain extent vulnerable to salinity (FAO 1992). Salinity leads to sinking land productivity and yield reductions (Hillel 2000).

De Vries and Simmers (2002) summarized the actual knowledge and latest advances in estimation of GW recharge processes in (semi)-arid regions. Recharge in these regions is highly determined by rainfall or irrigation and evapotranspiration (ET). Three main types of recharge are distinguished: direct, indirect and localized recharge. The first type is characterized by downward water percolation through the saturated zone in excess of soil moisture and ET. Indirect recharge is a water percolation through beds of surface water-courses. Localized recharge is an intermediate form resulting from the horizontal (near-) surface concentration of water in the absence of well-defined channels. Several processes of GW recharge through the soil are recognized, among which are diffuse percolation, macro-pore flow through root channels, fissures and cracks, and preferential flow. When aridity increases, direct recharge is likely to become less important than localized and indirect recharge, in terms of total aquifer replenishment: concentrated surface water flow (e.g. in irrigation canals) may play a major role in GW replenishment, while the vertical flow dynamics are determined by the rates of irrigation water application and ET within a particular season.

Sanford (2002) and Healy and Cook (2002) reviewed the methodologies and necessary considerations in estimating different aspects and rates of GW recharge. Böhlke (2002) provided a comprehensive study of the influence of agricultural practices on GW recharge rates and chemical loads showing that agriculture caused substantial increases in GW recharge fluxes and concentrations of chemicals. Salama et al. (1999) showed that recharge has a major impact on salt loads to the soil and GW. They discussed the processes of soil and water salinization which occur in different geological, hydro-geomorphologic, agricultural and climatic settings. The four important processes contributing to soil salinization include the processes of evaporation, transpiration, hydrolysis, and leakage. The physical and chemical processes are shown in Figure 2.1 (adopted from Salama et al. 1999):

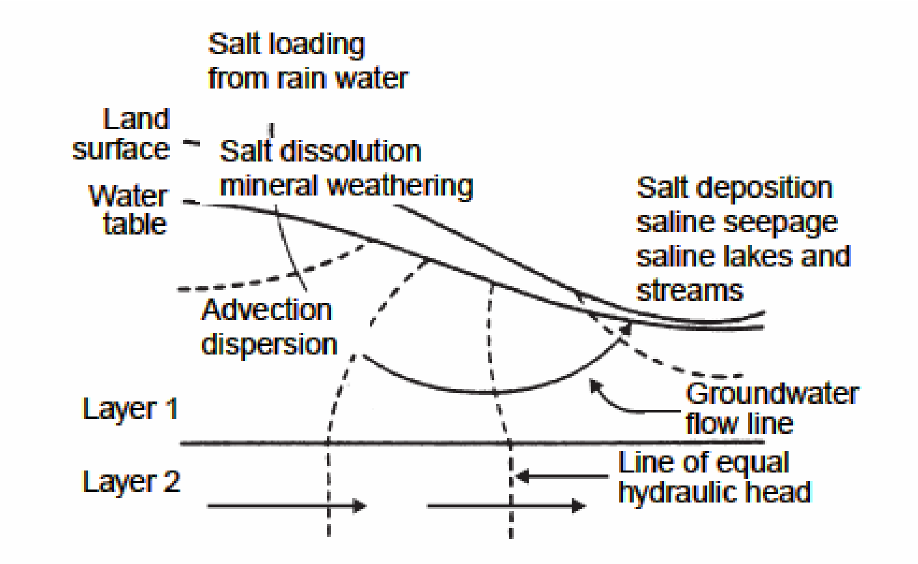


Figure 2.1: Conceptual model of soil and water salinization

Figure 2.1 shows that the processes involve the mineralization of the GW through salt dissolution, weathering and salt from external sources, followed by physical transport and accumulation of dissolved salts from upper areas towards depressions. The precipitation of salts into the soil root zone as well as the discharge of saline baseflow into streams and lakes occurs mainly in lowlands. Most of the salts in GW come from input loading, which includes aerosol salts, recharging saline water and salts contributed from mineral dissolution within the GW flow system. One of the important processes that adds salts to GW is mineral-dissolution reactions in the subsoil and, to a lesser extent, along the entire flow system.

Advection and dispersion are the two physical-transport processes responsible for the transport of dissolved salts from recharge to discharge areas. The pattern of transport by advection is influenced by the direction and rate of GW flow. Of importance in advection is the ability of the flow systems to collect excess recharge and GW flow over relatively large areas, and to focus that flow into localized discharge areas. In general, the distance between the recharge and discharge areas is not more than a few kilometers.

GW flow is mainly laterally downslope and occurs most often over shallow, less permeable bedrock. Transport by dispersion is most important at small scales (<1.0 m) as far as the generation of saline soils is concerned. At a larger scale (>1.0 m), dispersion occurs as a consequence of porous-medium heterogeneity, which is responsible for changes in direction and rate of GW flow. The effect of dispersion at this scale is to spread and homogenize mass in the system and to attenuate high salinity. Soil salinization occurs in areas of GW discharge or a rising water table when mineralized porewater at or near the ground surface continually evaporates and causes minerals to precipitate. A key factor controlling the amount of evaporation is the depth of the water table below the surface. In general, evaporation is minimal when the water table is below 1.5–3.0 m depth (depending on soil characteristics). Rising water tables can also lead to the formation of saline soils in recharge areas although GW discharge areas are commonly sites of the most active soil salinization due to greater salt fluxes.

2.2 Interaction of GW – surface water

Surface-water (SW) bodies are integral parts of GW flow systems (FAO 1995; Bos 1996; Winter 1999). GW interacts with surface water (SW) in nearly all landscapes, ranging from small streams, lakes and wetlands in headwater areas to major river valleys and seacoasts. SW and GW are closely linked to each other: a change in amount or quality in one inevitably leads to the subsequent changes in the other. These interactions are governed by the positions of the water bodies with respect to GW flow systems, geologic characteristics of their beds, and their climatic settings (FAO 1995; Winter 1999). Thus, for an effective management of the water resources, assessment of the interaction between SW and GW is necessary.

The concepts of GW – SW interactions are thoroughly reviewed in Sophocleous (2002). Hydrologic interactions occur by subsurface lateral flow through the unsaturated soil and by infiltration into or ex-filtration from the saturated zones. Different flow processes which occur due to interaction are explained. Of particular interest is the process of return flow, which is generated by GW being close to the ground surface. Even a small amount of shallow GW is enough to saturate soil and to discharge into the stream water (Sophocleous 2002). This onsets soil waterlogging/salinization mechanisms and determines the solute load to SW, causing its degradation.

Although it is generally assumed that topographically high areas are GW recharge areas and low ones are discharge areas, this holds true primarily for regional flow systems. The superposition of local flow systems associated with surface-water bodies on this regional framework results in complex interactions between GW and SW in all landscapes, regardless of a regional topographic position. Hydrologic processes associated with the SW bodies themselves, such as seasonally high surface-water levels and evaporation and transpiration of GW from around the perimeter of SW bodies, are a major cause of the complex and seasonally dynamic GW flow associated with SW.

2.3 Spatial and temporal aspects of GW table and salinity

The strong dependency of GW on topography and geology determines its spatial location and flow: GW levels are deep in undulating upland areas and near the surface in topographic lows of the landscape (Salama et al. 1999; Sophocleous 2002). Assuming a uniform surface water distribution and infiltration a GW flow will replicate the surface topography (Salama et al. 1999). The resulting GW flow pattern is controlled by the configuration of the water table, landscape position and the distribution of hydraulic conductivity in the rocks. In arid and semi-arid climates, the outline of the water table is subdued, and the hydraulic gradients are generally less steep. Slope, break of slope, and curvature control where GW discharge takes place (Salama et al. 1999). Topography generates GW flow systems of different orders that correspond to the dimensions of the relief of a catchment’s surface (Tóth, cited in Salama et al. 1999).

Tóth (in Sophocleous 2002) recognizes three distinct types of flow systems: local, regional and intermediate. Water in a local flow system flows to a nearby discharge area, such as a pond or stream. Water in a regional flow system travels a greater distance than the local flow system, and often discharges to major rivers, large lakes, or to oceans. An intermediate flow system is characterized by one or more topographic highs and lows located in between its recharge and discharge areas, but, unlike the regional flow system, it does not occupy both the major topographic high and the bottom of the basin. Areas of pronounced topographic relief tend to have dominant local flow systems, and areas of nearly flat relief tend to have dominant intermediate and regional flow systems.

The spatial distribution of flow systems also influences the intensity of natural GW discharge (Sophocleous 2002). The main stream of a basin may receive GW from the area immediately within the nearest topographic high and possibly from more distant areas. However, Tóth (1999) showed that GW discharge is not only confined along the stream channel but also extends throughout the discharge area downslope the basin boundary that separates areas of upward (discharge) from downward (recharge) flow.

The interactions between GW and surface water bodies are dynamic temporally and spatially. Soil and GW salinity dynamics, river water quality changes and subsequent environmental degradation are very complex and difficult to analyze because of the areal extent (difficulties for reliable data collection) and spatially complex and temporally dynamic nature of the interaction between factors that come into play. Adequate to the problem of sound assessment and prediction came from the development and coupling of spatial analysis tools within geographic information systems (GIS) and classical statistics (Wilson et al. 2000). This defines water resources assessment and management as inherently geographical activities requiring the handling of multiple forms of spatial and temporal data. In the development of GIS tools and increasingly large availability of elevation sources for construction of digital elevation models (DEM) and algorithms to extract flow paths and drainage networks it became possible to analyze and predict many hydrological processes including GW (Moore 1991).

GW monitoring and understanding with GIS and models enabled assessing the current status and solving particular problems related to water resources. GIS offer powerful new tools for the collection, storage, management, and display of map-related information (Burrough et al. 1998). Combining GIS and hydrological models can provide decision-makers with interactive analysis tools for understanding the physical system and judging how management actions might affect that system. GIS makes it possible to cross and overlay different maps with different map units, thereby improving the integration of different data sets. The role of GIS in the evaluation of the sustainability of land management systems lies in its capability to integrate and process various spatial data. An excellent overview of the role and developments in GIS science and tools for the spatial analysis is done in Wilson et al. (2000, a).

GIS has enabled agencies involved in hydrological data collection and analysis for management decision-making to transfer their data from tables to electronic forms.

Digitizing made it possible to include the other information from paper maps like soil properties, spatial location of canals and drains, river, and to generate geo-referenced layers of information. Layer overlay and data extraction within GIS-software tools (e.g., ArcView) enabled further statistical analysis of the current status and prediction of further trends, while modeling allowed changing scenarios for effective management interventions.

The application of GIS in hydrology and water management can be classified in analysis and management. Management in GIS includes data storage, recovery and visualization (García 2002). Hydrological networks, monitoring wells and other information, such as time, cost and periodicity of operation and maintenance works can be retrieved for further actions. The power of GIS comes with the possibility of modeling allowing the production of other layers of information based on existing data, for analyzing, predicting and correcting possible natural processes.

GIS also enabled an accurate estimation of the spatially distributed variables so that only a limited number of samples is needed for further generation of electronic maps within a GIS environment (Burrough et al. 1998). As the complete spatial coverage of the variable of interest is difficult or impossible to collect in the field, spatial tools for estimating and predicting spatial characteristics were developed (Isaak and Srivastava 1989, for further details see Chapter 3). Several of them, rapidly evolving and with special connections to water resources applications, are identified.

Kriging, Inverse Distance Weighted (IDW) and spline enable generation of good quality spatial and spatiotemporal models. These models allowed estimating unmeasured values based on scarce point data, with further analyses of factors governing these changes. Kriging was used extensively for the prediction of spatially distributed variables. Despite widespread recognition of kriging as best linear unbiased estimators (BLUE) its shortcomings were also reported (e.g., Lin et al. 2000). As pointed by Lin et al. (2000), the kriging process yields weighted-average estimates that may fail to preserve the variability of the investigated process. Minimizing the prediction error variance involves smoothing the actual variability (Journel and Huijbergts 1978). The estimated values based on kriging might display a lower variation than the actual investigated values.

Douglas and Loftis (1997) developed alternative spatial estimators for GW and soil measurements based on median estimation. These estimators produced better spatial representation of the phenomena. Due to time constraints, however, the proposed method was not tested and implemented in this study. A brief description of kriging is provided in Chapter 3.

As a representation of topography, the digital elevation model (DEM) has widely been used in hydrologic studies (Moore et al. 1991). Increasing availability of elevation point data and contours from topographic paper maps, as well as high-resolution images gave rise to the wide development of computer tools for the generation of DEM and derivation of primary and secondary topographic indices. For the description of the indices the reader is referred to Chapter 3.

Different algorithms for watershed delineation and drainage networks extraction (e.g. Tarboton 1997; Tarboton and Ames et al. 2001) from digital elevation models have been developed and widely used in studies of soil wetness indices, erosion and GW flow assessments. The development of methods to calculate topographic attributes (slope, aspect, or curvature) has provided the basic parameters required for flow routing and hydrologic models (e.g., Wilson and Gallant 2000, a). Flow tracing has allowed simulation of the movement of water, sediment, and other pollutants through landscapes and improved understanding and identification of potential sources of non-point source pollution.

García (2002) showed an example use of GIS and embedded distributed hydrologic modeling as a decision support system to assess and prevent flooding in a short period of time utilizing DEM. A method for predicting areas at potential salinization risk derived from high-quality DEM and remote sensing images was presented by Evans and Caccetta (2000). Existing soil salinity, soil types and GW depth and salinity were used together with derived topographic indices.

Example of using GIS tools and combining them with statistical tools to infer non-point source pollution was performed by Corwin et al. (1996). They used spatially distributed GW table and salinity, and soil properties to describe the sources of soil salinity in the Wellton-Mohawk irrigation district. Their conclusion was that GW electrical conductivity (salinity) and soil characteristics were the dominant factors governing soil salinization potential. The potential for GIS tools combined with statistical tools enabled for delineation of potential areas at salinity risk, which are dynamic over time. The implication is a management decision-making tool for better concentration of scarce resources for efficient management for sustainable food production.

Mohanty and van Genuchten (1996) described a conceptual framework for predicting basin-scale solute loading rates through and from the vadose zone coupling GIS tools with flow and transport deterministic models. They described how best to integrate currently available or future knowledge of surface hydrology, vadose zone hydrology, and GW hydrology so as to more effectively address specific non-point source pollution problems.

Ryan and Boyd (2003) described the new tool named CatchmentSIM that enables accurate hydrologic modeling using DEM and coupling in GIS. CatchmentSIM overcomes many of the limitations of the hydrologic algorithms adopted in the conventional GIS packages.

2.4 Features of GW table and salinity in the Khorezm region

In the plain topographic conditions of the Khorezm region GW is very shallow, and vertical movement prevails over horizontal flows in most of the area (Kats 1976). Within the whole region lateral GW flow is extremely slow being around 19 – 26 mm yr^{-1}, increasing to *ca*. 40 mm yr^{-1} in the areas of ancient river beds (Nurmanov 1966; Kats 1976). This creates adverse natural drainage conditions and requires constant operation and maintenance of artificial drainage network (Mukhammadiev 1982).

GW rises as a response to 1) hydraulic pressure caused by seepage from the canals, 2) recharge from the Amu-Darya River, and 3) deep infiltration of applied water for irrigation and the additional 'leaching' fraction. Locally, GW mounds occur near the canals during water conveyance over a distance of 200 – 600 m (Dzhabarov 1990). GW becomes shallow throughout the irrigated areas of the region partly including the adjacent non-irrigated lands. Precipitation does not have a significant influence on GW recharge (see Chapter 4 for details). Drainage discharge and ET constitute the main components of water outflow.

Seasonally GW rises during leaching and after irrigation events. Farther from the drains, GW outflow dynamics are largely influenced by evapotranspiration into the atmosphere. When inflow prevails over evapotranspiration and drainage capacity, waterlogging takes place (Hillel 2000). Salts dissolved in GW are forced into the topsoil and remain there as pure water evaporates, giving rise to soil secondary salinization. Annually GW becomes shallow during the growing period (March – August) and falls outside of it (September – February). GW regimes are thus largely determined by agricultural water management (Table 2.1). Climatic GW regimes cover a small part of the region far away from the irrigated fields.

Nurmanov (1966) showed that in the lower Amu-Darya River delta, GW rise after irrigation canals start conveying water to the fields at the beginning of the irrigation season occurs three times faster than GW fall. This has an important implication called 'seasonal salinity restoration', as upward GW table rise through capillarity takes place outside the growing season (in September – October) due to still high temperatures.

GW dynamics greatly depend on soil texture. In cases where the soils are fine-textured, the local lateral GW flow becomes difficult. Vertical GW dynamics (rise and fall) are slower than in the coarse soils, but GW rise is higher, which under particular conditions might reach the soil surface or come close to it. Coarser soils are easier to percolate, and lateral movement is also better. Salts can be retained in the fine-textured soils while they are easily flushed out in coarse ones. As a result, the phreatic surface is shallow in the fine-textured soils and its salinity higher, whereas it is deep and less saline in coarse soils.

Table 2.1: Genetic groundwater regimes in Khorezm

Indicator	**Specific GW input items (%)**			
	Irrigation water	**Precipi-tation**	**Filtration from the river**	**Underground inflow**
Irrigational	>75	<10	<10	<10
Irrigational – hydrological	25 – 50	<10	25 – 50	<10
Irrigational with increased subsurface inflow	50 – 75	<10	<10	25 – 50

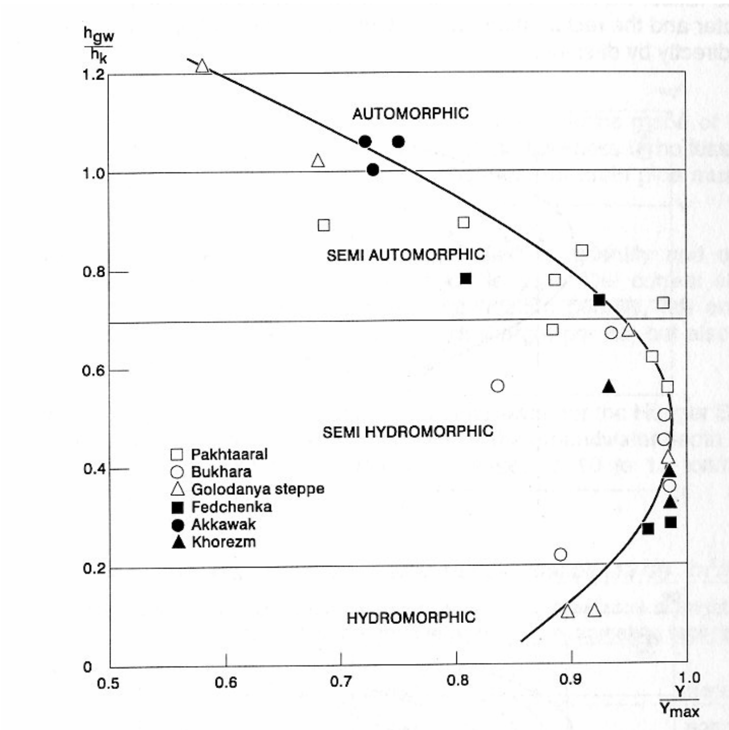
Source: Kats (1976)

In the case of a stratified structure of soils, the intensity of a GW table rise will depend on the order at which textural layers are present (Nurmanov 1966). As significant part of the soils in the region is stratified, this creates apparent difficulties in determining the best GW management strategies.

A shallow phreatic surface does not necessarily cause waterlogging and salinization (Hillel 2000). In cases where GW is non- or slightly saline, it can provide (additional) moisture to the root zone for plants, thus creating favorable growing conditions. Additional moisture coming from the shallow phreatic surface contributes to lowering the salt concentration in the soil root zone, and enables plant roots to take up nutrients. Irrigation-water supply can be reduced without yield losses. In such conditions it is desirable to allow the GW table to remain shallow. However, as a shallow phreatic surface could be a source of waterlogging, a defined specific threshold must be kept.

To recognize such phreatic surface conditions when GW influences soil moisture and salinity dynamics, the concept of 'critical GW depth' was defined, which received wide acceptance in the scientific community. Hillel (2000) showed that keeping GW below a certain level is indispensable for preventing the thread of waterlogging and salinity hazard, but lowering GW deeper than necessary does not give further effects and could be expensive. 'Critical GW depth' is defined as such phreatic surface level above which waterlogging and salinization may take place. Among many others it depends to a large extend on soil texture, hydraulic properties, and crops grown. Various studies conducted in the region and the other areas of the Amu-Darya River delta with similar conditions (e.g., Nurmanov 1966; Rakhimbaev, cited in Kats 1976) determined that an adverse impact of *saline* GW takes place when it reaches within 2.0 – 2.5 m, while with *low-saline* GW it should remain 1.0 m below the ground surface. Rakhimbaev (in Kats 1976) showed that preferably a GW table with a salinity level of 3 g L^{-1} should be kept below 1.9 – 2.5 m. Kiseleva et al. (year not known) defined phreatic conditions to be favorable when the GW table does not exceed 1.5 m and its salinity level is below 3.0 g L^{-1}. The variety of opinions about critical GW levels could be explained by the complexity of natural conditions in the region, mainly of soil texture, stratification and cropping patterns.

The height of capillary rise (h_k) and the depth to the GW (h_{GW}) have an effect on the water supply to the root zone (Dukhovny 1996, Figure 2.2). Four phreatic surface conditions are distinguished: hydromorphic, semi-hydromorphic, semi-automorphic and automorphic. Hydromorphic conditions occur when a major portion of the soil moisture comes mainly from shallow GW and much less from irrigation/precipitation. In contrast, automorphic conditions are determined by a deep phreatic surface, and moisture to the root zone is supplied from surface water application. The two other conditions are intermediate ones. Semi-hydromorphic refers to the condition when the relative proportion of water coming from the GW is higher than that from irrigation. Dukhovny (1996) claims that semi-hydromorphic conditions are the most optimal for Khorezm agriculture because the actual crop yield Y nearly reaches maximum yield Y_{max} (Figure 2.2). Rakhimbaev (in Shmidt 1985) conducted experiments in Khorezm to define the main conditions and factors that determine the GW levels under which waterlogging and salinization occur. The concepts of the critical threshold and assessment of the areas at risk of waterlogging and salinization are discussed in Chapter 4.



$$\frac{h_{GW}}{h_k} \approx 0.4 - 0.6$$

$$\frac{Y}{Y_{max}} \approx 0.95 - 1.0$$

Figure 2.2: Influence of relative groundwater level on cotton yield in Uzbekistan

3 MATERIALS AND METHODS

3.1 Area description

3.1.1 General information

The Khorezm region has a population of 1.3 million inhabitants as of 1999 (source: State Design and Research Uzgipromeliovodkhoz Institute) with a growth rate of ca. 2.8% over the past 11 years (MMS 1999) and a population density 230 people per square km. The total area is 562,192 hectares (Vodproject 1999), of which 275,000 ha are irrigated (MAWR 2000).

3.1.2 Location

The region is located in the northwestern part of Uzbekistan, in the lower Amu-Darya River reach (Figure 3.1). The region is surrounded by the deserts Karakum and Kizilkum, with an extremely arid continental climate. The geographic position of the region is between latitude 40°27` and 41°06` north, and longitude 58°31` and 61°24` east (Mukhammadiev 1982). The Amu-Darya River is at the northeastern border with the three districts of Karakalpakstan. The Dashhauz district of Turkmenistan and Amu-Darya district of Karakalpakstan form the northwestern border. Deserts are in the south, southwest and west of the region.

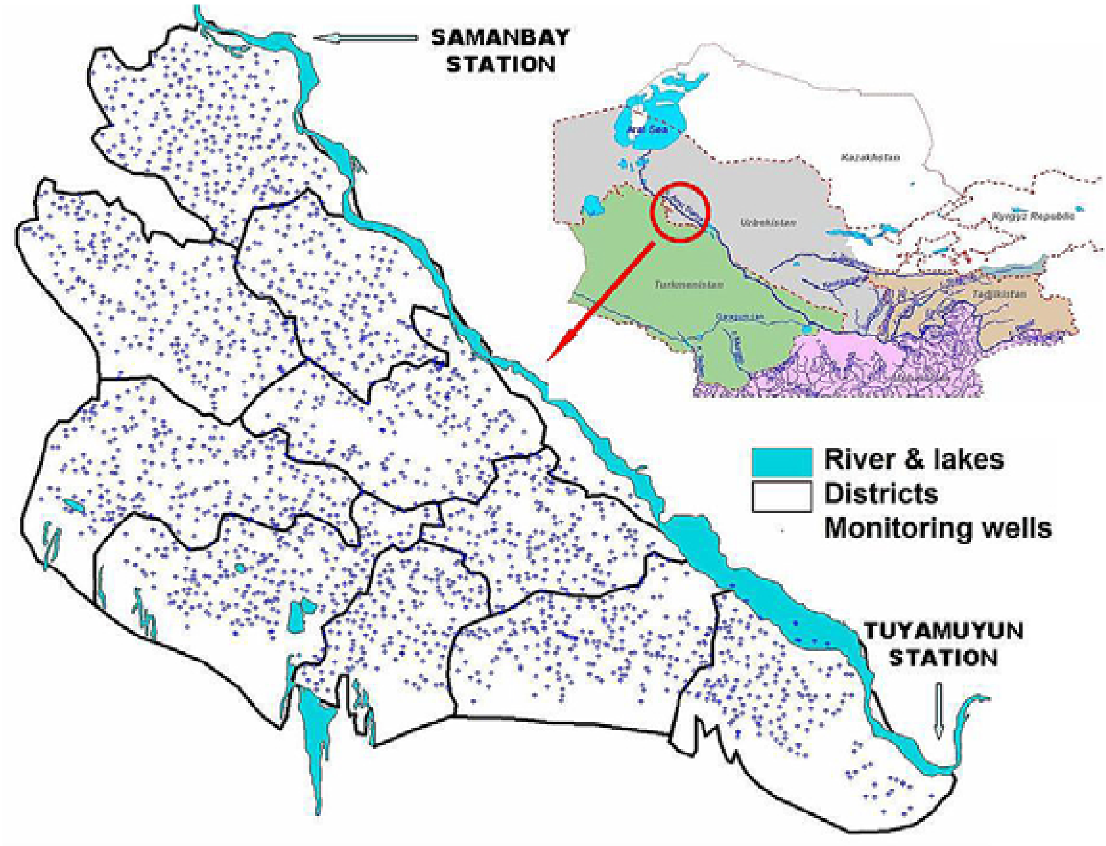


Figure 3.1: Distribution of monitoring wells and irrigation and drainage network in Khorezm

3.1.3 Climate

The climate in the Khorezm region is dry continental with very hot summers and cold winters (Mukhammadiev 1982; Kats 1976). According to the data from the Main Department of Hydrometcenter (Glavgidromet), the average temperature at the Urgench Meteorological Station during the period 1990 and 2000 in January was –2.2^oC and in July +28.2^oC (Table 3.1). Average maximum recorded *T* was +35.6^oC, observed in July, while average minimum *T* was –5.9^oC in January. According to Mukhammadiev (1982), the average maximum temperature during 1970 – 1980 in July was +28^oC, while the average minimum in January was –4.1^oC (Table 3.2). The temperature distribution pattern during the observation period follows the above values (Figure 3.2). Each line in Figure 3.2 indicates annual data within the study period.

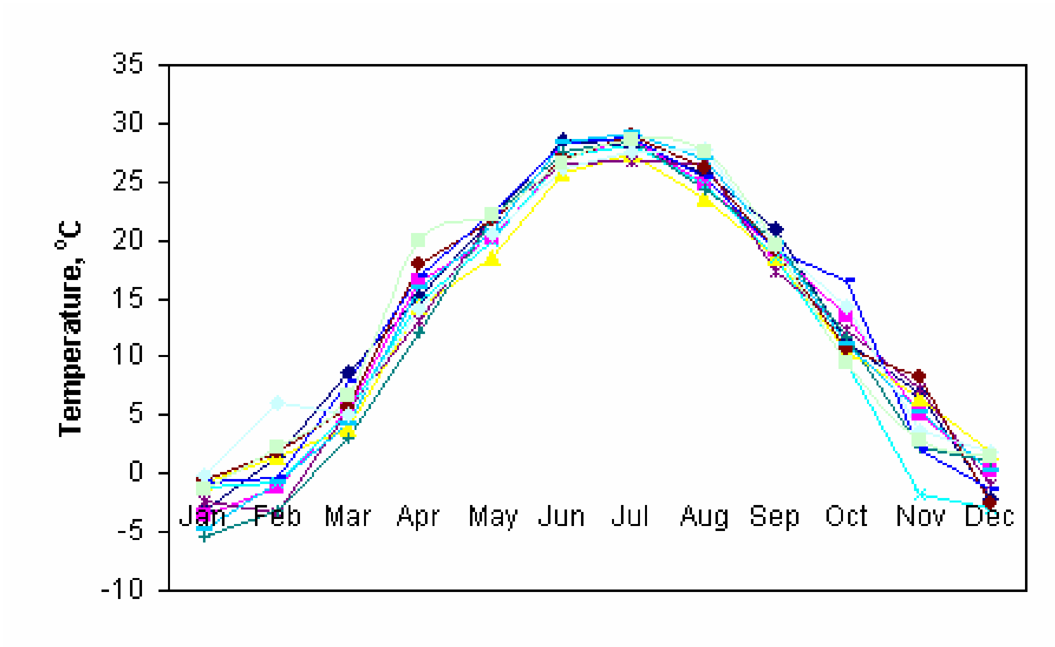


Figure 3.2: Long-term annual average temperature in Khorezm (1990 – 2000)

Source: Glavgidromet 1999

Table 3.1: Average annual meteorological indicators at the "Urgench" station in 1990 – 2000

Measurement period	**Average Air T (°C)**			**Average**		**Precipitation (mm)**
	Mean	**Max**	**Min**	**Soil T (°C)**	**Rel. humidity (%)**	
January	-2.2	2.6	-5.9	-1.6	80.0	13.7
February	0.3	6.1	-4.1	1.1	73.3	9.2
March	5.6	12.0	0.4	7.1	63.9	12.3
April	15.6	22.8	8.9	18.3	52.1	14.0
May	21.1	28.6	13.8	25.5	49.3	6.6
June	27.2	34.5	19.5	32.8	44.5	4.3
July	28.2	35.6	20.5	34.9	47.2	1.1
August	25.8	33.8	17.9	31.4	50.3	2.1
September	19.2	28.0	11.5	22.7	53.0	1.7
October	11.9	20.6	4.8	13.4	58.2	7.9
November	4.4	10.2	-0.6	4.4	71.6	10.2
December	-0.3	4.7	-4.3	0	80.2	8.3

Source: Glavgidromet 1999

Table 3.2: Monthly-average meteorological indicators at the "Urgench" and "Khiva" stations in 1970 – 1980

Period	Temperature (°C)	Relative humidity (%)	Potential evaporation (mm)	Precipitation (mm)
January	-4.1	75.0	16	5.6
February	-2.3	73.0	21	6.5
March	5.0	65.4	45	15.2
April	14.6	55.0	102	19.4
May	21.8	39.0	194	8.0
June	27.0	35.0	254	3.8
July	28.0	41.7	236	6.0
August	25.8	44.0	208	1.6
September	19.3	46.0	154	6.4
October	11.6	54.0	90	7.0
November	5.0	66.0	44	8.1
December	-1.4	77.0	19	9.2
Average	12.5	55.9	115	8.1

Source: Mukhammadiev (1982)

Table 3.1 shows that the high temperature and the low relative humidity occur during the four months May, June, July and August, leading to the highest water demand of the crops during these months. Precipitation is extremely low with an annual average of 90.4 mm in the period 1990 – 2000. Maximum rainfall was recorded in 1992 (173.4 mm) and a minimum in 1995 (34.8 mm). Precipitation does not have a significant influence on GW table dynamics except during rare wet periods. The number of precipitation days per annum generally does not exceed 35 – 40 days, which are scattered over the year. In contrast, potential evaporation is extremely high, exceeding the rainfall ca. 14 times (Mukhammadiev 1982). Evaporation rises in April reaching its maximum in July. Evaporation occurs even in winter, being 19 and 16 mm in December and January, respectively.

3.1.4 Relief, geology and geomorphology

The area of Khorezm is mostly flat with very gentle slopes. The slope extends from southeast towards northwest and from north towards south, being 0.00025 and 0.0002 m m^{-1}, respectively. Distinct micro- and meso-relief determines the presence of small local slopes of ~0.005 m m^{-1} (Mukhammadiev 1982). The topography of the region is distinguished by elevation points in the range 112 – 138 m asl (Kats 1976).

The meandering Amu-Darya River and its powerful ancient channels Dar'alik and Daudan intensively affected the soil lithologic structure in the region (Nurmanov 1966). The river carries sediments that are deposited along the river channel and temporary streams. As a result, coarse-textured particles deposited along the river banks have created levees, whereas finer textures deposited in the lowlands have given rise to heavy soils. After flooding periods, temporary streams changed into still lake water. Stratified soils originated in these areas, the stratification ranging from a few centimeters to some meters. Khorezm is called the 'ancient river delta', with a distinct contemporary river valley with so-called floodplain and first over-floodplain terraces, ancient flood-lands of the old river channels Dar'alik and Daudan as well as so-called Ozerno-Periphery (periphery lakes) areas (Tursunov and Abdullaev 1987; Popov et al. 1992).

Geological and hydrogeological investigations revealed that a heavy cover of quaternary depositions filled the depressions (Popov et al. 1992). The depressions intruded into the tertiary and cretaceous strata, which act as a basement rock, and from the hydrogeological viewpoint, form an impervious layer for the upper-stratum waters. The thickness of the quaternary stratum is 20 – 100 m.

The vertical cross-section reveals a highly stratified non-homogeneous structure, with the presence of local lenses. However, a certain pattern can be observed: the thickness of the upper loamy-clayey, sometimes sandy-loamy horizons is 1.5 – 2.0 m, which increases to 3 – 4 m over the ancient river channels, and to 6 – 8 m in the southern periphery of the region. This difference has a great influence on the GW table and salinity dynamics (Mukhammadiev 1982; Khodzhibaev 1979).

3.1.5 Hydrogeology

Kats (1976) defines "*hydrogeologic-climatic zoning*" and "genetic" types of *GW flow regimes* as criteria to assess the complexity of hydrogeologic conditions of irrigated areas. An assessment of the ameliorative conditions (levels of soil salinity, GW table and salinity) is based on those parameters. Hydrogeology in Khorezm is distinguished by difficult lateral GW flow and the prevalence of evaporation over outflow due to the dry arid climate, heavy soil textures and stratigraphy of the parent materials. As such, according to Kats (1976), Khorezm belongs to the category of basins of absent flow with moderately complex and complex hydrogeologic conditions.

GW regimes can be natural or human-induced (*i.e.*, affected by to irrigation). Climatic, hydrologic, subsurface inflow and mixed types are examples of natural regimes. There are three main GW regimes in Khorezm: 1) irrigational, 2) irrigational – hydrological and 3) irrigational with increased subsurface inflow (see Chapter 2).

The Amu-Darya River intensively influences the dynamics of GW in the floodplain and first above-floodplain river terraces, which cover a strip of land 2 – 3 km wide. That influence becomes weaker further inland. Irrigation practices determine the irrigational regime. It should be noted that despite the fact that the irrigated area constituted ca. 49% of the total area (Vodproject 1999), following irrigation the rising GW spreads into the nearby non-irrigated lands being thus more or less evenly distributed over larger areas. The third regime prevails over non-irrigated areas. Shallower GW tables are intensively evaporated in these areas during hot seasons causing land salinization.

The irrigational regime is distributed in most of the area and is characterized by (Mukhammadiev 1982):

– Occurrence of 'fresh GW lenses' of different sizes in response to irrigation,

– GW peaks and downs during seasonal irrigation and leaching, and annual rises and falls. The rates of rises and falls depend on the intensity of irrigation and drainage.

– GW fall is determined by movement toward drains in their vicinity and evapotranspiration (during growing period).

GW salinity is characterized by lower values in the vicinity of the Amu-Darya River, being of predominantly sulphate – hydrocarbonate and sulphate type. In contrast, the GW salinity level in the Ozerny region is of the chloride type (Mukhammadiev 1982; Kats 1976).

3.1.6 The Amu-Darya River

The Amu-Darya River is one of the two most important rivers of the Central Asian Republics (Dukhovny 2000, 2001). The average annual river flow is 75 billion m^3; the river has a catchment area of 309,000 km^2 and a total length of 2,540 km (FAO 2000).

It enters Uzbekistan upstream of the Surkhandarya region at Termez town and after meandering along the Turkmenistan-Uzbekistan border it flows into the Aral Sea. The sources of the Amu-Darya River are primarily snow and melting glaciers in the Tien Shan Mountains located in neighboring Tadjikistan and Kyrgyzstan (Chembarisov et al. 1989, 1996). Thus, major runoff occurs in the growing period, which is highly favorable for agricultural development in the basin.

The Amu-Darya River is the only major source of water for irrigation in Khorezm (Mukhammadiev 1982). Additional sources of water are local drainage and GW, which are used mainly in drought years. After the intensive development of the irrigation infrastructure in 1960s followed by huge water diversions upstream, the river began to drain the nearby area (Kats 1976). This was due to the significantly lowered levels of the Amu-Darya River, high water levels in the canals after switching to the gravity water supply in 1960s (Dzhabarov 1990), and rising shallow GW tables throughout the region. The long-term trends in the Amu-Darya River flow at the four monitoring stations along the different river reaches are shown in Figure 3.3.

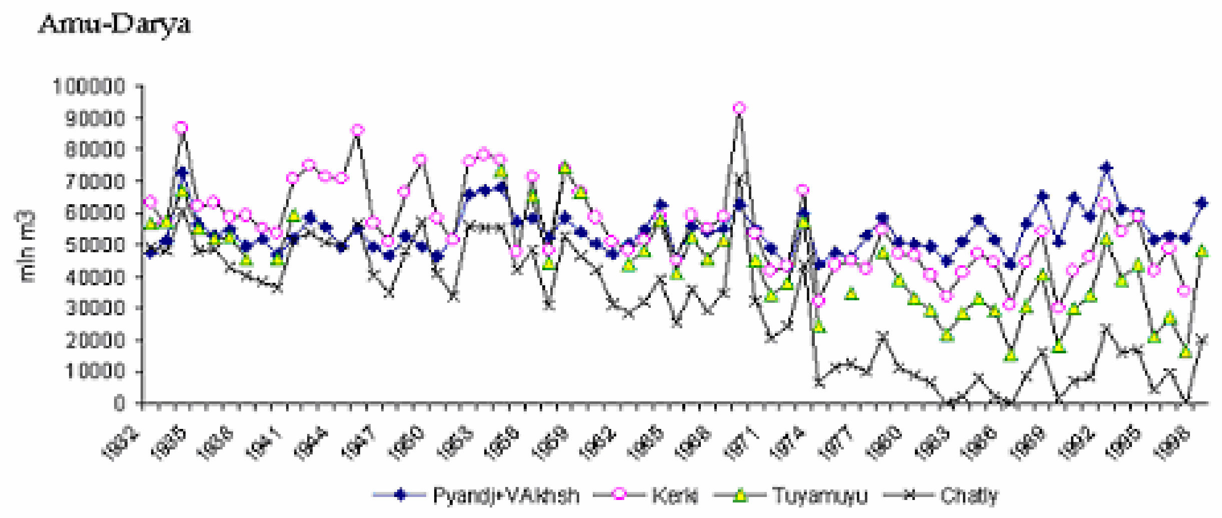


Figure 3.2: Long-term trend of the Amu-Darya River runoff for 1932 to 1999. The Pyandj-Vakhsh and the Kerky water-monitoring Stations are at the middle river reach, the Tuyamuyun Station is at the lower Amu-Darya River reach (the Khorezm region) and the Chatly Station is at the end reach of the Amu-Darya River

Source: FAO WAICENT

The river water quality is continuously deteriorating. According to Berdjansky and Zaks (1996), the change in salinity at the Tuyamuyun Station was from 0.51 g L^{-1} in the 1960s to 0.76 g L^{-1} in the 1980s and 0.91 g L^{-1} in the 1990s (Table 3.3). Data from

GME (only measurement station near the Tuyamuyun reservoir) showed changes from 0.91 g L^{-1} in 1991 to 0.94 g L^{-1} in 2000 (Table 3.4).

Table 3.3: Average salinity levels in the Amu-Darya River (Tuyamuyun Station, g L^{-1})

Period	**Salinity (g L^{-1})**
1956 – 1960	0.51
1961 – 1965	0.55
1966 – 1970	0.58
1971 – 1975	0.65
1976 – 1980	0.76
1981 – 1985	0.85
1986 – 1990	0.91
1990 – 1993	0.81

Source: Berdjansky and Zaks (1996)

Table 3.4: Salinity in the Amu-Darya River

Year	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Salinity (g L^{-1})	0.91	0.89	0.91	0.87	0.94	0.86	0.94	0.89	0.91	0.94

Source: GME 2000

Keyser (1996) showed that the Amu-Darya River has a cyclic salinization pattern. In early spring, melting waters are slightly saline. Saline leaching discharges lead to increases in water salinity, which remain such during summer and winter, until the next fresh water comes.

3.1.7 Soils

Soil horizons in the region, as in the whole river delta, were formed by ancient alluvium, covered by so-called agro-irrigational sediments (Tursunov and Abdullaev 1987; Popov et al. 1992). Intensive irrigation causes a constant increase in the body of the soils due to sediments from the river water. Shallow GW plays a major role in the soil formation processes.

Five distinct soil groups (Mukhammadiev 1982; Tursunov and Abdullaev 1987) exist in the Khorezm region: 1) meadow, 2) boggy – meadow, 3) meadow – ‘takir’, 4) boggy and 5) gray – brown soils. Dominant soils are meadow soils with different degrees of salinity. According to the FAO classification, the soils are 1) arenosol gleyic, calcaric (sodic), 2) arenosol, aridic, 3) cambisol, calcaric, 4) fluvisol, gleyic, humic and 5) solonchak, takyric and arenosols.

Until the 1960s, the Amu-Darya River carried ca. 0.1 km^3 of sediments into the delta; ca. 20 mm of sediment were deposited annually (Nurmanov 1966). However, after 1960, the river carried less sediment. Flow velocity during flooding exceeding 2 m s^{-1} caused erosion of the riverbanks and creation of new beds. The implication for this is a gradual rise of the irrigated fields and sedimentation of the canals and drains that require continuous maintenance.

Soil deposition can be divided into two broad classes: running and stagnant. Bringing sediments into the delta, the river created local highlands along its temporary streams and arms (Nurmanov 1966). Sedimentation of its bed forced the river to create new channels in topographically lower areas. Higher areas were thus filled with sands, and the lowlands, which originally had heavy-textured soils, began to be filled with sand. The areas between new and old channels underwent intensive sedimentation with heterogeneous alluvial particles, which gave rise to vertically stratified soil horizons, the horizontal extent being determined by the speed and direction of floodwaters laterally from currents.

Local lowlands farther from currents were filled with finer particles. As a result, clay and loam prevail in these areas, which are characterized by high salinization of the soils and extremely difficult ameliorative conditions.

According to Bogdanovich (cited in Nurmanov 1966), 20 % of the top 3-meter soil layer are alluvial sediments, 25% are stratified textures of mostly coarse origin and the rest 55% are so-called ‘lake’ or stagnant sediments (finer textures). Texture classes are as follows: particles of diameter 0.25 through 0.05 mm constitute 15 – 20%, diameter 0.05 through 0.01 mm 20 – 26% and less, and diameter >0.01 mm 55 – 60%. Thus, the soils developed in the Amu-Darya River delta are of heterogeneous stratified alluvial structure and texture.

3.1.8 Crops

Cotton (*Gossupium hirsutum*) is the most important crop in Uzbekistan, followed by wheat (FAO 2000). Uzbekistan is the fifth largest cotton producer and second largest exporter of cotton in the world after the US (http://www.ers.usda.gov/briefing/cotton/trade.htm). Much of the light industrial output is related to that crop, which is produced throughout the country and makes up about 40% of export earnings.

Cotton is a dominant crop in Khorezm (54.2% of the whole irrigated area in 2000). Rice occupied 8.2% before the introduction of winter wheat (9.4%) (DAWR 2002). Fodder and garden crops occupy the remaining irrigated areas.

Winter wheat (*Triticum aestivum*) was introduced in the region after independence in 1991. By promoting winter wheat, Uzbekistan aims at self-sufficiency in grain production. Following cotton, wheat is sown in mid-October and is harvested in mid-July.

Rice (*Oryza sativa*) is the third main crop grown in the region. Due to its geographic position, which is favorable for growing rice (plain deltaic area), the region was defined during former Soviet times as a rice-growing area.

Agricultural production in Uzbekistan is largely state-controlled. Targets for wheat, rice and cotton are set centrally and broken down by region, districts, and by individual farms. The state also directly controls production and prices of inputs and processing as well as exports of cotton and imports of wheat. The "State Order" system is set for cotton, wheat and partly for rice. District governors (and the public and private farmers in their jurisdiction) are compulsorily required to plant all available areas for each crop to fulfill the targets set each year.

3.1.9 Farming system

There are three main types of farming enterprises in Khorezm. In the public sector, the modifications to the farming system inherited from Soviet times are a transfer of state farms (*kolkhozes* and *sovkhozes*) into *shirkats,* which, however continue to operate very much like the old structures (FAO 2000). The *shirkats* are a transitional phase and are devolving into small private farms allocated to the *shirkats'* farm workers.

(Private) *farmers* and *dehkans* constitute the two other types of land management. Private *farmers* operate individual farms of 10 to 100 ha, depending on the area. The lease of their land is permanent and can be inherited by heirs. Despite their apparent legal independence, these farms depend heavily on the *shirkats* for irrigation, inputs and marketing and are often subject to the “State Order”, operative for wheat, cotton and rice. This category is intended eventually to include the bulk of farmers, but reform and privatization is moving slowly (FAO 2000).

"*Dehkans*" or household plots are limited by law to 0.25 ha of irrigated land. About half of this land is permanently situated and usually supports a house, while the other half is often temporary, moving from location to location within a *shirkat*. Most smallholders are part-time private *farmers*, and they grow a wide variety of crops. Some *farmers* cultivate for subsistence while others produce cash crops for income. They are an extremely important sector and account for a substantial proportion of agricultural output – reportedly 75% of food other than wheat that is produced in the country (FAO 2000).

In 2001 there were 114 state farms (*shirkats)*, 4818 private *farmers* and 182500 *dekhkan* farms in the Khorezm region as of 2002 (Vlek et al. 2001). There is no private ownership of land and no land market. *Shirkats* manage the majority of irrigated lands. Water within the region is distributed centrally by the Khorezm Department of Agriculture and Water Resources (DAWR) to the farms according to the size of the irrigated area in these farms and the crops grown.

A new system of water resource management and planning was recently introduced in the Amu-Darya River delta. The long discussions on effective use of water resources concerned the transition from administrative boundary water allocation to water management based on basin (sub-basin) boundaries. The new regulation (accepted in 2003) changed the structure of DAWR as well as of other regions in the delta, allowing the newly created *basin water resources association* (BVO) to make decisions regarding distribution of water to the Karakalpakstan, Khorezm and part of Bukhara regions.

3.1.10 Irrigation network and method of irrigation

From the 1940s, the main canals in Khorezm were reconstructed and the system of water diversion from the Amu-Darya River renewed (Kats 1976; Dzhabarov 1990). Before the 1930s, water was diverted by means of a simple water-wheal system allowing very little water diversion from the river (Mukhammadiev 1982; Dzhabarov 1990). With the construction of gravity-driven water head-gates in the Amu-Darya River, water use has increased sharply. Changes in water application amounts without the properly developed artificial drainage have led to GW rise that has worsened soil conditions (Dzhabarov 1990).

The water is supplied to the agricultural fields through a complex-hierarchy irrigation network consisting of main, inter-farm and on-farm canals. Temporary small ditches are constructed to facilitate water application to the field. The total length of the network was 15987.6 km as of 1997, of which only 10.9% was lined (Vodproject 1999). Sediments in the water of the Amu-Darya River clogged the bottoms and slopes of the canals, thereby increasing the efficiency of irrigation network. However, after the construction of the Tuyamuyun reservoir most of the sediments were deposited in the reservoir.

Surface furrow is the most common method of irrigation throughout the region. Negligibly small areas are irrigated with drip methods, mainly for research purposes. Papadopoulos (1996) argues that furrow irrigation rarely achieves an efficiency exceeding 50% at the farmer level due to non-uniform water application. Accurate leveling is the first factor among many for increasing water use efficiency and for coping with water scarcity in flat areas.

Water diversion form the Amu-Darya River is being realized through five irrigation canals. Tashsaka and Klichniyazbay are inter-region canals, water from which is supplied to the neighboring Turkmenistan. The Pitnyak-Arna, Urgench-Arna and Oktyabr-Arna canals supply water to the districts in Khorezm. Water supply measurements are done only at the intakes into main and inter-farm canals. The water is further distributed based on the calculation of the field areas in particular districts (farms) and crops grown. Water accounting is badly organized (Mukhammadiev 1982), resulting in huge water operational losses (tale-water) and recharge-contributing seepage losses.

To avoid water shortage problems, a system of water-storage reservoirs was constructed. The reservoirs are located at the eastern border of, at the entrance to, the region.

Leaching is practiced throughout the region as it is the main method for removing the soluble salts from the soil profile on a large scale and in a short-time period. Leaching water is distributed among the agricultural fields according to the soil salinity appraisal, which takes place in November. According to MAWR recommendations (1975), low saline fields should get ca. 4000 m^3 of water, moderately saline fields 5000 m^3, and strongly saline areas 6000 m^3. Water supply is divided into 2 – 3 applications of ca. 150 mm; time between successive applications is usually 2 – 4 days to weeks depending on water availability. Fields are divided into plots of 0.06 – 0.1 ha, and separated by ridges of 25 – 30 cm height. Water is first supplied to the fields located higher topographically, then to the lower fields to provide successive salt movement towards the drain.

3.1.11 Drainage network

The drainage network in the Khorezm region is mainly open horizontal. The total length of the network was 9254.9 km in 1997, while the length of the tile drains was 414.2 km (Vodproject 1999). The hierarchy of the drainage network is similar to the irrigation network in that on-farm drains collect discharge from the fields, while inter-farm and main drains collect and transport received drainage (while draining the nearby areas) out of the irrigated fields into the numerous small lakes located in the periphery of the region. The main receiver of drainage is the Sarykamish Depression, which was connected with the Aral Sea in former times. Very small amounts of drainage water are discharged directly into the Amu-Darya River. There remains an indirect adverse impact on the quality of the river of reduced water availability through diversion (reduction in the amount leads to increased salt concentrations).

Discharge and salinity in Khorezm is measured by Hydrogeologic Melioration Expedition (GME) staff once every 4 – 5 days. As it is extremely difficult to measure the discharge in each drain, only the inter-farm and main drains collecting drainage water from particular districts are measured. To estimate a drainage discharge of a particular district, the amount of the drainage effluent, transited by the main drains through the district from the upper-slope districts, is subtracted from the whole effluent leaving the district. On-farm drains are ca. 2 – 2.5 m deep, whereas inter-farm drains are 2.5 – 3.0 m. Main drains must be deeper in order to be able to receive and carry away all the drainage discharge from particular areas. However due to lithologic features (running sand at deeper horizons), it was not possible to achieve the designed depth for the main drains (Dzhabarov 1990). As a result the draining and carrying capacity of the whole drainage system are highly reduced. Drainage cleaning works could only maintain the achieved depth. The situation is aggravated by discharge of runoff surface waters into the drains thus actually increasing the discharge.

In order to improve drainage conditions in Khorezm, intensive reconstruction of the drainage network has been undertaken since 1942. Dzhabarov (1990) separated three distinct phases of the network reconstruction:

- *1942 –1950*, construction of local main and inter-rayon drains discharging drainage effluent to the local lakes and depressions

- *1950 –1961,* local lakes and depressions, which receive drainage discharge, were linked by the main collector drain *Ozerny* (*lake drain*), in order to lower water levels and release water out of the area (to the Sarykamish Depression)

- *From 1961,* main drains constructed, combining all the local drains into a network and discharging the majority of the discharge into the Sarykamish Depression.

The spatial influence of the drains depends on the geology, water-use pattern, depth of the drain and its wetted area, among other factors (Wolff 1996). Dzhabarov (1990) citing several researchers states that the draining ability of an open drain is ca. 160 –200 m to both sides.

3.2 Data collection and statistical analysis

This section describes the data collection, as well as the statistical analyses performed in this study to establish and explain the long-run spatio-temporal dynamics of GW table and salinity for the *whole* Khorezm region. Due to the nature of the analysis, a secondary data set was extensively used. Additional cite-specific information regarding the soil texture/conditions, possible factors influencing GW table and salinity and cropping patterns for the previous years (i.e., in the period 1990 and 2000) was collected during the field campaign. Data coding from paper to the Excel computer program, geographic coordinate identification and limited sampling for verification purposes were performed during fieldwork under the framework of the ZEF/UNESCO project with help of undergraduate students of Urgench State University. As the project aimed at local capacity-building, the students learned to use GPS, sampling techniques and introductory (geo)statistical analyses. The description of the data, analyses carried out and chosen methods are briefly summarized below.

3.2.1 GW table and salinity

GW table and salinity datasets were obtained from the Hydrogeological Melioration Expedition (GME) of the Khorezm Department of Agriculture and Water Resources, Uzbekistan. The data had been collected from monitoring wells during a period of 11 years (1990 – 2000). These wells were evenly distributed over most of the area (see Figure 3.1).

The GW table was measured every 5 days over the growing periods (March – August, including leaching) and every 10 days outside the growing period. There were 2300 monitoring wells as of 1990. Due to financial difficulties, which all the countries of the former Soviet Union faced, the maintenance and restoration of the existing and construction of new monitoring wells were reduced. In the year 2000, only 1987 working monitoring wells remained. The readings from these wells were retained for this study.

Where the GW table or salinity data were suspicious (e.g., too high/low salinity or too shallow/deep depth), field measurements were conducted using either the monitoring wells of GME or digging wells in the vicinity of the well. The GW salinity samples were analyzed using the hand-held express device of Chernishov, which allows analysis of the salinity of the water immediately after sampling. Some data appeared to be coded with errors, whereas the other data were true values. To gain understanding of the origin of unusually high/low values, the effects of environmental and management factors were assessed (visually or by communication with local specialists or inhabitants). When it was not possible to correct the data, erroneous data were deleted from the dataset.

The depth to GW is measured using a tapeline with a cylinder that flaps when it reaches the water surface in the well. A correction for the absolute elevation point for each well is performed by the GME staff for each measurement. GW salinity measurements are conducted three times a year every first day in April, July, and

October. The reason for conducting measurements in April is that the traditional leaching practice prior to irrigation takes place in March – April with the aim to remove the salts from the soil profile and to provide moisture to the soil in preparation for subsequent planting. Thus, evaluating GW salinity dynamics in April will help assess the influence of leaching practices on the dynamics of salinity in GW over time. July is a peak irrigation period when irrigation intensity is the highest. October falls outside the growing period, and the speed of the fall in the phreatic surface, when there is no recharge, can be assessed. The analysis of the GW table dynamics just outside the growing period is important, as seasonal salinity restoration might take place when an upward flux prevails over lateral outflow. The water samples are analyzed for total dissolved solids (TDS) and chloride content; TDS measurements were used for this study to characterize the GW salinity. The data were monthly-averaged.

The GW depth and salinity measurements were recorded only on paper. These data were coded in MS Excel (Microsoft Corp, Inc.), and the location of each monitoring well was geo-positioned using a handheld Garmin GPS 12 (Garmin International, Inc.) during fieldwork.

Monitoring wells were constructed with metallic pipes of different length (3 – 6 m), having an inside diameter of 90 – 110 mm. The different lengths used for construction of the wells are explained by the highly stratified nature of the soils in Khorezm. Wells were deeper in areas with heavy-textured soils (until the coarser soil is reached to ensure faster water movement to the perforated part of the well (pers. comm. with GME technician) and shallower in coarse soils. When the whole profile or underlying layer was running sand, the depth usually was 1.5 – 2 m below the ground surface. Sand – gravel filters were used to prevent fine soil particles from clogging the perforated parts.

3.2.2 Amu-Darya River runoff and salinity

The flow dynamics of the Amu-Darya River were assessed through measurements from two stations, the Tuyamuyun and Samanbay Stations, by the Main Department of Hydrometcentre (Glavgidromet) of the Cabinet of Ministers of Uzbekistan. The information about the water runoff in the river is probably measured daily from single points in the river reach. Monthly-averaged discharge measurements covering the period 1990-2000 were used in this study. The Tuyamuyun Measurement Station is located on the Amu-Darya River before it enters the eastern border of the region, and the Samanbay Station is on the western border with neighboring Karakalpakstan (see Figure 3.3). The difference in the discharges between these two stations allowed for the assessment of relative water-use patterns in Khorezm. For the estimation of the relative diversion and water use into the region the amount of water flow in the Tuyamuyun Station was subtracted from that of the Samanbay Station. Part of the water in this river reach is also diverted to the three districts in Karakalpakstan located on the right bank of the Amu-Darya River and a district immediately west of Khorezm. Water discharge (in billion m^3) was measured by sounding leads with spinners that measure flow velocity at different depths.

The salinity of the Amu-Darya River was obtained from GME, which has a single measurement point near the Tuyamuyun Station. The irrigation water salinity dataset is collected once every 10 days, and then monthly-averaged for further analyses. The TDS and Cl ions (in g L^{-1}) are measured; only TDS were used in this study.

3.2.3 Drainage discharge and salinity

Drainage discharge and salinity in Khorezm, which is measured by the GME, was used in this study. The drainage discharge is measured once every 10 days at the scale of a district by summing up the discharge in the main and inter-district drains coming from the topographically upper areas and subtracting it from the discharge leaving the district. Therefore, the number of measurement points equals the number of the drains passing through the district. The GME staff in each district has a map with the location of all the measurement points in the main and inter-district drains. The salinity in the drainage water is estimated by sampling water from the drains that transit discharge outside the district and taking average. The units of measurements are: drainage salinity in g L^{-1}, and discharge in million m^3.

3.2.4 Soil salinity

Soil salinity is measured by the GME. Soil salinity is assessed once every year after the growing period in November. Samples are measured in a laboratory in percent to soil dry weight from three soil depths (0 – 0.3 m, 0.3 – 0.7 m and 0.7 – 1.0 m) , which are then mixed to get an average of the 1–meter soil profile (SANIIRI 1975). The soil sample is then saturated with distilled water and the water extract is measured for the amount of soluble salts. Each sample covers ca. 10 – 20 ha and therefore, soil salinity sampling is much denser than GW samples. Three categories of salinity are distinguished: low saline area (0.02 to 0.06 meq L^{-1}), moderately saline (0.06 to 0.12 meq L^{-1}) and highly saline area (> 0.12 meq L^{-1}). Obtained salinity values are multiplied by the area that is assumed to be covered by samples (roughly 10 to 25 ha) to get the low, moderate and highly saline areas. To assess the long-term trends in soil salinity in Khorezm, the areas under the three above-mentioned categories were plotted on a graph. Since the total number of samples greatly exceeds 30,000 units, it was not possible to collect the secondary soil salinity data for the study period and geocode them for further interpolation.

3.2.5 Irrigation water use and salinity

The irrigation water use in the region is managed by the Khorezm Department of Agriculture and Water Resources (DAWR) based on the requests for water from the state farms. The state farms calculate their needs for water on a particular year based on the planned areas under crops. Water is then distributed by the district staff of DAWR after analysis of the water availability in the river.

Information on the irrigation water use is collected in a similar way to that of the drainage discharge, i.e., the total amount of water inflowing into each district by the main and inter-district canals is subtracted from the amount of the water leaving the district. The periodicity of irrigation water salinity measurements was identical to that of the Amu-Darya River salinity, i.e., every 10 days. Salinity estimation procedures in irrigation water are identical to the measurements of drainage discharge salinity, i.e., readings are obtained from the inflowing water. To assess the amount of salts entering and leaving a particular district, salts in g L^{-1} are multiplied by the amount of water (million m^3).

Apart from the measurements of water used in Khorezm, which are conducted by DAWR, the irrigation water use data are also available from the Khorezm Department of Statistics (KDS) and GME (data are supplied to these agencies by DAWR). Also, information on water distribution along the main canals supplying water to the Khorezm region and the autonomous republic of Karakalpakstan is available from the Department of the Amu-Darya River Irrigation Canals (UPRADIC). However, the dataset from UPRADIC was not used in this study. However, an assessment of the irrigation water use datasets taken directly from DAWR, GME and DMS showed high inconsistency among these datasets (Muller, unpublished). Therefore, a relative assessment of the water diversion and use in the Khorezm region during the study period was applied (explained in more detail in Chapter 4).

3.2.6 Irrigation/drainage network

The GIS layers of the irrigation and drainage network in Khorezm were digitized from cartographic maps at a scale of 1:50,000 by the Design Institute "Uzgipromeliovodkhoz", Tashkent. The distribution of the network is shown in Figure 3.1.

3.2.7 Soil lithology

The distribution of soil lithological zones (LZ) was made available to the ZEF/UNESCO project by the Design Institute "Uzgipromeliovodkhoz". More detailed information is available at http://www.fao.org/ag/agl/swlwpnr/ reports/y_nr /z_uz/uz.htm#hla.

3.3 Analysis

This section briefly summarizes the performed analyses followed by the discussion of the data processing and methods chosen for the study.

An analysis of temporal GW table and salinity changes over the period of 11 years (1990 – 2000) was performed to identify adverse trends in GW dynamics over time on a monthly and annual basis. The relations between GW table and salinity changes and streamflow dynamics, cropping patterns, drainage discharge over the investigated period for April, July and October were established using classical statistics and time series analyses.

Spatial dynamics of GW table and salinity were assessed through interpolated maps to obtain spatial distribution of these variables over the area. Four types of interpolation methods were used, among which are ordinary kriging (Isaaks and

Srivastava 1989), inverse distance weighted (IDW), spline and triangulated irregular network (TIN) (ArcGIS help). Other types of information (irrigation and drainage network, soil lithology, digital elevation model and its derivatives) were overlaid on GW layers in ArcView 3.2 GIS. A digital elevation model (DEM) was produced using the kriging and IDW methods (Hutchinson 1995). Data extraction and import into statistical software packages (S-Plus 6.0, SPSS 11.0) were performed for further analyses. Regression model and analysis of variance (ANOVA) were used to establish the relations between, and explain changes of, GW table and salinity with other variables.

A change detection method (Park et al. 2003) was applied to identify the changes that had occurred in GW salinity over time. The construction of the DEM and its derivatives, as well as the change detection method is described in more detail in the consequent sections below.

3.4 Data processing and methods

The assessment of GW flow characteristics based on topography was done by means of a DEM. The DEM was used to construct primary and secondary topographic indices. DiGeM (Conrad 1998), Idrisi (Clark Lab) and ArcInfo (ESRI, Inc.) were used to produce DEM and indices. The definition of DEM, as well as the indices and the algorithm used to create them, are described below.

3.4.1 Elevation data and DEM construction

The DEM was constructed for the whole Khorezm region with a grid size 15 x 15 m based on point elevation data (1910 readings). Ground truthing was not performed. The points were extracted by the ZEF/UNESCO project in Khorezm from topographic maps with the scale 1:50,000 and 1:100,000. The following topographic indices were produced: *aspect, curvature, plan and profile curvature, slope,* and *wetness index*. These indices were used to explain the variation in spatial dynamics of GW table and salinity in the region.

Elevation

Elevation is a height above the mean sea level. Among many possible applications, this index could be useful in studying surface and subsurface (GW) movement, sediment and solute transport.

Slope

Slope is a maximum rate of change in elevation and describes the steepness of terrain, determines the overland and subsurface flow, the energy of possible flow and thus, water and solute transport capacity. The steeper the slope the greater is the potential for water movement and solute transport.

Aspect

Aspect encompasses direction of steepest downhill. Aspect is important in studying evapotranspiration, and determines the direction of water movement along the steepest descent.

Curvature

This index represents a general areal curvature. It is calculated from the plan and profile curvature:

Profile curvature

Profile curvature is the curvature of the surface in the direction of the slope. This index is used to describe the rate of change of slope and identifies zones of the flow rate. Surface convexity and concavity are captured by this index. Flow acceleration and deceleration are greatly affected by particular profile curvature: surface- and groundwater will accumulate in concave areas thus giving rise to possible salinity accumulation, whereas concave curvatures increase surface flow rates and would probably result in deeper GW.

Plan curvature

The area with the surface perpendicular to the direction of slope is called plan curvature. It shows the rate of change of aspect. The plan curvature can be convex, indicating divergent flow, whereas in concave areas the flow will converge. Convergence indicates concentration of runoff and possible GW accumulation, and divergence being the opposite, will dissipate the runoff.

Wetness index

This index shows areas with soil moisture potential, accumulation of surface and groundwater and solutes. Thus, an analysis of potential waterlogging and salinization processes and areas prone to it can be performed.

3.5 (Geo)-statistical analysis

Statistics provide strategies and tools for using data to gain insights into real problems (Moore and McCabe 1999). They are used for collecting, organizing and interpreting numerical representation of the environmental variables. Given the temporal and spatial nature of the GW table and salinity, the following approach was chosen to achieve the objectives of this study:

- Exploratory data analysis,
- Interpolation,
- Environmental correlation.

3.5.1 Exploratory data analysis

When exploring the data, their interrelations, statistical grouping, spatial distribution, clustering, etc (Bourgault et al. 1997), the researcher should be attentive to any clue the data may give that may prove useful in later interpretations. Any uncovered features the particular dataset possesses could lead to failed results in future inferences.

Spatial analysis of distribution is also important, as it could reveal single outliers or clusters of high and low values. Whereas single values are most probably errors of different nature, clusters may be true representation of the variable under investigation (Isaak and Srivastava 1989). Since outliers may distort further interpretations, there must be a good judgment whether to retain or remove them.

3.6 Methods of interpolation

To assess the spatial distribution of the GW table and salinity, deterministic and geostatistical interpolation methods were used in this study. Brief descriptions of the kriging, IDW, spline and TIN interpolation methods are given below.

Classical statistics are powerful in qualitative and quantitative data analysis, but they do not take the spatial locations of data into account (Isaak and Srivastava 1989). Observations located spatially closer are more likely to have more common values than those located farther apart. The location-specific estimates of mean and variance of the samples will be more precise that the usual confidence intervals would indicate. Field properties have been recognized as showing spatial dependence (Cressie 1992). Geostatistics deal with spatially distributed variables provided than the exact locations have been recorded (e.g. with help of GPS).

Geostatistics are used when there is a need to estimate values at unvisited places based on actual point measurements. The estimated (calculated) values are then used to produce maps of the environmental variables. This allows correlation analyses with other environmental data. The accuracy of the raster maps produced depends heavily on the grid size set initially for interpolation. A reliability of the estimates is usually done via statistical estimation and calculation of confidence intervals about the estimates. However, there are a number of estimation techniques available for spatially dependent random variables that may produce different maps (Douglas and Lotfis 1997).

3.6.1 Kriging

Ordinary kriging is the popular interpolation method. It analyses and models the spatial dependency of the field measurements and calculates location-specific estimates and estimation errors using an estimator optimal for an assumed distribution of the data (normal or log-normal). If the estimation errors follow a known probability distribution, confidence intervals can be constructed for each estimate. However, usually many environmental data are not normally distributed and in most cases contain numerous outliers (Loftis et al. 1991). Thus, parametric estimators may fail to reliably model results.

In ordinary kriging, the first step is to construct a variogram from the scatter point set to be interpolated. A variogram consists of two parts: an experimental variogram and a model variogram. The experimental variogram is found by calculating the variance $\gamma(h)$ of each point in the set with respect to each of the other points and plotting the variances versus distance *h* between the points (Figure 3.4).

The existence of trends or *drift* must be checked before constructing a sample variogram. Drift is a systematic increase in values in a particular direction. The identified drift must be incorporated in the experimental variogram to produce correct maps of the investigated variables.

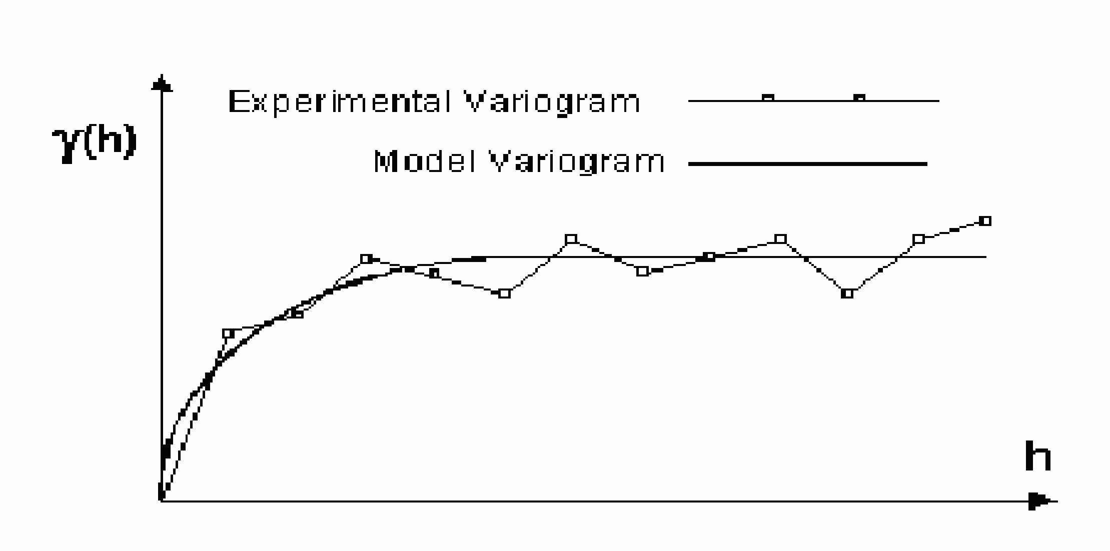


Figure 3.4: Experimental and model variograms used in kriging

Dots connected by lines represent estimated variances between the pairs of points separated by certain distances. The pairs located closer have smaller variances than those located farther apart. This is referred to as autocorrelation between the pairs. After some distance *h*, however, the variances become similar, i.e., do not increase. The autocorrelation becomes weaker with distance until at some certain *range* (separation distance) the calculated values are no longer are correlated. There are two more important parameters of experimental variograms. With the *range*, the squared differences in pairs of points reach the *sill*, i.e., the hypothetical least squares line though the points from the *range* onwards will be parallel to the x-axes. *Nugget effect* or *nugget variance* may be present in most environmental variables. It is a value of the experimental variogram at the origin, which must be 0 (the differences of the readings with themselves). However, measurement error or too broad distance between the readings might cause a jump of the variogram from zero to a value at very small separation distances, creating discontinuity at the origin.

Analysis of the variograms provides insight into the spatial features of the variable under investigation. Variogram *cluster* or *cloud* will reveal the apparent direction of the spatial continuity, e.g., preferential GW flow. *Range* will indicate the areal extent of similar values. A *nugget variance* is indicative of the location of observation wells being too far from the neighboring ones or measurement errors that resulted in large differences of readings among adjacent wells. That information should be assessed and recognized to be properly accounted for in interpretation.

Once the experimental variogram is computed, the next step is to define a model variogram. A model variogram is a simple mathematical function that models the trend in the experimental variogram. A brief description of the models and the underlying formulas is provided below.

Spherical model

$$\gamma(h) = 3/2(h/a) - 1/2(h/a)^3 \text{ for } 0 \leq h \leq a,$$

where h = lag or distance in x, y space,

a = range, at which a sill is reached.

Spherical models reach a sill at the range a, and the behavior at the origin is linear.

Exponential model

$$\gamma(h) = 1 - \exp(-(h/a))$$

Gaussian model

$$\gamma(h) = 1 - \exp(-(h/a)^2)$$

Kriging is a global interpolator. Global interpolation methods calculate predictions using the entire dataset. An interpolation technique that predicts a value that is identical to the measured value at a sampled location is known as an exact interpolator. Kriging is regarded as an exact interpolator provided there is no high nugget variance. Kriging is the most computer-intensive method used by a Geographic Information System (GIS).

3.6.2 Inverse Distance Weighted method

The Inverse Distance Weighted (IDW) interpolation method is a deterministic method. Deterministic means that IDW creates surfaces from measured points based on the extent of similarity compared to geostatistical (e.g., kriging), which utilizes the statistical properties of the measured points. The IDW is a local interpolator, i.e., predictions are made from the measured points within neighborhoods, which are smaller spatial areas within the larger study area. A deterministic interpolation can either force the resulting surface to pass through the data values or not. IDW is an exact interpolator.

The IDW interpolation method explicitly implements the assumption that spatially closer variables are more alike than those that are farther apart. To predict a value for any unmeasured location, IDW uses the measured values surrounding the prediction location. Closest values to the prediction location will have more influence on the predicted value than those farther away. Therefore closer points get more weight than those farther. Weights are proportional to the inverse distance raised to the power value. The optimal power value is determined by minimizing the root mean square prediction error (RMSPE). IDW produces best results if sample points are evenly distributed throughout the area and if they are not clustered.

3.6.3 Spline

Spline enforces two conditions during interpolation: 1) The surface must pass through the data points, and 2) the surface must have minimum curvature. This method is best suited for gently varying surfaces within a short horizontal distance, where change in physiography or any other phenomenon is not abrupt. It is not appropriate if there are large changes in the surface within a short horizontal distance because it can overshoot estimated values. Two options are available to achieve the interpolation: regularized and tension. Tension modifies the minimization criterion so first-derivative terms are incorporated into the minimization criteria (ESRI 1992). A larger “weight” argument increases the stiffness of the interpolation to conform to existing data. In comparison, the regularized option produces a smoother surface than those created by the tension option. The regularized weighted values between 0.5 and 0 are often suitable for many interpolations, while weighted values for tension can range between 0 and 10 (ESRI 1992). The regularized method yields a smoother surface compared to that of the tension method.

Like kriging, the spline method can be exact or non-exact depending on the user-specified parameters (http://www.usapa.army.mil/USAPA_PUB_search_p.asp).

3.6.4 Triangulated irregular networks

Triangulated irregular networks (TIN) represent three-dimensional surfaces in contrast to raster surfaces, which are created by kriging, IDW and spline. Raster represents a surface as a regular grid of a rectangular array of uniformly spaced cells with z-values. The smaller the cells, the greater the areal precision of the grid. TINs represent a surface as a set of irregularly located points linked to form a network of triangles with z-values stored at the nodes. The edges in TINs can be used to capture the position of linear features that play an important role in the surface such as ridgelines or stream courses. Because the nodes can be placed irregularly over the surface, TINs can have a higher resolution in areas where a surface is highly variable or where more detail is desired and a lower resolution in areas that are less variable or of less interest.

The input features used to create a TIN remain in the same position as nodes or edges in the TIN. This allows a TIN to preserve all of the precision of the input data while simultaneously modeling the values between known points. TIN models are less widely available than raster surface models and tend to be more expensive to build and process. The cost of obtaining good source data can be high, and processing TINs tends to be less efficient than processing raster data because of their complex data structure. TINs are typically used for high-precision modeling of smaller areas, such as in engineering applications, where they are useful because they allow calculations of planimetric area, surface area, and volume.

3.6.5 Validation

Validation is a method of assessing the performance of the interpolation methods to estimate values of the variable of interest at unknown locations through the analysis of the estimation errors (ArcGIS help). The calculated statistics serve as diagnostics that indicate whether the model and/or its associated parameter values are reasonable. Both validation and cross-validation use one or more data locations and then predict their associated data using the data at the rest of the locations. In this way, the predicted (estimated) value is compared to the observed value. The lower the estimation error the better the model estimates the unknown values.

Cross-validation uses all of the data to estimate the trend and autocorrelation models. Then it removes each data location, one at a time, and predicts the associated data value. For all points, cross-validation compares the measured and predicted values. In a sense, cross-validation "cheats" a little by using all of the data to estimate the trend and autocorrelation models. After completing cross-validation, some data locations may be set aside as unusual, requiring the trend and autocorrelation models to be refit.

Validation first removes part of the data, the so-called ‘test dataset’ and then uses the rest of the data, the ‘training dataset’ to develop the trend and autocorrelation models to be used for prediction. Validation creates a model for only a subset of the data, so it does not directly check the final model, which should include all available data. Rather, validation checks whether a "protocol" of decisions is valid, for example, choice of semivariogram model, choice of lag size, and choice of search neighborhood.

ArcGIS 8.2 provides an excellent tool for automatic generation of the cross-validation table and graphs for the ordinary and universal kriging interpolation methods. As for the IDW, spline and TIN interpolation methods, an original dataset was transformed into the test and training datasets. The test dataset in all the cases consisted of 10% of all of the data, and the training dataset of 90%.

3.6.6 Time series analysis

Availability of data arranged in time sequence enabled using an autoregressive integrated moving average (ARIMA) model for data analysis (Gupta 1999). Time series analysis is based on the assumption that successive values in the data set represent consecutive measurements taken at equally spaced time intervals. As in most other analyses, in time series analysis it is assumed that the data consist of a systematic pattern (usually a set of identifiable components) and random noise (error) which usually makes the pattern difficult to identify. Most time series analysis techniques involve some form of filtering out noise in order to make the pattern more salient. Gupta (1999) provided a comprehensive description and example of use of time series analyses in SPSS.

3.6.7 Groundwater recharge

Groundwater recharge is defined as water entering the saturated zone of an aquifer. It is a part of the concentrated precipitation or irrigation water over a certain area, which raised the GW table. Although a recharge does not necessarily mean waste of water as it can be recovered later, it shows ineffective water use, which was applied in larger than required amounts (except for the leaching fraction – certain amount of water used to dilute and move salts down from soil profile). Besides, increased salinity or toxicity levels in the GW would mean that it could not be reused later.

GW recharge was estimated utilizing the method reviewed in Healy and Cook (2002). It is based on GW level data and is applicable only to unconfined aquifers. This approach is termed water-table fluctuation and assumes that water recharging the aquifer goes into storage. It allows estimating the recharge over longer time intervals to produce an estimate of the change in subsurface storage. It is referred to as a *net* recharge. The *net* recharge is a difference in head between the second and first times of GW measurement. It therefore includes the input and output components of the storage that occurred in the period between the measurements. This method is best for shallow water tables, which follow frequent rises during irrigation/rainfall events and declines afterwards. If, however, the lateral GW flow to adjacent areas is fast, the method will not be appropriate, as it would estimate no recharge.

In arid and semiarid areas, high rates of ET and low precipitation dictate the need for the so-called *leaching fraction (LF).* It is a coefficient showing the part of the water applied in excess of the plant moisture requirements that must percolate down in order to dissolve and remove at least part of the salts from the soil profile (Ayers and Westkot 1985). Therefore, to estimate inefficient water use, the leaching fraction must be subtracted from overall recharge.

The equation to calculate the *LF* is:

$$LF = \frac{ECw}{(5 * ECe) - ECw)}$$

where *ECw* is salinity of irrigation water and *ECe* is the average soil salinity that could be tolerated by crops grown.

The *water requirement* (*WR*) that needs to be applied to achieve this *LF* depends on crop *ET* according to:

$$WR = \frac{ET}{(1 - LF)}$$

ET values were taken from Mukhammadiev (1982) and verified using data from Glavgidromet. Temperature, air humidity, wind speed and daily sunshine for the Khiva Meteostation were used to estimate monthly-average ET_o (mm day^{-1}) utilizing the Penman-Monteith method.

3.6.8 Change detection method

Detection of changes is an essential step to identify the causal relationships of any directional changes within the study region. Many ecological and environmental studies have proven that accelerated changes often occur in some localized areas (“hotspots”), while the majority of land surfaces showed gradual transitions or evolution from one state to another. Identification of such “hotspots” may greatly enhance an ability to identify significant processes underlying dynamics of investigated variables and allow more site-specific and targeted ecological and policy interventions.

For spatio-temporal environmental data, simple map comparison is often of limited use due to inherent seasonality of environmental variables. A simple multivariate statistical approach was developed to detect general long-term trends, which was first applied in a savannah landscape in Ghana to identify the human-induced land cover changes (Park et al. 2003). This approach was implemented in the study to account for the spatiotemporal changes in GW salinity.

In this approach, the total variance in spatio-temporal environmental data consists of three variance components:

$$\partial_t^2 = \partial_d^2 + \partial_s^2 + \varepsilon$$

where ∂_d^2 is caused by any directional or long-term trend, ∂_s^2 is due to seasonal and cyclic changes, and ε is the remainder or error term, which includes noise of data caused by measurement and instrumentation errors. The errors associated with measurement are difficult to separate from spatio-temporal data sets, and therefore they should be considered as a random error. The variance component caused by seasonal variations is the result of the time of irrigation, quality of incoming water, and possible weathering rates. After separating the seasonality and error components from the total variance of the GW salinity, the remainder should yield the long-term temporal changes.

In order to separate the variance component caused by the seasonal trend and the random error components, it is assumed that the variance of the GW salinity is linearly correlated with its mean. From the geochemical point of view, this implies that a higher concentration of solutes in the GW shows higher seasonal variations over a certain period of time. Park and Vlek (2003) studied various spatio-temporal data sets and conclude that many of them indicate a power relationship between the mean and total variance. Linear relationship was attained after their log-transformation.

4 TEMPORAL DYNAMICS OF GROUNDWATER TABLE AND SALINITY

4.1 Introduction

The GW table, its salinity and soil salinity are among the major factors that influence agricultural sustainability in Khorezm. Two types of effects can be observed from rising water tables and subsequent intensification of evaporation from the soil. *Negative* effects could be soil waterlogging and salinization, whereas *positive* ones are moisture supply into the soil profile (see Chapter 3).

The dynamics of GW table and salinity occur due to the linkage and interaction of GW with environmental factors, among which are climate, diverse soils, geology and hydrogeology. Changes in management practices related to land and water resources use in combination with the influence of environmental factors would inevitably result in complex interactions with GW, and in turn, the possible occurrence of the above-mentioned effects. The main concern is to maintain favorable conditions while taking necessary actions to avoid negative ones. This can only be achieved by understanding the causes of the changes in those influencing factors.

Negative effects on soil conditions (soil moisture, salinity, etc.) occur in areas where the GW is shallow and saline. A critical depth is defined for shallow GW tables, above which soil conditions may deteriorate because of waterlogging and salinization and the land productivity will reduce. A comprehensive summary of the discussion of the critical depth in Khorezm and in the other regions of Uzbekistan is provided in Shmidt (1985). Critical depth is found to be dependent upon several factors, among which are soil properties, soil salinity, GW salinity, ET and precipitation, methods of irrigation and agro-techniques, and crops grown. The critical depth is best defined based on the observed crop yields and taking into account GW table, soil and GW salinity. Kats (1976) recommended the following ranges of critical depth for the conditions of Khorezm based on lysimetric experiments:

- For floodplain and first-level near-floodplain areas (near the Amu-Darya River and main canals) 1.5 – 2.0 m,

- For the rest of the areas, which are distinguished by slow lateral and vertical water flow, 2.0 – 2.5 m below the ground surface.

Rakhimbaev (in Shmidt 1985) conducted experiments to define the critical depth to GW for conditions of Khorezm. According to his data, the critical depth varies between 1.0 and 2.8 m, being lower with higher GW salinity (Table 4.1).

Table 4.1: Critical depth to groundwater in Khorezm

GW salinity (g L^{-1})		**Average critical GW table (m) under Cl ion contents (%) in 1 m soil profile**		
TDS[1]	Cl[2] ion	0.005%	0.01%	0.015%
1 – 3	0.164 – 0.494	1.0	1.0 – 1.1	1.0 – 1.5
3 – 5	0.494 – 0.822	1.0 – 1.2	1.0 – 1.5	1.9 – 2.5
5 – 8	0.822 – 1.314	1.8 – 2.2	1.5 - 2.2	2.5 – 2.7
8 – 10	1.314 – 1.64	2.2 – 2.3	2.2 – 2.4	2.7 – 2.8

Source: Shmidt 1985
1TDS: total dissolved solids
2Cl: Chloride ion

Rakhimbaev found that the best yields of cotton in Khorezm were achieved over GW tables at a depth of 1.5 – 2.0 m but they depend to a great extent on the levels of GW salinity. This result was in agreement with that of Kiseleva et al. (year unknown). Table 4.2 (Shmidt 1985) shows the critical level of the GW table defined for Khorezm. It is seen that the critical depth of GW varies not only depending on GW salinity but also on soil texture and time of the year.

However, it should be noted that a shallow GW table does not always lead to salinization and waterlogging. According to Dukhovny (1996), Rachinsky (in Shmidt 1985) and Mukhammadiev (1982), shallow GW can provide a partial moisture supply favorable for plant growth (creating semi-hydromorphic conditions). In order to avoid soil salinization, percolation is necessary (at least temporarily) to leach out the accumulated salts from the root zone. Semi-hydromorphic conditions are favorable for Khorezm because surface water is not always available in the region, especially in areas remote from canals and the river, and good yields can be achieved provided leaching or irrigation with a leaching fraction is practiced (FAO 1992).

Table 4.2: Critical groundwater table for the Khorezm region based on soil texture and groundwater salinity

Period	GW salinity ($g\ L^{-1}$)	Level of GW under soil texture		
		Light	Medium	Heavy
	< 1	1.2 – 1.3	1.4 – 1.5	1.5 – 1.6
April	1 – 3	1.4 – 1.7	1.6 – 1.9	1.7 – 2.0
	3 – 5	1.7 – 2.0	1.9 – 2.1	2.1 – 2.3
	< 1	1.1 – 1.2	1.3 – 1.4	1.4 – 1.5
July	1 – 3	1.2 – 1.5	1.4 – 1.6	1.6 – 1.8
	3 – 5	1.5 – 1.8	1.7 – 1.9	1.9 – 2.1
	< 1	1.0 – 1.1	1.1 – 1.2	1.2 – 1.3
October	1 – 3	1.1 – 1.4	1.3 – 1.5	1.5 – 1.6
	3 – 5	1.4 – 1.7	1.5 – 1.8	1.8 – 2.0

Source: Shmidt 1985

The argumentation from the above-cited authors about the levels of GW appears contradicting. Indeed, it is difficult to judge how favorable or negative the situation is when assessing the sustainability of agriculture in Khorezm. However, one aspect was clearly defined by all the researchers and concisely summarized in Shirokova (2000): to ensure high land productivity, GW tables must be deeper and salinity lower in heavier textured soils compared to lighter textured ones. Therefore, the assessment of the areas that experience salinization and waterlogging should be done based on the water tables and their salinity levels, taking into account soil textures as another major critical factor. Only this will enable proper estimation of the negative temporal changes.

From the above, it follows that it is not possible to judge whether the irrigated areas in Khorezm experienced negative or positive temporal changes based on the separate assessment of the dynamics of GW table and salinity during the study period. Since soil lithology must be included in the assessment, it will be necessary to identify the spatial areas at risk of waterlogging and salinization from shallow saline GW in different textural classes during the study period.

4.1.1 Quality of groundwater salinity readings

The complete dataset of GW table and salinity was collected from the 1987 monitoring wells. Construction of the wells began in the 1960s (Kats 1976). Every year, new wells were added to the existing ones, gradually covering a wider area, until their number reached 1987 in 2000. This monitoring network belongs to GME and is the most widely distributed in Khorezm, which allows continuous assessment of the dynamics of GW table and salinity. After the breakdown of the Soviet Union financial difficulties have led to a substantial reduction of the construction of new and reconstruction/repair of the existing wells. Relocation of the wells that occurred in the areas of expanding urban areas in Khorezm has also slowed down during the study period. Thus, a number of values are missing in the dataset.

GW table and salinity samples were drawn from the wells, which have different, inhomogeneous depths, but in most cases perforate much deeper than the 3 meters as reflected in the documentation of monitoring wells at GME. The reason for this is as follows: The instructions for sampling the GW salinity issued by MAWR (1975) define that before sampling the GW for salinity measurements, the water accumulated inside the well must be pumped out and only the freshly inflowed water be collected. Only such water is considered to contain salts similar to those of the surrounding environment. A wide distribution of heavy textures in the upper horizons, where lateral subsurface water flow is extremely slow (see Chapter 3) and existence of sandy textures in the lower horizons, where subsurface flow is faster, forced the GME staff to locate the perforated parts of the wells in a sandy texture to avoid waiting hours until water flowed into the well. The number of technicians in each district equals the number of the farms. The average size of the farms is 1000-2000 ha. Since only one technician is assigned the task to collect samples or measure the GW table over the farm, and taking into account the size of the area and poorly equipped district departments with vehicles, the deep placement of the perforated parts of the wells was the generally accepted practice.

Dzhabarov (1990) investigated the soil conditions in Khorezm from the 1960s till the 1980s based on a literature review and through analysis of the data from the monitoring wells of GME. He showed that the readings of the GW salinity from the monitoring wells rarely exceeded 2 – 3 g L^{-1}. When laboratory analyses at GME revealed higher salinity levels, such values were considered erroneous and samples were drawn again. Dzhabarov showed that the salinity readings taken just near the monitoring wells but from upper heavier textured horizons are 2 to more than 4 times higher than those taken from the monitoring wells of GME. Personal samplings as well as the unpublished data of Forkutsa (pers. comm.) in 2001 showed similar results.

The explanation of the phenomenon of higher salinity levels in GW in upper soil horizons lies in the textural soil distribution. It is known that salts accumulate in heavier textures more than in lighter sandy textures. Khodzhibaev (1979) argued that the most saline soil strata in Khorezm are the upper GW strata, the salinity decreasing downward. Only at a substantial depth (10 m and deeper) GW salinity levels increase again. This is due to the fact that downward percolating surface water dissolves salts that are contained in the soil profile. These salts end up in the top GW layer and do not move further down since, according to Dzhabarov, there is little exchange of water and salts in upper and middle GW layers. This leads to the creation of a saline upper GW layer. Systematic underestimation of real salinity values can easily lead to inadequate decisions in agricultural management which jeopardizes agriculture through the ensuing constant soil salinization.

However, not all the measurements from the monitoring wells of GME should be discarded as non-reliable. According to Dzhabarov (1990) and Tursunov and Abdullaev (1987), GW salinity in upper light textures or well-leached soil profiles in Khorezm is very much similar to that in deeper profiles. Khodzhibaev (1979) and Mereshinsky (in Shmidt 1985) found that GW salinity in the region is similar along the profile of homogeneous soils. The changes in salinity are therefore similar throughout the depth under consideration (until the perforated part of the wells). However, it is difficult to separate those wells that are located in homogeneous and stratified soil profiles, due to the high variability of textures in the region.

4.1.2 Quality of groundwater table readings

Dzhabarov (1990) also discussed the problems related to proper estimation of GW tables from the monitoring wells of GME. Due to the expansion of urban areas, changes in land and water use as well as due to the developments of engineering facilities, some wells ended up outside or at the edges of the fields, or near newly constructed canals or drains, roads, etc. The readings of water tables from such wells could deviate from the actual values. Dzhabarov conducted an experiment on an 8-ha field to estimate the influence of the canals, drains and local topography on the GW table readings from 81 wells. The analysis showed that the readings from these wells ranged from 0.98 to 1.72 m with a coefficient of variation of 25%. The difference of topography within the field was 1.3 m; the influence of the above-mentioned factors together with the wetting front from irrigation canals was strong. These readings indicate that within one field two GW regimes occurred: hydromorphic and semi-hydromorphic. It is known that these two regimes have a different impact on agricultural production. The former leads to salinization problems even with low or medium saline GW, the latter is the most favorable if GW is not highly saline. Therefore, the readings of GW table in the monitoring wells of GME could be higher (water table shallower) or lower depending on the above-mentioned criteria. Further analysis of the representativeness of the monitoring wells that belong to the GME done by Dzhabarov revealed that only in the Yangiarik district the network of monitoring wells showed a true picture. Those of the Khazarasp, Bogot, Khiva and Yangibazar districts are fairly representative, whereas the networks in the rest of the districts are weakly representative.

The discussion above shows that readings of GW table must be precise in order to distinguish between hydromorphic and semi-hydromorphic conditions. Lack of precision can lead to improper estimation of the actual size of areas at risk from hydromorphic conditions. Areas with deeper GW tables can be regarded as experiencing intensive soil salinization and resources can be improperly allocated to such areas for prevention purposes, whereas the real areas at risk from shallow GW tables elsewhere can be overlooked. An attempt to estimate the location of the 1987 monitoring wells in the vicinity of canals, drains or other infrastructure with the help of GIS (in ArcView 3.2) was undertaken. It was, however, extremely difficult to trace each and every well, and therefore the best possible decision is to assume that the obtained findings were *relatively* correct. However, for reconnaissance purposes, more detailed field investigations are required to declare some particular areas to be at risk from shallow GW table.

In this chapter, temporal dynamics of the GW table and its salinity were analyzed to determine significant annual and seasonal changes that occurred in the Khorezm region during the period 1990 through 2000 and to identify the causes that determined these changes. Identifying the changes would help assess the influence of the GW table on agricultural sustainability within the study period and identify the factors that play a role in changing those conditions. Based on the results of the analysis of the temporal changes, the measurement periods were chosen for the spatial assessment of the areas at risk from shallow saline GW and delineation utilizing the interpolation methods (described in Chapter 5). These areas are targeted for future intervention measures. The objectives of this chapter were to 1) estimate the temporal changes in GW table and salinity during the study period and 2) identify the causes of the negative changes.

4.2 Characteristics of groundwater table and salinity in Khorezm

4.2.1 Seasonal dynamics of groundwater table

This section describes the seasonal dynamics of GW table during the months April, July and October 1990-2000. April represents the start of the growing season when leaching is applied, July the growing season, and October the month of harvest. The descriptive statistics of the GW table are shown in Table 4.3. The observed ranges of the GW table in all the three measurement periods indicate a prevailing shallow water table in Khorezm. The shallowest GW was found during the growing period (July), being on average around 125 cm below the ground surface over the 11 years, whereas the deepest water tables were recorded outside the growing period (October), being on average 182 cm. The GW tables in the upland regions of the Ferghana valley are 2.5 to 3 m, in the middle-reach regions (Kashkadarya, Navoiy, Samarkand) they are 2 to 3 m. Even in the regions similar to Khorezm in topographic conditions (lowland irrigated areas of the Syrdarya and Dzhizak regions) the average water tables are 1.5 to 2 m (GME unpublished annual reports). A shallow GW table means that it was close to, and in some parts of the region exceeded, the defined ‘critical threshold’.

During the study period, the average GW table in *April* was 136.8 cm. As the GW table in Khorezm during the winter periods is 2 – 3 m below the ground surface (Kats 1976), it must rise quickly following leaching, becoming shallow throughout the region. The average minimum GW table values, on average for the 11 years, was about 38 cm, the average maximum 400 cm. Standard deviation was 41.7 cm and coefficient of variation (CV) was 32.6 cm, showing wide local fluctuations in the levels of the water tables, because some areas experienced shallow water tables of 1 m below the ground surface (hydromorphic, negative conditions), whereas in other areas the levels of GW were 170 – 180 cm (semi-hydromorphic, favorable conditions).

Table 4.3: Descriptive statistics of groundwater table in cm for April, July and October in the period 1990 – 2000

Statistics	Measure-ment period	Year										
		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Mean	April	150.4	139.8	130.9	136.02	125.9	134.6	131.8	136.4	131.2	141.0	146.5
	July	119.6	114.7	117.1	121.36	120.8	124.9	117.2	128.5	122.7	128.6	164.6
	October	228.1	204.7	197.9	190.95	182.2	164.7	154.9	159.4	157.6	163.1	199.3
St.Dev.	April	45.2	43.4	43.5	43.2	41.4	44.3	43.9	44.5	43.9	47.4	48.9
	July	44.2	43.6	48.1	45.9	45.6	45.3	44.5	44.4	44.0	46.4	54.4
	October	54.1	53.7	56.6	59.4	58.1	54.1	51.4	52.6	50.4	51.6	60.3
Kurtosis	April	0.93	0.82	0.96	2.65	2.76	1.87	1.93	2.36	2.02	1.41	1.62
	July	1.15	1.58	2.72	2.15	1.49	1.78	2.96	1.95	1.43	1.47	0.96
	October	0.01	0.15	0.29	0.06	-0.08	0.11	0.64	0.41	0.57	0.74	0.48
Skewness	April	0.65	0.77	0.78	1.03	1.08	0.88	0.98	0.96	0.96	0.8	0.92
	July	0.91	1.12	1.33	1.18	1.02	0.95	1.27	0.93	0.94	0.95	0.73
	October	-0.17	-0.01	0.02	-0.04	0.05	0.38	0.61	0.53	0.47	0.56	0.51
CV	April	30.1	31.1	33.2	31.7	32.9	32.9	33.4	32.7	33.5	33.6	33.4
	July	36.9	38.0	41.0	37.9	37.8	36.2	37.9	34.5	35.9	35.9	33.0
	October	23.7	26.3	28.6	31.1	31.9	32.9	33.1	33.0	32.0	31.6	30.3
Min.	April	39	51	29	41	23	23	50	43	39	41	33
	July	34	50	35	34	33	29	31	34	29	40	40
	October	59	50	51	51	23	45	41	48	43	28	36
Max.	April	403	311	320	416	419	428	428	424	417	431	433
	July	336	300	414	377	363	421	402	420	370	383	456
	October	377	374	440	433	389	441	416	417	400	437	456
Count	April	1825	1931	1942	1945	1935	1916	1901	1865	1809	1757	1508
	July	1731	1884	1908	1900	1889	1864	1840	1793	1735	1687	1368
	October	1875	1941	1943	1932	1926	1901	1881	1818	1747	1631	1129

Source: Hydrogeologic Melioration Expedition 2001

The average GW-table levels during the observation period in *July* were recorded at 121 cm below the ground surface. The readings from the year 2000 were excluded from the average because this was the year of severe drought in Khorezm and the readings would have distorted the average value over the study period. The readings are steady-state since they were obtained well before or after irrigation events and so there was sufficient time for excess subsurface water to flow out. It is seen that the levels reached the critical threshold throughout the region. According to Forkutsa and Khamzina (unpublished data), shortly after irrigation events, GW tables in the experimental farm of the ZEF/UNESCO project in the Khiva district of the Khorezm region often reached 0.5 m, far exceeding the critical threshold levels. The CV for July (37%) was higher than for April measurements. Standard deviations, which are indicative of the spread of the values around the mean, revealed that lower readings (shallower GW tables) were far above 1 m. The minimum and maximum values were similar to those of the April measurements. This questions the capacity of the drainage network in Khorezm to sufficiently lower water tables during the growing periods.

Just after the growing period in *October,* an average GW table of 182 cm was recorded, which was slightly less than for April and July, but still showed a wide CV of 30%. Usually at this time, few cropped areas if any remain. After cessation of the region-wide irrigation the GW tables in other regions of Uzbekistan fall far beyond 2 – 3 m (GME, unpublished reports). In contrast to this, the GW tables in Khorezm are shallow even outside growing periods. Shallow water tables just outside growing periods can easily lead to the seasonal restoration of salts in soil as, in absence of downward percolating surface water, upward salt movement through soil capillaries occurs (see chapter 3). Higher GW table readings over the study period (standard deviation 55 cm and minimum values 43 cm) indicate that GW tables in October were unacceptably shallow and some local areas probably experienced salinization.

The descriptive statistics reveal that minimum values of the GW table in April, July and October were similar. The maximum values were also similar. Theoretically this situation is highly unlikely, because of the varying irrigation intensity and evapotranspiration in these months. Similar values could be explained by constant natural or management conditions (e.g. different soil textures, distance to irrigation or drainage canals, etc.). However, it is most likely that the readings stem from individual wells that are located far beyond irrigated fields or very close to constant water bodies, e.g., lakes. Therefore, those readings appear to be outliers, which could affect further analyses.

The descriptive statistics of the GW table indicate that water tables were shallow in all the measurement periods, being ca. 1 m below the ground surface in April and July, and 1.5 m in October. Compared to the critical levels in Table 4.2, it is seen that hydromorphic conditions prevailed in a substantial part of the irrigated areas in Khorezm over the study period. Information about GW salinity and soil lithology is necessary, but it can already be seen that a substantial part of the irrigated areas in Khorezm experienced waterlogging and possibly salinization. At the offset of the growing period (in October), the areas may have experienced "seasonal salinity restoration".

4.2.2 Seasonal dynamics of groundwater salinity

GW salinity in Khorezm was analyzed for the same measurement periods as for the water tables. Table 4.4 shows the descriptive statistics of GW salinity in April, July and October. Mean values of GW salinity for these measurement periods were quite similar being 1.81 g L^{-1} in April, 1.77 g L^{-1} in July and 1.68 g L^{-1} in October, which can be categorized as *low-saline*. This indicates that in areas with GW tables deeper than the critical levels, partial (less than 40%) moisture supply from GW will not cause intensive soil salinization in Khorezm (Sorokina 1985). Maximum salinity values were far beyond 10 g L^{-1}, reflecting locally highly saline GW, whereas minimum readings were around 0.5 g L^{-1}, corresponding to freshwater levels.

Average readings of GW salinity in April and July were at the level of ~ 1.8 g L^{-1}, with minimum recorded values of 0.5 g L^{-1} and maxima of 13 – 17 g L^{-1}, a range from almost freshwater levels to highly saline. Where GW salinity levels were low-saline, the risk of salinization is not substantial. In areas with the lowest values of GW salinity, it is even recommendable to keep GW tables at the level 1.5 – 1.6 or shallower (Kiseleva et al. year unknown). However, locations with maximum readings (high-salinity category) are at risk of soil salinization.

The average GW salinity values in October were similar to those of April and July (1.68 g L^{-1}), also falling into the low-saline category (Table 4.4). The CV of GW salinity for October was slightly higher than in April and July, being on average for the 11 years 57.5%. The standard deviation was similar to that of July, being 0.97 g L^{-1}. Thus, GW salinity only slightly reduced in October. Similarity of GW salinity in all the measurement periods is an unexpected outcome, since after the growing period the GW table usually falls because of cessation or reduction of (surface) water inputs. Normally, the lowering of the GW table is accompanied by an increase in salinity. The observed stable concentrations of GW salinity in October allows two explanations: either there is an outflow of some amount of salts with the drainage water, or, since lateral and deep vertical GW flow in Khorezm is negligible (Sorokina 1985), there is an upward movement of salts into the upper soil horizons. Since the first situation is unlikely, because the GW table in October (1.8 m) was near the bottom of most drains in the region (the depth of on-farm drains is ca. 2.0 m), salts from GW may have moved upward.

Table 4.4: Descriptive statistics of groundwater salinity in April, July and October in the period 1990 – 2000

Statistics	Measurement period	Year										
		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Mean	April	1.97	1.90	1.91	1.82	1.61	1.81	1.72	1.70	1.78	1.85	1.85
	July	1.84	1.77	1.79	1.71	1.80	1.75	1.71	1.73	1.72	1.79	1.85
	October	1.78	1.65	1.70	1.65	1.71	1.62	1.54	1.64	1.73	1.77	1.73
St.Dev.	April	1.10	1.09	1.16	1.11	1.12	0.96	0.91	0.92	0.86	0.88	0.91
	July	0.97	1.03	1.12	1.08	1.06	0.90	0.92	0.85	0.85	0.89	0.87
	October	1.07	0.98	1.19	1.09	1.13	0.85	0.86	0.83	0.86	0.94	0.87
Kurtosis	April	15.81	32.64	22.95	33.30	87.89	8.54	10.57	16.02	18.74	6.37	9.41
	July	13.94	28.13	42.44	39.22	15.33	10.95	13.43	10.94	17.83	7.25	10.63
	October	20.92	31.04	46.57	27.71	43.22	5.51	20.58	6.47	10.58	13.34	6.35
Skewness	April	3.1	4.0	3.7	4.2	6.1	2.3	2.5	2.8	2.8	1.9	2.2
	July	2.9	3.8	4.8	4.6	2.9	2.4	2.8	2.5	2.6	2.1	2.2
	October	3.4	4.0	5.1	3.9	4.4	1.9	2.9	1.9	2.2	2.4	2.0
CV	April	56.1	57.5	60.6	61.2	70.0	53.2	52.9	54.3	48.0	47.6	49.3
	July	52.9	58.0	62.6	62.9	58.8	51.7	54.0	49.0	49.7	49.8	47.0
	October	59.7	59.5	70.4	65.8	66.1	52.6	55.7	50.4	49.4	52.9	50.3
Min.	April	0.47	0.28	0.58	0.51	0.50	0.50	0.58	0.50	0.61	0.43	0.60
	July	0.50	0.53	0.55	0.50	0.49	0.55	0.50	0.50	0.56	0.48	0.50
	October	0.56	0.60	0.54	0.52	0.55	0.55	0.54	0.50	0.45	0.48	0.56
Max.	April	13.0	16.9	12.9	15.9	24.0	10.1	10.7	12.9	12.9	9.7	10.7
	July	10.8	13.1	17.3	15.9	12.9	11.2	11.4	10.0	12.9	8.8	11.4
	October	14.0	14.7	18.0	14.1	20.0	8.6	12.9	8.8	10.9	12.9	8.2
Count	April	1914	1922	1985	1979	1980	1970	1970	1970	1970	1969	1948
	July	1943	1910	1973	1978	1978	1970	1970	1970	1970	1948	1943
	October	1982	1856	1981	1980	1978	1970	1970	1970	1948	1948	1948

The minimum values of GW salinity for all the three measurement periods were identical, which is also true for the maximum values. This is similar to the minimum and maximum readings of the GW table, and therefore similarity of the readings could be explained by the location of monitoring wells either near constant water bodies or in close vicinity of canals or drains.

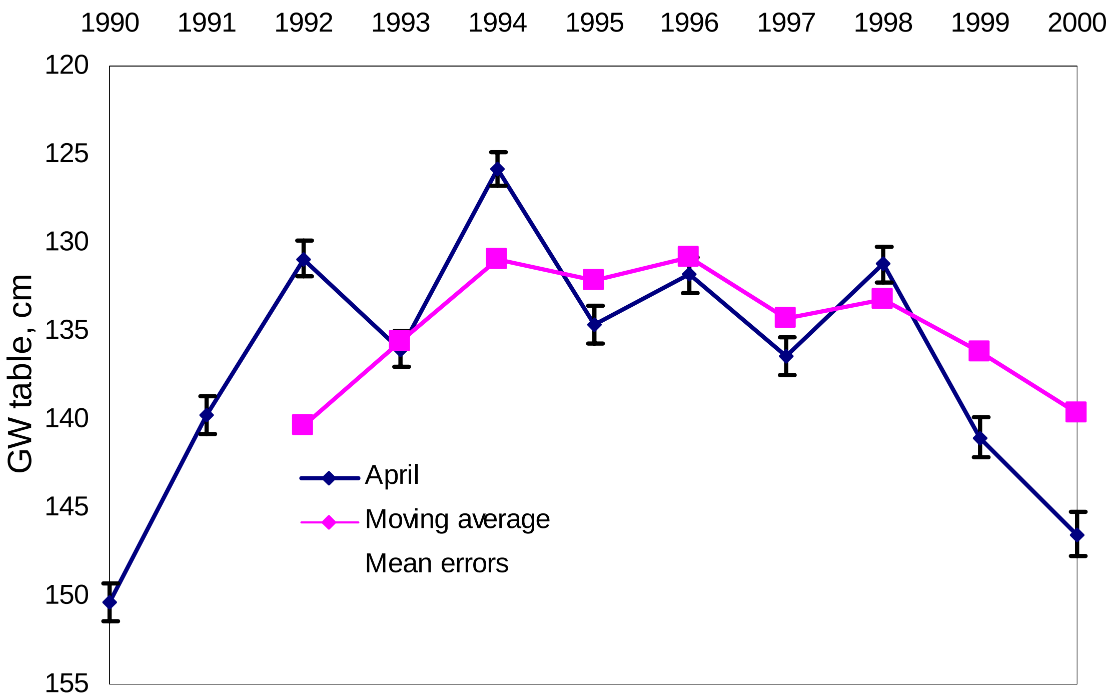
To summarize, the average GW salinity in all the measurement periods can be categorized as low-saline. This low-saline character of GW was observed in all the measurement periods over the study period despite the different intensity of irrigations. The salinity levels indicate that a risk of soil salinization exists only in areas with shallow GW tables that reached the critical threshold, whereas in areas of semi-hydromorphic conditions (GW table is ca. 1.5 – 1.6 m) it is even desirable to keep GW at shallow levels due to its low salinity. This may explain the observation of the farmers' common practice to maintain high GW tables. Although these generalizations are valid, there already are areas with extremely saline GW in areas that will need special attention, which will be discussed later.

4.3 Temporal dynamics of groundwater table and salinity

The aim of the analysis of the temporal dynamics is to identify the significant changes in GW table and salinity over the study period, to explain their effect on agriculture in Khorezm and to find out the causes for these changes. In the subsequent sections, the analyses of the temporal dynamics of GW table salinity during the study period are presented and conclusions drawn. The temporal analyses of the average readings of GW table and salinity were performed utilizing moving average techniques. Significant changes in temporal trends of GW salinity were identified by the analysis. A spatial assessment of the areas which experienced significant changes enabled an assessment of the areas at risk from shallow saline GW. Finally, those factors that led to changes in the identified temporal trends were determined.

4.3.1 Groundwater table changes

The dynamics in average GW tables in April, July and October are shown in Figure 4.1. Over the study period, GW table readings in April and October were more dynamic than those in July. In April, the GW table varied from 150.1 cm below the ground surface in 1990 to 125.8 cm in 1994. Following that year, the average GW table dropped to 145.7 cm in 2000. During the growing period in July, the water tables were shallow with average values ranging from 114.7 to 128.2 cm. Only in 2000 did they fall steeply to 163.3 cm below the ground surface. In October, a gradual rise in the GW table was observed from 228.2 cm in 1990 to 154.9 cm in 1996. From 1996, the phreatic surface was constant until 1999 (162.1 cm), after which it fell to 197.2 cm in 2000.



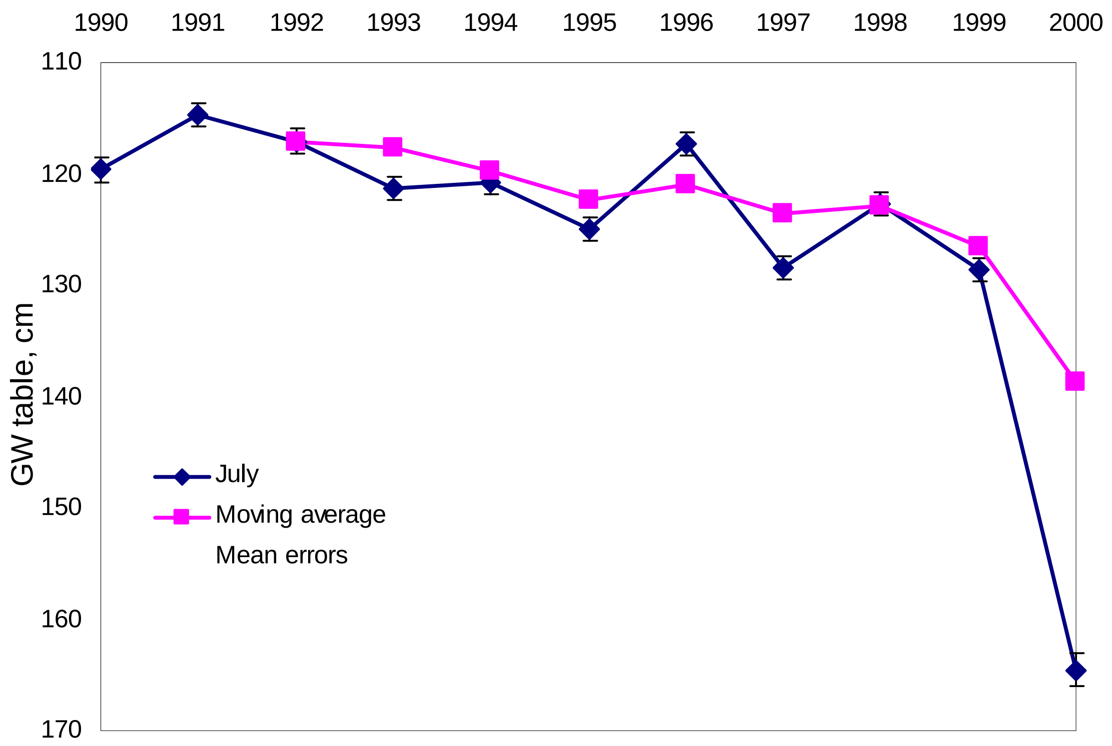


Figure 4.1: Average GW table in April (a), July (b) and October (c) 1990 – 2000

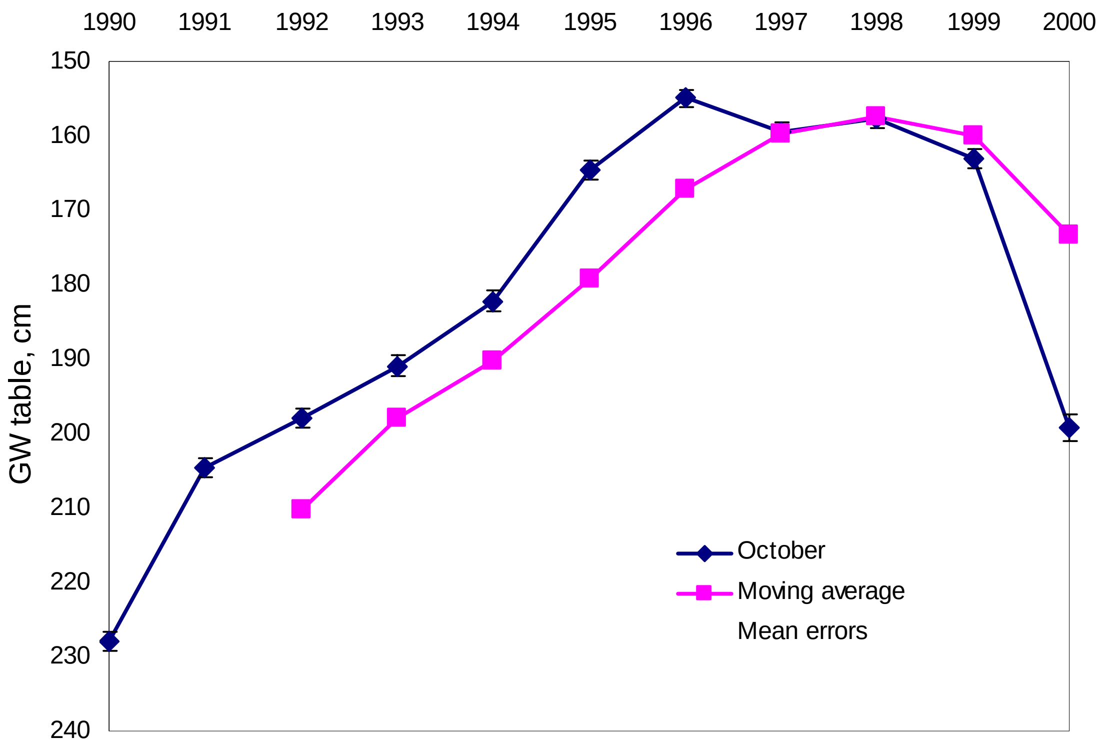


Figure 4.1: Continued

The observed temporal changes in GW tables during the study period suggest a trend in the July and October measurements, possibly related to a change in land and water management practices or natural conditions during the study period. There was an increasing change in average GW table in the measurement periods for April until 1994, with a decreasing pattern afterwards. Therefore, the readings of the GW table in 1994 and 1996 in April and October, respectively, were chosen for further analyses, and a statistical analysis of the difference in the means of these readings from those of 1990 and 2000 was performed in SPSS. For July the same years as for April, were analyzed.

To be able to state that the changes of the dynamics of GW table in the three measurement periods were not only fluctuations around the average but significant, a statistical analysis was performed. Prior to looking for significant differences in the means of the readings, it was necessary to check the dataset for statistical distributional assumptions. Histograms revealed that the distribution of GW table values in April and October was right-skewed (Figure 4.2). There were some outliers in the data set. Outliers can be either data typing/instrumentation mistakes or a representation of reality. The procedure described in Isaaks and Srivastava (1989) to decide on the removal of a certain percent of outliers was applied. After removal of outliers, the data set became normally distributed, which was confirmed by the Kolmogorov – Smirnov test in SPSS 11.0. Nevertheless, there were less than 5% of outliers at any dates of measurement.

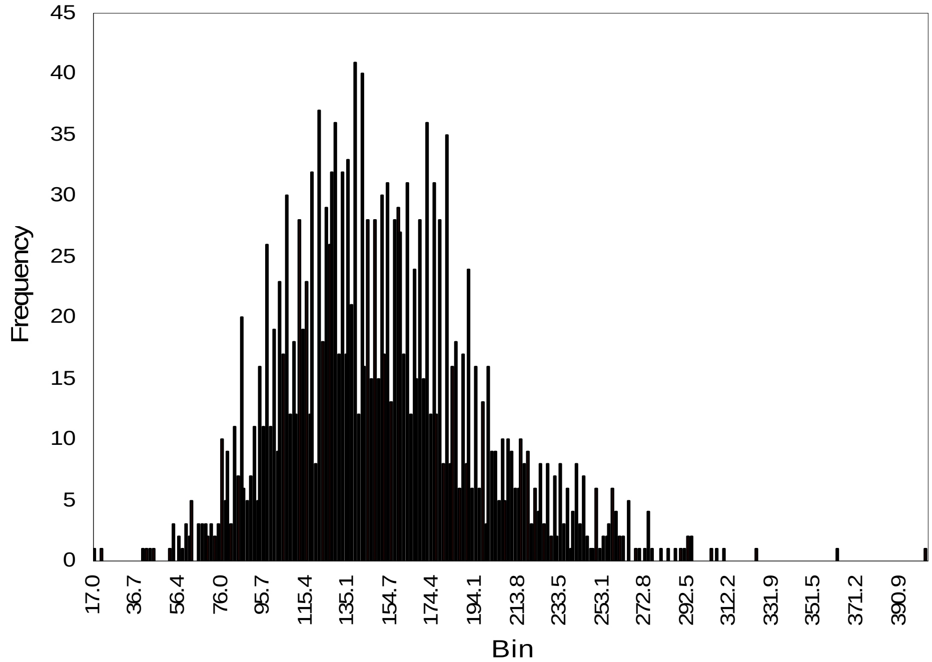


Figure 4.2: Histogram of groundwater table in April 1990

The results of the analysis (Table 4.5) show that the mean GW table values for April were significantly different in 1994 from those of 1990 and 2000, confirming the up- and downward trend. July readings were statistically similar for the measurement periods; only in 2000 was the change significant. In October, GW tables were statistically different in 1996 from 1990 and 2000. Therefore, three periods of measurement in April were retained for further analyses, namely 1990, 1994 and 2000. Despite the absence of difference, the same periods were taken for July with the purpose of comparing the changes over time. For October, the measurements for 1990, 1996 and 2000 were chosen.

Table 4.5: Test for statistical differences between measurements of groundwater table in April, July and October in 1990, 1994 and 2000

	April		**July**		**October**	
	1990 – 94	**1994 – 2000**	**1990 – 94**	**1994 – 2000**	**1990 – 96**	**1996 – 2000**
Z	-22.4(a)	-16.6(b)	-0.73(a)	-25.3(b)	-33.4(a)	-15.9(b)
Sig.(2-tailed)	0.00	0.00	0.47	0.00	0.00	0.00

a Based on positive ranks.
b Based on negative ranks.

4.3.2 Groundwater salinity changes

Average values of GW salinity for the three measurement periods are shown in Table 4.4 and Figure 4.3. In April, average GW salinity was 1.98 g L^{-1} in 1990, changing to 1.62 g L^{-1} in 1994 and to 1.85 g L^{-1} in 2000 (Figure 4.3, a). Changes in GW salinity in the July and October measurement periods were similar. In July, there was a downward salinity decrease until 1996 – 97 with a subsequent rise until 2000 (Figure 4.3, b). For October, a decrease from 1.81 g L^{-1} in 1990 to 1.55 g L^{-1} in 1996 was followed by an increase to 1.75 g L^{-1} in 2000 (Figure 4.3, c).

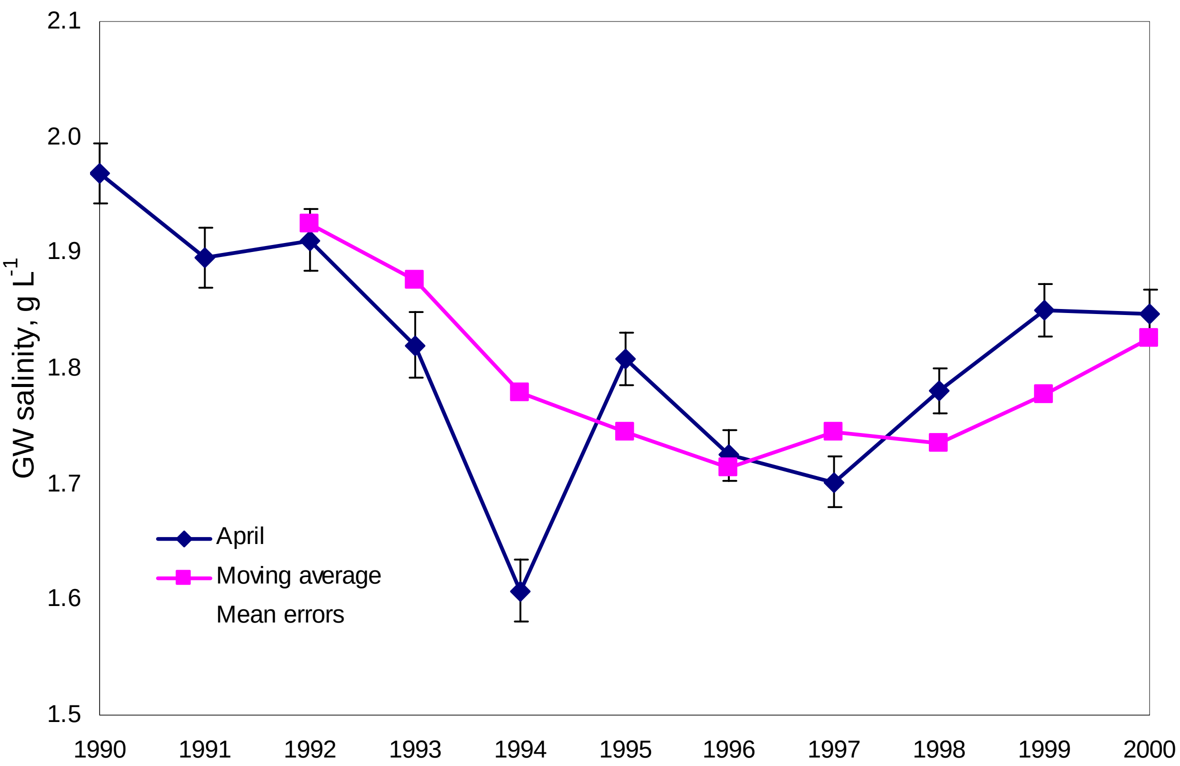
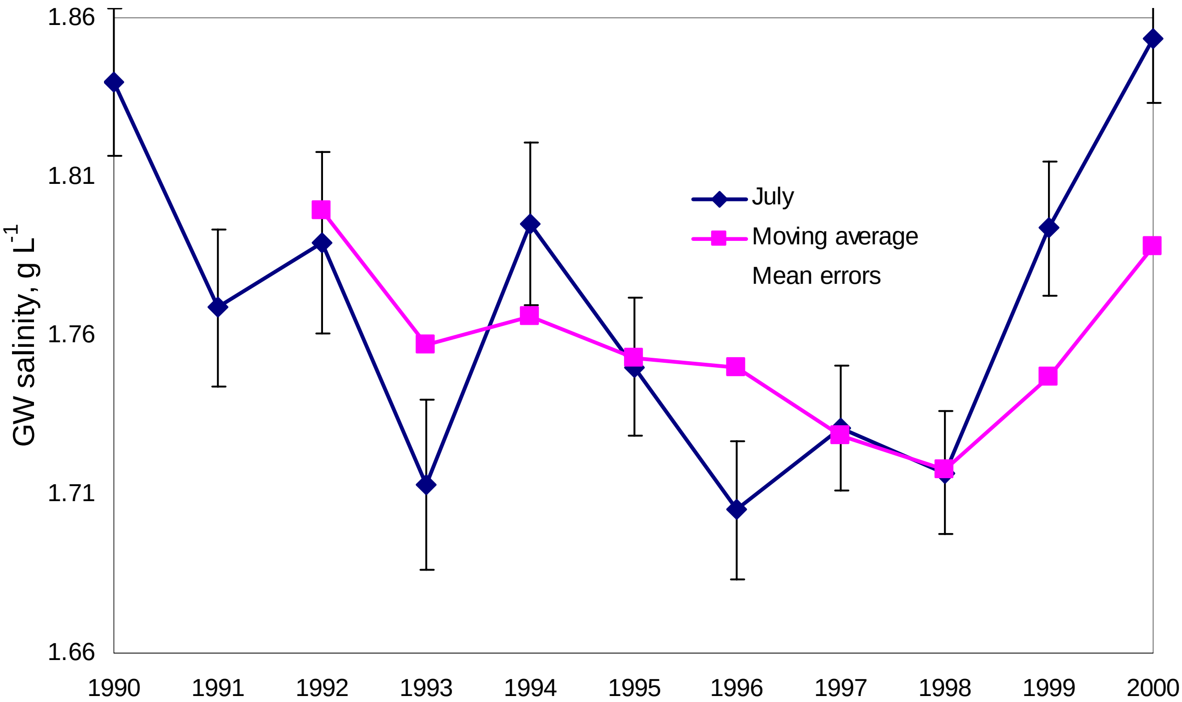


Figure 4.3: Average dynamics of GW salinity in April (a), July (b) and October (c) 1990 – 2000



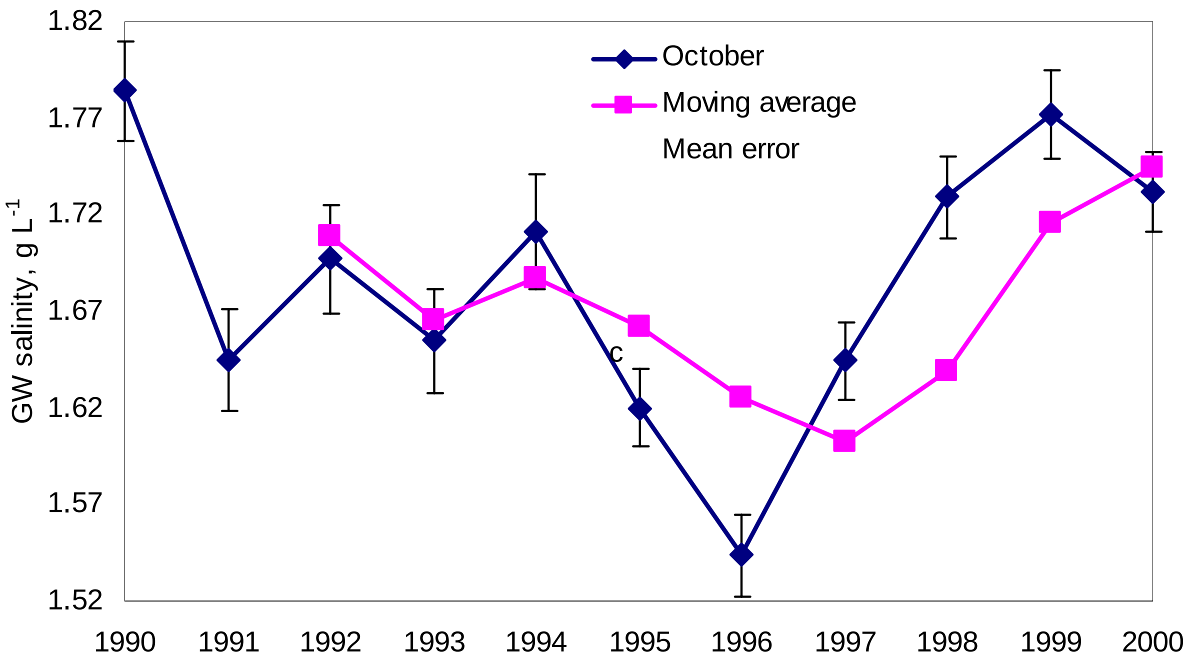


Figure 4.3: Continued

The moving averages for the salinity measurements in Figure 4.3 suggest downward patterns in April from 1990 to 1994, following an upward change to 2000. A similar pattern was observed for October readings, but here the downward change lasted until

1996. The years 1994 for April and 1996 for October seem to be the turning points in the dynamics.

The distributional assumption of GW salinity values was assessed prior to checking for significance of differences in average values for the chosen periods. The histograms revealed strong right-skewness in all the measurement periods. An example of this right-skewness is shown in Figure 4.4 for April 1990. After elimination of outliers, the histograms were more heavily skewed, suggesting that a log-transformation would be more appropriate for acquiring a bell-shaped distribution. Therefore, the formal non-parametric Wilcoxon-signed ranks test was chosen; it showed significant differences between the selected measurements (Table 4.6).

Table 4.6: Non-parametric test for difference between GW salinity in 1990, 1994 and 2000

	April		**July**		**October**	
	1990 – 94	**1994 – 2000**	**1990 – 94**	**1994 – 2000**	**1990 – 96**	**1996 – 2000**
Z	-34.9(a)	-35.4(b)	-35.8(a)	-5.28(b)	-35.3(a)	-35.8(b)
Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.00	0.00

a Based on positive ranks.
b Based on negative ranks.

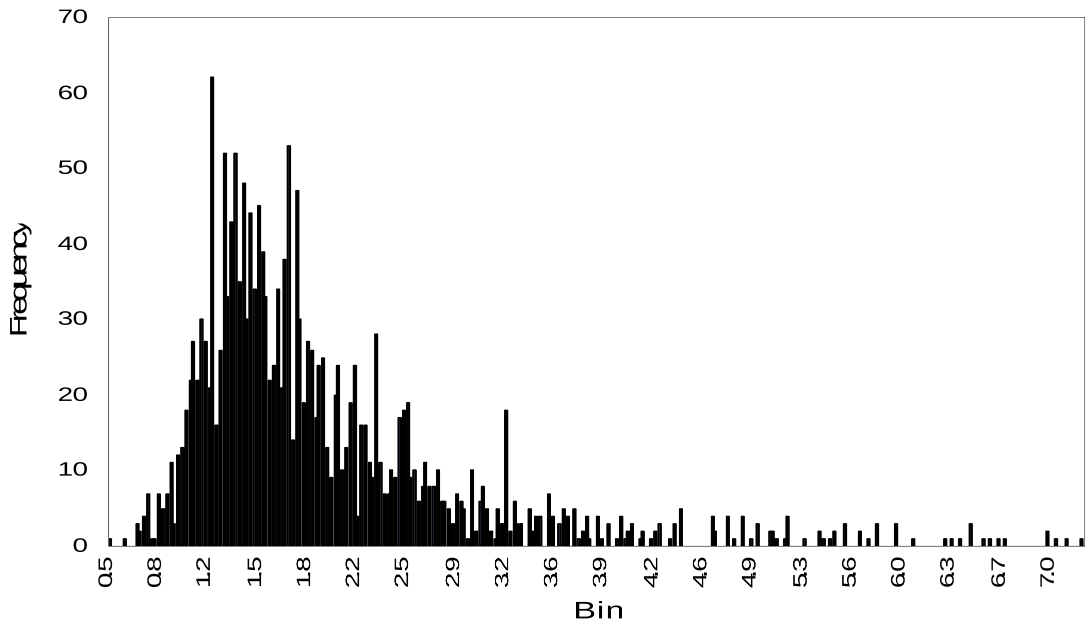


Figure 4.4: Histogram of groundwater salinity in April 1990

4.3.3 Groundwater salinity and soil salinity changes

The observed temporal changes in GW table and salinity measurements coincided with the temporal changes in soil salinization during the study period (Figure 4.5). The areas with moderately saline soils decreased until 1995, after which they increased sharply until 2000. Areas with strongly saline soils also increased after 1996. It should be mentioned that soil salinity is measured only in November in order to assess the saline areas and to define the leaching amounts for the subsequent year; therefore, soil salinization data can only be associated with the GW table and salinity measured in October.

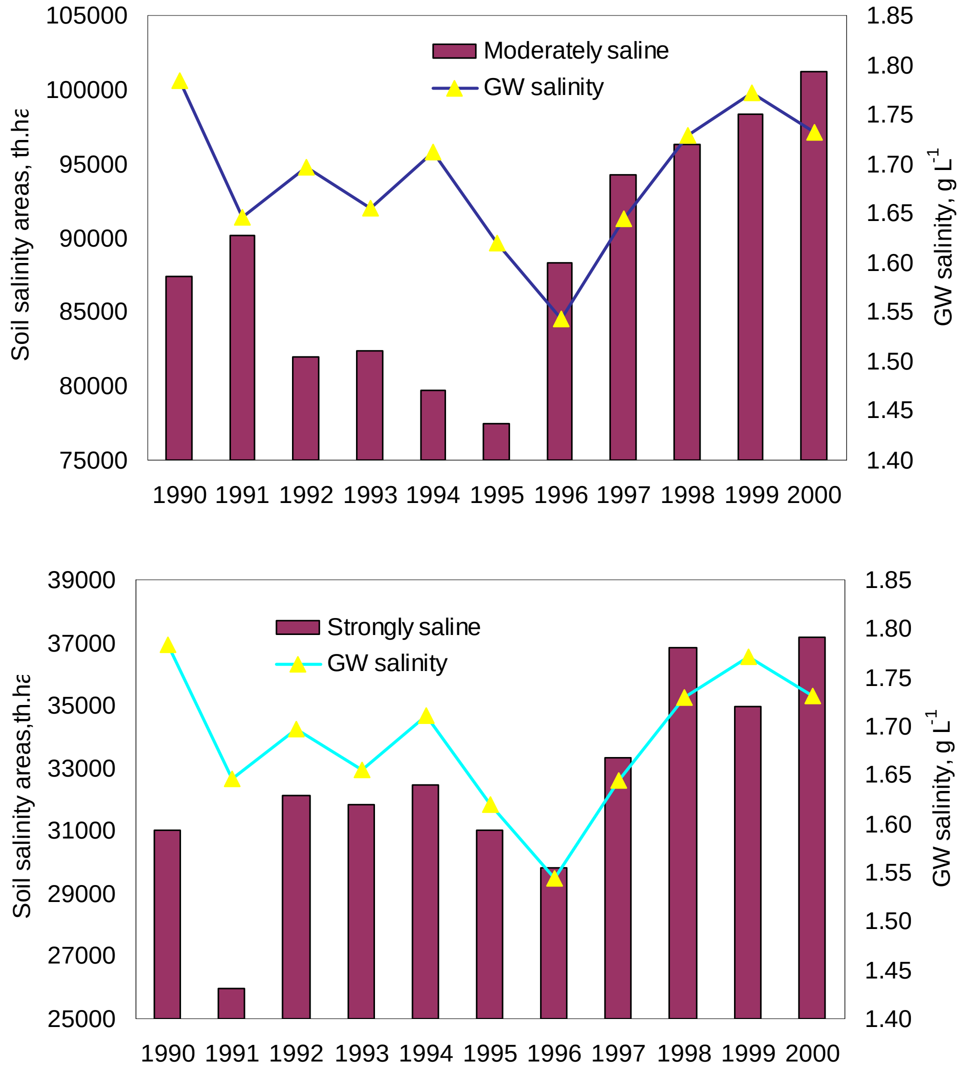


Figure 4.5: Soil salinity dynamics in Khorezm in 1990 – 2000
Source: GME

Whereas rising water tables can have both positive and negative implications for crop production, the changes in GW salinity after 1995 were negative. The similar temporal trend in soil salinity in November suggests a dependency between the soil and GW. Two distinct time frames can be distinguished, with a transition point being around 1995. Further analyses therefore focus on explaining the causes for the changes occurring during these two time frames.

4.4 Causes of groundwater table change in April and July

4.4.1 The Amu-Darya River runoff change

The changes in GW table and salinity can be explained by the changes in land and water management practices, i.e., amounts and salinity of applied irrigation water. Three datasets with amounts of water supply into the region were available from the Khorezm Department of Land and Water Resources, GME and the Department of Macroeconomics and Statistics, but all of them showed different, non-matching patterns. This could well be attributed to manipulations in figures of actual water supplies, due to the importance of surface water in crop production and frequent water shortages. Therefore, in explaining the changes observed in the GW table during the study period, the other variables were used as a proxy to water supply information.

The major input of water comes from the Amu-Darya River, since this is the main source of irrigation in Khorezm. The share of the other sources of water for irrigation (e.g., precipitation, subsurface water pumping, drainage re-use) is far smaller compared to the water withdrawals from the river. Therefore, a hydrograph of the river runoff was used as a proxy to infer the *relative* water-use patterns in Khorezm. The hydrograph shows that at the Tuyamuyun Station the water flow increased from 1990 through 1994, then decreased (Figure 4.6). A similar pattern can be seen in the hydrograph of the Samanbay Station: an increase from 1990 through 1994 and a substantial reduction to a complete cessation in subsequent years. Based on the hydrograph and the observed temporal changes in GW table and salinity and in soil salinity, two phases of the river runoff are recognized:

1) *1990-1994* (Phase I), with increased water flow through both stations, and

2) *1995 -2000* (Phase II), when the general runoff was reduced, with fluctuations in some drought and ample water runoff years.

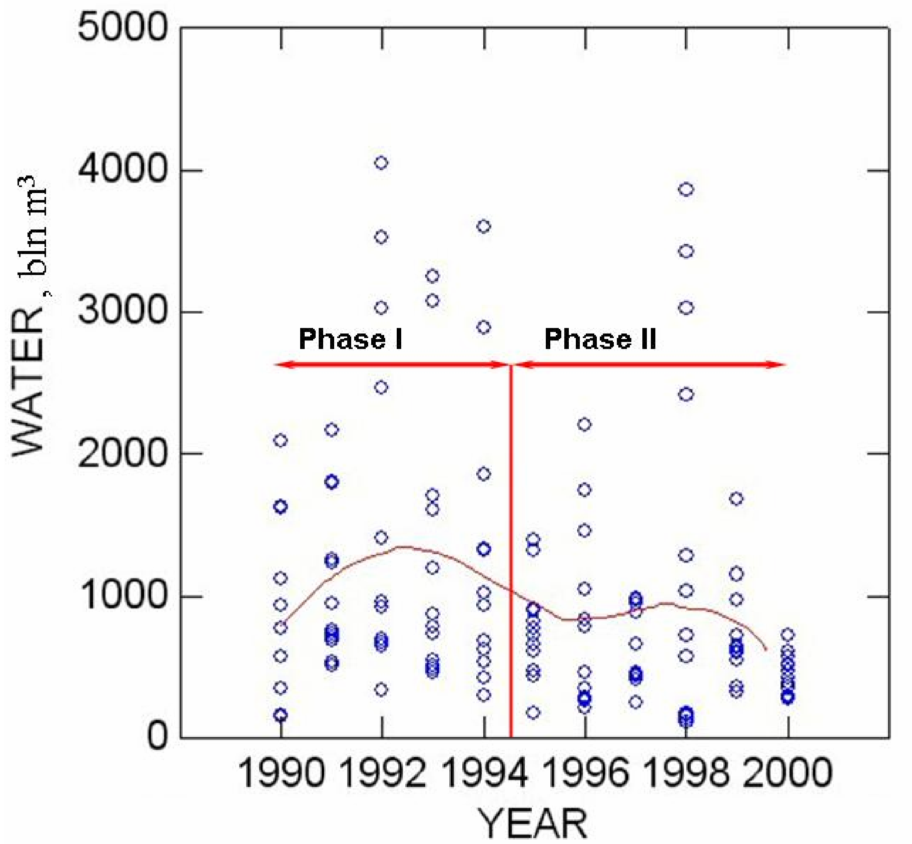


Figure 4.6: Hydrograph of the Amu-Darya River in 1990 – 2000
Source: Glavgidromet

As seen in Figure 4.6, river water runoff was not always sufficient for irrigation in the region and the neighboring republic along the right riverbank during the study period, let alone in further downstream areas. Furthermore, severe droughts heavily affecting the lower Amu-Darya River delta have become more frequent in the last decades (FAO 2002). Therefore, it is not possible to always rely on surface waters for coping with salinity in the region.

Average runoff from 1990 to 1994 (Phase I) was statistically different from that of 1995 through 2000 (Phase II) (Figure 4.7); more water was available during Phase I, whereas the flow reduced in Phase II. The runoff at the Samanbay Station downstream is a function of the flow at the Tuyamuyun Station upstream of Khorezm. It could be inferred that when the water outflow at the Tuyamuyun Station is not sufficient, all the water will be withdrawn for irrigation in Khorezm, leading to water shortage both in the region and in the downstream areas.

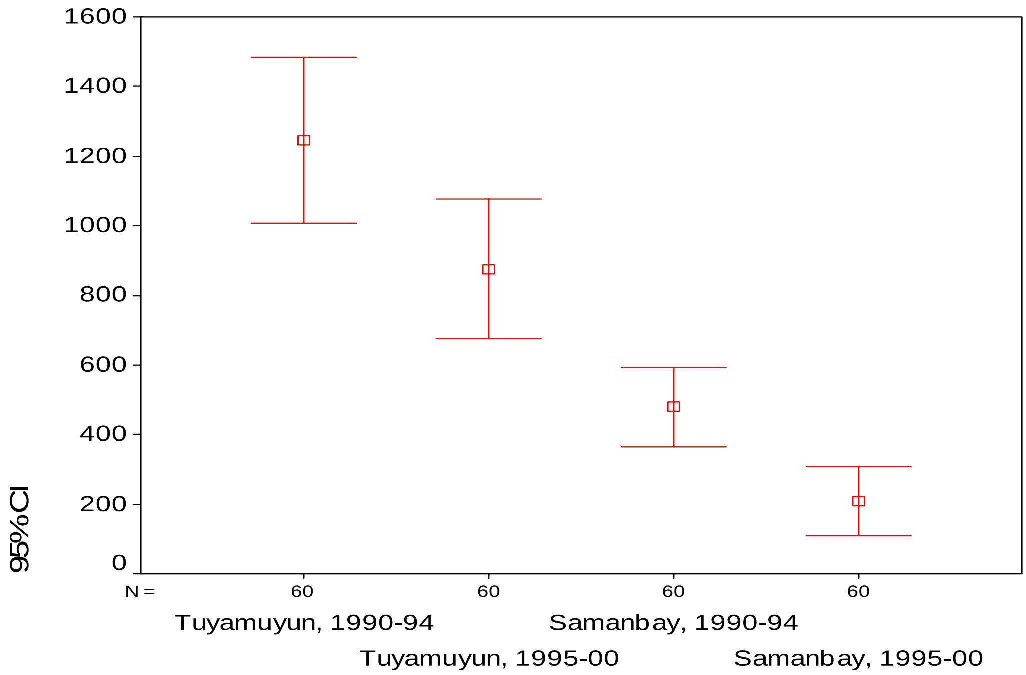


Figure 4.7: 95% confidence limits of the Amu-Darya River runoff in the Tuyamuyun and Samanbay Stations in 1990 – 1994 and 1995 – 2000, respectively

An increase in the river runoff itself could only explain the GW recharge in a relatively small strip of land, usually 2-3 km along the left river bank (Kats 1976; Nurmanov 1966). Changes in water consumption can be deduced from looking at GW table dynamics in the region. Water diversion and use is conventionally calculated from the difference in the river water flow between the two stations, neglecting losses from evaporation/infiltration, industrial and municipal uses (Figure 4.8). The difference in runoff was larger in 1990- 1994 (increased diversions), and smaller in 1995-2000 (reduced withdrawals), except for the very wet year 1998.

The rise in the GW table in the period 1990 – 1994 in April and 1990 – 1996 in October (Figure 4.1), and the shallow levels in July are indicative of the increasing intensive GW recharge through increased diversion from the river. Increasing water diversion in the years 1990 through 1994 was apparently done without consideration of the effect of rising GW tables in the region, which raises the issue of the necessity of a more strict control on regional and local levels. The increased diversion and water use in Khorezm caused a rise of GW tables and the occurrence of hydromorphic conditions (Chapter 2), indicating an insufficient ability of drainage to keep GW at a desirable semi-hydromorphic level. However, the difference in runoff cannot be used as statistical proof of increased water diversions into the region. That increase was further inferred by considering the water balance of the area.

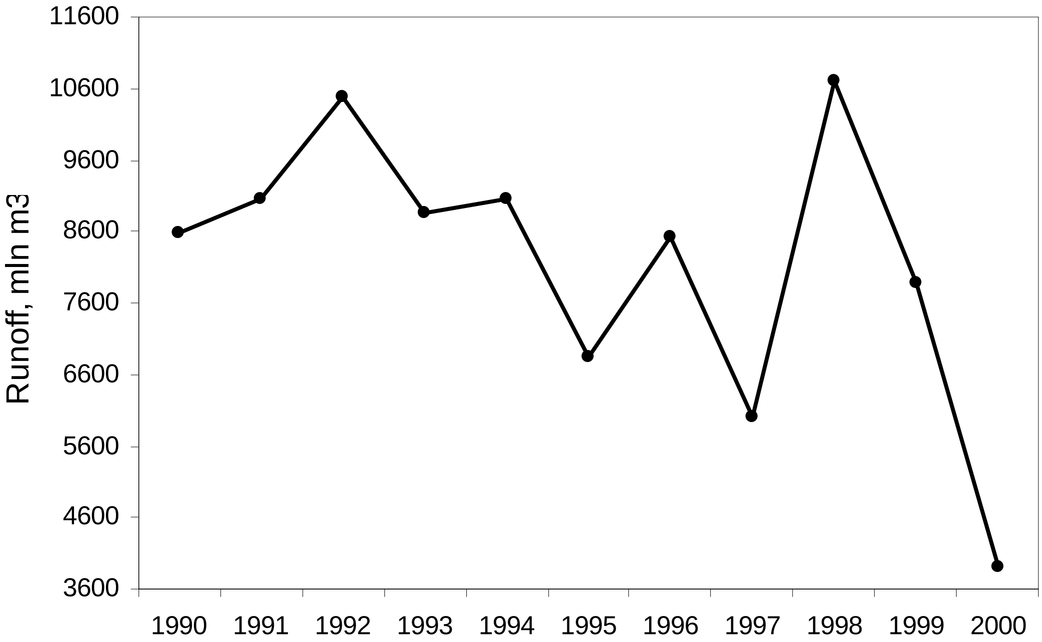


Figure 4.8: Difference in the Amu-Darya River runoff between the Tuyamuyun and Samanbay stations in 1990 – 2000

4.4.2 Drainage discharge

The water budget of the area can be used to assess the increased diversion of water from the river for irrigation in Khorezm. The water budget consists of input (inflow) of water with irrigation, precipitation, etc., and output with drainage, evapotranspiration (ET), etc. Any increase in the input would result in subsequent increase in the output. The most important water output in Khorezm is ET and drainage discharge (see Chapter 3). According to Berdjansky et al. (1996), increased water diversion from the river at the head-gates always results in increased drainage discharge from the irrigated areas. Therefore, the changes in water diversion and use in the region can be statistically inferred from the analysis of the hydrograph of the drainage discharge, the data of which is unbiased.

Descriptive statistics of the annual drainage discharge are given in Table 4.7. The discharge increased from 228.3 million m^3 in 1990 to 335.6 million m^3 in 1994. From 1995 onwards, a general decrease was observed, with drops and rises following the hydrograph of the river runoff. The monthly-average values of the drainage discharge in April 1994 were significantly different from those of 1990 and 2000 (Figure 4.9). Also the readings in October 1996 were similarly different from those of 1990 and 2000.

Table 4.7: Descriptive statistics of drainage discharge (mln m^3) in Khorezm in 1990 – 2000 (annual-average based on monthly data)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Mean	228.26	266.13	326.56	318.12	335.61	260.58	315.94	257.24	308.29	316.49	135.47
Median	203.72	292.07	347.69	335.93	351.68	272.26	335.79	289.75	332.89	290.15	116.25
ST DEV	171.87	198.12	244.75	233.37	270.09	167.63	220.54	153.70	216.27	183.32	96.68
Kurtosis	-1.59	-1.62	-1.67	-1.65	-1.38	-1.13	-1.17	-1.83	-1.36	-0.63	4.73
Skewness	0.33	0.11	0.13	0.12	0.33	0.18	0.19	-0.28	0.15	0.54	1.99
Range	441.17	515.64	656.04	607.72	733.41	492.24	625.20	386.15	599.24	573.86	351.82
Minimum	39.03	33.76	32.71	43.16	42.03	36.98	28.86	45.00	33.94	55.21	45.02
Maximum	480.20	549.40	688.75	650.88	775.44	529.22	654.06	431.15	633.18	629.07	396.84

The drainage discharge values increased until 1994 in April and until 1996 in October, but were more or less constant in July (Figure 4.9). These patterns were very much similar to those of the GW table dynamics (section 4.3). The correlation between drainage discharge and GW table was high, implying that increased water diversion caused both GW table rise and increased drainage discharge (Table 4.8).

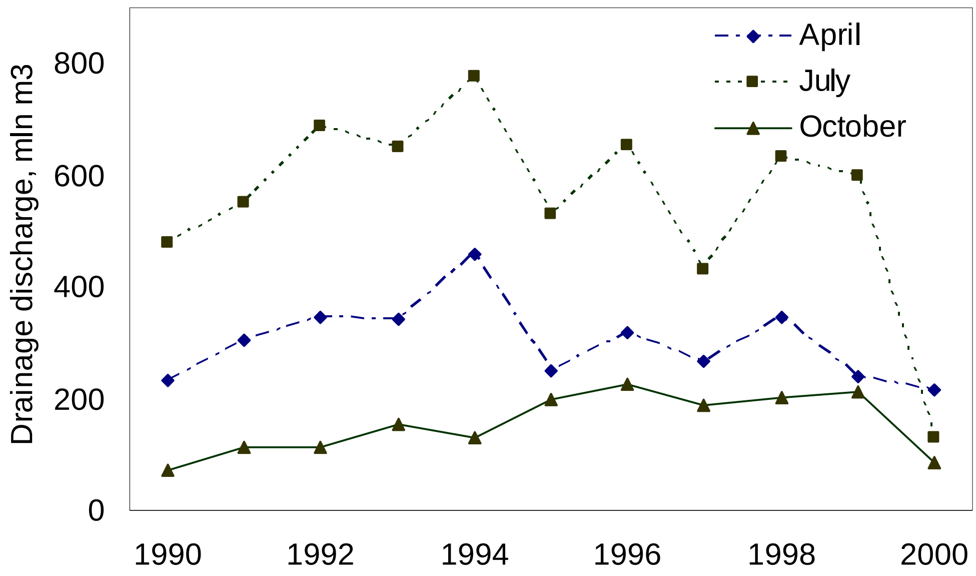


Figure 4.9: Average drainage discharge (mln m3) in April, July and October 1990 – 2000

Table 4.8: Correlation between drainage discharge and average groundwater table in Khorezm in April, July and October 1990 – 2000

Season	**April**	**July**	**October**
Correlation coefficient	0.69	0.87	0.89

The dynamics of the river flow explained 74% of the variations in the drainage discharge in *July* (Table 4.9). The correlation coefficient cannot be much higher, because the amount of diverted water cannot be equal to the amount of the outflow with drainage, as some part of the water is lost through evaporation, crop water use and other processes. The high correlation between river runoff and drainage discharge supports the hypothesis of the increased diversions before 1995 and the decrease thereafter.

Table 4.9: Correlation between drainage discharge and river runoff in April, July and October 1990 – 2000

Season	**April**	**July**	**October**
Correlation coefficient	0.44	0.74	0.0001

The correlation between the drainage discharge and the river runoff in April is lower compared to that of July, because in April a larger portion of the applied surface water recharges the aquifer and the soil profile (due to the lower GW table before leaching). Besides, the water for leaching in April is mainly released from the Tuyamuyun reservoir. The amount of accumulated water in reservoirs depends on the river runoff from previous years and, therefore, the more water is accumulated, the more it can be released and vice versa. The reservoir water-storage data were not available to analyze the relationship between water supply and drainage discharge.

In October, the river water flow is usually significantly reduced and irrigation has ceased, which explains the low correlation between drainage discharge and river runoff. However, an increase in the drainage discharge was observed (Figure 4.9), which could only be due to increased water inflow into the region outside the growing period.

The observed patterns of the hydrographs of the Amu-Darya river runoff and drainage discharge point to an increased water diversion and use in the region before, and reduction again after 1995. The increased water inputs caused the significant rise in the GW table despite the increase in drainage discharge, indicating that the drainage network is at its maximum capacity and further water applications would immediately result in shallower GW tables throughout the region. Increased water use caused the changes in GW table in April and July. However, the GW table rise in October cannot be explained by the changes in river runoff; there must have been other reasons for that phenomenon.

4.5 Causes of groundwater table change in October

Since surface irrigation is the major source of GW recharge, the changes in GW tables in October could be explained by possible continued water applications in order to grow crops in Khorezm outside the growing period.

Since independence, the policy of the government of Uzbekistan has been toward the reduction of the cotton monoculture monopoly to raise the production of grain crops, mainly winter wheat. Table 4.10 shows the area occupied by the major staple crops in Khorezm during the study period. Irrigated areas under winter wheat have been increasing from 3500ha in 1993 (1.7%) to 28700 ha in 1996 (13.5%), after which they reduced to a share of 7 – 9% of the land. Cotton areas were only marginally reduced from 1990 through 1999. Areas under rice were not changed much from 1992 through 1994 being ca. 28,000 ha (13.7%), but afterwards rose to 41,100 ha in 1996 (19.3%). After 1996 they fell continuously to 13,300 ha (8.2%) in 2000.

The GW table usually falls after the water diversion to the area has ceased. As wheat is sown outside the growing period and requires irrigation, canals continue supplying water to the fields, causing the GW table to rise. Since wheat was sown in a part of the irrigated area, a partial GW recharge should be expected. However, average GW dynamics show a considerable rise of 73 cm (the difference in the average readings in 1996 and 1990, Table 4.3).

Table 4.10: Agricultural crops grown in Khorezm and percentage increase in 1992 – 2000

Year	**Crops grown (ha) and percentage of the occupied area**					
	Cotton	**%**	**Rice**	**%**	**Wheat**	**%**
1992	106593	50.6	28189	13.4	5136	2.4
1993	111874	52.2	29534	13.8	3549	1.7
1994	101424	50.2	27430	13.6	11528	5.7
1995	100751	50.2	31908	15.9	13725	6.8
1996	99729	46.7	41192	19.3	28728	13.5
1997	99959	52.8	37065	19.6	16443	8.7
1998	99507	52.0	34565	18.0	16314	8.5
1999	98118	49.2	29033	14.5	14714	7.4
2000	87529	54.2	13294	8.2	15259	9.5

Source: Khorezm Department for Agriculture and Water Resources, 2002

The effects of the increase in areas under wheat on the changes in the GW tables in October were analyzed utilizing an *ARIMA* time series model (Gupta 1999). The analysis was performed in SPSS 11.0. The dataset for GW table and wheat showed non-stationarity (not shown); a first-order differenced transformation was performed. Following transformations, a linear autoregressive integrated moving average regression model (ARIMA) was defined as:

$$GW_t - GW_{t-1} = a + b*(GW_{t-1} - GW_{t-2}) + c*(Wheat - Wheat_{-1}).$$

The results of the ARIMA model are shown in Table 4.11.

The ARIMA model shows that irrigation of the areas cropped with the winter wheat caused the rise of the GW table in Khorezm in October. The predictor variable *wheat* and constant term were significant at the 95% probability level. One unit increase in variable *wheat* appears to have a small effect on the change in the GW table (*B* equals –0.002). This is because the areas under wheat were used instead of actual water applications. The negative sign of the coefficient *B* indicates that unit increase in areas cropped with wheat causes GW table rise (values of water tables become shallower). Thus, wheat production appears to account for 73 cm of the increase in observed GW table rise in October.

Table 4.11: Effects of increase in areas under wheat on changes in GW table, 1990-2000 (ARIMA model)

Analysis of Variance			
A	**DF**	**Adjusted sum of squares**	**Residual variance**
Residuals	5	460.34	91567609
Variables in model			
	B	**T-RATIO**	**Prob.**
AR1	0.21	0.45	0.67
Wheat	-0.002	-3.68	0.01
Constant	15.53	2.72	0.04

4.6 Causes for groundwater salinity changes

4.6.1 Water supply and salinity

In the same way as irrigation causes changes in the phreatic surfaces, it influences the salinity of GW by adding salts that are present in surface waters (Ghassemi et al. 1995). This is especially true for Khorezm, where the absence of lateral subsurface flow can easily lead to rapid accumulation of salts in the GW. Moreover, water availability in the Amu-Darya River can have an impact on salinity increase in GW, because the salt concentration increases with decrease of water runoff (Chembarisov et al. 1989). Both factors, amount and salinity of irrigation water, were used in an assessment of the impact of irrigation on GW salinity. Whereas the surface water salinity dataset was available (Table 4.12), the drainage discharge was used as a proxy to the amount of supplied water in Khorezm during the study period.

Table 4.12: Seasonal and annual average salinity of irrigation water (g L^{-1}) in Khorezm

Year	Measurement period			Average
	April	July	October	
1991	1.15	0.69	0.90	0.93
1992	1.44	0.59	0.91	0.94
1993	1.31	0.65	0.99	0.93
1994	1.17	0.57	0.96	0.87
1995	1.29	0.59	0.87	0.91
1996	1.26	0.61	0.77	0.86
1997	1.24	0.73	0.89	0.93
1998	1.13	0.66	0.94	0.88
1999	1.31	0.67	0.93	0.96
2000	1.32	0.76	0.98	1.01

Source: GME 2001

Figure 4.10 (a, b, c) shows the relationships between drainage discharge and GW salinity, and (d, e, f) between irrigation water salinity and GW salinity during the study period in April, July and October. The relationships indicate that salinity of irrigation water played an important role in salt accumulation in GW in April and October, but not in July. The changes in water diversion significantly influenced GW salinity changes only in October, as, when the outlier in the Figure 4.10a (circled) is removed, the correlation coefficient between GW salinity and water supply in April becomes weak. As leaching is the removal of salts from both the soil profile and GW, the observed pattern shows that the increased (or decreased) water supply for leaching did not bring the desired effects in GW salinity. In contrast, with the two outliers in Figure 4.10d removed, the correlation between salinity of irrigation and GW in April becomes stronger, indicating that salinity levels in surface water are the major factors of GW salinity change. An interesting feature is that despite intensive irrigation during the growing period in July, changes in GW salinity are not influenced much by irrigation amounts or by water salinity. The opposite can be seen in October, when most of the salts in irrigation water ended up underground.

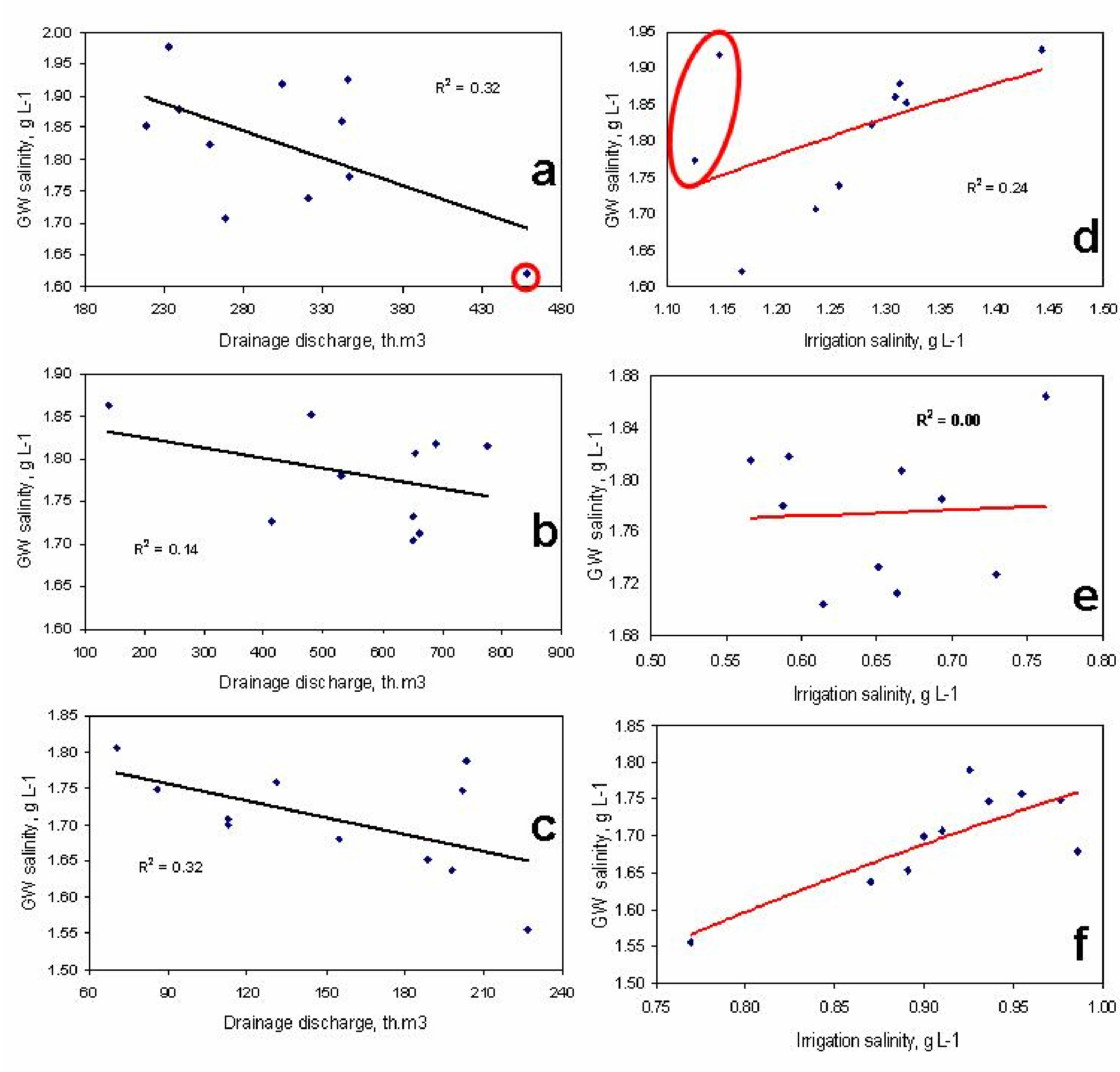


Figure 4.10: Relationship between GW salinity and drainage discharge in April (a), July (b) and October (c) and irrigation water salinity in April (d), July (e) and October (f) in 1990 – 2000

4.6.2 Drainage salinity

Salinity of the drainage water represents partly that of the percolated irrigation water and partly of the GW. Drainage discharge is therefore less saline only immediately after irrigation events. Most of the time it lowers shallow GW tables so that average drainage salinity in any measurement period must be similar to that of GW salinity. There was a high correlation of drainage and ground water salinity in April (0.68), whereas it was much lower in July (0.22) and completely missing in October (0.01, Figure 4.11).

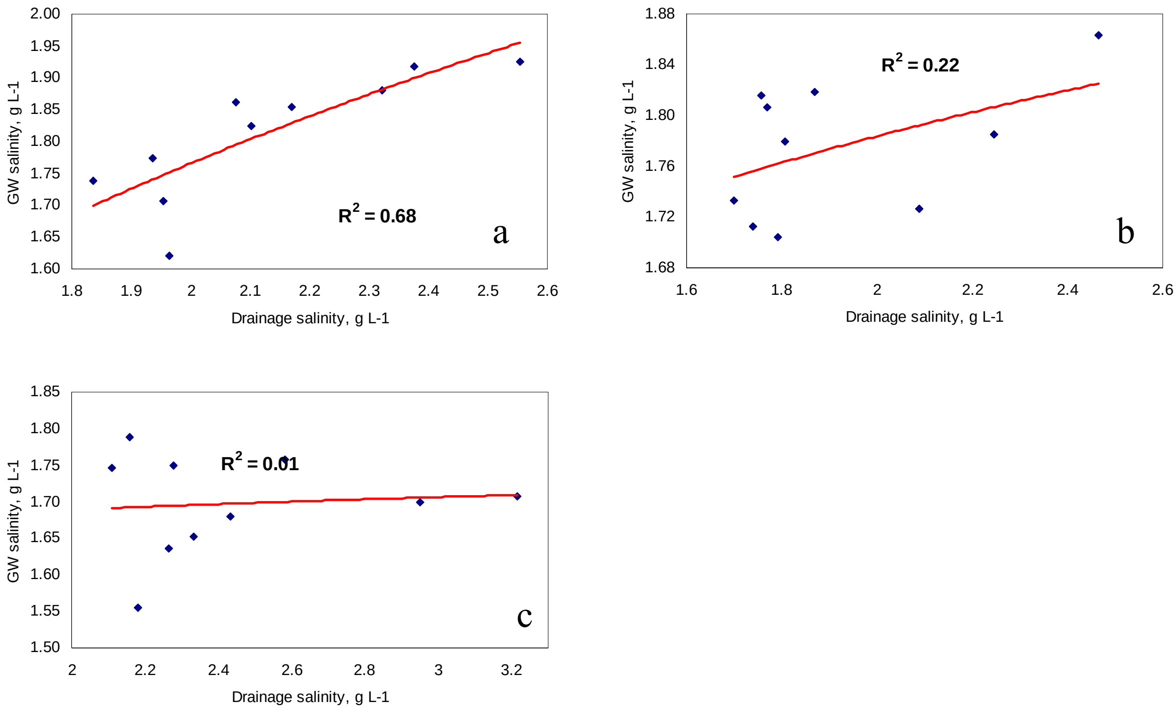


Figure 4.11: Correlation between drainage salinity and GW salinity in April (a), July (b) and October (c) 1991 – 2000

The high correlation coefficient between salinity in GW and drainage in April shows that leaching of salts is an important and efficient means to remove their excess from the soil profile and GW. The previous findings of the relationships among amount and salinity of surface water for leaching and GW salinity (see Figure 4.10) suggest that reduction of salts in GW could be achieved with lower water applications if applying saline surface waters could be avoided. However, this seems not to be an option actually available to the Khorezm farmer, who often has to rely on heavily saline irrigation water.

Low correlation between GW salinity and drainage salinity in July could be explained by rapid evaporation of shallow GW from the soil into the atmosphere and consequent uplifting of salts contained in that water. Among the other explanations may be: 1) the careless attitude among farmers in Khorezm to dispose surface water into nearby drains (pers. experience) and 2) salt uptake by plants, although negligible (Nature Protection Committee Report 1997). The lack of a relationship between GW and drainage salinity in October might be explained by the deeper GW tables in the region. The depth of most drains is 2.0 and shallower, and so, only baseflow from GW into drains can occur.

4.6.3 Groundwater table in districts

The rise and fall of GW table in Khorezm are explained by the amounts of water used for irrigation (section 4.5). GW table measurements in the districts showed that water tables were shallower in the southern part of the region in all the measurement periods. Therefore, it seems logical to conclude that southern districts were supplied with more surface water than the rest of the districts. The GW table in the southern districts was significantly different from GW tables in the districts in the central part of the region (Table 4.13). However, the southern districts appeared to receive much less water for irrigation compared to those in the central part as shown in Figure 4.12. It should be noted that the patterns of GW table and irrigation supply were similar in the three measurement periods. The causes for such phenomena are explained in Chapter 5.

Table 4.13: Test for statistical difference of means of groundwater table in the districts of Khorezm

N	Name of district	Significance[1]
1	Bogot	2, 5, 6, 8, 9, 11
2	Gurlan	1, 3, 9, 10
3	Khazarasp	2, 5, 6, 8, 9, 11
4	Khiva	5, 6, 9, 11
5	Khonka	1, 3, 4, 8, 10
6	Kushkupir	1, 3, 4, 8, 10,
7	Pitnyak	
8	Shavat	1, 3, 5, 6, 9
9	Urganch	1, 2, 3, 4, 8, 10
10	Yangiarik	2, 5, 6, 9, 11
11	Yangibozor	1, 3, 4, 10

[1]*Number of the district with which the mean difference was significant*

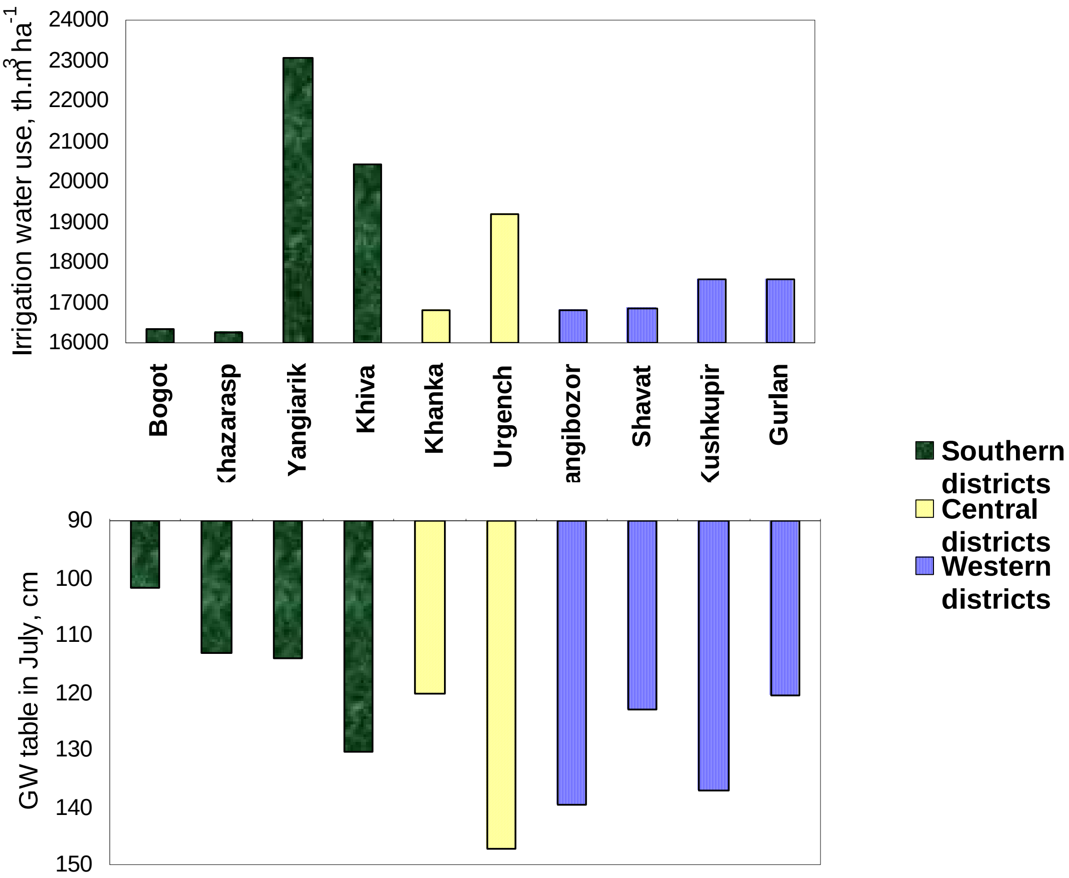


Figure 4.12: Average groundwater table and irrigation water supply in the districts of Khorezm in July 1990-2000

4.7 Discussion

4.7.1 Temporal dynamics of groundwater table and salinity

An analysis of the temporal dynamics of the GW table in Khorezm during the study period revealed that water tables were rising in April from 1.50 m in 1990 to 1.25 m in 1994 with a significant lowering until 1.46 m in 2000. A rise in October was observed from 2.28 m in 1990 to 1.55 m in 1996 followed by a decrease to 1.97 m in 2000. In July, only a slight decrease of water tables was observed during the study period, with a significant fall occurring only in 2000. The rising or constantly shallow GW tables are expected to have caused a significant increase of the areas at risk of waterlogging and salinization in the mid 1990s in Khorezm.

The more or less constant levels of GW in July (except 2000), despite the ample variations in annual water supply between dry and wet years, imply fast and probably substantial evapotranspiration of subsurface water out of the soil profile. This is consistent with the findings of Mukhammadiev (1982), who came to this conclusion based on data analysis from three research plots with heavy, medium and light soil textures.

4.7.2 Increased diversion and water use

The rise in the GW table in April and its shallow position in July is explained by the increased water diversions from the Amu-Darya River. According to Ikramova and Khodzhiev (1998), the Amu-Darya River has cyclic periods of ample and low water runoff. While low runoff years are repeated in ca. 4 – 6 years, ample runoff years come less frequently, in 8 – 10 years. The high runoff cycle occurred in the years 1990 through 1994, although 1998 was also a year with extremely high water runoff. Mukhammadiev (1982) showed that water is distributed depending on the river runoff of a particular year. This is still current practice, although the water-controlling agencies BVO "Amu-Darya" and MAWR strictly control the distribution (Dukhovny 2001). Increased diversions took place in Khorezm during the period 1990 to 1994, which led to higher water tables. The drainage network proved to be inefficient in removing excessively supplied water, especially in the southern part of the region.

Many illegally installed small pumps can be seen along most irrigation canals in Khorezm. The more water flowing in the canals, the more water can be taken out uncontrolled. It is expected that the newly formed Water User Associations (Zavgorodnyaya 2002) will help improve water distribution in the region.

4.7.3 Temporal groundwater table and salinity changes

Three datasets with the amounts of surface water for irrigation were available. One dataset was obtained from the Khorezm Department of Land and Water Resources, the other two from the Hydrogeologic Melioration Expedition and the Department of Macroeconomics and Statistics in Khorezm. However, comparison showed inconsistencies between the data, and especially different amounts during ample water runoff years.

Hiding the actual amounts of water diversion and use in the region can easily be understood from the following considerations. The region is located in the lower Amu-Darya River delta and, therefore, received the rest of the water left after massive withdrawals from the upper-stream areas. Moreover, the water from the Amu-Darya River and main canals is frequently stolen, which, however, is not often reported as it is difficult to catch the water thieves. Therefore, the better choice seemed to be the use of the drainage discharge, which is not manipulated.

The correlation between drainage discharge and GW table was relatively high in April (r^2 0.32) and July (r^2 0.74), indicating that the discharge can be used as a proxy to water diversion in Khorezm. However, it was very low in October (r^2 0.0001, Table 4.9). This is because the river runoff is highest in the period May through August, and is sharply reduced afterwards. With low water demand in October, the lack of correlation between the river runoff and drainage discharge in October is expected. Although the drainage discharge is proved to be a good proxy to the river runoff and water diversion and use in Khorezm, the relationships between the drainage discharge and GW salinity in April and July are weak. In contrast, the relationship between the salinity in irrigation water and groundwater in April was high and linear (except for two outliers, see Figure 4.10). Salinity of irrigation water is the highest in April (Table 4.12), and with the low drainage discharge, the salts from irrigation water seem to end up in the GW. It is seen that the use of the drainage discharge to explain the changes in GW salinity is inappropriate due possibly to sampling of salinity from deeper horizons.

The observed weak relationship between the drainage discharge and GW salinity in July (Figure 4.10 b) appears related to the high evaporative demand in July, and a larger amount of soil and surface water is evapotranspired before it reaches the GW.

In October, the higher correlation of both drainage discharge and irrigation salinity with GW salinity is related to the introduction of winter wheat. This has led to changes in the GW table since water continued to be transferred by the irrigation canals in October. Although probably a significant amount of water to irrigate wheat was applied in October as revealed by the hydrograph of the drainage discharge (see Figure 4.9), the share of the area under the wheat was not large compared to the total irrigated area (7 to 13%, see Table 4.10). Therefore, the water supplied to irrigate wheat could only influence the dynamics of GW salinity in local areas, whereas the GW salinity was assessed from all the monitoring wells.

The above discussion shows that water tables in Khorezm can rise and subsequently increase areas at risk from the increased water applications following the changes in cropping patterns. An example is the introduction of winter wheat in a relatively small area with a rise in the average level of the GW table to 73 cm. This clearly shows that changes in cropping patterns in Khorezm must be made with care.

One aspect of constantly shallow GW tables in Khorezm during growing periods is that many farmers in the region, especially in those remote from the irrigation network areas, rely on the blocking of drainage ditches when they anticipate or face a lack of surface water. Doing so, they raise the water tables to achieve a sufficient supply of moisture. This is quite an old technique (article on history of agriculture in Khorezm, author unknown). It is still widely practiced despite the negative consequences for GW and soil salinity, maybe because the benefits outweigh the problems in a situation where farmers very often face water shortages. The practice of raising GW tables to achieve a higher moisture level in the soil profile may be traced back to former times when water salinity levels were very low, overall water application over the whole region was lower and there was no threat from relatively deep GW tables.

This situation changed in the 1960s; both progressive GW table rise and soil salinization have been reported since then. Today, the high GW table, massive leaching and intensive irrigation help to maintain the productivity of land. If, however, water shortages become frequent, productivity will fall and soil restoration will become increasingly difficult or even irreversible.

4.8 Conclusion

Unacceptably shallow (around 1 m below the ground surface) as well as rising (in April and October) GW tables were observed during the study period in Khorezm. Although the GW salinity category was low, being in the range 1 to 3 g L^{-1} in all the measurement periods, ca. 65 – 70% of the irrigated areas during the growing period and from 1% to 44% outside the growing period experienced waterlogging and salinization processes. The situation was further aggravated due to the Khorezmian farmers' practice of raising water tables through blocking of drains in order to increase soil moisture, especially in areas remote from the river and canal. Only large amounts of leaching and irrigation water are expected to maintain favorable soil conditions. However, frequent water shortages in the Amu-Darya River can jeopardize soil quality and agriculture in Khorezm.

A clear contradiction is seen from the above-stated. The region is known to draw much more surface water for irrigation than necessary and at the same time farmers (especially far from the river and canal areas) apply the drain blocking practice when anticipating or facing lack of water. This problem arises due to huge amounts of surface water that are lost through seepage from canal bottoms and laterals of the irrigation network. Instead of being supplied to the fields, the lost surface water recharges GW causing rising water tables and resulting in a large share of the areas at risk in Khorezm.

The fact that shallow saline GW causes waterlogging and salinization is well known. The problem is well investigated in Khorezm and clear indicators were identified from a number of studies (see Table 4.1 and 4.2). In this study, which covered a period of 11 years, large areas at risk from shallow saline GW were delineated using the TIN interpolation method. The areas at risk from shallow saline GW in April and July were similar throughout the study period, whereas in October they rose from 1% in 1990 to 44% in 1996 and had not reached the level of 1990 again at the end of the study in 2000 (5%).

It can be deduced from the temporal dynamics of the GW table in October that the drain blocking practice is not solely responsible for the rise and thus shallow GW tables in Khorezm. Introduction of winter wheat, which is irrigated just outside growing period, caused a GW table rise by 73 cm throughout the region (see Table 4.3). However, the areas under wheat were only 7 to 13% of the irrigated areas (see Table 4.10).

The situation described above seems to be a vicious cycle: the water management agencies in Khorezm increase the water supply to the region as much as possible, and at the same time rising saline GW tables cause an increase in the areas at risk of waterlogging and salinization. The situation is further aggravated because the farmers block the drains, which also causes salts in GW to retain and move upwards. If more accurate readings of GW salinity (from upper GW layers) were available, the actual areas at risk could actually be much larger.

The main and inter-farm irrigation canals are operated by the state water management agencies. Only 10% of these canals were lined in 1998 (Vodproject 1999). The seepage from the canals and percolation into the GW aquifer in Khorezm are the largest from these canals. Moreover, the construction of the Tuyamuyun reservoir caused reduced turbidity in the water and thus decreased sedimentation of the canal bottoms and laterals and increased percolation into the GW. Resolving the infiltrational water losses should result in 1) increased surface water availability, and 2) lower GW tables.

The insufficiency of the capacity of the drainage network was inferred from the analysis. The topographic flatness of the region and a wide distribution of medium and heavy soil textures cause shallow GW within the irrigated fields and lead to waterlogging and salinization. It is clear that a conventional open drainage network is not sufficient to maintain semi-hydromorphic conditions and other alternative designs must be implemented. However, this may not solve the problem as long as farmers, especially in areas remote from the river and canals, continue applying drain blocking when there is a lack of surface water. Also, water management agencies will need to stop drawing more river water than necessary, substantial parts of which recharge GW.

The findings and conclusions on the soil conditions were made based on the 1987 monitoring wells, the readings from which were assessed temporally during the period 1990 through 2000. The actual areas at risk of waterlogging and salinization could be different if there were a denser areal coverage of monitoring wells and if the GW salinity assessment were to be made in the upper horizons. However, the data allowed a relative assessment, implying that a more precise analysis is indispensable in target areas.

5 SPATIAL DYNAMICS OF GROUNDWATER TABLE AND SALINITY

5.1 Introduction

Chapter 4 was dedicated to the temporal analysis of GW table and salinity fluctuations. In order to address the problems of salinization and waterlogging in the irrigated areas in Khorezm, which stem from shallow saline GW, it is necessary to properly assess the spatial distribution of the GW table and salinity. This will allow assessing the role of environmental variables and management options (spatial distribution of soil properties, irrigation/drainage network, water bodies, etc.) and identifying the target areas and management actions for remediation or alleviation. Therefore, the present chapter is dedicated to the spatial analysis of GW table and salinity for the three controlling years of each season identified in Chapter 4.

After having identified the time frames of significant changes in GW table and salinity, three important questions are: 1) how large is the area at risk from shallow GW tables, 2) had the critical threshold been reached at the defined measurement periods, and 3) which are the areas with shallow *and* saline GW? These questions could only be answered utilizing GIS techniques. Four GIS methods were used in this study to characterize the spatial distribution of the variables: inverse distance weighted (IDW), kriging, spline and TIN methods. A detailed description of the spatial analysis of the GW table and salinity as well as the comparison of these techniques and degree of uncertainty of spatial interpolation was given in Chapter 3. In the present chapter, the findings of the spatial estimation of areas experiencing shallow and saline GW are presented.

The areas at risk can be identified and mapped based on interpolation from a limited number of samples. In view of the limited number of samples for the spatial mapping of the GW table and salinity, it is first necessary to identify an interpolation method that allows proper prediction (estimation) of the values for the places between the measured points. It should be noted that these two terms are used interchangeably in a geostatistical jargon. Each interpolation method makes assumptions about how to determine the estimated values. The best method would produce an assessment with the minimum estimation errors. The errors can be associated with several factors, among which are areal coverage with samples, nested samples in areas where abrupt changes occur, physiography and topography, etc. (Cressie, 1993). Regardless of the interpolator, the more input points and the more even their distribution, the more reliable the results.

The interpolation of GW table and salinity was performed in ArcInfo 8.2 and ArcGIS 8.2 (ESRI, Inc). Visualization and delineation of the obtained interpolated maps was performed in ArcView 3.2. It should be mentioned that the total area of the region assessed in ArcView 3.2 differed from the actual area of Khorezm due to the errors present in the paper maps from which digitizing was done. The total area of the Khorezm region is 562,192 ha, whereas the area of the region in the digitized map (see Figure 3.3) is 458,497 ha, and therefore the errors constituted some 20%. Therefore, showing the size of the areas under the GW table and salinity levels estimated in ArcView could be misleading, but the percentages of the individual areas to the total area given in ArcView can be used.

The prediction accuracy of the chosen interpolation methods was compared, and the best performing method was retained for the further analyses of the spatial distribution of the GW (Atkinson 1999). The produced maps of GW table and salinity were analyzed against the other environmental variables and engineering facilities. The objectives of this chapter therefore were to 1) estimate the accuracy of different interpolation methods in delineating areas with groundwater table and salinity, and 2) establish the factors influencing the spatial and temporal distribution of GW table and salinity.

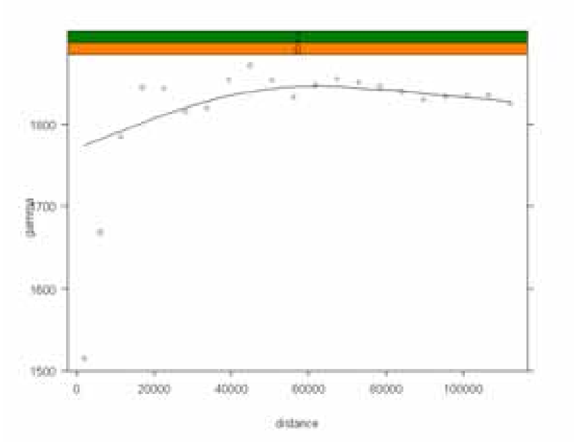
5.2 Spatial analysis of groundwater table

5.2.1 Kriging

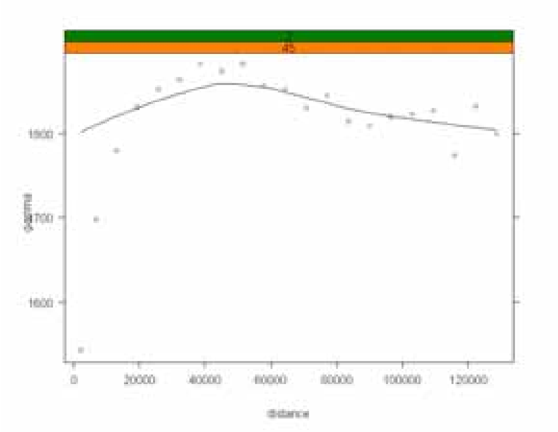
Since most statistical analyses are based on the normal distribution of values in a dataset, checking the statistical distribution of the GW table was the first step in the analysis. Although kriging as a best linear unbiased predictor does not require normal distribution in data, normality is necessary to obtain probability maps on which this method is based (ArcGIS help file). The existence of outliers was the cause of right-skewness in measurements of GW table (Chapter 4). After the removal of less than 5% of outliers and omitting the measurements from the rice fields, normality in data distribution was attained.

Variogram cloud analysis is indispensable for revealing pairs of values that significantly deviate from the rest pairs, as such outliers can have a negative impact on prediction accuracy. Variogram cloud analysis showed no extreme pairs of readings (outliers). Since heterogeneity and stratigraphy of soils in Khorezm might have caused the heteroskedasticity (local variability of mean and standard deviation of a variable) in GW level, variability in data was checked from nine marginally overlapping moving windows, as described in Isaak and Srivastava (1989). The analysis showed no heteroskedasticity, i.e., the trends of the average values and their standard deviations in each window were similar. There appeared to be no trend (global change) in the data. However, there was anisotropy (local change in data) in all the measurement periods including those in October. The two directions of anisotropy were in the north – south and southeast – northwest, which could possibly be attributed to the subsurface water flow from the Amu-Darya River to the south of the region and the overall flow towards the direction of slope (see Chapter 2). Plotting variograms in these two directions for all the chosen measurement periods produced clearer structures compared to the variograms in the other directions (Figure 5.1). The variogram in the direction east – west had a clearer structure with a longer range (distance of autocorrelation). Since more similar values appeared along that direction, modeling the GW table using that directional variogram produced more reliable estimates at unmeasured locations.

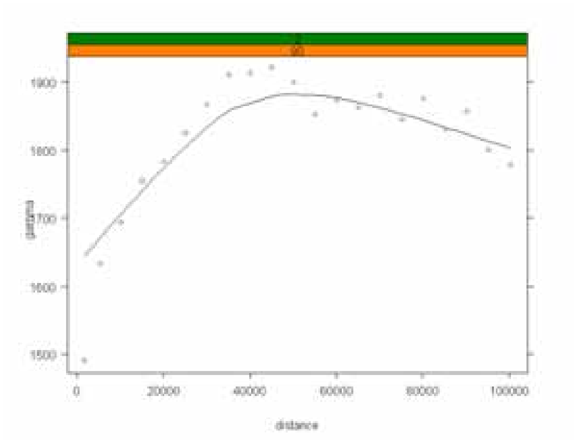
A drop in variance at the end of the fitted kriging functions was observed in the directional variograms in northeast and east-west directions in April and July (Figure 5.1). It is indicative of a change of GW table readings in these directions. The patterns of the variograms were similar for April and July; only in October did the variograms continued to rise with increasing lag intervals, except for 1996. Figure 5.1 also indicates that outside the growing period, water tables in the years 1990 and 2000 were extremely different from the rest of the measurements, with a general decline in GW with distance along the directions of anisotropy. Patterns of the variograms in October 1996 suggest constant water tables in the region in this period.



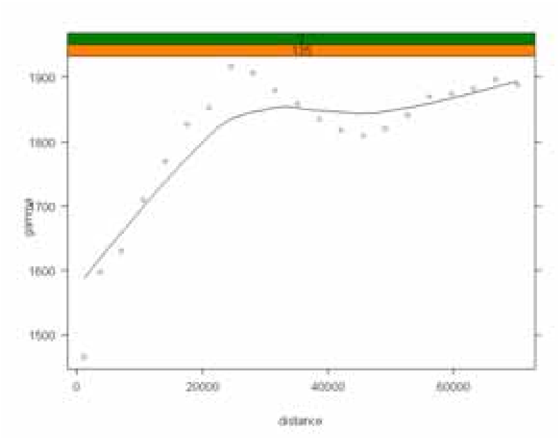
April 1990, 0°



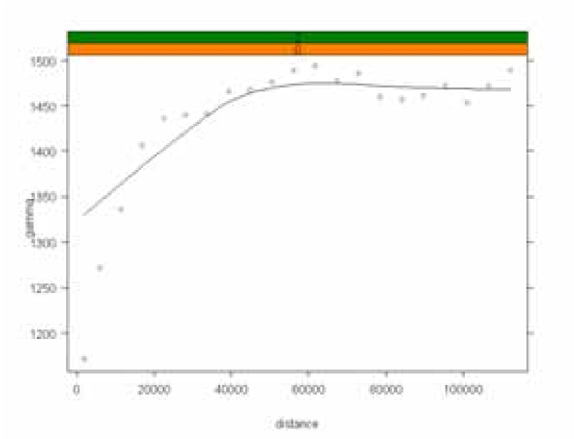
April 1990, 45°



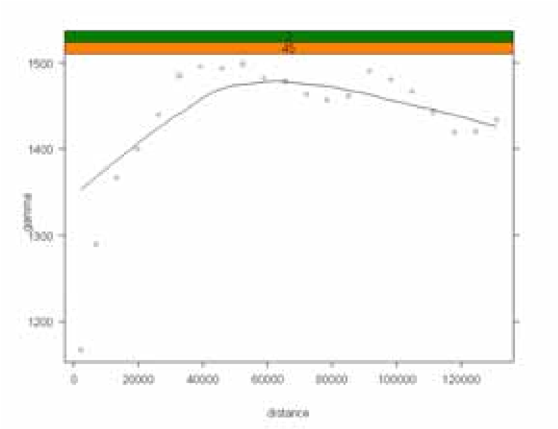
April 1990, 90°



April 1990, 135°

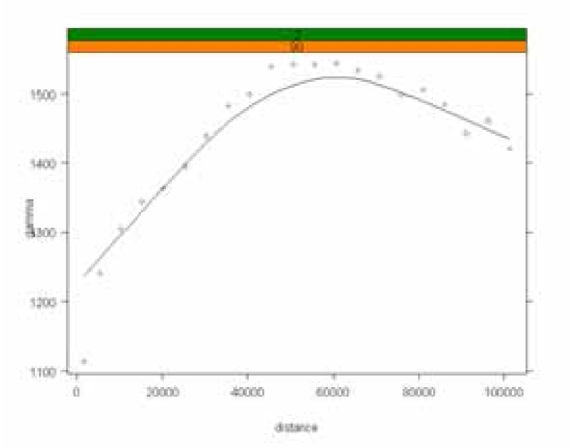


April 1994, 0°

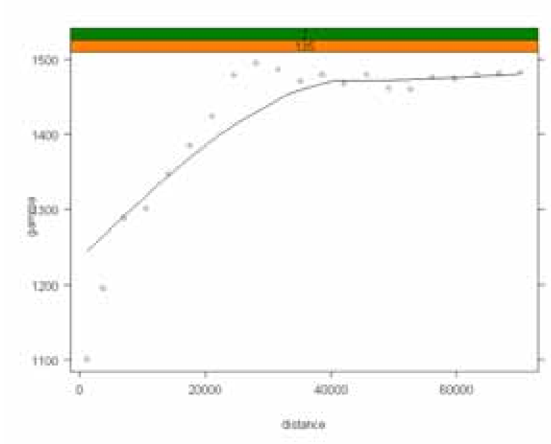


April 1994, 45°

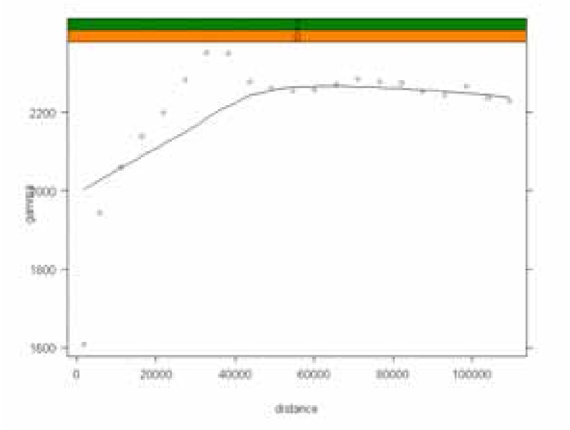
Figure 5.1: Directional variograms of groundwater table



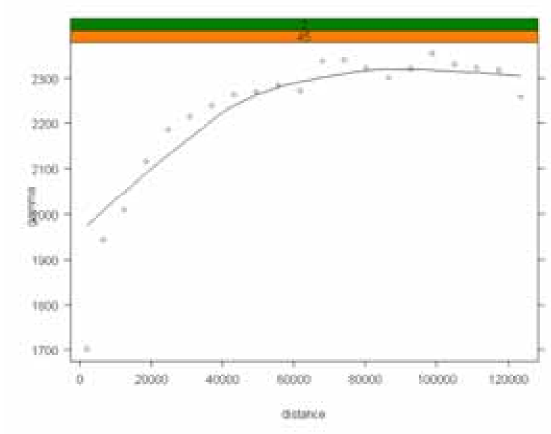
April 1994, 90°



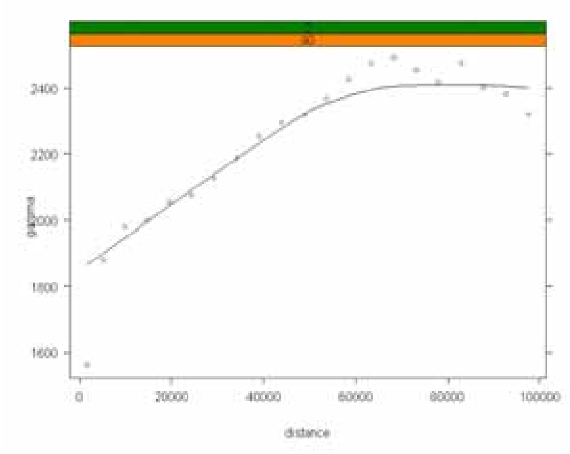
April 1994, 135°



April 2000, 0°



April 1994, 45°



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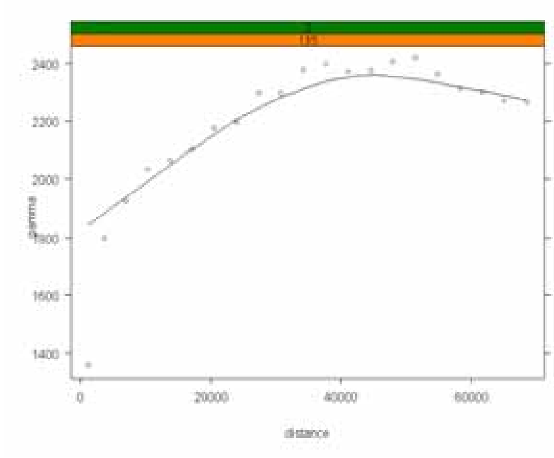
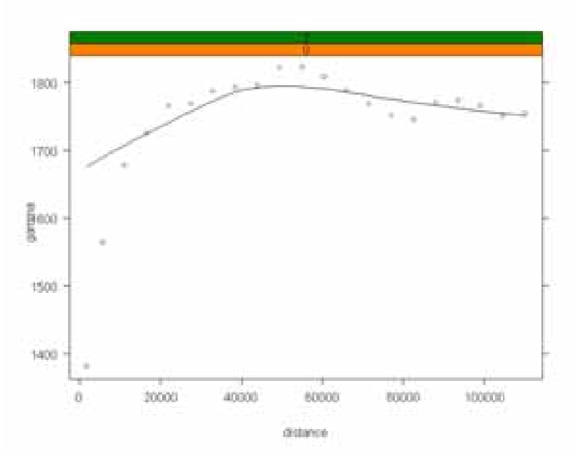
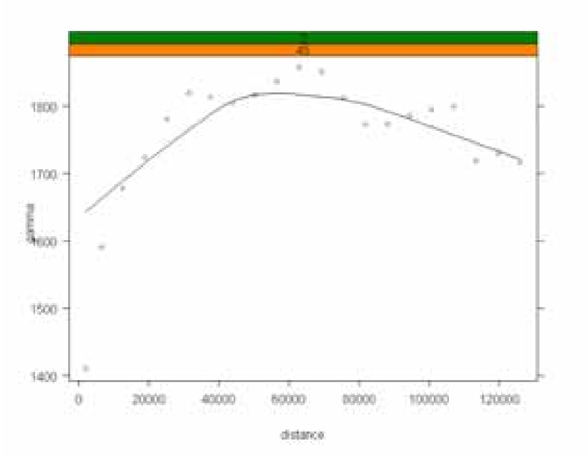


April 1994, 135°

Figure 5.1: Continued



July 1990, 0°



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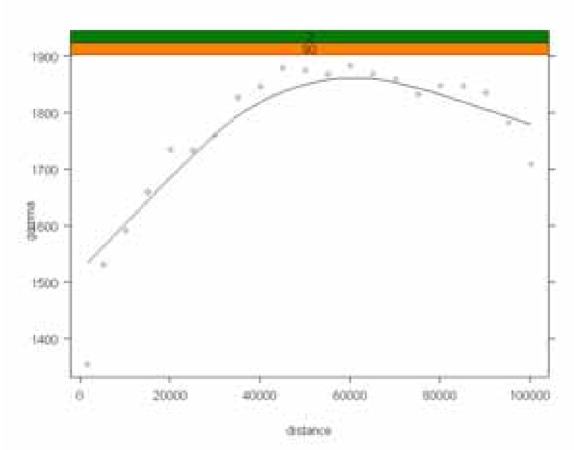

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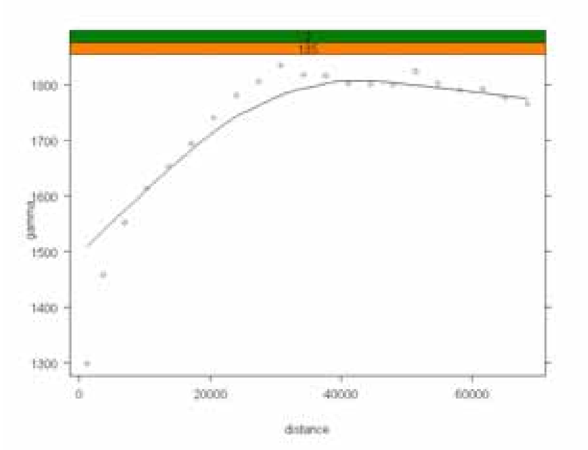

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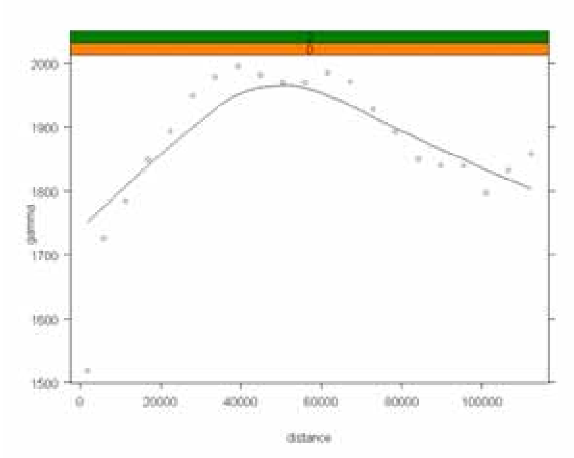

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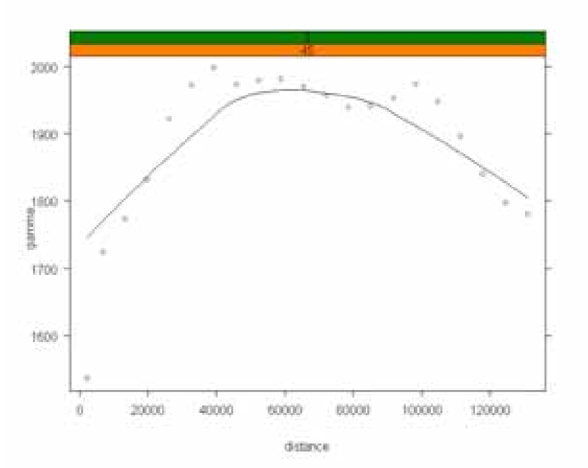

July 1994, 45°

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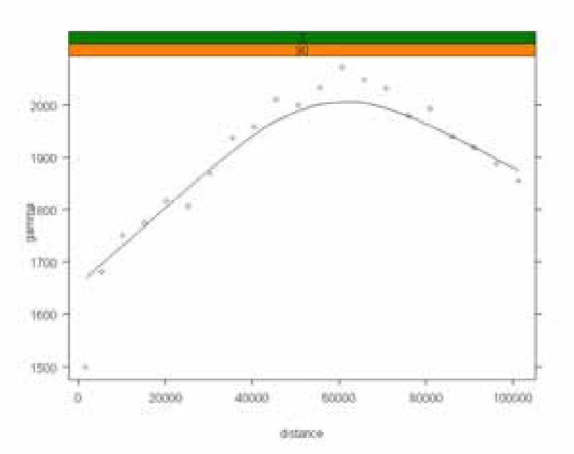
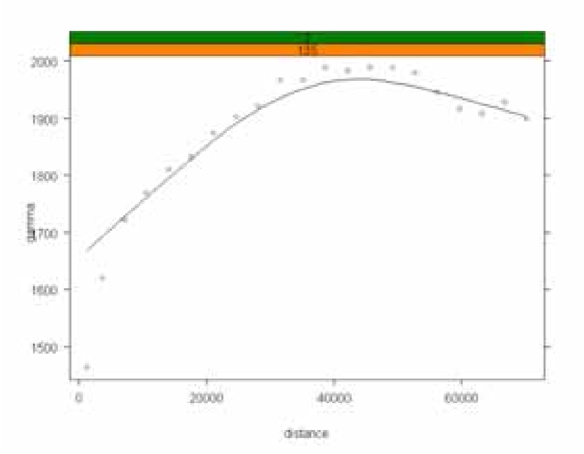
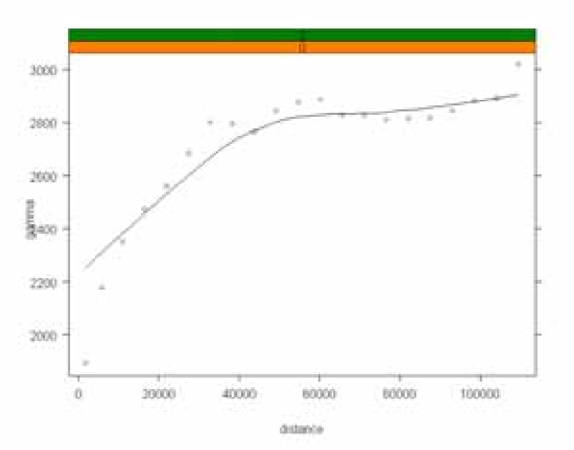


July 1994, 90°



July 1994, 135°



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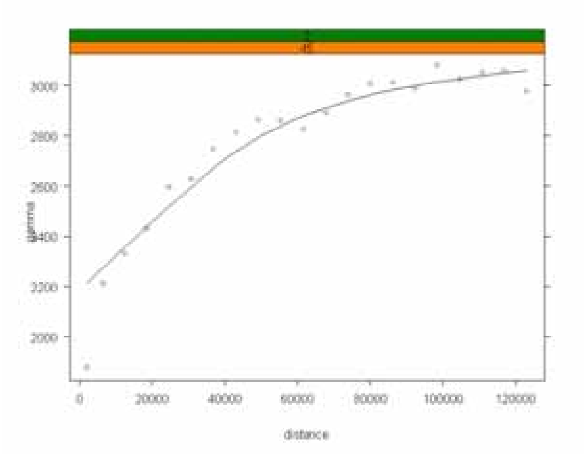

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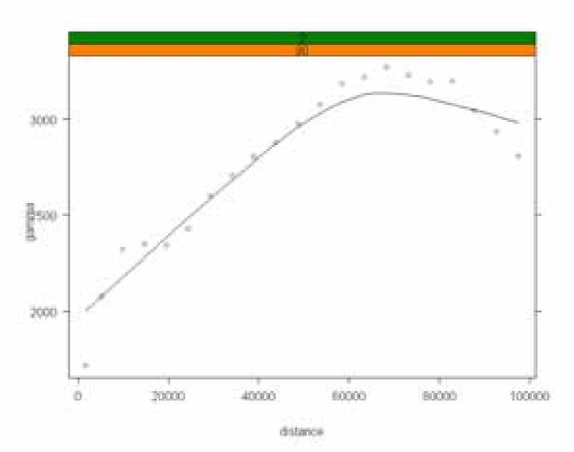

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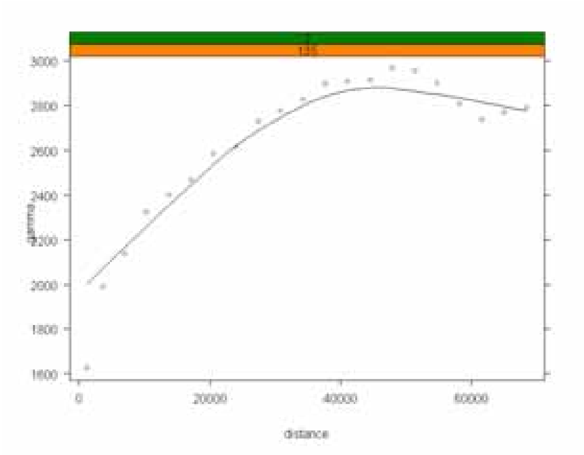

July 2000, 135°

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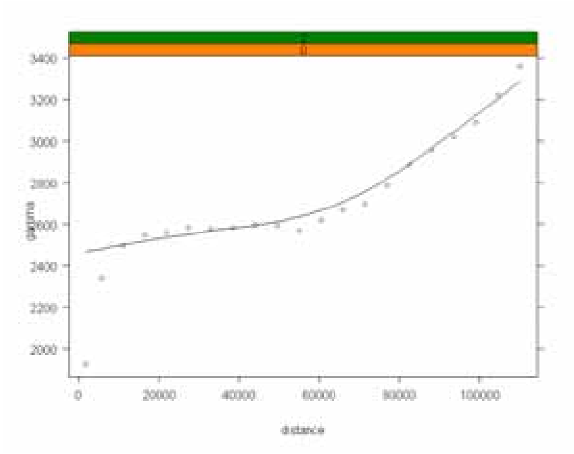
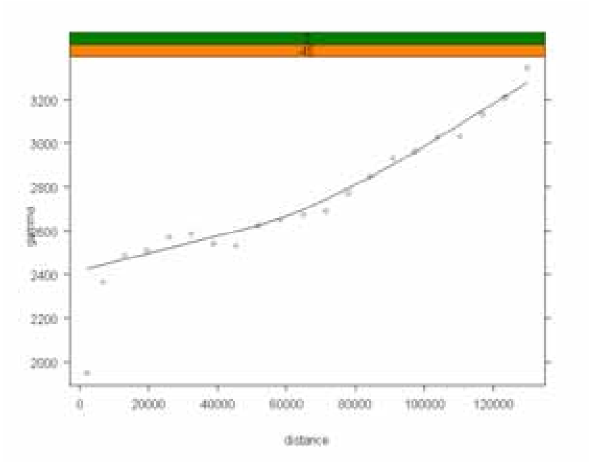
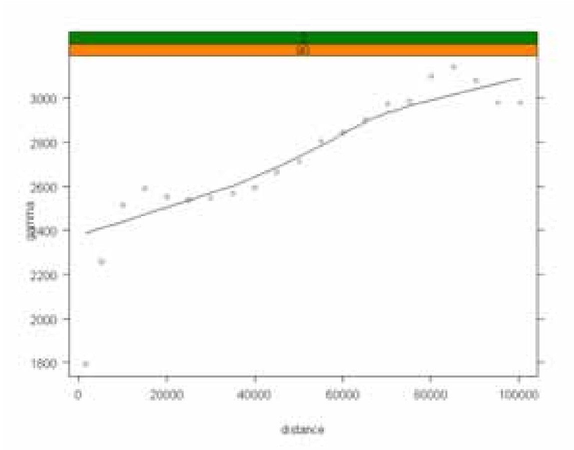


October 1990, 0°



October 1990, 45°



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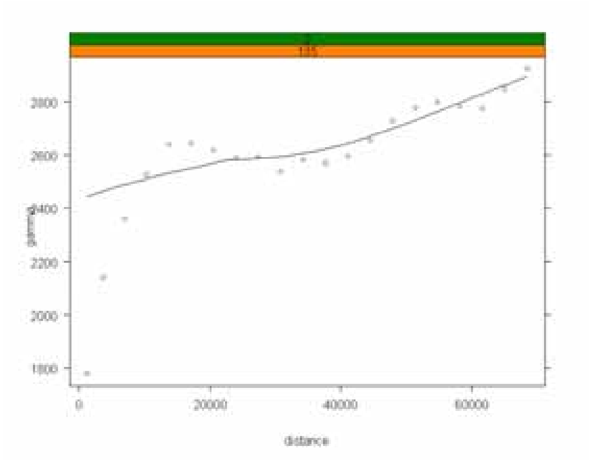

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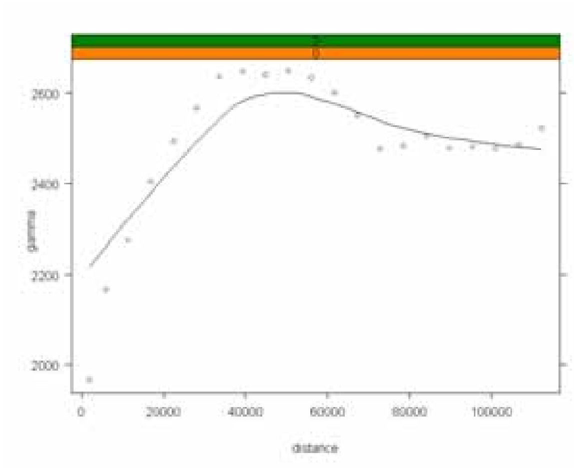

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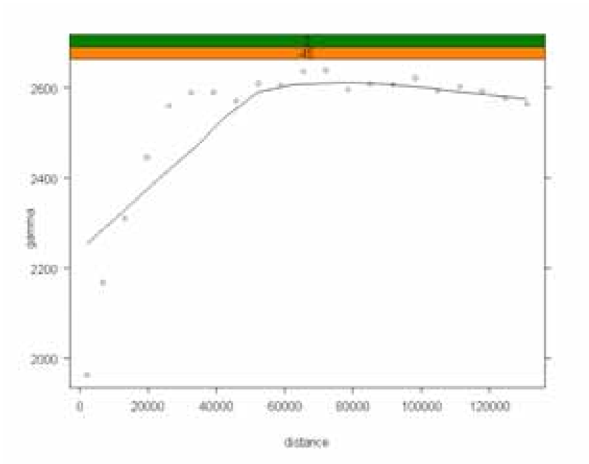
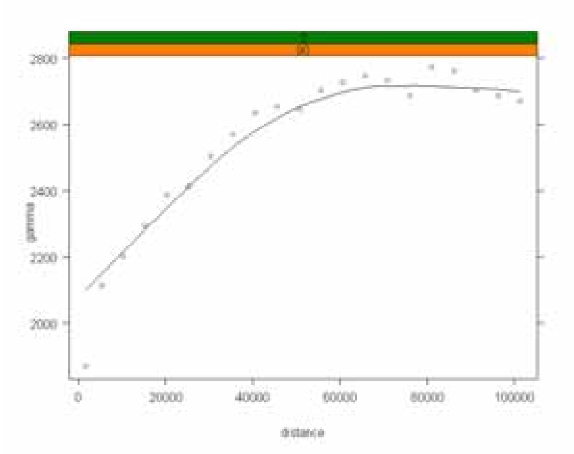
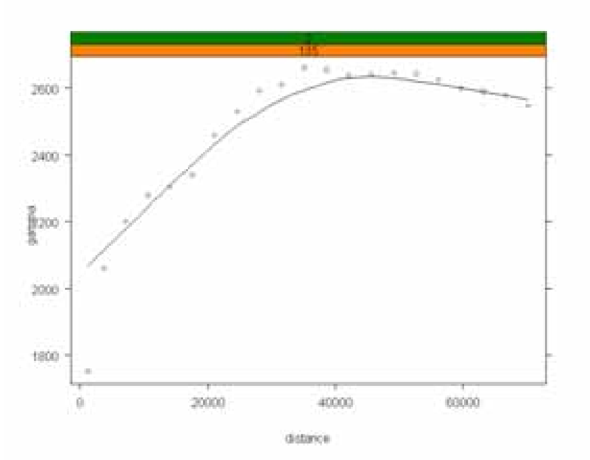


October 1996, 45°

Figure 5.1: Continued



October 1996, 90°



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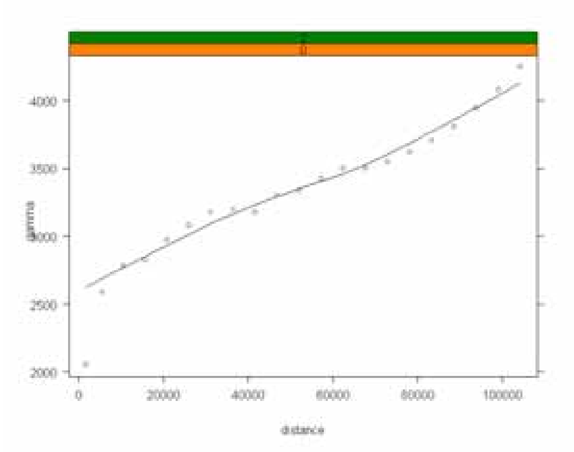
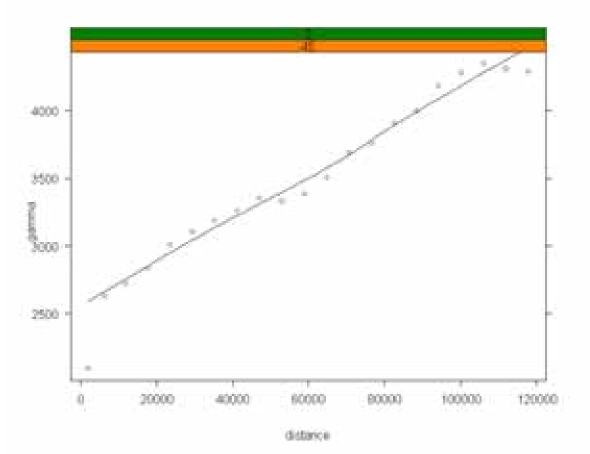
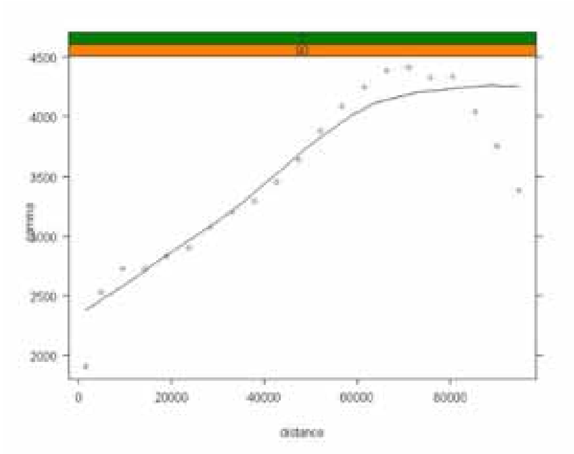


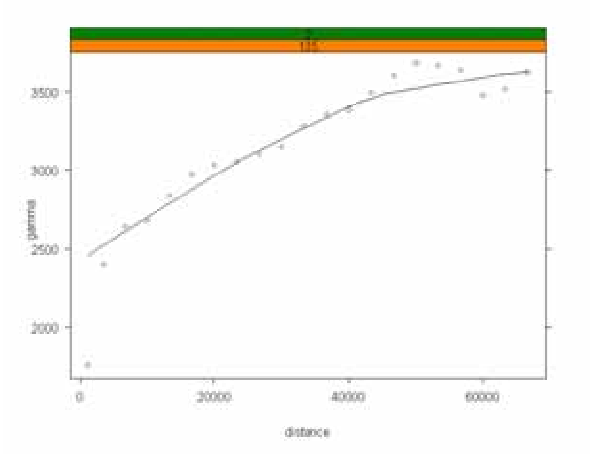
October 2000, 0°



October 2000, 45°



October 2000, 90°



October 2000, 135°

Figure 5.1: Continued

A large nugget variance is seen in the variograms for all the measurement periods. This is indicative of the high variability of the readings taken from the nearest monitoring wells. Several explanations exist for large nugget variance, among which are measurement/instrumentation errors and small scale variability (Isaak and Srivastava 1989). But the most likely reason is the too coarse spacing between the monitoring wells as well as the possible influence of canals, drains and other environmental factors on the readings (see Chapter 4). Kriging allows modeling the spatial distribution of variables, which have a *nugget* variance although the resulting interpolated maps would contain inherent estimation errors. Large errors are known to have a negative influence on the estimation or explanations for the observed spatial phenomena.

Despite large nugget variance, there was a clear range in most of the variograms. The range was clearer in the directions of anisotropy (Figure 5.1). The minimum observed value of the range was 7.41 km whereas the maximum was 17.4 km. This shows that autocorrelation exists at the extent of ca. 70 – 170 ha (average field size is ca. 2 – 4 ha). However, the difference in the range is also attributed to the different models that were fitted to variogram scatter points.

Two models, spherical and exponential, appeared to better explain the variogram behavior (Table 5.1). When fitting a model to scatter points of the variograms, the better model was chosen based on the smaller mean square error. It appeared that the exponential model was more frequently the better choice.

Table 5.1: Parameters of kriging interpolation method for groundwater table

Year	Measurement period	Range	Sill	Nugget	Function
1990	April	17373.15	337.81	1515.85	Spherical
	July	7407.20	513.99	1304.83	Exponential
	Oct	883672393.27	6703365.10	2314.94	Spherical
1994	April	8454.38	402.80	1084.75	Exponential
	July	8337.90	498.64	1465.85	Exponential
1996	Oct	28242.53	659.08	1965.62	Spherical
2000	April	9383.39	724.68	1594.78	Exponential
	July	16839.51	1227.36	1818.76	Exponential
	Oct	454006.37	14789.35	2435.15	Exponential

An analysis of the chosen parameters of the model in making the best possible estimation of the values at the unknown locations was done through cross-validation. Table 5.2 shows the prediction and standard errors of the estimated (predicted) versus measured values of GW table. The values of average standard errors for most measurement periods are close to the associated root mean square errors. This is indicative of the correct assessment of the variability in the data by the chosen parameters of the kriging model. Greater average standard errors over the root mean square errors indicate that the model in most cases slightly overestimated the variability of interpolated values. The variability of estimations in all the measurements in 2000 and in 1990 (except for the measurement in April) were overestimated, those in 1994 (1996 in October) were underestimated. Similar information is contained in the root mean square standardized error. The standardized mean and root mean prediction errors were close to zero and one, respectively in all the measurement periods, which indicates that the model parameters were chosen correctly.

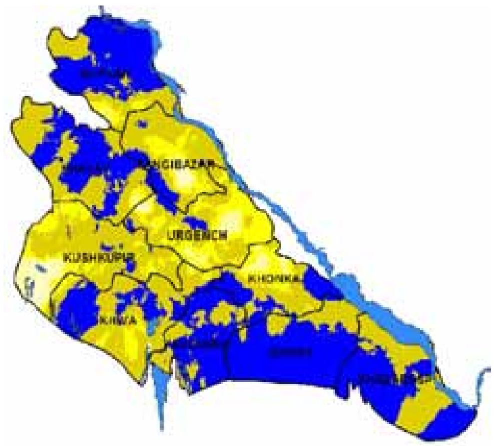
Table 5.2: Prediction and standard errors of estimated versus measured values of groundwater table with kriging interpolation method

Measure-ment period	Mean Errors	Root-Mean-Square Errors	Average Standard Errors	Mean Standardized Errors	Root-Mean-Square Standardized Errors
Apr-90	0.053	40.89	40.58	0.00133	1.007
Jul-90	0.006	38.67	39.73	0.00006	0.973
Oct-90	-0.005	46.94	49.25	-0.00048	0.953
Apr-94	-0.114	37.04	36.17	-0.00313	1.023
Jul-94	-0.196	40.99	40.59	-0.00463	1.009
Oct-96	0.043	44.04	43.9	0.0007	1.004
Apr-00	-0.039	42.35	42.59	-0.00095	0.994
Jul-00	-0.15	44.4	45.59	-0.00337	0.974
Oct-00	-0.189	47.22	48.08	-0.00412	0.983

However, the root mean square prediction error was close to or exceeded 40 for most estimated measurements. This shows that although the model parameters were chosen correctly, the model estimated values with a large error. Cross-validation analysis in ArcGIS 8.2 revealed that the error (subtraction of estimated and measured values) was from 0 to 150 cm. Examination of the prediction standard error map clearly reveals higher errors in sparse data areas, whereas low errors can be associated with the denser data areas. Low (close to zero) estimation errors prove that kriging performs well in delineating the spatial distribution of GW table, whereas high errors show the need for denser measurements in Khorezm to improve accuracy of mapping.

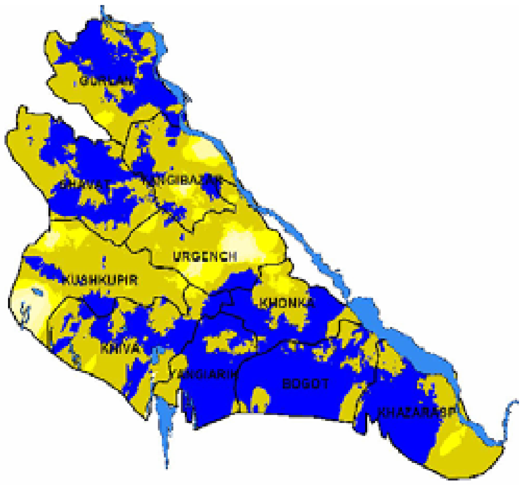
Figure 5.2 shows the maps of the GW table in April, July and October 1990, 1994 (1996 in October) and 2000 estimated using the kriging method. The areas with GW tables at 1 m below the ground surface and shallower are shown in blue. This color was used to separate the areas with GW tables at or above 1 m in all the maps interpolated using the other three interpolation methods. In the maps, the areas at risk of waterlogging and salinization appear in the southern, western and north-western districts of the region, namely in the Pitnyak, Khazarasp, part of Bogot and Yangiarik, Khiva, Shavat and Gurlan districts.

April 1990



July 1990

April 1994



July 1994

Figure 5.2: Maps of groundwater table in April, July and October 1990, 1994 (1996 in October) and 2000, generated using the kriging interpolation method

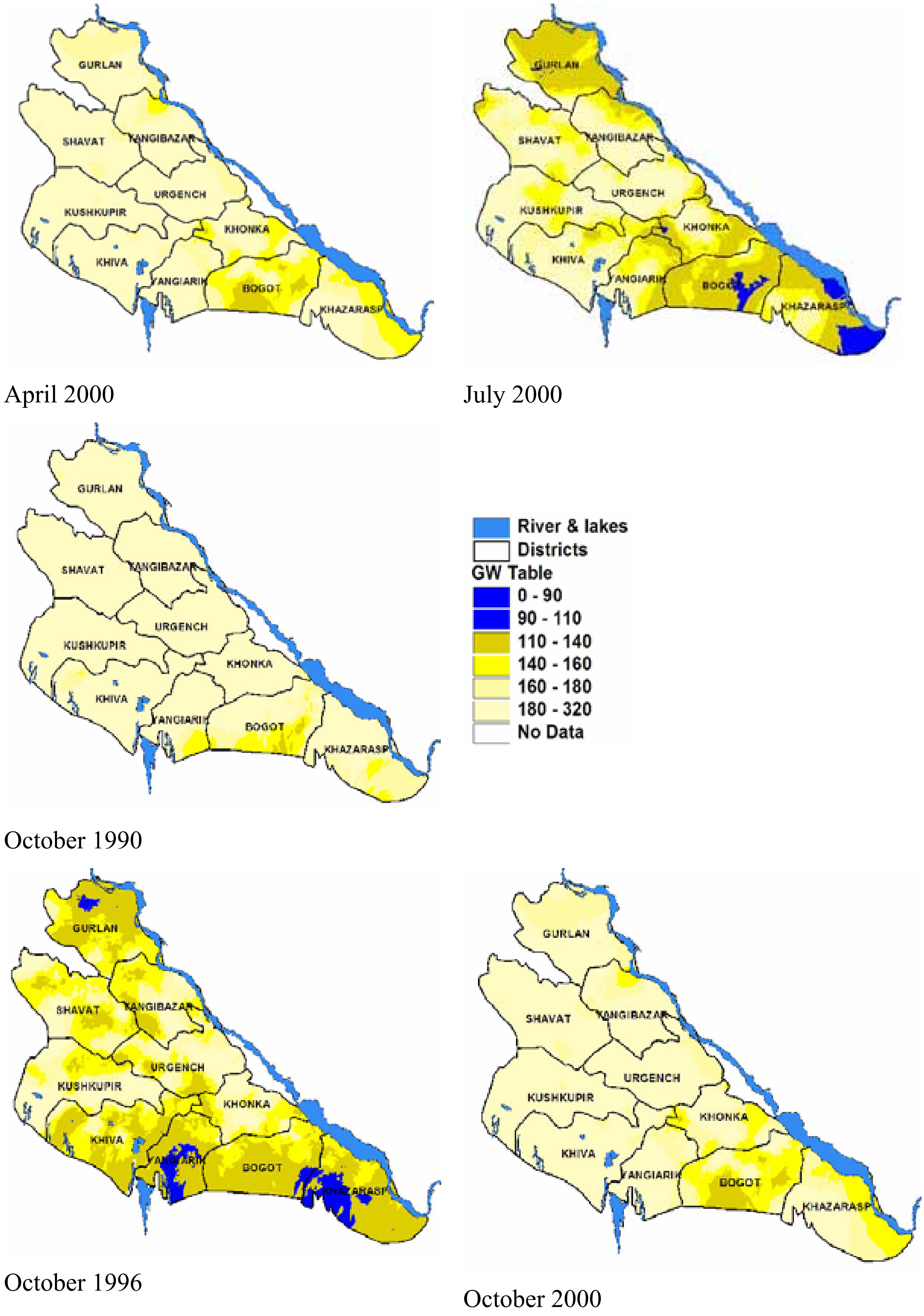


Figure 5.2: Continued

5.2.2 Inverse Distance Weighted method

The inverse distance weighted method (IDW) was chosen because unlike kriging, which makes use of statistical modeling to assess the uncertainty of estimation, the IDW is based on a simple mathematical algorithm. As with kriging, estimation efficiency is achieved by minimizing the root mean square prediction errors. Table 5.3 shows the mean and root mean square prediction errors. The lowest prediction errors were achieved in IDW by adjusting a power value, which was then assigned to nearby measured values. The power value was best adjusted by making the shape of the search neighborhood oval, with a longer axis from east-south to north-west (direction of anisotropy).

Table 5.3: Interpolation and standard errors of interpolated versus measured values of groundwater table in April, July and October with IDW

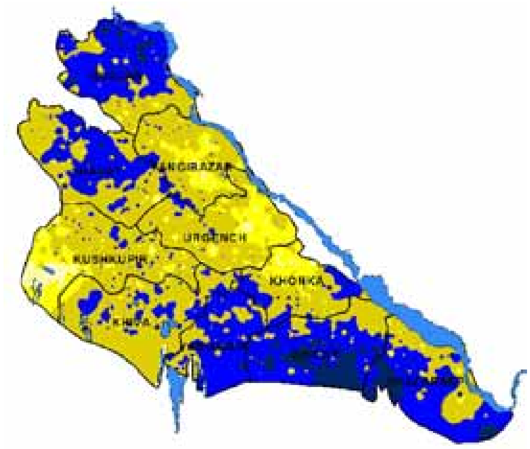
Measurement period	Mean error	Root-Mean-Square error
April 1990	0.12	40.7
July 1990	0.199	38.4
October 1990	1.05	46.9
April 1994	0.12	36.8
July 1994	-0.16	40.8
October 1996	0.298	43.7
April 2000	0.42	42.2
July 2000	0.43	44.7
October 2000	1.26	45.7

The mean prediction errors ranged from 0.1 to 1.3. The better estimations (lower values of the mean error) were achieved for the April and July measurements in 1990 and 1994, whereas the values in October 1990 and 2000 were much higher. Despite the different mean errors, the root mean square errors equaled ca. 40 for all the measurement periods, which is similar to the values estimated by kriging. Comparing the performance of the IDW and kriging, the mean error and root mean square estimation errors were only slightly smaller in kriging in most of the measurements. However, the mean errors were smaller with kriging, which is indicative that kriging performs better than IDW.

The observed difference in the estimation errors in IDW for different measurement periods can be explained by the changes in local water tables due to different irrigation intensity during and outside growing periods. Frequent water scarcity years can also cause the differences in local water tables in the region. The IDW method is highly dependent on the outliers in the search neighborhood. Despite the estimation errors being similar to those for kriging, the IDW method might be inappropriate for an assessment of the spatial GW table and salinity in Khorezm for the different measurement periods.

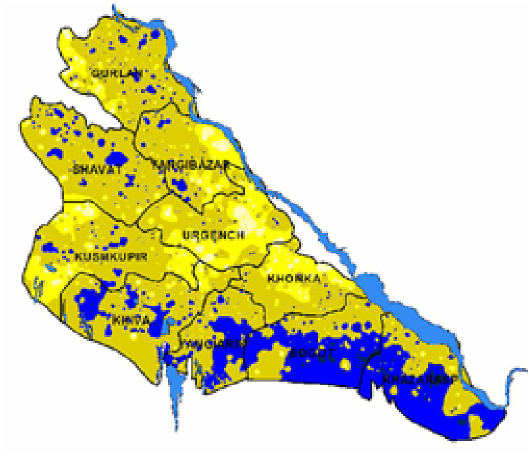
Figure 5.3 shows the maps of GW table in April, July and October 1990, 1994 (1996 in October) and 2000. Similar to the results of the kriging method, the GW tables were shallower in the southern and western parts of the region and during the same measurement periods. Similarity of the maps suggests that the kriging and IDW methods estimate the spatial distribution of the GW table similarly despite the difference in the involved calculation algorithm.

April 1990



July 1990

Figure 5.3: Maps of groundwater table in April, July and October 1990, 1994 (1996 in October) and 2000, generated using the IDW interpolation method

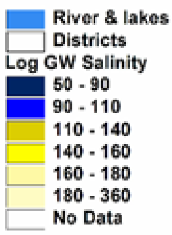


April 1994

July 1994

April 2000

July 2000



October 1990

Figure 5.3: Continued

October 1996

October 2000

Figure 5.3: Continued

5.2.3 Spline

In performing the interpolation with spline, the *regularized* method was chosen because the *tension* method produced extremely unrealistic estimates of the GW table and salinity, with values exceeding the real values by several orders of magnitude. The weight parameter was chosen as 0.1 with the number of the neighboring points 12. An interpolation was performed in ArcINFO 8.2.

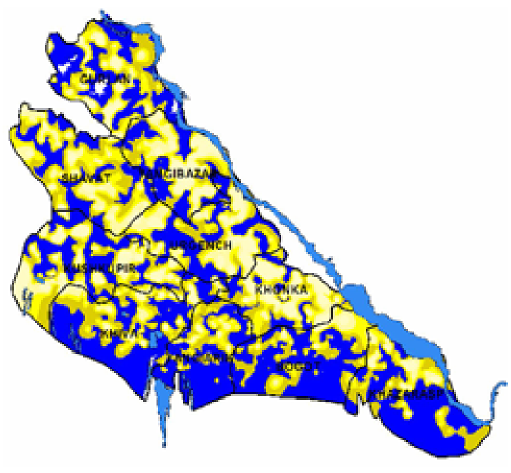
Unfortunately ArcGIS, does not offer such an excellent tool as cross-validation for the spline interpolation method. In order to validate the estimations made by all the interpolation methods, the dataset of the GW table was divided into the training and test parts. The test part contained 10% of all the measurements (ca. 199 sample points). The April, July and October measurement periods of GW table from the year 1990 were chosen for validation purposes. Table 5.4 shows the prediction errors by the spline method.

Table 5.4: Prediction errors of estimated versus measured values of groundwater table in April, July and October 1990 with spline method

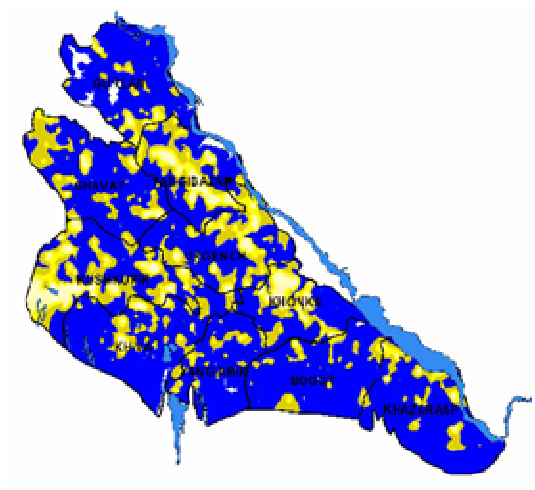
Measurement period	Mean error	Root-Mean-Square error
April	1.055	1311
July	-4.64	1213
October	1.704	1506

It is seen that the root mean squared prediction errors were extremely large for all the measurement periods. The mean errors were smaller for the measurement period in April 1990, whereas higher errors were found in July. The assessment of the areas at risk from shallow saline GW in Chapter 4 shows that the maps generated by the spline method estimated larger areas at risk in all the measurement periods compared to the other two interpolation methods. Especially unrealistic was the estimation of the areas at risk in October. This, together with the high root mean square errors, suggests that the spline interpolation method cannot be used for interpolation and delineation of the areas with saline and shallow GW in Khorezm.

The estimated areas at risk of waterlogging and salinization using the spline method are shown in Figure 5.4. The spatial distribution of the GW table is patchy in these maps, without clear spatial domains. The patterns of the more shallow GW tables in the southern and western parts of the region are not as visible as in the maps interpolated using the kriging and IDW methods.

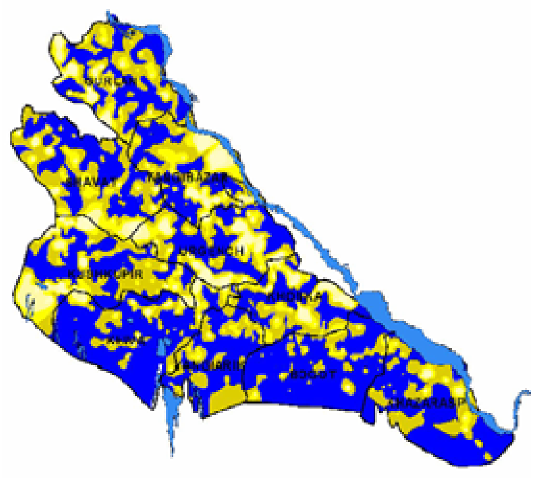


April 1990

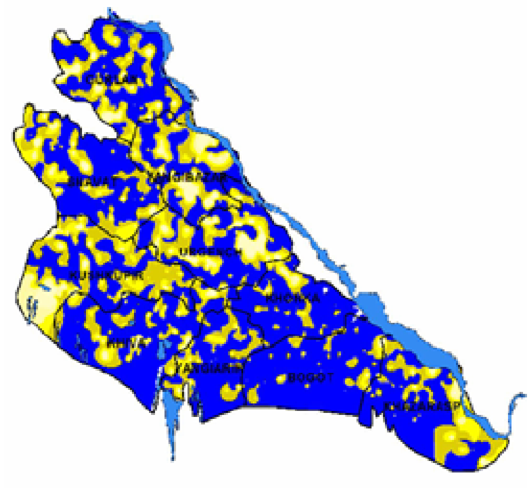


July 1990

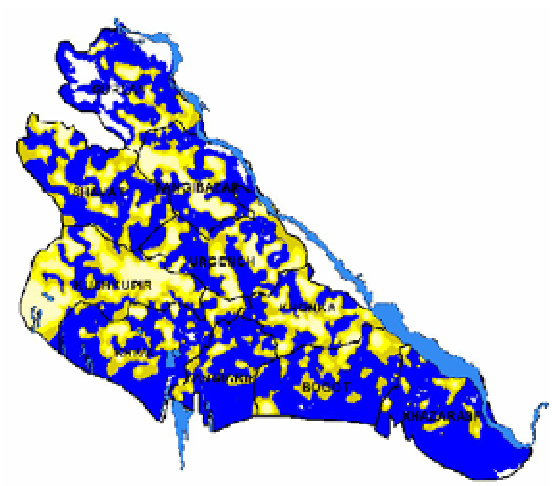
Figure 5.4: Maps of groundwater table in April, July and October 1990, 1994 (1996 in October) and 2000, generated using the spline interpolation method



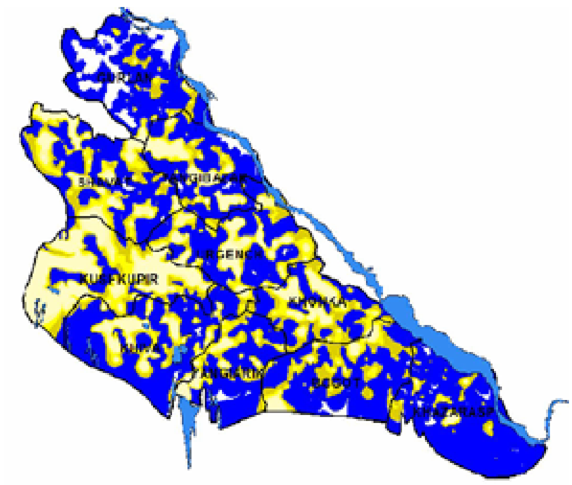
April 1994



July 1994



April 2000



July 2000

October 1990

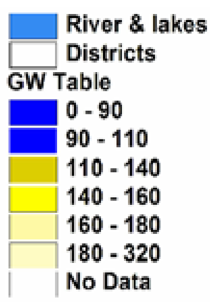
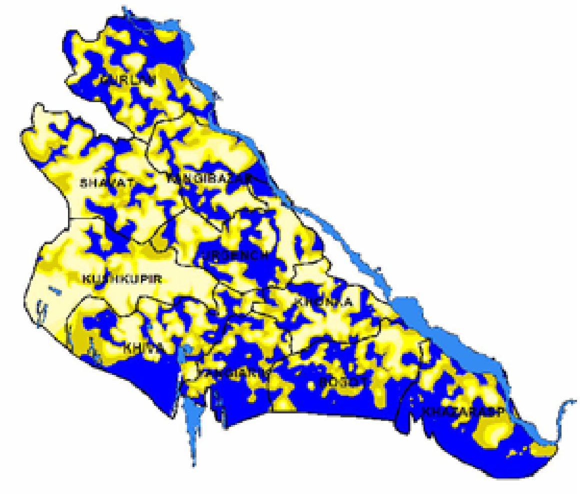
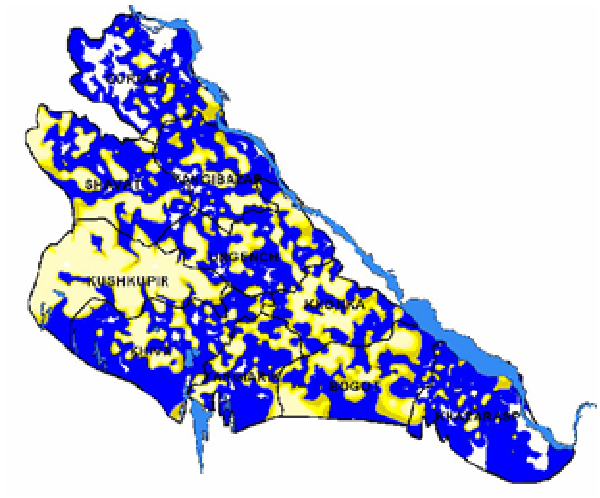


Figure 5.4: Continued



October 1996



October 2000

Figure 5.4: Continued

5.2.4 Comparison of kriging, IDW and spline methods for estimating groundwater table

The comparison of the performance of the three interpolation methods was possible through an analysis of the minimum generated mean and root mean square errors and an analysis of the "plausibility" of the estimation of the areas at risk from shallow saline GW. Table 5.5 shows the prediction errors of the three interpolation methods using the same training and test dataset.

Table 5.5: Prediction errors of estimated versus measured values of groundwater table in April, July and October 1990 for three interpolation methods

Measurement period	**Mean error**			**Root-Mean-Square error**		
	Spline	**IDW**	**Kriging**	**Spline**	**IDW**	**Kriging**
April	1.055	0.12	0.053	1311.89	40.7	40.89
July	-4.64	0.199	0.006	1213.29	38.4	38.67
October	1.704	1.05	-0.005	1506.48	46.9	46.94

The spline method is seen to have the highest prediction errors (both mean and root mean square prediction errors) in comparison to the other two interpolation methods. Based on Table 5.5, the spline method therefore appears to be an inefficient method for the spatial assessment of GW table in Khorezm, whereas kriging is the best interpolation method. From the practical point of view, IDW is also acceptable, as the errors do not highly deviate from those of kriging. IDW does not require any knowledge of (geo)statistics and can be relatively easily implemented by water management agencies in the analyses of the GW table.

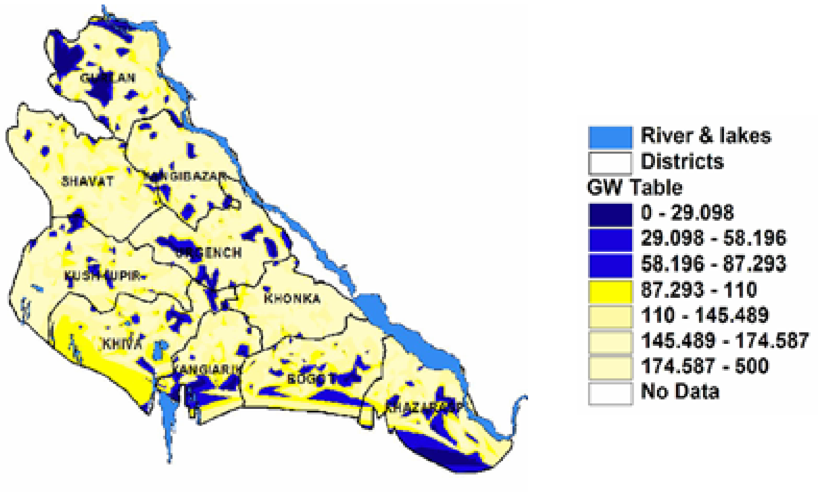
5.2.5 Triangulated irregular networks (TIN)

The TIN interpolation method is widely used in Uzbekistan to delineate areas with shallow and saline GW. Decision-making is based on the information contained in paper maps generated by the TIN method. Therefore, the performance and efficiency of this method of interpolation was assessed against the other methods. Figure 5.5 shows the GW table interpolated for April, July and October 1990. It is seen that the distribution of GW table in all these measurement periods was relatively similar to that estimated using the spline method. In order to assess the performance of TIN, prediction errors of the TIN were analyzed from the same training and test datasets. The results of the analysis are shown in Table 5.6.

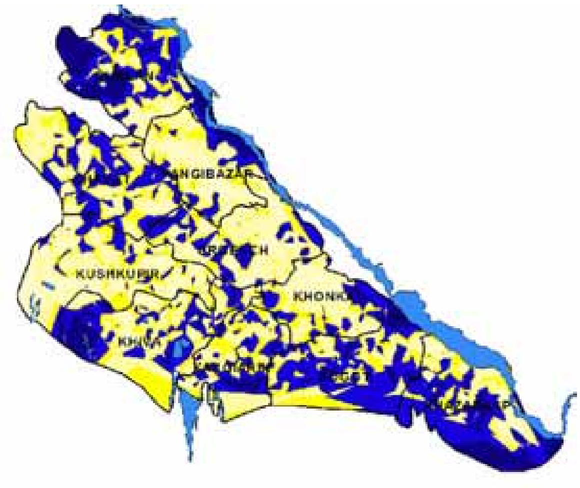
It is seen that TIN produces much higher prediction errors than all the other interpolation methods. Mean prediction errors were the largest in April, lower in July and lowest in October. However, the root mean square error of TIN for October was the highest (Table 5.6). This shows that TIN is not acceptable for the spatial assessment of GW table and salinity in Khorezm as it can produce improper estimates with large estimation errors.

Table 5.6: Prediction errors of estimated versus measured values of groundwater table in April, July and October 1990

Measurement period	Mean error				Root-Mean-Square error			
	Spline	IDW	Kriging	TIN	Spline	IDW	Kriging	TIN
April	1.055	0.12	0.053	8.850	1311.89	40.7	40.89	889.79
July	-4.64	0.199	0.006	-4.698	1213.29	38.4	38.67	882.40
October	1.70	1.05	-0.005	-1.298	1506.48	46.9	46.94	1021.04



April 1990



July 1990

October 1990

Figure 5.5: Maps of groundwater table in April, July and October 1990, 1994 (1996 in October) and 2000, generated using the TIN interpolation method

5.3 Spatial analysis of groundwater salinity

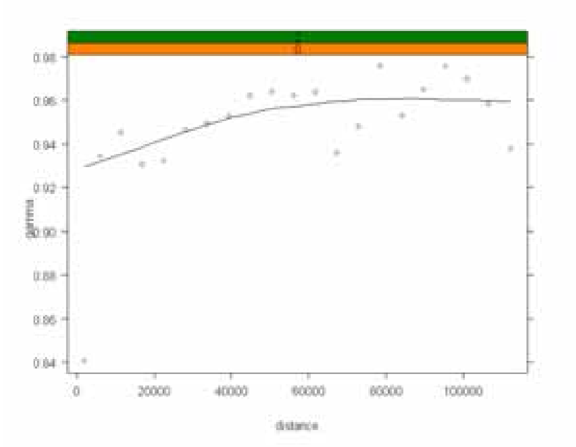
5.3.1 Kriging

The analysis of the statistical distribution of the GW salinity data in Chapter 4 revealed high right-skewness and the existence of outliers. However, after the removal of less than 5% of the outliers and logarithm transformation, a good approximation to normal distribution was attained.

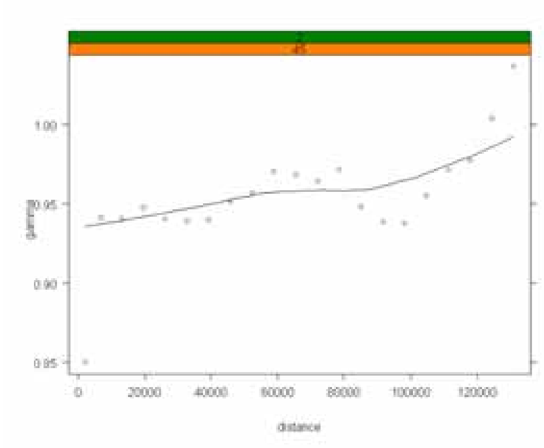
Variogram cloud analysis was performed to identify significantly deviating pairs of values. Analysis of the graphs of variogram clouds generated in ArcGIS showed no outliers. Furthermore, no heteroskedasticity was observed from the analysis of the average values and standard deviations from moving average techniques (Isaak and Srivastava 1989). A clear trend (constant increase of GW salinity readings in a particular direction) was observed in the east-western direction and a smoother one in the north-southern direction. Therefore, universal kriging was applied to the dataset of GW salinity to remove the trend.

There was also anisotropy in the variograms of GW salinity data in the direction similar to that for the GW table (Figure 5.6). Anisotropy can also be seen in the north-south direction as revealed by the trend analysis. Incorporating anisotropy in the direction south-east to north-west resulted in smaller estimation errors.

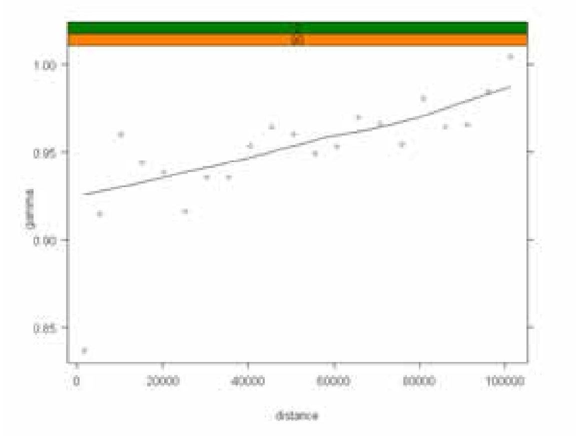
As seen in Figure 5.6, the directional variograms for most measurements of GW salinity do not have a clear pattern. Only in April 1990 and 2000 did the variograms have an upward shape of the fitted model with increasing distance between the pairs of points. For all the remaining measurement periods, the structure was the opposite; decreasing variance with distance is indicative of the changing values of GW salinity at far distances. For some periods, pure nugget variance existed in the variograms, revealing a lack of spatial autocorrelation and thus, possibly poor estimation. The most poorly structured variograms were for April and July 1990 in almost all directions, whereas structures existed in some directions in the others measurement periods.



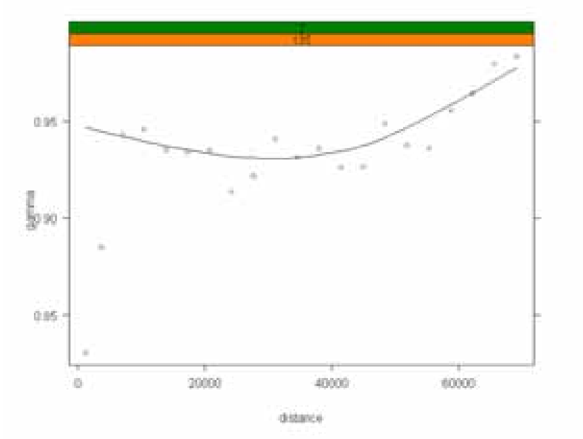
April 1990, 0°



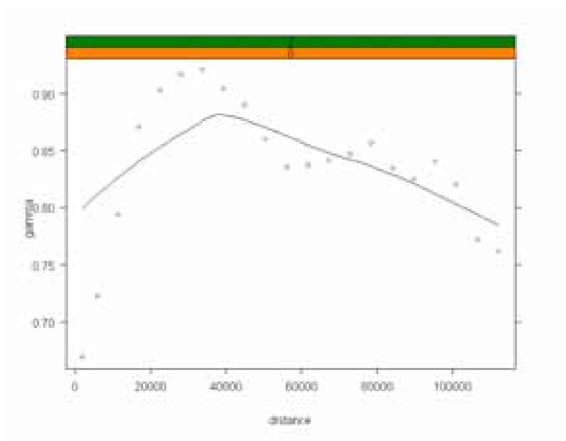
April 1990, 45°



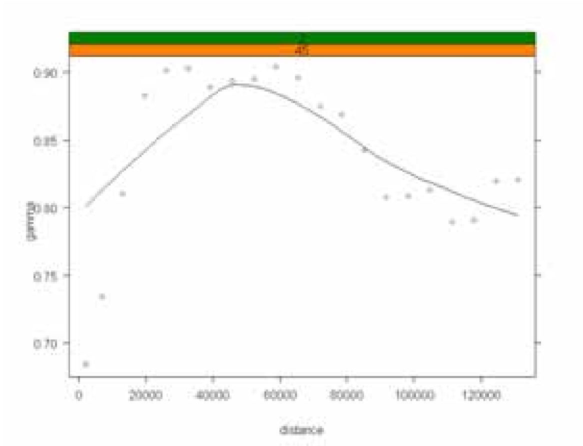
April 1990, 90°



April 1990, 135°

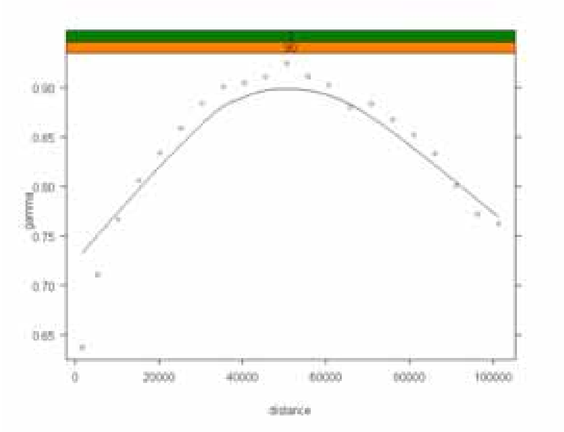


April 1994, 0°

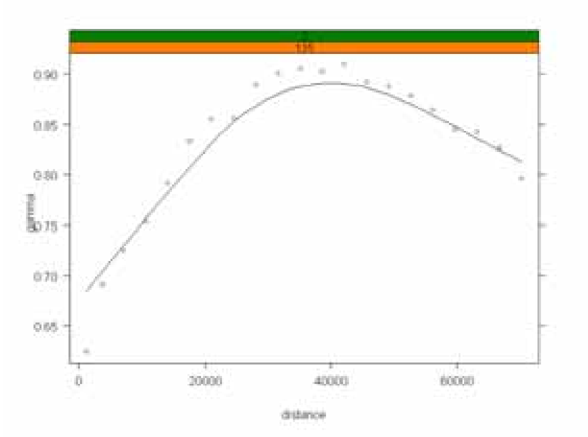


April 1994, 45°

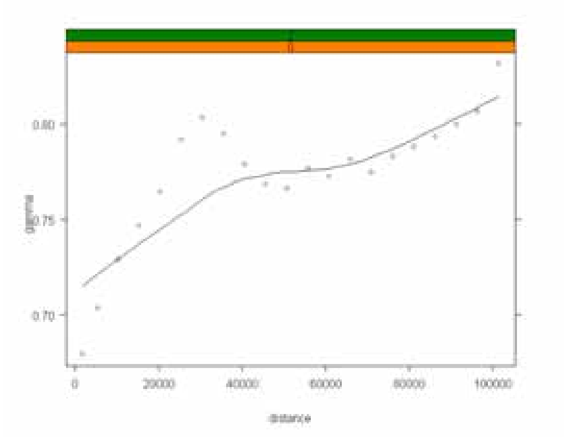
Figure 5.6: Directional variograms of groundwater salinity



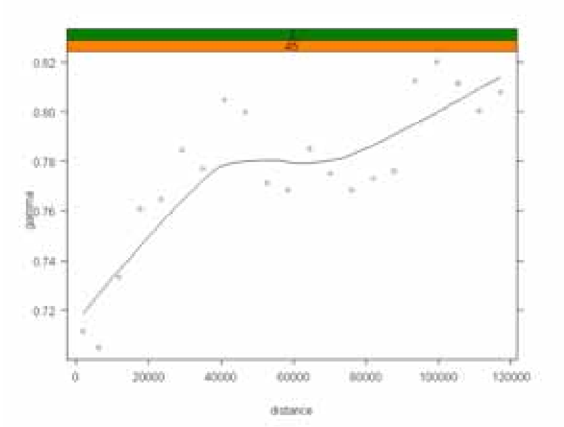
April 1994, 90°



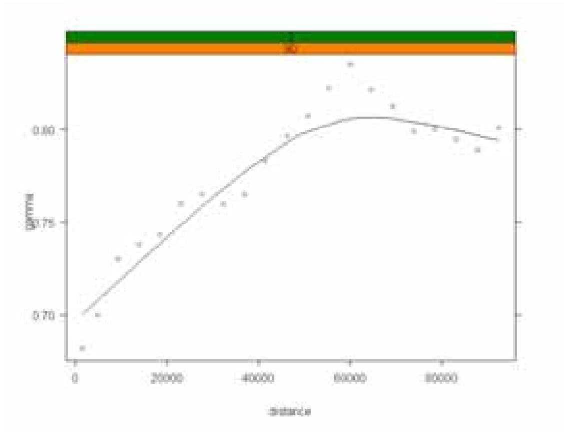
April 1994, 135°



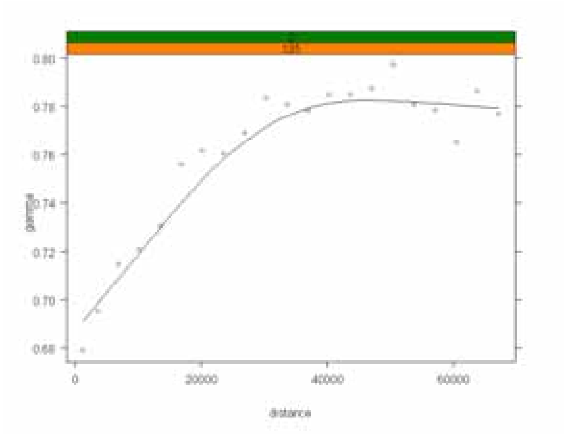
April 2000, 0°



April 2000, 45°

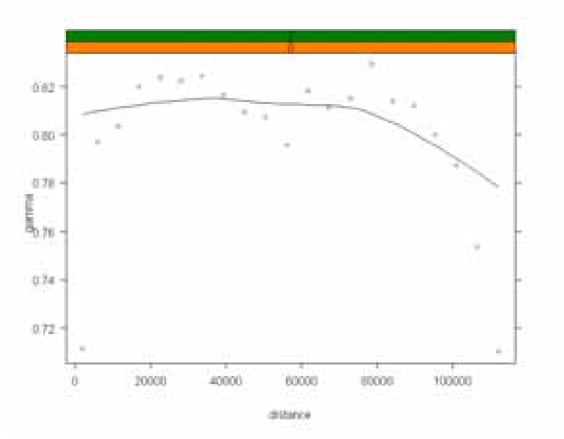


April 2000, 90°

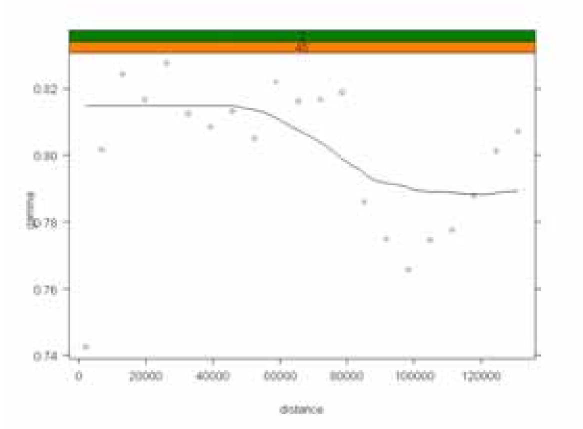


April 2000, 135°

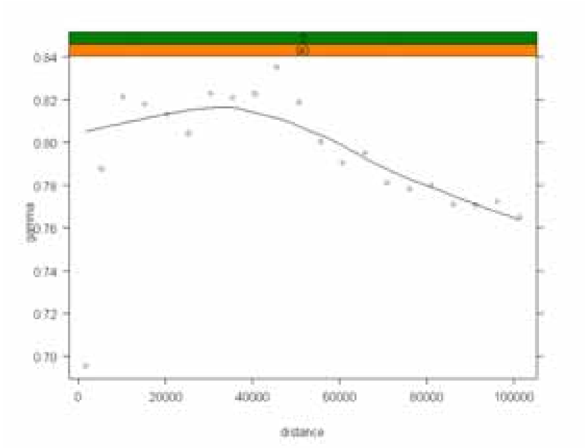
Figure 5.6: Continued



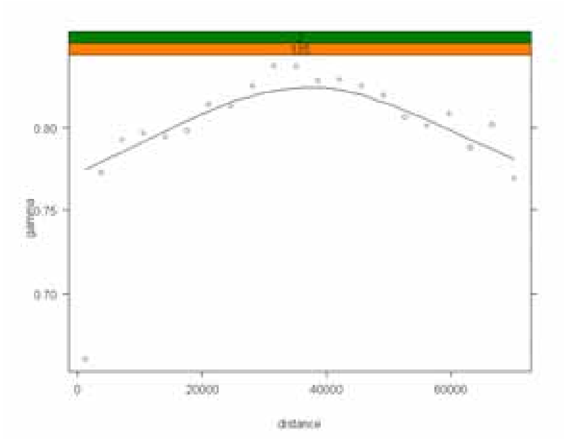
July 1990, 0°



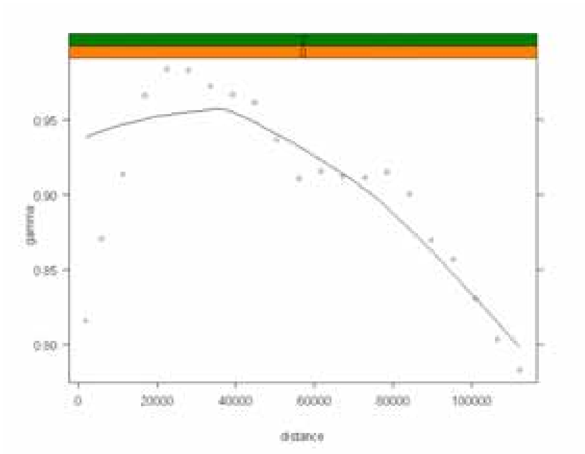
July 1990, 45°



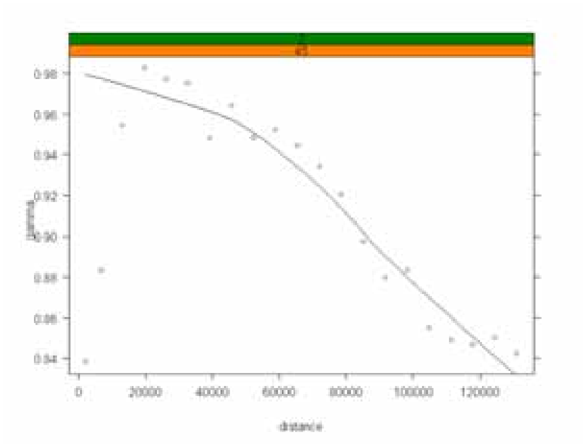
July 1990, 90°



July 1990, 135°

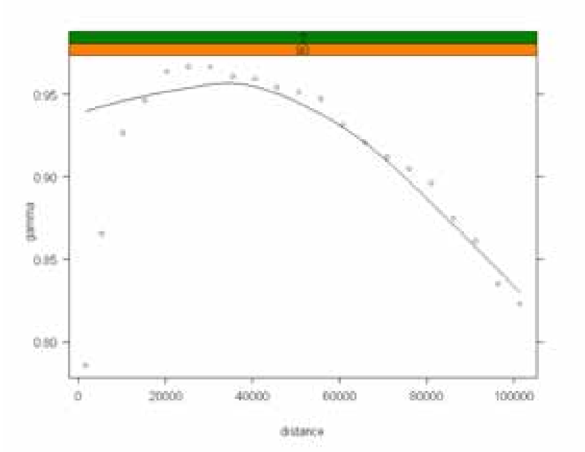


July 1994, 0°



July 1994, 45°

Figure 5.6: Continued



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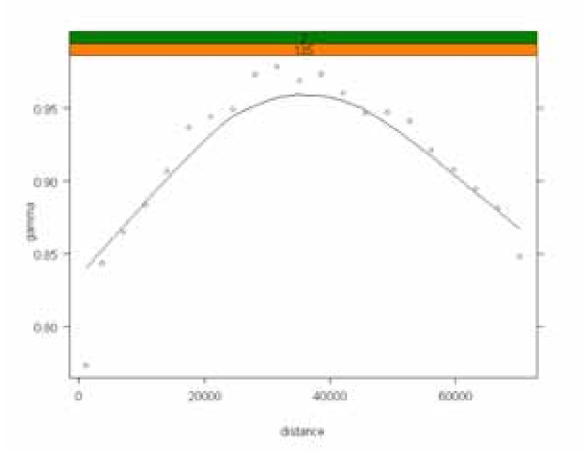
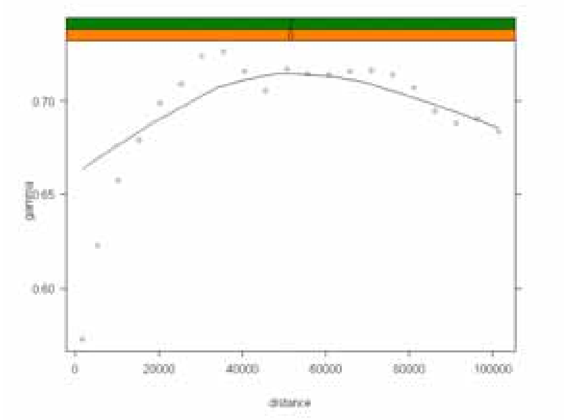
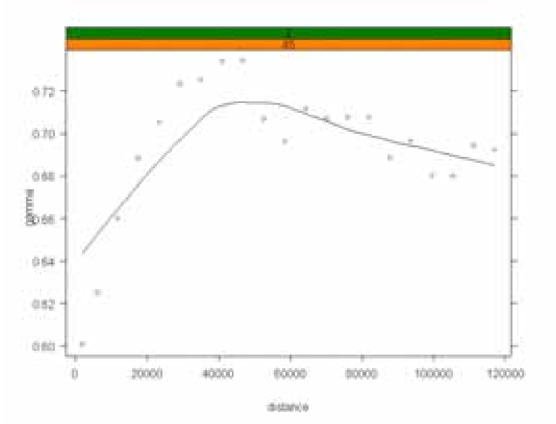


July 1994, 135°



July 2000, 0°



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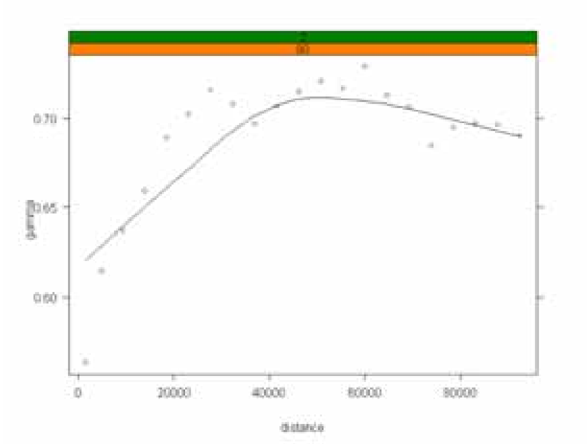

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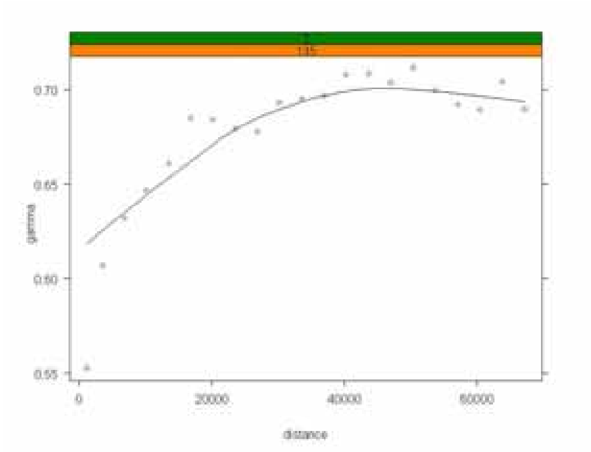
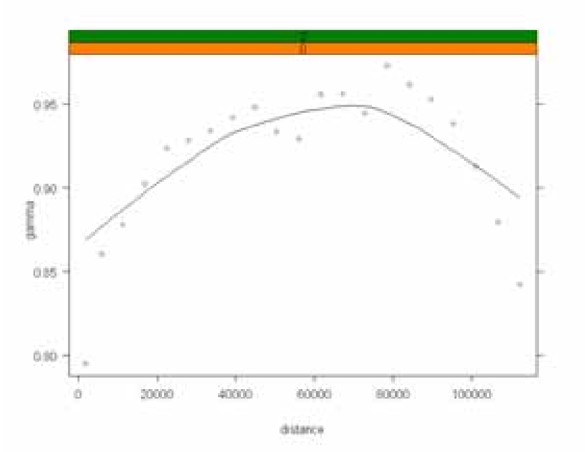
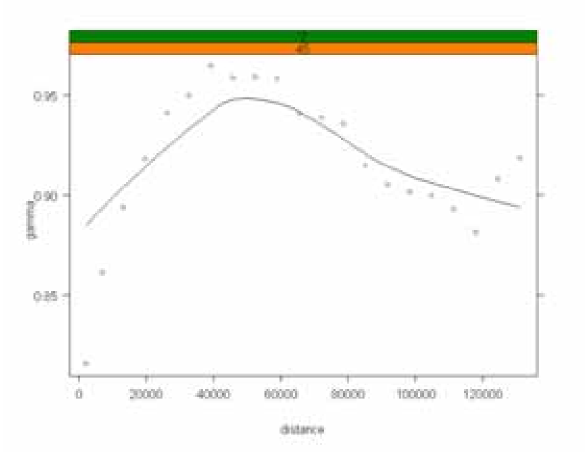


July 2000, 135°

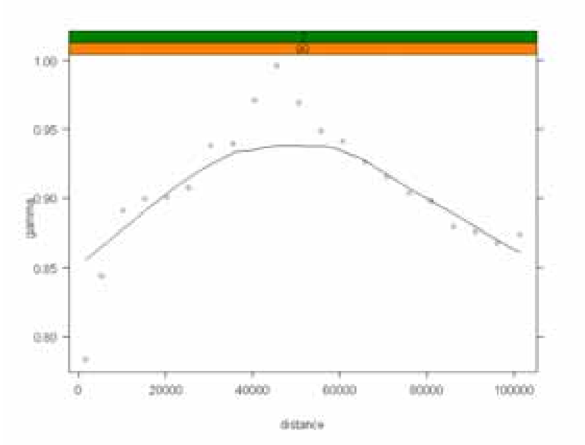
Figure 5.6: Continued



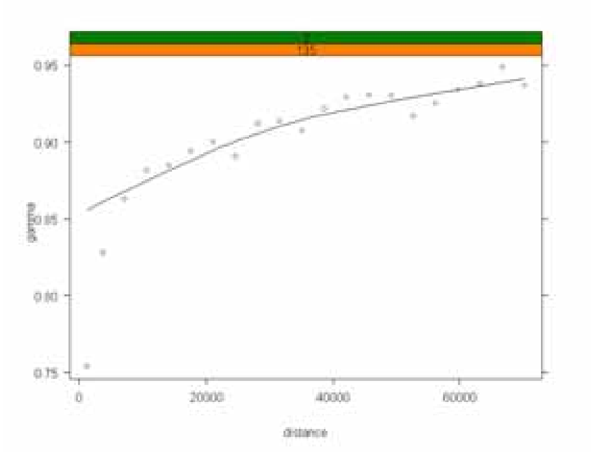
October 1990, 0°



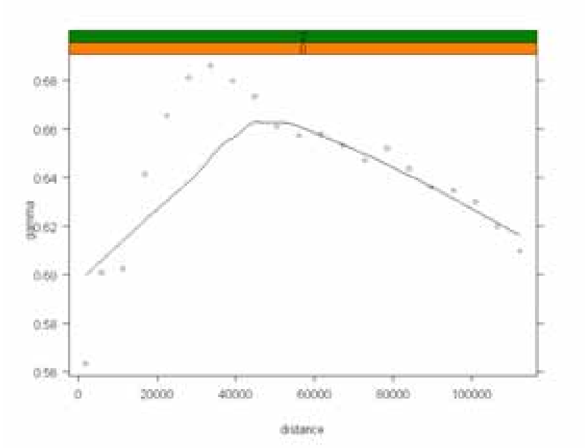
October 1990, 45°



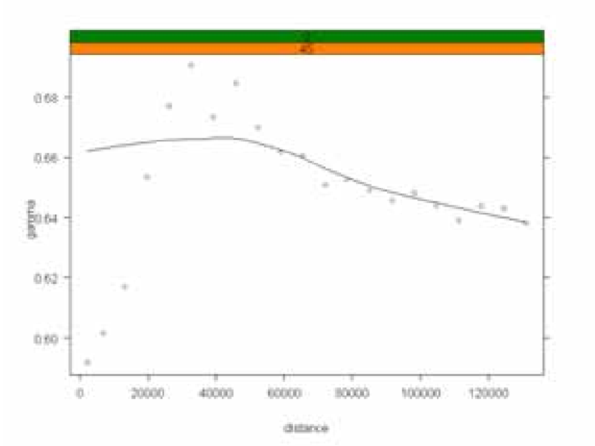
October 1990, 90°



October 1990, 135°

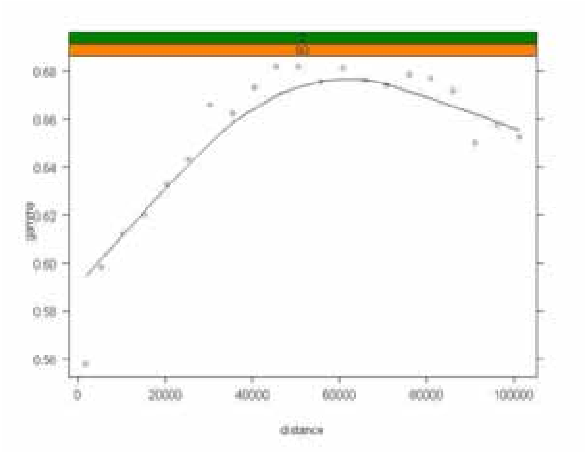


October 1996, 0°

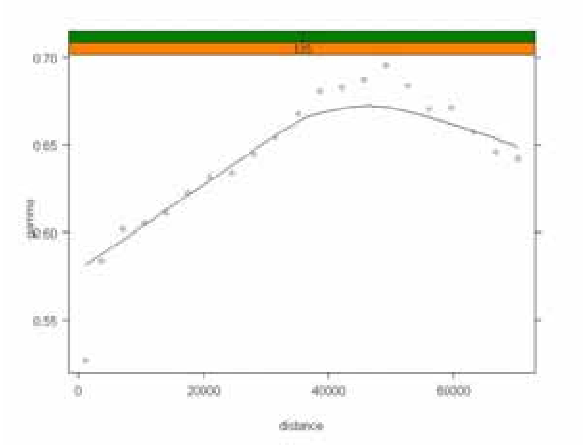


October 1996, 45°

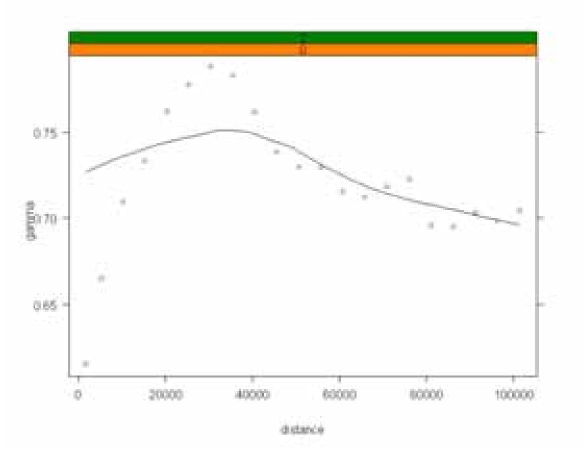
Figure 5.6: Continued



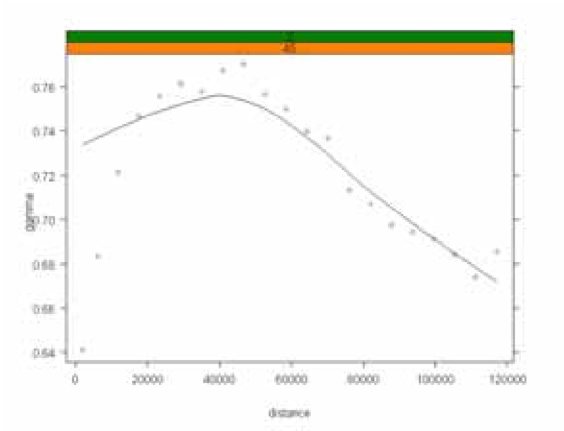
October 1996, 90°



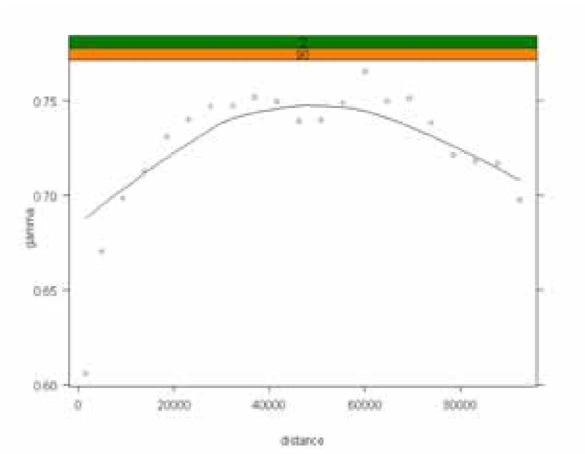
October 1996, 135°



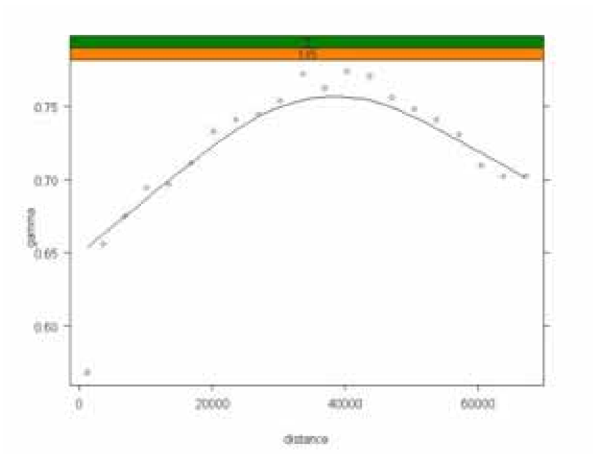
October 2000, 0°



October 2000, 45°



October 2000, 90°



October 2000, 135°

Figure 5.6: Continued

There was a high nugget variance in all the measurement periods. The large nugget variance indicates high variability of the nearest sampled points, which can negatively influence the kriging estimation. A similarly high variance was previously observed in variograms of the GW table. The same explanation is offered for the high nugget variance in the readings of GW salinity as in those of the GW table (too coarsely spaced monitoring wells). However, the effects of collinearity, caused by soil textural heterogeneity, stratigraphy and local land and water management practices must not be underestimated. Even with the best interpolation method, ineffective coverage of the samples or small scale effects of other environmental variables will always produce large prediction errors.

Despite the high nugget variance, the rather clear structure of the variograms in the direction of anisotropy (south-north to east-west) and the longer range (autocorrelation between the data points) allowed the fitting of a model with the smallest estimation errors. The parameters of the variograms are presented in Table 5.7. In contrast to the variograms models of GW table where the exponential model gave the better fit, the spherical model produced a lower estimation error in most measurement periods. The range of readings was from ca. 8 to 32 km, indicating a higher degree of autocorrelation compared to that for the GW table and thus, larger areas with similar values of GW salinity.

Table 5.7: Parameters of kriging interpolation for groundwater salinity

Period	Year	Range	Sill	Nugget	Function
April	1990	2.9E+08	310.84	0.92	Exponential
	1994	18054.3	0.25	0.62	Spherical
	2000	25769.2	0.11	0.68	Spherical
July	1990	32790.4	0.81	0	Spherical
	1994	32785.3	0	0.93	Spherical
	2000	20470.6	0.13	0.58	Spherical
Oct	1990	7817.69	0.16	0.78	Exponential
	1996	25217	0.1	0.56	Spherical
	2000	17574.7	0.11	0.63	Spherical

Cross-validation revealed good performance of the selected parameters in estimating values at unmeasured locations despite the erratic variograms and high nugget variances in most directional variograms. The standardized mean prediction error was close to zero, the root mean squared prediction error was small and values of the average standard errors were close to the root mean square errors. The model underestimated the variability of the estimations in all cases, as the average standard errors were lower than the root mean square errors.

Table 5.8: Prediction and standard errors of estimated versus measured values of groundwater salinity with universal kriging

Period	Year	Mean Error	Root-Mean-Square Error	Average Standard Error	Mean Standardized Error	Root-Mean-Square Standardized Error
April	1990	0.00027	0.180	0.168	0.0015	1.069
	1994	0.00074	0.190	0.173	0.0042	1.1
	2000	-0.00049	0.173	0.156	-0.0031	1.114
July	1990	0.00039	0.177	0.155	0.0024	1.142
	1994	0.00008	0.197	0.186	0.0004	1.059
	2000	0.00007	0.167	0.152	0.0004	1.094
October	1990	0.00048	0.187	0.175	0.0027	1.068
	1996	-0.00029	0.189	0.175	-0.0017	1.077
	2000	0.00069	0.177	0.163	0.0042	1.082

Similar to the estimation of the GW table, the root mean square estimate for GW salinity in individual locations was high, with a maximum of 0.71 g L^{-1}. However, the average estimate was 0, and the estimation standard error map showed that the highest uncertainty values were again associated with areas lacking actual measurements. Based on this, it can be concluded that the monitoring network in Khorezm is coarse, and allows only the relative assessment of GW table and salinity. In the areas with denser sample points, the difference between the measured and estimated values was close to zero indicating that kriging performs well in delineating GW salinity with the existing dataset.

The maps of the GW salinity estimated in the same periods in April, July and October using the universal kriging are shown in Figure 5.7. The areas with moderate (1 to 3 g L^{-1}) salinity are shown in blue, which was used to delineate higher-saline GW areas estimated with the other interpolation methods. It can be seen that the higher GW salinity areas occur both in the western and southern districts.

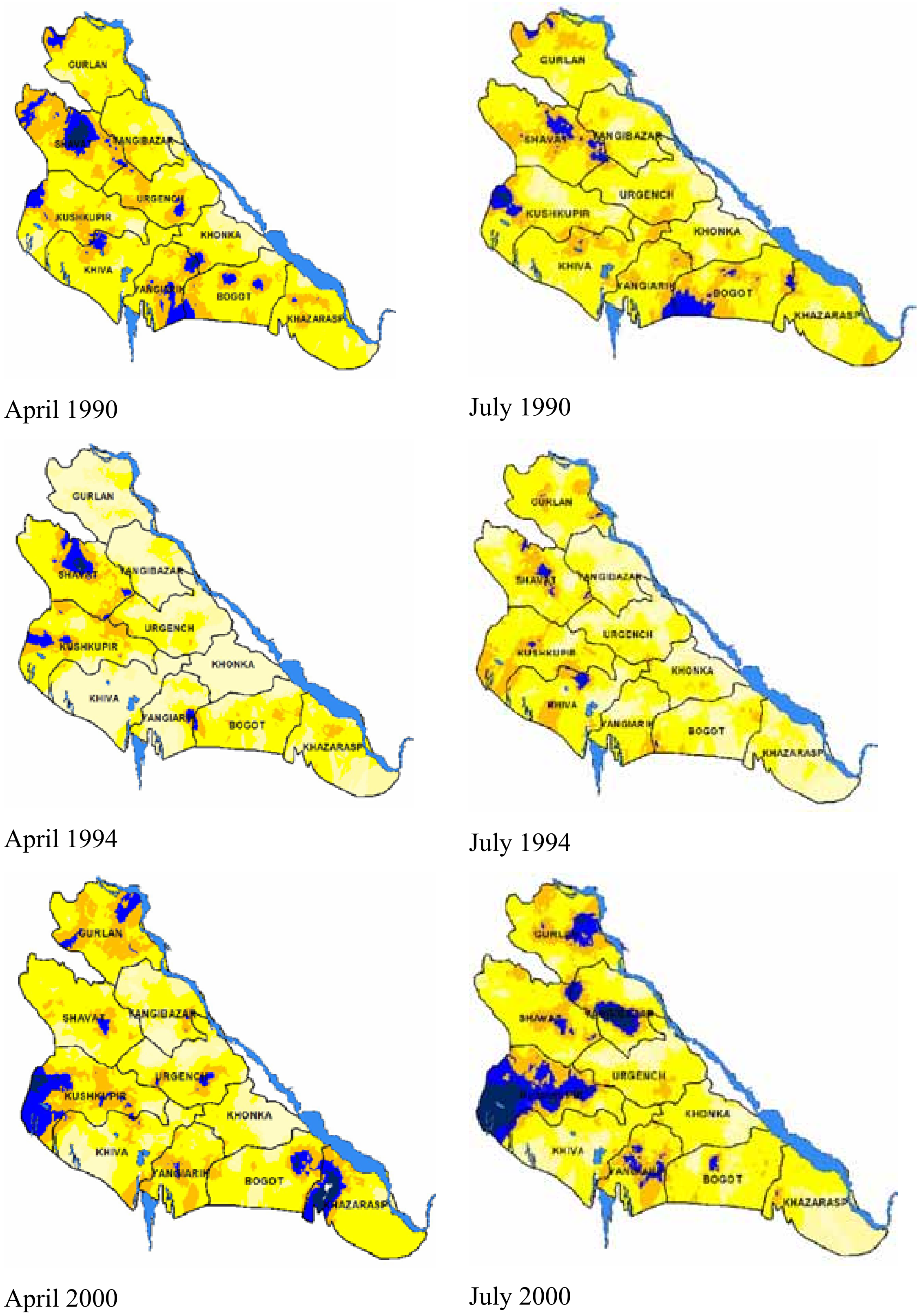
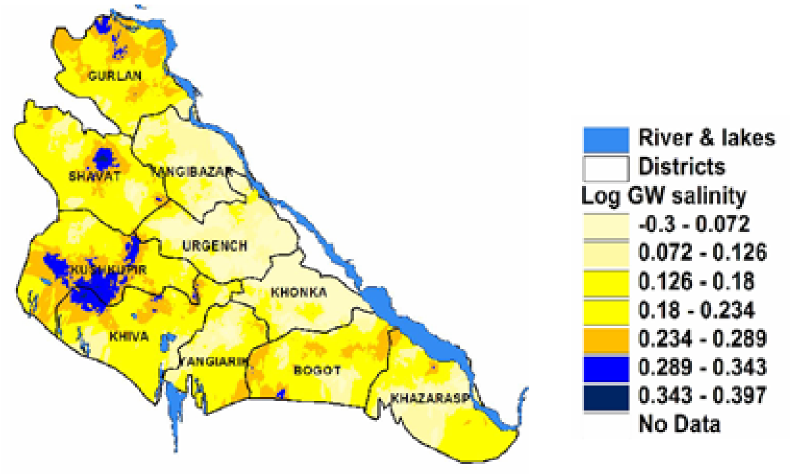
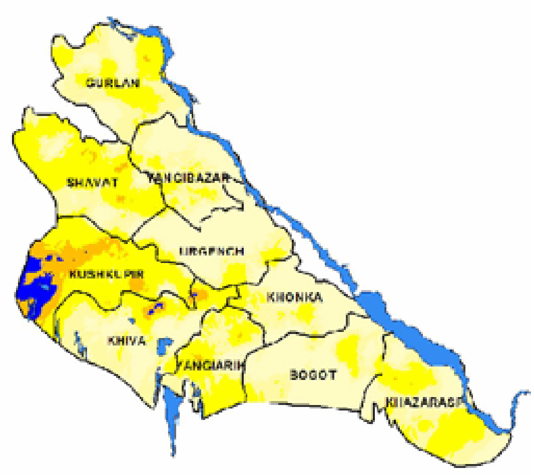


Figure 5.7: Maps of groundwater salinity in April, July and October 1990, 1994 (1996 in October) and 2000, generated using the universal kriging interpolation method



October 1990



October 1996

October 2000

Figure 5.7: Continued

5.3.2 Inverse Distance Weighted

Table 5.9 shows the mean and root mean square prediction errors of interpolation with IDW. As with the GW table measurements, the root mean square prediction errors were minimized by adjusting the power value with the same shape of the search neighborhood (oval, east-south to north-west). The mean prediction errors were much smaller than those for the GW table, ranging from 0.000045 to 0.0015. Root mean square errors were small; 0.18 g L^{-1} on average. This shows that the IDW method performs well in assessing the spatial distribution of GW salinity. However, the prediction error maps indicate similar problems regarding the deviation of the estimation from true measurements, the range being 0.67 g L^{-1}. The highest deviations are associated with the areas lacking actual measurements, whereas in denser data locations the deviations are small.

Table 5.9: Prediction errors of estimated versus measured values of groundwater salinity with IDW

Measurement period	Mean error	Root-Mean-Square error
April 1990	0.0013	0.178
July 1990	0.000045	0.174
Oct. 1990	0.00067	0.186
April 1994	0.00042	0.188
July 1994	0.00034	0.197
Oct. 1996	0.0015	0.188
April 2000	0.00031	0.173
July 2000	-0.00046	0.164
Oct. 2000	0.00047	0.177

In a comparison of the performance of the IDW and the universal kriging methods, the mean and root mean square prediction errors were similar for all measurement periods. This shows that both kriging and IDW produced relatively reliable estimates of GW salinity based on the existing dataset. Unlike the poorer estimation of GW tables in Khorezm (different irrigation intensity caused more abrupt changes in water tables), IDW performed better with the spatial distribution of GW salinity, probably because salinity was more constant in the region. The spatial domains of the GW salinity interpolated using the IDW method were estimated similar to the universal kriging, but the magnitude of the areas differed (Figure 5.8).

April 1990

July 1990

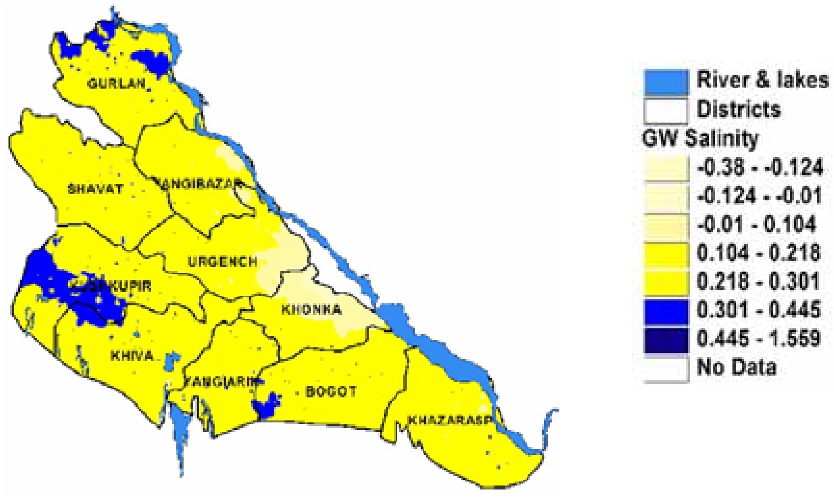
April 1994

July 1994

April 2000

July 2000

Figure 5.8: Maps of groundwater salinity in April, July and October 1990, 1994 (1996 in October) and 2000, generated using the IDW interpolation method



October 1990

October 1996

October 2000

Figure 5.8: Continued

5.3.3 Spline

The *regularized* method of interpolation with spline was used to delineate the areas with high GW salinity. The same parameters as with the GW table were chosen, i.e., weight 0.1 and number of the neighboring points 12. An interpolation was performed in ArcINFO 8.2 with the same training and test dataset.

Table 5.10 shows the mean and the prediction errors of the spline method. It is seen that a more or less constant distribution of values of GW salinity in Khorezm resulted in similar mean and root mean square prediction errors. Although mean prediction errors were small, the root mean square errors were high. The assessment of the areas with shallow saline GW in Chapter 4 show that the areas estimated with spline method were much larger than those estimated by kriging and IDW. To confidently judge whether the spline method is reliable enough to delineate the spatial distribution of GW salinity, it is necessary to compare the spline methods with the two other interpolation methods.

Table 5.10: Prediction errors of estimated versus measured values of groundwater salinity with spline method

Measurement period	Mean error	Root-Mean-Square error
April 1990	-0.0105	4.536
July 1990	0.0288	4.365
Oct 1990	-0.0414	4.234

The maps of the GW salinity estimated using the spline method are shown in Figure 5.9. Unlike the maps of GW salinity estimated using the universal kriging and IDW methods, the moderately and highly saline areas estimated b the spline method appear to be scattered all over the region. The proportion of moderately and highly saline areas was larger in the southern and western parts of Khorezm compared to the other areas, which is similar to the estimation by the kriging and IDW methods. However, each of these areas is much smaller in the maps utilizing the spline method compared to those using kriging and IDW.

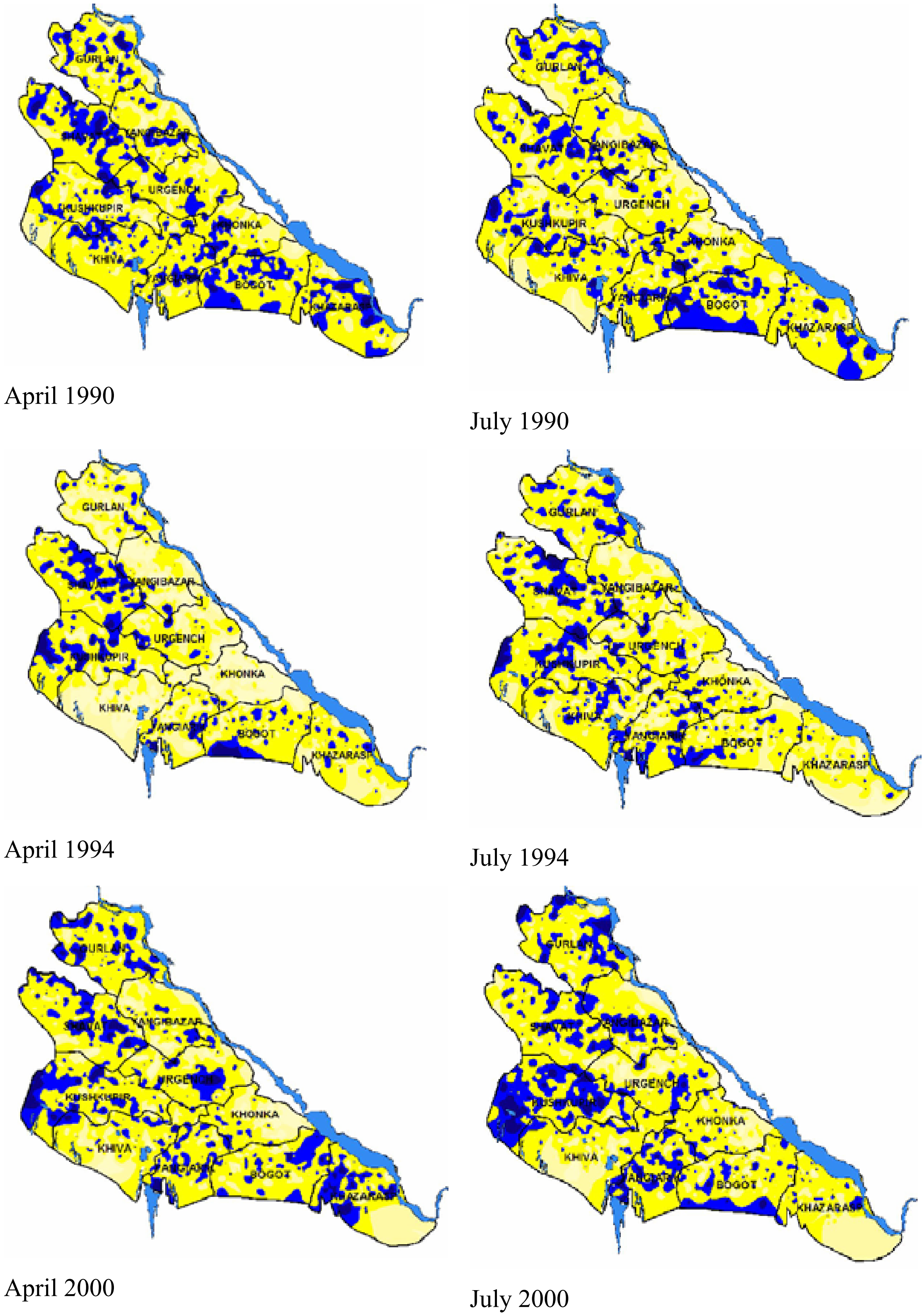
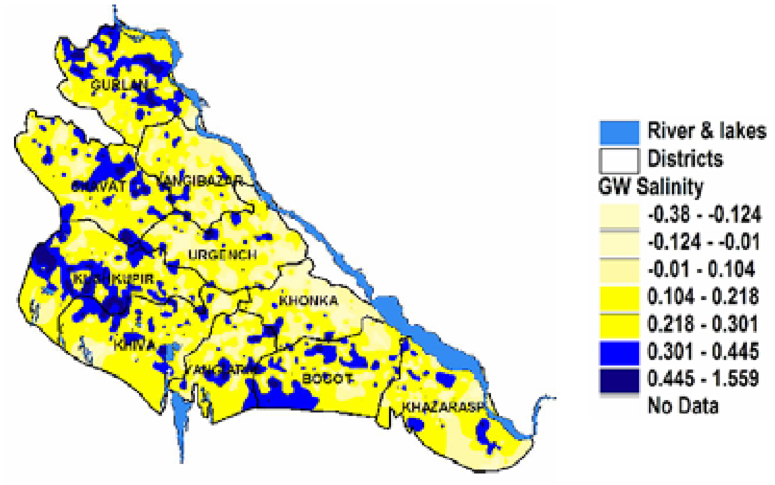
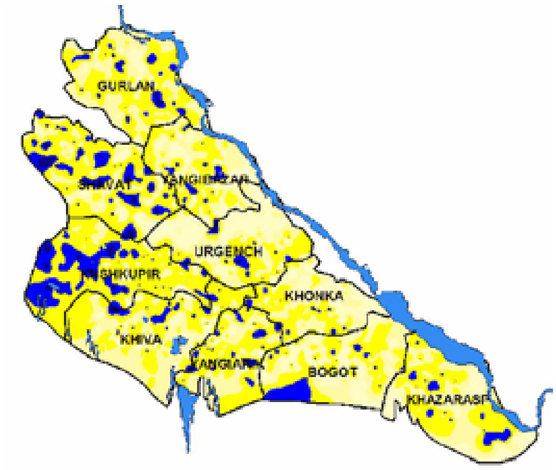


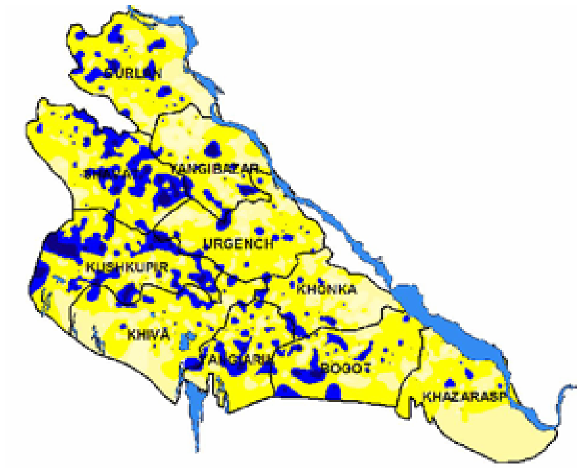
Figure 5.9: Maps of groundwater salinity in April, July and October 1990, 1994 (1996 in October) and 2000, generated using the spline interpolation method



October 1990



October 1996



October 2000

Figure 5.9: Continued

5.3.4 Comparison of kriging, IDW and spline methods for estimating groundwater salinity

Comparison of the performance of the three interpolation methods was possible through an analysis of the minimum generated mean and root mean square errors as well as the analysis of the "plausibility" of the estimation of the areas at risk from shallow saline GW done in chapter 4. Table 5.11 shows the parameters of the three interpolation methods. It can be seen that the performance of the two methods IDW and kriging was similar and better than that of the spline method. However, due to the coarsely spaced monitoring wells, the errors of the kriging and IDW methods were high suggesting that only a relative assessment of the areas at risk could be achieved. This finding is identical to that in Chapter 4.

Table 5.11: Prediction errors of estimated versus measured values of groundwater salinity in April, July and October 1990 with three interpolation methods

Measurement period	Mean error			Root-Mean-Square error		
	Spline	**IDW**	**Kriging**	**Spline**	**IDW**	**Kriging**
April	-0.0105	0.0083	-0.0044	4.536	2.736	2.676
July	0.0288	0.000008	0.0042	4.365	2.487	2.526
October	-0.0414	0.0072	0.00827	4.234	2.650	2.587

5.4 Estimation of groundwater table and salinity using cokriging

Cokriging interpolation was applied with the aim to improve the estimation accuracy by successively including GW table and salinity as co-variables. Table 5.12 shows the estimated prediction errors. The standardized mean prediction errors for both datasets of GW table and salinity were similar to those estimated by the ordinary and universal kriging for the separate variables. A minor difference was that the average standard error for GW salinity in all cases was slightly lower than the root mean square prediction error, indicating that the variability of estimations was underestimated.

In general, the cokriging did not perform better than ordinary kriging for GW table and universal kriging for GW salinity, which could be attributed to a low correlation between the water tables and salinity contents.

Table 5.12: Prediction and standard errors of estimated versus measured values of groundwater table and salinity with cokriging

Measurement period	Mean Error	Root-Mean-Square Error	Average Standard Error	Mean Standardized Error	Root-Mean Square Standardized Error
Groundwater table					
April 1990	0.054	40.89	40.58	0.001353	1.007
July 1990	-0.080	36.97	35.09	-0.002362	1.053
Oct. 1990	-0.038	42.34	42.56	-0.000934	0.994
April 1994	0.050	38.40	37.81	0.001166	1.015
July 1994	-0.160	40.88	39.75	-0.003765	1.027
Oct. 1996	-0.150	44.39	45.50	-0.003348	0.975
April 2000	0.038	46.78	48.04	0.000256	0.974
July 2000	0.048	43.97	43.17	0.000761	1.020
Oct. 2000	-0.199	47.21	48.02	-0.004071	0.984

Table 5.12: Continued

Measurement period	Mean Error	Root-Mean-Square Error	Average Standard Error	Mean Standardized Error	Root-Mean Square Standardized Error
			Groundwater salinity		
April 1990	0.00067	0.180	0.169	0.003849	1.064
July 1990	0.00080	0.189	0.175	0.004552	1.081
Oct. 1990	-0.00030	0.174	0.156	-0.002100	1.117
April 1994	0.00080	0.177	0.160	0.004968	1.101
July 1994	0.00015	0.198	0.187	0.000787	1.055
Oct. 1996	0.00028	0.166	0.152	0.001802	1.097
April 2000	0.00073	0.187	0.179	0.004002	1.041
July 2000	0.00020	0.189	0.179	0.001245	1.053
Oct. 2000	0.00080	0.177	0.167	0.004820	1.060

5.5 Summary: Selection of the best-performing method

Summarizing the results of sections 5.2 and 5.3, the kriging and IDW methods of interpolation performed better in delineating the GW table and salinity areas in Khorezm compared to the spline, although in sparsely measured areas the estimated values from both kriging and IDW deviated largely from the actual values. Kriging performed slightly better than IDW in delineating areas with uniform GW table due to smaller prediction errors, whereas the IDW method was slightly better in delineating areas with GW salinity in the region. Prediction errors from spline were quite large, which resulted in improper delineation of the areas at risk from shallow saline GW (Chapter 4). This method is found unacceptable for mapping GW table and salinity in the Khorezm region. The TIN interpolation method, which is widely used for the mapping of GW table and salinity in Uzbekistan, produced larger prediction errors than the other methods. The use of this method is therefore not considered appropriate for the region.

Since the areas at risk from shallow saline GW were similarly estimated by kriging and IDW, the maps generated by kriging were retained for further analyses of the causes for spatial distribution of GW table and salinity.

5.6 Assessment of areas at risk from shallow saline groundwater

The areas at risk of waterlogging and salinization from shallow saline GW were assessed based on the criteria summarized in Table 4.2. The risk was assumed to be present when the GW table reached a certain level as indicated in Table 4.2 under low, medium and heavy categories of both GW salinity and soil texture. When reaching the critical level, GW evapotranspires into the atmosphere, whereas the salts move upwards and remain in the upper soil layers. The digital soil texture map provides the general structure of the sandy, loamy, loamy-clayey and sandy-loamy soils from the upper horizons (Figure 5.10). This soil map is a generalization of the highly stratified heterogeneous soil profiles in Khorezm. Further simplification was done when assuming that loamy and clayey-loamy soils constitute heavy textures. Sandy loamy and loamy textures in the northern areas were designated as medium textures, and sands were placed in the light textural class.

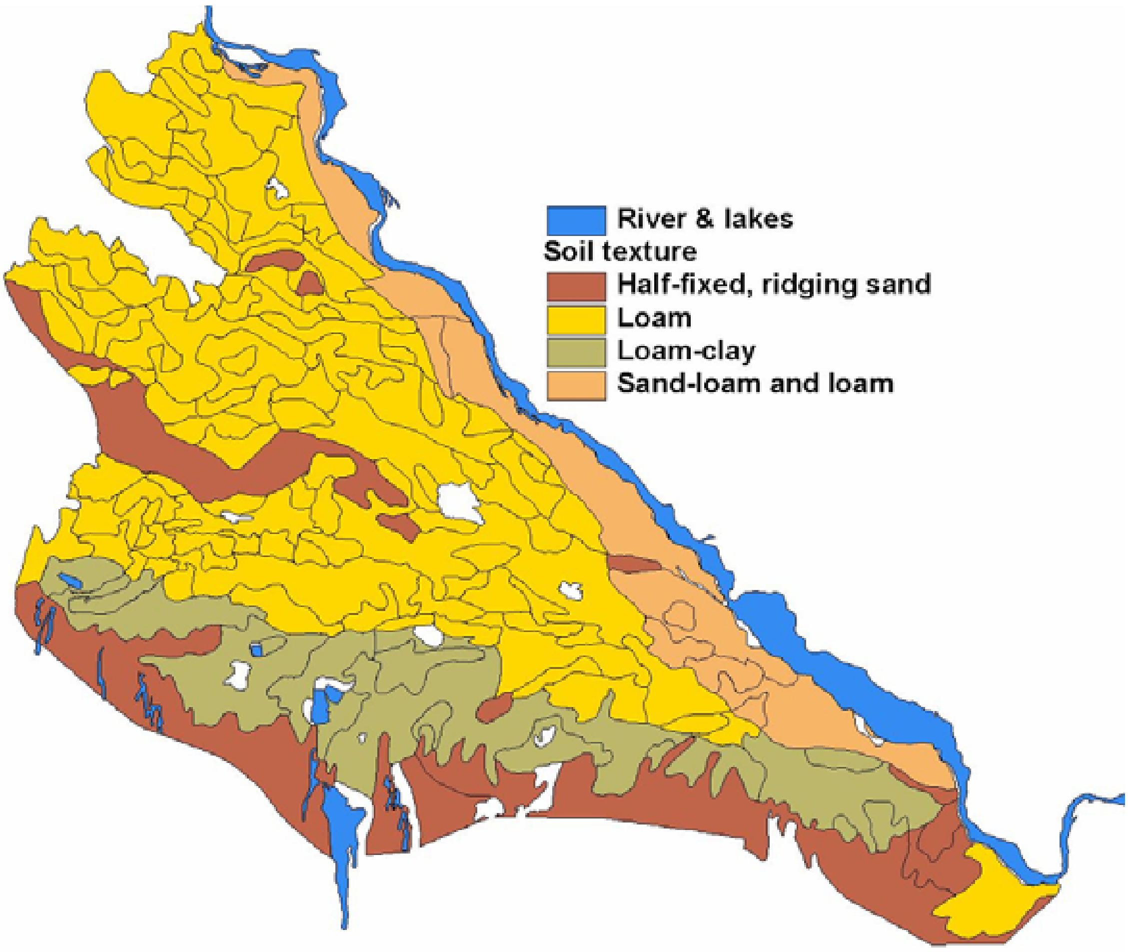


Figure 5.10: Soil lithology map of Khorezm

Table 5.13 presents the areal assessment of the spatial distribution of the GW table from the four interpolation methods. The assessment of the areas with the TIN method was performed for comparison with the three other methods in April, July and October 1990. GW salinity was mostly 1 – 3 g L^{-1}. The areas with GW salinity >3 g L^{-1}, although small, represent areas of high risk. They range from 0 to 2% and are, therefore, not shown. The largest share of the areas at risk was in the heavy textural soil classes.

Kriging and IDW interpolation methods produced similar estimates of the areas at risk (Table 5.13), although kriging estimated slightly larger areas than IDW in most of the measurement periods except July 2000. The differences between these two methods and the spline were substantial, with the areas at risk assessed by the spline method being much larger. The areas estimated by the TIN method, which is widely practiced in Uzbekistan to delineate the areas with GW tables and salinity, were similar to those of the spline method. It is interesting to note that if the estimation by the TIN method is indeed not efficient, the actual areas could have been overestimated throughout the whole monitoring period.

Table 5.13: Percent of areas at risk from shallow saline groundwater.

			April						**July**					
			1990		**1994**		**2000**		**1990**		**1994**		**2000**	
GW salinity g L^{-1}			**< 1**	**1–3**	**<1**	**1 – 3**	**< 1**	**1 – 3**	**< 1**	**1 – 3**	**< 1**	**1 – 3**	**< 1**	**1 – 3**
Percent of areas with GW under soil texture	**Light**	**Kriging**	0	12.9	1.8	11.8	0	13.0	0	12.3	0	12.8	0	4.9
	Medium		0	7.0	1.7	5.7	0.5	7.5	0	7.4	0	7.2	0	6.4
	Heavy		0	49.2	6.0	43.2	0.1	49.4	0	49.0	0	48.9	0	35.0
	Total		0	69.2	9.5	60.7	0.6	69.9	0	68.8	0	69.0	0	46.3
	Light	**Spline**	0	16.1	1.9	13.1	0	15.5	0	16.1	0	15.6	0	14.8
	Medium		0	8.0	2.7	5.8	0	8.2	0	9.1	0	8.7	0	8.9
	Heavy		0	59.5	8.7	52.3	0	58.7	0	60.7	0	60.6	0	54.7
	Total		0	83.5	13.3	71.2	0	82.4	0	85.9	0	84.9	0	78.4
	Light	**IDW**	0	12.6	0.3	12.4	0	12.1	0	12.2	0	12.2	0	4.6
	Medium		0	6.9	1.2	5.6	0	7.0	0	7.0	0	7.0	0	5.6
	Heavy		0	46.5	2.5	44.0	0	45.6	0	46.4	0	46.3	0	33.5
	Total		0	66.0	3.9	62.0	0	64.7	0	65.7	0	65.5	0	43.7
	Light	**TIN**	0	15.4						15.9				
	Medium		0	7.9						8.9				
	Heavy		0	58.4						59.8				
	Total		0	81.7						84.5				

			October					
			1990		1996		2000	
GW salinity g L^{-1}			< 1	1 – 3	< 1	1 – 3	< 1	1 – 3
Percent of areas with GW under soil texture	Light	Kriging	0	0.2	0	8.4	0	0.8
	Medium		0	0	0	3.5	0	0.4
	Heavy		0	0.6	0.5	31.2	0	4.6
	Total		0	0.8	0.5	43.2	0	5.8
	Light	Spline	0	9.8	2.9	11.0	0	13.7
	Medium		0	2.3	1.4	4.3	0	8.1
	Heavy		0	16.1	4.0	37.8	0	46.4
	Total		0	28.3	8.4	53.1	0	68.2
	Light	IDW	0	0.2	0	6.4	0	0.6
	Medium		0	0	0	3.1	0	0.7
	Heavy		0	0.8	0	27.3	0	4.9
	Total		0	1	0	36.9	0	6.2
	Light	TIN		5.5				
	Medium			2.1				
	Heavy			8.5				
	Total			16.1				

As estimated by the kriging and IDW methods, ca. 65-70% of the areas were at risk of waterlogging and salinization from a shallow saline GW table in April and July (Table 5.13). These areas remained virtually unchanged during the whole study period. In July, the kriging and IDW realistically estimated the reduction of the areas at risk from ca. 66% in 1990 and 1994 to ca. 47% in the dry year 2000. The areas at risk as estimated by the spline method were also constant in April, being ca. 83%. In contrast, in July, spline estimated a very small change from ca. 85% in 1990 and 1994 to ca. 78% in 2000. The areas at risk assessed by the TIN method were ca 82-85% in April and July, and 16% in October 1990. These areas were smaller compared to those estimated by the spline method but still much larger compared to the kriging and IDW methods. The situation in October was similar in 1990 and 2000, but in 1996 the areas at risk rose from ca. 1% (kriging and IDW) to ca. 36 – 43%. The assessment of the areas at risk in 2000 by the spline method (68%) is questionable, because the year 2000 is known as an extreme drought year (FAO Special Report 2000) and GW tables were deep in the region (see Figures 5.2 to 5.5).

5.7 Factors influencing spatial distribution of groundwater tables in Khorezm

This section describes the reasons for the spatial distribution of the GW table in Khorezm. The analysis was performed in ArcView 3.2 on maps produced with the kriging interpolation method (see Figure 5.2). Since software automatically generates a legend for water table values, and legends in April, July and October were different (GW shallower in April and July and deeper in October), a legend with similar values was applied for all the maps.

5.7.1 Ancient Amu-Darya River beds

Two strips of deeper GW table can be distinguished in the region (see Figure 5.11). Delineation was clearer in April 1990 and 2000 and in July 2000, i.e., when the GW tables were deeper during the growing periods. Outside the growing periods, these strips can be distinguished only in October 1996, when GW tables were shallower compared to the October readings in the years 1990 and 2000. Both strips occur in the center of the region; the first strip extends in the direction east-west, and the second strip from south-east to north-west. The strips of deeper GW table cross the districts Khanka, Urgench, Shavat and Kushkupir. Incidentally, standard error kriging maps for all the measurements showed higher prediction errors around the areas of the deeper strips due to sparser distribution of the monitoring wells. Analysis of the satellite image (DLR 2000) shows that there are less irrigated areas around these strips and that therefore there is a less dense distribution of the monitoring wells (see also Figures 3.3 and 5.2).

The image in Figure 5.11 shows the location of two beds of the ancient Amu-Darya River, Dar'alik and Daudan. The two strips of deeper water tables correspond to the areas of the two beds. The lithology of the beds is distinguished by coarser sediments (Tursunov and Abdullaev 1987). It can be deduced that the GW table was deeper in those areas due to coarser textures of the upper soil layers and parent materials, where, according to Kats (1976) lateral subsurface water movement is faster than in the rest of the areas. This demonstrates the important role texture plays in the spatial distribution and flow of GW table in Khorezm.

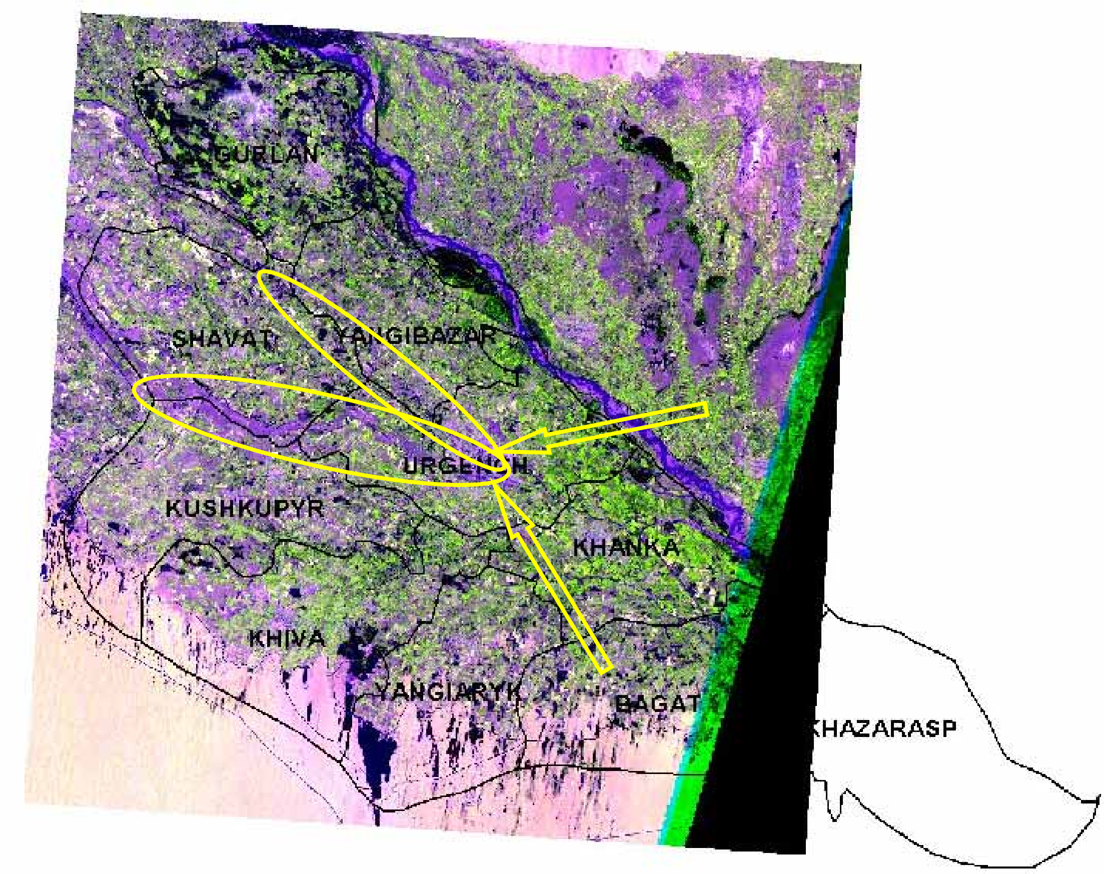


Figure 5.11: Satellite image of the Khorezm region, showing two ancient Amu-Darya River beds: (1) center towards north – west (2) east – west
Source: DLR, C.Conrad

5.7.2 Influence of lithology on spatial groundwater table

Since deeper GW tables in the areas of coarser textures are indicative that lithology can play a substantial role in the spatial distribution of GW tables in Khorezm, further analysis was focused on a relationship between the spatial distribution of GW table and soil textures. Within the Khorezm region, four distinct lithological zones (LZ) are present (see Figure 5.10). Detailed soil properties of each zone were not available due to the complex nature of fluvial sediments, but the maps provided general soil textural classes. It is seen in the map that there is a clear linear pattern of the spatial distribution of soil textures along the Amu-Darya River. Khodzhibaev (1979) described the texture as becoming heavier towards the southern and western parts of the region, thus creating difficult conditions for subsurface lateral flow.

To analyze the influence of the lithology on the spatial distribution of the GW table in Khorezm, the values of the GW table in each of the LZ were compared for significance of the difference. A statistical analysis was performed by overlaying the layers of LZ and GW tables in ArcView 3.2. The *GetGridValue* ArcView extension was used for the extraction of data from ArcView 3.2 into the MS Excel format with subsequent import into SPSS 11.0 (see http://arcscripts.esri.com/ scripts.asp?pg=1&sb=1&ob= asc&eDate=&n = &top=&eLang =&eProd =4&perPage= 10&eDesc= on&eQuery=get+grid+value).

Each textural class of the LZ was assigned a numerical value; the difference of estimated values of GW table among these zones was compared using ANOVA test in SPSS 11.0. The *Tamhale T2* method was used for a *post hoc* test for an interpretation of the results, since the variances were not significantly homogeneous (Gupta 1999). Table 5.14 shows the results of the analyses.

Table 5.14: Multiple comparisons of means of GW table among lithological zones

No of lithological zone*	**Significance**								
	April			**July**			**October**		
	1990	**1994**	**2000**	**1990**	**1994**	**2000**	**1990**	**1996**	**2000**
1	2, 3, 4	2, 3	2, 3, 4	2, 3	2, 3, 4	2, 4	2, 3, 4	2, 3, 4	2, 3, 4
2	1, 4	1, 4	1	1, 4	1, 3, 4	1, 4	1, 3, 4	1, 4	1, 4
3	1, 4	1, 4	1	1	1, 2	4	1, 2	1, 4	1, 4
4	1, 2, 3	2, 3	1	2	1, 2	1, 2, 3	1, 2	1, 2, 3	1, 2, 3

**1: Loam, 2: Loam – clay, 3: Sand, 4: Sand - loam and loam*

The analysis showed the significant influence of the textural class of the LZ on the spatial distribution of GW table in Khorezm (Table 5.14). The 'significance' column in Table 5.14 indicates that GW tables were significantly different among the LZ in all the measurement periods. It is interesting to note that the GW table was shallow in the southern part, which is characterized by coarser sandy textures. Although clear from the results of the analysis, these findings should be treated with care since the soils in Khorezm are highly heterogeneous and the digital map is a simplification of the different textures in the region.

However, further analysis of the changes in GW tables in the chosen measurement periods (see Figure 5.2) showed that the spatial changes in water tables in each of the measurement periods from years with reduced (1990) to higher (1994) to again reduced (2000) water availability were 1) constant, i.e., the southern part of the region was always shallower compared to the rest of the areas, 2) these shallow water tables appeared in both heavy loamy – clayey and light sandy textures (cf. Figure 5.10). However, as seen in the maps, the areas of the two ancient river beds had deeper GW during the study period.

5.7.3 Drainage network efficiency

The influence of highly heterogeneous and stratified soils together with the amount of irrigation water (see Chapter 4) on the distribution of shallow GW tables in the region questions the effectiveness of drainage network in keeping the GW table below the critical threshold. The drainage network was conventionally designed throughout the region as open ditches of main, secondary and tertiary structure (see Chapter 2). Open horizontal drains are the main form of drainage in Khorezm; tile drains exist only in negligibly small lengths. On-farm drains have a depth of 2 m, whereas the maximum depth of the inter-farm and most main drains does not exceed 2.5 m due to the dominant sandy textures. Most on-farm drains are far apart from each other, the distance being 400 – 500 m. Drainage subsystems can be distinguished from the hierarchy, each subsystem consisting of the one main drain, all the inter-farm drains, which discharge water into that main drain, and on-farm drains that are connected with the inter-farm drain.

Five such drainage subsystems exist (Figure 5.12). In order to confidently state that these drainage subsystems were not equally efficient in lowering GW tables, the differences in the GW table in each drainage subsystem were compared using the ANOVA test in SPSS 11.0.

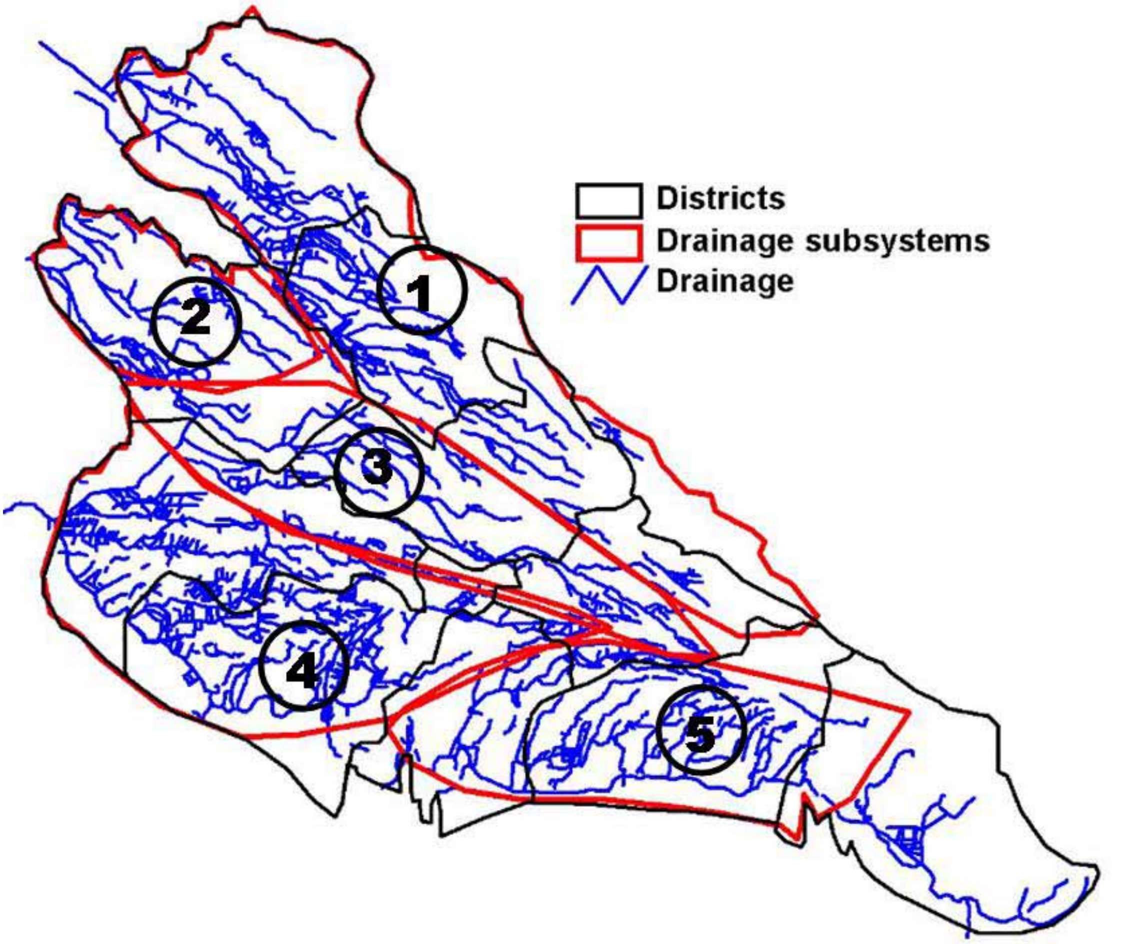


Figure 5.12: Distribution of drainage network and five drainage subsystems in Khorezm

The results of the ANOVA test are shown in Table 5.15. The homogeneity test (not shown) revealed significant differences between the variances of the groups of GW tables among different drainage subsystems, indicating that *Tamhene T2* should be used for the *post hoc* interpretation of the results (Gupta 1999). Analysis shows that the difference in GW tables between the subsystems of drains was significant in most cases (Table 5.15).

The analysis shows that despite the similar structure of the drainage network in Khorezm, the drainage subsystems (4 and 5) in the southern part were found to be inefficient in keeping the GW below the critical levels (see Figure 5.2). Non-efficiency of the drainage subsystems numbered 4 and 5 in Figure 5.12 cannot be explained by more intensive irrigation in the southern parts, since the cropping patterns are similar throughout the region. Moreover, it was found that GW tables were shallower in the districts located in the southern part of the region, which received less irrigation water compared to the other districts.

Table 5.15: Multiple comparisons of means of GW table among drainage subsystems

April 1990 – 1994					April 1995 – 2000				
Subsystems		Mean Diff	Sig. Level	Sig.	Subsystems		Mean Diff	Sig. Level	Sig.
1	2	4.69	0.00	Yes	1	2	11.83	0.00	Yes
	3	-3.12	0.97	No		3	-3.09	0.98	No
	4	29.74	0.00	Yes		4	31.14	0.00	Yes
	5	12.61	0.00	Yes		5	12.31	0.00	Yes
2	1	-14.69	0.00	Yes	2	1	-11.83	0.00	Yes
	3	-17.81	0.00	Yes		3	-14.92	0.00	Yes
	4	15.05	0.00	Yes		4	19.32	0.00	Yes
	5	2.08	1.00	No		5	0.49	1.00	No
3	1	3.12	0.97	No	3	1	3.09	0.98	No
	2	17.81	0.00	Yes		2	14.92	0.00	Yes
	4	32.86	0.00	Yes		4	34.24	0.00	Yes
	5	15.73	0.00	Yes		5	15.41	0.00	Yes
4	1	-29.74	0.00	Yes	4	1	-31.14	0.00	Yes
	2	-15.05	0.00	Yes		2	-19.32	0.00	Yes
	3	-32.86	0.00	Yes		3	-34.24	0.00	Yes
	5	-17.14	0.00	Yes		5	-18.83	0.00	Yes

The drainage subsystem No. 4 in the south is located close to the main collector drain Ozerny. Ozerny collects most of the drainage discharge and leads it out of the area to the Sarykamish Depression (Chapter 3). As such, this drain should have the greatest influence in lowering the GW table. Yet the phreatic surface was found to be quite shallow within the domain this subsystem. Even in October, when water use was lower than during the growing period, this area experienced shallower GW tables.

The observed pattern of shallow GW table reflects the failure of the drainage network in keeping the irrigated areas in Khorezm free from shallow saline GW. Thus, land productivity is jeopardized through soil salinization. At least two problems can be clearly identified at this stage. The first problem is the too coarse spacing of the on-farm drains with respect to lowering GW tables in the field. The second is the lacking ability of the network to dispose of the drainage discharge resulting from the agricultural activities in the region. While the first problem is 'local', the second is more 'regional". Both problems must be resolved simultaneously.

5.7.4 Digital elevation model and topographic indices

Another factor that determines GW flow is topography. The topography in Khorezm has been largely formed by sediments coming with the meandering Amu-Darya River (Tursunov and Abdullaev 1987). Deposition of coarse sediments along the temporal river beds and numerous arms that crossed the region in the past created local highlands (levees), compared to local lowlands where fine textures were deposited (see Chapter 3 for details). While GW flow dynamics are faster in the former, so-called *lake* facies, those in the latter, known as *near-bed river* facies, are much slower. Therefore, the topographic features are expected to play an important role in the spatial distribution of GW tables in Khorezm.

The digital elevation model (DEM) was constructed from 1910 elevation points, which were obtained from paper maps with scales of 1:100,000 and 1:50,000. These points cover the whole region and small adjacent areas (Figure 5.13). Sampling density was coarser in some areas in the center around the Urgench district, in the west in the Kushkupir district and in the south of the region than the other areas.

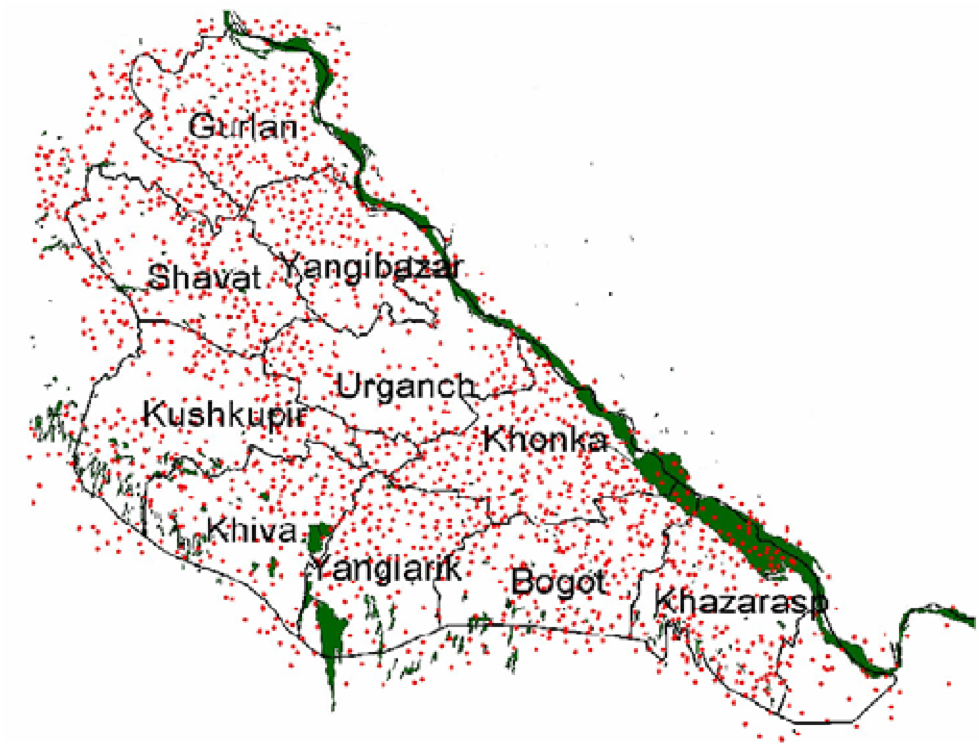


Figure 5.13: Topographic elevation points in Khorezm

Prior to interpolation, the dataset was checked for the assumptions of normal distribution and existence of outliers. The histogram of the DEM showed bimodality and right-skewness (Figure 5.14, a). Bimodality was likely to be associated with the different sources of information (paper maps of scales 1:50,000 and 1:100,000). Normal distribution was not attained after transformation of the dataset to logarithmic, natural logarithmic and square-root scales (Figure 5.14, b). Therefore, an untransformed dataset with all the data, including outliers, was used for the construction of the DEM.

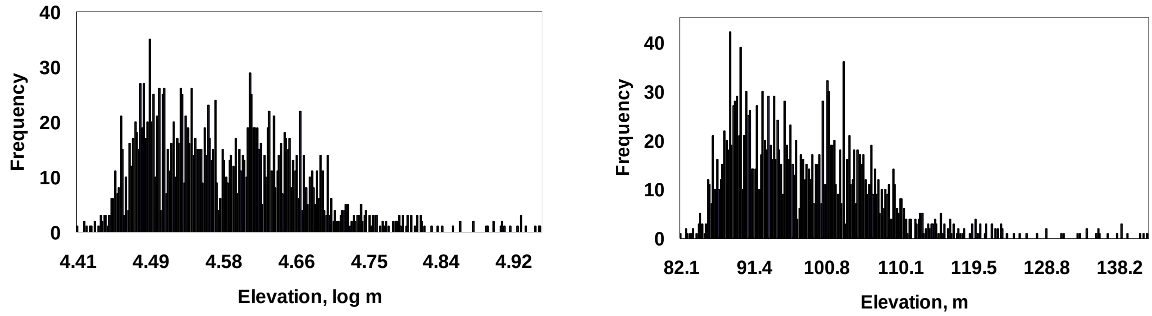
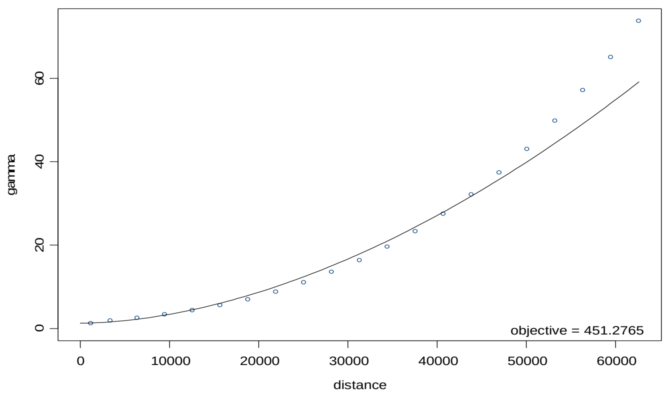


Figure 5.14: Histograms of the elevation (a), after log-transformation (b)

Ordinary kriging was chosen for assessing the spatial patterns and interpolation of the DEM. The interpolation was performed in Surfer 7 (Golden software, Inc 1999). The parameters for kriging (range, sill, and nugget) were defined in S-PLUS 6.0 Spatial Analyst. The variogram model showed a *power* increase (Figure 5.15), and so the *sill* was not present. As the variogram model was spherical, a *slope* was calculated. The parameters of the variogram are shown at the right-hand side in Figure 5.15.



Range – 1.7992

Nugget – 1.2857

Slope – 1.3552 e – 007

Figure 5.15: Variogram model for elevation in Khorezm

The DEM map is shown in Figure 5.16. It shows a gradual inclination of the surface from east to west. To produce the best possible results without loss of local features, the lowest possible size of 15x15 m pixel was chosen that was deemed to account for the local features in the DEM.

Seven topographic indices were produced for the analysis and estimation of subsurface water flow related to terrain using DiGeM 2.0 software (Conrad 2002; http://www.geogr.uni-goettingen.de/pg/saga/digem/). This software was used for filling the sinks and pits and extracting the seven topographic indices, implementing a number of methods: The Zeverbergen and Thorne method was used for creation of slope, aspect, and curvatures, the convergence index was produced with the Koethe and Lehmeier method, and the Freeman method was used for calculating flow accumulation and wetness indices. The indices were converted to ASCII format and imported into ArcView 3.2 (ESRI, Inc). The *Get Grid Value* ArcView 3.2 extension was used for the extraction of spatial point information for further statistical analyses.

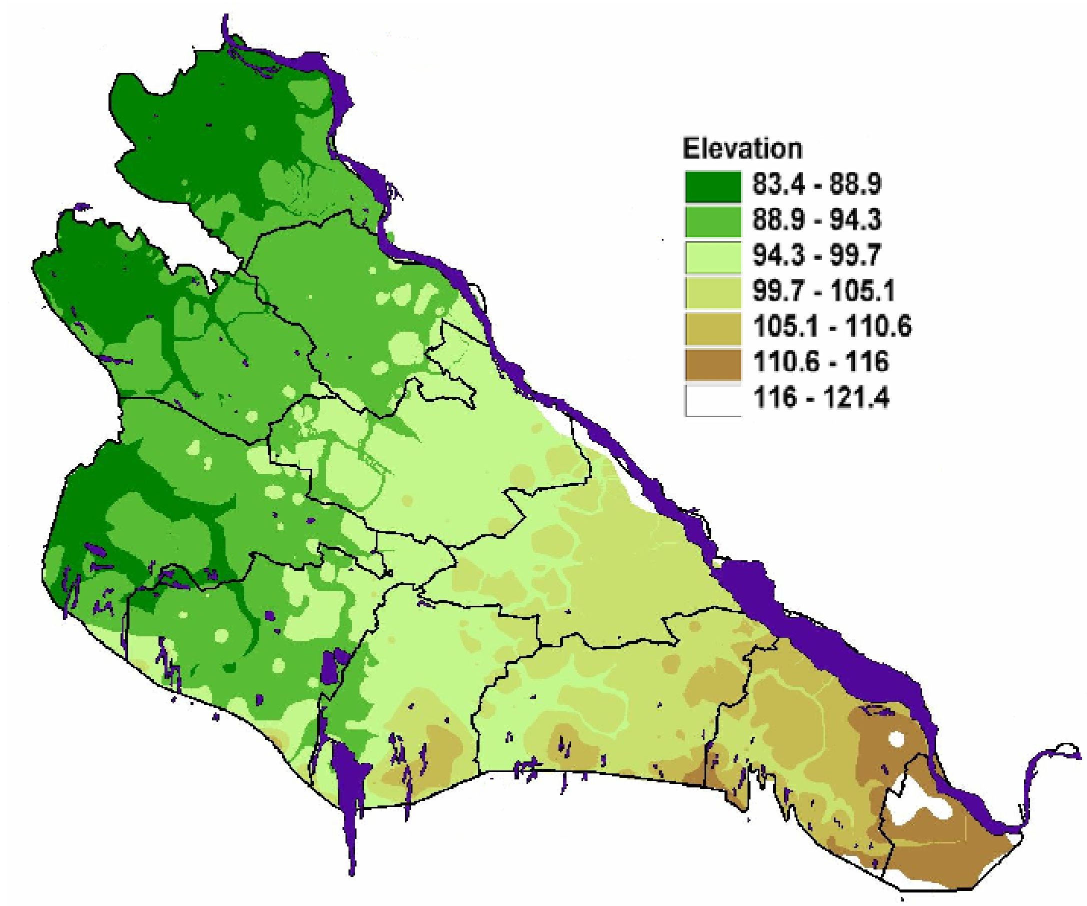


Figure 5.16: Digital elevation model for Khorezm

Despite the finest possible grid size in creating the DEM, the indices did not reveal any clear visual pattern (*slope* is shown in Figure 5.17). Due to the extremely flat deltaic area, the topographic indices and flow directions could not be clearly identified using too coarsely measured elevation points. As a result, many local features were lost during interpolation; the analysis did not show any correlation with the GW table.

For the sake of producing a clearer DEM and topographic indices, 1200 elevation points available for the Khiva district were interpolated in the TOPOGRID command in ArcINFO 8.2. Although the structure of the DEM for the district became much clearer, no similar visual features of topographic indices and GW table in the Khiva district were observed; this was confirmed by the ANOVA test (not shown). Apart from the still coarse distribution of the elevation points, this could be attributed to the peculiarities of farming in Khorezm, where different amounts of irrigation caused wide local fluctuations of GW tables. The differences in water tables were due also to vertically highly stratified and heterogeneous soil textures.

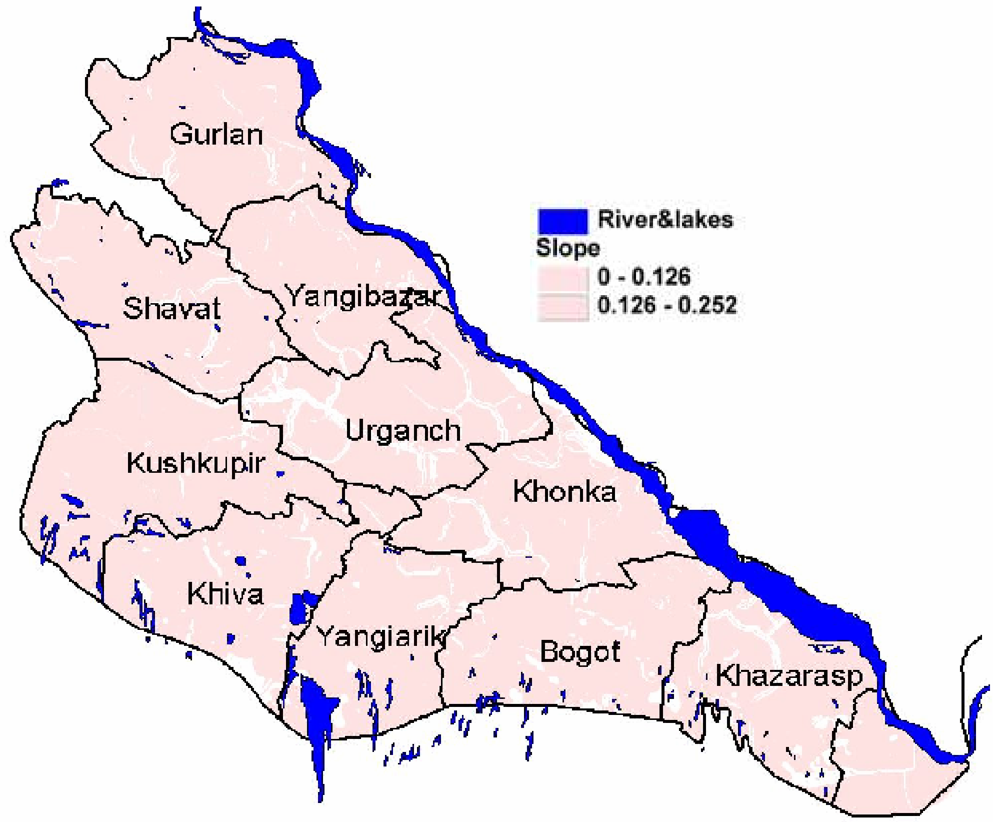


Figure 5.17: Slope calculated from digital elevation model, degrees

Outside the growing period, GW would most likely follow the topography in Khorezm. This assumption was verified using the measurements of GW tables in January 1990. However, the analysis showed no relation among the spatial distribution of GW table and topography. This is attributed to the too coarsely sampled elevation points. Extreme flatness of the region, the bimodality and high right-skewness in the elevation dataset were a clear indication of the necessity to measure the elevation much more precisely. High *nugget* variance, seen earlier in the analysis of the variograms of the GW table, also indicate that monitoring wells were too widely spread. A detailed survey capturing each and every possible topographic landscape change is indispensable for a precise analysis of the effect of topography on the spatial distribution of GW table.

5.7.5 Effects of other possible factors on GW table dynamics

The possible influence of the spatial location of main and inter-farm irrigation canals and the distance to the river in the north and lakes in the south on the GW table dynamics was also analyzed. The subdivision of the irrigation network into subsystems similar to that of the drainage network subdivision was performed in ArcView 3.2. In particular, the influence of the distribution of main and inter-farm drains on GW table dynamics in the central (deeper GW tables) and southern and western parts of the region (shallower GW tables) was checked. The analysis does not reveal any significant influence of the above-mentioned factors on GW tables. For some periods of measurement, the GW table was shallower near the river than further away. Apparently the irrigation practices, influenced by cropping patterns under conditions of flat topography, played a more important role in GW dynamics.

5.8 Factors influencing spatial groundwater salinity distributions

5.8.1 Ancient Amu-Darya River beds

Two strips of lower GW salinity, similar to those observed for the GW table, were apparent in all the measurement periods including October (see Figure 5.11). Visual association between spatial GW salinity distribution and the two ancient river arms Dar’alik and Daudan suggests that faster subsurface flow dynamics also cause less salinity accumulation in GW and indicate the importance the LZ play in GW salinity dynamics.

5.8.2 Soil lithology

The maps of GW salinity for all the measurement periods reveal a clear visual resemblance with the distribution of the lithological zones (see Figures 5.7 and 5.10), which was confirmed by the multiple comparison analysis (Table 5.16). GW salinity values were compared among the four lithological zones (LZ) with the ANOVA test; the procedure to extract the data from ArcView and import them into SPSS was the same as with the analysis of the GW table. The *Tamene T2 post hoc* test was used, because the variances of GW salinity were not significantly homogeneous (Gupta 1999). Similar to the spatial GW table distribution, GW salinity was significantly different among the LZ in Khorezm. Combined with the results of the comparison of spatial distribution of water tables among LZ and the influence of the irrigation water salinity (Chapter 4), it is possible to conclude that both textural distribution of soils and irrigation water salinity are the factors with the greatest influence on GW table and salinity in Khorezm. Detailed field experiments are necessary to find efficient forms of drainage networks for the different LZs.

The visual analysis of the maps produced by the kriging and IDW interpolation methods (section 5.5.2) showed that as with the spatial distribution of the GW table, there were no clear differences in GW salinity among the heavy textures. Moreover, 1) differences were more or less apparent in the southern and western parts of the region, and 2) GW salinity was less in the areas of the two ancient river beds.

Table 5.16: Multiple comparisons of means of GW salinity among lithological zones

No of lithological zone*	Significance								
	April			July			October		
	1990	994	2000	1990	1994	2000	1990	1996	2000
1	2,3,4	3,4	4	2	4	2,3,4	4	4	2,3,4
2	1,3,4	3,4	3,4	1,3,4	3	1,4	3,4	3	1,3,4
3	1,2,3	1,2,4	2,4	2	4	1,4	2,4	2,4	1,2
4	2,3,4	1,2,3	1,2,3	2	2,3	1,2,3	1,2,3	1,3	1,2

**1 – Loam, 2 – Loam – clay, 3 – Sand, 4 – Sand – loam and loam*

5.8.3 Irrigation network

GW salinity dynamics are influenced by the salinity of applied irrigation water in April and October (see Chapter 4). The possible impact of the spatial distribution of the irrigation canals on GW salinity was analyzed. The command areas under the main irrigation canals were separated into three subsystems of the irrigation canals and the distance along each canal from its inlet was calculated in ArcView 3.2 (Figure 5.18).

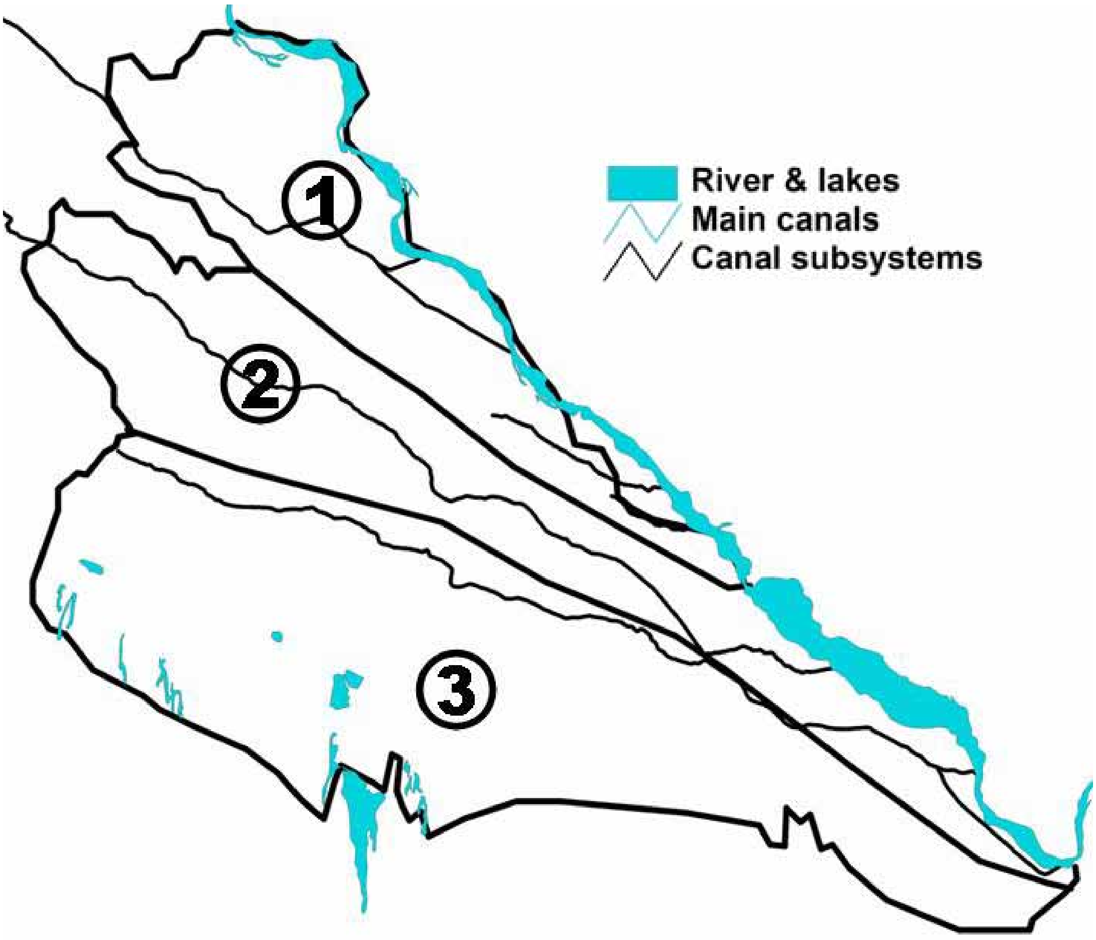


Figure 5.18: Distribution of subsystems of main irrigation canals in Khorezm

There was highly scattered but clearly increasing GW salinity with increasing distance from the irrigation canals (Figure 5.19). The analysis of the *t-statistic* showed that a line was significantly different from zero (analysis not shown here). This situation could especially be harmful during dry years when salinity concentration in the river water is high. The fact that seepage from the irrigation canals is a significant part of the GW recharge in Khorezm is well recognized (Mukhammadiev 1982; Dzhabarov 1990). It is therefore important to prevent GW recharge and salinity increase by taking measures for clogging slopes and bottoms of the canals.

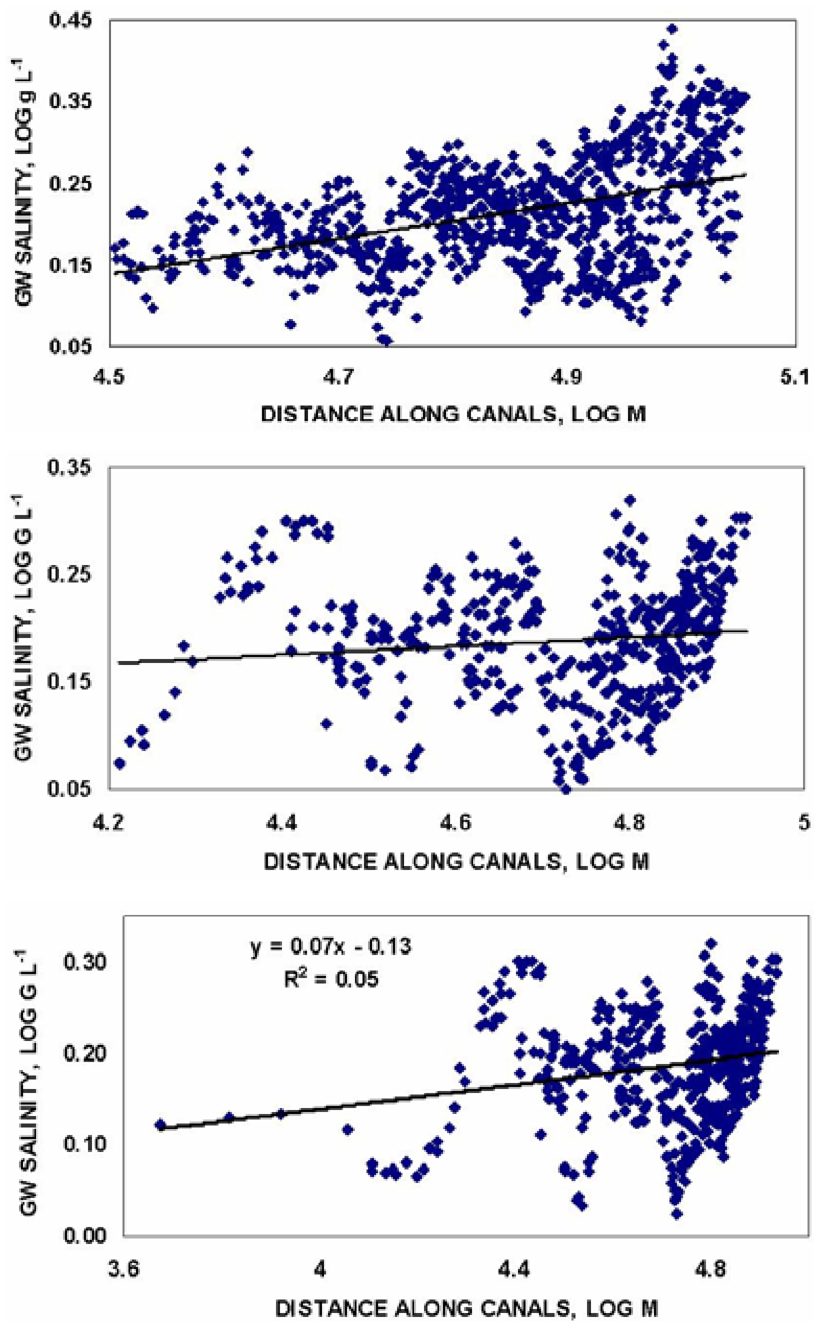


Figure 5.19: Increase in GW salinity with distance from irrigation canals

5.8.4 Topography

Maps of GW salinity (e.g., Figure 5.7) clearly show the higher salinity in the western part of the region. The influence of salts contained in irrigation water on GW salinity could possibly be explained by their accumulation in GW in topographic depressions in the far western part. The GW salinity became higher along the topography from the southeastern to northwestern parts of Khorezm (Figure 5.20).

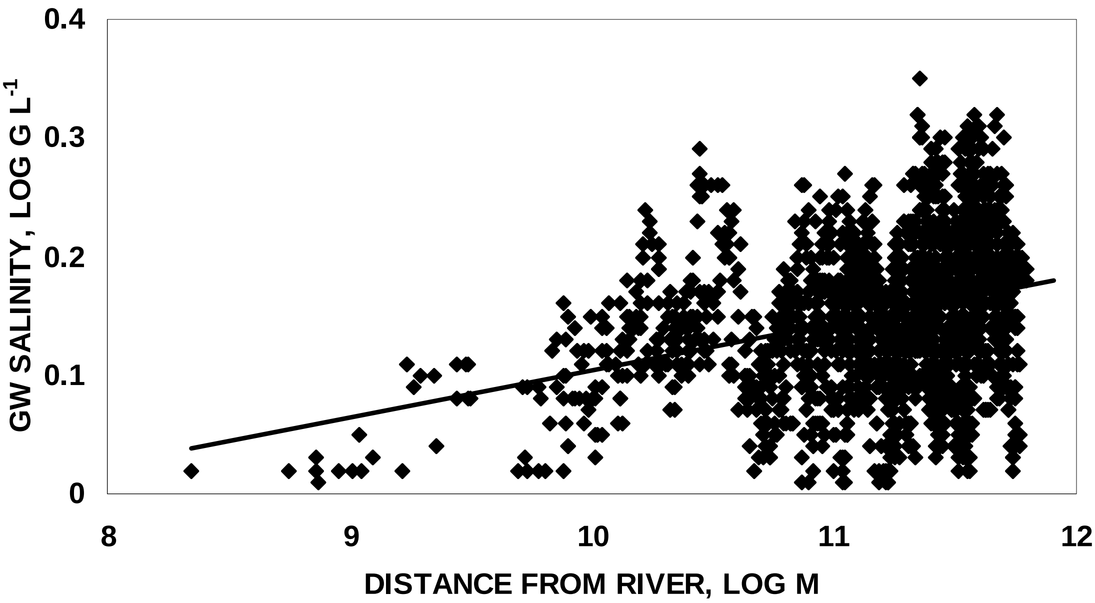


Figure 5.20: Increase in GW salinity with topography

Given the overall flatness of the topography in Khorezm and therefore, fast rates of salt accumulation in soil and GW it is important to be able to efficiently and timely drain the GW to control the salinity accumulation in GW.

5.9 Identification of spatial patterns of groundwater salinity

This section describes the significant spatial changes that occurred in GW salinity in Khorezm during the same dates of the measurement periods in April, July and October over the study period. While some areas could have had constant GW salinity levels or gradual changes, other localized areas may have experienced rapid changes, both negative (increase in salinity) and positive (decrease). It is important to identify those areas which have experienced rapid temporal changes in GW salinity. Identification of such 'hotspot' areas and detailed analysis of the causes of rapid changes will be important in the possible prevention of salinization.

A change detection method developed by Park et al. (2003) was applied to the GW salinity data. The description of the method is provided in Chapter 3. To identify the long-run changes in the spatial distribution of GW salinity it is necessary to separate the seasonal variations that occurred due to irrigation intensity, irrigation water salinity, measurement errors and other possible causes from the long-run changes. For that, it is assumed that the variance of the GW salinity is linearly correlated with its mean. From the geochemical point of view, this implies that a higher concentration of solutes in the GW shows higher seasonal variations over a certain time period.

Sixteen randomly selected measurements of the GW salinity in all the three periods in April, July and October were chosen for analyses. The relationship between mean and standard deviation of the GW salinity was linear with a high coefficient of determination (Figure 5.21). While most points in Figure 5.21 are scattered along the regression line, some significantly deviate both in positive and negative directions. It is assumed that the areas that show significant deviation from the regression line reflect significant, possibly human-induced, GW salinity changes, which were caused by other than seasonal land management and measurement errors. The variance components caused by seasonality and errors were removed from the total variance using a residual analysis.

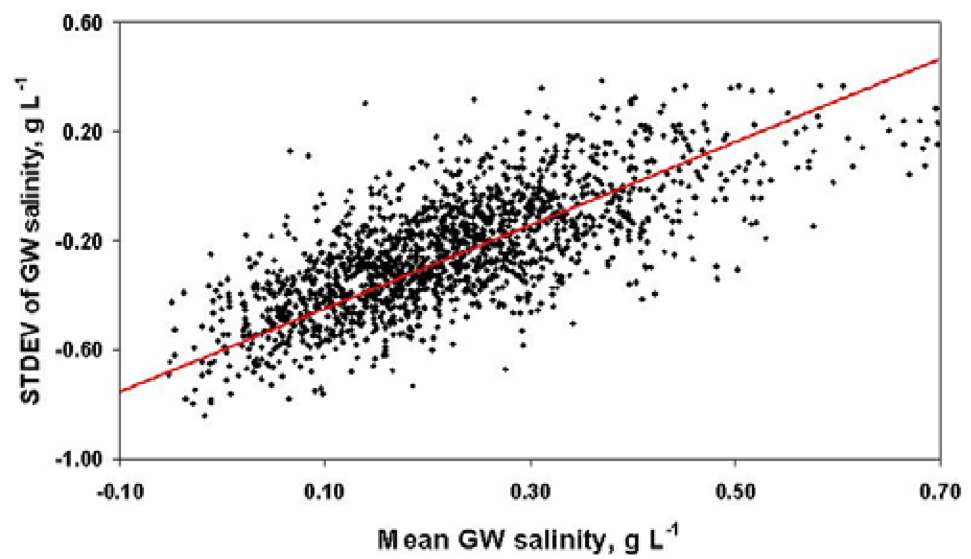
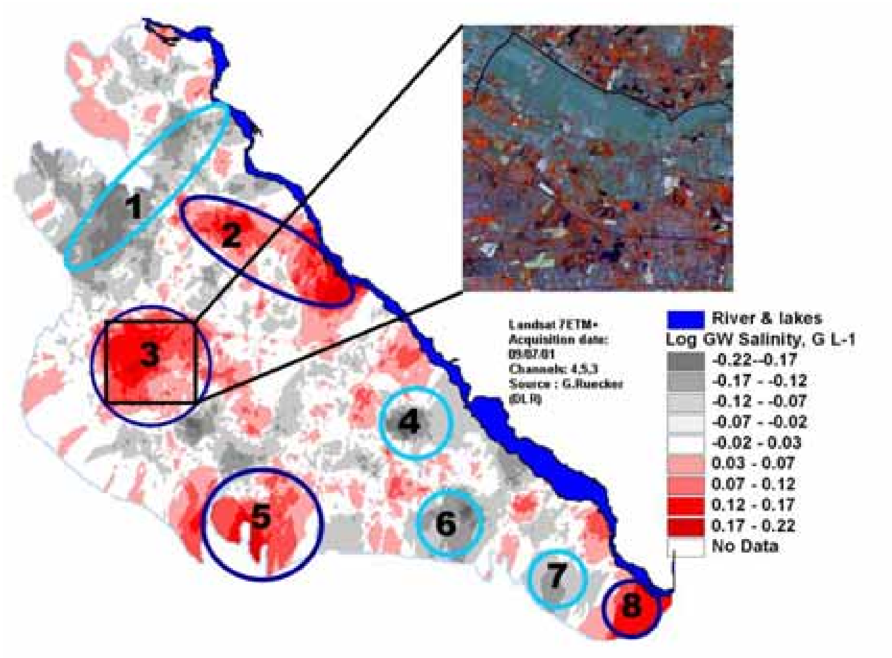


Figure 5.21: Relationship between average and standard deviation of GW salinity

The residuals of the GW salinity are presented in Figure 5.22. A standard deviation scale was chosen for the legend, which separates both positive and negative values from the mean. The scale indicates the relative intensity of GW salinity changes (*salinity change index*) over the last 10 years. A higher positive salinity change (red color) indicates increasing temporal trends in GW salinity, whereas a negative change (grey color) indicates decreasing trends. Comparison of the maps in Figures 5.22 and 5.4 shows that areas with changing salinity occurred in all lithological zones.



Priorities	Center Coordination
1. Shavat	60.2011, 41.7370
2. Yangibazar	60.5099, 41.7237
3. Kushkupir	60.2696, 41.5560
4. Khanka	60.8928, 41.4799
5. Yangiarik	60.5142, 41.3528
6. Bogot	60.8936, 41.3398
7. Khazarasp…	61.1399, 41.2586

Figure 5.22: Identified local areas with rapid temporal changes (hotspots) of groundwater salinity during the study period

Hotspots No 2 and 3 in Figure 5.22 occurred near the areas of the two ancient Amu-Darya River beds (see Figure 5.11). It was shown in Chapter 3 that these areas are distinguished by coarser textures and faster GW dynamics. Although both spatial GW table and salinity were found to be deeper and less saline in these areas, rapid negative temporal changes occurred there within the study period. Another hotspot area (No. 5) occurred in sandy soils. This is an area of the lakes that serve as local receivers of drainage discharge (see Figure 5.10). Possibly, the hotspot appeared here because of the limited capacity of these lakes to contribute to lowering GW tables.

Hotspot area No. 1 is within a larger area that experienced higher GW salinity compared to the rest of the region (see Figure 5.7). However, appearance of this hotspot indicates a decrease in GW salinity in this area over the study period. The hotspot areas Nos. 2, 4 and 7 occur in the close vicinity of the Amu-Darya River. Whereas the hotspots Nos. 2 and 7 are the areas with negative (increasing) changes in GW salinity, the area No. 4 is the area with decreasing GW salinity. Obviously, the vicinity to the Amu-Darya River cannot explain the occurrence of the hotspots Nos. 2, 4 and 7.

The discussion above suggests that the occurrence of the hotspots of rapidly increasing GW salinity in the region can be explained neither by the spatial distribution of the soil texture, nor by topography. This is confirmed by the lack of the causal relationship between the GW salinity and these environmental variables (Figure 5.23). The hotspots appeared in areas with differing topography and among different soil texture, clearly indicating that some other factors, possibly changes in management or cropping patterns, were the causes of the hotspot occurrence.

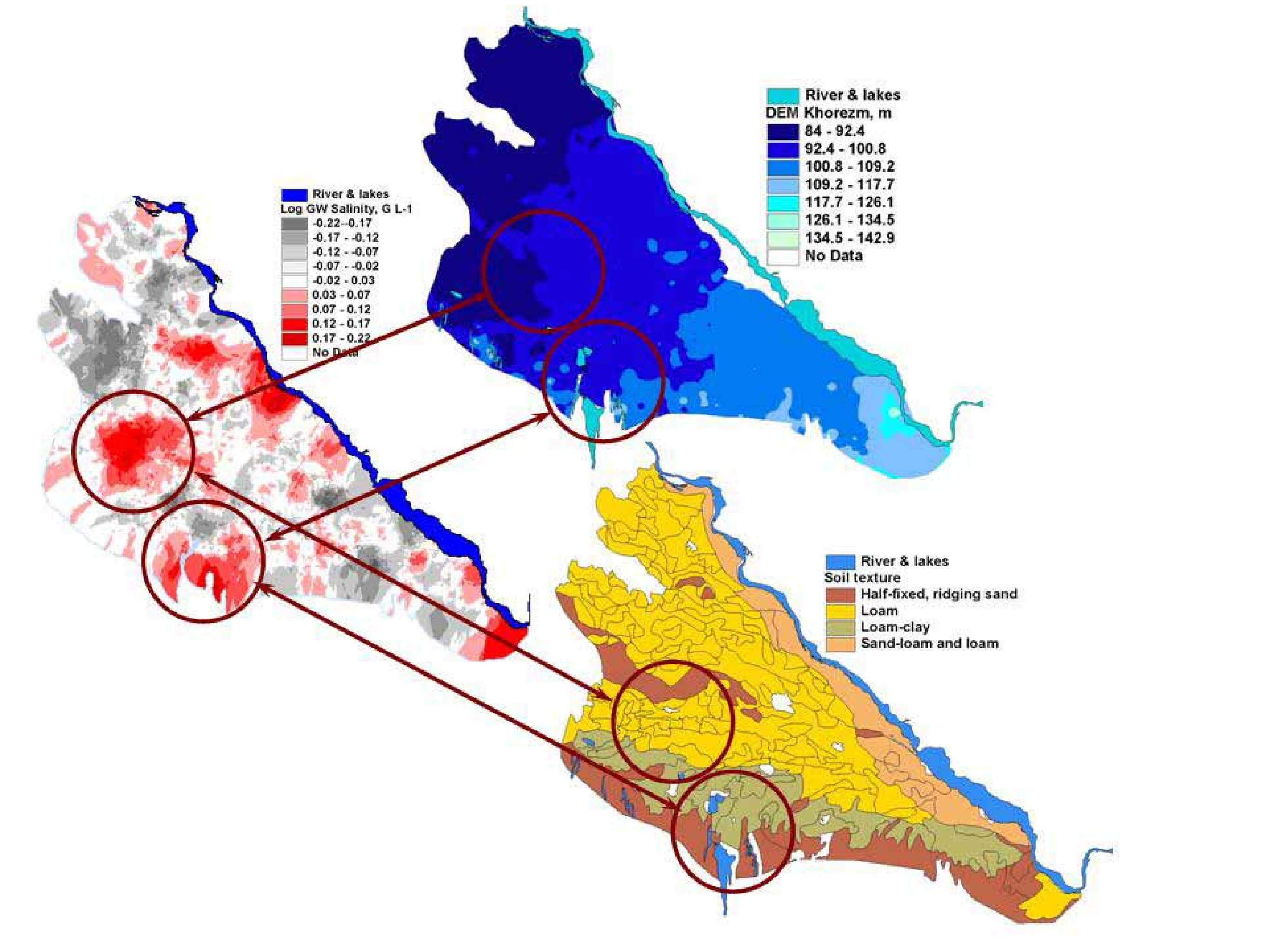


Figure 5.23: Relationship between GW salinity and topography and soil texture

The existence of the spatial domains indicates that there are some relatively large areas that have experienced negative changes in GW salinity. Since these hotspots are not merely related to single factors like soil lithology, a more detailed analysis is indispensable in those areas to establish the most important factors influencing the occurrence of the hotspots through time in Khorezm. An important factor that should be included in the analysis is the human factor. In scientific communities, it is widely accepted that certain technological and policy interventions at a national level may not be appropriate at the local level. One of the fundamental stumbling blocks for more effective policy intervention is the spatial heterogeneity of socio-economic and biophysical conditions at the local level. Over the whole Khorezm region, there is a large variability of soil types, irrigation systems, and parent materials. Locally, farmers may also respond differently to policy changes, due to their cultural, natural and socio-economic situation. Furthermore, such spatial heterogeneity of natural and socio-economic factors often leads to localized accelerated changes over the landscape ('hotspots'). Ignoring the development of hotspots may lead to false conclusions regarding the stability in production capacity of the system. The strong spatial heterogeneity of groundwater salinity variation observed in Khorezm calls for a more site-specific approach to water use and management in order to preserve local environmental conditions.

5.10 Discussion

5.10.1 Introduction

GW table and salinity are among the major factors that determine waterlogging and salinization processes, which negatively influence soil ameliorative conditions in Khorezm. It is therefore indispensable to identify and delineate the areas at risk from unacceptably shallow saline GW and to assess the influence of natural and management factors on occurrence of the negative conditions. However, proper identification of the areas at risk from shallow saline GW depends to a great extent on the choice of the interpolation method. Therefore, the first step in the analysis was to assess and choose the interpolation method that produces the best estimation of the areal distribution of GW table and salinity with the least estimation errors from existing samples.

5.10.2 Quality of interpolation

The performance of the three interpolation methods, kriging, IDW and spline, which have different calculation algorithms, was compared in this study. As a fourth method, the TIN interpolation method was included in the comparison, because it is widely used in Uzbekistan for the assessment of the spatial distribution of GW table and salinity. The comparison of these methods allowed: 1) identification of the best possible method of spatial assessment of GW table and salinity, 2) assessment of the sufficiency of the areal distribution of monitoring wells in Khorezm to accurately capture the spatial dynamics of GW, and 3) proper estimation of the location and magnitude of the areas at risk from shallow saline GW.

The mean and root mean square prediction errors by the kriging estimation method in assessing the unmeasured areas with respect to GW tables and salinity were similar to those produced by the IDW method. In contrast, the spline and TIN interpolation methods produced much larger errors compared to those of kriging and IDW. Although the kriging and IDW methods are found to be much more appropriate for assessing the spatial distribution of GW table and salinity, the large root mean square error indicates that the performance of these methods must be increased for a more precise assessment.

As seen in Chapter 5, both the kriging and IDW methods estimated a similar magnitude of the areas at risk of waterlogging and salinization in Khorezm (see Table 4.7). The areas estimated by these methods were much smaller than those estimated by the spline and TIN methods. Moreover, as discussed in Chapter 4, the spatial distribution of both GW table and salinity estimated by the spline and TIN were patchy, without clear patterns, whereas they were clear in the kriging and IDW maps.

One of the most important source of errors is the low density of the monitoring wells, which does not allow precise estimation of the spatial distribution of GW table and salinity within the fields. Although the GW table in Khorezm is measured at a sufficient *time interval* (once in 5 days during the growing period), the coarse spatial coverage of the monitoring wells does not allow a precise assessment of the GW table. Each well estimates the spatial distribution of GW table and salinity in an area of ca. 140 ha. Considering an average field size in the region of only ca. 2 – 4 ha and a dispersion (i.e., not concentration) of higher (rice) and lower (cotton, orchards) water-demanding crops, in each case the GW table was estimated in one field out of 35 – 70 fields that could have been either intensively or extensively irrigated. Whereas it is likely that in the fields with similar cropping patterns, the spatial distribution of the GW table can be similar (either shallower or deeper), in the areas with different irrigation intensity and soil texture the difference in water tables can be high.

Not only is it difficult to estimate the number of monitoring wells needed to *precisely* capture the GW table and salinity in the region, it is also difficult to estimate these two factors using the existing readings from the monitoring wells belonging to Hydrogeologic Melioration Expedition (GME). The kriging interpolation method allows the estimation of the effective number of the wells by assessing the nugget variance between the readings. The effects of a wide distribution of heterogeneous and stratified soil textural classes can be taken into account. What is apparent is that even doubling the existing number of wells will not help solve the problem.

There are two most likely explanations for the coarse spacing between the wells: lack of resources for new wells and insufficient knowledge of (geo)statistics. Better resources alone would not have sufficed; a better understanding of the complex (geo)statistical principles is necessary for proper handling of measurements of GW table, salinity and relevant spatial factors (e.g., soil salinity). Once it has been realized that the measurements are not reliable, other assessment methods can be sought, e.g., farmers could install at least one well in their fields and provide measurements of the GW table and water samples for the GME staff in return for information relevant to their farming activities.

Although the kriging method proved to be one of the best methods for delineating the GW table and salinity in Khorezm, it requires the knowledge of statistics and geostatistics as well as computers powerful enough to handle a large number of data points. IDW also requires computer processing, but from the practical viewpoint this may be the best interpolation method for the conditions in Khorezm. A more precise (i.e., denser) sampling remains an important factor whatever interpolation method is chosen.

The use of an incorrect interpolation method or large prediction errors can have serious negative implications. The large estimation errors indicate that GW table and salinity in Khorezm are improperly delineated. Apart from the sparse spacing between the monitoring wells, the sources of large errors were identified in Chapter 4 as being the influence of canals, drains, lakes and the river on the readings of individual wells, too deep perforation, etc. Improper delineation of GW table and salinity can easily lead to incorrect assessment of the magnitude and location of the areas at risk of waterlogging and salinization. The comparison of the four methods shows that both TIN and spline assessed much larger areas at risk compared to kriging and IDW. Since the water management agencies face a severe lack of resources the over-estimation of areas at risk will scatter the scarce resources to areas where perhaps agricultural production is not actually jeopardized by shallow or saline GW.

In contrast to the maps of GW table and salinity produced by the spline and TIN methods, the maps from kriging and IDW show clear spatial domains of shallower and more saline GW in the southern and western parts of the region. These are the potential areas of more targeted management measures. Shallower and more saline GW is indicative of a need for denser drainage network to cope with the negative effects. Local areas (field scale) must be identified in these areas after detailed investigation of all the factors listed in Table 4.2, taking into account the crop yields as the best indicators of the negative (hydromorphic) or positive (semi-hydromorphic) effects.

5.10.3 Soil lithology

The maps of GW table and salinity show shallower and more saline GW in the southern and western parts of the region, whereas GW was deeper and less saline in the central part. Deeper and less saline GW in the central districts was observed despite the more intensive irrigation compared to those in the southern part (see Chapter 4).

The influence of the soil textures on spatial distribution of GW table and salinity in Khorezm has been discussed by many researchers (e.g., Nurmanov 1966; Kats 1976; Mukhammadiev 1982). Nurmanov and Mukhammadiev showed that although surface water infiltrates very slowly down and laterally through the heavy textures, the GW can rise very high. Therefore, in the heavier textures, GW is often shallow after the commencement of irrigation and drops very slowly after the growing period. In such soils, the salinity levels are higher, which can be attributed to the slow lateral flow.

Nurmanov (1966) showed that the regional lateral subsurface water outflow within the two ancient river beds Dar'alik and Daudan is around 40 mm yr^{-1}, which is much higher than in the other areas of the region, where the lateral flow does not exceed 19 to 26 mm yr^{-1}. Mukhammadiev (1982) discussed the fact that the wide distribution of the two powerful as well as smaller beds resulting from the numerous floods of the Amu-Darya River in the past can be used to construct the drainage ditches. Lighter textures would allow faster water movement, and thus more efficient and deeper water tables. This is in agreement with the maps produced utilizing the kriging and IDW methods as well as the results of the analysis (see Tables 5.13 and 5.15).

However, a visual analysis of the maps of GW table and salinity shows that 1) the spatial changes within the different textural classes are not clear, i.e., there were areas with deeper GW within the heavier textures, and 2) the GW table was always shallower in the southern part of the region despite the wide distribution of the light sandy textures in the periphery of the region. The appearance of these two situations is most likely because 1) the map of the soil texture in Figure 5.10 is a generalization of the extremely heterogeneous and stratified soil textures in the region and 2) coarse spatial distribution of the monitoring wells and especially deep samples of GW salinity probably could not properly capture the spatial distribution of GW table and salinity.

Personal communication with the farmers and local experts in Khorezm as well as own observations showed that the soil textures differ within the individual fields. Moreover, stratification and existence of lenses of heavier or lighter textures lead to different characteristics of lateral and vertical GW fluxes, making the spatial distribution of GW table and salinity very heterogeneous. When estimating the behavior of GW table and/or salinity, a precise field-scale sampling of the soil textural distribution is indispensable for a correct assessment.

According to Khodzhibaev (1979), a vertically thick heavy clayey loamy layer exists in the southern part of the region. This layer is clearly seen in Figure 5.10 within the Khiva, Yangiarik, Bogot and Khazarasp districts. It reduces the southward subsurface flow from the river, causing stagnant water and the prevalence of vertical over horizontal flow. In such conditions, even a small amount of surface irrigation water will always cause a significant rise of the GW table in the southern part. Apart from this, a northward seepage flow exists from the Turkmen Canal at the border between Turkmenistan and Khorezm (Sorokina, 1985; Vostokova, 1999; Tsytsenko et al, 1999). In recent years, the Turkmen Canal (formerly the canal Tashauz branch) increased in size, becoming more like a river with respect to size and water runoff (Orlovsky 1999). The canal was constructed in sandy soils. The subsurface flow leaves the canal on both sides, one flow reaching the southern part of Khorezm and meeting the southward flow from the Amu-Darya River. The combined flow becomes slow, with a flux moving towards the Sarykamish Depression. The existence of both the heavy soil texture and the flux from the Turkmen Canal likely caused the shallower GW in the south.

5.10.4 Drainage network efficiency

The analysis in section 5.5.2 shows that the southern districts experienced shallower and more saline GW during the transition from 1990 to 1994. A shallow saline GW can bee seen even in the light sandy textures in the periphery. The findings in section 5.5.3 show that the drainage subsystem No. 4 in Figure 5.12 was found to be inefficient in lowering the GW in that part of the region. However, the above discussion about the strong influence of the flux from the Turkmen Canal as well as the existence of the thick heavy textural soil horizon shows that most likely it is not the drainage subsystem that is inefficient in lowering GW tables in the south. It seems that even a denser drainage would probably not resolve the problem with shallow saline GW there due to the much stronger effect of the stagnant subsurface water in the heavy soil textures and the seepage from the Turkmen Canal. Sorokina (1985) showed that the shallow GW in the southern part was due to a wide spatial distribution of the rice-producing farms at that time. To solve the problem of shallow saline GW in this area, it will probably be necessary to reduce the water-demanding crops there. This 'simple' solution will, however, difficult to achieve in practice, because rice is vital for both the state farms and dehkans and private farmers.

The drainage network in Khorezm is conventionally designed as an open ditch system. The ditches are 2 to 3 m deep due to sandy layers that appear locally (see Chapter 3). In the unpublished annual GME reports, the increasing length of the drainage network per area after a particular year is seen as a positive achievement. Although a detailed research is necessary, unpublished data (Forkutsa) and personal visits to the irrigated fields in Khorezm showed extremely high water tables during the growing period in heavier soil textures even in the vicinity of a drain; this applied even more to the water tables farther away from the drains. This observation, combined with the findings in chapters 4 and 5, show that the drainage network most likely cannot effectively lower GW tables in the region, especially in the areas with heavy soils. To avoid shallow and saline GW, alternative drainage designs are indispensable.

Figure 5.12 and a subsequent GIS analysis show that the spacing between the drains is too wide, in some areas being as much as 400 – 500 m. Combined with a wide spatial distribution of heavy soil textures, where lateral flow is difficult, this is indicative of the inefficient drainage system in Khorezm. Own perception and the opinion of Dzhabarov (personal communication) is that the existing drainage network does not lower the GW table everywhere in Khorezm due to the above-mentioned problems. The drainage network seems to reduce the GW table and remove salts only 'globally', meaning that the discharge is assessed from the total drainage discharge from the region. Within the fields, GW tables are shallow, which is especially true during growing periods. The lack of attention paid to shallow GW tables within a field is perhaps due to too widely spaced monitoring wells, the method of interpolation and the way the spatial data are handled: paper maps become outdated as they are drawn by hand by one technician. Such maps are produced 1 – 2 months after the GW table/salinity data are collected, and are not informative due to their awkward size and the fact that quick processing is not possible (overlaying irrigation/drainage canals, etc.).

Dzhabarov (personal communication) described his experience with respect to the inability of drains over the heavy textured soils to lower GW tables due to the lack of lateral subsurface flow in those areas. However, the agriculturally most productive areas are those where the soils are loamy and clayey. Therefore, proper drainage solutions are required in the areas with heavy soils to obtain the maximum possible crop yields.

5.10.5 Digital elevation model

Numerous researchers (e.g., Tursunov and Abdullaev 1987; Kats, 1976; Mukhammadiev 1982) have shown that during the soil formation process in Khorezm, the large number of temporal currents from the meandering Amu-Darya River created highland areas (levees) where coarser materials were deposited. At the same time, farther away from the currents, stagnant water brought finer sediments. Therefore, in topographically higher areas water flow is faster compared to lowlands, where vertical fluxes dominate. Despite that, no relationship whatsoever between spatial distribution of GW table and salinity and topography was observed. Personal communication with farmers in Khorezm showed that apparent salinity spots can be distinguished in topographically lower areas, while higher crop yields are frequently achieved in higher lands provided surface water reaches these areas.

The lack of the otherwise obvious relationship between topography and GW table and salinity can be clearly attributed to the large distance between the monitoring wells as well as to the clearly insufficient coverage of elevation points. As pointed out by Hutchinson (1995), flatter areas require denser measurements of topography, and nested sampling is necessary in areas with abrupt topographic changes. The effects of soil heterogeneity and stratigraphy seemed to be eliminated when the readings of the GW table in January 1990 in the Khiva district were taken for the analyses. However, despite that, and despite the denser available elevation points for the Khiva district (1200), there was no correlation. Although this could be true for the southern part of the region (subsurface inflow from Turkmenistan) and the northern part (influence of the Amu-Darya River), for the rest of the region there must have been a relationship between these variables.

5.10.6 Irrigation water salinity

In the literature, evidence indicates freshwater tables near the canals due to seepage of less saline surface irrigation water. However, this process causes the salts from the nearby areas to dilute and mix with the surface waters. Since the percolation is the most significant part of the GW recharge (Mukhammadiev 1982), the areas remote to the river and main canals receive more saline irrigation water; this was verified by the analysis in section 5.6.3.

However, the recorded changes in the salinity of the irrigation water in the districts near to and farther from the river and canals were negligible. Unlike the information on the amounts of irrigation water, data on the salinity of the irrigation water are not subject to manipulation, which means that they are reliable. Moreover, such minor changes will probably not affect the deeper subsurface water layers. Therefore, these results are questionable.

5.10.7 Hotspot identification

Hotspot identification was performed on GW salinity with the purpose of identifying the changes of the spatial dynamics of GW salinity through time in Khorezm. The flatness of the area makes the region highly prone to waterlogging and salinization from shallow saline GW. Several factors (e.g., heterogeneous stratified soils, spatial influence of irrigation/drainage network, local agricultural practices, etc.) promote more pronounced negative processes over some areas, whereas the changes can be smoothened over the other areas. If the influence of the environmental variables/management practices having a profound negative impact can be identified, then more specific, targeted management measures to overcome these effects can be undertaken. It is, therefore, necessary to identify the areas where the most abrupt changes occurred with further detailed analysis of the factors influencing these changes. It is also necessary to identify the areas with constant dynamics or insignificant changes for comparison and verification purposes.

Two hotspot areas (Nos. 2 and 3) were identified in the areas of the ancient Amu-Darya River beds (Figure 5.22). The dynamics of GW table and salinity in these areas were discussed in previous sections. Although the prediction error map produced by the kriging interpolation method shows higher errors in these areas due to much sparser samples compared to the rest of the areas in the region; there was a sufficient number of the wells. The other hotspot areas appeared in the vicinity of the Amu-Darya River (Nos. 2 and 4). While hotspot No. 2 is the area of the rapid negative changes in GW salinity, hotspot No. 4 is the area of constant or gradual change. It is also seen that the hotspot areas occurred in all lithological zones.

The occurrence of the hotspots can probably be explained by the following. The changes in agricultural practices after breakdown of the former USSR in 1990s could be characterized as being probably more negative than positive. As reported by missions of FAO and EBRD, drainage ditches become degraded due to the difficult financial situation of the majority of private farmers and state farms. According to law, the farmers are responsible for cleaning the on-farm irrigation and drainage canals. However, facing a severe lack of financial support, the farmers pay more attention to cleaning the irrigation canals than to cleaning the drainage ditches. Furthermore, to improve their financial situation, the farmers put more emphasis on growing cash crops like rice and wheat, which require more water. As shown above, the water was not always of good quality, leading to increased salinity during drier years.

There is a clear need for in-depth analysis of the identified hotspot areas to establish the most influential factors of increased GW salinity in these areas. Further analysis will show if the present analysis did indeed identify hotspot areas, since the readings of GW salinity were obtained from deeper horizons as well as from too coarsely spaced monitoring wells.

5.11 Conclusions

Analysis of the different interpolation methods for estimation of the GW table and salinity in Khorezm showed that the TIN method, which is widely used in Uzbekistan, appears to estimate the spatial distribution with large errors (see Table 5.6). The spline method estimated the areas with similarly large errors. In contrast to these methods, the performance of the kriging and IDW methods was acceptable since the errors were much smaller compared to the two other methods and the mean errors were close to zero.

The results of the comparison of the four methods (see Tables 5.6 and 5.11) and the discussion in Chapter 4 show that the use of TIN in Khorezm based on the sparse distribution of the monitoring wells has led to improper estimation of the spatial distribution of GW table and salinity. The fact that the wells were too sparsely distributed can also be seen from the high kriging nugget variance for all measurement periods. Improper delineation has apparently resulted in false management conclusions about the distribution of GW table and salinity in the region and improper decisions on where to allocate the resources for alleviation purposes.

Because the kriging interpolation method is a global estimator (i.e., it estimates spatial distribution from the whole dataset) and a geostatistical method (i.e., it estimates the probability of errors), its performance was found to be more acceptable, although locally there were large prediction errors associated with sparser location of the wells. Since IDW estimated the spatial distribution of GW table and salinity with similar smallest prediction errors (see Tables 5.6 and 5.11) and spatial patterns (Figures 5.3 and 5.8), this method appears to be the better choice over the TIN method.

However, the performance of even the most accurate interpolation method can be unsatisfactory with insufficient spatial coverage of the area with samples. Therefore, the management decisions to alleviate the negative consequences from shallow saline GW in Khorezm are limited to the areas with smaller prediction errors, whereas additional information, and thus resources are required in areas where the prediction errors are large. Moreover, taking into account heterogeneity and stratification of soils in the region, reliable information is indispensable to estimate the salinity of GW. Therefore, the land and water management agencies must consider ways to increase the spatial coverage and reliability of the readings of GW table and salinity.

It is apparent that increasing the number of the monitoring wells and sampling by the GME is not the right solution. Instead, farmers have to be involved in the measurement process itself. However, most farmers are interested in keeping the GW tables shallow as a means of coping with the lack of surface water. Apart from enormous losses of surface water through seepage from the canals, water thievery is common but very difficult to prevent. Therefore, raising the efficiency of the complete irrigation network to increase secure water supplies to the remote districts and individual fields along the irrigation canals is the first priority. The farmers could then be involved by providing them with benefits (e.g., replacing some of the cotton fields with rice or vegetables), which should be decided by region and district Khokimiats.

There are huge areas at risk of waterlogging and salinization. Apart from already shallow water tables in the region due to flat topography and lack of outflow, it is most likely that the farmers raise the GW tables in the fields where fruits/vegetables are grown, because the water is first allocated to the cotton, wheat and rice (under State Order) fields. The negative effects of raised GW affect the whole area in the vicinity of the blocked drain.

The spatial distribution of GW table and salinity was found to be influenced by the soil lithology (see Tables 5.13, 5.15 and Figure 5.10). Shallower and more saline GW appeared in the areas with heavier soil textures, except for the southern part of the region. It was hypothesized that the distribution of a distinct thick heavy textural layer in the southern part and the subsurface flux from the Turkmen Canal lead to stagnant water here, causing immediate rise of GW. The shallow saline conditions most likely caused intensive waterlogging and salinization in the irrigated areas of the Pitnyak, Khazarasp, Bogot, Yangiarik and partly Khiva districts.

The distribution of shallow saline GW in the south of the region shows a clear need to increase the density of the drainage network here. It is likely that the insufficient attention paid to the drainage coverage in the southern part (see Figure 5.12) is due to the patchy, unclear patterns of GW table and salinity estimated by the employed interpolation method. However, the influence of the two above-mentioned factors questions the possibility of lowering the GW table with increased drainage density. Detailed research on the magnitude and spatial location of the influence of the subsurface flux from the Turkmen Canal, the negative impact on crop yields, and thus the necessary alleviation measures, is necessary, but it is already clear that in such conditions, increasing the drainage density will not help to lower GW.

It is obvious that reducing water for irrigation will lead to lower GW tables. Therefore, changing cropping patterns by substituting high water-demanding crops seem to be the better strategy. However, since the highest water-demanding crop is rice, such a policy may cause many farmers to suffer. Careful spatial distribution of the cropping pattern, increased drainage density near the rice fields and measures to reduce seepage are more appropriate. A precise estimation of the water inputs and capacity of the receivers of the drainage discharge must be balanced.

Deeper and less saline GW is clearly seen in the central and western part of the region (Figures 5.2 and 5.7). It can be attributed to the ancient Amu-Darya River beds, which are distinguished by lighter sandy soil textures. As mentioned by Mukhammadiev (1982), these two beds as well as other areas of smaller ancient temporal currents could serve as drainage pathways all over the region. However, wide distribution of heavy textures requires other drainage solutions than open ditches.

A more saline GW in the western part of the region can be attributed to increasing salinity of the irrigation water along the canals because of the dilution of salts from the nearby areas. However, as the change in salinity of the surface waters was small, increasing GW salinity is more likely due to the use of the drainage discharge when there is a lack of surface water. Decreased salinity is seen in the maps of the April and July measurements in 1994, when more water was available, whereas the salinity was higher in 1990 and 2000, when less water was available. In any case, the problem can most likely be solved by lining the canals to both reduce seepage losses and increase the water supply to the remote areas.

The change detection method revealed the existence of several spatial domains experiencing rapid increases in GW salinity. The analysis showed a shallow GW table in these areas. The hotspot areas appeared in all the lithological zones, including the areas of ancient river beds. The detailed analysis can provide insights into the causes of rapid negative changes in GW salinity over these areas and reveal the most important factors.

6 GENERAL DISCUSSION

6.1 Introduction

The discussions in chapters 4 and 5 were dedicated to the reliability and problems of the findings of the temporal and spatial analyses of GW table and salinity, respectively. This chapter provides a discussion of the contradicting and conforming issues from these two analyses. Only few conforming or contradicting issues appeared because of the nature of the analyses in the two chapters; those that are related to each other are discussed below.

6.2 Assessment and implications of groundwater table and salinity dynamics in Khorezm

Agriculture in Khorezm depends on irrigation, the main source of which is the Amu-Darya River. However, extensive water diversion and use leads to a rise in the GW table, which, combined with salinity and diverse soil textures, causes salinization and waterlogging. These have a negative impact on land productivity and crop yields in the region.

The temporal assessment of the dynamics of the GW table from 1987 monitoring wells in Khorezm during the period 1990 to 2000 revealed that the water table was shallow, reaching and exceeding the critical threshold defined for the region. The critical threshold was established for conditions of Khorezm to be around 1 m below the ground surface, but can be deeper depending on the levels of GW salinity and the soil texture, among other factors (see Table 4.2). Although GW salinity during the study period was low, the assessment of the areas at risk of waterlogging and salinization with kriging and IDW interpolation methods revealed that ca. 65 – 70% of the irrigated areas in Khorezm were affected during the growing periods, and it is hypothesized that large amounts of water for irrigation are used to maintain productivity. Although the share of the areas with shallow saline GW in October during the study period was lower than in April and July, the areas at risk rose from 1% in 1990 to 46% in 1996.

Spatial analysis of the GW table and salinity using four interpolation methods showed that the TIN method, which is widely used throughout Uzbekistan and in

Khorezm in particular, predicted the spatial distribution of GW table and salinity with large estimation errors (see Table 5.6). Maps generated with the TIN method were patchy and without clear patterns (see Figure 5.5). Such maps cannot show where the GW table and salinity pose a threat to agricultural activities, and where the situation is favorable (semi-hydromorphic conditions). In contrast to the TIN, the kriging and IDW interpolation methods predicted the clear spatial patterns of GW table and salinity with lower prediction errors. Distinct spatial domains are seen in Figures 5.2, 5.3, 5.7 and 5.8 (maps of GW table and salinity) with shallower and more saline GW in the southern and western parts of the region.

From the above-stated it can be deduced that the areas at risk of waterlogging and salinization are widely distributed, and the assessment of the spatial location and extent of GW table and salinity in Khorezm during the monitoring period using the TIN interpolation method seemed to be erroneous. Most likely, this resulted in less attention paid to the areas where GW was shallower and more saline in terms of irrigation (intensity and cropping patterns) and drainage (density). Moreover, paper maps are extremely outdated; the schematic location of the irrigation and drainage networks was done 20 to 25 years ago and since then the networks have undergone several changes (personal communication with GME technicians). Spatial delineation of GW table and salinity is done by hand and these paper maps are awkward to use (ca. 1.5 x 2.0 m); they do not allow alternative assessments by changing the conditions, e.g., cropping pattern or drainage density.

6.3 Temporal seasonal and annual changes in groundwater table and salinity and soil lithology

Temporal assessment revealed that water table values rose in April and October from 1990 to 2000, but July values remained constant in this period (see Table 4.3 and Figure 4.1). The rise in the GW table in April was from 150.1 cm in 1990 to 125.8 cm below the ground surface in 1994. In October, a gradual rise in the GW table was observed from 228.2 cm in 1990 to 154.9 cm in 1996, which was constant until 1999 (162.1 cm), after which it fell to 197.2 cm in 2000. In July, the water tables ranged from 114.7 to 128.2 cm during the period 1990 to 1999, with a significant decrease in 2000 to 163.3 cm below the ground surface.

Because the temporal changes in GW salinity in the period 1990 to 2000 mirrored the changes in the GW table for the same measurement periods (see Table 4.4 and Figure 4.3), the areas at risk of waterlogging and salinization were found to be constant during the study period in April and July, then being ca. 65-70% of the irrigated areas (see Chapter 5). However, as discussed in section 4.5, the readings of GW salinity were drawn from the wells perforated deeper than 3 m below the ground surface, and therefore the majority of wells could not reflect the salinity in the upper layers of the subsurface water. This indicates that a more precise measurement of GW salinity is necessary to more reliably identify the temporal patterns through time. Since the dataset of the GW table was more reliable, the GW table rise and its implications are discussed in subsequent paragraphs.

The findings of the spatial analyses (see section 5.5.2) show that the distribution of the GW table in Khorezm has been influenced by both soil lithology and irrigation water applications. Therefore, water tables were expected to be shallower from 1990 to 1994 (i.e., during ample water runoff years) in the areas with heavier soil textures, due to a more difficult lateral outflow of subsurface waters. However, further analyses revealed that the most prominent changes in GW tables occurred in the southern part of the region, which is distinguished by the light sandy layers in the periphery of Khorezm (see Table 5.4). This was true for the seasonal changes in the GW table in all the measurement periods (see Figure 4.7).

This phenomenon can be explained by the influence of the Turkmen Canal and by the thick heavy texture causing stagnant water in the southern districts of Khorezm (see section 5.6). It is likely that the GW tables will be constantly shallow during irrigation seasons no matter how dense the drainage network is in those areas. Therefore, despite the fact that increased diversion and water use in the region followed the increased water runoff in the Amu-Darya River, water tables were always shallower. Except for the southern part, in general the water tables were found to be shallower in the heavier soil textures and deeper in lighter ones, including the areas of the ancient Amu-Darya River beds, although areas with deeper GW within the heavy soil textures existed. The difference in water tables was obscured during peak growing periods in July, probably due to intensive irrigation.

6.4 Hotspot identification

The hotspot areas, which were defined based on the rapid changes in GW salinity, appeared in different soil lithological zones of the region. Analysis of the temporal changes in the GW table over these areas revealed the generally shallow water tables, which were either rising before and falling after 1994 or were more or less constant. In contrast to GW tables, GW salinity was found to be increasing over these areas. The main limitations of these findings are the deeper perforation of the monitoring wells and their coarse location. The data reliability of the readings has not been discussed, because it was very difficult to establish which technicians had been performing their jobs conscientiously and which had not.

The appearance of the hotspot areas indicates that agricultural activities are jeopardized from saline GW and consequent soil salinization. Since the hotspots are related to the agricultural practices and natural conditions, to avoid or reduce adverse impacts from salinization in the hotspot areas it is necessary to investigate the causes of the occurrence of the hotspots and define a site-specific approach towards sustainable agricultural activities. Moreover, the investigation of the occurrence of the hotspots can reveal the causes of adverse processes and identify the necessary actions that can be implemented in other areas where such processes can potentially occur.

6.5 Summary

Summarizing the above-stated, the apparent predominance of shallow and saline GW in the region is in part a result of the selected interpolation method, which is not able to properly predict the spatial distribution of the GW. It was not possible to distinguish between the areas at risk (hydromorphic) and favorable (semi-hydromorphic) soil conditions by the TIN method. Therefore, it is likely that the problem areas did not receive enough attention from the land and water management agencies due to the inherent prediction errors of the interpolation method.

Analysis showed that areas with constantly shallower and more saline GW exist in the southern part of the region. The influence of the flux from the Turkmen Canal as well as the existence of the heavy textured soil horizons in the south of Khorezm caused conditions of stagnant water here and immediate water table rise with the start of the irrigation season. Shallower and more saline areas in the south of the region are hypothesized to appear despite the density of the drainage network.

The occurrence of areas with rapidly increasing GW salinity in different soil textures has to be analyzed in more detail due to the current sparse location of the monitoring wells, and sampling of GW salinity done in deeper horizons

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7 RECOMMENDATIONS

7.1 Introduction

The following recommendations for improving the agricultural practices in Khorezm are based on the findings of the analyses of temporal and spatial dynamics of GW table and salinity assessed in April, July and October from 1987 monitoring wells during the period 1990 to 2000. The limitations of the findings are also discussed.

One recommendation *for the land- and water-resources management agencies in Khorezm is to substitute the widely accepted TIN interpolation method with the better performing kriging and IDW methods.* However, the use of kriging requires that the technicians be skilled in statistics and geostatistics, subjects which are currently not taught in Uzbekistan. Moreover, few organizations have computers, and computer work is frequently limited to typing in the data. Although the use of the IDW method is computer-demanding, this method is easier to implement.

The dynamics of GW table and salinity were assessed from 1987 monitoring wells, which were more or less evenly distributed over the region (see Figure 3.3). However, despite the relatively dense network of monitoring wells in Khorezm, this network was only able to reveal *relative* values of GW table and salinity in the region. This conclusion was drawn from the following considerations:

1. Since there are 275,000 ha of irrigated areas in the region, each of the 1987 wells covers approximately 140 ha. Considering the average size of a field in Khorezm is 2 – 4 ha, and taking into account that areas with high water-demanding (rice) and low water-demanding (cotton, wheat, orchards) crops are intermingled, such an assessment cannot be precise at the required level.
2. Individual monitoring wells are located in close vicinity of the irrigation canals or drainage ditches, which can influence the readings, making them unreliable.
3. Despite the fact that the values of the mean prediction errors of the kriging and IDW interpolation methods were close to zero, a large root mean square error was observed (see Tables 5.6 and 5.11). Combined with the high nugget variance of the kriging method observed for GW table and salinity in all the measurement periods, the large errors indicate that the spacing between the

monitoring wells is too large, and even the best possible interpolation method will not produce satisfactory results with the sparsely measured samples.

4. The perforation of the monitoring wells is too deep down; the wells allow the assessment of the salinity in GW from the deeper horizons only, whereas according to Dzhabarov (1990) the fastest and most significant changes in salinity appear in the upper soil horizons.

As GW table and salinity data are only relative, they most likely can neither be used for the *detailed* analyses of the changes in GW table and salinity on the field scale nor on the larger farm/district scale. Since it will most likely be prohibitively expensive to increase the number of monitoring wells, alternative solutions must be proposed. *The recommendation here is to apply a non-traditional approach to estimating GW table and salinity*. The best approach seems to be to involve the farmers in the measurement of the GW table and sampling of salinity for further analyses. Clearly, the farmers must benefit from their services in some way, perhaps by recommendations of where to allocate their crops and how to irrigate their fields with the least possible labor and financial input, etc.

7.2 Spatial distribution of groundwater table and salinity

The maps of GW table and salinity revealed shallower and more saline GW in the southern and western districts (see Figure 4.7). *These are the priority intervention areas in terms of increased density of the drainage network*. However, the discussion in Chapter 5 shows that the subsurface flux from the Turkmen Canal as well as a thick heavy soil layer in the southern part will always cause shallow GW here, which will make conventional drainage solutions difficult. It is very likely that the construction of a denser drainage network would not be very efficient and could be a waste of resources because of the above-mentioned problems. Moreover, the limited capacity of the periphery lakes and the Ozerny main drain to receive the drainage effluent will not make intensified drainage an efficient solution.

The better solution for the southern part of the region seems to be to reduce the water inputs through introduction of less water-demanding crops. In spite of being the highest water-demanding crop, rice is an important staple food in Khorezm, and reduction of the areas under that crop would inevitably negatively affect mostly the dehkans and private farmers. According to Mukhammadiev (1982), the largest part of the GW recharge comes from the seepage from the canals, which increased in recent years due to reduced water turbidity after the construction of the Tuyamuyun reservoir. *Therefore, it would probably be more effective to line the canals in the southern part of the region while conducting a tough policy towards the production of rice in the area.*

The more saline GW in the western part of the region was attributed to the increased salinity in the irrigation water along the main canals. Indeed, the surface water dilutes the salts from the nearby areas, whereby the water salinity along the canal increases. However, the dataset of the irrigation water salinity shows that the change was insignificantly small. Most likely, the shallower and more saline GW in the western part of the region resulted from the wide distribution of the heavier soil textures, where the lateral GW flow is much slower than the vertical. A detailed investigation of these areas is necessary to establish the factors that brought about the shallow and saline GW conditions, but it seems from the GIS analysis that the spacing between the drains in heavier textures should be denser. *Taking into account the sparse location of the monitoring wells, this recommendation can be true for much larger areas.*

Lowering GW tables in the western part via a more effective drainage network could be a better management option, since even a higher GW salinity will be less harmful deeper down along the soil profile. However, installing a denser conventional drainage network in this area might probably not be the proper solution because of the heavy soils. Alternative drainage designs must be introduced. Although many proposals with respect to tile drainage have been presented (e.g., Kats 1976), it is likely that in conditions of extensive water diversions and high drainage discharge together with the limited capacity of discharge-receiving depressions in Khorezm, the capacity of the tile drains may not be sufficient to lower the water tables. Prior to introduction of the tile drains, 1) a detailed investigation and pre-test are necessary, and 2) irrigation canals must be lined first.

The shallow water tables during growing periods can be attributed to the artificial blocking of drainage ditches by farmers. The farmers seem to apply this measure when they anticipate or face a lack of surface water, especially in the areas remote to canals and the river. Facing a lack of water, neither are the farmers against shallow water tables in their fields, nor are they able to afford appropriate measures for the implementation of sophisticated drainage techniques. *Therefore, it is necessary for the water management decision makers to 1) find ways to increase the water supply to the remote districts, the best strategy here being saving water from deep percolation, 2) improve the drainage system by implementing the efficient alternative designs based on the research of the influence of GW table and salinity on crop yields. Alternative options would also be to 3) reduce the share of high water-demanding crops or 4) reduce the total cropped and irrigated area, e.g., by introducing a high-value crop.*

7.3 Hotspot areas

Hotspot areas in Khorezm were identified based on the analyses of the GW salinity. The hotspot areas correspond to the areas that experienced rapid negative changes (increase) in salinity. These areas appeared in all lithological zones of Khorezm, which indicates that not only natural conditions (like heavy soil textures) are responsible for worsening soil conditions and increasing salinity in the region. Identification of the hotspots will enable a more detailed investigation of the causes for increasing salinity in the areas and thus appropriate actions to prevent or mitigate the adverse effects. The hotspot areas can be associated with so-called marginal lands, i.e., land that cannot be fully used for agricultural production for numerous reasons, which include too shallow and saline GW. *A detailed investigation of the causes for the occurrence of hotspots and the associated natural conditions/management factors will enable an assessment of the most sustainable long-term agricultural practices. If an area proves to be unproductive (marginal), resources can be reallocated to better areas, while other activities can be designed in the hotspot areas (e.g., growing of salt-tolerant commercial trees or halophytes).*

7.4 Summary

To summarize, the following recommendations are made to alleviate the negative consequences of the shallow saline GW in Khorezm:

1. It is necessary to implement the interpolation method that estimates GW tables and salinity in unmeasured areas from the limited number of monitoring wells with minimum errors,
2. Since the number of the monitoring wells is insufficient and there is no means of increasing their number as required for proper prediction of GW table and salinity, it is necessary to find alternative ways for a more precise estimation of the GW table and salinity. One way could be to involve the farmers in Khorezm in helping to collect data through continuous monitoring in their fields for a mutual benefit.
3. The shallower and more saline areas in the southern and western parts of the region were identified in the maps of GW table and salinity. Since increased drainage density will not be likely to improve the situation, it is vital to define alternative measures. Whereas reducing the high water-demanding crops and lining the canals seems to be the better solution in the southern part of the region, deepening of the GW tables through alternative drainage solutions (tile drains) would be more effective in the western part of the region, which is distinguished by heavier soils.
4. To cope effectively with the farmers' ancient practice of raising the GW table by blocking the drains, an efficient water supply is indispensable. As a general recommendation to cope with shallow GW tables during irrigation periods it is necessary to improve the drainage network, the criteria for such measures being the crop yields.
5. As the analysis of the data set for the 11-year study period shows, the occurrence of the hotspot areas is not an occasional or random event. These hotspots must be analyzed in detail to gain understanding of the underlying processes governing the worsening local conditions. If it is not possible to eliminate the hotspots or prevent their occurrence such areas should be further investigated with respect to being used economically to produce salt-tolerant commercial trees or halophytes.

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