39 Box Stage Model (Version 2.0)

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Contents

Abstract

This user manual describes a new implementation developed in the R scripting language of the 39-Box (compartment) stage model developed from an earlier version. The model simulates water stage and flow in the Arthur R. Marshall Loxahatchee National Wildlife Refuge. A companion 39-Box Mass model is under development which will simulate concentrations of chloride, sulfate, and phosphate in the Refuge.

Chapter 1

Quick start

In order to productively apply the 39-Box model, users will need to have a basic familiarity with programming in R. To run the model, both R and R-Studio must be installed. In this quick start section, it is assumed that the model scripts will be executed using the R-Studio environment.

To begin using the model, users may follow these steps:

1. Obtain the distribution compressed file $39BoxStageV20.zip$) containing the model folders and files. This will be available from the GitHub repository github.com/MWaldon/Loxahatchee-39-Box-Model

2. In R-Studio create a new project with an appropriate name. Select any desired path on your computer for the project home directory.

3. Copy the folders from the distribution zip file to the new project home directory.

4. Open the file runStage.R from the installed Rscript folder

5. In the dropdown menu "Sessions/Set Working Directory" choose "To Source File Location." This points the working directory path to the Rscript folder.

6. In the editor window click "Source."

7. Move to the console window (click in the Console window or press Ctrl+2) and then, in answer to the prompt, hit enter to accept the default filename.
8. Click the "Plots" tab (or press Ctrl+6).
9. A plot should open and plot one point for each day of the model run.
10. When the model has completed a series of plots will be drawn.

See the Workflow section (4.4) for more information on running the model.

Chapter 2

Introduction

2.1 Model need

The Arthur R. Marshall Loxahatchee National Wildlife Refuge (Refuge) has been impacted by excessive levels of phosphorus and other contaminants in stormwater inflows. Major restoration projects by the South Florida Water Management District (SFWMD) and the US Army Corps of Engineers have been implemented to reverse these impacts. In addition to reducing the concentration of nutrients and contaminants, these projects have reduced total inflow and altered the pattern of inflows.

As the restoration of the Refuge continues, quantitative methods are needed to predict the impacts of existing and proposed management changes by quantifying changes in the quantity and quality of refuge water brought about by restoration efforts. The 39-Box Model was developed to meet many of these needs. The 39-Box Stage Model predicts the stage (*i.e.* water surface elevation), water depth, and flow over the Refuge. A companion model, the 39-Box Mass Model, is in development. It will link to the output of the stage model and predict concentrations of selected constituents. The 39-Box models delineate 39 compartments that overlay the refuge canal and marsh (Figure 2.1).

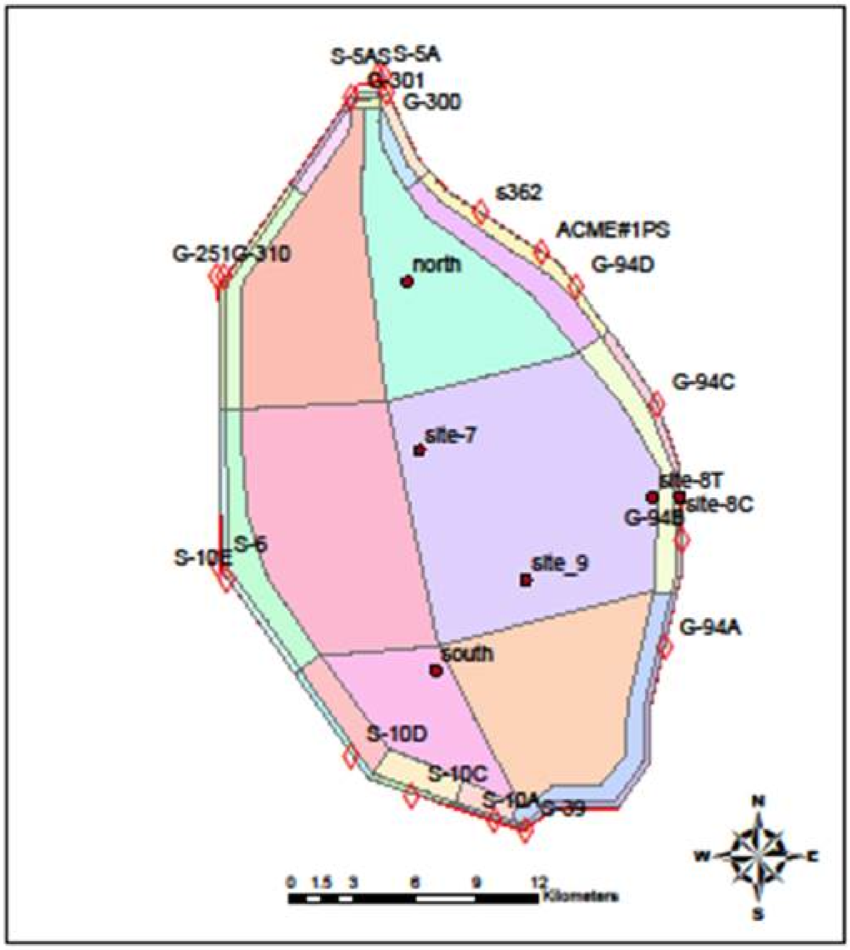


Figure 2.1: The arrangement of the the 39 model Compartments is shown along with Refuge stage gauges and inflow/outflow structures (Bazgirkhoob et al., 2015).

This manual details a new implementation of the 39-Box (compartment) Stage Model is a code translation to the R scripting language from the earlier version of the 39-Box Model that was developed using the Berkeley-Madonna simulation environment. That earlier version developed over a decade from the Refuge 9-Box Model and earlier SRSM models. In addition to stage, these earlier models all simulate concentrations of chloride, total phosphorus, and sulfate in the Refuge.

This manual aims to provide users with an understanding of both the theory and the implementation of the model. The objective is to give users the ability to accurately simulate various water management scenarios for the refuge to gain a better understanding of the dynamics of this wetland. In addition to a basic understanding of R programming, model users should have a general familiarity with the Refuge geography, hydrologic features, and water quality. For more information, users are directed to the Refuge Comprehensive Conservation Plan (USFWS, 2000).

2.2 A.R.M. Loxahatchee National Wildlife Refuge

The Arthur R. Marshall Loxahatchee National Wildlife Refuge was established in 1951 in Palm Beach County, Florida, USA. The Refuge covers an area of 145,188 acres (226 square miles) and includes Water Conservation Area 1 (WCA-1). WCA-1 is a remnant of the Everglades River of Grass wetland ecosystem.

The refuge protects a diverse mosaic of habitats, including sawgrass, cattail, sloughs, and tree-island communities. This expansive protected wetland is a crucial habitat for a wide variety of wildlife. It supports more than 250 species of birds, 60 species of reptiles and amphibians, 40 species of butterflies, and 20 types of mammals. Visitors to the refuge can frequently observe alligators, bobcats, white-tailed deer, and various species of birds, including the federally endangered snail kite.

Prior to development, water in the Refuge flowed in a generally north to south direction as flow through shallow sloughs, and sheetflow over the marsh. In contrast, today the perimeter of the WCA-1 wetland is encircled and isolated by a borrow canal and levee. As a result, water flow over the wetland now begins and ends at the perimeter canal.

All inflows and outflows between the perimeter canal and surrounding agricultural and urban areas are controlled by water control gates and pumps. All of these inflows and outflows are monitored, and daily discharge monitoring records are archived and made available by the South Florida Water Management District (SFWMD). The availability of this monitoring was essential for accurate model development.

Water stage and movement are important factors controlling the plant communities in the Refuge 2.2, and these factors are controlled by the water sources and losses in the Refuge 3.2. Seasonal patterns of water stage determine the hydroperiod of the marsh, and water movement transports plant nutrients throughout the Refuge. Additionally, the Refuge is a source of water for downstream Everglades wetlands including the other water conservation areas and the Everglades National Park.

In addition to its ecological value, the Refuge is an important part of the water supply and flood management system of South Florida. During times of heavy rain, stormwater may be pumped directly into the Refuge, or after passing through stormwater treatment areas. During the dry season, the Refuge provides a supply of water to the Southeast Florida coast to prevent saltwater intrusion into surface or groundwater sources of water used for agriculture and municipal water supply.

The US Army Corps of Engineers has the responsibility of balancing the needs for water in controlling flow out of the Refuge through the S-10 gates. To meet that responsibility, the Corps, in consultation with all affected parties, developed a water regulation schedule for the Refuge. The current regulation schedule took effect in 1995 (Figure 3.6).

Purpose and scope of the 39-Box Stage Model The 39-Box Stage Model predicts the stage (water surface elevation), water depth, and exchange flows in

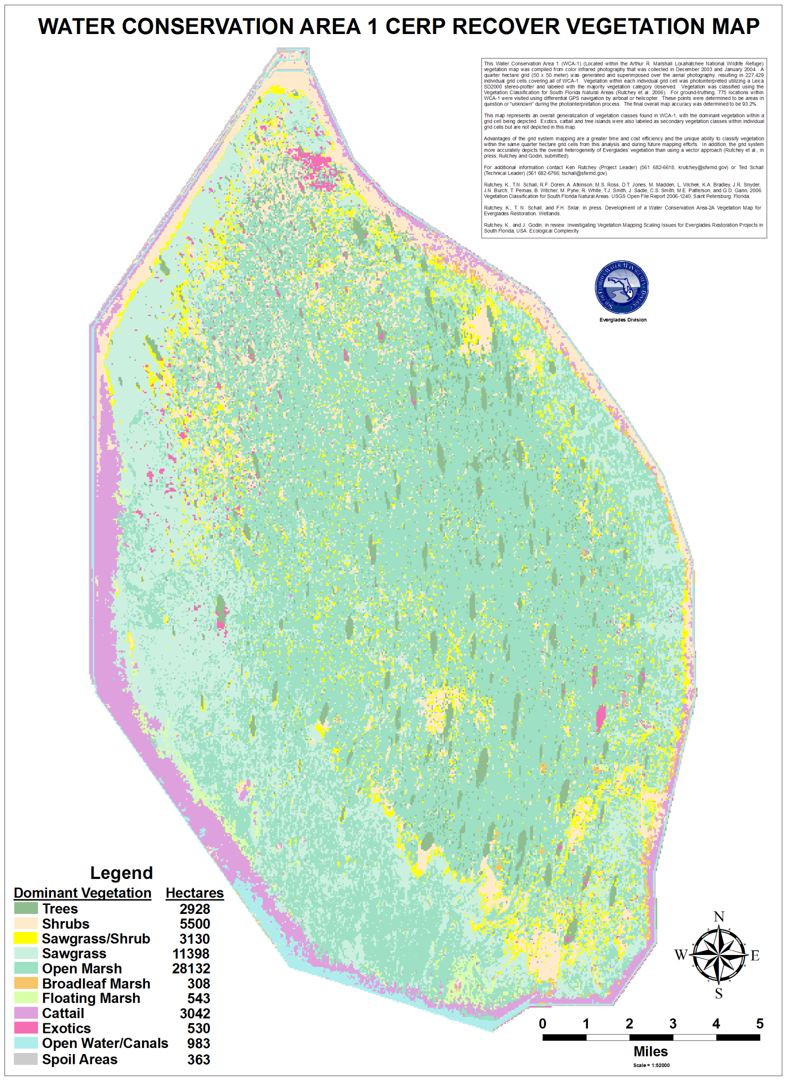


Figure 2.2: Refuge vegetation map compiled from color infared photography collected in December 2003 and January 2004 (credit SFWMD).

the Refuge Canal and wetlands. These stage predictions are generated from a series of compartmental water budgets. The model divides the Refuge into 39 boxes (also termed compartments, nodes, or tanks), and water movement into and out of each box is estimated to give a rate of volume increase or decrease for each box. The boxes were first delineated in the 9-Box Model based on available water quality monitoring data (Wang et al., 2008) and further divided in the 39-Box design to provide greater insight into the impacts of water management alterations.

2.3 History of model development

Investigators have worked to develop Refuge water stage computer model since the late 1970s (Arceneaux, *et al.*, 2007). Notably, Richardson *et al.* (1990, 1993) recognized the need for a stage model to understand how Refuge water management impacts hydroperiod and vegetation. They developed a GIS-linked hydrologic model of the Refuge by adapting an earlier Everglades-wide water model. Their Refuge model defined 750 square grid cells measuring 3000 feet by 3000 feet to represent the Refuge marsh area.

In the early 2000s, the US Fish and Wildlife Service was funded to develop an enhanced monitoring and modeling program for the Refuge. The modeling effort of this program developed at the University of Louisiana under the mentorship of project principal investigator Dr. Ehab Meselhe. Technical management of the modeling effort was led by USFWS senior hydrologist Dr. Michael Waldon. This modeling project developed two complimentary modeling approaches. One approach applied a high spatial resolution commercial hydrodynamic and water quality model Mike-Flood (Chen, *et al.*, 2009.). The second approach applied simpler compartmental modeling for simulation of Refuge water quantity and quality. The 39-Box Model was a part of this compartmental modeling effort.

Compartmental modeling in this project transitioned through various computer programs and modeling platforms. Version 1 of the model (Arceneaux *et al*, 2007; Meselhe *et al*, 2007a, 2007b) was implemented as a daily water budget using a Microsoft Excel workbook for water volume modeling, and the EPA WASP model simulating chloride and total phosphorus concentrations. Versions 2 and 3 of the SRSM were transitional and no longer available. SRSM version 4.0 (Meselhe *et al*, 2009; Roth and Meselhe, 2010) was developed using the commercial numerical differential equation solver package of Berkeley Madonna (Macey *et al*, 2000). It allows greater clarity in coding, supports shorter time steps obviating the need for the ad hoc procedures of Version 1.0, and provides a well-documented user interface. It simulates the water budget, regulation schedule related discharges, and constituent dynamics for chloride (Cl), sulfate (SO4), and total phosphorus (TP), over a period from January 1, 1995 to June 30, 2009.

Wang (Wang et al., 2008) applied cluster analysis of chloride, total phosphorus, sulfate, and calcium concentrations measured at sites distributed throughout the Refuge to objectively determine the number of compartments and to spatially delineate these compartments with similar features within the refuge. That delineation led to a 9Box (compartment) model structure (Wang et al., 2012).

The 9-Box model was calibrated and performed well when compared to historic observations. However, there was concern that the model might not perform as well when simulating some management scenarios. This concern led to further disaggregation of the 9-Box model into the 39-Box configuration applied in the current model.

As with the SRSM and 9-Box model, the 39 Box model is based on a link-node conceptualization. Each node in a link-node model has the state variables of water volume, as well as constituent masses for concentration modeling. Stage, depth, and constituent concentrations are calculated from the state variables of compartment volume and total constituent mass. Link flow is in the direction from higher to lower stage of its end nodes. For each link, an upstream and downstream node is arbitrarily defined so that positive flow moves in the upstream to downstream direction, and negative flow moves from downstream to upstream. Flow of water and transport of constituent mass (mass flux) occur between nodes through links.

In programming terminology, links and nodes (compartments) are objects defined by their parameters (properties) and processes (methods). Links have properties of length, width, depth, and water surface slope, and processes of flow rate. Nodes have the property of surface area and volume, and have the process of volume accumulation. Each of these models (SRSM version 1, SRSM version 4, 9-Box Model, and 39-Box Model) has specific advantages and limitations. The models were designed to be a complementary suite. As such, the 39-Box Model is not intended to replace the other models, but instead to provide additional options for Refuge modeling applications.

2.4 Major assumptions and limitations

To avoid misinterpretations and erroneous conclusions from model results, it is essential that model users bear in mind the major model assumptions and limitations associated with this model.

Much of the data used in this model is archived as daily averaged values. This includes stage, flow, precipitation, and evapotranspiration data. This averaging may limit the ability of the model to accurately simulate some rare events, but should not significantly impact longer-term accuracy.

Each model cell represents an area rather than a single point, and each cell uses a single soil elevation. Some site-specific characteristics may need to be considered when comparing model results with data from monitoring sites.

Area-averaged precipitation was used to develop the daily rainfall depth time series.

Loss of water to groundwater (termed seepage loss of recharge) is modeled as proportional to cell stage minus a constant stage representing water stage outside the refuge. This assumption may underestimate water loss during drought conditions.

Discharge of regulatory water releases are adjusted daily in response to canal water stage. Historic releases generally follow this pattern, but were dependent on manual operation of gated control structures which could be affected by the availability of personnel, and other contingencies.

Chapter 3

Model Description

3.1 Conceptual framework

The refuge is compartmentalized into 39 compartments (also termed boxes, nodes, or cells), and each is classified as canal or marsh. The compartment surface areas are assumed constant (Table 1), and cover all of the marsh area totaling 4.03 $millionm^2$ and the canal area totaling 560.02 $millionm^2$. Mapping of the cell boundaries was based on results of a cluster analysis (Wang, *et al.*, 2008) The link-node diagram of the refuge is shown in Figure 3.11. Compartments 1-11 represent the canal cells and compartments 12-39 represent the marsh cells(Table 1 and Figure 3.11).

Conceptually, the 39-Box model is made up of 39 compartments or nodes and 52 links between nodes (Figure 3.11). The compartments have properties of water volume, depth, and stage or water surface elevation. Eleven nodes define the perimeter canal and 28 nodes cover the marsh. Links have the property of flow rate or discharge. Each link has a single upstream node and a single downstream node such that positive flow moves from upstream to downstream.

3.2 Data sources

Data from numerous water quality, meteorological, stage, and discharge monitoring stations in and surrounding the refuge were used in model development. Relevant to the stage model, these stations provided measurements of inflow, outflow, water level, water depth, precipitation, and evapotranspiration. Although there are numerous monitoring stations, some model cells in the marsh and canal have no associated water quality or monitoring station. All data in this model version were imported from previous model versions. Figures 3.3, 3.5, 3.12, and 3.13 map the location of monitoring sites in the Loxahatchee Refuge. Cell soil elevation was estimated from the Refuge Mike-Flood model.

3.3 Water volume and stage simulation

The model calculates the derivative of volume by maintaining a water budget for each cell. That is, the rate of increase, or decrease if negative, of cell volume is equal to the sum of all inflows minus the sum of all loss rates. Water depth is then calculated from volume, and stage is calculated by adding depth to the bed elevation (soil elevation) of the cell.

3.3.1 Cell water budget

Cells gain water volume through precipitation and inflow from adjacent linked cells. Canal cells may also receive inflow from structures including pumps and gates. Water is lost from cells through seepage to groundwater, evapotranspiration, and flow to adjacent cells through links (Figure 3.1.

Water volume in each cell is the state variable simulated by the model. The rate of change (*i.e.* the derivative) of cell water volume is calculated from the difference between the sum of all water flows entering each cell minus the sum of all flows leaving the cell. Water volume is then integrated by the function *radu* which is *deSolve* library of ordinary differential equation (ODE) solvers.

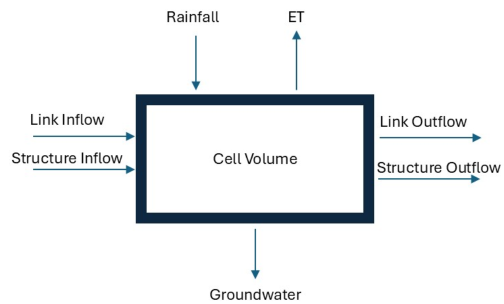


Figure 3.1: Components of water budget for individual cells.

Water depth in each cell is calculated from the relationship between cell depth and cell volume. For marsh cells, depth is simply cell volume divided by a constant cell surface area. For canal cells, the cross-sectional geometry of the canal is used to calculate the relation between cell depth and cell volume. Canal cell depth is measured above the lowest point in the cross-section. Stage (water surface elevation) is calculated by adding cell depth to bottom elevation. All stage and bottom elevations in the model are relative to the NGVD29 datum.

3.3.2 Inflow and outflow

Water flows into and out of the model domain through inflow, outflow, seepage to groundwater, precipitation, and evapotranspiration. Nineteen inflow/outflow structures are represented in the model. The structure inflow timeseries are defined using historical data. Structural outflow may optionally be defined from historic flows or calculated to approximate past structure management based on the water regulation schedule of the Refuge.

3.3.3 Water flow between compartments

Internal flows (m^3/day) between adjacent model cells are termed link flows which follow paths termed links. Conceptually flow between cells occurs through a link between every pair of adjacent model cells. It may be helpful to think of model cells as tanks, and to think of links as pipes between adjacent cells. Links in the 39-Box model are designated by index numbers from 1 to 52 (Figure 3.11). The type of model link is classified as 3 types (*linktype* canal-canal (cc), canal-marsh (cm), and marsh-marsh (mm). There are 11 cc links, 11 cm links, and 30 mm links in the model. Each link has four properties: upstream cell number, downstream cell number, width (m), and radius (m). Cell radius is the estimated length of flow between the upstream and downstream cells.

Link flow is considered positive for flow from the upstream cell to the downstream cell, and negative otherwise. Link flows are calculated in the function $Link.Flow.calc(Depth, Stage)$ using a power law formula (Kadlec and Knight, 1996).

$$LinkFlow = 10^7 * B * Width * Depth^3 * \frac{Stage_{up} - Stage_{dn}}{Radius} \tag{3.1}$$

Where B is a link-type dependent constant

$(cc = 6.97621, cm = 1.13863, mm = 4.55002)$,

$Width$ is the width (m) of the shared polygon edge estimated from GIS mapping, $Depth$ is the modeled depth of the downstream cell (m), $Stage$ is the cell water surface elevation (m), and $Radius$ is the flow length of the link estimated as the distance between the centroids of the upstream and downstream cells. Link flows are calculated by the function $Link.Flow.calc$, and net link flow into each of the $ncell = 39$ cells is calculated by the function $link2cell$.

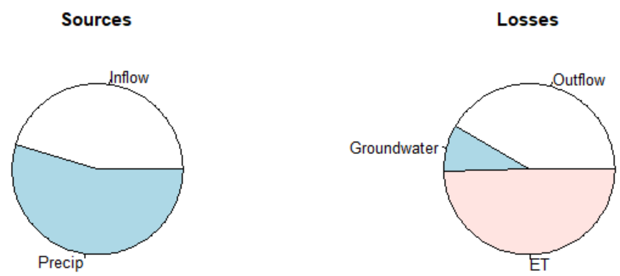


Figure 3.2: The relative importance of total sources and losses of water in the Refuge. This figure was plotted using R script $WaterBalance.R$.

3.3.4 Link velocity

Volumes and link volumetric flow rates are required in model calculations. Link flow velocities (cubic meters/day) are not required for water budget calculations, but are calculated by the function $sim.Velocity.calc()$ from link flow rates and are stored as a matrix ($sim.Velocity$) in the model output dataset.

3.4 Overall Refuge Water budget

Water flows into and out of the Refuge through water control structures located on the perimeter canal levees. Precipitation is also a source of water, while water is lost through ET (evaporation and transpiration by plants) and groundwater recharge or seepage (Figure 3.2). Link flows, ET, and loss to groundwater are calculated dynamically and may therefore vary during each day of simulation. Precipitation and all structure inflows and outflows are constant over each day during the simulation.

Inflow/outflow structures

A total of $nstruct = 19$ inflow and outflow structures are modeled (Figure 3.3). In the model code, these 19 water control structures are named:

$S39, G94A, G94B, G94C, ACME2,$

$ACME1, S362, G300, S5AS, S5A,$

$G301, G310, G251, S6, G338,$

$S10E, S10D, S10C, S10A.$

The percent of total historic inflow and outflow for each of these structures is presented in Figure 3.4. Three structures, $G300$, $G301$, and $S5AS$ function for both inflow and outflow.

3.4.1 Inflow

Historic inflows for the period January 1, 1995 through June 30, 2009 are read from an Excel spreadsheet $INFLOW39.xlsx$ in the script $make_datasets.R$. This spreadsheet was used to load flows into the model versions. These flows are stored in an R dataset file $39 - Box - Datasets.Rdata$.

The function $Qinfunc(DAY)$ returns total inflow discharging into each canal cell on a single day. This function is used by the function $QinExternal.calc$ to populate a matrix $QinExternal$ with each row containing the daily inflows to each of the $ncanal$ canal cells on each day.

Rainfall

In development of previous models, precipitation, specifically daily rainfall depth, was combined from a number of weather station sites around the Refuge in order to create a single time series dataset. This data is read by the script $make_datasets.R$ into the the PET data frame as $PET\$P$.

3.4.2 Outflow

Historic outflows for the period January 1, 1995, through June 30, 2009, are read from an Excel spreadsheet $OUTFLOW39.xlsx$ in the script $make_datasets.R$. This spreadsheet was used to load these flows into the model versions. Additional historic outflows that are not related to the regulation schedule, termed non-regulatory outflows (water supply or major storm operations),

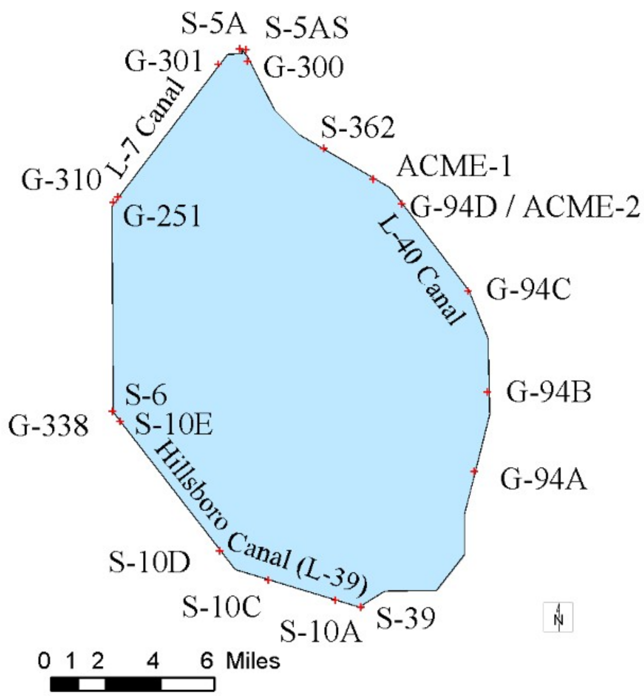
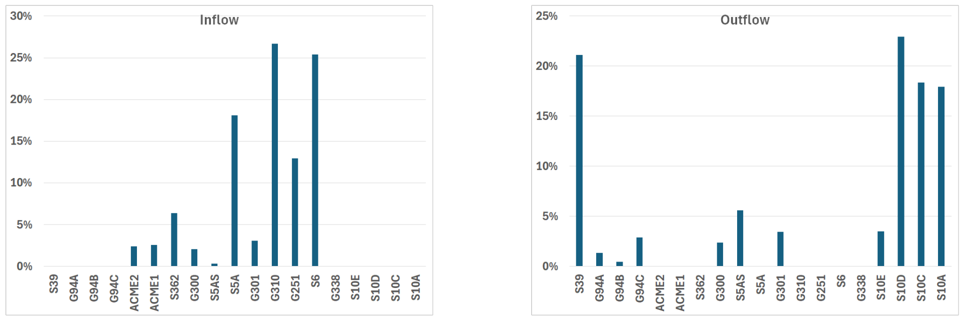


Figure 3.3: Inflow/outflow control structures (Bazgirkhoob *et al.*, 2015).



(a) (b)

Figure 3.4: Percent of historic total structure inflow (a) and outflow (b) for the period 1/1/1995 to 6/30/2009.

are read from an Excel spreadsheet $Regulation39.xlsx$. These flows are stored in the R dataset file $39 - Box - Datasets.Rdata$.

Historic versus calculated outflow

The parameter $CalcQRo$ determines whether structural outflows used in a simulation scenario follow historical flows ($CalcQRo = FALSE$) or are based on the Refuge Regulation Schedule and calculated from stage ($CalcQRo = TRUE$). Calculated outflows are usually the appropriate option because most modeling scenarios test impacts of altered water management, water supply, or climate change, and the outflows need to adapt to these changes.

Calculated outflows

Calculated outflow is determined from the difference between the floor of the A1 Zone of the Regulation Schedule (Figure 3.6; USFWS, 2000; Neidrauer, 2004) and the simulated stage at the USGS 1-8C stage gauge. The current regulation schedule was established in May 1995. Therefore, simulated stage using calculated regulatory outflows and outflows for dates prior to May 1995 should not necessarily track historic values.

The R function $QCalcOutS10(S10Stage, A1)$ calculates the total regulatory outflow from ΔS, the difference between its arguments, the simulated stage

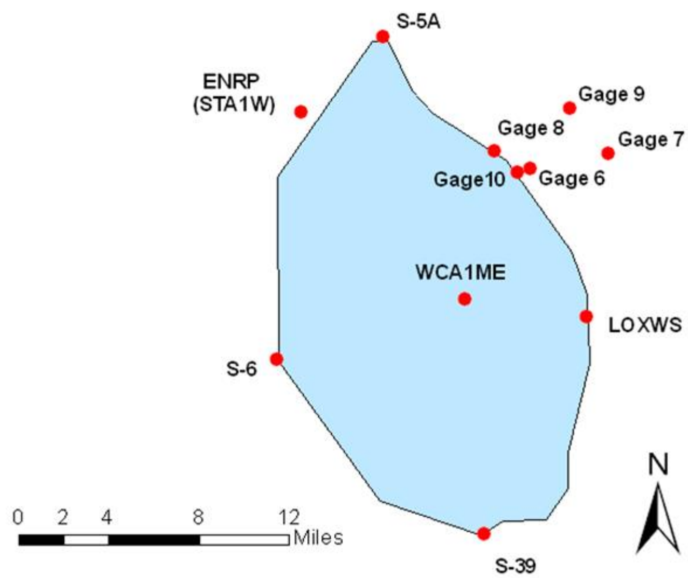


Figure 3.5: Location of rain gauges (Bazgirkhoob *et al.*, 2015).

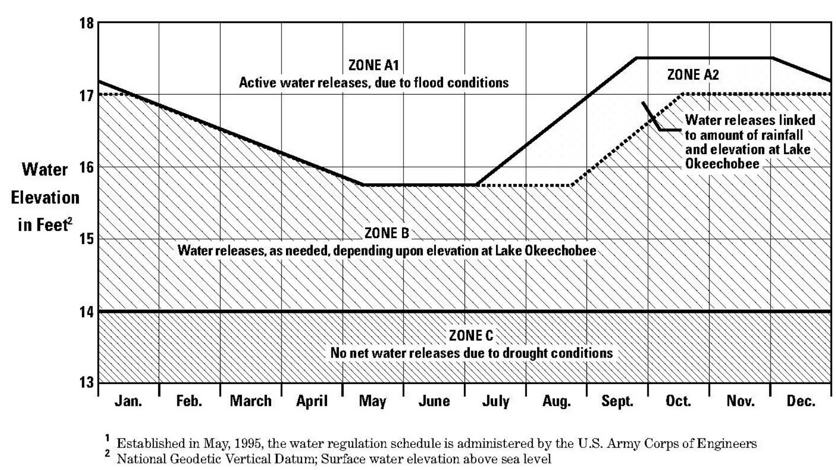


Figure 3.6: The Loxahatchee Refuge Regulation Schedule (Arthur R. Marshall Loxahatchee National Wildlife Refuge Comprehensive Conservation Plan(2000)).

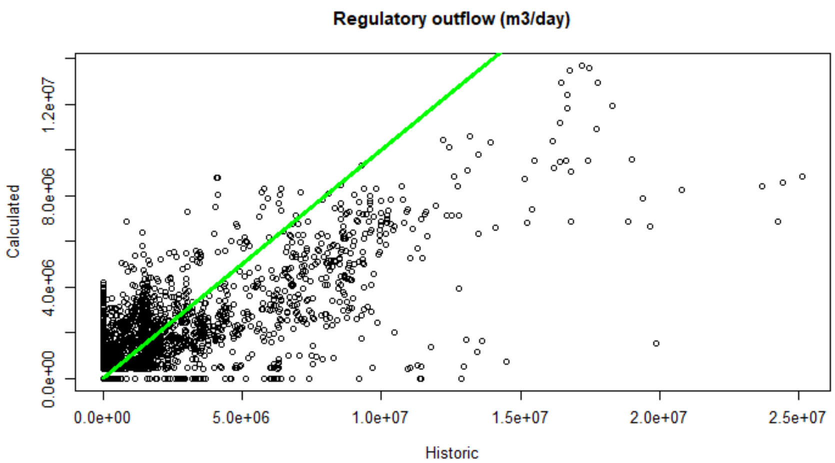


Figure 3.7: Total daily regulatory outflow (m^3/day) from 1/1/1995 to 6/30/2009 are plotted against historic values. The green line is a line of perfect fit.

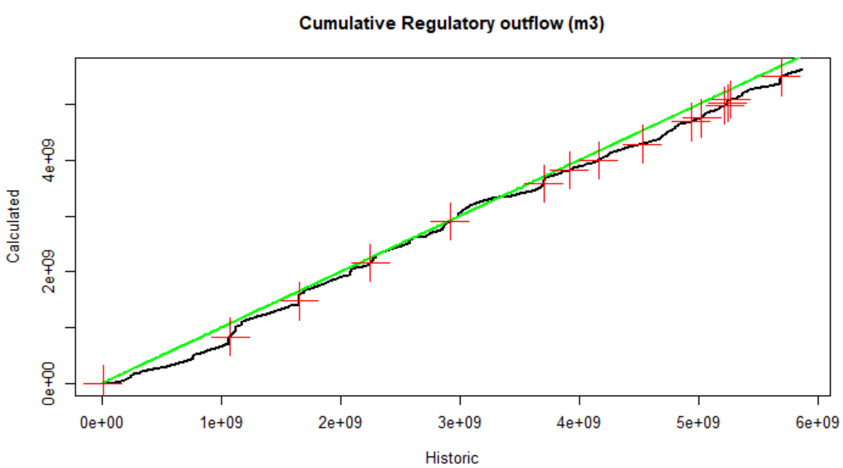


Figure 3.8: Cumulative total of daily regulatory outflow (m^3/day) from 1/1/1995 to 6/30/2009 are plotted against cumulative historic values. The green line is a line of perfect fit. Red crosses are plotted on January 1 of each year.

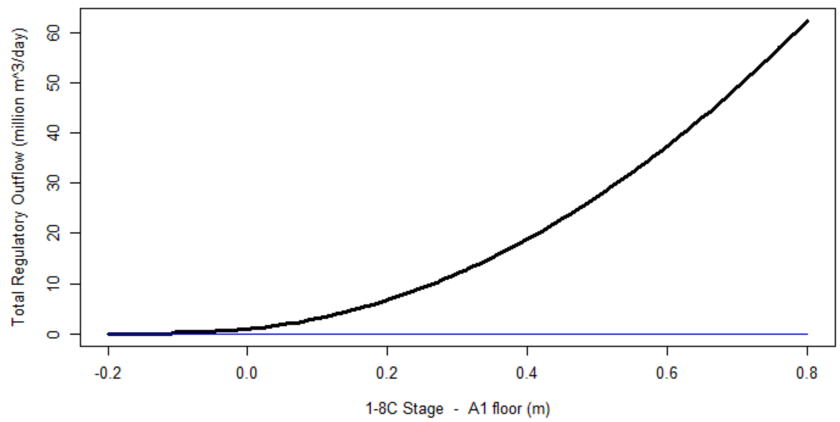


Figure 3.9: Calculated total regulatory outflow (million m^3/day) function (Eq 3.2) plotted against the amount that stage at the USGS 1-8C gauge exceeds the A1 floor stage (m). The blue line is zero outflow.

at the USGS 1-8C gauge (cell 9) and the zone A1 floor stage. The zone A1 floor stage is calculated in function $A1Floor(DAY)$ as a function of the day of the year (1 to 366). Calculated outflow is zero when $\Delta S < -0.1$. Otherwise

$$Q = -0.9541909 + 12.9026725\Delta S + 79.9679408\Delta S^2 \tag{3.2}$$

where ΔS is the stage at the USGS 1-8C gauge,and Q is the regulatory outflow in millions of cubic meters per day ($10^6 m^3/day$).

Evapotranspiration

Evapotranspiration (ET) represents the movement of water into the atmosphere through the combined processes of evaporation and transpiration. The rate of water loss through ET depends on temperature, wind speed, and water availability. ET is a significant component of Everglades water budgets(German, 2000; Roth and Meselhe, 2010). Potential ET is the rate

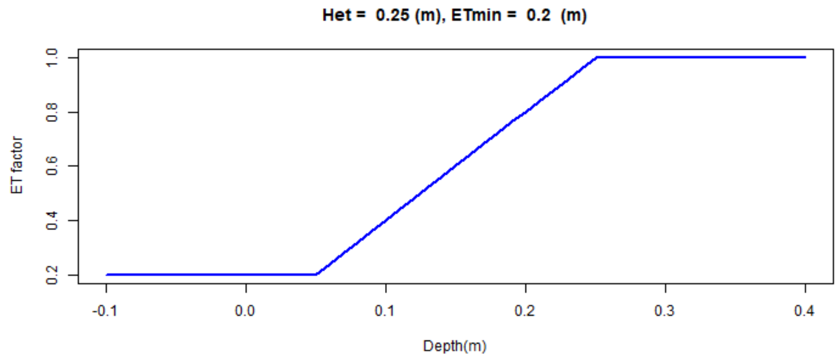


Figure 3.10: The dimensionless evapotranspiration reduction factor is a function of 2 parameters, Het and $ETmin$. The factor is calculated by the function $Fet(depth)$.

at which water is lost through ET under completely flooded conditions. The time series of daily potential ET used here was initially downloaded from DBHYDRO for use in the earlier SRSM model (Roth and Meselhe, 2010).

Actual ET may be less than potential ET because less water is available for ET when conditions are dry. This reduction in ET is modeled in function (function $Fet(d)$) as a dimensionless depth-dependent multiplier (Figure 3.10.

3.5 Temporal scale

Daily average values are used for input time series data for flow, rain depth, ET, and stage. Daily values are used because they are more generally available and because the use of more frequent data (hourly, for example) would greatly increase the size of the datasets. Although daily values are believed to have acceptable temporal resolution, future studies might examine the sensitivity to the use of more frequent data.

3.6 Model Structure

The model spatial structure is diagrammed in Figure 3.11. The model divides the Refuge into $ncell = 39$ cells and connects the cells with $nlink = 52$ links providing flow paths between adjacent model cells.

3.7 Time, day, and date

The model simulates time as a continuous variable measured in days from a base time of midnight on the morning of January 1, 1995. Days are counted as integers, with day one corresponding to January 1, 1995. When the variable $time = 0$ the date and time are January 1, 1995 at 0:00 hours, and $time = 1$ is 24 hours later, January 2, 1995 at 0:00 hours. Thus, a model output for time equal to an integer n corresponds to the end of day n and the beginning of day $n + 1$, and the day corresponding to any time greater than zero is the integer part of time plus one. Three functions are included with the model to clarify this relationship in the R code.

```
Day2TIME(d)   function converts model day to time at the beginning of day
Date2Day(d)   function converts a date (type character or date) to day
Day2Date(d)   function converts model day to date (type date)
```

3.8 Parameters

Model parameters are constants used in model calculations. Most model parameters are set in a separate R script that is selected at run time by the user. The "base run" parameters are set in the script *39BoxBase.R*. This file should not be edited by the user. When running alternatives, a renamed copy of this file should be created and the copy edited to provide any parameter changes. This filename should then be entered when prompted by the *runStage.R* script. The filename will then be used to name the output file.

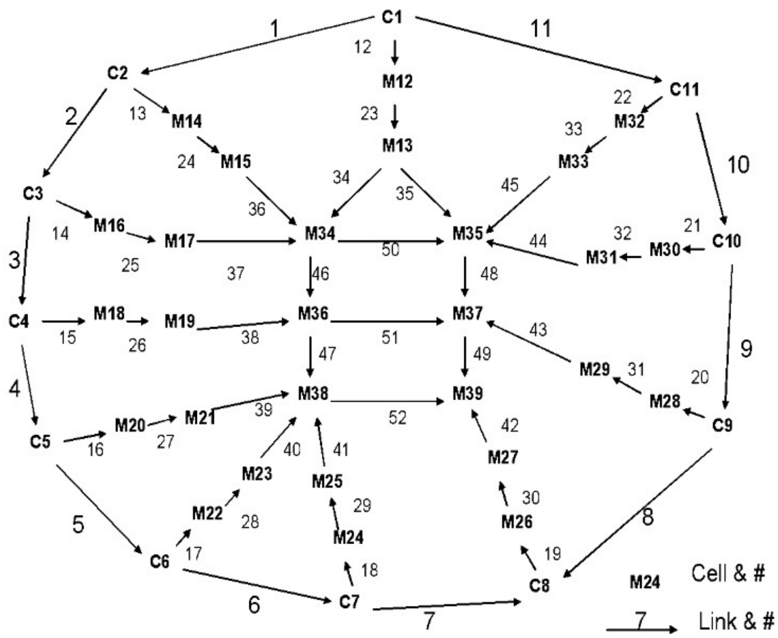


Figure 3.11: Link-node diagram of the compartments and links (Bazgirkhoob *et al.*, 2015)

3.9 Time series and geometric data

A large amount of data are required to run the stage model. Although these data are generally available for the Refuge, the task of collecting, cleaning, formatting, and saving all of the data required to run the model is a large part of model development.

Time series data are required by the model to define historic conditions of flow, precipitation, and ET. Geometric data provide measurements for model cells and links.

3.9.1 Input data types and sources

Data for the current model version come from spreadsheets used to build the Berkeley Madonna model, or were exported from the Berkeley Madonna model. Spreadsheets used to create the current model dataset include:

```
CellParameters.xlsx - data transferred to dataframe "cell"
  "Area" - surface area of cells
  "Elevation"- cell ground surface elevation
  "MinVol" - minimum cell volume

LinkParameters.xlsx - data transferred to dataframe "link"
  "Radius" - radius of link
  "width" - width of link
  "linkupdn" - upstream and downstream link numbers

INFLOW39.xlsx - data transferred to dataframe "Inflow"
  "INFLOW" - historic inflows by structure

OUTFLOW39.xlxs - data transferred to dataframe "Outflow"
  "OUTFLOW" - historic outflow by structure

Regulation39.xlsx - data transferred to dataframe "NonReg"
```

```
  "Regulation" - non-regulatory outflows

PET39.xlsx - data transferred to dataframe "PET"
  "PET" - potential evapotranspiration

Volume-Stage-Canal.xlsx - data transferred to dataframe canalVS
  "S-V" - canal cell stage-volume pairs

obs_stageall.xlsx - data transferred to dataframe "Stage.Obs"
  "obs_stageall" - observed stage for calibration
```

3.9.2 Dataset creation

The script $make_datasets.R$ imports time series and geometric data, and stores the compiled data in R data structures saved in the file $39 - Box - Datasets.Rdata$.

3.10 Model Implementation in R

This model version was developed in the R programming language using the RStudio programming environment. R is widely used and is well suited for data handling. R supports versatile graphics development, and includes comprehensive statistical analysis tools. R has the disadvantage of being slower than alternative languages and modeling platforms including Berkeley-Madonna which was previously used. R is especially slow when compared with compiled languages such as FORTRAN, C, and Modelica.

3.10.1 Rationale for porting to R

The previous version of the 39-Box Model was implemented in the Berkeley Madonna simulation environment. Berkeley Madonna has several advantages. Berkeley Madonna provides a relatively simple and flexible user interface for writing algebraic and differential equations that describe the system being modeled. It also provides an interface for parameter optimization, sensitivity analysis, and graphics production.

However, Berkeley Madonna has some limitations. Although the model input for Berkeley Madonna may be shared as text files or in the proprietary *.mmd input files, the Berkeley Madonna simulation environment must be purchased by users in order to run simulations. Berkeley Madonna is also not widely used. These limitations led to the decision to translate the 39-Box model into the R programming language.

R is a widely used open source programming language. In addition to the core R language, many library packages are freely available that extend R's capabilities. R is an interpreted rather than a compiled computer language. This is an advantages in ease of use and program development, but because R is interpreted execution of an R program can be orders of magnitude slower than a similar compiled program.

3.10.2 Key R program libraries used

A number of packages must be installed before running the model. In R-Studio, packages are installed from the Tools tab. Required libraries are invoked in the "Preamble" section of the model code near the beginning of the program.

```
library(chron)       # date functions
library(stats)       # statistics functions
library(deSolve)     # ordinary differential equation solvers
library(lubridate)   # additional date functions
library(dplyr)       # data manipulation
library(readxl)      # read Excel worksheets
library(matrixStats)# colMin function
```

3.10.3 File structure and organization

The model is implemented in files within a parent directory named $39 - Box$. Folders within the parent folder contain most of the model implementation.

Rscript - All script and function files

DataSets - Data including Excel and csv files

Documentation - Model documentation and figures

maps - Various map files

Calibration - Files related to model calibration

Output - Model output

Some of the files in these folders are copied from previous model versions and are not needed to run the current R model version.

Model scripts and code files

39BoxStage.R - This is the main model script which is executed each time the stage model is run.

39BoxStageConstants.R - This script sets the model constants needed for the 39-Box Stage model. The script is executed each time the model is run. Separating the stage model parameters into a separate file allows the user to save alternative model run settings in unique files and then copy the desired file to *39BoxStageConstants.R* when needed for model execution. It also allows the user to save this script file along with model output for a specific model scenario run.

Day2Date.R - Contains the 39-Box day and date functions.

depth.R' - Contains functions to calculate cell depth and volume.

Main functions and their purposes

The use of functions simplifies code debugging and results in a more modular program that is easier to maintain and modify.

Day2Date - Converts model day to date

Date2Day - Converts date to model day

$Day2TIME$ - Converts day to time

$Cell.Depth.calc$ - Calculates cell depth from volume

$Cell.Volume.calc$ - Calculates cell volume from depth

$Canal.BF.calc$ - Calculate canal bank-full parameters

$QoutHistoric$ - Historic canal outflows by cell on DAY

$Qinfunc$ - Historic canal inflows by cell on DAY

$A1Floor$ - Regulation Schedule A1 floor stage

$QCalcOutS10$ - Calculated regulatory release

$QoutCalcCell$ - Distributes calculated outflows among canal cells

Fet ¡- Calculate ET depth reduction factor (dimensionless)

$Link.Flow.calc$ - Calculate link flows

$link2cell$ - Link flows added/subtracted to/from cells

$derivs$ - Called by function ODE, returns d/dt cell volume

Output file

The model output filename is set in the $39BoxStageConstants.R$ script using the constant $run.filename$ and is assigned the file extension $Rdata$.

3.11 Model calibration

The previous version of the 39-Box model was calibrated and tested for stage and depth using USGS stage data (Figure 3.12, and depth measurements observed at water quality monitoring sites (Figure 3.13. Depth measurements in the Everglades are typically termed depth to Consolidated sediment (DCS). This distinction is needed because there is often an observable thin layer of detrital floc covering the sediment surface.

Parameters related to water transport were also calibrated by comparing monitored chloride concentration monitoring data with simulated chloride concentration. At the time of this writing, there has been no effort to calibrate the new translated model. In the future, a new model calibration study could be conducted using data extending beyond 2009, and employing the chloride model (39-Box Mass Model) which is currently in development.

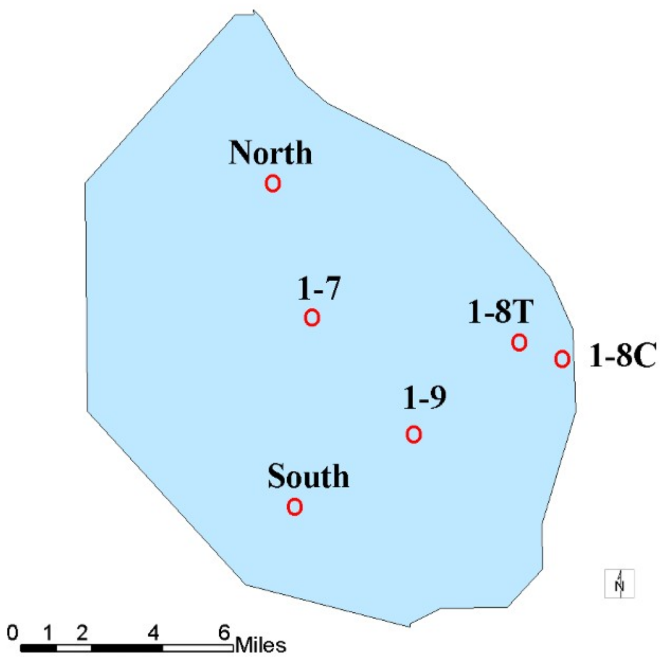


Figure 3.12: Location of USGS stage gages (Bazgirkhoob *et al.*, 2015).

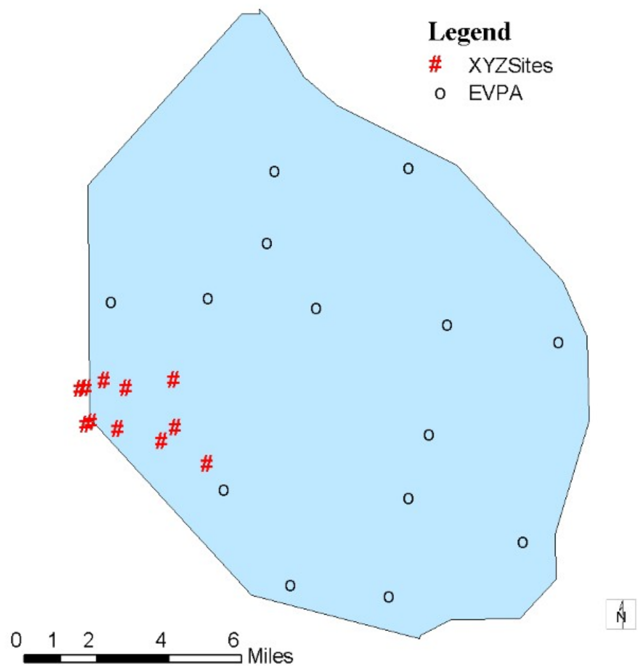


Figure 3.13: EVPA and XYZ water quality monitoring sites provide water depth observations that were used to calibrate the previous version of the 39-Box model (Bazgirkhoob *et al.*, 2015).

Chapter 4

Running the Model

4.1 Model package description

The 39-Box stage model package is a collection of data files and script files. Some scenarios will involve only a simple change to a model parameter. However, many of the possible scenarios that users may wish to study using the model will require an understanding of the data and R scripts that are used during a model run.

Much of the data used in the model are read from Excel spreadsheets that were used in the development of previous models. In other cases, data were exported from the earlier SRSM model (Roth, *et al.*, 2010). Data used in the simulation were compiled into an R dataset by the script *make_dataset.R*. Datasets and some constants are saved in an R data file $39 - Box - Datasets.Rdata$.

There are a number of R scripts included in the model package, including:

- *runStage.R* This is typically the script that starts a model run. The script sets the name of the model constants file as the default, $39BoxBase.R$, or as a user entered filename. It runs the script chosen constants script followed by $39BoxStage.R$, and then $39BoxStageStdGraphs.R$.

- 39*BoxBase.R* Default model constants are set in this script. To avoid confusion, users are urged to not edit this script. Instead, when running a scenario that requires changing constants users are advised to edit needed changes in a copy with a new descriptive name. Then enter this filename when prompted.
- 39*BoxStage.R* This script executes the simulation.
- 39BoxFunctions.R Model functions are defined in this script. It is sourced by 39*BoxStage.R* at the beginning of the model run.
- 39BoxStageStdGraphs.R Plots a number of standard graphs at the end of the model run.
- WaterBalance.R Runs an analysis of the model water balance.

All of the model script files include extensive comments that provide self-documentation of many details that are not described in this manual.

4.2 System requirements and installation

No detailed information is available on computer memory and storage requirements. Memory usage in RStudio is displayed in the small memory usage widget in the Environment pane. The widget pie chart displays the total amount of system memory in use, and the number displays the approximate amount of memory in use by R objects, libraries, and packages. The color in the widget changes to red when you run out of memory.

However, often it will not be necessary to create a new model directory.

4.3 Output

Model results are saved after a model run in an R dataset in the Output folder. The output filename is set to a user-specified filename (variable name $filename$) at the beginning of the run. The output file has the extension *.Rdata*. This file is created by these lines of code at the end of the

$39BoxStage.R$ script.

```
# Save output
save(run.title, filename, sim.Volume, sim.Depth, sim.Stage,
sim.Outflow, sim.Linkflow, sim.Velocity,
file=paste("../Output/",filename,".Rdata", sep=""))
```

- *run.title*, and $filename$ are the user specified title used in graphs, and the input/output file name.
- $sim.Volume$, *sim.Depth*, and *sim.Stage* are matrices of daily values (rows) for all cells (columns).
- $sim.Outflow$ is a matrix of daily outflow (row) for all canal cells.
- $sim.Linkflow$, and $sim.Velocity$ are matrices of daily values (row) of discharge and velocity for all links (columns).

Values in the rows of the output matrices are instantaneous values at the start of the day. The first row of the output matrices holds the initial values at time 0:00 on the first day of simulation. In general, output matrix row n holds the value at the beginning of day n and row $n + 1$ holds the value at the end of day n. Daily average values are not calculated by the model. However, daily average value for day n may be approximated as the average value for row n and row $n + 1$.

4.4 Workflow

There is no fixed set of steps required to analyze a new model scenario. In this section, some general guidelines for scenario analysis are suggested, and an example scenario is presented.

In running a scenario, it is important to not make inadvertent changes to the distributed base model files. Changing these files could result in unknowingly modifying other scenario analyses. If changes to distributed model files cannot be avoided, then all model files should be copied to a new folder dedicated to that scenario.

As an example, consider a scenario concerning the date that the S-6 pump was diverted. Historically, the S-6 pump discharged into the perimeter canal in the southwest of the Refuge. This inflow was diverted to WCA-2 in 2001. In the model flow record, the last day of inflow from the S-6 pump was March 30, 2001. In this example scenario, consider how this diversion changed marsh stage by removing this inflow beginning before 1995. Comparison of Refuge hydrological response to the S-6 diversion is seen by comparing the period 1995 to 2001 with and without S-6 inflows.

Files needed for this scenario are included with the distributed model. Note that users are advised not to edit the original files in the distribution. To create this scenario, the file $runStage_NoS6inflow$ was copied from the distributed file *runStage.R*. Two sections of the new file were edited as shown below.

First section sets inflow from the S-6 to zero:

```
# ----------------------------------------------------------
# On the following lines make any changes needed for the current scenario.
  # This may alter constants, loaded dataframes, or redefine functions.
  # Example: To model the impact of increasing flow through the S39 by 20%
  #   NonReg$S39 <- 1.2*NonReg$S39
  # Save this modified file with a new filename (i.e. not as runStage.R).

  # set the S-6 inflow to zero
  Inflow$S6 <- 0
  # set the end date of the simulation to March 30, 2001
    # This is the last day of historic S-6 flow > 0.
  Stop.Date  <- as.Date('2001-03-30')


# ----------------------------------------------------------
```

Second section calls a new graphics script:

```
# ----------------------------------------------------------
# On the following lines add any final statistical calculations, or graphics
```

```
# run a graphics script
source("S6ScenarioGraph.R")
```

The file script was then executed (sourced), and at the user prompt name the output file $NoS6Inflow$ was entered. This created a new output file $NoS6Inflow.rdata$, produced 2 graphics (Figures 4.1 and 4.2). It also printed the result that the hydroperiod of interior marsh cell 36 changed from having an average of 0.6 days per year with depth below a threshold of 0.1 m to 16.2 days below this threshold.

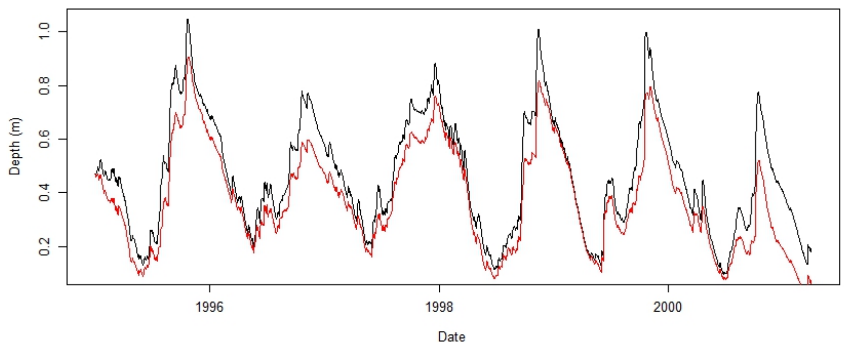


Figure 4.1: Depth in cell 36 with (black) and without (red) inflow from the S-6 pump.

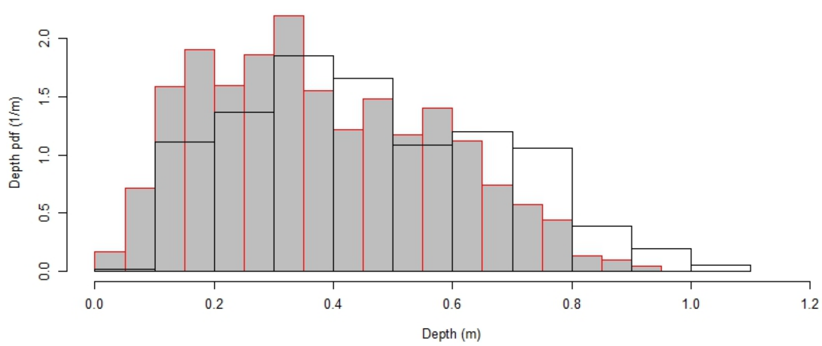


Figure 4.2: Histogram of depth in cell 36 with (black) and without (red) inflow from the S-6 pump.

Chapter 5

References

Arceneaux, J., E. A. Meselhe, A. Griborio, and M. G. Waldon. 2007. The Arthur R. Marshall Loxahatchee National Wildlife Refuge Water Budget and Water Quality Models. Lafayette, Louisiana: University of Louisiana at Lafayette in cooperation with the U.S. Fish and Wildlife Service.

Bazgirkhoob, Hamid, Ehab A. Meselhe, and Michael G. Waldon. 2015. A.R.M. Loxahatchee National Wildlife Refuge Refuge 39-Box Model User's Manual (revised). Prepared for the U.S. Fish and Wildlife Service under a cooperative agreement with the University of Louisiana at Lafayette.

Chen, C., E. A. Meselhe, and M. G. Waldon. 2009. A.R.M. Loxahatchee National Wildlife Refuge Hydrodynamic Modeling with MIKE FLOOD (Version 2.0). Prepared for the U.S. Fish and Wildlife Service.

German, E. R. 2000. Regional evaluation of evapotranspiration in the Everglades. Water-Resources Investigations Report 2000-4217. U.S. Dept. of the Interior, U.S. Geological Survey.

Macey, R., Oster, G., Zahnley, T., 2000. Berkeley Madonna User's Guide Version 8.0. University of California, Department of Molecular and Cellular Biology, Berkeley, CA.

Meselhe, E., Arceneaux, J., and Waldon, M. G. (2007a). Mass Balance

Model Version 1.01. Report #LOXA-07-002, University of Louisiana Lafayette in cooperation with the US Fish and Wildlife Service, Lafayette, LA.

Meselhe, E., Arceneaux, J., Waldon, M. G., and Wang, H. (2007b). A.R.M. Loxahatchee National Wildlife Refuge Water Quality Model Version 1.00. Report #LOXA-07-003, University of Louisiana Lafayette in cooperation with the US Fish and Wildlife Service, Lafayette, LA.

Neidrauer. 2004. Water Conservation Area Regulation Schedules. Presented at the Technical Oversight Committee Meeting, August 2004.

Richardson, J. R., W. L. Bryant, W. M. Kitchens, J. E. Mattson, and K. R. Pope. 1990. An evaluation of refuge habitats and relationships to water quality, quantity, and hydroperiod: A synthesis report. 166 pages + map, Cooperative Fish and Wildlife Research Unit, Univ. of Florida, Gainesville, FL.

Richardson, J. R., W. L. Bryant, and W. M. Kitchens. 1993. A spatial hydrologic model of Loxahatchee National Wildlife Refuge and its integration into a GIS analysis. Pages 450-454, Wetlands: Proceedings of the 13th Annual Conference, New Orleans, Louisiana, June 1992. M. C. Landin, ed., Society of Wetland, Scientists, South Central Chapter.

Roth, W. B., and E. A. Meselhe. 2010. The Development of a screening model for the Arthur R. Marshall Loxahatchee National Wildlife Refuge. 189 pages. Lafayette, Louisiana: Prepared for the US Fish and Wildlife Service, Department of Interior, by the Institute of Coastal Ecology and Engineering, University of Louisiana-Lafayette.

USFWS. 2000. Arthur R. Marshall Loxahatchee National Wildlife Refuge Comprehensive Conservation Plan. 362 pages. Boynton Beach, Florida: US Fish and Wildlife Service.

Wang, H., E. A. Meselhe, M. G. Waldon, D. D. Surratt, S. Abdou, C. Chen, and M. C. Harwell. 2008. Compartment delineation for a wetland water quality model in the Northern Everglades, Florida, USA. Journal of Environmental Hydrology, 16: Paper 36.

Wang, H., E. A. Meselhe, M. G. Waldon, M. C. Harwell, and C. Chen. 2012. Compartment-based hydrodynamics and water quality modeling of a Northern Everglades Wetland, Florida, USA. Ecological Modelling, 247: 273–285.

Appendix A

Glossary of Terms

Cell - may also be termed a **box**, **compartment**, **tank**, or **node**. A cell covers a specified contiguous area, and all cells cover the entire area of the model domain. A cell is an object with the properties of type (canal or marsh), area, volume, soil elevation, average depth, and stage.

Depth - Height of the water column above the consolidated marsh soil surface (see DCS).

DCS - depth to consolidated sediment (DCS) is the depth measurement used in Everglades monitoring programs.

Elevation - Height above a specified datum. All elevations in the 39-Box model are relative to the NGVD29 datum.

Link - connects adjacent cells with a flow path. A link is an object with properties of type(canal-canal, canal-marsh, marsh-marsh), upstream cell, downstream cell, width, radius (or length), discharge, and velocity.

Object - a programming concept that has properties and methods. Here, objects are primarily defined using data frames with properties assigned in the data frame definition (for example cell$type), and methods are defined using functions (for example the function $Cell.Depth.calc(v)$ returns cell depths given their volumes).

Refuge - The Arthur R. Marshall Loxahatchee National Wildlife Refuge in Florida, USA.

Regulation schedule - A water control plan for managing outflow from the Refuge.

SFWMD - South Florida Water Management District

STA - Stormwater Treatment Area, a constructed wetland treatment system.

Stage - The water surface elevation above a specified datum surface.

WCA - Water conservation area