Modelling Irrigation Water Management under Water Shortage and Salinity Conditions: 1- Evaluation of The Current Irrigation and Drainage Management Practices in South Kazakhstan

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ABSTRACT

The WAVE model was modified to include the effect of salinity on crop transpiration, and used to simulate soil water balances, to investigate long-term salinity build-up in the root zone, and in conjunction with a crop yield response model to assess their effect on crop yield. The WAVE_MS model has been applied to evaluate current irrigation and drainage practices in South Kazakhstan. According to the results of simulation runs, cotton yield in the area would be reduced to a very low level within 25 years if irrigation and drainage practices are not changed. Inadequacy in water applications and increasing soil salinity are brining about this reduction. For the problem considered in this study, the WAVE_MS model, along with the crop yield response model, can be used as a tool for assessing the impact of different irrigation and drainage scenarios on crop yield. The results demonstrate that the modelling approach is robust and applicable under arid and semi-arid conditions and to a wide range of water shortage and salinity conditions.

Keywords: ***water management, salinity, mathematical modelling.***

INTRODUCTION

Water stress and salinity are at present significant threats to sustainable irrigated agriculture in many parts of the world. With continued rapid population growth, and increasing dependence on irrigated agriculture to maintain food security, it is essential that improved approaches to irrigation and drainage management be found. The problems recently experienced in South Kazakhstan serve to highlight the issues. Cotton yields were reduced by about 40% due to water and salinity stress over period of about 10 years following deterioration of irrigation and drainage management systems. This in turn resulted in considerable decrease in net incomes from crop production (ADB, 1997; Mott MacDonald, 1999). Sustainable irrigation and drainage management to maintain and improve crop production is one of the most significant needs in areas under the effects of water stress and salinity. What is required in managing water and soil salinity is a means of assessing how different irrigation and drainage practices affect potential crop yield, and long term sustainability. For this reason, there is an urgent need to research robust and more efficient modelling approaches to improve assessment of crop yield associated with water and salinity stress.

Advances in computer technology in recent decades have permitted improvements in mathematical modelling of crop, soil and climate systems. Vadose zone models can provide useful information about the impact of different irrigation and drainage practices. Many models have been developed and used to simulate water and solute flux in the crop rootzone (Vanclooster, *et al.*, 1994; Fernandez *et al.*, 2002; Simunek, *et al.*, 1996; Simunek, *et al.*, 1999; Droogers *et al.*, 2000; Wang *et al.*, 2001; Zhang and Dawes, 1998; Van Dam *et al.*, 1997; Van Dam, 2000; Smets *et al.*, 1997; Joshi *et al.*, 1995). These models can deal with the interaction between the soil and crop and water management variables such as irrigation, leaching and drainage. They can be used to determine the most beneficial combinations between water management variables leading to sustainable crop production. Vadose zone models are increasingly being used to evaluate alternative management practices and subsequently to identify the most efficient management strategies for different sets of conditions (Querner *et al.*, 1997; Droogers and Kite, 2001; Droogers and Torabi, 2002; Kite and Droogers, 2000a; Qureshi *et al.*, 2002).

A modified WAVE_MS model (Saleh, 2006) has been developed for modelling irrigation water management under water shortage and salinity conditions. The developed approach leads to a computational procedure that is able to deal with the combined effects of water and salinity stress on crop transpiration and on crop yield. This paper describes the application of the WAVE_MS model to the Makhtaaral Region of South Kazakhstan to evaluate the present irrigation and drainage practices.

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MATERIALS AND METHODS

The WAVE_MS model Set-up and Calibration

The ability of any mathematical model to produce reliable output depends on the availability of reliable input data, as well as the accuracy of the model in representing the physical processes of the prototype. In most systems being modelled there are process representations that cannot be adequately parameterised by field measurement alone, perhaps because of high spatial variability. Because of this, most models require calibration. Calibration is the process through which model parameters are modified to enable the model to closely match the field observations (Gupta *et al.*, 1998). In the WAVE_MS model, the parameters are those required by the van Genuchten equation (van Genuchten, 1980):- saturated and residual soil moisture content (θ_s and θ_r), the inverse of the air entry value (α), the shape parameters (n and m). The calibration of solute distribution constant (K_d) is required for salinity model.

Field determination of these parameters is very difficult and values may vary widely between relatively close locations. Trial and error procedures can be used, however, to refine parameter values to those that yield optimum simulation of soil moisture and salinity. This is the calibration approach adopted here.

Field Data Collection

The University of Edinburgh has been involved with Mott MacDonald (consulting engineers) on the Water Resources Management and Land Improvement Project (WRMLIP) in South Kazakhstan. The project investigated water management practices, and much of the data collected has been available for and widely used in the research described in this paper.

Mott MacDonald (2003a) have presented field data collected at three pilot areas in the Makhtaaral region of South Kazakhstan. The programme commenced in October 2000. The objective of the data collection programme was to collect the data necessary to calibrate the mathematical models of the irrigation system being developed by the WRMLIP project. In particular the data were required for the WAVE_MS model.

The following data were collected during 2001 at each pilot area (Mott MacDonald, 2002):

- Daily meteorological data for the Lenina weather station, including rainfall, daily air temperature and relative humidity data.
- Physical soil characteristics (particle size distribution, bulk density, porosity, infiltration, field capacity, wilting point etc.). Soil characteristics have been observed at a number of locations in each of the pilot areas, with sampling at different depths from the surface to a depth of 3 m.
- Time series of soil moisture characteristics with depth based on laboratory analysis of soil samples collected.
- Chemical composition of irrigation water, soils, groundwater and drainage water.
- Time series of groundwater levels.
- Leaching and irrigation water applications, timing and field distribution.
- Crop characteristics for cotton, including planting dates, development stages, rooting depths and yields.
- An evaluation of water and salt balances in the pilot areas during 2001.

The field data collection programme in 2001 provided infiltration characteristics at different depths as well as definition of permanent wilting point and saturated moisture content at different depths. These data were obtained by laboratory analysis of soil samples taken at 200 mm depth intervals from the three pilot areas, with 9 sampling locations in each pilot area. The WAVE_MS model was set-up for each location using the terminal infiltration rate and soil properties for the sampling point closest to that location as model input. There were no measurements of soil moisture tension data during the 2001 collection programme. The pilot areas were Birlik, Karaoi and Makhtali. The locations of the pilot areas are shown in Appendix 1 ((Mott MacDonald, 2003a).

In 2002, automatic soil monitoring equipment was installed in the pilot areas, providing continuous and discrete observations of soil moisture content, soil moisture tension and electrical conductivity measurements. Soil moisture was measured at a large number of sites in each pilot area using the Diviner probe, which is portable and permits a soil moisture profile to be observed. Soil moisture was also measured at three depths (300, 600 and 1000 mm) at the centre of each pilot area using the EnviroScan sensor. This equipment was fixed and permitted continuous measurements. A considerable number of dual measurements of soil moisture by Diviner probe and gravimetric laboratory analysis were carried out in each pilot area. However, the evaluation of the soil monitoring equipment results highlighted certain problems associated with the data obtained from both the soil monitoring equipment and from gravimetric soil moisture analysis. Significant variations were found between the data measured by each of the methods. The 2002 field data collection programme also provided soil electrical conductivity measurements using a Sigma Probe. A problem associated with this instrument was that, it was unable to produce reliable measurements of conductivity in the very dry soil samples for the top 200 mm of soil.

Meteorological Data

The climate of South Kazakhstan is continental. The semi-arid steppes are characterised by extremely low rain, hot summers and cold winters. Climatic data were available from the Lenina weather station for the period 1990-2001. Lenina lies in the centre of the project area and is representative of the area (Mott MacDonald, 2000b). The WAVE_MS model requires daily rainfall and reference crop evapotranspiration data as primary input. Figure 1 presents a summary of mean monthly precipitation, temperature, relative humidity and potential evapotranspiration (ET_o)at the Lenina meteorological station.

The coldest month is January in which the mean daily air temperature is about $-2.0\,^{\circ}C$. The hottest month is July with an average of $27.9\,^{\circ}C$. The annual rainfall averages 310 mm and this falls mainly in winter and spring. The highest relative humidity is recorded in January, February and December at 83%, 80% and 80% respectively. Lowest values of relative humidity of 45% and 46% occur in June and July respectively.

Mean monthly reference crop evapotranspiration, ET_o, was determined for Lenina by Mott MacDonald (2000b). Potential evapotranspiration reaches its highest value of 6.9 mm/day in June. The lowest average evapotranspiration values of 0.67 mm/day and 0.65 mm/day occur in January and December respectively.

RESULTS AND DISCUSSIONS

Soil characteristics

The WRMLIP field data collection programme provided both soil physical and chemical property data. The organic matter content in the project area was very low at 1.0%-1.5%. According to the Kachinsky classification criteria (WUFMAS, 1999), the upper soil layers, mostly to 1-meter depth are classified as medium loam whereas light loam is the most common classification in the lower 2 meters of the soil profile. The average values of bulk density over all the soil layers are in the range from 1.42-1.67 g/cm^3, 1.41-1.7 g/cm^3 and 1.41-1.56 g/cm^3 in the Makhtali, Birlik and Karaoi pilot areas respectively. Higher bulk density values were identified in the plough pan layer 20-40 cm. The average porosity values ranged from 36.5%-46.2%, 37.5%-47.2% and 43.0%-47.2% in the Makhtali, Birlik and Karaoi pilot areas respectively. No significant variations in the soil porosity were identified between the three pilot areas. The soil of the study area can be considered as extremely porous in most depths.

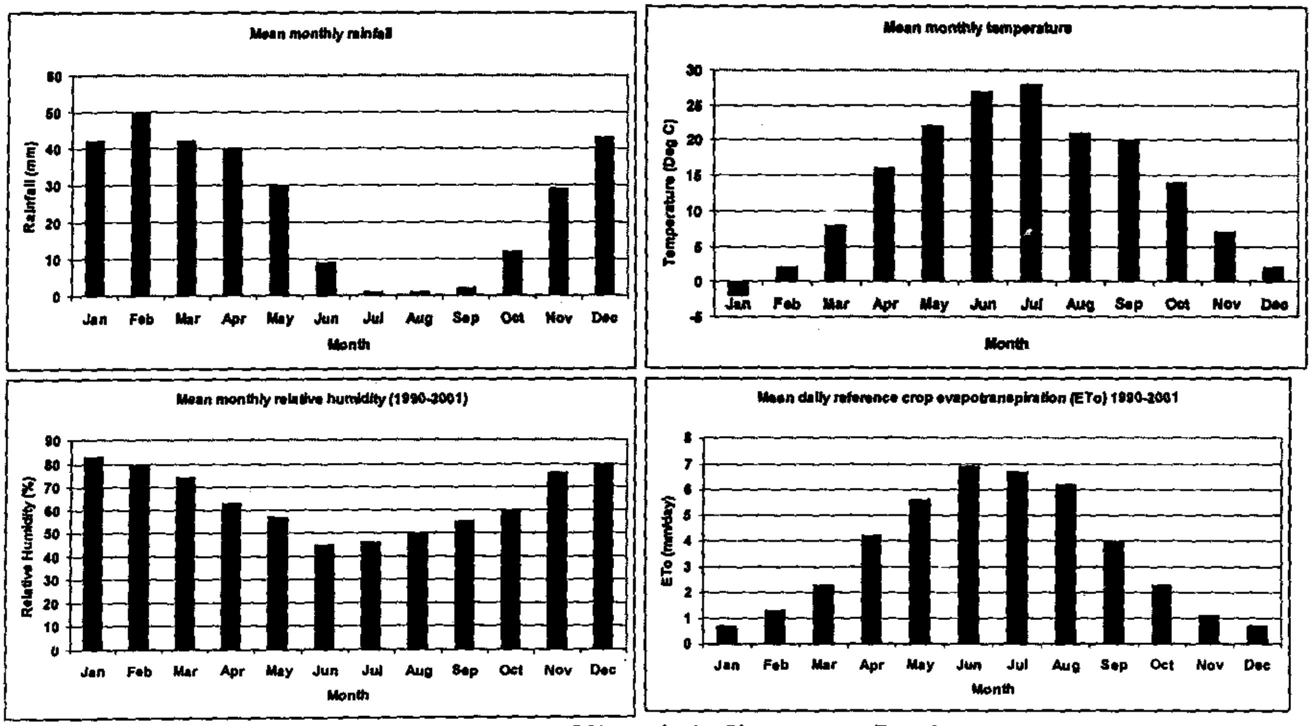


Figure 1. Climatic indicators at Lenina

The WRMLIP data collection report provided soil salinity data at different depths for each pilot area in terms of total soluble salts (TSS) along with the ionic balances in % of salts by weight of dry soil. Local classification of salinity is based on the percentage of salts by weight in an aqueous extract of soil and on chloride concentration, whereas the International classification of salinity is based on the electrical conductivity (EC) of a saturation extract of the soil (WUFMAS, 1999). There were no electrical conductivity measurements available in the years 2000 and 2001. However, a relationship was established between percentages of total soluble salts (TSS) and electrical conductivity (EC) (Mott MacDonald, 2003b) on the basis of EC measurements in 2003.

The average values of TSS for each layer were used as initial values for WAVE_MS. According to the local classification, soils in Makhtali and Birlik is classified as highly saline in the upper soil layers to moderately saline in the bottom layers below the rootzone. Soils are classified as non-saline in the Karaoi area. On the basis of the international classification system (WUFMAS, 1999), the majority of layers in Makhtali and Birlik tend to be classified as highly saline, and in Karaoi are classified as slightly saline instead of non-saline with the local classification. Soil salinity in Makhtali and Birlik is above the threshold value for damage to most crops based on the criteria described in the FAO Irrigation and Drainage Paper 56 (Allen *et al*, 1998). However, it is still below the threshold value in Karaoi.

Soil salinity has significantly increased in the WRMLIP project area since 1990. There has been a significant increase in the area classified as moderately saline. The total area classified, as moderately saline in 1990 was 4495 hectare (21% of the Phase I area) and 6123 hectare (29% of the Phase II area) in the Phase I and Phase II areas respectively. Within a 9 year period, these areas had increased to be 9644 hectare (45% of the Phase I area) and 10334 hectare (49% of the Phase II area) in the same phases respectively (Mott MacDonald, 2004). The average rate of increase has been 2.4% and 2.0% per year respectively.

Crop Characteristics

The crop characteristics such as crop coefficients (K_C), rooting depths and leaf area index (LAI) at various stages of growth are needed to run the WAVE model. Data on cotton stages of growth were collected during the 2001 field data collection programme. The length of cotton growth stages and the values of K_C used during the modelling are presented in Table 2.

The data collection report (Mott MacDonald, 2003a) also provides root depth and distribution data in each of the pilot areas, measured during 2001. These data were used as input in the WAVE_MS model. These data are presented in Table 3.

Leaf area indices are used in the WAVE model to partition evapotranspiration into evaporation and transpiration. The leaf areas used in modelling are presented in Table 4.

Table 2. Growth stages for cotton in pilot Areas

Stage of growth	Kc	Dates of Stage (and length in days)		
		Makhtali	Birlik	Karaoi
Planting	0.4	17/4	1/5	14/4
End Initial stage	0.4	19/5 (32)	31/5 (30)	18/5
End development	1.15	29/6 (41)	10/7 (37)	27/6 (40)
End mid stage	1.15	19/08 (52)	1/09 (52)	17/08 (50)
End late stage	0.6	15/10 (56)	15/10 (45)	15/10 (58)

Table 3. Crop root development in each pilot Area

Makhtali		Birlik		Karaoi	
Date	Depth (mm)	Date	Depth (mm)	Date	Depth (mm)
29/5	400	9/6	200	27/5	600
29/6	600	10/7	600	27/6	1400
21/7	1400	3/8	1000	15/7	2200
14/8	2000	27/8	1600	12/8	2800
15/10	2400	15/10	1800	15/10	3000

Table 4. Leaf area indices used in WAVE Modelling

Days from planting	Leaf area
6	0
7	2.35
37	5.60
150	6.40
181	0.0

Recent Irrigation Practices

Leaching water depths, dates of application and salinities in 2001 are presented in Table 5. Tables 6 and 7 show depths, dates and salinities of the irrigation water application. In 2001, irrigation water was applied only twice during the growth period between mid April and October. However, water was applied only once at Makhtali location P15, and at Birlik P3 and P12. Water application in Makhtali and Birlik was not uniform in either leaching or irrigation and varied across the pilot areas.

WAVE Model Parameterisation

Water Transport Parameters

The water transport module requires soil moisture retention and hydraulic conductivity parameters to be specified for each soil layer. These parameters are required by the van Genuchten (1980) equation. The WAVE_MS model was set-up initially with soil hydraulic parameters derived from the field observations of soil moisture content and soil moisture tension.

Table 8 presents the critical pressure head values used to model the effect of water stress on crop transpiration according to the function proposed by Feddes *et al.*, (1978). These values were based on the values recommended in the WAVE reference manual (Vanclooster *et al.*, 1994).

Crop coefficients and leaf area indices values used for the WAVE_MS modelling are presented in Tables 2 and 4.

Table 5. Leaching applications at modelled locations within the project area, 2001

Location	Dates	Leaching Depth (mm)	Water Salinity (g/l)
Makhtali, location P3	11 Mar – 13 Mar	60	0.8
Makhtali, location P9	11 Mar – 13 Mar	60	0.8
Makhtali, location P15	6 Mar – 7 Mar	147	0.8
Birlik, location P3	26 Jan – 2 Feb	184	0.8
Birlik, location P12	8 Mar – 11 Mar	251	0.8
Karaoi, location P3	9 Mar – 15 Mar	156	0.792
Karaoi, location P6	9 Mar – 15 Mar	156	0.792

Table 6. First Irrigation applications at modelled locations within the project area, 2001

Location	Dates	Irrigation Depth (mm)	Water Salinity (g/l)
Makhtali, location P3	4 Jul – 5 Jul	65	1.436
Makhtali, location P9	4 Jul – 5 Jul	65	1.436
Makhtali, location P15	24 Jun – 25 Jun	86	1.436
Birlik, location P3	1 Aug – 2 Aug	33	1.2
Birlik, location P12	2 Aug – 3 Aug	65	1.2
Karaoi, location P3	28 May – 5 Jun	92	1.046
Karaoi, location P6	28 May – 5 Jun	92	1.046

Table 7. Second Irrigation applications at modelled locations within the project area, 2001

Location	Dates	Irrigation Depth (mm)	Water Salinity (g/l)
Makhtali, location P3	18 Aug – 20 Aug	70	1.214
Makhtali, location P9	8 Aug – 20 Aug	70	1.214
Makhtali, location P15	-	-	-
Birlik, location P3	-	-	-
Birlik, location P12	-	-	-
Karaoi, location P3	15 Jul – 18 Jul	43	1.128
Karaoi, location P6	15 Jul – 18 Jul	43	1.128

Table 8. Critical pressure head values used in WAVE modelling

Parameter	Description	Value
h_0	The pressure head below which the plant roots start to extract water from the soil	-10
h_1	The pressure head below which the roots start to extract water optimally from the soil	-46
h_2	The pressure head below which the roots can no longer extract water optimally	-500
h_3	The pressure dead at which the water uptake by plant roots ceases	-16000

The top boundary condition is determined by the allowable minimum pressure head at the soil surface and the maximum ponding depth. A maximum ponding depth of 10 mm has been used. When the maximum is reached, the excess water runs off. The lower boundary condition was specified by the observed groundwater level, for calibration purposes.

Solute Transport Parameters

There are several parameters that need to be specified for use in the solute transport module. Table 9 lists the model parameters used along with the values adopted.

The a_k, b_k and f values are based on the values recommended in the WAVE reference manual (Vanclooster *et al.*, 1994). Most other values are based on field data. f, and α are required when the mobile/immobile concept is considered.

C_YIELD Parameters

The yield response to water and salinity functions in the C_YIELD programme require the following data in addition to the data collected and used in the WAVE_MS model:

- Crop yield response factors required by Rao function (Rao *et al.*, 1988) to model crop yield response to water. In this research the C_YIELD model was set-up using crop yield response factors for each stage of growth published in Doorenbos and Kassam (1979). The values used for cotton were 0.20, 0.5, 0.45 and 0.25 for vegetative, flowering, yield formation and ripening growth stages respectively.
- Soil salinity threshold value, which is required to model yield response to salinity. For cotton, the value of the threshold salinity adopted was 7.7 dS/m, (Allen *et al.*, 1998).
- The rate, at which relative crop yield declines with increasing salinity, which is also required for salinity modelling. The model was set-up with value of 5.2 (Allen *et al.*, 1998).

WAVE_MS Model Calibration

The WAVE_MS model was set-up and calibrated using the field data from October 2000 to October 2002. Calibration was based on simulation of soil moisture content, and soil moisture tension (which was available for 2002 only), and soil salinity.

Methods of Establishing Simulation Quality

To assess the simulation quality and subsequently the calibrated model performance, some statistical tests (Loague and Green, 1991; Vazquez and Feyen, 2003; Xevi *et al.*, 1996; Legates and McCabe, 1999) were used. The statistical measures used in evaluating simulation quality, are Mean Absolute Error (MAE), Relative Root Mean Square Error $(RRMSE)$, Coefficient of Efficiency (EF_2), Coefficient of Determination (CD), Coefficient of Residual Mass (CRM) and Pearson type Goodness of fit index (R^2).

Fitting Soil Moisture Retention Curves

Soil moisture content and soil moisture tension relationships in the form of soil moisture retention curves, were developed at each of the pilot sites from the observed field data. These curves were conditioned by observed data of soil moisture tension and volumetric soil moisture contents at saturation and at wilting point at different depths at each pilot area. These data are summarised in Table 10 below. The objective has been to develop soil moisture retention curves that match the observed soil moisture data and reflect the field situation at each site. Soil moisture retention curves were fitted

Table 9. Solute transport parameters used in WAVE modelling

Parameter	Description	Value
Dif	Chemical diffusion coefficient of the considered solute in pure water $(mm^2\ day^{-1})$	0.01
a_k	Empirical constant used in the calculation of the effective diffusion coefficient	0.075
b_k	Empirical constant used in the calculation of the effective diffusion coefficient	10
f	Fraction of the adsorption sites situated in contact with the region	1
K_d	Distribution coefficient $(Litres\ Kg^{-1})$	5
λ	The soil solute dispersivity (mm)	77
α	Empirical transfer coefficient (day^{-1})	0.01

through a trial and error process of adjusting the α, n, and m parameters of the van Genuchten equation.

The soil moisture content and soil moisture tension data recorded at different depths for each of the pilot areas are plotted in Figure 2 along with the fitted retention curves. The parameters for the fitted retention curves are given in Table 11. These parameter values were used as initial values in the WAVE_MS model calibration.

It is clear from Figure 3 that the quality of much of the soil moisture and soil moisture tension data is poor, and that it lacks consistency. The observed data should lie on a well defined relationship, but generally do not. The data are also available only for a relatively narrow range, with no data close to either saturation or wilting points. It is understood that equipment was late in arriving on site, and that this led to difficulties in calibrating equipment and resulted in very low and very high soil moisture contents being missed. The fitted soil moisture retention curves were adapted to pass through the available data at each site as well as possible. There are problems in the observed soil moisture tension data at many depths as there is a wide scatter between observed soil moisture tension data at the same moisture content.

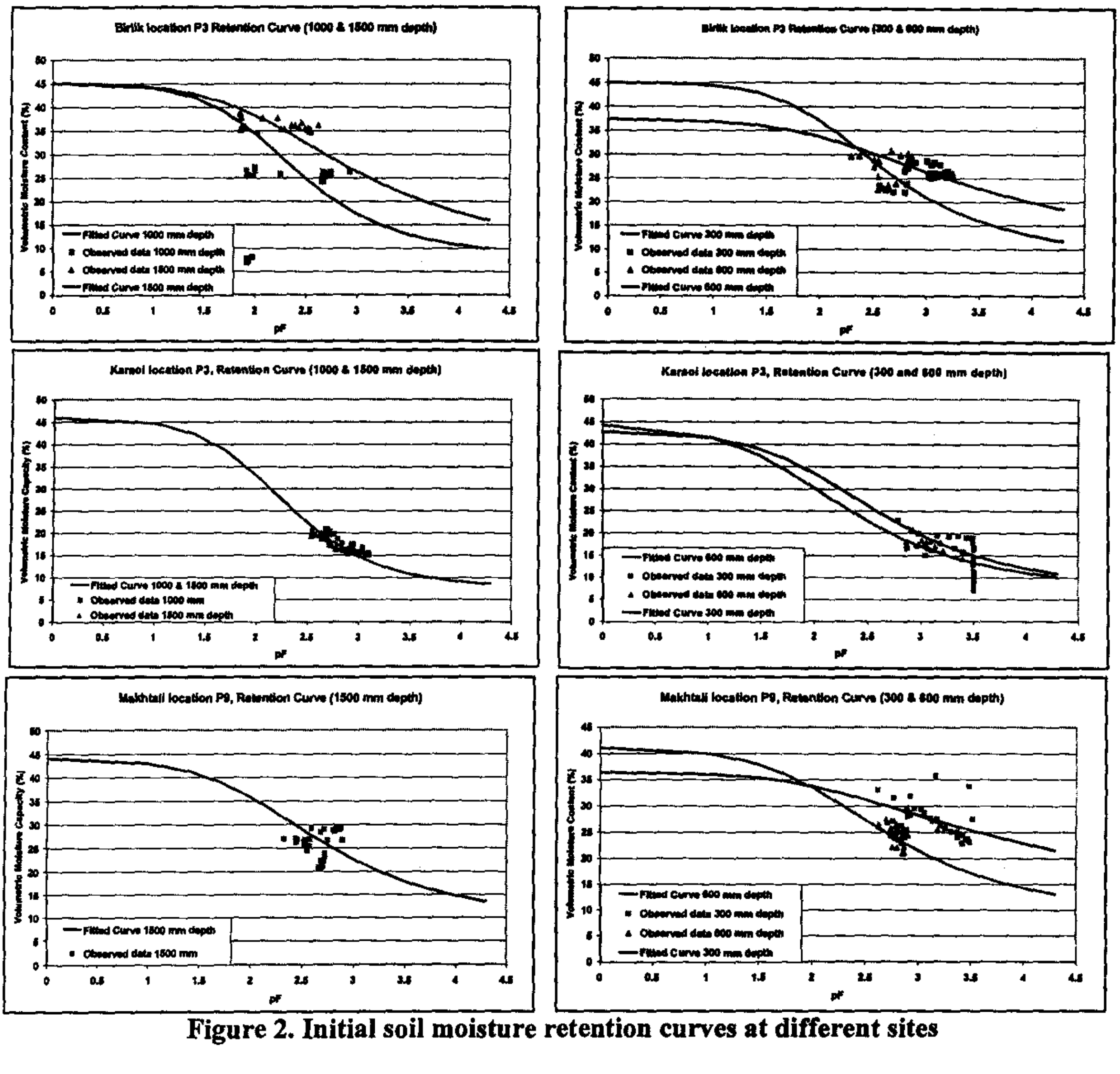


Figure 2. Initial soil moisture retention curves at different sites

Table 10. Saturation θ_s and residual soil moisture contents θ_r at different soil depths

Soil depth (cm)	Makhtali		Birlik		Karaoi	
	θ_s	θ_r	θ_s	θ_r	θ_s	θ_r
0 – 20	46.2	9.3	47.2	8.4	46.5	7.7
21 – 40	36.5	9.3	37.5	8.4	43.0	7.7
41 – 60	41.3	9.3	45.0	8.4	44.6	7.7
61 – 80	42.9	9.3	46.7	8.4	47.2	7.7
81 – 100	44.4	9.3	46.8	8.4	47.2	7.7
101 – 150	44.6	9.3	46.6	8.4	46.8	7.7
151 – 200	44.8	9.3	45.0	8.4	45.5	7.7
201 – 250	45.0	9.3	43.6	8.4	44.7	7.7
251 – 300	44.1	9.3	43.3	8.4	44.9	7.7

Table 11. Fitted soil moisture retention curve parameters at different soil depths

Pilot Area	Depth, mm	Parameter		
		α	n	M
Makhtali, location P9	300	0.01	1	0.15
	600	0.01	1	0.4
	1500	0.01	1	0.4
Birlik, location P3	300	0.01	1	0.2
	600	0.01	1.3	0.35
	1000	0.01	1.2	0.5
	1500	0.01	1	0.3
Karaoi, location P6	300	0.01	1	0.5
	600	0.02	1	0.5
	1000	0.01	1.2	0.6
	1500	0.01	1.2	0.6

Soil Moisture Content Calibration

Following preliminary fitting of the soil moisture retention curve characteristics to the observed data, calibration of these parameters was carried out with WAVE_MS through matching observed and simulated soil moisture content. Using the parameter values presented in Table 11. large differences were found between observed and simulated soil moisture content at some depths especially in the top soil layers where simulated soil moisture content was often higher than observed. However, simulated soil moisture contents fit well with those observed at many depths at the locations under consideration, and only small differences were found at some other depths with patterns of changing soil moisture being reasonably simulated.

There are some issues related to data quality. For example, in early March following leaching, soil moisture content should be close to saturation. At Makhtali and Karaoi observed soil moisture content in this period was around 30% at Makhtali and 25% and Karaoi. The problem is thought most likely to be associated with sampling errors, particularly during 2002 data collection programme. In 2002 soil moisture was measured using automatic soil monitoring equipment and gravimetric laboratory analysis at a large number of sites in each pilot area. However, problems associated with the data obtained from both the soil monitoring equipment and from gravimetric soil moisture analysis were reported in the evaluation of the soil monitoring equipment results (Mott MacDonald, 2003b). Sample sizes for gravimetric measurements were smaller than standard, and calibration of some of the automatic equipment may have been based on incorrect gravimetric data.

Recognising that there have potentially been errors in soil moisture content measurement, and the soil moisture tension measurements used to derive the moisture retention curves, the soil moisture retention parameters were adjusted to improve the WAVE_MS model performance in simulating soil moisture. A series of model runs was carried out for the two years of observed soil moisture content data. In these runs the values of parameters used in the soil moisture retention and hydraulic conductivity equations (θ_s, θ_r, α, m, and n) were modified in a trial and error process to determine values that permitted reasonable simulation of the observed soil moisture data. In these runs observed groundwater levels were used as the lower boundary condition for the model.

By modifying the soil moisture retention parameters described above, the simulated soil moisture content could match quite well with that observed in the four soil layers examined at most sites in the project area. Figure 3 is typical examples and show good agreement between observed and simulated soil moisture for the two years of observations available.

Generally, the modified WAVE model has satisfactorily simulated soil moisture content at all locations under consideration. The statistical indices show a reasonable model performance in predicting soil moisture content. R^2 ranged between 0.36 and 0.75 in most depths within the areas under consideration. In the calibration of soil moisture content using ECOMAG model which describes the processes of soil infiltration, evapotranspiration, soil water content, surface and subsurface flow and groundwater flow, Motovilov *et al.* (1999) considered that simulation results are considered to be good for values of $R^2 \geq 0.75$, and satisfactory for R^2 between 0.36 and 0.75. In addition, the values of the coefficient of efficiency EF_2 and the coefficient of determination CD, ranged between -0.08 and 0.66; 0.12 and 0.98 respectively which are reasonably close the optimum value of 1.0 at most sites. The coefficient of residual mass CRM show that the model predicted soil moisture content with minimum overestimation or underestimation in most sites.

The calibrated values of the soil moisture retention parameters for each of the sites modelled are summarised in Table 12. The calibrated soil moisture retention parameters $(\theta_s, \theta_r, \alpha, m, and\ n)$, result in re-defined soil moisture retention curves. These are shown in Figure 4. With the exception of the surface layers at Makhtali, the curves still represent the data reasonably well. It is known that a high water table at Birlik certainly caused problems with some of the automatic equipment in 2002, but the reason for the large discrepancy in the 300 mm and 600 mm depth layers at Makhtali are not clear. There are clearly discrepancies between the soil moisture content and soil moisture tension data at this site.

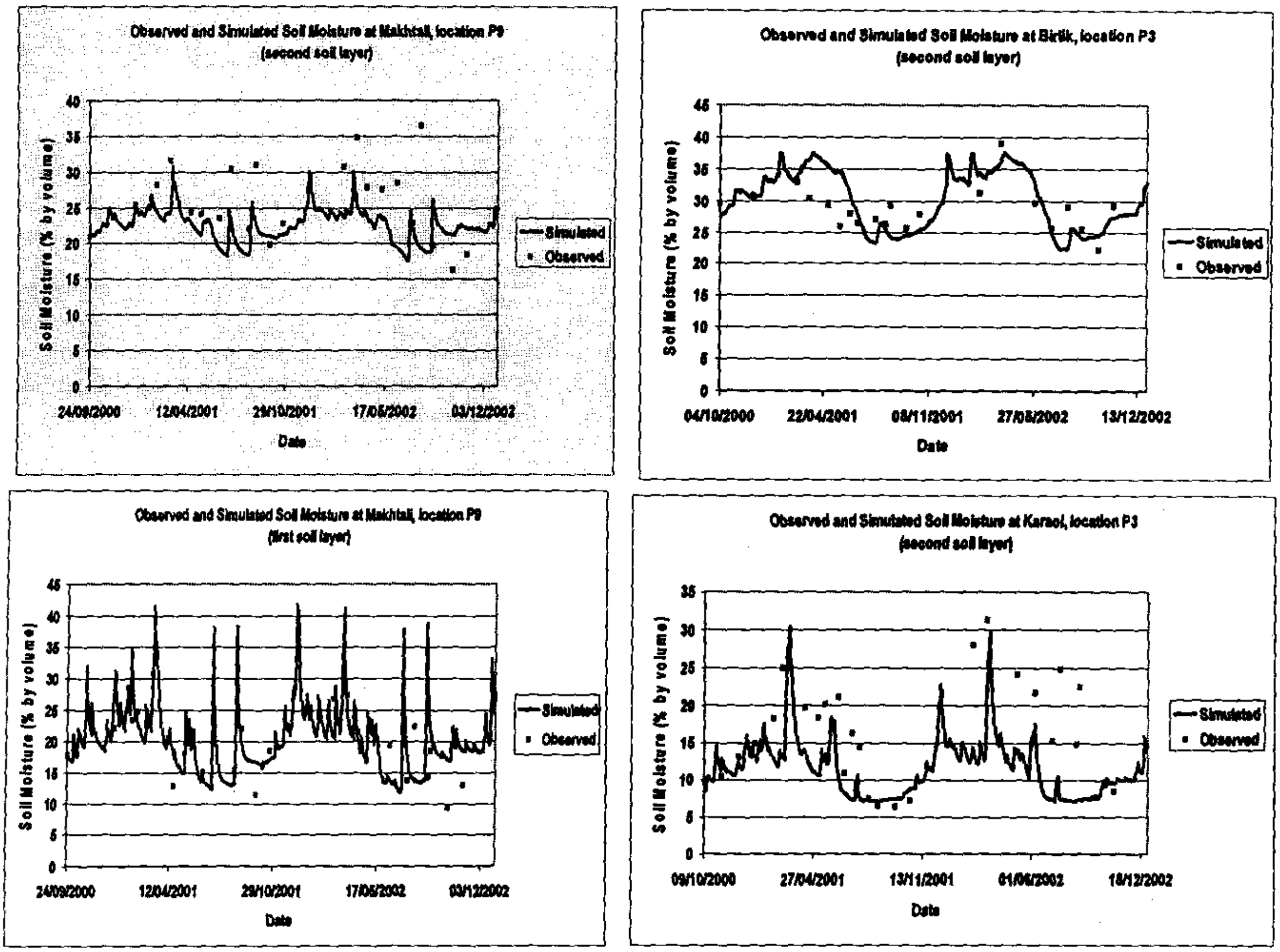


Figure 3. Simulated soil moisture at different sites

Table 12. Final Calibration Parameters

Pilot Area	Location	Layer	Depth	MRC Parameters				
				θ_r	θ_s	α	n	m
Makhtali	P3	1	0-200	9	46	0.03	1.5	0.4
		2	200-400	9	37	0.02	1.3	0.3
		3	400-600	9	41	0.02	1.2	0.4
		4	600-8000	9	44	0.01	0.8	0.3
Makhtali	P9	1	0-200	9	46	0.03	1.4	0.4
		2	200-400	9	37	0.02	1.3	0.3
		3	400-600	9	41	0.02	1.2	0.4
		4	600-8000	9	44	0.01	1.0	0.35
Makhtali	P15	1	0-200	9	44	0.03	1.3	0.4
		2	200-400	9	46	0.03	1.4	0.3
		3	400-600	9	37	0.03	1.4	0.4
		4	600-8000	9	41	0.01	0.8	0.3
Karaoi	P3	1	0-200	7	44	0.05	1.6	0.6
		2	200-400	7	43	0.04	1.5	0.5
		3	400-600	7	45	0.05	1.4	0.5
		4	600-8000	7	46	0.01	1.1	0.4
Karaoi	P6	1	0-200	7	47	0.06	1.6	0.5
		2	200-400	7	43	0.04	1.5	0.5
		3	400-600	7	45	0.05	1.4	0.5
		4	600-8000	7	46	0.01	1.1	0.4
Birlik	P3	1	0-200	8	47	0.01	1.0	0.4
		2	200-400	8	38	0.004	1.0	0.4
		3	400-600	8	45	0.01	1.0	0.4
		4	600-8000	8	45	0.004	1.0	0.4
Birlik	P12	1	0-200	8	47	0.02	1.2	0.4
		2	200-400	8	38	0.01	0.8	0.4
		3	400-600	8	45	0.02	1.2	0.4
		4	600-8000	8	45	0.01	0.7	0.4

Soil Moisture Tension

Following soil moisture calibration, simulated soil moisture tension was compared with observed soil tension data where it was possible to do so. Time series of soil moisture tension data are available at different depths at Makhtali location P9, and at Karaoi location P3. The observed soil moisture tension data collected from the central site of Birlik were used in the calibration of Birlik location P3 at which there were no observed data available. Figure 5 shows the soil moisture retention curves at different sites and depths.

At Birlik, for all depths, there is reasonable agreement between observed and simulated soil moisture tension in terms of magnitude, and the results are as good as could be expected in the light of the moisture retention curves given. The effect of wetting and drying due to water application and root water uptake was not clear even in the top layer. In other words, the observed soil moisture tension data were less sensitive to irrigation application as compared with the simulated soil moisture tension. It is unfortunate that no data were available for the leaching period. No reliable tension data were available for the Birlik pilot site at locations P3 and P12. Moreover, according to the Working Paper No. 30 (Mott MacDonald, 2004), the monitoring equipment were not working efficiently particularly in Birlik due to poor drainage and water logging.

In Karaoi, the water table is lower than at Makhtali and Birlik, and this is clearly reflected in the relatively higher soil moisture tensions observed in the lower soil layers. The impact of two water applications on the soil moisture tension data is apparent in the upper soil layer. Perhaps the observed soil moisture tension data in this pilot area are more reliable than in other areas. The simulated data fitted the observed reasonably well. The simulated soil moisture tension matches well with the observed in the three depths under consideration, and especially in the bottom layer at a depth of 1500 mm.

In Makhtali, location P9, there has been clear influence of the second irrigation application on the observed soil moisture tension data in the upper soil layer. However, it is apparent that the first irrigation was not effective, possibly because of the amount applied was too small. The results show an under prediction of the observed soil tension values at 300 mm depth.

However, the simulated soil moisture tension matches well with the observed in the other depths, especially in the bottom layer at 1500 mm depth. The under prediction of the observed soil moisture tension data at 300 mm depth could be related to the chosen parameters in the soil moisture content calibration, but in view of the data problems that were known to exist, a further iteration of calibration was not carried out.

Soil Salinity

The soil salinity calibration was divided into two stages, in the first stage, a series of model sensitivity runs were carried out for the period 2001-2025. In these runs the sensitivity of salinity build up over the simulation period to the solute distribution constant (K_d) was tested. This parameter is required in the mobile/immobile concept. In the second stage, soil salinity calibration was carried out by running the model for two years using observed soil salinity data at different depths from the pilot areas under consideration. The objective was to match simulated and observed soil salinity by changing the distribution coefficient K_d using a trial and error process.

The sensitivity of the solute distribution constant (K_d) was tested for values of 0.5, 1.0, 2.0, 3.0, and 5.0. Figure 6 shows the influence of K_d on salinity build up, assuming Karaoi soil characteristics. This parameter has a great effect on salinity build up by controlling the mass of solutes adsorbed on the soil complex. The higher the value of K_d, the greater the mass of solutes adsorbed on the soil particles in the top three layers. As a result the simulated leaching would be less effective than with lower values of K_d. In the bottom layer (600-8000 mm depth), there was slight increase in soil salinity with increasing the K_d value due to the continuous accumulation of salts in this layer from the water table.

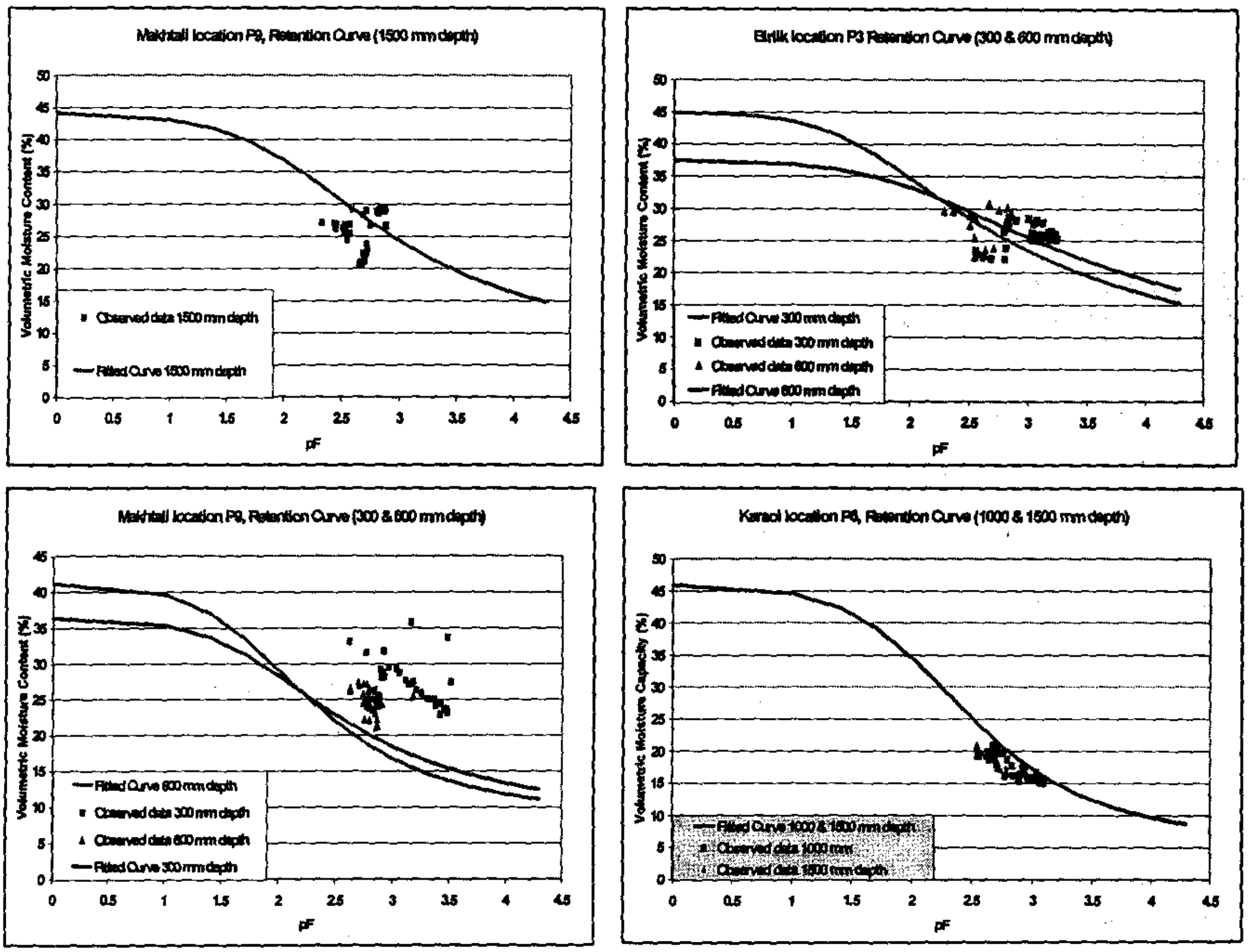


Figure 4. Fitted soil moisture retention curves at different sites

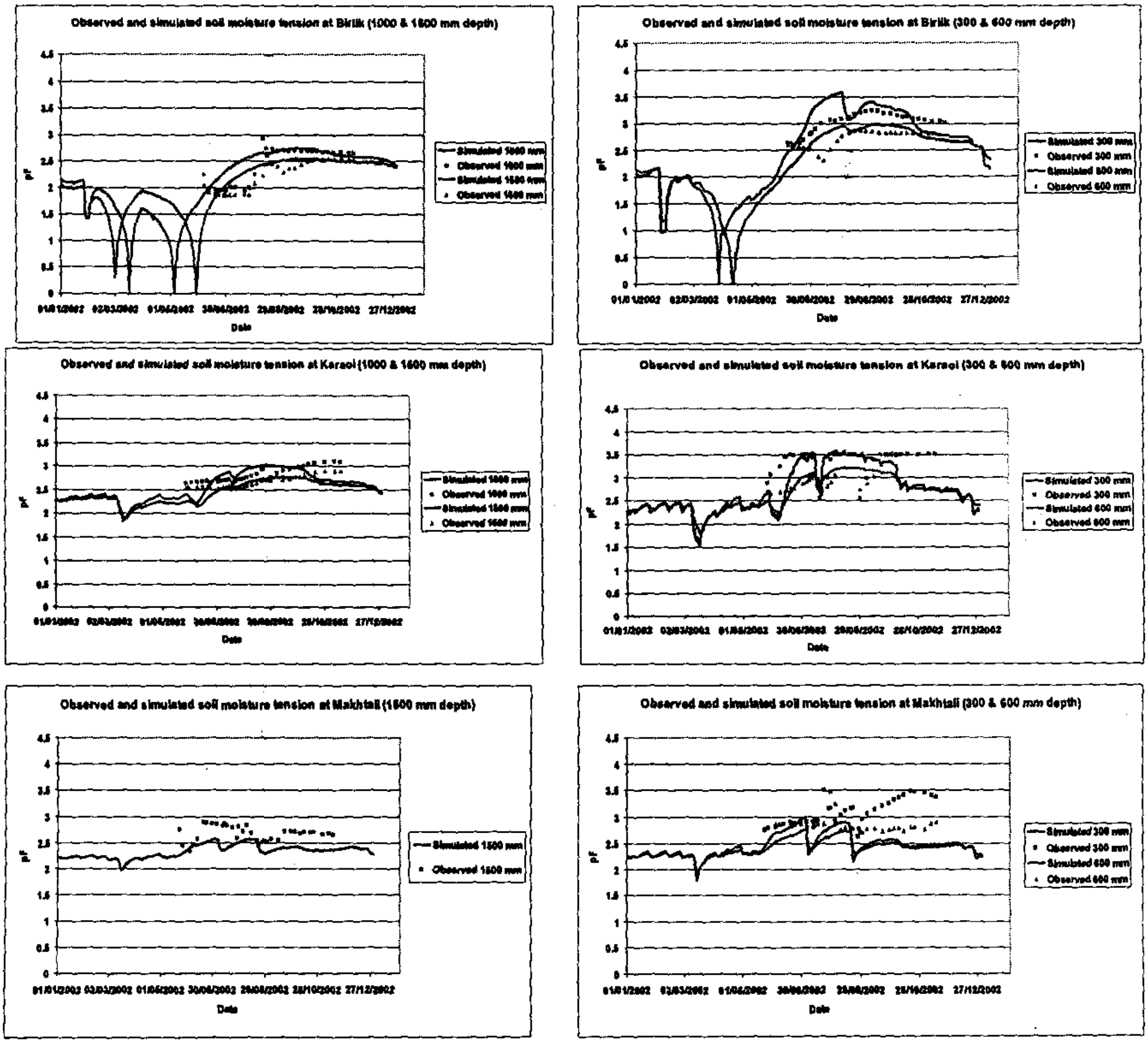


Figure 5. Soil moisture tension at different sites

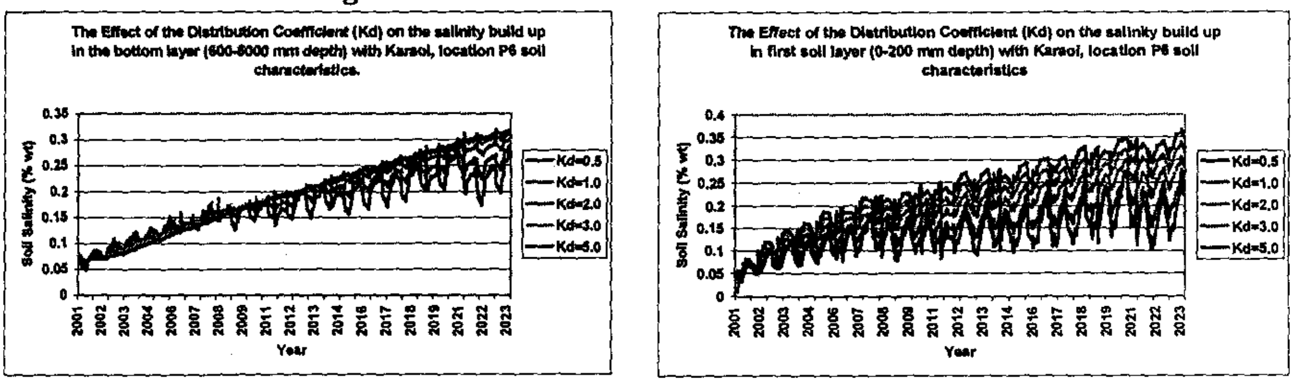


Figure 6. Salinity Build up at Karaoi, location P6

With high values of K_d lower crop yields are simulated than with low values of K_d, because a higher mass of solutes remains in the soil root zone. According to these results, it is very important to determine a value of K_d that permits reasonable salinity simulation, and reflects the observed salinity level in the project area accurately. The difficulty is that, only a few soil salinity observations are available and are insufficient to permit confident definition of K_d. A K_d value of 1.0 was chosen as being a representative value for the whole area, except for Birlik, where a value of 2.0 has been used.

Establishment of efficient irrigation and drainage practice become easier if the most effective variables or parameters influencing response are identified. Another series of model sensitivity runs were carried out for the period 2001-2025. In these runs the sensitivity of irrigation and drainage management variables such as irrigation water application, irrigation water quality, leaching amount and drainage rate were tested to examine their effect on salinity build up over the simulation period. These variables are considered to be the most important factors for the establishment of efficient irrigation and drainage management practices. Sensitive variables are those that have a significant effect on salinity build up. Variables that are identified as significantly sensitive need to be treated more carefully in the construction of the scenarios required for the establishment of efficient irrigation and drainage water management. The sensitivity analysis was performed by varying each of the above mentioned variables while others were kept constant.

The sensitivity of the irrigation water application was tested in the range of 100 - 400 mm in increment of 100 mm in the rate of 100 mm each 30 days while leaching amount, irrigation water salinity and annual drainage were kept constant at 300 mm, 1000 mg/l and 200 mm, respectively. Figure 7 shows the salinity build up in the rootzone under different irrigation water applications. It is clear that, irrigation water application has a great influence on simulated salinity. Soil salinity increased by 49% as irrigation water application increased from 100 to 400 mm. The simulation results show that, with irrigation water salinity of 1000 mg/l, large irrigation application cause more salt accumulation in the rootzone even with 300 mm leaching. Irrigation water quality also has a significant impact on the salinity build up in the rootzone. The lower the quality of the irrigation water, the higher the salt loads in the rootzone (Figure 7). With large irrigation water applications of low quality, keeping salinity levels in the rootzone under control can only be achieved with adequate drainage rate (Figure 7). In other words, salinity levels in the rootzone cannot be kept constant unless the amount of salts added to the profile through irrigation water equals the amount of salts leached from the profile by drainage.

Under low salinity conditions such as those of Karaoi, location P6, increasing the leaching amount from 100 to 300 mm has only a small effect on the salinity build up in the rootzone, which remains similar using 100, 200 and 300 mm of leaching over the simulation period (Figure 7). Soil salinity slightly decreases with increasing leaching. Accordingly, this variable can be ignored under such conditions. Key parameters in this case are irrigation water application and drainage rate.

Simulating salinity build up in the WAVE_MS model requires calibration of the distribution coefficient K_d, and to do this a high frequency of data on observed salinity are required throughout the calibration period. The fewer the samples the less well constrained is the calibration. Unfortunately, the available soil salinity data for the WRMLIP project are poor in number and quality. Because of this, great difficulty was experienced in trying to produce matches between the simulated and observed data. In the calibration processes it was not possible to reach a reasonable agreement between observed and simulated soil salinity. The restrictions in getting a good model performance in simulating soil salinity are the number and quality of the field data. The soil salinity data collected during fieldwork were very few and had some shortcomings. These shortcomings could be related to sampling errors and heterogeneity.

Figure 8 shows the simulated and observed soil salinity in selected pilot areas. In addition to the graphical presentation, the high variation between observed and simulated soil salinity values is indicated by low values of R^2, EF_2 and relatively high values of CD. There are, however, few data points and while clearly the simulation of the order of magnitude of salinity is satisfactory, the data do not permit detection of increasing trends or seasonal variability. In addition, the reason for differences at some locations is thought be related to laboratory error. However, the statistics indices appear better at Karaoi, location P3 than at other sites.

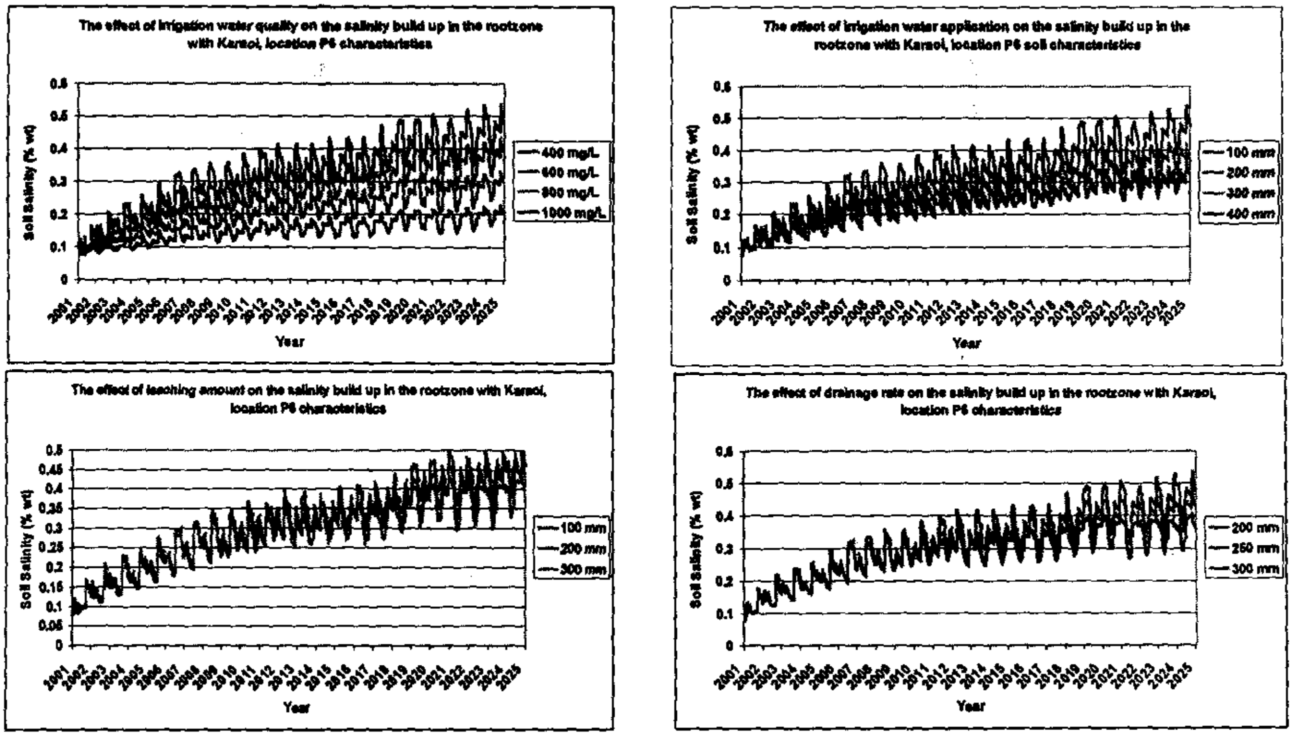


Figure 7. Impact of irrigation water application, irrigation water quality, drainage rate and leaching amount on the salinity build up

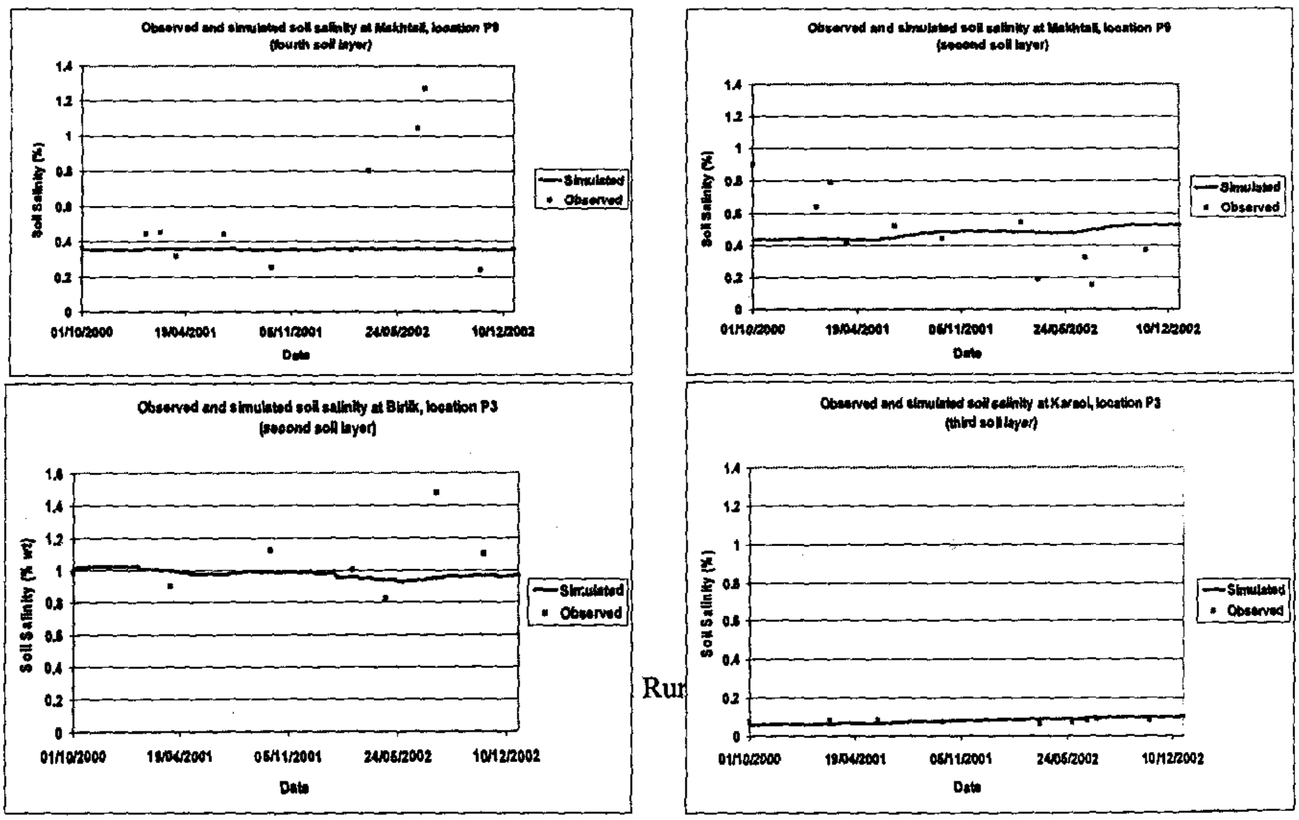


Figure 8. Makhtali site P9 Calibration Run - Soil salinity (200-400 mm depth)

Evaluation of the current irrigation and drainage management practices

The modified WAVE model has been applied to evaluate current irrigation and drainage practices in the three pilot areas in the WRMLIP project area. The simulations have been driven by available historic rainfall and potential evapotranspiration data. Only13 years of historic data were available and the historic sequence was simply repeated to provide a 25 year simulation period. This was considered to be sufficiently long to detect long-term salinity impacts.

In the simulation of the current irrigation and drainage practices, the actual irrigation time, amounts applied, and the present level of soil salinity at each location, as recorded in 2002 (Mott MacDonald, 2003a), were used as model inputs. The objective was to assess the effect of the water application, leaching amount and drainage rates on salinity build up, crop transpiration and subsequently on crop yield.

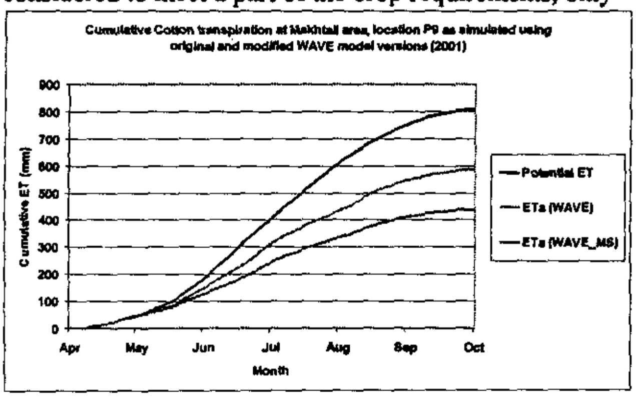
Crop water requirements

It is clear that since the 1990's, water supplies to the project area have been significantly lower than required for sustainable crop production. Reasonable crop yield cannot be achieved without adequate irrigation. Reductions in cotton yield in the region are attributed to inadequacy of irrigation, in addition to other factors such as soil salinity and waterlogging. Mott MacDonald (2003c) reported that soil water stress is the dominant factor effecting crop yield; the effect of salinity and water logging is significantly lower at the present time at most locations.

In all pilot areas in 2001, the total water applications (both irrigation and rainfall but excluding leaching application) were very low and could meet only 13%-17%, 20%-26% and 26% of the total crop water requirements in Birlik, Makhtali and Karaoi areas respectively. Even if the leaching amounts are considered to meet a part of the crop requirements, only 35%-47%, 32%-37% and 44% of the seasonal water requirements would have been met. Under the current conditions, crops in most locations have part of their water requirements met by root water uptake from the shallow watertable. Simulation results indicate that the amount of water supplied by the upward flux from the shallow watertable during the growing season in 2001 met 10%-35% of the total crop water requirements, depending on location.

Figure 9 shows cumulative potential and simulated actual crop evapotranspiration at location P3 in the Karaoi pilot area in 2001. The simulated actual crop evapotranspiration during the growing season from mid-April to mid-October was about 473 *mm* compared with 809 *mm* potential evapotranspiration. About 35% of the total crop water requirement (60% of the actual water use) at this location was met through the upward flux from the water table. Only 67% of the potential crop yield was achieved. In terms of individual growth stages, there was a reduction in the crop water requirements by 7%, 26%, 50% and 51% for vegetative, flowering, yield formation and ripening stages respectively. This resulted in yield reductions of 2%, 12%, 25% and 33% for the same growth stages respectively. As the soil salinity in Karaoi area is still under the threshold value for salinity stress, crop transpiration simulated using original and WAVE_MS model versions was the same and the reduction in crop transpiration and yield was due to only the effect of soil water stress.

Cotton plants in the Makhtali and Birlik areas are under the effects of both soil water stress and salinity stress. As a result, crop transpiration is lower than in Karaoi. For example, at location P9 in the Makhtali area, the simulated actual crop transpiration was about 440 *mm*; meeting only 54% of the total crop water requirements (Figure 9). 234 *mm* (53%) of the actual crop water use was provided by upward flux from the



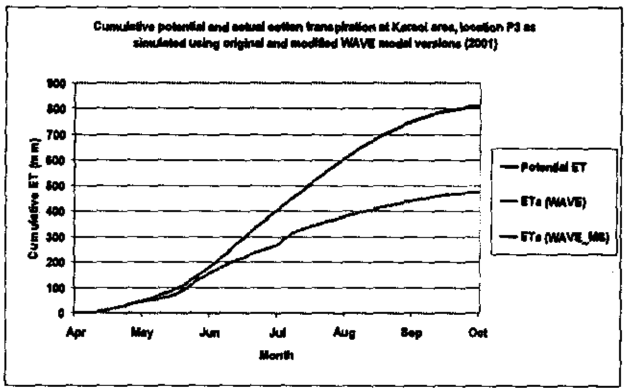


Figure 9. Simulated potential and actual cotton transpiration at Karaoi and Makhtali areas

water table. The simulated crop yield was 54% of potential. As soil salinity in the Birlik and Makhtali areas is above the salt-tolerance threshold value, crop transpiration simulated using original WAVE model was higher than that simulated using the WAVE_MS model because the original version doesn't take into account the effect of salinity stress on transpiration.

Soil Salinity

According to the salinity data presented in the data collection reports(Mott MacDonald, 2003a), soil salinity in the Birlik and Makhtali areas is above the salt-tolerance threshold value of 7.7 dS/m for cotton (0.47% of dry soil weight). However, it is below threshold in the Karaoi area. The WAVE_MS model has been used to predict the soil salinity over a 25-year (notionally 2001 – 2025) simulation period. Although, water applications have been low in recent years, adequate supply would have led to a worse salinity problem than now exists in some locations in view of the poor drainage that has existed. The simulation results indicate that, rootzone salinity at Makhtali location P9 would rise by about 51% by the year 2025 (Figure 10) if recent irrigation and drainage practices were to continue. This would result in crop yield reduction due to salinity stress of about 44%, in addition to the reduction due to water stress. Figure 10 shows that soil salinity in other soil layers follows the same trend as salinity in the rootzone. The rate of salt accumulation in all layers is relatively slow. Although there was no drainage, the water table in the area falls from 4.5 m to be lower than 7.5 m over most of the simulation period as a result of the water uptake by the plant roots.

In the Birlik area, a solute distribution constant (K_d) value of 2.0 was used in the simulation, which is higher than the K_d values, used for other locations. A K_d value of 2.0 means that the leaching process is less effective than if the value was 1.0. However, root zone salinity in Birlik increased from 0.6% to only 0.71% over the simulation period to reduce the yield by about 33% in addition to the reduction due to water stress. Figure 11 shows salinity build up at location P3 in the Birlik area. As a result of the higher water table in this area, salinity build up rate in the bottom soil layers is high. However, salinity build up in other layers is relatively slow. This is as a result of the continuous leaching of salts each year and the fact that salt loadings are relatively low because of inadequate irrigation. The threshold value given in the following figures is the salinity at which crop yield begins to be affected.

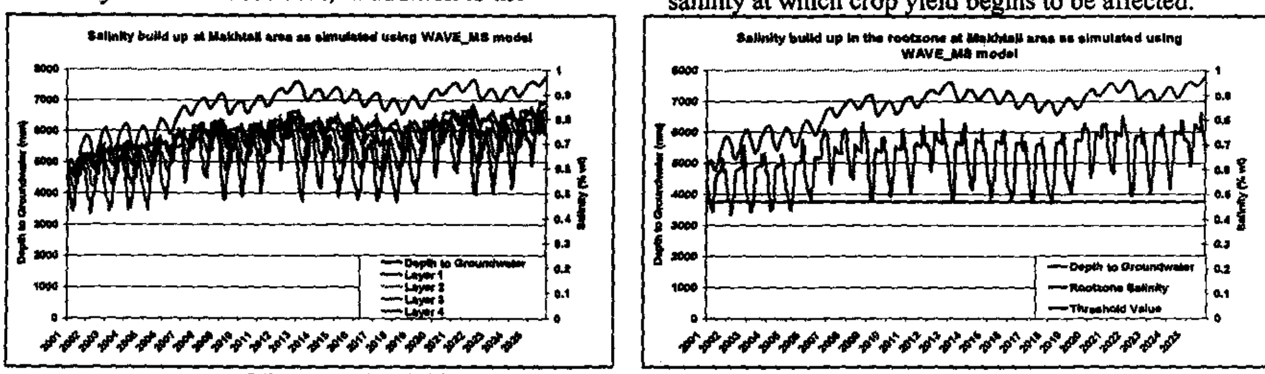


Figure 10. Salinity build up at Makhtali area, location P9

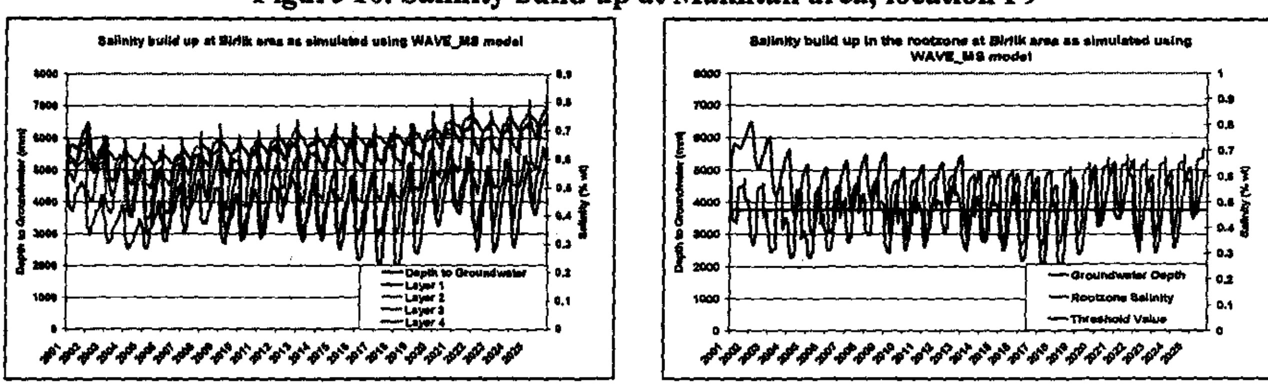


Figure 11. Salinity build up at Birlik area, location P3

In the Karaoi area, soil salinity remained under the critical value over the entire simulation period. The rate of salt accumulation is similar in all soil layers. The amount of salts added to the soil profile is similar to that observed at Makhtali. Over the 25 year simulation, 3.7 Kg/m^2 of salt is added to the soil profile compared with 4.0 Kg/m^2 and 3.0 Kg/m^2 added to the soil profile at Makhtali and Birlik areas respectively. Figure 12 shows salinity build up in the root zone at Karaoi location P3. At Karaoi soil salinity started from a lower base, but there could eventually be a salinity problem.

As there was no salinity or waterlogging effects in the Karaoi area, the reduction in crop yield over the simulation period is related to the water stress only. The fluctuations in the depth to groundwater from one year to another are related to the variation in the seasonal rainfall and crop transpiration between years.

Crop yield

Long-term historical data on crop yield are not available to permit evaluation of the impact of the current irrigation and drainage management practices.

The WAVE_MS model has been used to assess the combined effect of water supply, soil salinity, and waterlogging on crop yield.

Two years (2001 and 2002) of observed cotton yields in the pilot areas expressed as a percent of potential maximum yield (taken as 3.9 $tonne/ha$) were compared with simulated yields using the WAVE_MS model. Results are shown in Table 13. There is an overestimation of the cotton yield by 14% at Makhtali and Karaoi in 2001. However, a good match with the observed yields was obtained at Birlik in both years. The model underestimates cotton yield by about 21% and 9% in Makhtali and Karaoi in 2002, respectively. The overestimation of cotton yield in Makhtali and Karaoi in 2001 can be related to factors such as plant diseases and nutrients deficiency, which caused yield reduction in addition to the effects of water stress and salinity. The model has only considered water and salinity stress. In 2002 the yield simulation at Birlik and Karaoi was reasonably good, but the very high yield reported for Makhtali was not reproduced. It is thought likely that there has been some anomaly in this data.

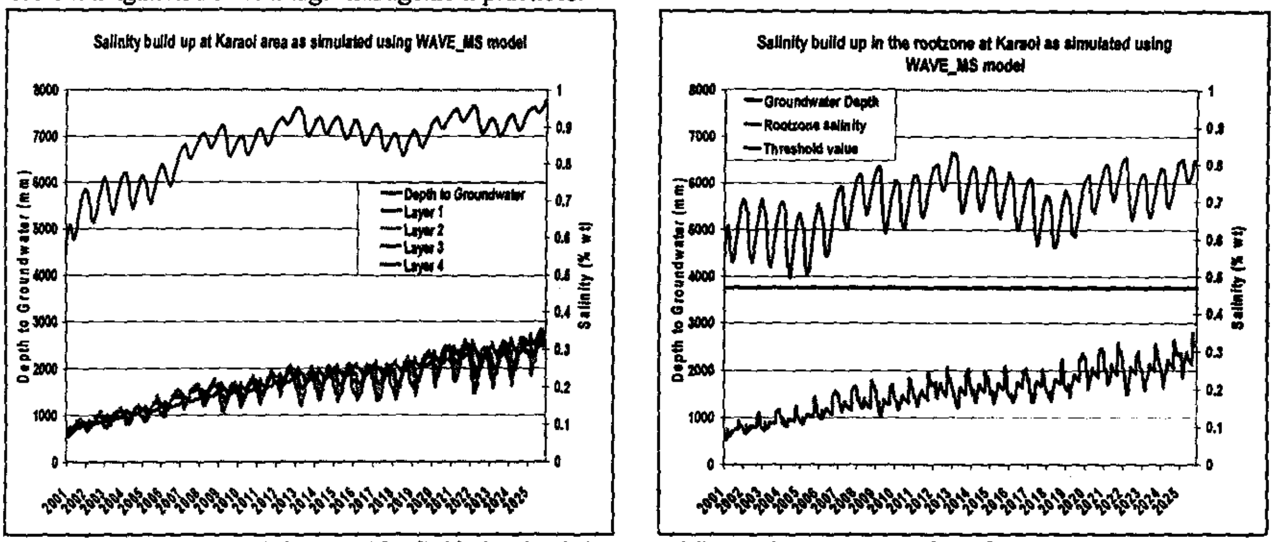


Figure 12. Salinity build up at Karaoi area, location P3

Table 13. Average observed and simulated cotton Yield in pilot areas, (%)

Pilot Area	Average Yield (%)	
	Observed	Simulated
	2001	
Makhtali	40	54
Birlik	48	46
Karaoi	53	67
	2002	
Makhtali	75	54
Birlik	53	51
Karaoi	78	69

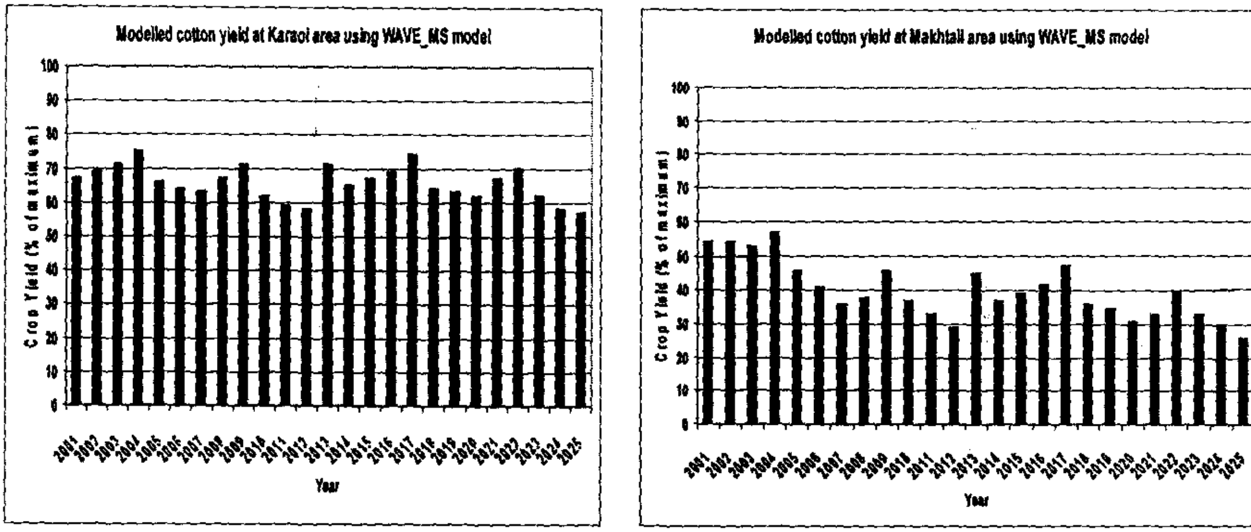


Figure 13. Cotton yield at Karaoi and Makhtali areas as simulated using modified WAVE_MS model

Cotton yield was simulated using the WAVE_MS model for a period of 25 years (2001-2025) to investigate long-term water stress and salinity effects on cotton yield, assuming that recent irrigation and drainage practices continued. In the Makhtali and Birlik areas, cotton yield is under the effect of both soil salinity and soil water stress. As a result, the average reduction in crop yield was about 50% in the year 2002 in both areas. Average yield in these two areas decreased sharply from the initial values of about 54% and 45% in the first year of simulation. Figure 13 shows that by the year 2025, with continuation of recent irrigation and drainage practices, 70% of the potential crop yield would be lost from the Makhtali area. Increasing soil salinity is the cause of continued decline in yields.

Since soil salinity in the Karaoi area remains below the threshold value for salinity stress throughout the simulation period, reduction in cotton yield is attributed to soil water stress only. The reduction in yield would remain around 30%-40% until the salinity exceeds the threshold value (Figure 13). At that time the reduction in yield will increase as the salinity increases. The combined effect of water stress and salinity is more harmful to crop yield than the individual effect of water stress. The slight fluctuations in crop yield from one year to another are related to variations in the seasonal rainfall between years.

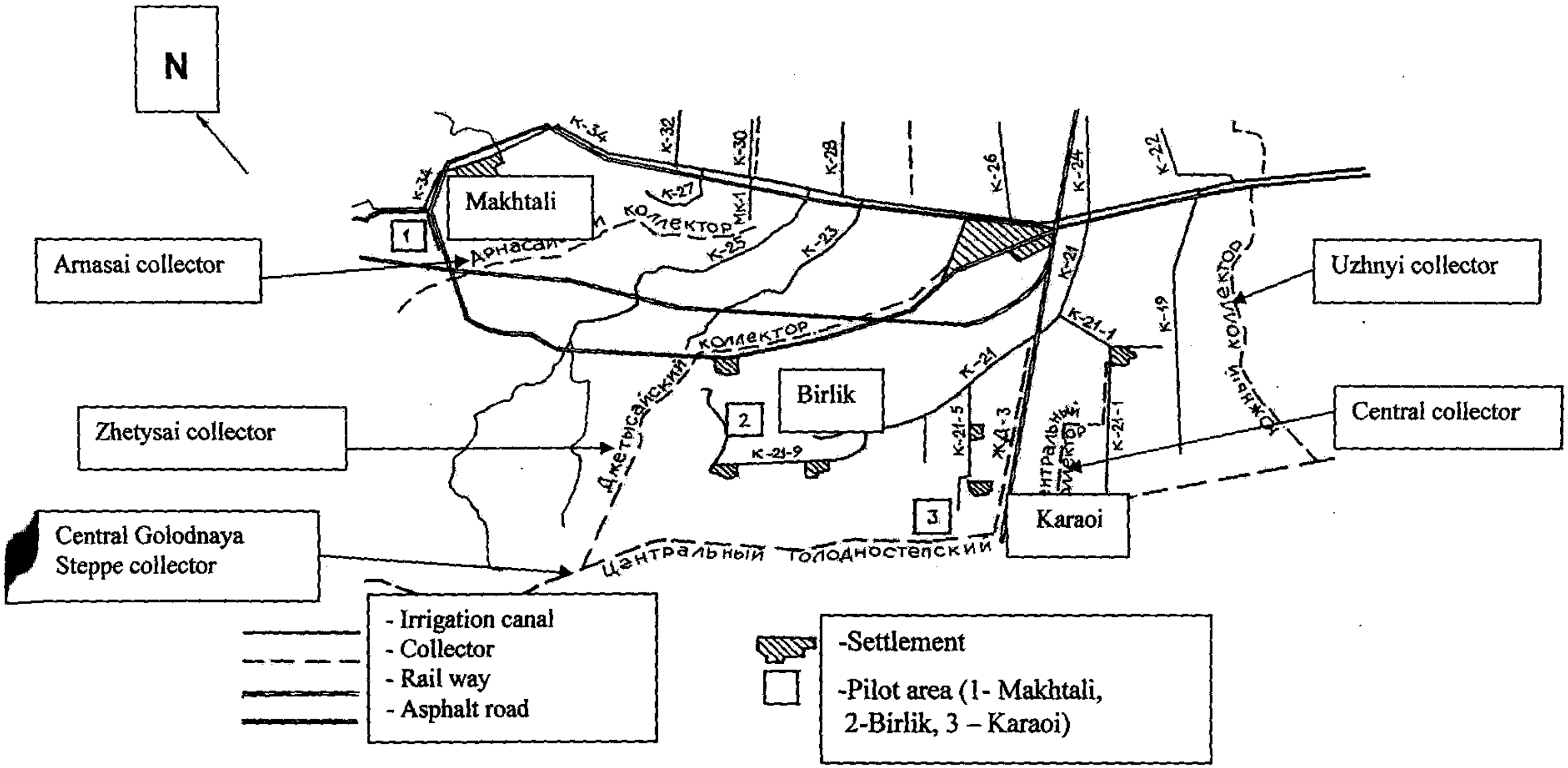
CONCLUSIONS

The modified model was set-up and calibrated using field data collected by Mott MacDonald from three pilot areas in South Kazakhstan. In terms of soil moisture content and soil salinity, the calibration results have been satisfactory. However, soil salinity and soil moisture tension calibration was restricted by the number and quality of the data from the pilot area data collection programme. Soil salinity and soil moisture tension calibration need to be improved when more data of good quality become available. The results show poor performance in simulating soil moisture tension and soil salinity. Model calibration is limited by the number and quality of soil moisture tension and salinity data, more frequent and careful monitoring of these field data are required. The model would require re-calibration when more soil salinity data of good quality become available. An on-going field programme would permit more reliable calibration and validity of the model. The more data of good quality that can be collected the better will be model performance.

Generally, the reasonable agreement between observed and simulated soil moisture gives confidence that the WAVE_MS model can be used to predict long term water balance as well as investigating long-term salinity build up in the root zone and the effect of moisture and salinity stress on crop yield.

From the WAVE_MS simulation outputs, it is clear that the irrigation supply to farmers has been inadequate in recent years. Irrigation applications for cotton have been significantly less than its requirements and there has been water stress during most of the growth period. Were current practices to continue there would be a continued decline in crop yields as a result of water stress and an ever increasing soil salinity.

Appendix A: Pilot area locations



Pilot area locations

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الملخص العربي

نمذجة رياضية لإدارة مياه الري تحت ظروف نقص المياه والملوحة العالية:
١– تقييم الإدارة المتبعة للري والصرف في جنوب كازاخستان

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إن النموذج الرياضي WAVE قد تم تطويره ليتضمن تأثير الملوحة العالية على البخر- نتح وتم استخدامه لمحاكاة حركة الماء والأملاح أي بمعنى آخر التنبؤ بمستويات الرطوبة بالتربة وكذلك دراسة ميكانيكية التوازن الملحي بمنطقة الجذور على المدى البعيد. كذلك أمكن استخدامه في تقييم تأثير الإجهاد الفسيولوجي الناتج عن نقص المياه والملوحة العالية على إنتاجية المحاصيل من خلال تضمينه إحدى دوال الإنتاج المستخدمة. النموذج المطور في صورته الجديدة تم استخدامه في تقييم الإدارة المتبعة للري والصرف في جنوب كازاخستان. النتائج المتحصل عليها أظهرت أن إنتاجية محصول القطن ستنخفض إلى معدلات متدنية جداً خلال ال ٢٥ سنة القادمة إذا لم تتغير هذه الإدارة. التدني في إنتاجية القطن سوف يكون بسبب عدم كفاية كميات الري المضافة وكذلك تراكم الأملاح في منطقة الجذور لتصل مستويات لا يتحملها النبات. هذه الدراسة أثبتت أن النموذج المطور هذا يمكن استخدامه في تقييم تأثير سيناريوهات مختلفة للري والصرف على إنتاجية المحاصيل. النتائج أثبتت أيضاً أن هذا النموذج صالح للاستخدام في المناطق الجافة وشبه الجافة تحت ظروف ومستويات مختلفة نقص المياه والملوحة.