WATER TABLE RISE AND CONCRETE DETERIORATION IN THE SUBSURFACE ENVIRONMENT

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ABSRACT

Water table rise is one of the severe problems of growing public concern in the Kingdom. It could cause environmental and structural damage if not controlled properly. One of the major problems associated with the water table rise is the contamination and deterioration of subsurface structures that has been reported by many organizations. The extent of concrete deterioration depends greatly on moisture rise in the subsurface environment which is an integral part of the complex natural groundwater system. The position of water table significantly influences the process of moisture rise in both soil and buried concrete structures. The effect of moisture rise in the subsurface environment on the structures is not limited to the bearing capacity of the foundations but also has a major influence on the integrity of the substructures. Shallow water tables in coastal areas have high concentrations of different salts that attack, chemically, the substructures. The effect on structural materials is intensified when the material is chemically reactive or can disintegrate in the saline environment. This paper presents some of the results of a preliminary investigation on the behavior of a coastal water table with a particular reference to the impact of water table rise on concrete deterioration in the subsurface environment. We conclude that this complex problem due to the harsh chemical attack of the groundwater is of major concern in the Kingdom that demands comprehensive investigation of the integrated system dynamics of groundwater flow, moisture rise, and the corresponding movement of water and contaminants in the embedded concrete structures. An advanced computer-based model that promises a better prediction of the relationship between the groundwater fluctuation, moisture rise in soil and the corresponding water flow and chemical movement in underground concrete structures appears to be an essential tool for assessing the potential threats of corrosion and other types of deterioration due to contamination in subsurface structures. The model predictions also help in design and evaluation of remedial alternatives.

KEYWORDS

Water table, moisture rise, concrete deterioration, subsurface environment, groundwater contamination, groundwater modeling, capillary rise.

Field measurements in the study area indicated the possibility that free moisture due to capillary rise in reinforced concrete buildings exists at a greater height than expected, Such a rise in moisture which is an integrated part of water table rise phenomenon would promote deterioration of the buried structures such as foundations, pipes, and other underground facilities. Therefore, it appeared essential to initiate a preliminary investigation to establish a better understanding of the processes by which contamination and deterioration of materials occur in concrete structures in the study area. The objectives of this study were to (i) develop an understanding of the impact of salt content in soil and/or groundwater on moisture rise above the water table in fine-grained composite soils, and (ii) to analyze the water table fluctuation in the study area.

This research work was conducted in three main studies. These are (i) laboratory study, (ii) field investigation, and (iii) simulation and modeling of water table fluctuation. This paper presents a brief description and some of the results of these three studies with a particular emphasis on the importance of an integrated modeling approach for comprehensive investigation.

LABORATORY STUDY

The laboratory study consisted of the construction of three sets of soil columns and monitoring of moisture rise in these columns as a function of time until the moisture rise became stable. Three trial tests were conducted in the laboratory using these soil columns. The results of the trial tests helped in (a) developing a procedure to produce required compaction in the soil columns, (b) developing a procedure to obtain samples from the soil columns at different locations, (c) improving the design of the soil columns, (d) understanding the type and quantity of material required for construction of the columns and developing construction procedures, and (e) developing preliminary data on the effect of contamination on capillary rise in soil columns.

The details of the trial tests are summarized in Table 1. In the first group, two soil columns using clean sand and clean water were used. The second trial test consisted of two columns using soil with 5 percent NaCl and clean water. The third trial test consisted of eight soil columns. Two different sizes of columns (diameters 190 mm and 287 mm) were used in all trial tests. The columns were built in duplicate and contained clean and contaminated soil with clean and contaminated water in different combinations. For contaminated water, sabkha groundwater (brine) was used at 50 percent dilution. For soil contamination, 5 and 10 percent NaCl was mixed with the soil.

Results of the first (without salt) and second (with salt) laboratory trial tests are shown in Figure 1, where the small diameter soil column shows a higher capillary rise of water than the large diameter soil column. This is most probably due to the higher compaction of soil resulting in higher density and thus smaller voids in the small diameter soil column. This was attributed to the low capacity of the vibrator used. The small diameter column was vibrated to higher compaction than the large diameter column due to the low mass of sand in the column.

The moisture rise pattern observed in the third trial test is presented in Figure 3. The results of all laboratory tests clearly show that as the salt concentration (contamination) in the soil and/or water decreases, the capillary rise increases. High capillary rise was observed in columns containing clean sand even when the fluid was diluted sabkha brine. However, the highest rise was observed for clean sand and potable water. One explanation for the phenomenon is that dissolved salt in water slightly increases its surface tension and thereby lowers the capillary potential of the soil.

Table 1. Summary of trial tests showing number of columns used.

Test	Clean Water Clean Soil	Clean Water Contaminated[3] Soil	Clean Soil Contaminated[3] Water (50% Groundwater [4]	Contaminated[3] Soil Contaminated[4] Water
1. First Trial	2	-	-	-
2. Second Trial	-	2[1]	-	-
3. Third Trial	2	2[2]	2[1]	2[2]

[1] 5% NaCl [2] 10% NaCl [3] Contaminated [4] Groundwater

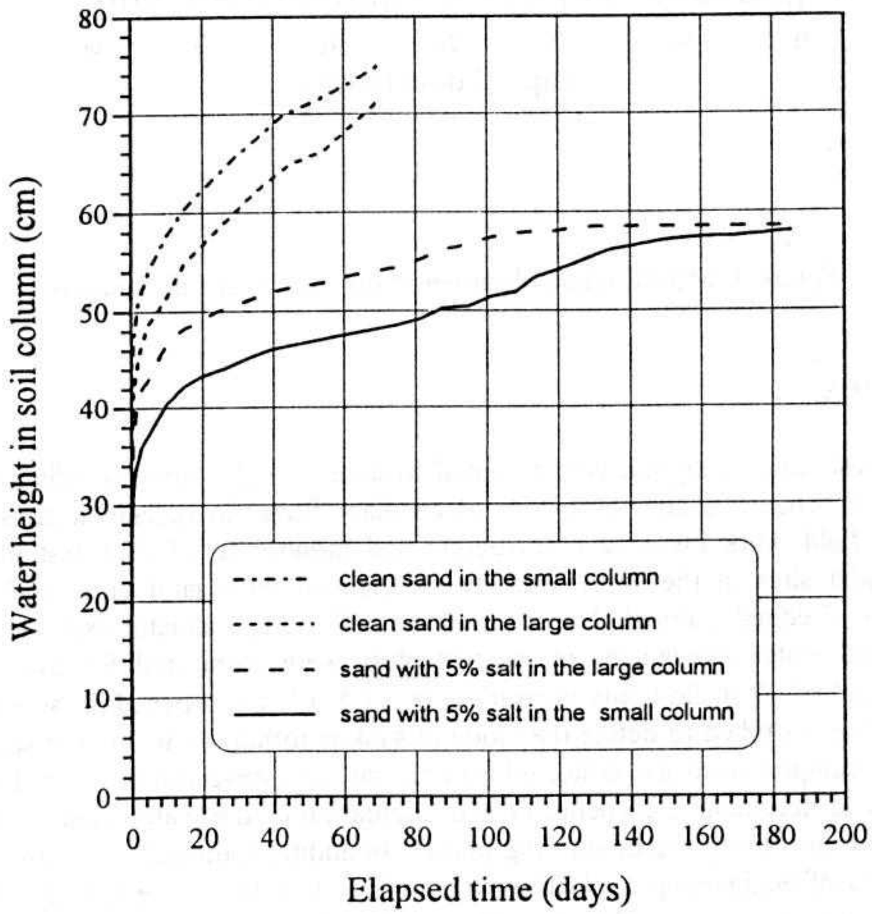

Figure 2. Moisture rise observed in the first and second trial soil columns.

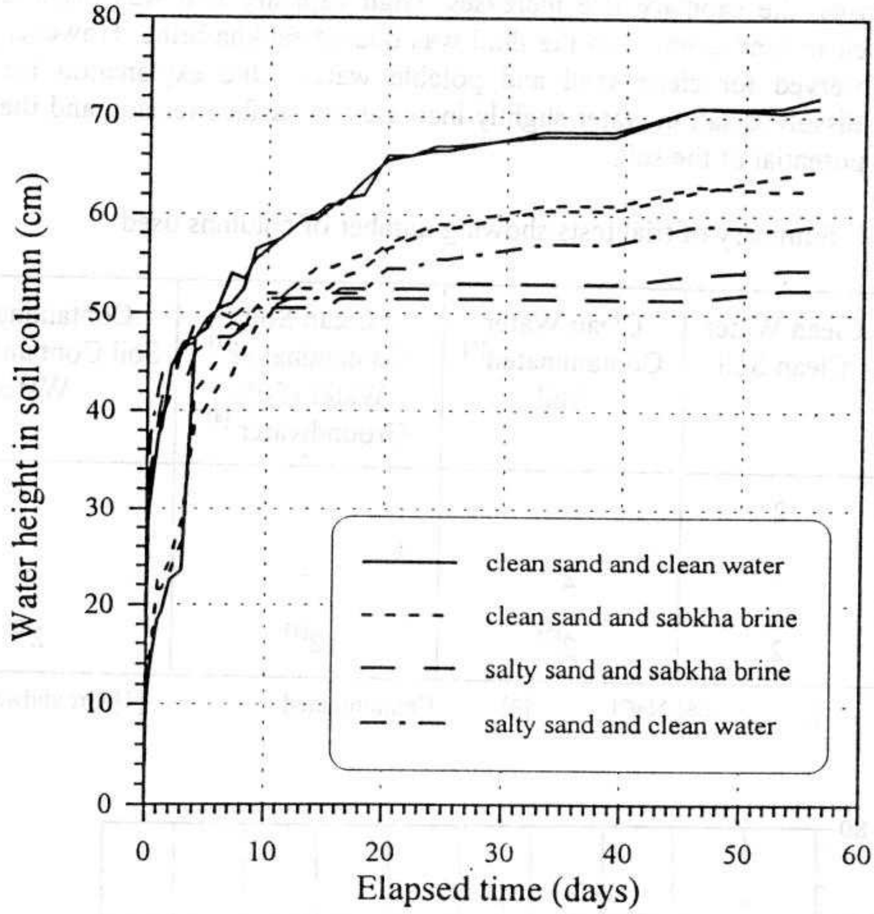

Figure 3. Moisture rise observed in the third trial soil columns.

FIELD STUDY

The field investigation program was designed to build a better understanding of moisture and salt rise mechanisms and the extent of capillary fringe in reclaimed soils placed on sabkha. The field work involved constructing and monitoring of four test plots at two selected sabkha sites in the study area, two reclaimed with sand dune and the others reclaimed with dredged material. The scope of the field study was later expanded to 20 test plots. Salt and water movements in the test plots were monitored for over a year. In addition, a total of 40 shallow pits measuring $1*1*1.5\ m^3$ were opened along two profiles. Soil samples were studied to define the mode of sabkha formation within the selected sites. Groundwater samples were also collected from the selected observation wells in and around the test plots to determine the chemistry and fluctuation of the water table as affected by seasonal variations during the monitoring period. In addition, the natural setting of sabkha and the effects of engineering applications on sabkha dynamics were tested within the 16 test plots. A summary of the field work is presented in Table 2.

Table 2. Summary of field work.

1	Test Plots	20	Test plots were established at two undisturbed sabkha locations and monitored for 12 months. 16 of the plots were part of additional work.
2	Observation Wells	25	Wells around the test plots were monitored to study water regime in the selected sites.
3	Pits	40	Shallow pits of $1*1*1.5m^3$ were dug and studied
4	Natural setting of Sabkha in the selected area		Geological, shallow hydrogeological, physiographical, osmotic sediments.

The moisture rise and distribution in dune sand (DS) and dredged materials (DD) observed in one of the test plots are shown in Figures 4 and 5 which show that the moisture moved upward in both soils (DS and DD) and reached a maximum height of 75 cms above the water table after 156 days from the start of field monitoring. Figure 6 illustrates the progress of moisture movement in both soils with time. The chloride contents, selected as an indicator of salt, were found to migrate from the sabkha brine and precipitated within the pores of the soil materials (Figure 7). The salt distribution along the soil profile ranged from 80 t0 2000 mg/L. The distribution of salts in the pores of the soils was highest at the groundwater level and decreased gradually upward. Maximum height of salt movement reached 75 cm (Figure 7) which is in close agreement with the depth of the capillary fringe (Figures 5 and 6).

SIMULATION AND MODELING

The main objective of this preliminary simulation and modeling exercise was to establish the general nature and behavior of the groundwater system in the study area. It included the formulation of a conceptual model based on available geological and groundwater-related information involving accepted principles of groundwater hydrology. This conceptual model then provided the basis for the study of flow behavior in the subsurface environment by applying a detailed dynamic computational model suitable for the groundwater system under investigation.

Available information on groundwater monitoring network details, area topography, water table fluctuation and groundwater quality monitoring data, aquifer characteristics, irrigation and landscaping water application, and the tidal history were also collected, reviewed and analyzed. The existing monitoring network consists of about 400 observation wells. Groundwater monitoring data for about 200 observation wells, selected on the basis of their operational conditions, were collected for a period of 159 months (i.e. from August 1988 to October 1993). The preliminary analysis of the raw data revealed that regular monitoring of water table fluctuation on monthly basis started from September 1988 and continued for 16 months. After April 1990, water table observation data is available for the month of October 1990, 1992 and 1993 only. Contour maps of water table positions at various time levels have been prepared and analyzed to understand the dynamics of groundwater flow system.

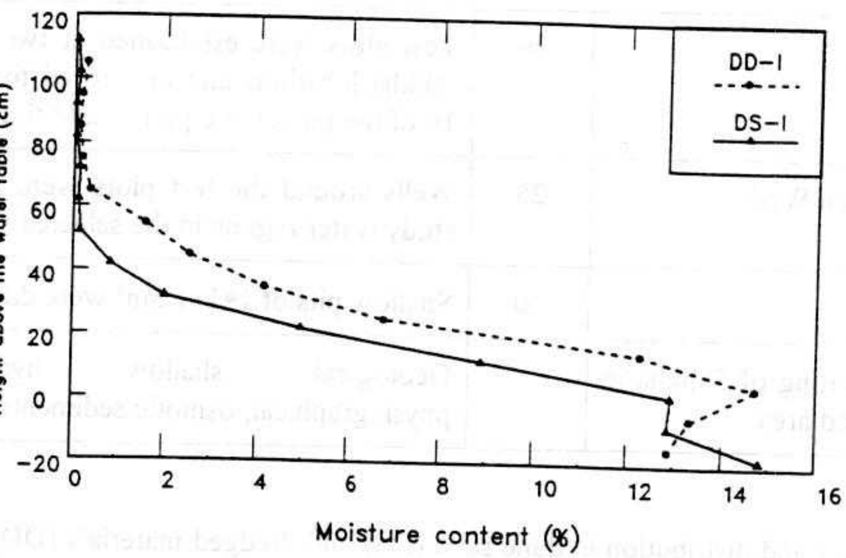

Figure 4. Moisture profile above water table observed in September 1993.

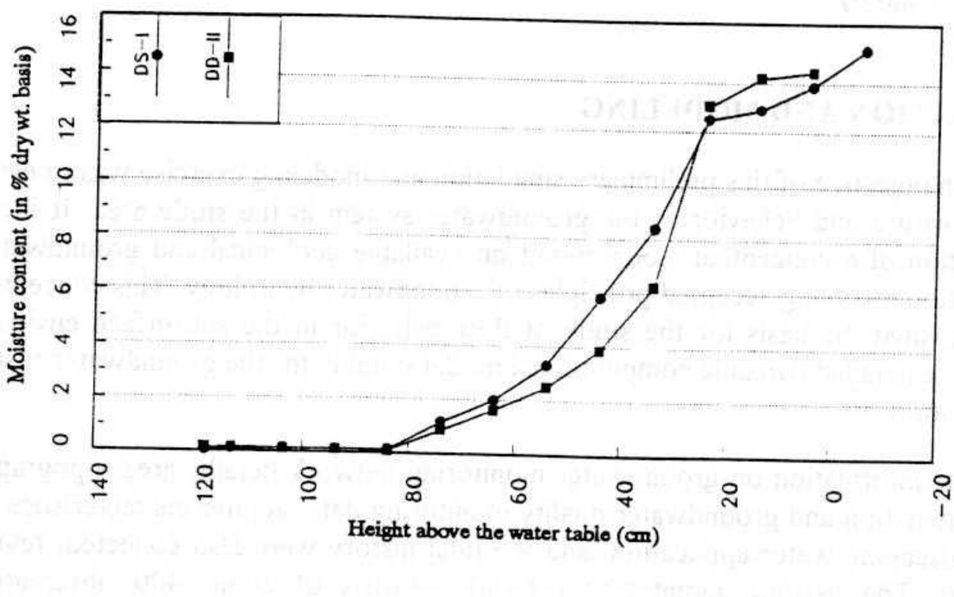

Figure 5. Moisture profile above water table observed in January 1994.

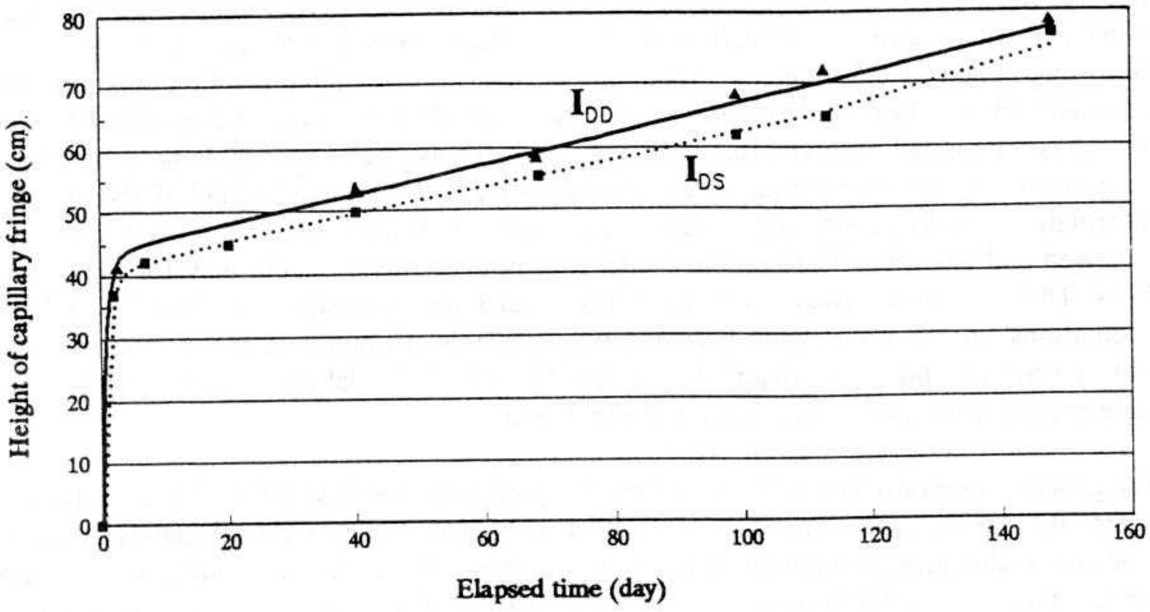

Figure 6. Height of capillary fringe observed between August 1993 and January 1994.

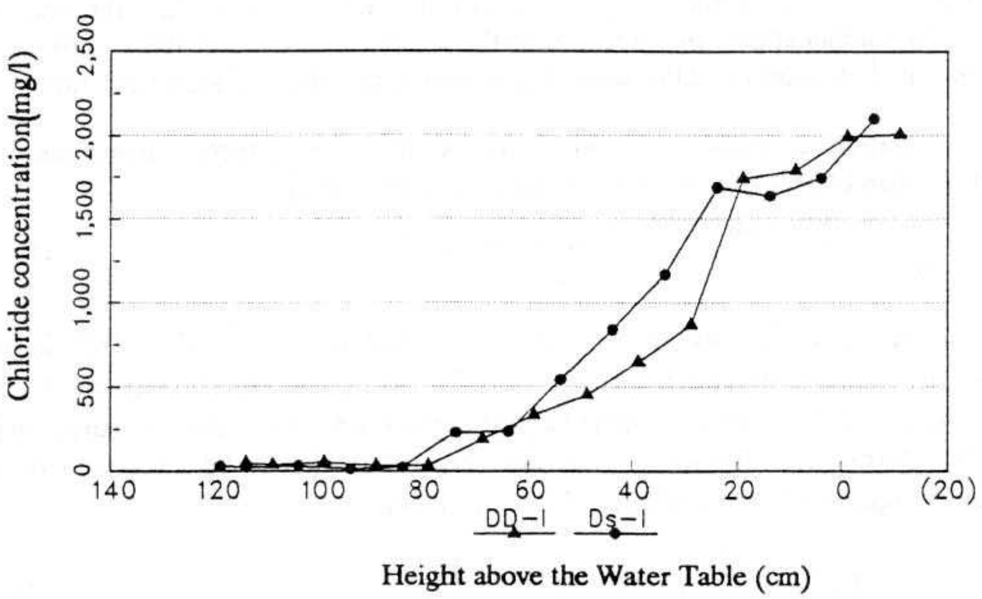

Figure 7. Chloride distribution in soil observed in January 1994.

The analysis of groundwater monitoring data for the selected period indicated a maximum water-table fluctuation of 3.40 meters, a minimum fluctuation of 0.08 meters with an overall mean fluctuation of 0.57 meters. Maximum change in water table position was observed between October 1992 and October 1993. The most obvious cause of this unusual rise is the excessive rainfall observed that year. However, the average water-table position change observed during this monitoring period was negligible with a cumulative fall of about 4 cms. Information on irrigation and landscaping water application has also been collected, reviewed and analyzed. The predicted tidal history data was available only for the year of 1994. This tidal data however was not utilized since no information on the effect of tidal fluctuations on the water table behavior was available. Continuous monitoring of water table position is, however, required to assess the effect of tidal fluctuations on the water table and incorporation of tidal effects in simulation.

The general observation to be gleaned from the preliminary analysis of available information is that the aquifer under investigation is of a complicated nature that demands advanced modeling techniques for a comprehensive investigation. The water table fluctuation patterns for most of the observation wells were found to be of a random nature, indicating the presence of a significant influence of various natural and man-made factors due to rapid urbanization and development in different sectors in the study area.

Based on the conceptual model developed for the study area, a two-dimensional transient flow field, which appears to be a good approximation of the real three-dimensional aquifer, was assumed since the governing equation for the two-dimensional case can be obtained by integrating the general equation over the thickness of the aquifer [Pinder and Gray, 1997]. In addition, the governing equation obtained by integrating over the aquifer thickness helps, with reasonable accuracy, in analyzing the multilayer aquifer system using the concept of quasi-three-dimensional approach. Because of the existence of a water table in the aquifer, both the water table position and the saturated depth are functions of space and time.

The general equation describing unsteady groundwater flow in three-dimensions can be written in Cartesian coordinate system [Mercer and Faust, 1980] as

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})+R=S_s\frac{\partial h}{\partial t} \quad (1)$$

Where, K_{XX}, K_{YY} and K_{ZZ} are the hydraulic conductivities in X, Y and Z directions respectively, h is the hydraulic head, and $\partial h/\partial x, \partial h/\partial y,$ and $\partial h/\partial z$ are the hydraulic gradients in X, Y and Z directions respectively. R is the source/sink term (recharge, leakage or evaporation rate). S_S is the specific storage. Equation (1) may be integrated over the thickness of the aquifer (Pinder and Gray, 1997) to obtain

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y})+W=S\ \frac{\partial h}{\partial t} \quad (2)$$

Equation (2) is an aerial groundwater flow equation where T is the transmissivity, S is the storage coefficient and, W is the source and/or sink term. In water-table aquifers, the transmissivity is a function of hydraulic head. Following Bredehoeff and Pinder (1970), equation (2) can be written as,

$$\frac{\partial}{\partial x}(K_{xx} b \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy} b \frac{\partial h}{\partial y}) + W = S_y \frac{\partial h}{\partial t} \quad (3)$$

Where Sy is the specific yield of the aquifer and b is the saturated thickness. It should be noted here that the above equation (3) is a nonlinear partial differential equation (PDE), because b depends on head.

The solution of equation (3) with appropriate boundary and initial conditions represents the predicted behavior of the water table. Numerous numerical models are available that solve equation (3) for different boundary and initial conditions. After an extensive review of available models, the most widely used groundwater simulation package, $MODFLOW^{EM}$, developed by USGS (McDonald and Harbaugh, 1988), has been selected to simulate the flow conditions in the study area. The selected computational model (MODFLOW) was then tested and validated for a more general case of a complex aquifer having various features such as various types of boundary conditions, pumping, recharge wells, or both, and distributed source, rivers and lakes, etc. In all cases, the model predictions converged to the same steady state results reported in the MODFLOW literature. After validation, the selected groundwater model was calibrated by matching the model predictions with those observed from the groundwater monitoring program at selected points inside the study area. A rectangular area of 294.32 km^2 covering the monitoring network of about 200 selected observation wells was selected as the problem domain for this investigation. A finite difference technique was used in the development of the computational model selected for this study. Accordingly, the selected problem domain was divided into a total of 2091 rectangular cells (Figure 8). Based on their positions with respect to the irregular area (134.69 km^2) covered by the selected observation wells, these cells are classified as inactive and active assigning the codes of 0 and a zone number (1,2,....107) respectively (Figure 8). The active cells were used in both calibration and simulation. The water-table elevation and depth were computed at the centroid of each cell at various time horizons.

The preparation of the model input data involved the computation or determination of the values of various model parameters for each cell in the mesh. These values were obtained from the available information at specific points in the domain using suitable interpolation techniques, extrapolation techniques or both. The two fundamental properties of the aquifer, the hydraulic conductivity and the storage coefficient, were estimated from the very limited information. The initial estimates of hydraulic conductivity were made from the field values provided for few locations in the study area. The study area was divided into 107 active zones to account for the heterogeneity in hydraulic conductivity of the aquifer. The average of the optimized values of hydraulic conductivity in 107 active zones of the active cells was found to be $3.7X10^{-6}$ m/sec where the field value obtained from the pumping test was $3.68X10^{-6}$ m/sec. The hydraulic conductivity in both x and y-directions was assumed to be the same. No information was available on the specific yield and the layering details of the aquifer. Therefore, a constant value of 0.10 for the specific yield was assumed which is within the usual range (0.01 to 0.30, Freeze and Cherry, 1979). Similarly, a single layer shallow unconfined aquifer of constant bottom elevation at -15m was used in both model calibration and simulation. The preliminary analysis of the water table monitoring data indicated no constant/specified head along the boundaries of the irregular domain. The active cells on the boundary were considered as a flux boundary having a specified inflow or outflow rates, determined by the proper matching of the simulated and observed water-table elevations during the process of calibration. The average inflow and

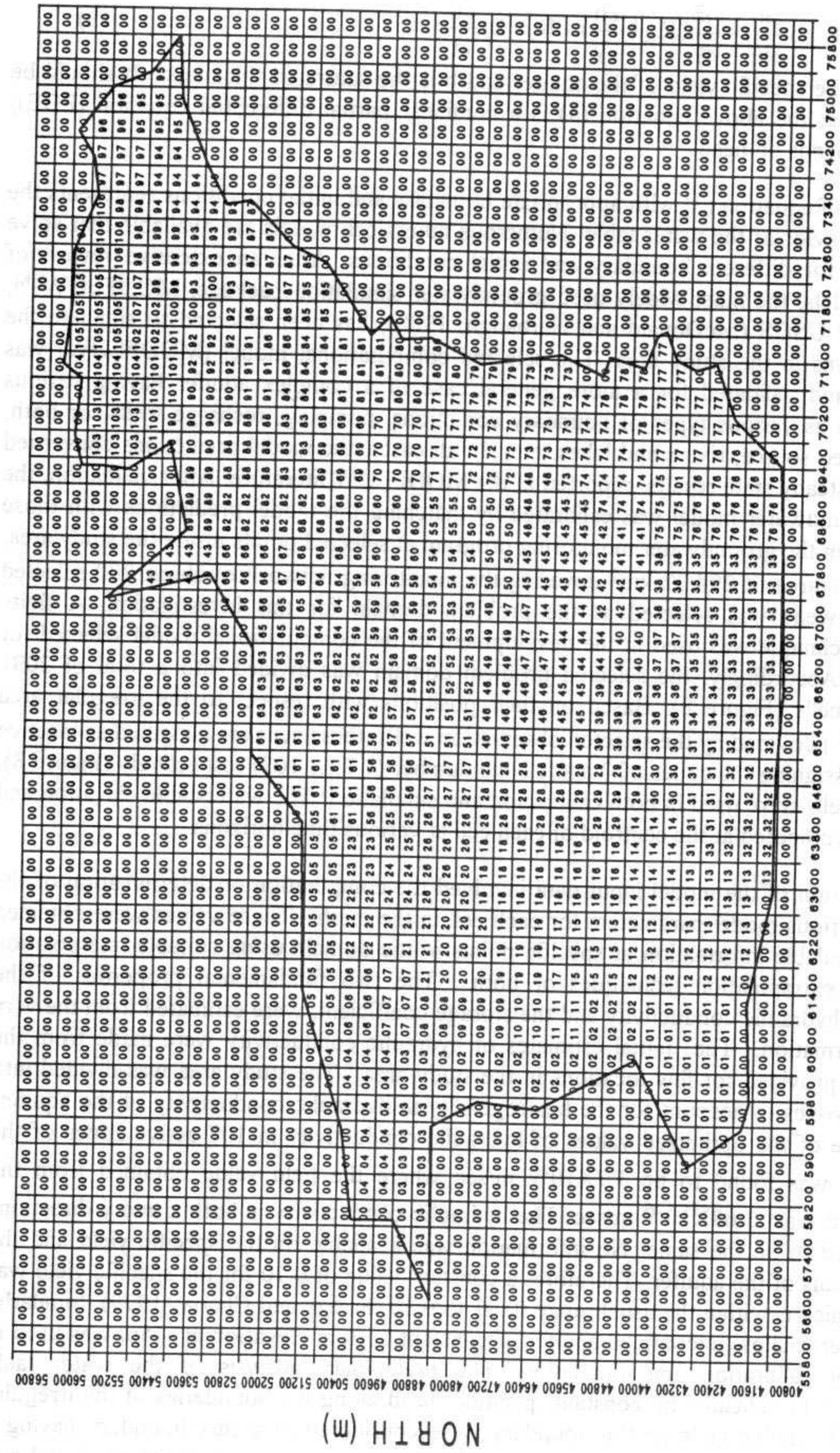

Figure 8. Zones of hydraulic conductivity variations (0 to 107).

outflow rates were determined for the selected calibration period of 12-month (October 1992 to October 1993) in order to be used for future prediction of the water-table behavior under different scenarios to be investigated.

The month of October 1992 was selected as the starting time for simulation in the calibration process. The observed values of water-table elevations at the centroid of various cells, which were estimated from the observed values in 198 observation wells of the monitoring network in October 1992, were used as the initial water-table position for the transient simulations.

The effects of various natural processes—such as evaporation, precipitation, and unknown natural and human-induced factors, for example, land-scaping and irrigation, the presence of underground structures, leakage from underground pipelines and drainage system, or other flow diversion factors such as pumping from specific locations and dumping inside the study area, or natural unknown barriers causing flow diversion, etc.—were incorporated in terms of discharge or recharge from the respective cells.

The simulation model was calibrated for a period of 12 months (October 1992 to October 1993) by a method of history matching using MODINV which utilizes an optimization technique to make necessary adjustments in various influencing factors to obtain a satisfactory match between the observed and the simulated values of the water-table positions at each active cell. The comparison of the simulated and observed values of the water-table position is given in Figure 9. A value of $8.44126X10^{-2}$ for the deviation index (defined as $\sum_{i=1}^{np}(H_s - H_o)^2$ where, np is the number of active cells excluding those close to the inactive cells, H_S, and H_O are the simulated and observed water-table elevations respectively) was accepted as satisfactory.

The values of net discharge or recharge rates necessary for a satisfactory match between the observed and simulated position of water table at various active cells were determined by the optimization technique using MODINV during the process of model calibration, which included considering the prevailing natural and human-induced conditions. The initial overall recharge scenarios were obtained from simultaneous optimization of hydraulic conductivity and recharge in 107 zones. The final net recharge rates at each active cell were determined by further optimization of cell recharges keeping the hydraulic conductivity values fixed at the optimized cell values computed from 107 zonal values using linear interpolation..

The selected simulation model, after proper calibration, was used to quantify various components of the overall groundwater system and to predict the groundwater behavior under various scenarios. The future behavior of the water table was predicted for the next five years, starting from October 1993, using the calibrated model. The first run investigated the worst case, assuming the rainfall total from 1992 to 1993 (190 mm). The other two runs were made to study the effect of 25% and 50% reduction in overall recharge scenarios on the behavior of the water table. A summary of the predicted effect is shown in Table.3. The extreme water table change patterns under various conditions are presented in Figure 10.

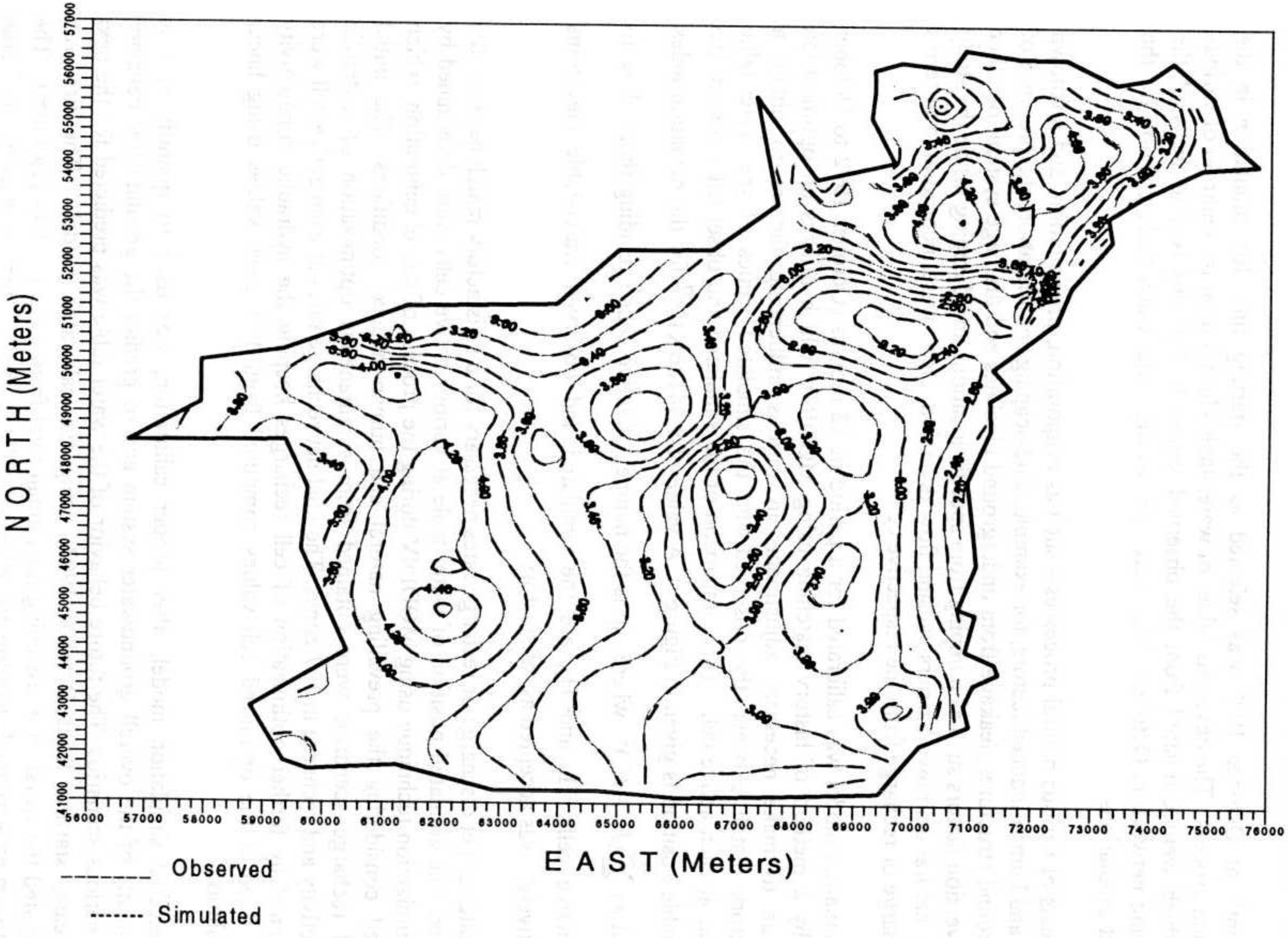

Figure 9. Comparison of simulated and observed water table elevations (October 1993).

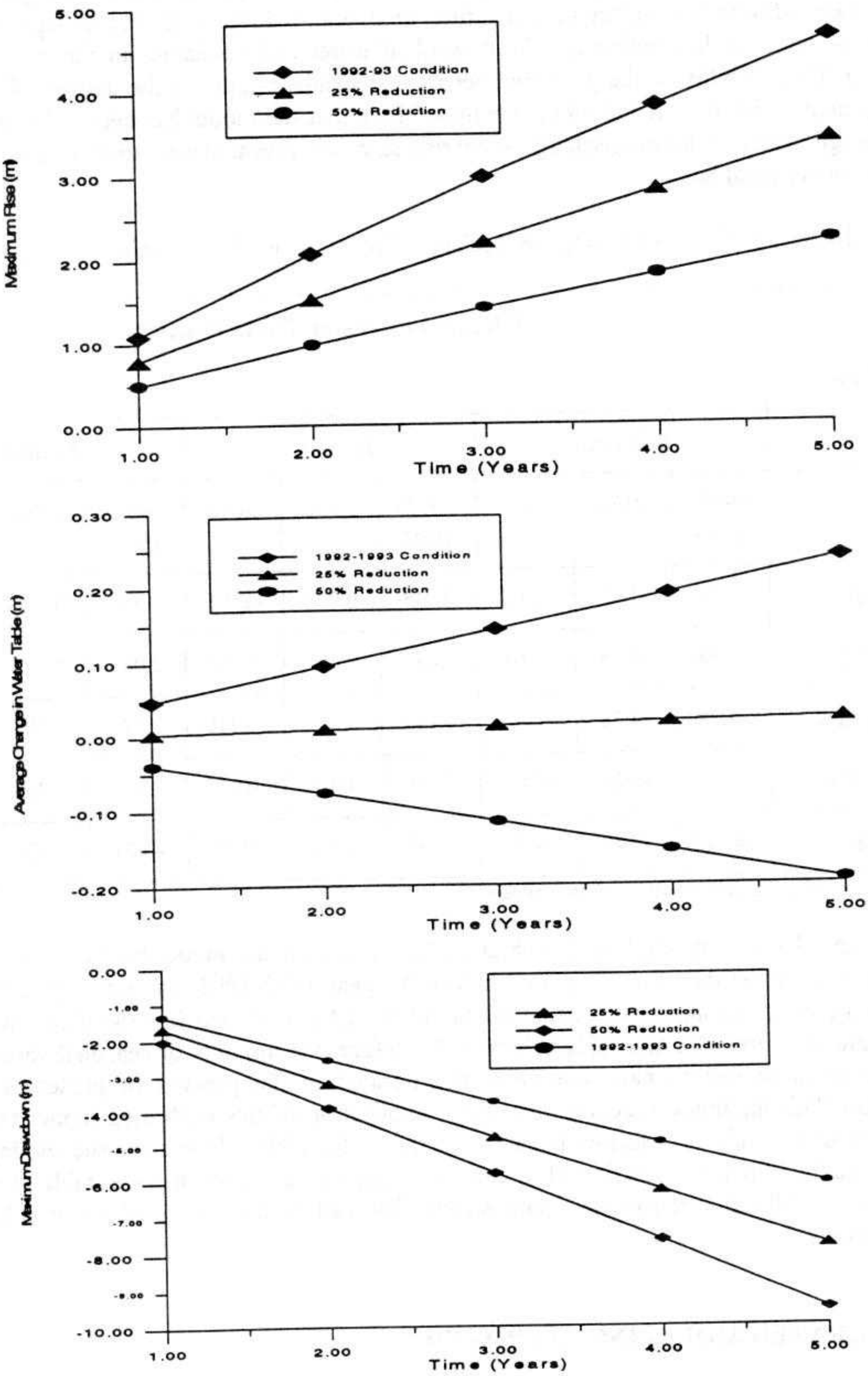

Figure 10. Simulated Water Table Change pattern with time under various conditions.

It can be concluded from this preliminary investigation that if no significant changes in the prevailing conditions takes place in near future, an overall reduction of net recharge by 25% appears to be a viable solution for the control of water table behavior in the study area. However, the reliability of the predicted behavior depends greatly on the degree of further development in the area. It should be mentioned here that the model has been calibrated for the average yearly recharge-discharge scenarios since no recent observation was made on monthly or seasonal basis.

Table X.3. Effect of Change in Recharge Scenarios on Water Table Position

Time	**Changes in Water Table Position**								
	Minimum			Average			Maximum		
	1992-1993	25%	50%	1992-1993	25%	50%	1992-1993	25%	50%
One Year	-1.32	-1.67	-2.01	0.048	0.004	-0.039	1.08	0.79	0.50
Two Years	-2.58	-3.25	-3.93	0.095	0.009	-0.077	2.065	1.518	0.969
Three Years	-3.78	-4.78	-5.8	0.143	0.013	-0.116	2.978	2.194	1.405
Four Years	-4.95	-6.28	-7.64	0.19	0.018	-0.115	3.823	2.823	1.813
Five Years	-6.113	-7.80	-9.55	0.238	0.022	-0.19	4.621	3.420	2.204

* - indicates drawdown + indicates rise

On the other hand, simulated results obtained by calibrating the model based on available monthly observation data for any period before the year 1992-1993 may not represent the close field conditions since the unusual rainfall observed in that year has significant impact on the natural course of water table behavior. Therefore, the monthly or seasonal variations in the controlling factors have not been incorporated in the process of present model calibration. This limitation precludes the direct application of this calibrated model for the prediction of monthly or seasonal behavior of the water table. However, the model can easily be applied for the prediction of monthly or seasonal variations in water table position by simply re-calibrating the model using recent observation data collected on monthly or seasonal basis.

AN ITEGRATED MODELING APPROACH

The results of this study strongly emphasize the importance of a comprehensive study of the groundwater system that demands an integrated modeling approach to address the complex natural process of saturated-unsaturated flow dynamics coupled with mass transport at regional level and considering the tidal effects. The integrated simulation model should be capable of simulating coupled flow and mass transport in both soil and concrete under saturated and unsaturated conditions considering the effect of tidal fluctuations. This task is pretty complex and challenging because it demands (i) multi-disciplinary expertise for appropriate mathematical representation of the physics of the problem, (ii) incorporation of different physical, chemical and biological processes in soil, water and concrete, (iii) advanced numerical techniques to solve the governing equations, and (iv) huge laboratory and field investigation and monitoring data for the estimation of processes constants and model calibration.

CONCLUSIONS

Moisture rise in the subsurface environment is an integrated part of water table rise phenomenon that would promote deterioration of the buried structures such as foundations, pipes, and other underground facilities. Both laboratory and field studies confirmed that the moisture rise in soil due to capillary action is depressed by salt contamination. The field study also revealed that the rise in shallow water table is most probably associated with the reclamation and development activities in the study area. Extensive review and analysis of monitoring data indicated significant influence of various natural and man made factors on the irregular pattern of water table fluctuation. It can be concluded from the this preliminary simulation investigation that if no significant changes in the prevailing conditions take place in near future, an overall reduction of net recharge by 25 percent appears to be a viable solution for the control of water table behavior in the study area. However, the reliability of the predicted behavior depends greatly on the degree of further development in the area.

Since the contamination and deterioration of subsurface structures represents a growing public concern and a major area of scientific research, a comprehensive investigation is essential to evaluate the integrated system dynamics of groundwater flow, moisture rise, and the corresponding movement of water and contaminants in soil, groundwater and the embedded concrete structures under both saturated and unsaturated conditions. Such a study will definitely help in establishing a better understanding of the relationship between the water table fluctuation, moisture rise in soil, and the flow of water and contaminants in buried concrete structures. It also has tremendous practical applications, especially in development and implementation of effective methodology for the protection of subsurface structures from the potential threats of corrosion and other types of deterioration due to contamination.

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