APPLICATION OF MIKE SHE AND MIKE11 FOR INTEGRATED HYDROLOGICAL MODELLING IN SOUTH FLORIDA

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INTRODUCTION

The South Florida Water Management district (SFWMD) includes the largest wetlands in North America, stretching from the Kissimee River to Lake Okeechobee to the Everglades and finally to Florida Bay. Historically this wetland was a river about 50 miles wide and only a few inches deep on average. In the past numerous canals have been build in order to drain some of the land for residential development and agriculture. Recently there has been a move to restore parts of the Everglades system to more historic conditions and now work is proceeding to allow overbank spilling, channel meandering and reduction of impacts from overabstraction of ground water. The very complex wetland flow system and the interactions between surface water, ground water and evapotranspiration processes indeed make the Everglades restoration project a difficult technical task which can only be addressed using an advanced technical approach. Mathematical modeling tools plays an important role in SFWMD's water management and numerous different modeling tools are applied in SFWMD. The MIKE SHE technology was adopted by SFWMD in 1997 in order to further SFWMD's capabilities in regard to integrated surface water and ground water modeling. Since 1997 the MIKE SHE modeling system has been enhanced and tailored to SFWMD needs as part of an SFWMD model application and software development project. This project is concluded in July 1999. In parallel with model development and model testing MIKE SHE has been applied to a number of modeling studies in South Florida. These studies are different both in regard to scope, hydrologic system and modeling scale. Although these studies are model application studies aiming on specific purposes they have also served as valuable and complex real-life test cases. These studies include:

- The Everglades Nutrient Removal (ENR) study – which simulates the hydrologic and hydraulic functioning of a constructed wetland, in order to improve the understanding of the hydrologic system in particular with regard to quantification of the sub-surface flows and the overall water balance components.
- The Isolated Wetlands study – which is a small scale study focusing on impacts on wetlands from ground water extractions
- The Caloosahatchee river basin study - which deals with the water balance of the Caloosahatchee river basin in order to optimize the future use of the available water in the catchment

The present paper presents the model set-up and calibration of the ENR modeling study.

THE ENR MODELING STUDY

The Everglades Nutrient Removal (ENR) project is a 15 km2 constructed wetland designed and operated for the demonstration of phosphorous reduction from agricultural runoff. The ENR is located in South Florida at the eastern edge of the Everglades Agricultural Area (see Figure 1).

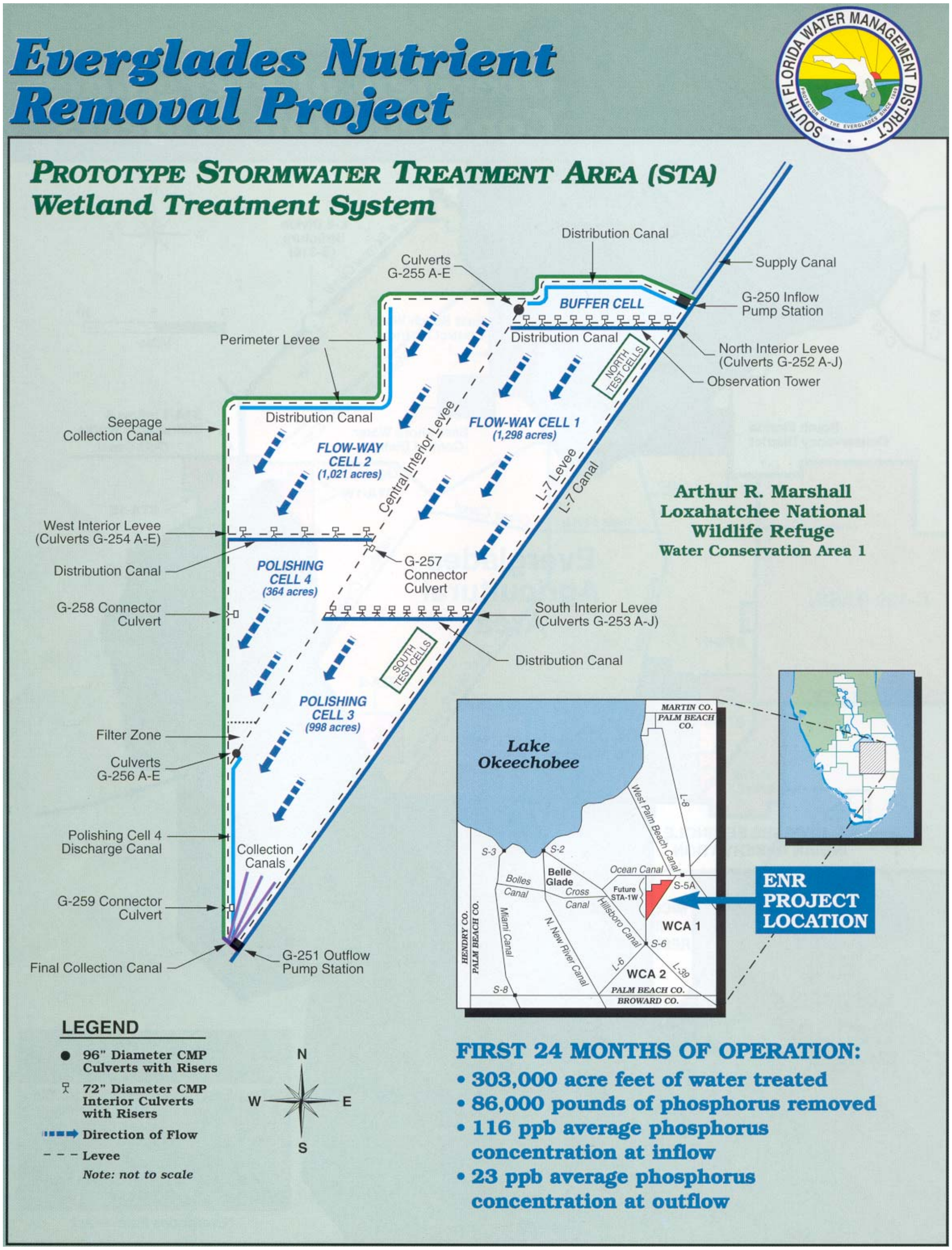


Figure 1 Index Map and Location of the ENR project (Source: SFWMD)

The main objectives of the ENR model application are:

- To demonstrate the use of the integrated modeling system and to demonstrate that the model functions correctly, by applying the model to reproduce field data measured in a hydraulically and hydrologically complex wetland system in South Florida (the ENR project)
- To provide a more detailed water balance for the ENR project, in particular with regard to sub-surface flows in and out of the ENR project.

The ENR Project

The ENR project is primarily covered by Okeechobee muck soils (peat soils) with very small topographic relief and an average ground elevation of about 3 meters. To the east the L-7 levee separates the ENR project from the Loxahatchee wildlife refuge (Water Conservation Area 1 – WCA1). The northern and western sides of the ENR are encompassed with a seepage canal that separates the ENR levee from agricultural fields (sugar cane). A 12 km levee surrounds the ENR and internal levees separate the five interior cells. The project consists of two parallel treatment trains of two cells each and a buffer (distribution) cell. The eastern treatment train carries water from the buffer cell to cell 1, then to cell 3 and finally to the outflow pump. The western treatment train carries water from the buffer cell to cell 2, then to cell 4 and finally to the outflow pump.

The hydraulics of the ENR is controlled by a number of hydraulic structures. The inflow pump station (G250) lifts water from the delivery canal into the buffer cell. The outflow pump station (G251) lifts effluent water back into the WCA1 from where it flows towards the Everglades. Inter cell flows are regulated with culverts (with raisers) located in the interior levees. Culverts are located at G252, G255, G253, G254, G256 (see Figure 1). Moreover, two culverts (G258 and G259) diverts water from the ENR to the seepage canal. These two culverts are however seldom used. Seepage water is re-circulated through the G250S pump.

The ENR project is intensively monitored (evapotranspiration, rainfall, water flows, surface water and ground water stages, vegetation coverage) providing a good data basis for model building and calibration.

The hydrogeologic system comprises only the surficial aquifer system which incorporates 4 geologic sequences (muck, marl/limestone (caprock), limestone with interbedded sands, sand and limestone).

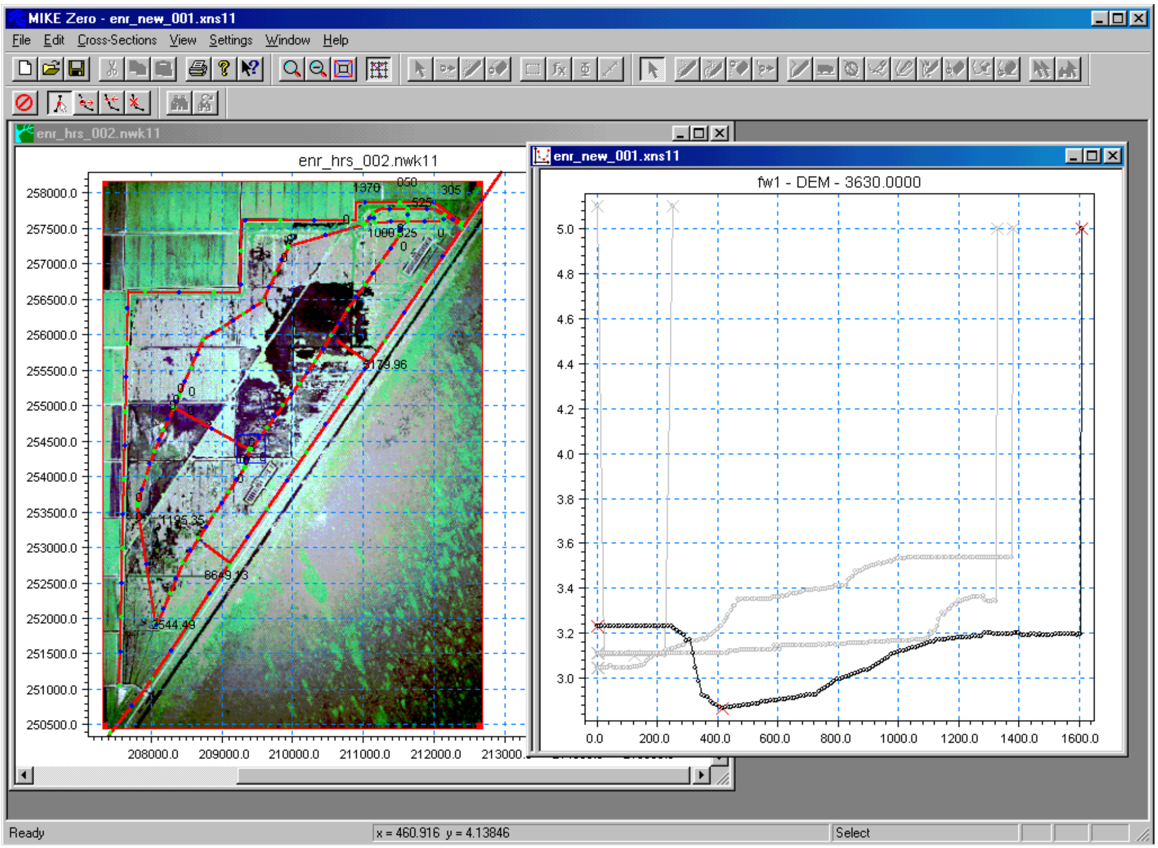


Figure 2 **Layout of the Hydraulic Model of the ENR. The figure shows the branches included in the model (left view) and 3 cross-sections from cell 1 (right view).**

UNDERSTANDING OF THE HYDROLOGIC SYSTEM

Prior to the modeling the following understanding of the hydrologic system was developed. The ENR receives water from the inlet pump, as direct rainfall and as seepage from the WCA1. The primary water source and by far the most important is the inlet pump. The surface water level in WCA is kept close to 5 metres while the surface water level in the ENR is close to 3.5 metres. Consequently there is a head drop of about 1.5 metres over a distance of about 20 metres (the width of the L-7 levee). The seepage flows through the L-7 levee are collected in a ditch that is connected to the ENR through a number of small culverts. A portion of the seepage water flows below the L-7 ditch and creates a zone along the L-7 levee with subsurface inflows to the ENR. In the western part of the ENR there is downwards seepage zone created primarily by the water level difference (about 1 meter) between the ENR water stage and the water stage in the seepage canal. Very high seepage rates are measured at some places along the seepage canal levee.

The seepage canal drains a substantial amount of water. The flow in the seepage canal is in the order of 1 m3/s, which is close to 10% of the flow rate at the inlet pump. A portion of the water may reach the seepage canal as direct seepage through the western perimeter levee carried by cracks or by preferential flow paths in the levee fill material. In the modelling it is however assumed that the primary water source is seepage water from cell 2 and cell 4 plus subsurface flows from the WCA1. The following has been observed:

- The seepage canal intersects the low permeable caprock layer and is in direct hydraulic contact with the sand/limestone aquifer. This is supported by the fact that piezometric heads in the sand/limestone responds almost instantly to water level fluctuations in the seepage canal created by the seepage return flow pump. This is also supported by the seepage canal geometry (bottom elevations) compared with the bottom elevation of the caprock layer. Consequently the seepage canal drains a substantial part of the subsurface flow that takes place in the sand/lime-stone aquifer, and the sand/lime stone layers is the primary source of the water in the seepage canal.

- Piezometric heads measured in the ENR as well as piezometers located in the levee cores, indicate relatively small hydraulic gradients across the caprock layer and dynamics that are almost identical to the ENR surface water stage dynamics. This indicates high vertical permeability through the caprock and that a secondary porosity domain (fissures, cracks etc) controls the seepage rather than the matrix porosity.

- The flow in the seepage canal is correlated with the water level in the ENR (only visually determined, not through correlation analysis).

On that basis it is assumed that seepage water infiltrates rapidly through the caprock to the sand/limestone aquifer from where it flows horizontally towards the seepage canal. A portion ends up in the seepage canal and a portion continues to the agricultural areas. The primary seepage zones are Cell 2 and Cell 4.

The assumption that the caprock is vertically highly permeable is fundamental for the model and probably the single most important assumption of the ENR model. As described above many field data supports this assumption.

CONCEPTUAL MODEL

Based on the understanding of the hydrologic system a conceptual model was established. The conceptual model is a simplified, but functional, description of the natural ENR system. The conceptual model must represent the main features and driving forces of the ENR site and be suitable for implementation in a mathematical model.

Surface Water Flow

The surface water flow is modelled in the 1-dimensional MIKE 11 model. The main objective of the surface water modelling is to simulate a correct and dynamic water level. A correct description of the surface water dynamics is essential for simulating the head gradients between the surface water levels and the ground water levels. The surface water incorporates the following ENR features:

- the inflow pump as a measured discharge time-series (Q-boundary)
- The buffer cell, cell 1, cell 2, cell 3, cell 4, the seepage canal and ditch along the L-7 levee
- Culverts G252, G255, G253, G254 and G256 are included
- Operation of the risers is not considered. The culverts are considered fully open constantly.
- Overland flow within the ENR is not considered. All surface water flow within the ENR is considered 1-dimensional and is simulated entirely by MIKE 11

- the outflow pump is represented as a pre-scribed Q-boundary. Consequently the difference between the inlet and outlet flows must be balanced by sub-surface flows and rainfall and evapotranspiration, in the ENR.

The branches included in the ENR model is shown in Figure 2.

Evapotranspiration and Infiltration Model

Unsaturated zone flow and actual evapotranspiration is calculated using a newly developed simple infiltration and evapotranspiration module (DHI, June 1999). This module is developed for SFWMD but it is implemented as a generic MIKE SHE component. The new module constitutes a simple alternative to the Richards equation formulations adopted in previous versions of MIKE SHE. The input for the module is:

- Time-series of potential evapotranspiration rates (measured in 3 lysimeters inside the ENR)
- Vegetation coverage described in terms of leaf area index and rooting depth
- Soil maps with basic hydraulic properties (wilting point, field capacity, saturated water content and constant infiltration capacity)

On that basis the model calculates the average water content in the root zone, the actual evapotranspiration and the ground water recharge.

Groundwater Flow

The subsurface flow components considered include the entire surficial aquifer system. Based on the field data available and on an evaluation of the hydrological functioning of the aquifer system the following 4 layers have been incorporated into the mathematical model:

- layer 1, which incorporates organic soils (muck) and fill material along the levees.
- layer 2, which incorporates the relatively low-permeable marl/lime-stone interface (often referred to as caprock).
- layer 3, which incorporates limestone with interbedded sands.
- layer 4, incorporates the relatively high-permeable sand/limestone aquifer system.

The groundwater flow model adopts MIKE SHE preconditioned-conjugate-gradient solver. The applied boundary condtions are a combination of constant head, time-varying head and general (head-dependent-flux) boundaries. The upper layer adopts a general head boundary condition in all model grids located in WCA1. The reference-head is the measured surface water stage in WCA1. Along the exterior model boundaries pre-scribed (fixed or time-variant) head boundaries are adopted. These are, to the extent possible, based on field data such as water levels in canals (layer 1) or measured piezometric heads in the deeper layers.

The hydraulic properties of the aquifer system were estimated based on results of various field studies and previous modeling studies. Subsequently, the hydraulic properties were adjusted through model calibration.

The model uses a horizontal discretization of 50 m and 4 computational layers in the vertical. This leads to almost 100.000 computational cells in the groundwater model. In combination with the relatively complex surface water model and the infiltration/evapotranspiration model the ENR model is a relatively big and computationally demanding model. The model was calibrated on field data for a 1 year period (1995). A calibration run (1 year) takes about 3 hours on a 400 MHz PENTIUM PC.

Model Calibration

The model is calibrated by reproducing water levels and water fluxes measured in the field. As previously mentioned the MIKE11 surface water model adopts a Q-boundary at the inlet and the outlet pump. On average the outlet flow is about 10% less than the inlet. As both the inlet and outlet flows are fixed the integrated MIKE11/MIKE SHE model is bound to balance the net loss with the sum of inflow, outflow and storage. In other words the sum of rainfall, evapotranspiration, subsurface flows and storage in the ENR must equal the net loss. Adopting bot fixed in and out-flow boundaries is rather untypical when using MIKE SHE, and it is often a “dangerous” approach as it forces the model to produce water inflows or outflows across open model boundaries. Often these flows unknown and difficult to verify. Hence, even though the inlet and outlet flows are correct (boundary conditions) and simulated water levels are correct the model may still be producing unrealistic results. In the ENR model this approach however seems feasible of the following reasons:

- the main objective is to quantify the subsurface flows. Applying fixed flow boundaries at the inlet and the outlet links the model uncertainties to the subsurface flows and evapotranspiration calculation only (disregarding the uncertainty on the measured data)
- the model is calibrated on a combination of flows in the L-7 ditch (seepage from WCA1), on flows in the seepage canal and on water stages within the ENR. All of these are highly sensitive to the hydraulic conductivities of the aquifer systrem. For instance, if the vertical and horizontal hydraulic conductivity is too low the water stage in the ENR will be too high. This happens because the model is bound to loose about 10% of the inlet flows (mainly as seepage losses). In order to generate sufficient seepage a large hydraulic gradient between the ENR and the seepage canal is required (because the hydraulic conductivities are too low). Simultaneously, a higher water level in the ENR creates less subsurface inflows from WCA1.
- the unknown portion of the subsurface flows (seepage in- and out of the ENR and flow below the L7 ditch, the ENR and the seepage canal) can subsequently be quantified. This portion is also highly sensitive to the hydraulic conductivity of the aquifer.

Examples of surface water and groundwater calibration results are shown in Figure 3 through Figure 5. Surface water and groundwater stages are simulated with a precision of a few centimeters by the model. In some periods, for instance January-February, there are relatively large deviation between observed and simulated results. This is attributed to structure operation (raisers in connection with culverts) which are not yet considered in the model.

Figure 6 shows monthly accummulated flows in the seepage canal and in the L7 ditch. Themain remaining calibration effort will be related to getting a more precise simulation of these fluxes. In the present model the deviation between modeled and observed accumulated flows are just below 10%. The calibration target for the final model is 5%. With regard to the L7-ditch the seasonal variation is not reproduced by the model. The reason for that is being investigated. There may be a problem in general with the L7-ditch measurements. The “measured” data in the L7-ditch are computed as a function of the head difference between WCA1 and the ENR.

Figure 7 shows the simulated seepage rates on 30 July 1995. Negative rates indicate downward flows. As compared to the seepage rates measured by SFWMD the simulated rates are generally slightly lower. The measured seepage rates vary from 0.85 cm/day to 340 cm/day. The highest simulated seepage rates were 28 cm/hours simulated at ENR202 and ENR201 (in cell 2 just inside the perimeter levee). The measured seepage rates are however point measurements and it should perhaps not be expected that a grid average seepage should be directly comparable with a point measurement. The very high seepage rate (340 cm/day) is substantially above the average measured seepage rate which is 54 cm/day. These measured data will be considered as one of the calibration targets during the final model calibration.

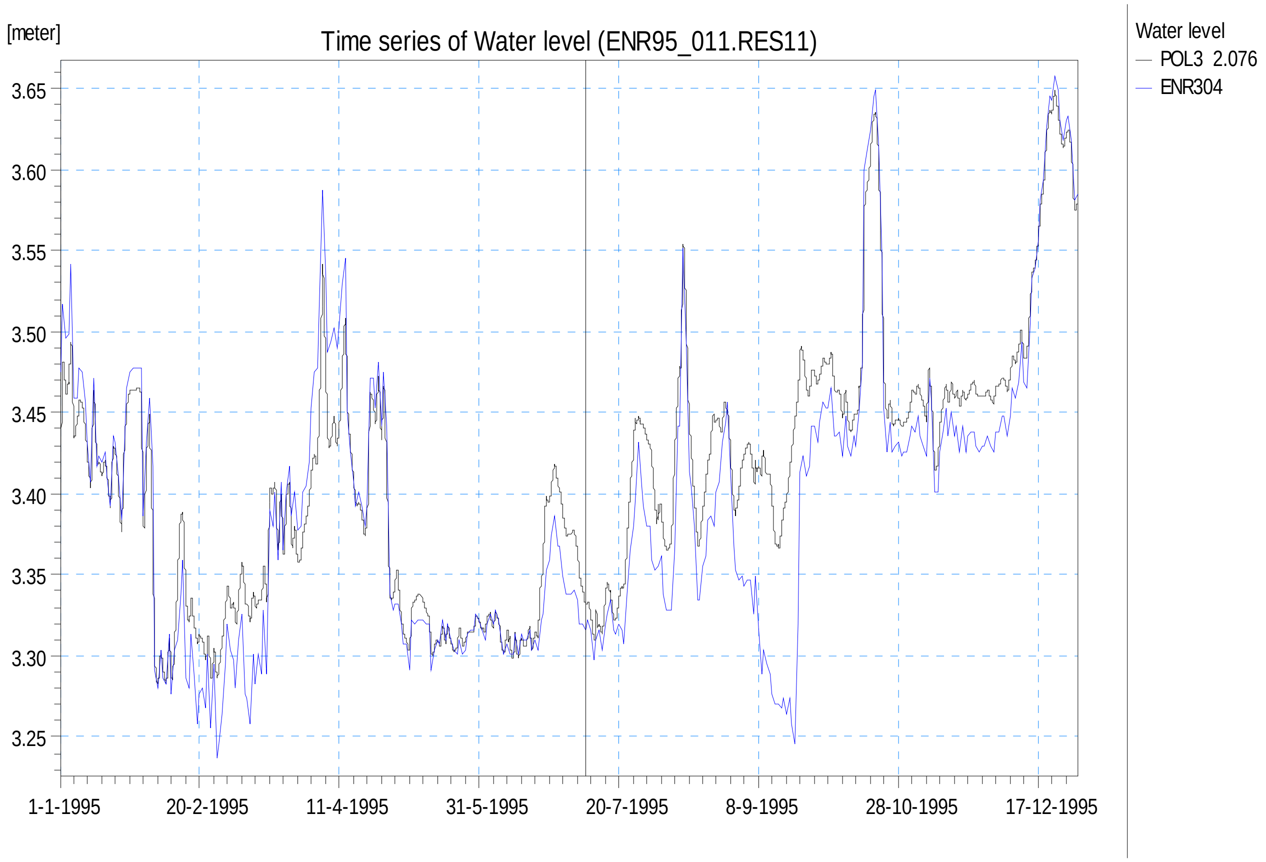


Figure 3 **Simulated and Observed water level (ENR304) in Cell 3**

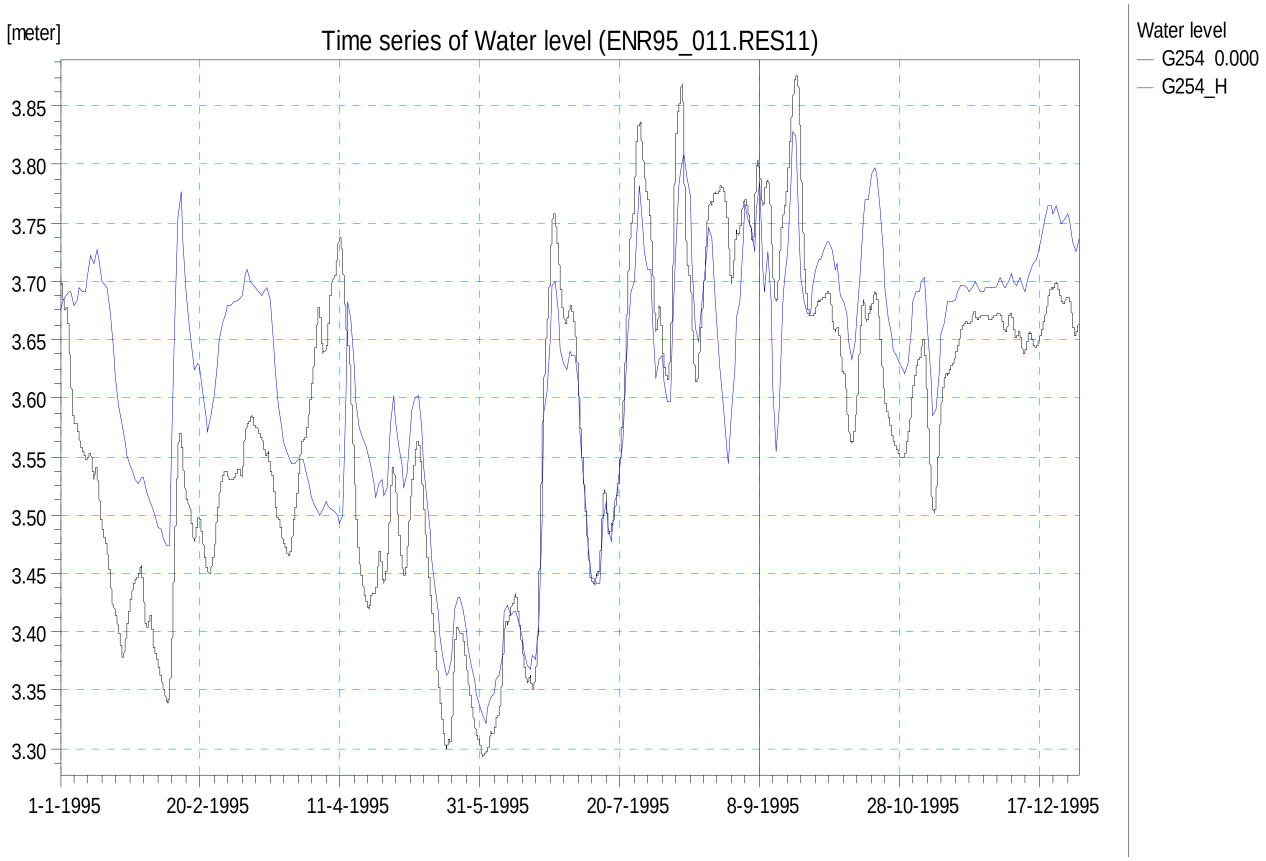


Figure 4 **Simulated and Observed (G254_H) Surface Water Stage in Cell 4.**

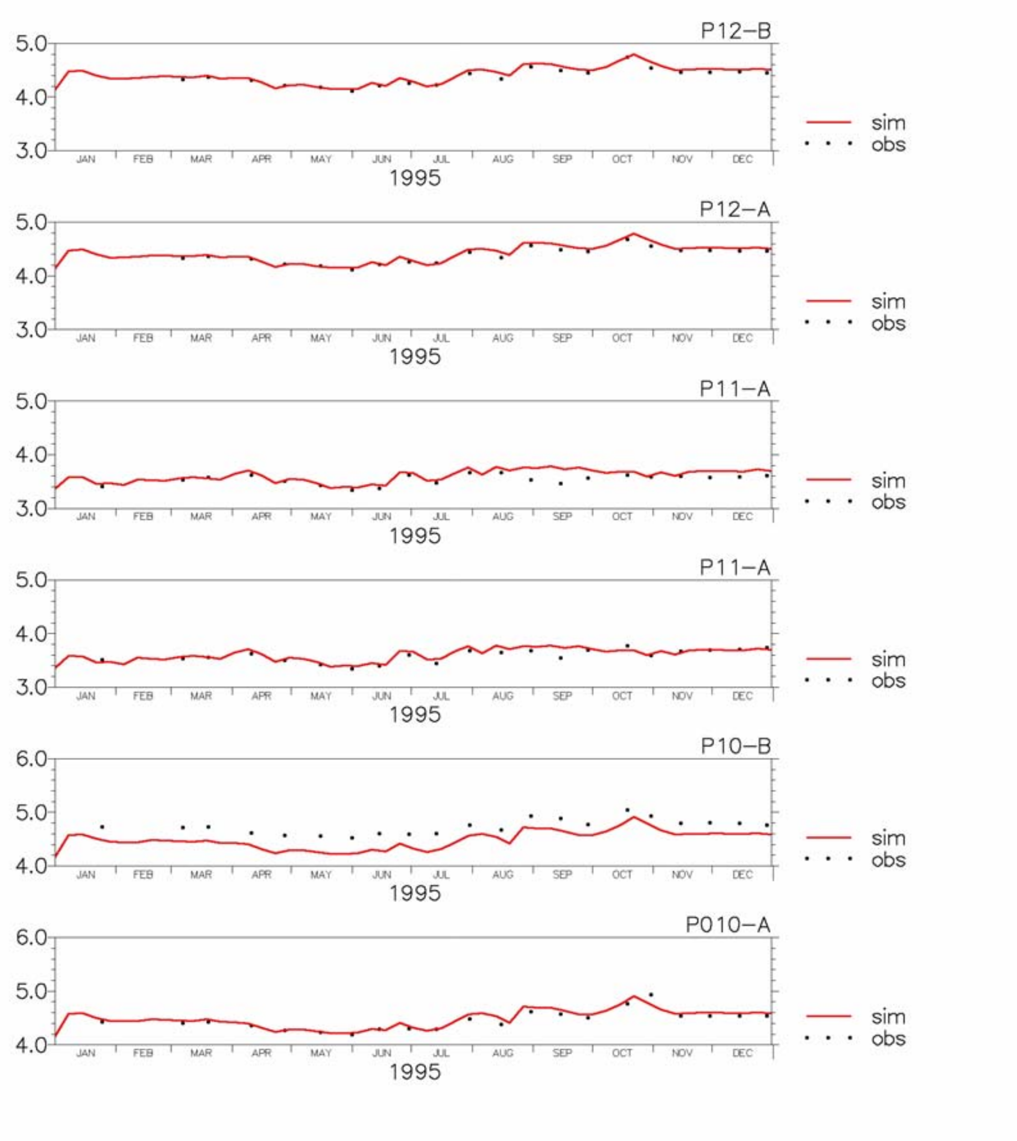
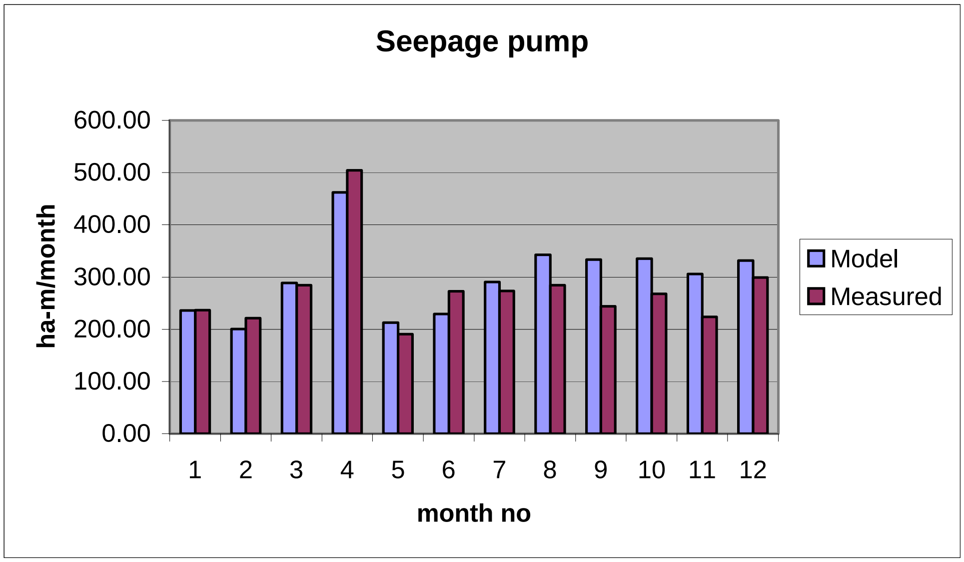


Figure 5 Simulated and Observed in groundwater levels for piezometer wells inside the ENR.



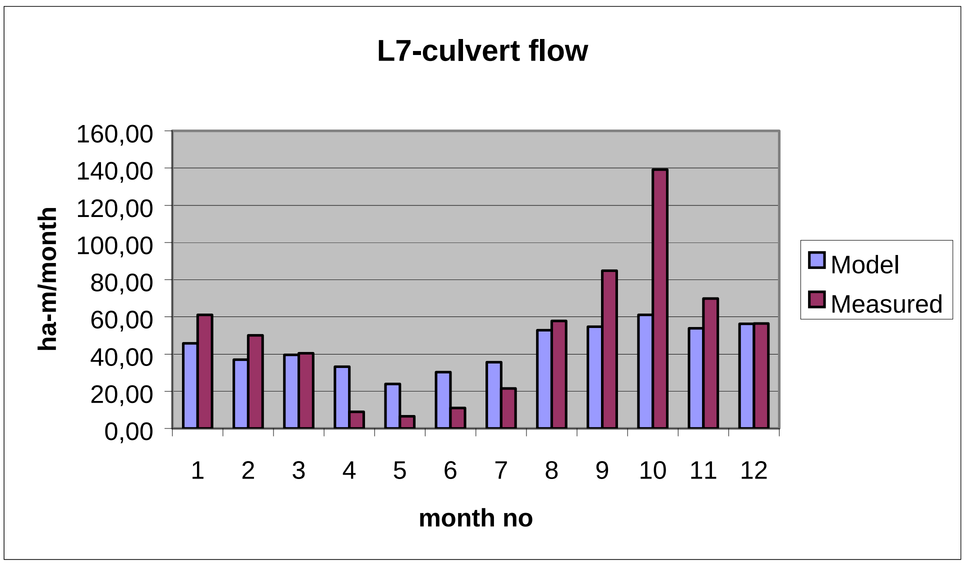


Figure 6 **Monthly measured and simulated flows (ha-m) at the G251 outflow structure, the G250S seepage pump and through the L-7 culverts.**

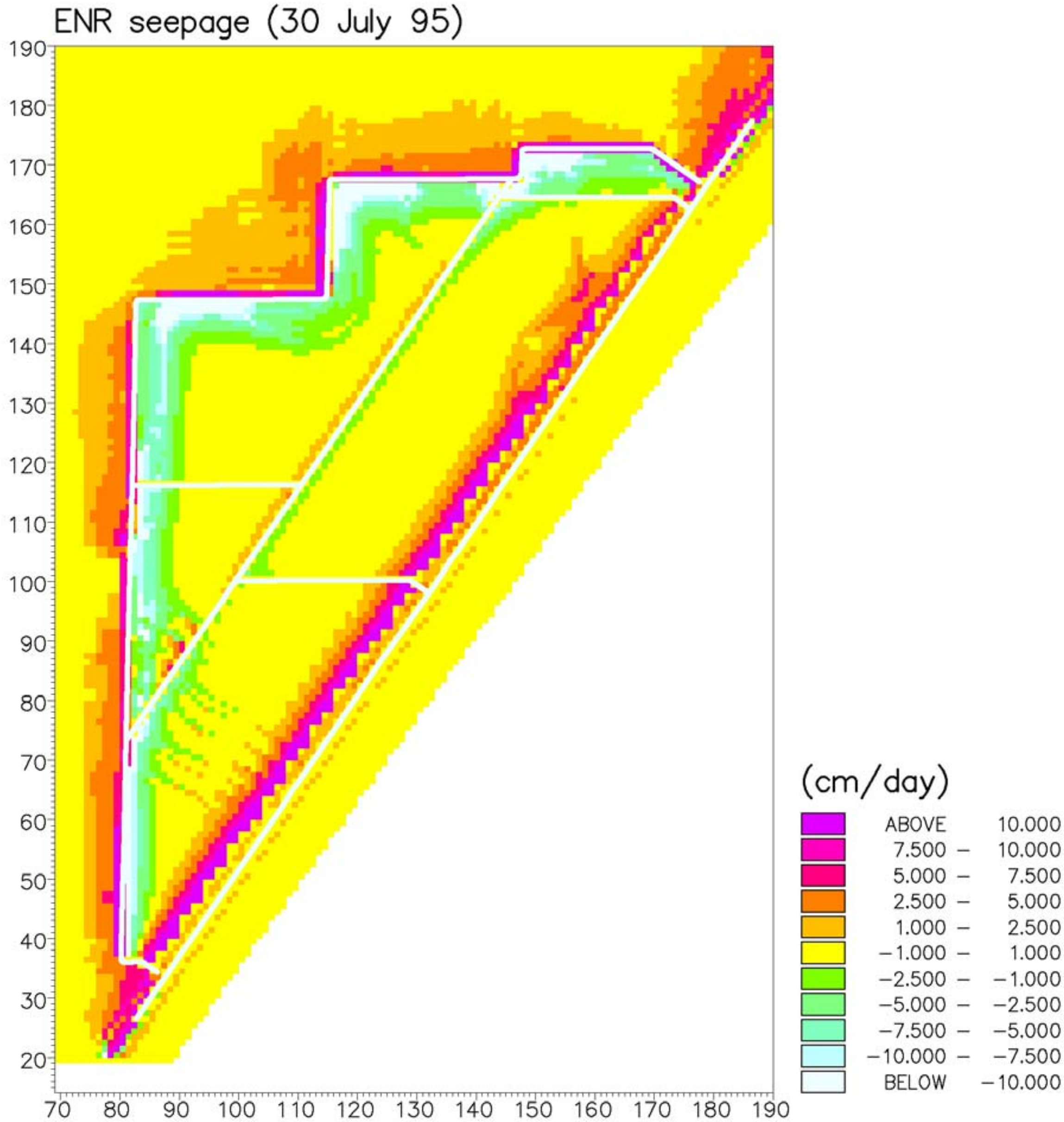


Figure 7 **Seepage Rates within the ENR (negative means downflow)**

CONCLUSIONS

The main purpose of building the ENR model were:

- To demonstrate the use of the integrated modelling system and to demonstrate that the modeling system functions correctly, by calibrating and applying it to model the functioning of a complex wetland system in South Florida
- To provide a more detailed water balance for the ENR project, in particular with regard to sub-surface flows to and from the ENR project.

In regard to the first objective the preliminary ENR model results and other model applications in South Florida has proven that the MIKE SHE/MIKE11 modeling system is capable of simulating the complex hydrologic regime of South Florida.

In regard to the second objective the established ENR model includes all the main features of the ENR represented in a physically based manner. It has demonstrated an ability to reproduce field data with good precision both with regard to water levels and discharges and with regard to reproducing the dynamics observed in the field. The model also gives a good estimate of the sub-surface flow components. It is however still required to improve the simulation of the seepage canal flows and the L7-ditch flows. The final model calibration will focus primarily on these issues.

When successfully calibrated the model will be used to:

- establish a detailed water balance for the ENR project
- a detailed quantification of subsurface flow components
- a particle-tracking simulation will be carried out to map the flow path of the ENR seepage water, in particular with the purpose of quantifying the direct seepage from the ENR to the surrounding agricultural area.

REFERENCES

DHI, June 1999. MIKE SHE Water Movement Module. User’s Guide and Technical Reference Manual.