CHAPTER 13

SIMULATING THE EFFECTS OF SALINIZATION ON IRRIGATION AGRICULTURE IN SOUTHERN MESOPOTAMIA

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INTRODUCTION

One of the most significant topics concerning the evolution of Mesopotamian settlement and agriculture discussed over the last half-century is that of the relationship between progressive salinization and the decline of settlements in the southern alluvium. Since Jacobsen and Adams (1958) first published their findings, scholars have begun to consider the potential relevance of progressive salinization and how it could have transformed the southern Mesopotamian landscape (Jacobsen 1982; Powell, 1985; Artzy & Hillel 1988). Salinization is considered to be one of the likely reasons why major settlements, cultural influences, and the centers of political power shifted to more northern regions such as Babylon in the second and first millennium BC (Jacobsen & Adams 1958; Chew 1999). In addition, it is frequently stated that societies in the southern Mesopotamian alluvium overexploited or mismanaged irrigation agriculture, causing major cities to decline in certain periods (Jacobsen 1982; Redman 1999). While the consensus is that there were major episodes of salinization, such as during the late third and early second millennium BC, Powell (1985) has argued that salinization may not have been a significant problem due to the strategies that were used to mitigate it. In essence, the inhabitants of settlements in southern Mesopotamia were not simple victims of mismanaged agriculture, but were capable of mitigating salinization through simple technologies and strategies such as engineered leaching (i.e., deliberate flushing of the soils with excess irrigation water). In fact, improving drainage, leaching salt from soils, and leaving fields fallow for some period does limit salinization in soils, making even salt-prone regions of Mesopotamia productive for agriculture (Gibson 1974; Powell 1985). Nevertheless, it is unclear how effective management strategies were in southern Mesopotamia and if societies were able to prevent long-term salinization with the agricultural techniques available to them.

To address the effects of salinization over time and how it may have been mitigated by Mesopotamian farmers, this chapter presents a model incorporating social behavior involved in agricultural management and environmental processes affecting the irrigation of, and movement of salt into, soil layers. The chapter attempts to answer the following questions: 1) could agricultural strategies reasonably limit progressive salinization, and 2) under what conditions do adaptive strategies fail to inhibit salinization? The model is applied to settlements and field systems in the Nippur and Uruk regions dating to the Ur III period (i.e. roughly 2100-2000 BC), a period that has been purported to show increasing salinization (Maekawa 1984). To answer the above questions, data gathered from ancient sources are used where possible and modern information is also incorporated to fill specific knowledge gaps (see Chapter 5). By answering these questions, it is possible to obtain insight into how settlements may have declined or communities adapted to progressive salinization in the southern Mesopotamian alluvium from the late third millennium to the early second millennium BC.

The chapter begins by introducing the topic of progressive salinization in Mesopotamia, followed by a summary of social and environmental data and the processes applied in the model. Model notation and the code utilized are made available via this chapter and PANGAEA's (see supplementary data hyperlink referenced for this chapter) data server. Background data on the case study regions, including the physical and cultural landscapes, and inputs used to understand the effects of salinization are then provided (see also Chapters 2 to 4). Four different modeling and simulation scenarios are introduced. The results of these and the overall benefits of the applied approach are finally discussed.

BACKGROUND

Historical Background

Texts from southern Mesopotamia suggest that salinization began to be a major problem for agriculture in the late third and the first half of the second millennium BC (Jacobsen 1982; von Bothmer et al. 2003). The textual data indicate that barley (Hordeum vulgare) supplanted wheat (Triticum spp.) as the primary crop in parts of the alluvium. As barley is more salt tolerant (FAO 2012), its increased presence in the textual sources suggests that salinization might have limited the cultivation of wheat, which previously was the more common crop. A decline in crop yields is noted by Jacobsen (1982), who examined the sources from Lagash (Girsu). Yields of 2537 liters per hectare[1] were recorded in approximately 2400 BC; however, by about 2100 BC 1460 liters per hectare were recorded. In another part of the plain, yields for Larsa had shrunk to an average of roughly 897 liters per hectare by ca. 1700 BC (Jacobsen & Adams 1958; Jacobsen 1982). Maekawa (1974) comes to the same conclusion concerning the drop in yield from seed rations; he even claims that the drop in productivity was already present at the end of the Akkadian period (2334-2154 BC) in the area of Lagash. By ca. 2350 BC, the proportion of different kinds of crops in the fields was as follows: barley 80%, emmer 15%, and wheat 0.6% (Maekawa 1974; Jacobsen 1982). At the time of Shulgi’s (2094-2047 BC) 47th regnal year, the proportion is as follows: barley 97.8%, emmer 1.7%, and wheat 0.2% (Maekawa 1973-74; Jacobsen 1982; Maeakawa 1984).

Although a shortfall in production during the third and early second millennium BC is observed, the question remains: what yield should be considered 'normal' or expected, given the climate and environmental conditions in the southern Mesopotamia alluvium (Foster 1986)? Even if yields were declining due to increased salinization, one can assume that since, by the third millennium BC, the alluvium had been occupied for thousands of years, local populations would not only have been aware of the challenges of salinization but would have attempted to mitigate its effects on agriculture. The written sources suggest that fallowing, natural leaching, and possibly some form of engineered leaching, perhaps by washing or flushing salt away from fields through additional water and engineered works, were employed (Jacobsen 1982; Powell 1985). Drainage canals could have been dug to remove excess water from fields, thereby preventing the water logging which can increase salt accumulation in soils, but the evidence for such canals is not entirely clear (Poyck 1962; Artzy & Hillel 1988); such canals would have been a significant undertaking even in recent times. Even if some form of salinization mitigation was practiced, it is not clear how effective this would have been in limiting the problem. In regions such as southern Iraq, where even modern irrigation techniques have only created temporary solutions to salinization (Al-Layla 1978), the most effective method to combat salinization is often simply to leave fields fallow (Gibson 1974). Nevertheless, short-term fallowing could prove to be only a temporary solution: in poorly drained and high-water table areas salt may continue to accumulate on the surface and within the root zone. Farmers, therefore, may have needed to decide to leave fields fallow for very long periods or simply abandon them. Based on the the unknown factor to which significant salinization may have affected agriculture and the uncertainty surrounding methods by which it could have been mitigated, any chosen model needs to incorporate the physical processes of salinization as well as address possible strategies that could have attempted to limit its effects. The intent of this model is to determine those areas where irrigation agriculture could have been reasonably successful in parts of southern Mesopotamia, thus giving us an idea not only of the limits of agriculture, but also of how relatively resilient agricultural systems might have become as a result of the actions of local farmers.

[1] At 0.65 kg/l this is approximately equal to 1649 kg/ha

The Process of Salinization

Salinization, specifically the addition of sodium chloride to agricultural fields, often occurs in areas where there is poor drainage or naturally high levels of salt in soils (e.g., saline-alkali soils), as well as excessive irrigation water, low rainfall, a high water table, insufficient plant uptake of crop water, and high levels of evaporation (Chhabra 1996; Smedema & Shiati 2002). Salt added from salty irrigation water, combined with the increase of salt through capillary rise in areas of high water tables, together with evaporation (which leaves salt on the surface to accumulate), are the most significant processes that add salt to the root zone of plants. The lack of rainfall or other water which can be used to leach salt from fields prevents effective removal of salt from soils. Poor drainage keeps any standing water on fields and evaporation subsequently concentrates the salts within the irrigation water or on fields. Hot and dry weather, as experienced in southern Mesopotamia, ensures that the evaporation rate acts quickly to concentrate salt on the surface. In addition, crops may not be able to transpire sufficiently quickly to ensure that water is removed from fields before the salts contained within water are deposited. As stated above, fallowing and some form of leaching or drainage could assist in minimizing salinization. In addition, rainfall helps to leach salt from fields. Plants such as Proserpina stephanis and Alhagi maurorum often grow on fields during fallow years, thereby providing the benefit of drying out subsoil layers, fixing nitrogen levels, and limiting salt capillary rise. If salt is not fully removed from underlying layers – that is, layers below the root zone – it can reappear, particularly when irrigation is practiced after a period of fallowing. In third and second millennium BC southern Mesopotamia, the combination of poor drainage, capillary action (and thus a high water table), rapid evaporation, lack of rainfall, effective leaching, and salty irrigation water are together assumed to have been the leading reasons why progressive salinization became a major problem for irrigation agriculture (Jacobsen & Adams 1958; Gibson 1974; Artzy & Hillel 1988).

METHODS

To address salinization, it is necessary to employ a method that incorporates social and environmental factors affecting salt, specifically sodium chloride, as it accumulates or diminishes in the root zone. While there are effective models such as SaltMod (Bahçeci & Nacar 2007) which can address the issues discussed here, the problem with such models is that they require a number of variables to be known or sufficiently understood for the model to be effective. Any workable model should address the fundamental processes affecting salinization in southern Mesopotamia, but should also be simple enough to be populated with data that could be reasonably understood, as an alternative to more complex modeling. In this case, the social-ecological model presented here attempts to balance relevant processes contributing to salinization yet still to be simple enough to be employed in cases where data are less certain or not available.

The model used here is similar to that presented by Altaweel & Watanabe (2012). One main difference from the earlier (2012) model is that different functionalities have been employed to address capillary rise and leaching, while also providing added flexibility to address environments such as southern Iraq. The basic structure of the model used, however, is largely the same. Figure 13.1 provides a guide that allows the reader to follow the flow of the model and the Appendix of this chapter gives the mathematical notation for model functions. Additionally, readers can download the model code from PANGAEA (see link provided, as above) and evaluate or use the model as needed. A significant part of the model allows sodium chloride to accumulate in soils during the process of irrigation, using the core functionalities and model advanced by Prendergast (1993). The functions and model have been chosen because the relatively few variables employed make it ideal for cases where data are limited. The data needed for this model could, however, be determined from existing sources or derived from comparable landscapes and settings. To summarize, the functions used here are derived from Prendergast's model, which assumes salt from irrigation and rainfall builds up in the root zone; salt buildup is measured using electric conductivity (EC) within the root zone, which is expressed as decisiemens per meter (dS/m) (a measure also applied in this chapter). In this model, the leaching fraction and evaporation affect how salt accumulates in the root zone under irrigation. Crop yields are then determined based on overall salt content in the root zone and the crop's tolerance to salt. Barley, which is relatively resilient against the effects of salinization, provides higher yields in the model than wheat. For details on the methods using the model of Prendergast as employed in this paper, see (2-7) in the Appendix.

In addition to saline irrigation water, the capillary rise of salt is also relevant to salt accumulation within the root zones of crops. This paper applies a simple function ((1) in the Appendix: Jorenush & Sepaskhah 2003) that allows for capillary rise to operate using a given average and standard deviation. While Jorenush and Sepaskhah discuss more complex functions that address capillary rise, a relatively simple part of the process is chosen here. This minimizes the inputs needed to apply this function within the present social-ecological model. In essence, capillary rise is directly integrated into Prendergast's model. To allow for leaching behaviors, whether they result from natural causes or to some extent from engineering, a decay function similar to those used elsewhere is applied (e.g., Lyle et al. 1986). Within the present model, this allows for multiyear leaching of salt from soils (see (1) in the Appendix). A separate Metropolis-Hastings Markov (Chib & Greenberg 1995) algorithm is employed to generate rainfall amounts (R in the Appendix; see (3)), which is then applied to the irrigation routines of the model. This allows for seasonal variation in rainfall that, in turn, affects salt accumulation in the root zone. By combining all these physical processes, the model as a whole is able to address how salinization is affected by irrigation water, capillary rise, leaching, and rainfall.

In addition to physical environmental processes, human behaviors (i.e., (1) and (8) in the Appendix) are used to model agriculture practices and to make decisions that mitigate the build-up of salt in the root zone. Conceptually this follows the model advanced by Altaweel (2008) and with the same behaviors as those applied by Altaweel & Watanabe (2012). In other words, rule-based and stochastic calculations affect human decisions and the outcomes of those decisions. To summarize, the main human operations used in the irrigated agricultural systems under discussion are as follows: decide to irrigate, thus providing water to crops and leave fields fallow, so that either natural or some form of engineered leaching occurs.

Although it is not known whether engineered leaching, or human actions that promote leaching and the draining of fields, would have been applied in late third and early second millennium Mesopotamia, it is assumed from both modern and ancient irrigation systems that some type of leaching should be employed (see (1) in the Appendix). The values represent a process of decreasing salt content in the root zone (Jacobsen & Adams 1958; Gibson 1974; Leffelaar & Sharma 1977). For ancient Mesopotamian farmers, a critical decision during irrigation was the estimation of what period of time fields should remain under fallow (see (8) in the Appendix), as during such periods salts would have been leached from the soil. It was also necessary to know what level of salinity could be tolerated: such a decision is based on yield, how positively or negatively crops react to salt-affected root zones, and how forcefully a farmer reacts to increased salts. Actors in the model can choose to allow for extended fallowing (see (8) in Appendix), which also enables the leaching of salts to occur over extended periods (i.e., (1) in the Appendix). For scenarios involving extended fallowing, salinity might be tolerated at some level as long as overall yield reduction is minimal; by avoiding excessive, fallowing total agricultural losses are minimized and fields are allowed to recover. This implies that, even if agricultural production of fields is maintained at relatively low yields over long periods, they may still be potentially more productive than those fields that produce high yields for short periods and then have to be abandoned for relatively long periods before they become productive again. In summary, farmers needed to ascertain beneficial fallowing periods that balanced some level of crop loss over a given period with over-irrigation and excessive cropping, which result in high salinization and severe crop reduction.

As shown in Figure 13.1 and summarized in the Appendix, human and environmental factors include the addition of excess water by irrigation, capillary rise of groundwater, leaching, and rainfall, all of which contribute to or reduce soil salinity. Farmers conduct the process of irrigation and provide water to fields. The yield quantity enables farmers to decide whether or not to extend fallowing periods, and thus allows fields to be leached beyond those of typical biennial fallow cycles. Decisions made by farmers (as agents) are based on an agent-based method (Bonabeau 2002) in which stochastic and process modeling are applied to allow for variations in soil salinity within the root zone.

The model can be summarized in a step-by-step manner as follows: farmers first decide if they should plant or leave fields fallow during a year (i.e. 'Agriculture Step' in Fig. 13.1 (1)), regular fallowing being based on biennial rotation. If a field is left fallow, then a leaching operation is scheduled for that year, which leads to the fallow/leaching results shown in Figure 13.1. If the farmer decides to plant a crop (Fig. 13.1-2), a field is then scheduled to be irrigated (13.1-4) during that year. Meanwhile, rainfall (13.1-3) is applied using the Markov process, ensuring that runoff and rainfall salinity affects the model functions. The process of irrigation (Fig. 13.1-4) entails several sub-processes (Fig. 13.1-4b to 13.1-4.e) each of which determines the salinity in the root zone (Fig. 13.1-4a). These sub-processes (Fig. 13.1-4b-e) include the amount of rainfall as well as the amount of irrigation water applied and its salinity. Based on these functions, a barley yield is produced (Fig. 13.1-5), which in this case is a value between 0.0 to 1.0, a scale that provides a relative measure of how greatly the yield is affected by salinity and the crop's tolerance to salt. Therefore, a yield result of 1.0 indicates that there is no effect from salinity, while a yield of 0.0 indicates a 100% yield loss due to salinity. Depending upon the yield, farmers decide if it has become necessary to leave fields fallow for any extended period beyond regular fallowing (Fig. 13.1-6). If long-term fallowing is not needed, the regular crop cycle continues with only one fallow year. This model was calibrated through statistical comparisons with modeling results from comparable studies (Prendergast 1993; Jorenush & Sepaskhah 2003) in order to determine if plausible outcomes could be produced using the functions described here.

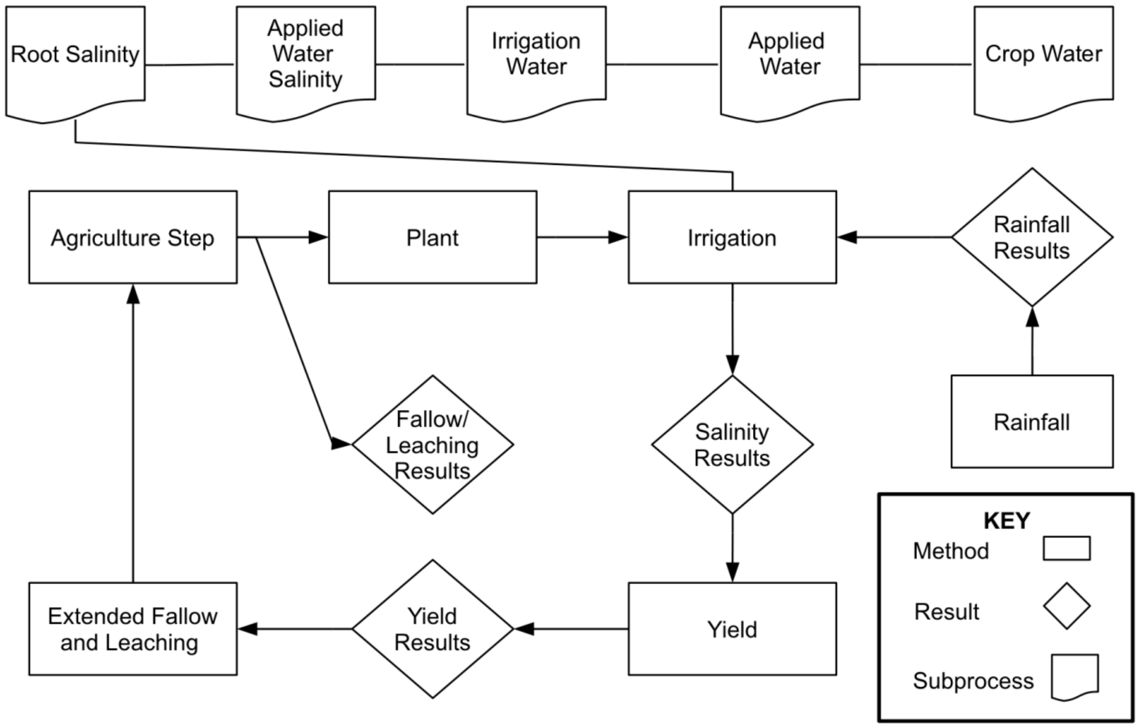

Fig. 13.1 The social-ecological salinization model employed in this chapter depicted at a general level. Model functionality starts with the Agriculture Step method, with the arrows showing the flow and order of functions; see details in the Appendix.

SOUTHERN MESOPOTAMIAN CASE STUDY

The case study investigates regions surveyed by Adams (1981) near Nippur and by Adams and Nissen (1972) around Uruk. In these publications, the authors state that salinization probably played a major role in the decline of settlement in certain periods. Similarly, studies by Buringh (1960) on modern soil conditions also indicate that, in recent periods, much of the southern Mesopotamian alluvium has been prone to progressive salinization, indicating that this problem persists today. As an example of settlement decline, there seems to have been a substantial decline in the total number of hectares occupied, and number of sites, starting at the beginning of the second millennium BC and lasting until the middle part of that millennium (Adams 1981:143, table 13). As discussed in Chapter 3, the Ur III and Isin-Larsa periods may represent the apex of settlement in the alluvium, with the roughly 500 years following this time representing a decline in total settlement (Ur 2013).

Using the survey results cited, several sites dated to the Ur III period, and these sites, together with their regions, have been chosen for this modeling exercise. The sites in the Nippur region include Nippur, Tell Drehem, Tulul Werrish (Adams site no. 983), Isin, and no. 1071 (in Adams 1981); in the Uruk region the sites include Uruk, Umm al-Wawiya (No. 439), Larsa, Imam ʻAbbas al-Kurdi (444), and Tell Abla (432) (Adams & Nissen 1972). The Ur III period has been chosen because at that time, based on the survey results, the population level would have been relatively high, although yields already appear to have begun to decline (Jacobsen & Adams 1958; Maekawa 1974; Jacobsen 1982). This suggests that salinization may have taken hold in the region even though population level was still high or even growing. Therefore, the Ur III and later periods could be used to show how increased salinization may have rendered large populations less resilient as salinization became progressively more difficult to manage. For this study, Dr. Carrie Hritz has provided the locations of sites and canals, these data being derived from her research on the ancient landscape of the alluvium (Hritz 2005, 2010, and Chapters 2 & 3). In addition, elevation data, specifically that from the Shuttle Radar Topographic Mission (SRTM: USGS 2012), are used to distinguish topographic variations of only a few meters between the canal levees and the plain and, in turn, to delineate locations of fields (Fig. 13.2). The elevation data, together with the variation of landscape features, also make it possible to distinguish areas with potentially higher or lower leaching capacity. Such images clearly distinguish the remains of canal levees: these can be assumed to have been the locations of the levee fields (i.e., the better-leached fields), whereas lower areas away from the levees would have accommodated the basin fields.

Buringh's (1960) and Powers' (1954) assessments of soil types in the southern alluvium help determine key model inputs, specifically leaching factors, depth of soil profiles, and the relative level of the water table. In southern Mesopotamia, many regions are classified as saline-alkali soils, although variations in salinity depend upon the proportions of clays, silts, and sand affecting drainage. Irrigated soils in southern Iraq also have high rates of capillary movement of saline water due to high water tables (Barica 1972; Goudie 2003). Such rates of capillary movement are also used as inputs in the model.

By combining the relative elevations of the terrain and soil typology, the field systems can be categorized as follows: levee crest (LC), levee slope (LS), and basin (B) fields (see also Chapter 2). Levee Crest (LC) fields occupy relatively well-drained areas along the banks of canals; these have lower clay content and coarser sediments such as silt and sand. Levee slope (LS) fields are less well drained, with poorer leaching of salt and more significant clay content; however, there are still significant amounts of silt in these soils, which allow for some leaching to occur. Basin fields have the worst drainage and lowest leaching rates, because of the high percentages of clay.

In the late third millennium and early second millennium BC, climate conditions were probably hot and dry, and agriculture would have been heavily dependent upon irrigation (Issar & Zohar 2007). If this was the case, then the salinity of irrigation water would have been relatively high, as a lower rainfall would have resulted in greater concentration of salt in the irrigation water as well as lower rates of leaching. In order to reflect these fairly dry conditions, rainfall data from Diwaniyah and Samawa, gathered between 1930 and 1955 in southern Iraq, have been applied to the Nippur and Uruk regions respectively. Rainfall is derived from a Markov algorithm which determines rainfall amounts for a given area and time. Temperature provides a relative estimate of evaporation (NOAA 2012) which has been estimated for the hot and dry conditions of southern Mesopotamia using the study of Al-Khafaf et al. (1989). Other variables include the thickness of the soil layers and electric conductivity (EC) for the water table (Jorenush & Sepaskhah 2003). Table 13.1 indicates all variables and data sources used. These variables are incorporated in the salinization model presented in the Appendix; a significant number of these variables can be estimated to a reasonable level, whereas variables which are less certain are tested in modeling scenarios.

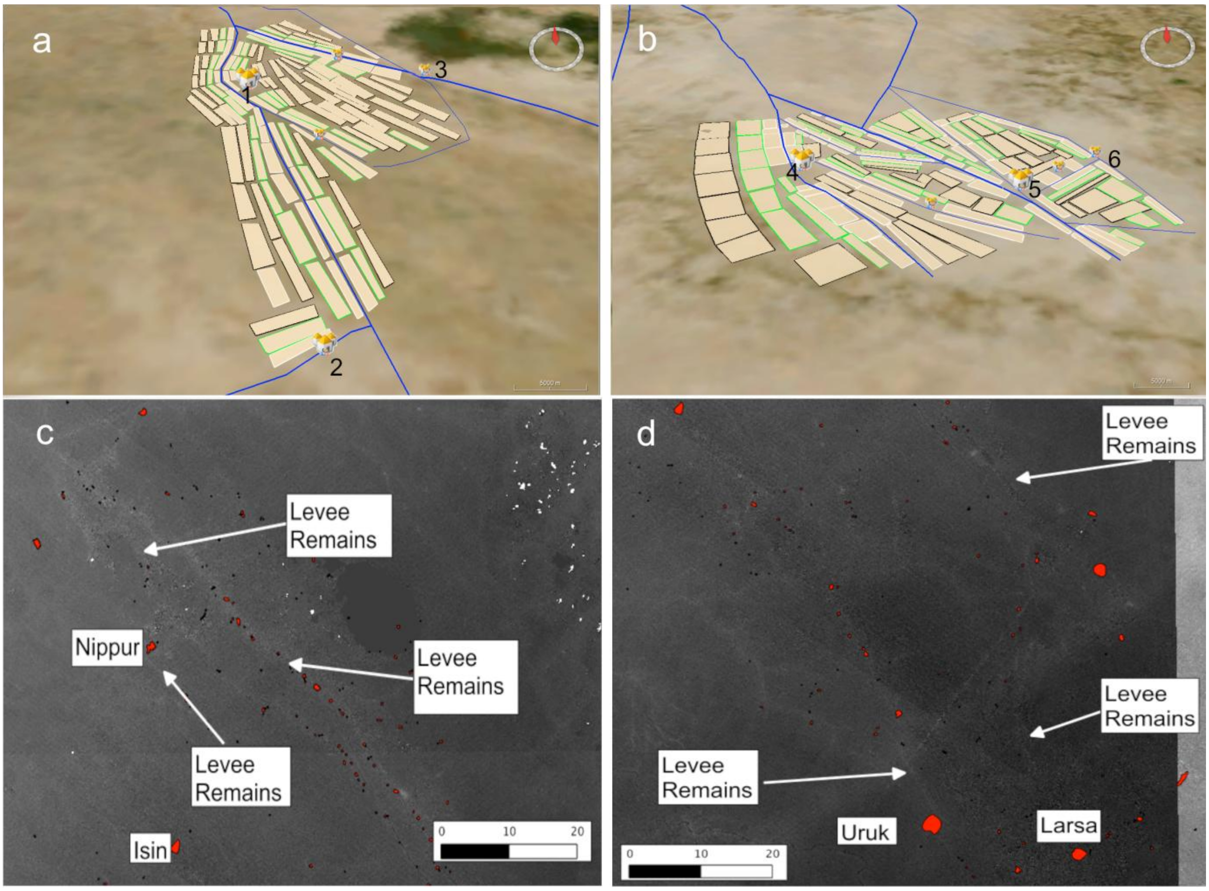

Fig. 13.2 The Nippur (a&c) and Uruk (b&d) case study regions as used in the simulations (a&b) with sites (house icons), agricultural fields (polygons next to sites), and canal systems shown as linear features running near settlements. The SRTM data (c&d) are used to distinguish canal levees and relative elevation changes in the modeled region (i.e. darker to lighter colors indicate lower to higher elevations respectively). Numbers 1-6 (in a&b) represent Nippur, Isin, No. 1071, Uruk, Larsa, and Tell Abla respectively.

Possible decisions taken by farmers include the mitigation of salinization by encouraging long-term leaching, which operates during extended periods of fallowing. The associated yield loss is tolerated by farmers, and when the interval of fallowing (i.e. through the scaling of fallows) extends beyond biennial fallow this is considered to diminish the effects of progressive salinization. While specific values are difficult to estimate from existing data, extended fallowing must have been the primary method of decreasing salt in soils (Gibson 1974). Agricultural practices, as they are described in ethnographic and textual sources, are used to form steps within the model. For example, water would have been allocated to farmers at different times and rates, with farmers near the heads of canals being likely to receive more irrigation water than those further downstream (Poyck 1962; Fernea 1970), and barley forms the primary crop being modeled (Jacobsen 1982). Leaching fractions for different field types are determined from studies cited in Table 13.1. Planting would have occurred in the autumn, with irrigation conducted in the spring. Variables relevant to the growth of barley include a salinity threshold and percent yield reduction (FAO 2012). The model variables that include those used in decision-making by farming communities are listed in Table 13.1.

Table 13.1. The model variables and sources applied in the case study. Variables listed here are those referenced in the model shown in the Appendix.

Data Input	Data Source	Data Input	Data Source
Pan Evaporation/Coefficient (E_p)	Al-Khafaf 1989	Water Table Conductivity (EC_{wt})	Jorenush and Sepaskhah 2003
Empirical Coefficient (K)	Al-Nakshabandi and Kijne 1974	Yield Response Factor (K_y)	Doorenbos and Kassam 1979
Rainfall Salinity (C_r)	Prendergast 1993	Leaching Fraction (LF)	van Hoorn 1981; Lyle et al. 1986
Irrigation Salinity (C_w)	Kiani and Mirlatifi 2012; Prendergast 1993	Capillary Rise (J)	Jorenush and Sepaskhah 2003; Goudie 2003
Threshold Salinity (A)	Barrett-Lennard 2002; FAO 2012	Landscape and Settlements	Adams and Nissen 1972; Adams 1981; Hritz 2005; USGS 2012
Crop Coefficient (K_c)	Araya et al. 2011	Rainfall (R)	NOAA 2012
Soil Typology	Powers 1954; Buringh 1960	Percent Yield Reduction (B)	FAO 2012
Fallow Seasons (FA)	Jacobsen and Adams 1958	Salt Tolerance (ST)	
Yield (Y)	Barrett-Lennard 2002; FAO 2012	Fallow Season Scaling (T)	Poyck 1962; Gibson 1974
Soil Layer (d)	Barica 1972; Dieleman 1977	Leaching Efficiency (E_l)	van Hoorn 1981

RESULTS

Four model scenarios are applied for the Nippur and Uruk regions. Scenario one models a baseline case to show the effects of salinization in the root zone; scenario two adjusts the baseline case to demonstrate the effects of high salinity on field types; scenarios three and four demonstrate crop management strategies under different high-salinity conditions.

The first scenario provides the basic variable inputs used, which are derived through parameter testing and sweeps (North & Macal 2007); the other three demonstrate some variations on key behaviors and parameters assessing salinization alleviation strategies. The intention, therefore, is to determine how salinization may have progressed in different field types and whether strategies to combat salinization could have been effective. Although not all tested values are shown for the scenarios, key results are indicated. Values used in the first scenario, which consists of two sub-scenarios (1.a & 1.b), are listed in Table 13.2; other scenarios derive from values shown here. In total, 266 field blocks (102 located on the LC, 68 LS, & 96 B)[2] have been used, with each block representing multiple fields and with specific field types being bundled together. Field blocks are further subdivided into the Nippur (38 LC, 34 LS, & 58 B) and Uruk (64 LC, 34 LS, & 38 B) regions. In effect, the areas modeled are intended to represent samples of the irrigation zones and field types present during the Ur III period. The scenarios extend for 200 simulated years and are executed 1000 times in order to account for model stochasticity.

[2] LC= levee crest, LS= levee slope and B= basin, as defined above.

Table 13.2 Inputs used for the first scenario (sub-scenarios 1.a & 1.b) including standard deviations (σ) applied for specific variables (as used in the stochastic operations). Some variables have different values for the three field types (LC, LS, & B respectively) in the Nippur and Uruk regions; these are indicated by the forward slashes and the letters 'N' and 'U' for Nippur and Uruk regions respectively. All scenarios use or deviate from values indicated here.

Variable	Value	σ	Variable	Value	σ
(E_p)	1.1 m	0.2 m	(EC_{wt})	5/8/12 dS/m	
(K)	0.6		(K_y)	1	0.05
(C_r)	0.008 dS/m		(LF)	Scenario 1.a: N: 0.25/0.20/0.18 m U: 0.20/0.20/0.10 m Scenario 1.b: N: 0.25/0.20/0.15 m U: 0.20/0.175/0.10 m	Scenario 1.a: N: 0.05/0.04/0.03 m U: 0.05/0.04/0.03 m Scenario 1.b: N: 0.05/0.04/0.03 m U: 0.05/0.04/0.03 m
(C_w)	2.0 dS/m		(J)	Scenario 1.a: N: 0.40/0.50/0.70 m U: 0.45/0.60/0.80 m Scenario 1.b: N: 0.30/0.40/0.60 m U: 0.35/0.50/0.70 m	Scenario 1.a: N: 0.10/0.13/0.18 m U: 0.10/0.15/0.20 m Scenario 1.b: N: 0.075/0.10/0.15 m U: 0.075/0.125/0.175 m
(A)	8.0 dS/m		(R)	see NOAA 2012 tables	
(K_c)	0.83	0.075	(B)	5.0% per dS/m^{-1}	
(FA)	1		(ST)	0	
(Y)	1		(T)	0	
(d)	5		(E_l)	Scenario 1.a: 0.50/0.45/0.40 Scenario 1.b: 0.40/0.35/0.30	

Scenario 1

This scenario tests baseline cases in which fields are tested to determine how quickly their root zones become salinized under biennial cropping. Two sub-scenarios are implemented in Scenario 1, with results indicated on Figures 13.3 to 13.5. Both sub-scenario inputs are shown in Table 13.2. It is intended in this scenario to establish reasonable inputs which create qualitatively significant results demonstrating how salinization progresses. In this case, a long period elapses before there is balance in the salt content, especially in the basin fields. While the resulting variations between scenario 1.a and 1.b are not substantial for LC and LS fields, basin fields do show significant differences (Figs. 13.3 & 13. 4).

For the Nippur region (Figs. 13.3 & 13.4a), root zone salinization in basin fields attains a salt balance; this occurs when the amount of salt leached roughly equals salt added, thus flattening the salinization curve. This balance occurs within 100 years in scenario 1.a, whereas salinization continues to increase throughout the duration of scenario 1.b (Fig. 13.3 & 13.4c).

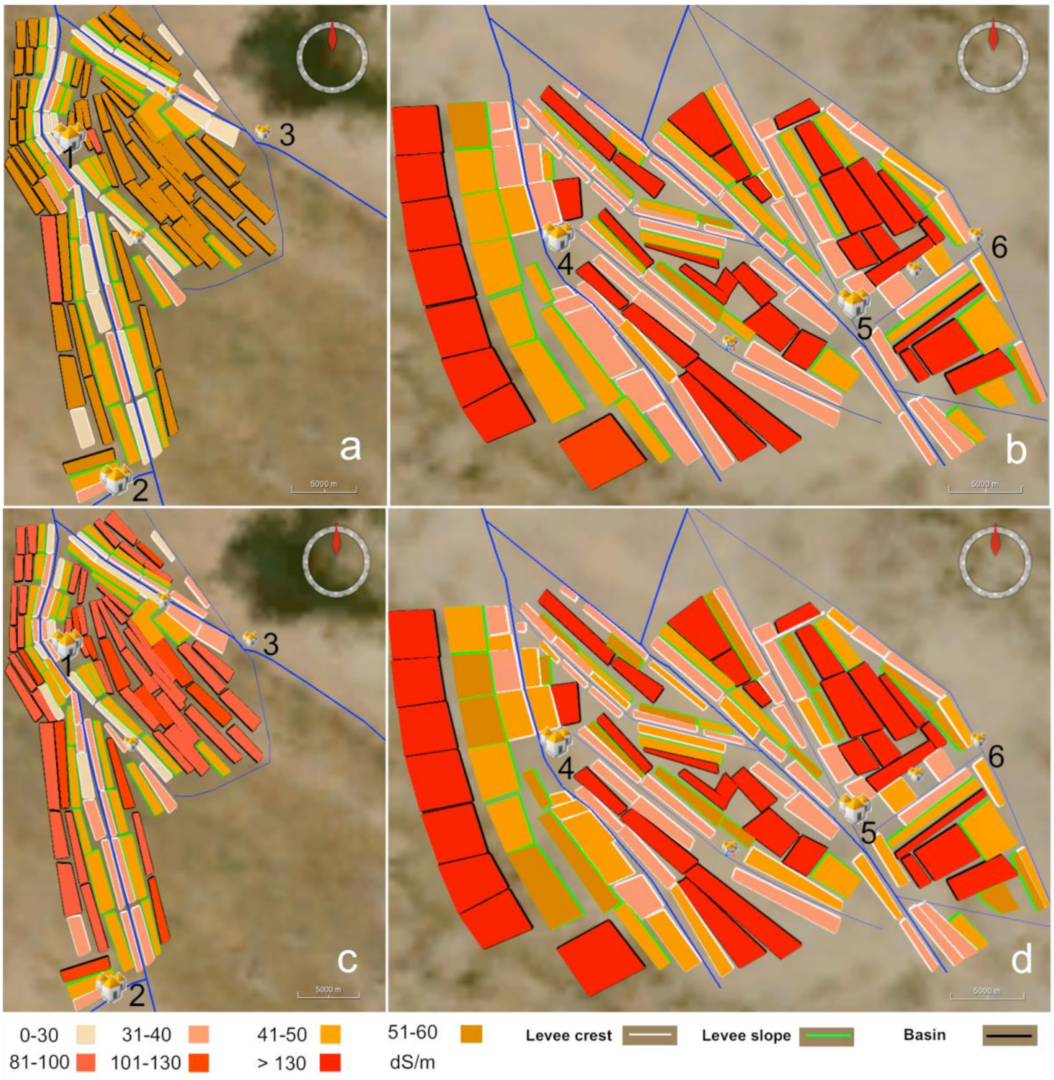

Fig. 13.3 Root zone salinization (dS/m) for fields at year 200 in scenario 1 for the Nippur (a&c) and Uruk (b&d) regions. Letters a&b show scenario 1.a and c&d show scenario 1.b. Numbers 1-6 represent Nippur, Isin, No. 1071, Uruk, Larsa, and Tell Abla respectively.

In the Uruk region, the basin fields never attain a root zone salt balance throughout the entire 200-year scenario (Figs. 13. 3-13.4 b&d). For all field types in the sub-scenario, yields are not dramatically different between those of scenario 1.a (Fig. 13.5 a&b) and scenario 1.b (Fig. 13.5 c&d). In this scenario, yields for the field types appear to reach stability within 50 years after simulations began, while in the case of the sub-scenarios all basin fields become completely unproductive within roughly 40 years. It is noticeable that all field types are affected by increasing root zone salt.

This scenario is intended to establish a qualitative representation of what may have occurred in the Nippur and Uruk regions. It clearly demonstrates that basin fields quickly become heavily saturated with salt after only a few seasons. Although fields higher up the levee are less prone to salinization, they too are affected by some degree of salt accumulation. However, since salt concentration reaches a very high level in basin fields, it is also very likely that this would begin to affect LC and LS fields, as the (already high) water table would rise further and negate some of the advantages of the better-leached fields. Such a scenario, therefore, needs to be tested before salinization reduction strategies can be addressed.

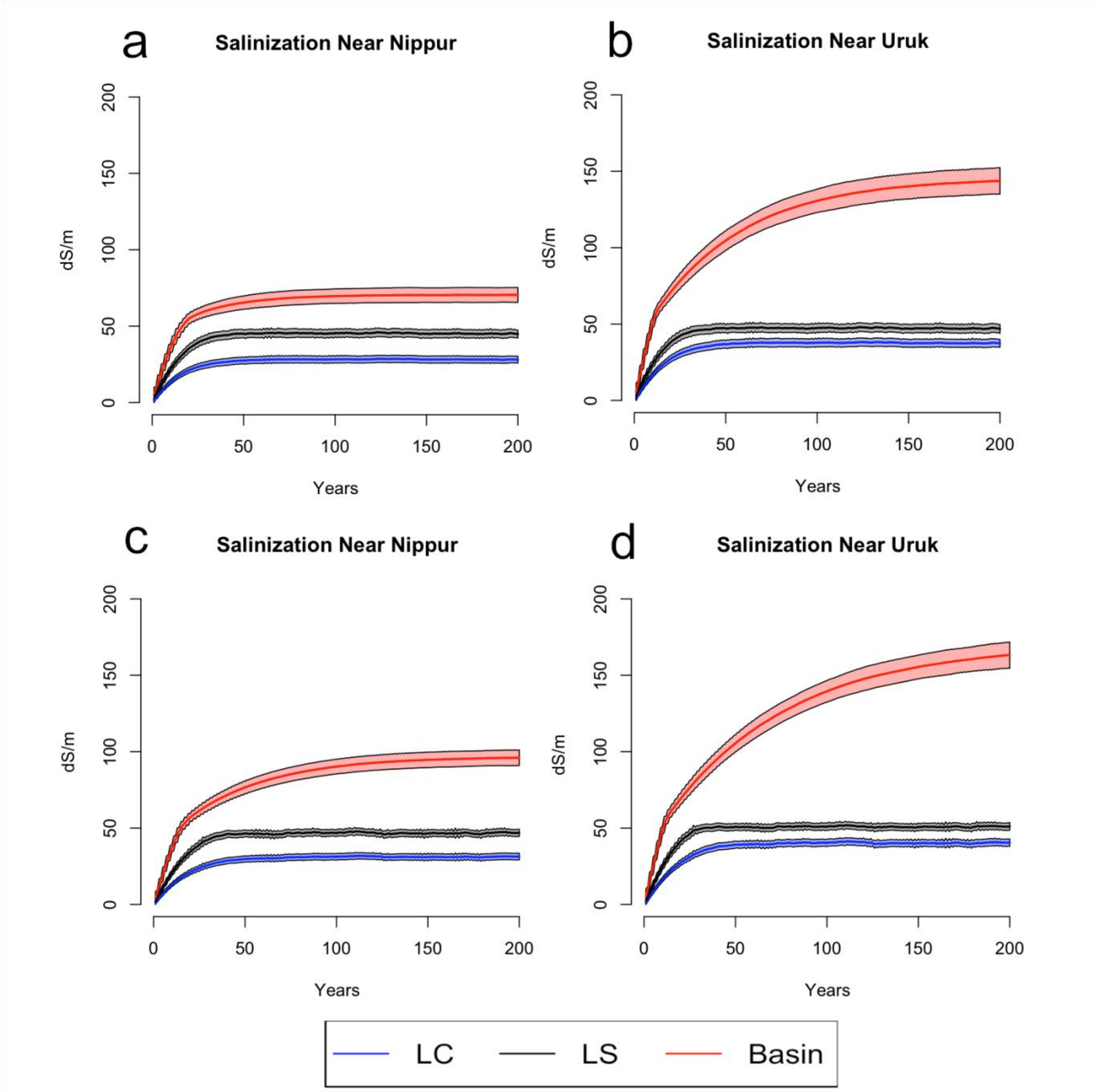

Fig. 13.4 Average root zone salinization (dS/m) shown during the length of simulation runs. Letters a&b show scenario 1.a and c&d show scenario 1.b. Shaded areas indicate one standard deviation from the mean in simulation results. The top curve represents the flood basins, the center curve the levee slopes, and lowest the levee crest.

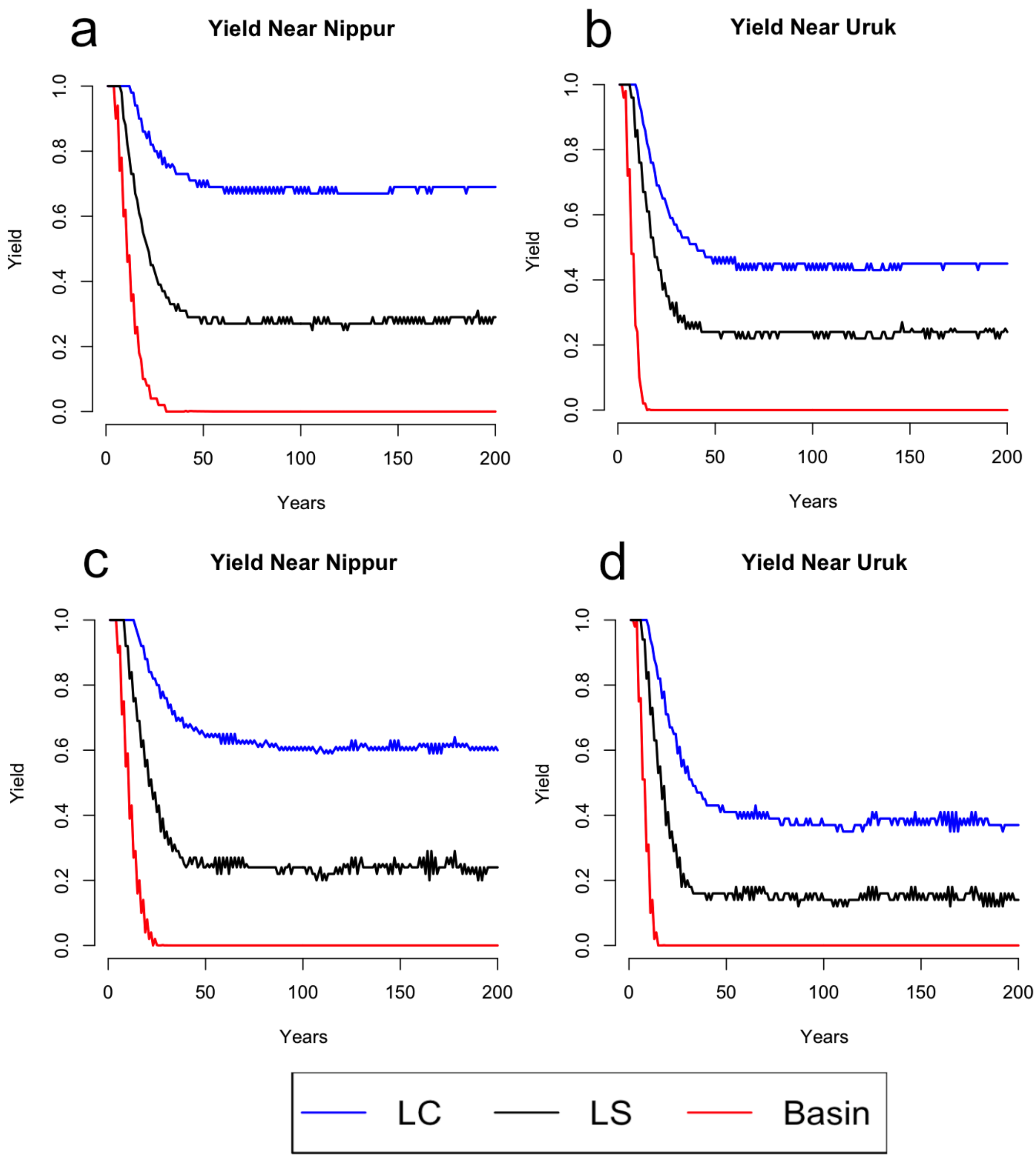

Fig. 13.5 Average yield (0.0-1.0) shown during the length of simulation runs. Letters a&b show scenario 1.a and c&d show scenario 1.b. Here the top curve represents the levee crest, the center curve the levee slope and the lowest, the flood basin soils.

Scenario 2

Scenario 1 demonstrated that basin fields can quickly become progressively salinized in their root zones and that this process can quickly affect other field types. In Scenario 2, the results from scenario 1.b are again employed, but the simulation is modified slightly to allow the salinized basin fields to affect the better-leached fields upslope (i.e., LC & LS fields). In this model, when root zone salinity in the basin fields becomes greater than 60 dS/m, LC and LS fields then adjust their leaching factors to values incrementally closer to those of basin fields during each year. However, when fields show less than 60 dS/m, they incrementally revert closer to their initial leaching factors. These actions are intended to mimic the effects that take place during salinization or leaching. This is because these processes not only affect the specific fields under consideration, but also the rise of groundwater and salt content in the surrounding fields.

In summary, the raised salinity in basin fields affects the salinity rates of LC and LS fields for both the Nippur and Uruk regions. Figure 13.6 shows the results of this modification, which employs the inputs from scenario 1.b. In the Nippur region (Fig. 13.6a), root zone salinity in all field types becomes very similar by year 200; in the Uruk region (Fig. 13.6b), since it takes far longer to attain a salt balance, salinity in the LC and LS fields never reaches that of the basin fields. Crop yield declines are now comparable for both the Nippur and Uruk regions (Figs. 13.7a and 13.7b) because the advantages of the LC and LS fields are negated by excessive salinization, which begins in the basin fields and then spreads to the LC and LS fields. For all field types in this scenario, even after 200 years, fields do not reach a salt balance. Because this might more accurately reflect a situation where salinization begins to affect all field types, the model behaviors of Scenario 2 are used in the following two scenarios.

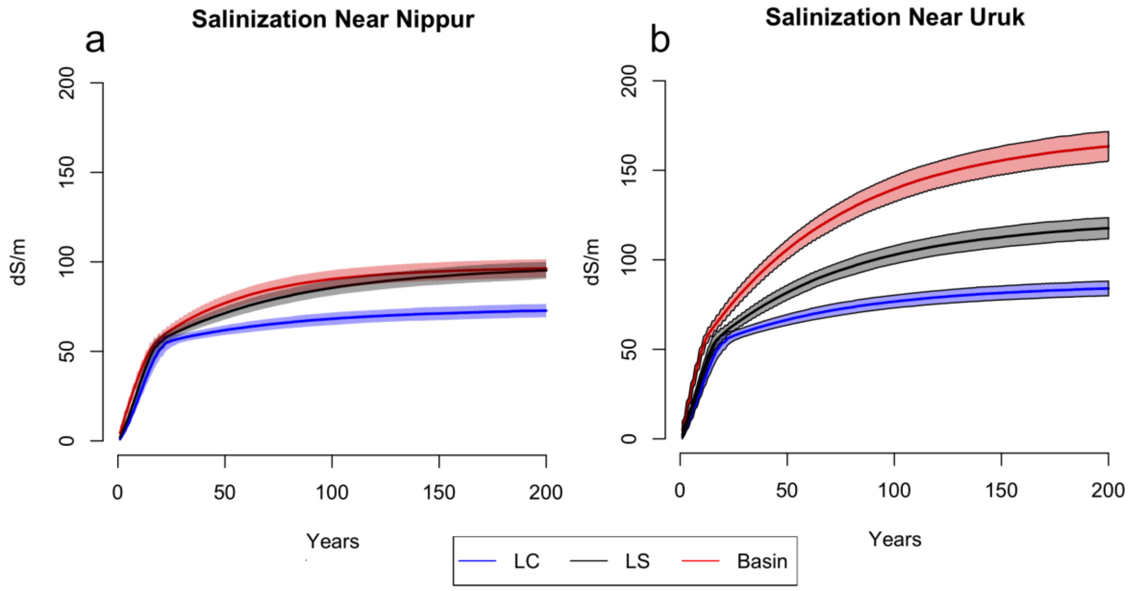

Fig. 13.6 Root zone salinity (dS/m) displayed for the Nippur (a) and Uruk (b) regions in scenario 2; shaded areas indicate one standard deviation in results. The top curve represents the flood basins, the center curve the levee slopes, and lowest the levee crest.

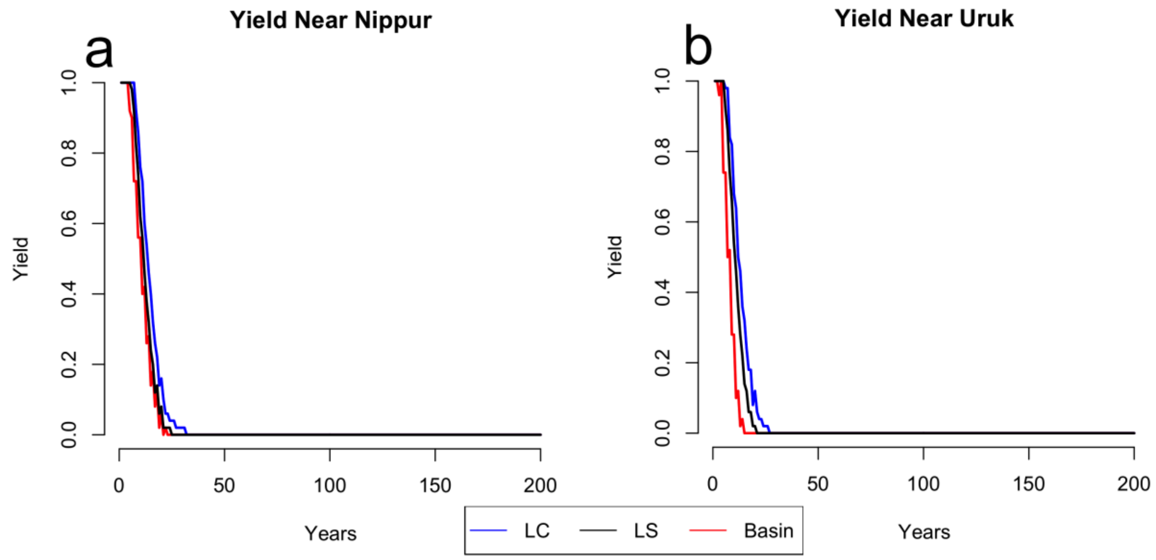

Fig. 13.7 Average yield based on scenario 2's root zone salinity in the Nippur (a) and Uruk (b) regions. Although all are very similar, the flood basin result is the left-hand curve.

Scenario 3

Root zone salinity can be reduced via the use of extended fallowing as noted above. The benefit of this technique is that it can reduce salt content in the fields either as a result of leaching resulting from rainfall or by deliberate flooding of the soils (i.e. engineered leaching), both of which remove salt from field soils. This scenario is executed by modifying the ST and T values or salt tolerance and fallow scaling values respectively, as discussed earlier and indicated in Tables 13.1 & 13.2. The ST value represents the yield reduction that a farmer might tolerate before extended fallowing is initiated. In other words, farmers monitor yield losses according to ST levels and then react by determining how long fields should be left fallow. This reaction is represented by input T. As an example, a ST value of 0.8 would signify a 20% reduction in yield; in other words, when yield reaches 0.8 then extended fallowing should be practiced. The variable T in effect represents sensitivity to salt content and yield loss; as fields are increasingly affected by salinization, T values indicate how long farmers are willing to leave their fields fallow. Therefore, T is employed to determine whether longer or shorter fallow periods are more beneficial for yields.

Building on the above discussion, different ST and T values are indicated in Tables 13.3 & 13.4; the results indicate the average yield for scenario 3.a (Table 13.3) and the number of fallow years (Table 13.4). The ST columns indicate the modeled salt tolerance values; the rows in which the values are found indicate yield (Table 13.3) and the number of fallow years (Table 13.4) for the specified T values (i.e., 10, 15, 20, 25) for each value of ST. For example, in Table 13.3, an input for ST=0.8 and T=25 results in yields of 0.82, 0.64, and 0.3 for the LC, LS, and B fields respectively in the area of Nippur. The same principle applies to Table 13.4.

Based on the above, the optimal yield and fallow year results are highlighted in the tables. The results suggest that after some additional years of fallow, a relatively minor tolerance to salt (i.e., at ST=0.8) is optimal. Although additional fallowing years are not always needed in consecutive years, extra fallowing dramatically improves yields for all field types. One result to note is the basin fields in the Uruk region, which might best be left fallow for, on average, between two and three years (i.e., over consecutive years). By only slightly extending fallowing periods, as shown in Table 13.4, it is possible to obtain dramatic improvements in yields, as seen by contrasting Table 13.3 and Figure 13.7. Thus, by comparing the best yield results in Table 13.3 with Figure 13.5 c&d (i.e., scenario 1.b[3]), it is evident that yield outputs are considerably improved in scenario 3.a. For example, LC fields in scenario 3.a produce a yield of 0.82 when ST=0.8 and T=25; this is a 24% improvement in yield compared to scenario 1.b, in which (shown in Fig. 13.5c) the average yields for LC fields are 0.66. An average of 1.04 fallow years seems to improve yields significantly.

For other field types, the improvements are even more dramatic. When comparing the optimal yield results of scenarios 1.b and 3.a, it is evident that Nippur LS and basin fields show 139% and 1060% percent improvement respectively. For the Uruk region, LC, LS, and basin fields show 73%, 218%, and 58% improvement respectively. Therefore, adding an additional fallow year as yields are reduced to the 0.8 level, or sometimes several consecutive years, significantly reduces overall root zone salinity and results in major improvements in yields. Nevertheless, while scenario 3.a shows that progressive salinization driven by capillary rise could be limited, yields are still significantly affected by salt. In particular, basin fields in the Nippur and Uruk regions are more than 40% affected by root zone salinity.

Scenario 3.b is run in order to determine whether extreme capillary rise could be limited by extended fallowing. This helps highlight the possible limits of extended fallowing. In scenario 3.b, ST and T values are set at 0.8 and 10; these inputs produce relatively good yields in scenario 3.a. Capillary rise (J) values are set to 1.0, 1.5, and 2 meters for all LC, LS, and B fields respectively; these are comparable to those inputs in areas with very high capillary rise (Goudie 2003). Figure 13.8 gives the results of yields (Fig. 13.8 a&b) and fallow years (Fig. 13.8 c&d) for the Nippur and Uruk regions. Basin fields are seen to be heavily affected by this increased salinity, with substantially increased fallow years that take 50-100 years to stabilize. Overall, yields average 0.75, 0.5,

[3] Which employ the same inputs used in scenario 3.a, but without the modification from scenario 2.

and 0.34 for the LC, LS, and B fields (respectively) in the Nippur region. In contrast, in the Uruk region the results are 0.7, 0.47, and 0.26 for the LC, LS, and B fields, respectively. This demonstrates that agriculture is considerably restricted by high capillary rise, although the resulting yield declines are not as drastic as might be expected.

Table 13.3. Average yield results from scenario 3.a based on salt tolerance (ST) values and fallow season scaling (T). Values, from left to right in the T columns, represent LC, LS, and B fields in the Nippur and Uruk regions. Highlighted values indicate the best results.

Region	ST	T=25	T=20	T=15	T=10
Nippur	0.8	0.82/0.64/0.30	0.82/0.66/0.36	0.8/0.70/0.44	0.78/0.74/0.58
	0.7	0.76/0.6/0.32	0.74/0.62/0.36	0.74/0.66/0.46	0.72/0.66/0.56
	0.6	0.68/0.58/0.30	0.68/0.58/0.34	0.68/0.6/0.38	0.66/0.58/0.44
Uruk	0.8	0.74/0.52/0.18	0.76/0.58/0.22	0.78/0.64/0.26	0.76/0.70/0.30
	0.7	0.70/0.50/0.18	0.70/0.54/0.22	0.70/0.58/0.26	0.68/0.62/0.30
	0.6	0.64/0.48/0.18	0.64/0.50/0.20	0.62/0.52/0.26	0.60/0.56/0.30

Table 13.4 Average number of fallow years from scenario 3.a based on salt tolerance (ST) values and fallow season scaling (T). Values, from left to right in the T columns, represent LC, LS, and B fields in the Nippur and Uruk regions. Highlighted values indicate the best results.

Region	ST	T=25	T=20	T=15	T=10
Nippur	0.8	1.04/1.89/6.87	1.02/1.53/4.61	1.01/1.26/2.81	1.0/1.09/1.65
	0.7	1.01/1.62/6.06	1.01/1.37/3.96	1.0/1.18/2.42	1.0/1.06/1.49
	0.6	1.0/1.38/5.59	1.0/1.22/3.8	1.0/1.11/2.45	1.0/1.03/1.53
Uruk	0.8	1.31/2.63/11.57	1.18/1.98/6.57	1.09/1.48/3.66	1.02/1.17/2.63
	0.7	1.18/2.44/11.97	1.1/1.86/7.04	1.05/1.43/3.57	1.01/1.15/2.29
	0.6	1.1/2.12/11.1	1.05/1.67/6.96	1.02/1.34/3.73	1/1.12/2.08

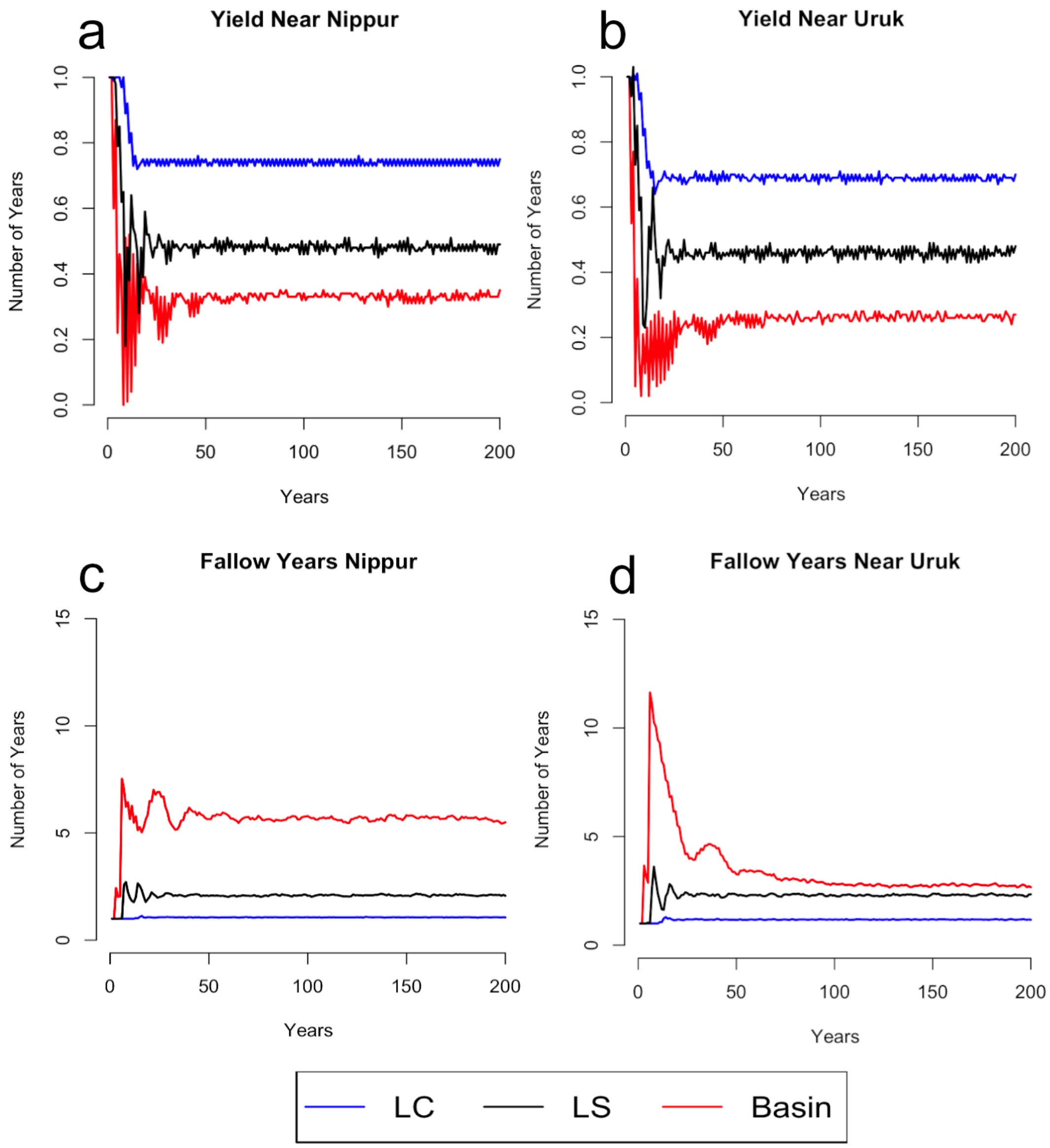

Fig. 13.8 Yield (a&b) and fallow years (c&d) in the Nippur (a&c) and Uruk (b&d) regions in scenario 3.b. Here for a & b the top curve represents the levee crest, the center curve the levee slope and the lowest, the flood basin soils. For c & d the flood basin is represented by the top curve, the levee slope by the center curve, and the levee crest by the lowest.

Scenario 4

The previous scenario shows that, by simply leaving fields fallow for extended periods, farmers are able to limit the effects of root zone salinity, which therefore results in significantly improved yields. Although crop yields are still drastically affected by salt buildup in soils, this level of salinization could have been contained as long as settlements did not have to depend on maximum production from all available fields. In other words, if there were sufficient fields to provide for settlement populations, then even reduced yields due to salinization may not have been a major problem. The question of how salinization could have become such a problem so that it reached a point that settlement may have declined, even if spare fields were available, needs to be investigated. This would require that the limits of extended fallowing are tested.

In the present scenario, another major factor of salinization – the increased salinity of irrigated water – is tested. This value is controlled by the C_w variable. The results in Scenario 4.a demonstrate the outcome when C_w equals 5.0 dS/m. Alternatively, scenario 4.b demonstrates the results when C_w is set to 7.0 dS/m, with the ST and T values at 0.8 and 10 respectively.

Table 13.5 summarizes the yield results for scenario 4.a, with the results formatted in a similar layout to Table 13.3 (i.e. showing and matching ST and T values and yield). In this case, it is clear that shorter fallow periods and lower tolerance to salt seem to be the best strategies for mitigating the effects of increased irrigation water salinity. Therefore one obtains the best results with ST and T values set to 0.8 and 10 respectively, with root zone salinity (Fig. 13.9 a&b) and fallow years (Fig. 13.9 c&d) being the lowest for these inputs. Although yields clearly decline more in this scenario than in previous cases, even these results suggest that some alleviation is possible. For example, this decline of yields would result if farmers extended fallowing at that point when salt accumulation first became significant. The graphs in Figure 13.9 show that it would take about 50 years for salt content and fallow years to reach a balance, with the initial few decades requiring a far greater average fallow years due to high levels of salinity (Fig. 13.9 c&d).

For scenario 4.b, in which irrigation salinity increases to 7.0 dS/m and in which ST and T are set to 0.8 and 10 respectively, yield results are far worse. Yields average 0.30, 0.20, and 0.16 for the LC, LS, and B fields in the region of Nippur, which compare with 0.22, 0.16, and 0.08 for equivalent fields in the Uruk region. Figure 13.10 indicates salinity in the root zone and simulated average fallow years for the Nippur and Uruk regions respectively (Fig. 13.10 a&c, and 13.10 b&d). It is clear from this that, in order to reduce salinization to lower levels, much longer fallow periods are required – considerably longer than what is evident in scenarios 3.b and 4.a. This is clear despite the fact that T is set to 10, which is a relatively low value compared with the other T settings in Table 13.5. It should be noted that Figures 13.10 a&b show that all field types have similar root zone salinity, whereas the fallow years required for fields in the Nippur region (Fig. 13.10c) are actually greater for LC and LS fields than B fields. Differences in fallow years between field types in the Uruk region are also lower in this scenario (Fig. 13.10d), which indicates that high levels of irrigation-induced salinity diminish the advantages of better-leached fields. From Figure 13.10d, it is clear that it takes nearly 120 years to achieve a salt balance, after which both root zone salinity and average fallow years stabilize. Figure 13.11 shows fallow years in individual fields at Year 200 for scenario 4.b. This figure shows some remarkably long fallow periods (in years) for individual fields. For example, fields in the Nippur region (Fig. 13.11a) have fallow periods that reach 15 years or more, whereas in the Uruk region (Fig. 13.11b) some B fields require more than 25 years of fallow to recover.

Table 13.5. Average yield from scenario 4.a based on salt tolerance (ST) values and fallow season scaling (T). Values, from left to right in the T columns, represent LC, LS, and B fields in the Nippur and Uruk regions.

Region	ST	T=25	T=20	T=15	T=10
Nippur	0.8	0.50/0.28/0.12	0.56/0.32/0.14	0.62/0.38/0.18	0.68/0.44/0.24
	0.7	0.52/0.30/0.14	0.56/0.32/0.16	0.60/0.38/0.18	0.62/0.44/0.24
	0.6	0.52/0.30/0.14	0.54/0.34/0.16	0.56/0.38/0.18	0.56/0.44/0.24
Uruk	0.8	0.32/0.20/0.06	0.38/0.24/0.08	0.44/0.30/0.10	0.50/0.36/0.10
	0.7	0.36/0.22/0.06	0.40/0.26/0.08	0.46/0.30/0.10	0.50/0.36/0.10
	0.6	0.36/0.22/0.06	0.40/0.26/0.08	0.44/0.30/0.10	0.48/0.34/0.12

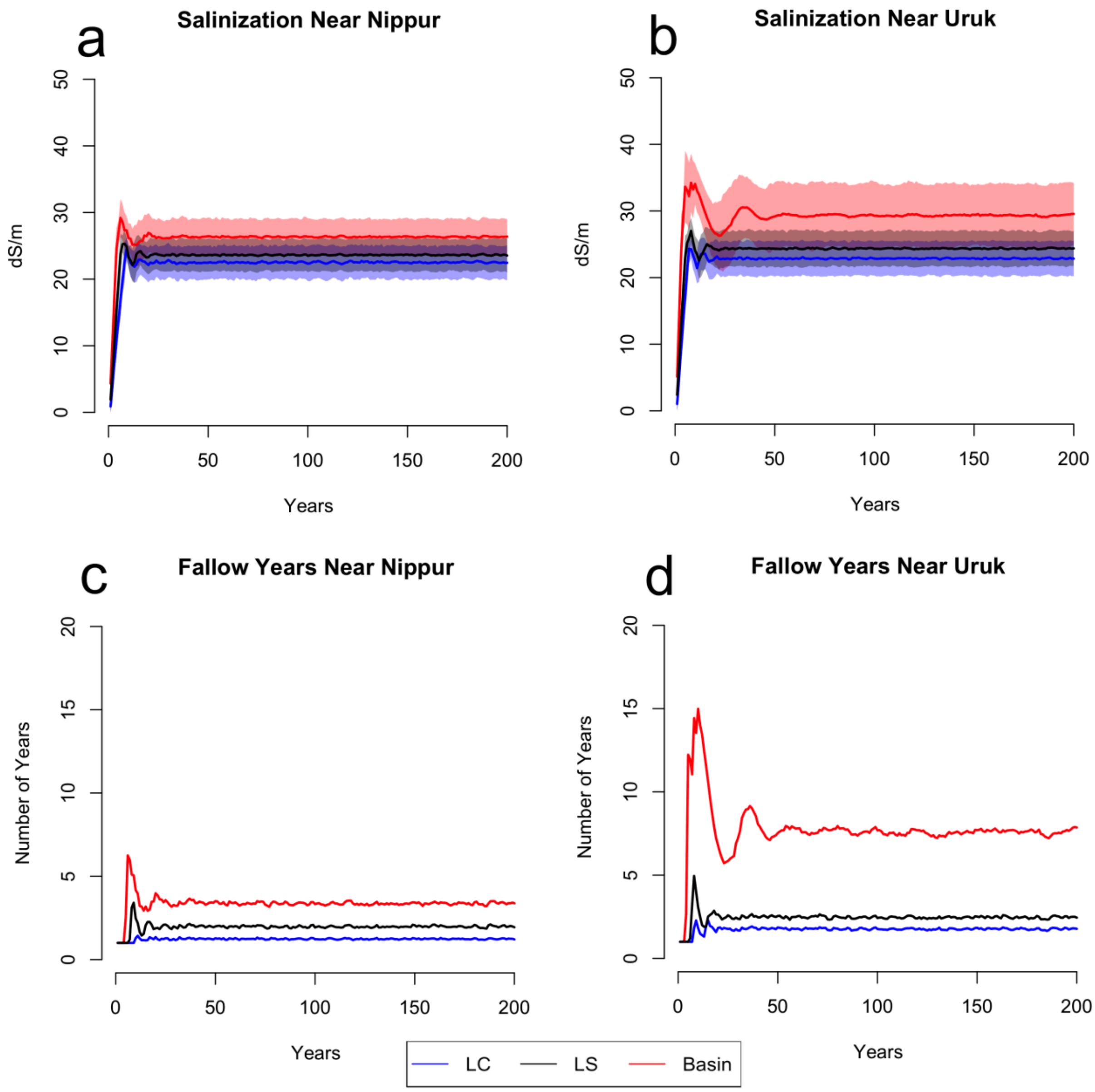

Fig. 13.9 Average root zone salinity (dS/m) and number of fallow years for scenario 4.a for setting ST=0.8 and T=10 in the Nippur (a&c) and Uruk (b&d) regions. The shaded colors in a&b indicate one standard deviation in the results. In all cases the flood basin soils are represented by the top curve, the levee slope the center curve, and the levee crest by the lowest curve.

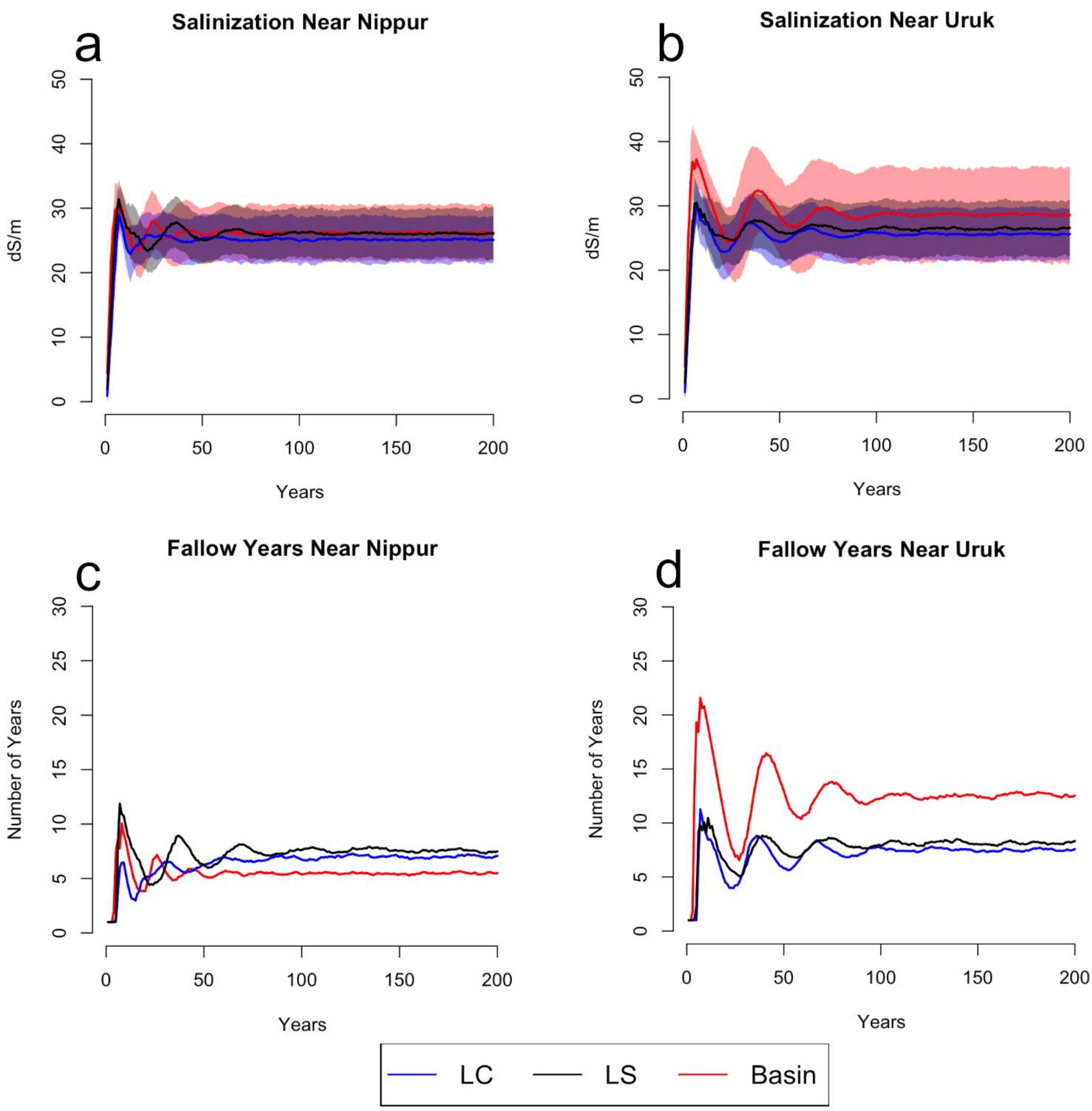

Fig. 13.10 Root zone salinity (dS/m) and average number of fallow years for scenario 4.b in the Nippur (a&c) and Uruk (b&d) regions. The shaded colors in a&b indicate one standard deviation in the results. In b & d) the basins soils are indicated as the top curve, in c) the basin soils are indicated by the lower curve. In the case of a) their is little difference between all 3 curves.

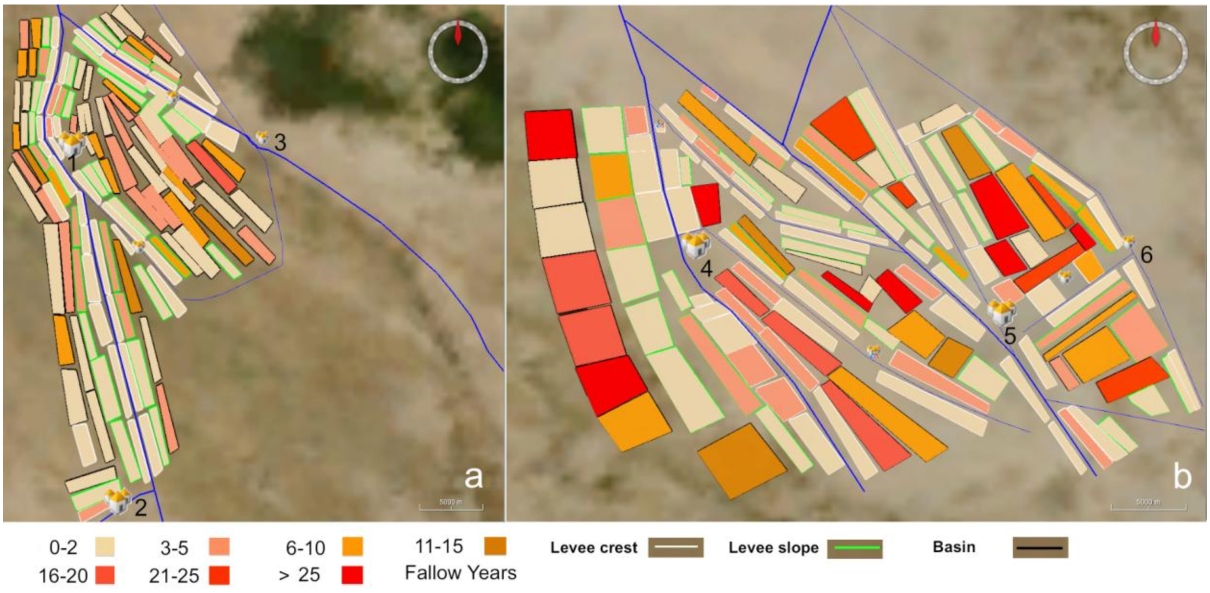

Fig. 13.11 Fallow years shown for different fields in scenario 4.b in the Nippur (a) and Uruk (b) regions. Numbers 1-6 represent Nippur, Isin, No. 1071, Uruk, Larsa, and Tell Abla respectively.

DISCUSSION AND CONCLUSIONS

The scenarios applied in this chapter demonstrate how progressive salinization could have affected agricultural developments in southern Mesopotamia. First, from scenarios 1 and 2, it is clear that salinization could become a significant problem in areas of southern Mesopotamia where capillary rise is a critical factor. Such capillary rise could negate advantages seen in better-leached fields such as those along levees. In scenario 2, LC, LS, and B fields did not attain a salt balance after 200 years. Based on these results, mismanagement by over-irrigation would lead to rapidly diminishing yields.

Scenario 3 introduces a crop management scheme whereby extra fallowing is allowed so that the high water table can be reduced and the salt content of such fields can be reduced by leaching. In scenario 3.a, fallow years are extended, on average, between one and two years for LC and LS fields, for both the Nippur and Uruk regions, and between two and three years for basin fields in the Uruk region. This extension of fallow is sufficient to dramatically improve yields. Although in all cases fields are still affected by root zone salinity, the average yields indicate that the effects of capillary rise could be mitigated by simply conducting extended fallowing as required, or over a period of a few years. Scenario 3.b shows that very high rates of capillary rise can affect yields even more profoundly. However, if such salt-affected yields could be sufficient to provide for settlement yield requirements (that is, cereal demand), then even relatively high capillary rise could be manageable. Nevertheless, when there is less flexibility to leave fields fallow for extended periods and there are insufficient spare fields less affected by salt, this could result in both agriculture and associated settlements being vulnerable to crop failures or considerable agricultural shortfalls.

Scenario 4 is intended to show that, although it is possible to reduce progressive salinization with extended fallowing, root zone salinity becomes more difficult to alleviate as irrigation water increases in salinity. In both the Nippur and Uruk regions, this scenario demonstrates that when irrigation salinity exceeds 5.0 dS/m, yields decline markedly. Once salinity is increased to 7.0 dS/m, irrigation agriculture becomes largely impractical for all types of fields, as even the best yields are reduced by 70%. That is, many years of fallowing are needed to reduce even the best-leached fields. This creates problems with overall yields because, in aggregate, longer fallow periods reduce total productivity since there are many consecutive years with no production. This suggests that irrigation salinity becomes difficult to manage when it is greater than 5.0 dS/m, as yields become severely reduced. Moderate levels of capillary rise, such as within the range used in scenario 3.a, might be manageable by practicing extended fallowing; however, high irrigation water salinity is not as easily addressed since fields need to remain fallow for much longer periods.

To summarize the overall results and their significance: simulations suggest that high water tables, and associated capillary rise, could be relatively contained through extended fallowing. Capillary rise could be a problem when crops are managed poorly, as over-irrigation contributes to a high water table and thus greater capillary rise; however, as long as farmers practice sufficient fallowing strategies that promote the leaching of salts, and capillary rise is not too extreme, then it would be a relatively minor problem. This may explain why salinity was not necessarily a problem for long periods during the third millennium BC and earlier. Irrigation agriculture in southern Mesopotamia, even where there is a moderate risk of capillary rise, does not necessarily result in dramatically reduced agricultural production, as long as extended fallowing systems are maintained and extra fields can be brought into cultivation to allow salt-affected areas to recover. This answers the first question posed in the introduction, namely, how can root zone salinity be limited?

The second question posed in the introduction concerns the inability of adaptive strategies to limit salinization. This is modeled in Scenarios 3.b and 4, which demonstrate how increased capillary rise and irrigation water salinity restrict agriculture. Scenario 4 shows that strategies used in scenario 3 do not work well if irrigation water becomes too saline, because the root zone becomes heavily salinized and much longer fallow periods are needed to reduce salinity. Scenario 4 mimics cases where high aridity, and thus a greater concentration of salt in water, is present (Paranychianakis & Chartzoulakis 2005). The results achieved in scenario 4 are comparable to those demonstrated by modeling for the Diyala region in the Old Babylonian period (Altaweel & Watanabe 2012).

Increased aridity may, therefore, explain why settlements in the Diyala (Adams 1965), Nippur (Adams 1981), and Uruk regions (Adams & Nissen 1972) appear to decline during the Old Babylonian period. Even though some scholars have suggested that more arid conditions prevailed in the first half of the second millennium BC (Issar & Zohar 2007), a direct cause-and-effect relationship between aridity and greater salinization during the Old Babylonian period for the Nippur and Uruk regions remains unclear. It should also be noted that prior to the decrease in settlements that occurred during the Old Babylonian period and later (Chapter 3; Ur 2013), settlements in the three regions mentioned were widespread and many large towns existed. This suggests that over-irrigation was possible given that these settlements would have required large quantities of irrigation, which could have led to results comparable to those of scenarios 2 or 3.b. However, if capillary rise was the most significant inhibitor of agricultural production and therefore settlement, the simulation results suggest that over-irrigation had to be at very high levels for this to be a major problem. In fact, such levels might be too high and not plausible for this issue to be the most significant factor for progressive salinization. More likely, combinations of scenarios 3.b and scenario 4 could explain the occurrence of progressive salinization during the Old Babylonian period. This is because the modeled levels of salinity in irrigation water (i.e., between 5-7 dS/m) seem to be credible values for parts of modern Iraq (Jaradat 2002). Further empirical data showing proxy environmental indicators for greater aridity and salinity in the vicinity of Nippur and Uruk are, nevertheless, needed in order to demonstrate that these factors applied to the Old Babylonian period in the regions modeled. For now, the results achieved by this modeling exercise demonstrate that a combination of social and environmental processes contribute to progressive salinization, through both capillary rise and irrigation salinity. On the other hand, populations could have adapted to progressive salinization if strategies to minimize it were taken. Simulation results not only demonstrate to what extent and under what conditions salinization could be limited; they also indicate that irrigation-induced salinity could have ultimately become a major constraint on settlement and agriculture in southern Mesopotamia if conditions such as over-irrigation and greater aridity became prevalent.

APPENDIX

Below is the mathematical notation for the social-ecological salinization model applied in Chapter 13; as stated, the model code is available in PANGAEA (see link provided). The model is based on the one published in Altaweel & Watanabe (2012); however, specific updates have been made to the capillary rise and leaching functions within that model. Therefore, the functions found in that publication, along with those found in this chapter, are presented together. Figure 13.1 can be used as a guide to the model's functionality, with the numbers shown in this figure being referenced here and placed within parenthesis (e.g., (13.1-1) for step 1 in Fig. 13.1). For instance, a representation of (1) would indicate the first function that is discussed in this section. The model notation below largely applies variables commonly used in the irrigation-related literature. Some variables indicated in Table 13.2 and shown in the model notation apply standard deviation values, which are used in normal distributions and in the present model to create values from a random number generator.

The model begins with a check, occurring once a year, in the Agriculture Step (13.1-1) to determine if a field should either remain fallow and be leached or be irrigated and cultivated. The decision to determine if a field should be left fallow and leached is based on a predetermined crop rotation schedule, or whether the farmer had previously and deliberately chosen not to crop for a period beyond the regular fallow schedule (13.1-6). For fields that remain fallow, salt is leached through a leaching decay function. If a field is irrigated, then a capillary rise function is scheduled for that year. Capillary rise can also take place during fallowing; however, the leaching function accounts for this. The general function is then stated as:

$$NC_f < FA_f \rightarrow C'_{sf} = C_{0sf} * e^{-LF_f E_{lf} NC_f}$$
$$NC_f \geq FA_f \rightarrow C'_{sf} = 2 * (EC_{ef} + (\frac{1.5 J_f (EC_{wtf}) S}{d_f} \qquad (1)$$

where NC is the number of years a field (f) has remained fallow, FA the number of years a field should remain fallow, which is typically 1 unless modified (8-below), and C_s root zone salinity. The C_{0s} value represents initial salinity in the root zone at the time a field is left fallow. For fields remaining fallow (i.e., NC is less than FA for f), root zone salinity (C_s) is reduced using a decay function with C'_{sf} being the modified root zone salinity. In this case, LF is the leaching factor for a specific field (f) that applies leaching efficiency (E_l) and number of fallow years (NC) in the decay function. If a field is to be irrigated (i.e., NC is greater or equal to FA), then C_s is scheduled for capillary rise. In this case, C_s is modified for f by calculating the electrical conductivity in the soil saturation extract (EC_e). This is calculated by taking C_s and dividing it by 2.0, capillary rise (J) in meters, water table conductivity (EC_{wt}), the ratio of root water uptake (S) (assumed to always be 1.0 for all fields), and the thickness of the soil layer (d) in meters for f. Multiplying the result by the ratio 2.0, converts the soil saturation extract to root zone salinity; this ratio was also used for determining EC_e above (Maas & Hoffmann 1977; Prendergast 1993).

Whereas a fallow field has no further functions for the remainder of the year, a field that is scheduled for irrigation, or when NC is greater than FA, is subsequently planted using the 'Plant method' function? equation? (Fig. 13.1-2) during the autumn. This prepares the field for the irrigation process and instructs the model to irrigate during that year. In parallel, a Metropolis-Hastings Markov chain function is used in 'Rainfall' (Fig. 13.1-3), which produces the rainfall values in the area during the year. Next, when irrigation is scheduled to occur, the main Irrigation method (Fig. 13.1-4) triggers the sub-process 'Root Salinity' (1.4a), which is stated as:

$$C'_{sf} = C_{sf} + 0.5K * C_{if}(1 + 1 / LF_f) \qquad (2)$$

where the modified root zone salinity (C'_s) for f uses the empirical coefficient (K), water salinity (C_i), and a leaching fraction (LF). Both K and LF are model inputs, with K being used for all fields rather than being a specific field value (see Tables 13.1 and 13.2). For C_i, the 'Applied Water Salinity' sub-process (Fig. 13.1-4b) is used:

$$C_{if} = R^* C_r + W_f * C_{wf} / (R + W_f) \tag{3}$$

with R, representing rainfall amount in meters, now applied and adjusted for runoff (i.e., determined in the Markov rainfall process (Fig. 13.1-3)), C_r reflecting rainfall salinity, W infiltrated irrigation depth, and C_w the salinity of infiltrated irrigation. Both C_r and C_w are model inputs, while infiltrated irrigation depth (W) is determined by the 'Irrigation Water' sub-process (Fig. 13.1-4c):

$$W_f = I_f - R \tag{4}$$

where I represents applied water. The 'Applied Water' sub-process (Fig. 13.1-4d) is called to determine I for a field:

$$I_f = \frac{CW}{K_y(1 - LF_f) * (Y_f + K_y - 1)} \tag{5}$$

with CW representing crop water, K_y the yield response factor for all fields, Y the yield (measured between 0.0-1.0; 0.0 reflects no yield due to salinization and 1.0 indicates no adverse effects from salinization), and LF representing the leaching fraction for a field. All values, except CW, are inputs. Crop water is determined by the 'Crop Water' (Fig. 13.1-4e) sub-process:

$$CW = 0.85 K_c * E_p \tag{6}$$

with K_c representing crop coefficient and E_p pan evaporation, which are both model inputs. This last sub-process allows root salinity to be determined in (2). Based on root salinity, yield can now be determined in the 'Crop Yield' (Fig. 13.1-5) function:

$$Y_f = 100 - B(\frac{C_{sf}}{2.0} \tag{7}$$

which applies percent yield reduction (B) for a unit of salinity increase and the threshold salinity value (A), or the maximum salinity with no yield reduction in the root zone. Both B and A are static inputs known from FAO (2012) studies. The 2.0 value is the ratio for converting root zone salinity to soil saturation extract mentioned in (1) above. Based on yield, farmers then decide whether a field should be left fallow and leached for an extended period that lasts beyond normal (i.e., biennial) fallowing using the 'Extended Fallow' and 'Leaching' (Fig. 13.1-6) operation:

$$\begin{gathered} ST_f > Y_f \text{ ® } FY_f = 1 + ((ST_f - Y_f) * T)^2 \\ FY_f > FA_f \text{ ®} \| FA'_f := FY_f \| \end{gathered} \tag{8}$$

in which ST is a salt tolerance value, or the yield level that salt buildup is tolerable (set as an input prior to executing the model), FY is the number of years for a field to be left fallow based on yield loss, and T is a scaling value to regulate the number of fallow seasons. If FY is greater than FA, or the number of years a field should be fallow (see (1) above), then FA is modified to FY’s value and rounded to the nearest integer. This method allows an extended fallowing time beyond regular fallowing to allow for natural, or possibly engineered, leaching of salt. To summarize, yield is used by farmers to determine whether a field is stressed by salinization; if a field is considered sufficiently stressed then a farmer leaves a field fallow for a period beyond regular fallowing as calculated in (8).

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