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HEC-ResPRM
Prescriptive Reservoir Model

Quick Start Guide

Version 1.0
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14. ABSTRACT
HEC-ResPRM is a software environment developed to facilitate using HEC-PRM for data-intensive multi-objective water resource system operation studies. HEC-PRM ("Prescriptive Reservoir Model") is a generalized computer program that performs deterministic network-flow optimization of reservoir system operations. HEC's Data Storage System (HEC-DSS) is used for storage and retrieval of input and output time-series data. This introductory guide leads the reader through the 3 modules of the software, using a simplified but informative example to illustrate the modeling process. The HEC-ResPRM software, its documentation, and the digital files for the example treated here are available on the HEC website.

15. SUBJECT TERMS
HEC-ResPRM, Water Resources System Optimization, Reservoir Optimization, Computer Program

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Use of the software described by this document is controlled by certain terms and conditions. The user must acknowledge and agree to be bound by the terms and conditions of usage before the software can be installed or used. For reference, a copy of the terms and conditions of usage are included in Chapter 11 of this document so that they may be examined before obtaining and loading the software. The software described by this document can be downloaded for free from our internet site (www.hec.usace.army.mil).

HEC cannot provide technical support for this software to non-Corps users. Non-Corps individuals should use any internet search engine to locate a vendor that can provide support for the HEC software of interest. However, we will respond to all documented instances of program errors. Documented errors are bugs in the software due to programming mistakes not model problems due to user-entered data.

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CHAPTER 1

Introduction

Welcome to the HEC-ResPRM Quick Start Guide. This document will take you through the steps needed to develop a water resources system optimization model using HEC-ResPRM. Use this document to get a quick overview of the program and its basic features. If you already use the HEC-ResSim reservoir simulation software, many tools and features of HEC-ResPRM will be familiar. HEC-Res (the interface for both ResSim and HEC-ResPRM) offers a useful modeling environment for viewing and organizing model data. The models you construct in these software can help inform reservoir operating decisions and improve planning and management of water resources systems.

This Quick Start Guide provides a brief overview of the software followed by examples that demonstrate its application. It is intended to give users a quick introduction to the software without delving deeply enough to be either a complete User's Manual or a Technical Guide.

For further information, including some technical background, about the HEC-PRM software engine and its implementation of generalized network flow programming, refer to the HEC-PRM User's Manual. In the future, a User's Manual for HEC-ResPRM will offer more depth on the use and application of the software. Users may also find the HEC-ResSim User's Manual to be a helpful reference concerning some of the shared layout and features of these software packages. All HEC-ResPRM users should familiarize themselves with the general techniques, application, and uses of reservoir optimization.

1.1 What is Reservoir Optimization?

Optimization is the approach to solving problems that seeks the best solution by maximizing (or minimizing) a set of goals in the form of an objective function, subject to specified constraints. Reservoir management can be improved by using optimization modeling in conjunction with the time-honored empirical approach. Optimization modeling can be used to identify the optimal long-term operational strategy for a system of reservoirs. The information obtained from an optimization model can then be used to adjust and improve upon rules developed over years of experience and observation. Optimization can also support the adjustment of current operation strategies to reflect changing priorities and needs within the system.

Several different optimization algorithms are available to implement deterministic models. Among the most popular are linear programming, network flow programming, dynamic programming, and optimal control.

Deterministic optimization has been used over the last 40 years in efforts to improve the operation of water resource storage and conveyance systems (Young, 1967; Jettmar and Young, 1975; Bhaskar and Whitlatch, 1980; Karamouz et al. 1992). There is no single or clearly established way to derive operating rules based on time-series results of optimal flows. A variety of statistical and graphing methods can be used (Lund and Ferreira, 1996).

Because most reservoirs serve many purposes (e.g., water supply, recreation, flood protection, hydropower, and navigation), reservoir system operation can easily be posed as a multi-objective optimization problem (Ko et al., 1992; Harboe, 1992). Several multi-objective techniques have been adapted for use in the water resources field and applied to reservoir optimization (Cohon and Marks, 1975; Cohon, 1978). In water resources, different goals are often non-commensurate (measured with different units) and conflicting (improving the performance of one objective requires sacrifice from another). When several objectives are considered, the goal changes from optimality to non-inferiority, i.e., searching for a compromise solution in which no objective can be improved without harming one or more other objectives.

Multi-objective techniques can be grossly divided into two categories: generating techniques and techniques which incorporate knowledge of the decision-maker's preferences (Cohon, 1978). In generating techniques, the analyst provides the decision-maker with a choice of trade-offs amongst the non-inferior solution set. In case of two objectives, the trade-off can be graphed as a curve (an indifference curve); for three objectives it forms a surface.

1.2 What is HEC-ResPRM?

HEC-ResPRM is a software environment developed to facilitate using HEC-PRM for data-intensive single or multi-objective reservoir system operation studies. HEC-PRM is the computational core of the more user-friendly HEC-ResPRM software.

HEC-PRM ("Prescriptive Reservoir Model") is a generalized computer program that performs deterministic network-flow optimization of reservoir system operations. PRM "prescribes" optimal values of flow and storage over time by minimizing penalty functions located throughout the water resource network. PRM can be used for multi-reservoir, multi-objective problems. The network flow problem is formed by placing upper and lower bounds on reaches, and penalty functions are used in the objective function to guide the solution to optimal.

PRM identifies the allocation of water that maximizes total benefits by minimizing the costs associated with poor performance for all defined system purposes. Performance is measured with user-provided penalty functions based on flow, storage, or both. To determine the optimal water allocation, PRM represents the physical system as a network, and the operating problem is formulated as a minimum-cost network flow problem. The objective function of this network problem is the sum of piecewise-linear approximations of the penalty functions. An off-the-shelf solver (using a modified Simplex Algorithm) is used to determine the optimal allocation of water within the system. The results of the solver are processed to report and display reservoir releases, storage volumes, channel flows, and other pertinent variables. The Res implementation also allows users to produce graphical results directly from the Graphical User Interface (GUI).

The simplicity and versatility of the HEC-PRM model formulation has enabled its use in a wide variety of studies. Fields of application include development of reservoir system operating rules, shared vision planning, multi-objective management, hydrologic-economic modeling, conflict resolution, climate change impact assessment, and trans-boundary cooperation. PRM has been applied to several large and complex water systems including the Columbia River System, the Missouri River System, the Mississippi Headwaters, and California's water resource system. (See Chapter 9 for references.)

The HEC-ResPRM software is designed to further the efficiency and ease of use of HEC-PRM, particularly for multi-objective studies. The multi-objective nature of water resource problems can be addressed by allowing any number of penalty functions (including those with differing units) to be added at any network location. The HEC-ResPRM environment is in large part shared with HEC-ResSim – a sister reservoir system simulation tool. The integration of PRM into the HEC-Res modeling platform was made to facilitate the joint development and use of simulation and optimization models. The HEC-Res modeling system allows different network configurations and model runs to be managed and visualized within a single interface, thus forming a robust platform for complex, data-intensive modeling studies. HEC's Data Storage System (HEC-DSS) is used for efficient storage and retrieval of input and output time-series data.

1.3 HEC-ResPRM Data Requirements

Here are the typical data needs for performing a reservoir optimization study with HEC-ResPRM. Optional data are in italics.

Background Maps of Watershed (optional):

At a minimum, you must have a good understanding of the layout of the reservoir system (the network of streams and locations of reservoirs and important points in the watershed). Optional background maps are helpful for setting up your model and visualizing its spatial layout and can be in the form of:

- *various GIS, CAD, and image file types*
- *data from existing ResSim model of the watershed*

Physical Data:

Physical data are used to develop model constraints and allow the model to calculate penalties.

- reservoir outlet capacities
- *elevation-storage-area relationships (optional)*
- upper and lower stream capacity (i.e., bankfull capacity and zero or base flow)

Hydropower Data (optional):

- *outflow-energy generation relationship*

Historical or Synthetic Time-Series:

- local inflows
- *evaporation (optional)*

Historical Time-Series (optional):

These time-series can be compared to the results of your optimization runs.

- *reservoir storage*
- *reservoir release*
- *inflows*
- *stream flows*
- *diversions*

Desired Objectives and Constraints for the System:

These objectives and constraints are the data used to build penalty functions – the main driver of the optimization. The penalty functions relate cost to flow or storage, and are combined to construct the model's objective function. The data must be analyzed and interpreted to develop the penalty functions.

- *flood control*
- *environmental*
- *navigation*
- *water supply*
- relationships between ranges of flow/storage and values (monetary or otherwise) of objectives

Optimization vs. Simulation: PRM stands for Prescriptive Reservoir Model. "Prescriptive" indicates that a specific solution is *prescribed* by the model, itself, as in the case of Optimization. (The modeler does not explicitly tell PRM how to operate the reservoirs.) Simulation models, such as ResSim, are considered to be "descriptive," because they offer a general description of the system by following modeler-specified rules.

CHAPTER 2

User Interface

The main interface of HEC-ResPRM consists of a title bar, a series of menus, a toolbar on the left-hand side, a main map window, a module selector showing one of three modules (Watershed Setup, Network, or Optimization), and other module-specific features (Figure 1). To work with HEC-ResPRM, you must sequentially go through the three modules, using the Watershed Setup Module to layout your model, the Network Module to add data, and the Optimization Module to compute and review results. The rest of this section will help to familiarize you with the interface, modules, and tools therein.

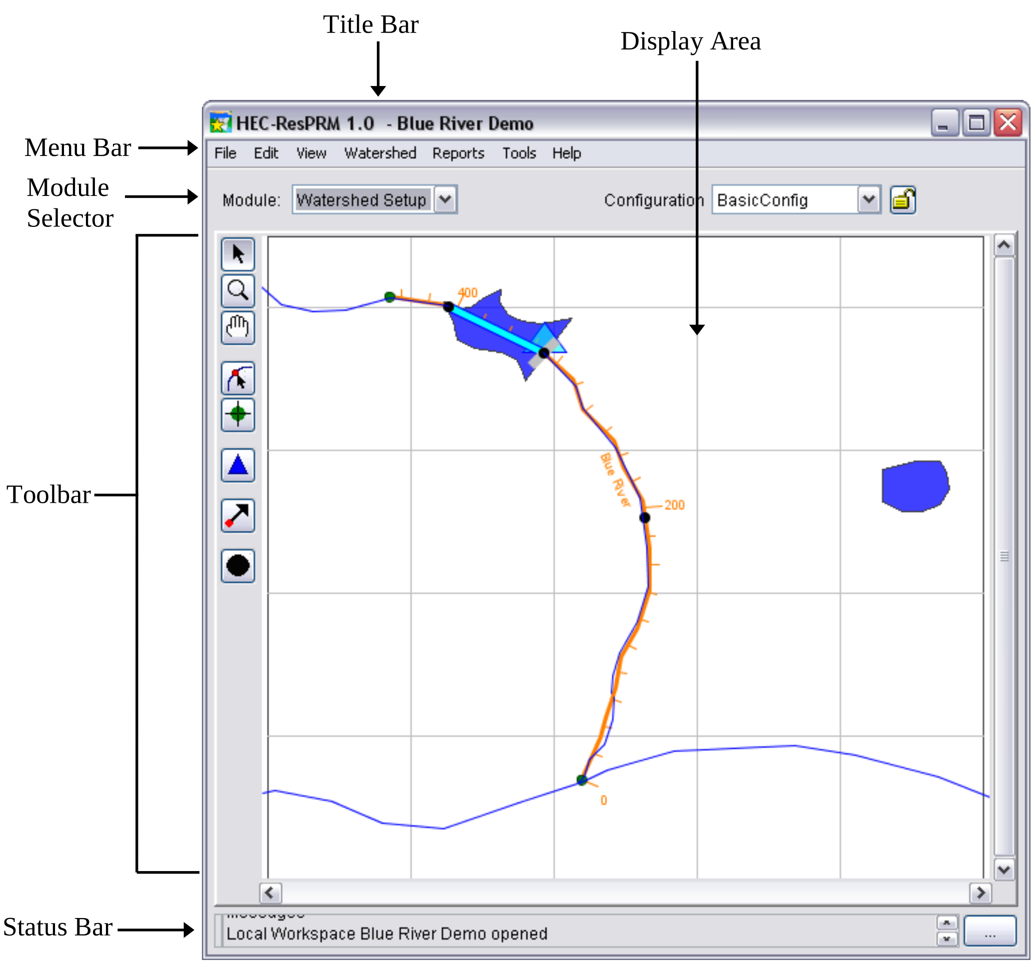


Figure 1: The main HEC-ResPRM interface includes a map, toolbar, module selector, and status bar.

2.1 Starting and Exiting the Program

Once HEC-ResPRM version 1.0 has been installed, start the program as follows:
On your desktop, double-click on the HEC-ResPRM icon or from the **Start** menu, select **Programs → HEC → HEC-ResPRM**.

The first time you start the program, you will be prompted to agree to the Terms of Use. You must scroll down (and read) through the text before you are able to select the agreement option. Upon initial use, you will also see an introductory screen containing the version and contact information. This screen will disappear after a few moments. The same information is available from HEC-ResPRM's **Help** menu by selecting the **About** option (Figure 2).

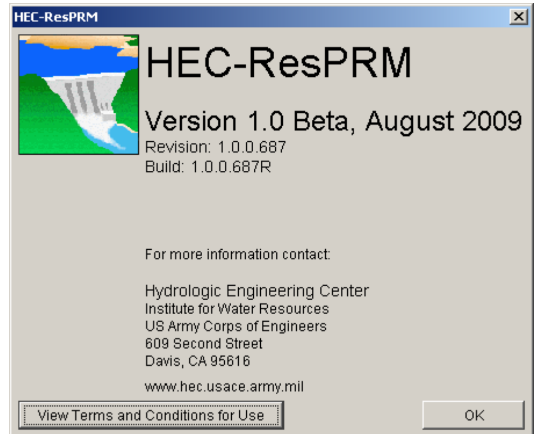


Figure 2: Version and contact information can be accessed from the About menu.

To exit the program, select **Exit** from the **File** menu on the Main Window. The program will prompt you to save all files. Selecting the "x" in the upper right hand corner of the Graphical User Interface (GUI) will also exit the program, but this approach is not recommended due to the potential for loss of data.

2.2 What is a Watershed?

In HEC-ResSim and HEC-ResPRM terminology, a **Watershed** is a collection of data associated with a model of a particular water resources system or study. Each watershed can contain the information to conduct multiple alternative runs. Data for HEC-ResPRM includes the physical layout and properties of the system, time-series input and output, and information associated with the optimization such as penalty functions, parameters and settings. Watershed data are viewed and edited in HEC-ResPRM through three separate modules: **Watershed Setup** (includes Configurations of projects), **Networks** (includes building Run Alternatives), and **Optimizations** (where the model alternatives are run and results reviewed), which will be described later. After performing an Optimization on one or more Alternatives you can view and print results in both tabular and graphical forms. This guide provides basic steps for using the GUI to enter data, run Optimizations, and view results.

2.3 What are Watershed Locations?

A **Watershed Location** is the place on disk where you store your watershed, otherwise known as your working directory. You can have multiple watershed locations, although a given watershed cannot span multiple locations. Each watershed location must be given a name, such as "MyHEC-ResPRMModels," and a path specification that identifies the directory where you want to store your watershed data.

Before you can create or open a watershed, you must define at least one watershed location; do so by selecting **Options** from the **Tools** menu. The Options Editor is shown in Figure 3.

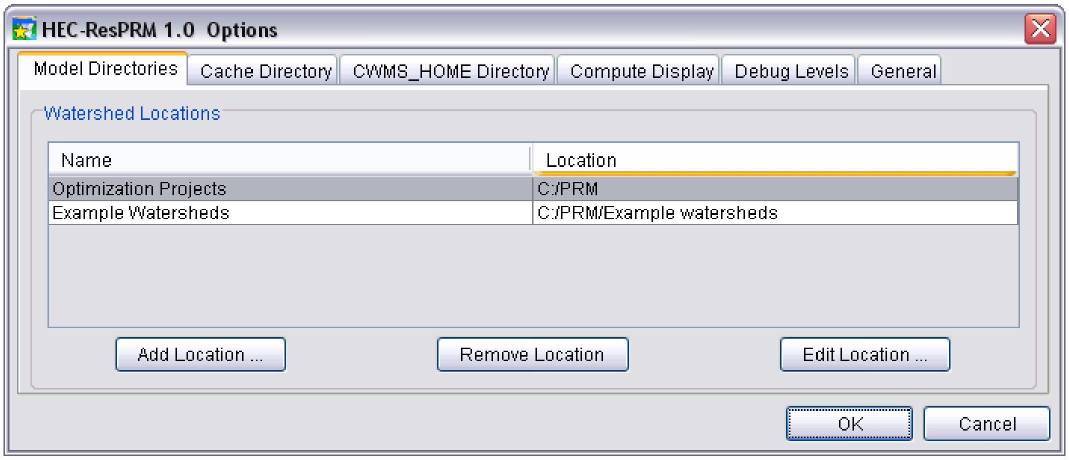


Figure 3: From the Tools menu, select the Options Editor and then the Model Directories tab in order to create or select a Watershed Location.

The first tab of the Options editor, Model Directories, is used to define Watershed Locations. To add a new location to the list, press the **Add Location…** button. The Add Watershed Location screen will appear (Figure 4). Browse to the area on disk where you want to build your watershed; then give this "location" a name and press **OK**. If this is the first time you are using HEC-ResPRM, you will also be prompted to confirm a cache directory.

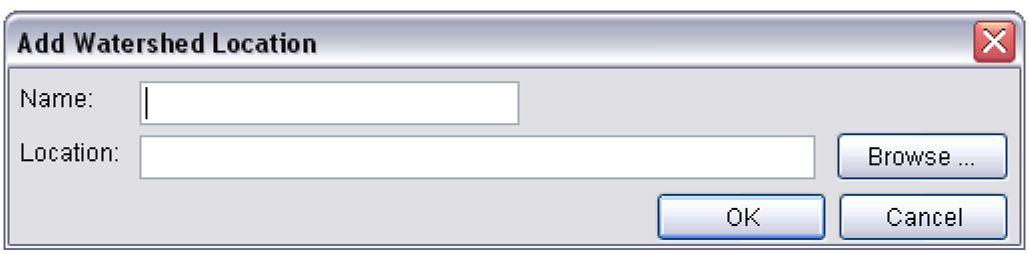


Figure 4: Choose any name for your Watershed Location, then browse to the directory where you will store your project data.

Project files will be stored in a "base" directory under the specified Watershed Location. If you are creating a watershed for the first time, HEC-ResPRM will automatically create the base directory. If, on the other hand, you were given a watershed by another user and wish to open it, you must make a directory called "base" under your Watershed Location directory and then place the watershed directory under it. Multiple watersheds (HEC-ResPRM models) can be stored under each Location's base directory. For example, if a modeler gave you a watershed

Setting up at least one Watershed Location is mandatory: Before you can do anything in HEC-ResPRM, you must have a Watershed Location defined. This is where all project data are stored.

called "American," and you wanted to put it in your "Optimization Projects" watershed Location (Figure 3), then you would use a Windows file explorer to place the directory called "American" in the path "C:/PRM/base/."

2.4 What are Modules?

The HEC-ResPRM software is divided into three **Modules**. Each module provides access to specific types and directories of data within the watershed data tree. The three modules within the HEC-ResPRM program are:

- **Watershed Setup**
- **Network**
- **Optimization**

Figure 5 provides a graphical illustration of the three modules that make up HEC-ResPRM. Refer back to this figure as you learn more about the function of each module to help keep the concepts organized. A more detailed depiction of the modules can be seen in Figure 6.

When you build a watershed in HEC-ResPRM, you will construct your model by stepping through each of the modules. Once you have completed the model layout, you will make updates by going back and forth between the Network and Optimization Modules. It is important to understand each of the modules and how they interact with each other. You will start with the Watershed Setup Module, where you will draw a Stream Alignment, the basic shape and connectivity of your basin. Then you will build configurations of projects – reservoirs and diversions. The next step—adding physical data and penalty functions—is done in the Network Module. Compute options are set by creating Alternatives, each of which is based on a Network. The Optimization Module is used for running optimizations on selected Alternatives.

The following sections provide brief introductions to the purpose and function of each module. Additional information and discussion is included in Chapter 4.

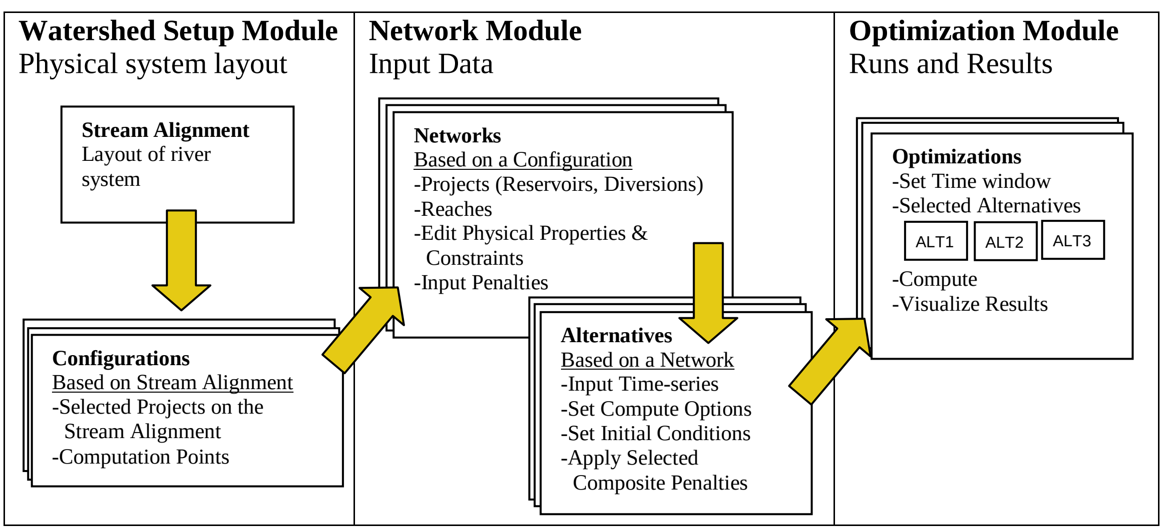


Figure 5: HEC-ResPRM Modules (similar to the ResSim organization).

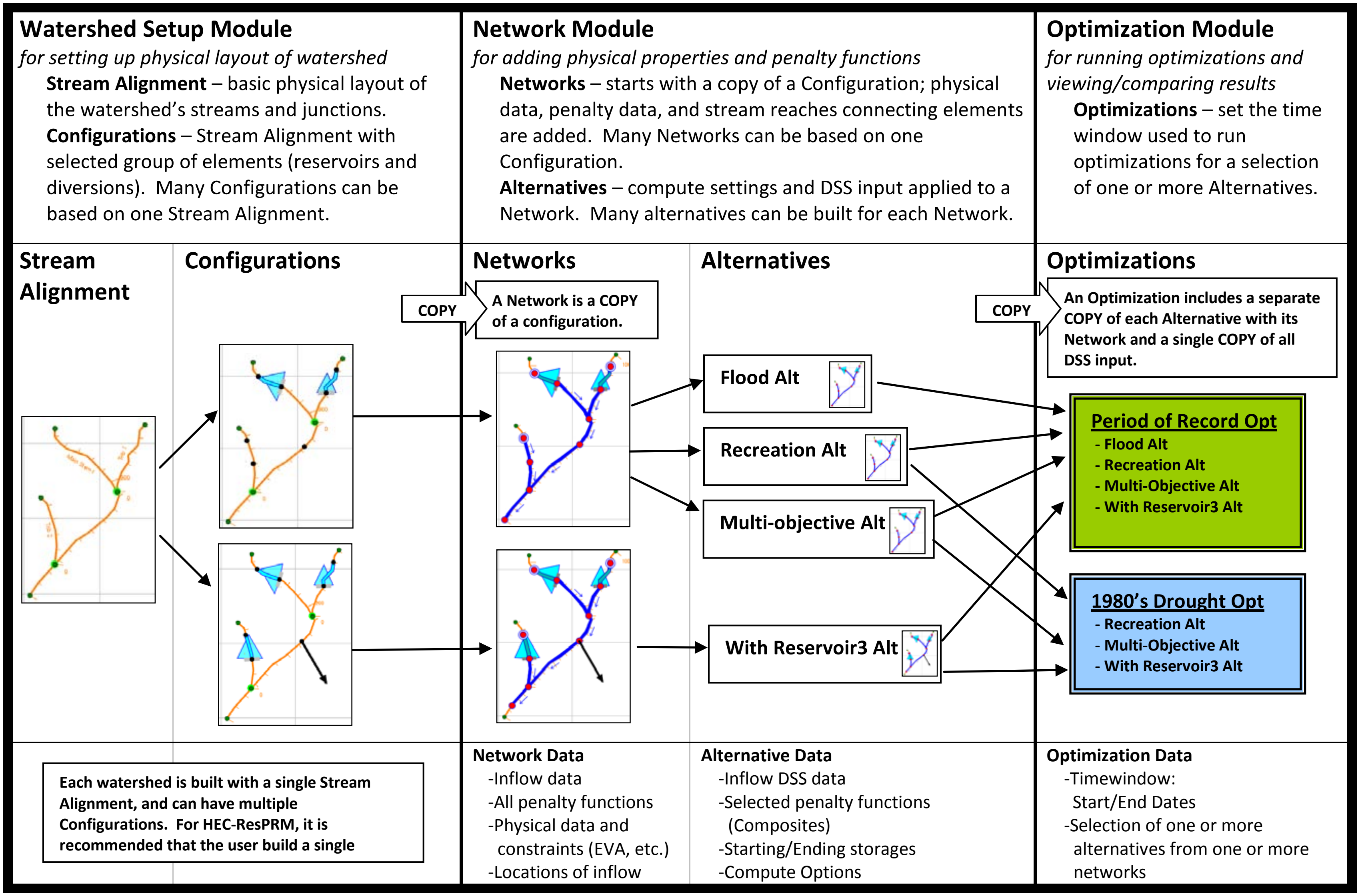


Figure 6: Each module requires the setup and entry of specific data. Changes to any module can require updates to other modules, so it is important to recognize how each module interacts with the others.

2.4.1 Watershed Setup Module

The **Watershed Setup Module** is used for laying out the physical extents of your model - the basic shape and branches of the river system you are working with - and setting up one or more sets of projects (Configurations) you wish to model.

In the initial opening window of the **Watershed Setup Module,** most menus and tools are inactive (grayed-out). They will remain so until a watershed is created or opened, which can be done by selecting **New Watershed** or **Open Watershed** from the **File** menu in the Watershed Setup Module. New Watersheds can only be created in the Watershed Setup Module. (If you are not in the Watershed Setup Module, change modules using the dropdown menu in the upper left of the GUI.) When a Watershed is created, the system establishes a directory tree where all files pertaining to the Watershed will be stored. If your Watershed locations directory was, for example "C:\HEC-ResPRM_Watersheds" and your new watershed name is "Demo," all the files relating to this project will be found under the path: "C:\HEC-ResPRM_Watersheds\Base\Demo\".

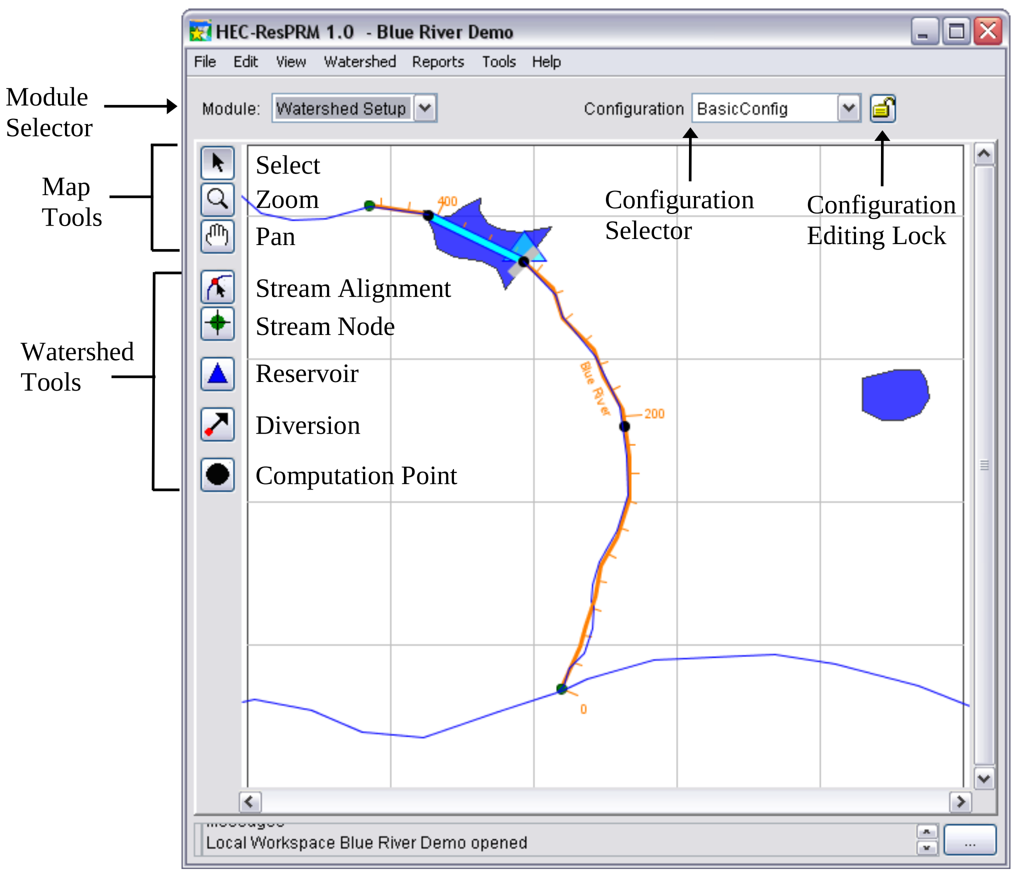


Figure 7: Watershed Setup Module: Opened Watershed is named in title bar (Blue River Demo). Background map displays a river, reservoir, and city.

Figure 7 shows the main window of the Watershed Setup Module after opening an existing watershed named "Demo." The map region occupies the majority of this window. It contains a background map (blue features: rivers, a reservoir, and a city), a stream alignment (the orange line with tick marks), and a reservoir element (bright blue triangle).

Background maps are optional but they are helpful when tracing the stream alignment. Project elements such as stream reaches, reservoirs, and diversions are added onto the stream alignment. The stream alignment forms the "back bone" onto which all the different elements will be added. All configurations of various project elements to be analyzed for this watershed share a common stream alignment. Stream alignments can be created in HEC-ResPRM or imported from various spatial data formats.

The **Watershed Setup Module** main window has the following menus:

File – This menu will appear in all modules and most editors. In the main window, it always includes the options **Open Watershed**, **Save Watershed**, **Save Map As...**, and **Exit**. In the Watershed Setup Module, the option **New Watershed…** is also included. These options relate to the overall watershed data.

Edit – This menu will appear in all modules and most editors. This menu is module specific. The edit options will be relevant to data elements currently available for modification.

View – View options relate to all modules. Options include adding **Layers** that are displayed in the map region and defining the **Unit System** for viewing.

Watershed – This menu is only available in the Watershed Setup Module. Watershed options relate to the entire watershed, as well as to the individual configurations and the stream alignment. Options include **Configuration Editor**, **Update Computation Points**, **Import** and **Export** (of stream alignment and impact areas), and **Save Configuration**.

Reports – Predefined reports and tables are listed in this menu. This menu appears in all modules, but its content is module-specific. In the Watershed Setup and Network Modules, most of the reports detail input data. In the Optimization Module, the reports mainly detail optimization results.

Tools – User settings, properties, and extended tools such as **HEC-DssVue** and scripting are found here.

Help – This option currently displays version information only. Online help is not yet available.

> ☆ **When initially opening HEC-ResPRM:** To open or create a new watershed, you must be in the Watershed Setup Module.

2.4.2 Network Module

The **Network Module** is used for inputting and editing element data, including penalty functions, and placing additional elements onto the stream alignment. Figure 8 shows an example of the Network Module window for the Demo watershed. This example shows a Network named "Base2004." The map region displays two stream reaches which have been created in the **Network Module**, along the previously traced stream alignment. The white haloes around the nodes at the upstream end of the reservoir and in the middle of the lower reach indicate inflow points, where time-series of flow data are linked to the model.

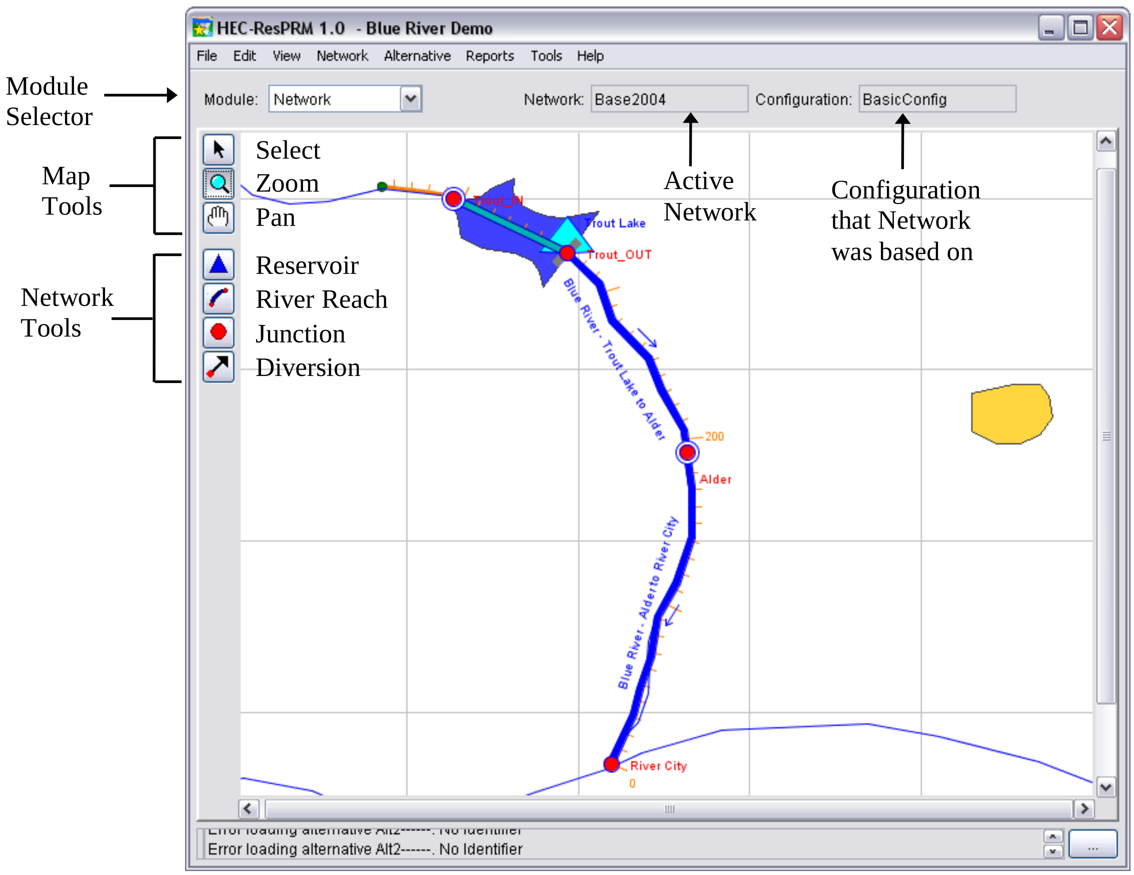


Figure 8: Network Module: Blue River Demo with open network Base2004.

To edit element data, first select the appropriate tool from the tool bar on the left side of the window, then right-click on the element. A shortcut menu appears with options to edit data defining the element. Alternatively, select the general pointer tool from the top of the toolbar on the left side and right-click on any element to view the shortcut menu.

The menus that are new or unique to the **Network Module** are listed and described below:

> **Edit –** This menu will appear in all modules and most editors. The edit options available for reservoir networks include **Reservoirs**, **Reaches**, **Junctions**,

and **Diversions**. The **Penalty Manager** can also be accessed from this menu, or the **Edit** menu in the **Optimization Module**.

Network – Network options are used in defining the network and configuration to be used. Options include **New**, **Open**, **Reopen**, **Save**, **Save As**, and **Rename**. Also included are the **Update Network from Configuration** and **Delete Networks** options.

Alternative – The only option in this menu is **Edit**. This opens the Alternative Editor, which will enable you to create, edit, and save Alternatives.

Reports – Predefined reports and tables are listed in this menu. Options include **Reservoir List**, **Reach List**, **Junction List**, and **Diversion List**. An **Advanced** option is also available that shows a summary table of the **Network** elements and their connectivity. These reports are currently deactivated in HEC-ResPRM.

2.4.3 Optimization Module

While the Watershed Setup and Network Modules are used for setting up the watershed layout and input data, optimization runs are actually made in the **Optimization Module**. The **Optimization Module** is designed to organize Alternative runs, run optimization models based on the Alternative's settings, and to visualize and analyze results. The Optimization takes place through the HEC-PRM engine and solver. For each optimization, you must specify the time span over which to perform the model run and the Alternatives that you want to analyze. Graphical results can be produced for one or more Alternatives included in the Optimization.

The Optimization Module is shown in Figure 9. This view shows an open optimization (named "Early 2000s") with the "AllPenalty" Alternative set as active (for the purpose of editing) and Alternatives "Flood," "Fish," and "AllPenalty" selected for plotting.

The menus that are new or unique to the **Optimization Module** are listed and described below:

Edit – This menu will appear in all modules and most editors. The edit options available for the Optimization Module include **Script List** selection, **Set Active Alternative,** editors for **Reservoirs**, **Reaches**, **Junctions,** and **Diversions**, and **Penalty Manager**.
Optimization – Optimization options are provided for creating, opening, saving, and editing Optimizations. Options include **New**, **Open**, **Re-Open**, **Close**, **Edit**, **Save**, **Delete**, and **Info**, as well as **Compute Penalties**.

Alternative – The only option in this menu is **Edit**. This opens the Alternative Editor, which will enable you to edit and save Alternatives.

Reports – Predefined reports and tables are listed in this menu. Except for **Penalty Report**, these produce text files representing input, output and log files for the DOS-based PRM engine.

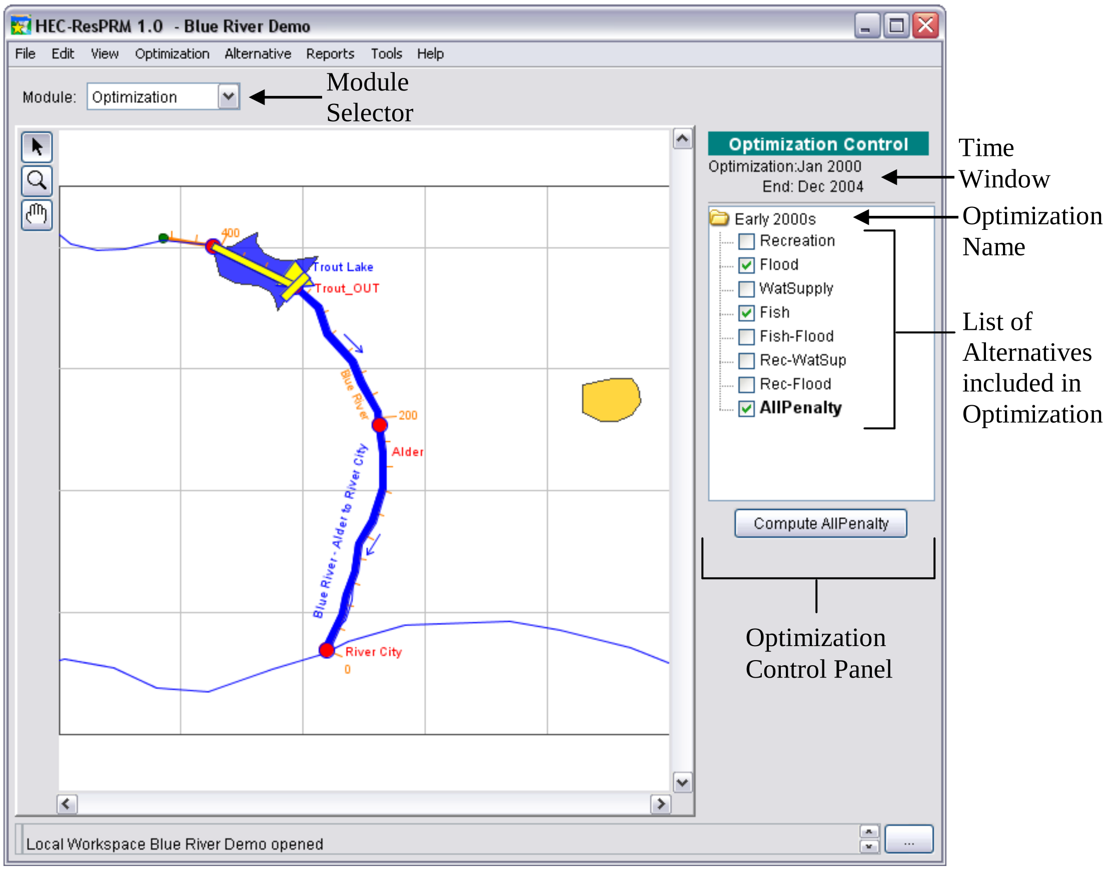


Figure 9: The Optimization Module's main feature is the Optimization Control Panel.

CHAPTER 3

Understanding Penalty Functions

This section gives a brief introduction to penalty functions – the foundation of your HEC-ResPRM model. Well-conceived penalty functions are essential to a good HEC-ResPRM model. So, before you begin to build your model, you should spend some time gathering data and analyzing it to develop meaningful penalty functions.

3.1 Understanding the Model Network

A network flow model consists of a system of arcs and nodes. In HEC-ResPRM, you construct a Network that represents a physical system, where nodes are junctions and reservoirs, and arcs are river reaches. To build a single model network that represents the whole network flow problem, the network must encompass both space and time. To accomplish this, the physical network is expanded in time, such that a duplicate physical network exists for each time step (Figure 10). The larger network is made up of the duplicate networks, connected by storage arcs, which represent reservoir storage (or flow in time) from one time period to the next.

Each arc is a possible path of flow, and a unit cost is associated with each arc. The **unit cost** is the cost, or penalty, incurred by one unit of flow taking this path. A simple penalty function, as entered into HEC-ResPRM, captures this cost. The slope of the penalty function is the unit cost.

The goal of the optimization solver is to find the minimum-cost path for each unit of flow in the network over the time window. Finding the minimum-cost path is accomplished through a linear programming technique called the Primal Network Simplex Method. To learn more about this approach, see the HEC-PRM User's Manual. The solution to this problem is the set of minimum cost (optimal) releases and flows for every time step. These results provide insights about the system's operations and objectives under varying conditions and can be used to develop or improve operating rules.

3.2 What are Penalty Functions?

The objective function for the PRM model is the composite of all penalties at all locations. This function is minimized for all time steps and elements simultaneously in order to find the optimal solution, or the best allocation of water for the entire system. In order to formulate a minimum cost linear network flow problem, penalty functions are needed.

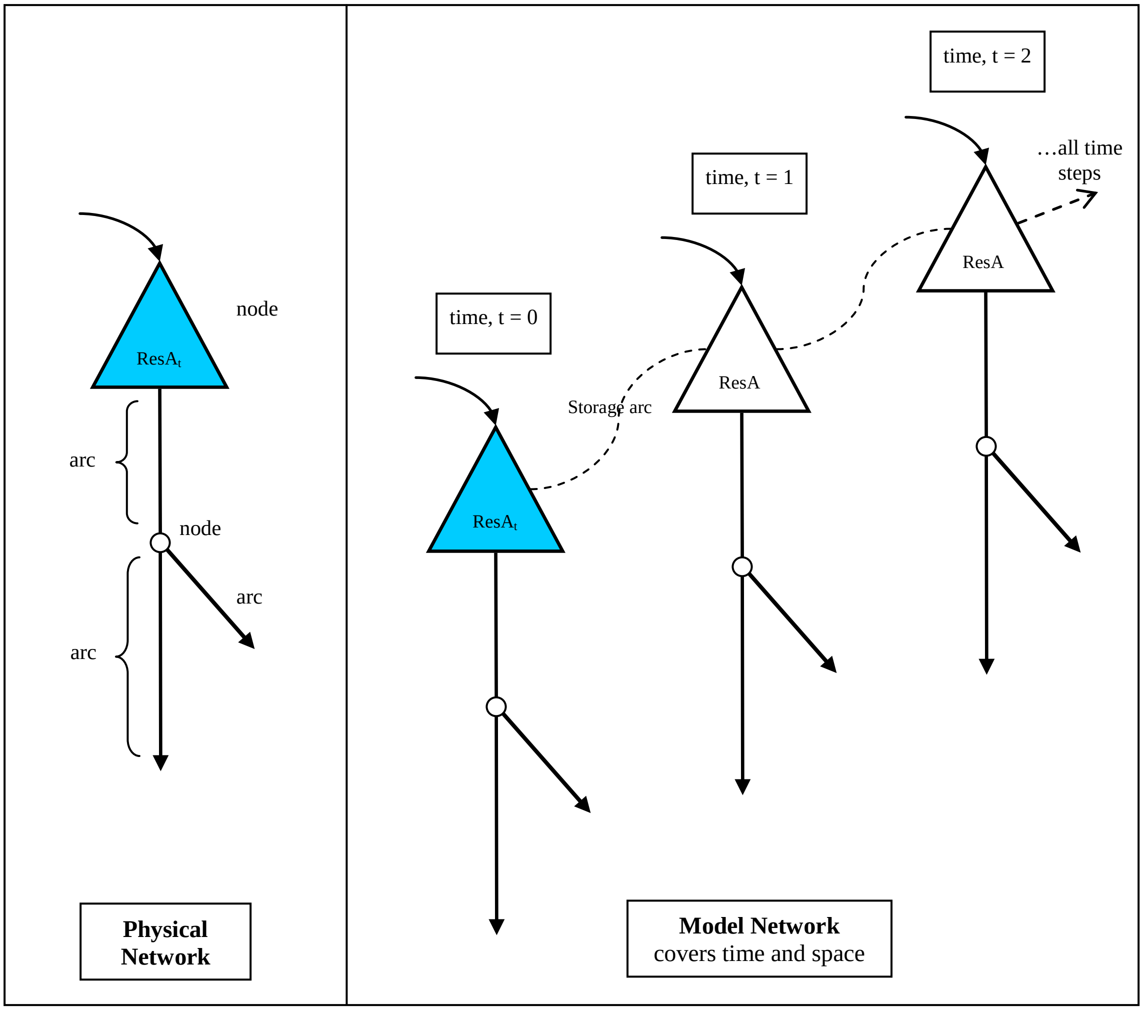


Figure 10: The model network used to create the network flow problem consists of the physical network expanded in time.

Penalty functions associate a penalty or reward (negative penalty) with levels of flow or storage (flow in time). It is the penalty functions that drive the solution to the optimization problem, which is why it is so essential to provide HEC-ResPRM with meaningful penalty functions – ones that truly represent the values of the system. A penalty function is a representation of unit cost in terms of relationship between penalty and flow (or storage).

For example, a simple penalty function may be demonstrated by the case of a water supply diversion. A hypothetical city will pay $1000 for each kilo-acre-foot of water delivered. This $1000 can be considered a benefit, in other words, a negative penalty. The penalty function would look like Figure 11.

Network Flow Programming requires linear penalties in order to keep the overall problem linear, but often, the best representation of the value of flow along an arc is not linear. This occurs when the cost of flow along an arc is different for different ranges of flow. For example, there is likely a limit to the amount of water the city would be willing to purchase, based on its population or need. At a certain point, the city would stop paying for water because its full need

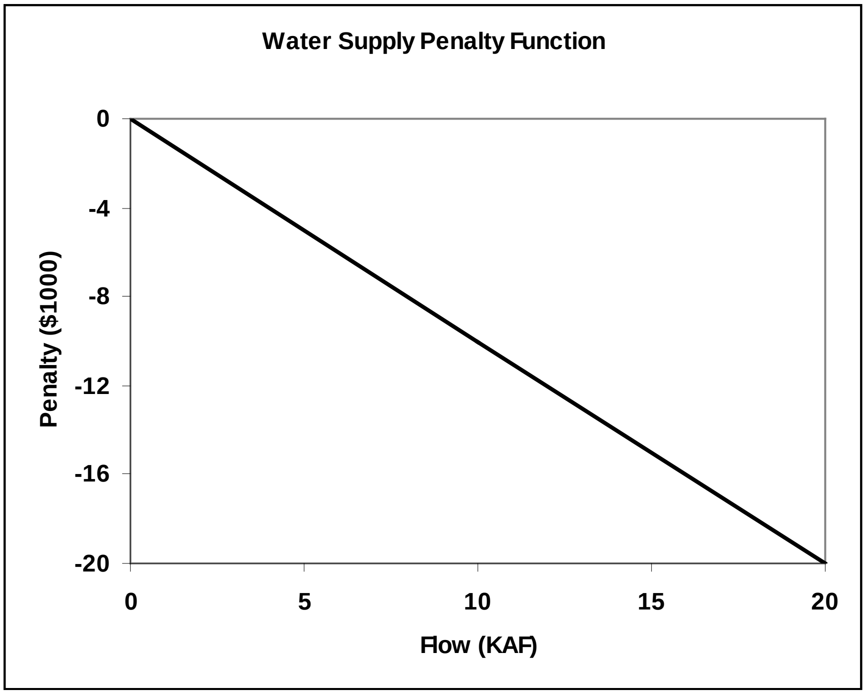


Figure 11: A simple water supply penalty function has a constant slope, and therefore, a single unit cost. In this case, the negative slope indicates a decreasing penalty.

is met. Too much water diverted might even cause flooding – which would suggest a true cost instead of a benefit. Such cases can be handled by developing piecewise linear penalty functions (Figure 12). The nonlinear penalty function is approximated with linear segments. Using many segments can more closely approximate some nonlinear functions, but the problem becomes more computationally-intensive.

To return to the concept of the problem network, recall that each arc in the network has a single unit cost associated with it. When the Composite Penalty function for an arc has more than one associated unit cost (i.e., is piecewise linear), then the arc in the network is further broken down such that each segment of the piecewise linear penalty function is its own arc. This aspect of the modeling process is not visible to the HEC-ResPRM user, but it is helpful to understand that PRM processes the HEC-ResPRM data to create this complex network to represent the whole model. This network is then sent to the solver.

Finally, the complete network can be written mathematically with a set of linear equations. The solver selects paths of the minimum cost for each unit of flow, up to the upper bound of that arc. The Primal Network Simplex Method uses an iterative process to find the optimal solution.

Minimize Slope: The solution to an optimization problem, as represented in HEC-ResPRM, is one that minimizes the unit cost of flow along each arc. Minimizing these costs is accomplished by distributing flows to the arcs whose penalty functions' have the minimum slope.

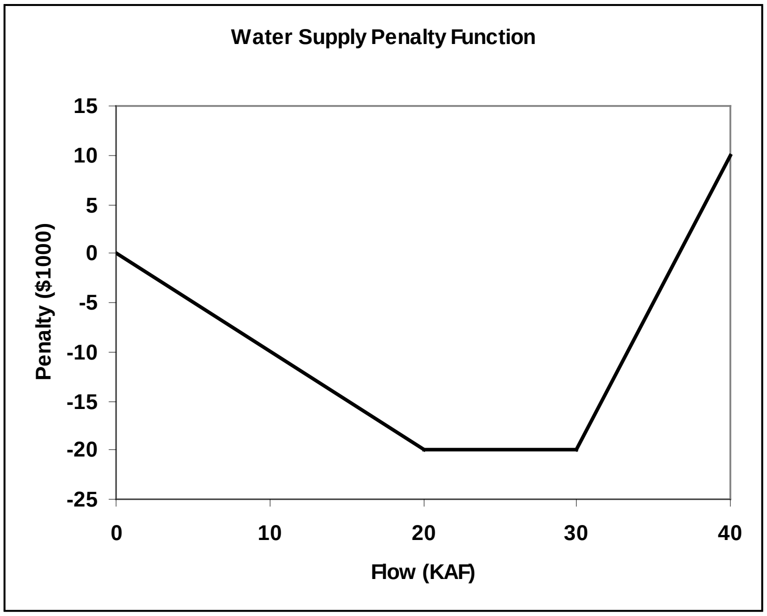


Figure 12: The water supply penalty function is represented more accurately with piecewise linear segments instead of a single unit cost. Here, the city is willing to pay a unit cost of $1000 (per KAF) up to a maximum of 20 KAF. Deliveries greater than 30 KAF will cause flooding damage of $3000 per KAF.

3.3 What is Convexity?

When the slope of a penalty function (unit cost) increases as you move from lower to higher levels of flow or storage, the penalty function is considered **convex**. Penalty functions for which the slope does not consistently increase from one segment to the next are **non-convex**. The Simplex Algorithm cannot solve non-convex problems without some modification or extension. Because cost is being minimized, the algorithm attempts to fill the lowest cost arcs first. For a non-convex function, filling the lowest cost arcs first results in a solution that is not physically possible. (For example, if a unit cost of 0 is associated with flows from 75 – 100 KAF/mon and a unit cost of 10 is associated with flows from 0 – 75 KAF, the solver fills the 75 – 100 arc first. Physically, this does not make sense, since flows from 0 – 75 KAF must occur before flows can occur in the higher range.) To deal with such cases, the solver can use a special technique that ensures the arcs are filled in the proper order. In terms of the Simplex approach, this technique is called **Restricted Basis Entry**. Restricted Basis Entry is a compute option available in HEC-ResPRM.

When non-convex penalty functions are used, a globally optimum solution is not guaranteed. The solver may converge upon a **local solution**, which means that there may be lower cost solutions, but the local solution is lower cost than adjacent solutions. (Learn more about this by reading about the Simplex Algorithm.) Therefore, the user has the decision to either simplify the model such that all penalty functions are convex, or accept the risk of not getting a **global solution**, and possibly repeating model runs with different initial values or compute options to improve the chances of finding a global optimum.

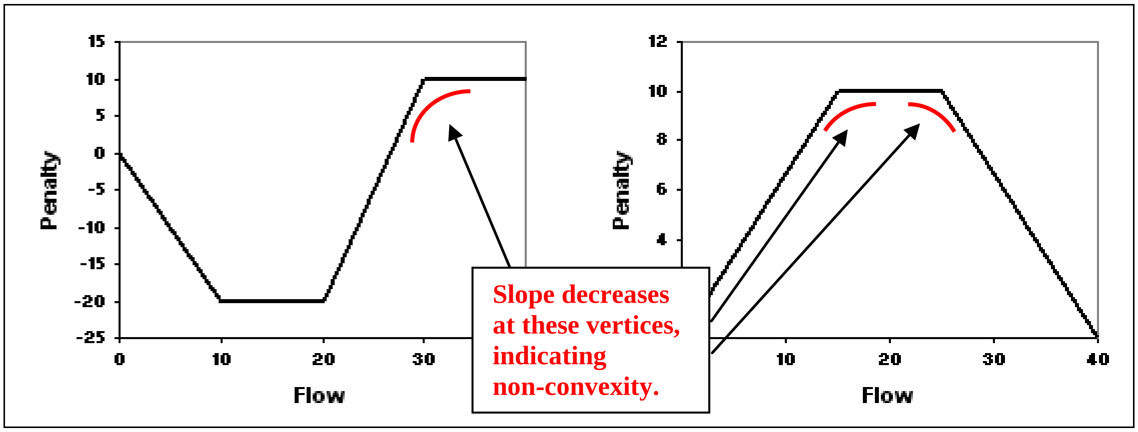


Figure 13:These piece-wise linear penalty functions are considered non-convex because the slope of a segment at a higher range of flow is less steep than some segments at lower ranges of flow. If viewing the function from below, the shape is concave.

3.4 Developing Penalty Functions

In order to develop penalty functions, it is first necessary to determine the existing priorities and relationships between various demands and needs on the system. Penalties can be economically based, or they can use other measures to account for objectives that cannot be quantified in monetary units. Penalty functions are developed in multiple ways. If financial information is available, it can be used to develop straightforward penalty functions, based on the marginal cost or benefit of a unit of water. When monetary data are not available, or an objective does not relate directly to a monetary value, penalty functions can be based on percent achievement of target flow/storage, habitat units, or other indices. Some models use penalty functions based strictly on the relative priority of the various interests in the watershed.

The important features of a penalty function are its shape and magnitude. Penalty functions describe the relationship between the decision variable (flow or storage) and the unit cost to the system. The unit cost may be a constant or a changing value based on the decision variable. Negative penalties can be used to indicate positive impacts of a unit of water. When developing non-economic penalty functions, the shape and magnitude of the functions are somewhat arbitrary, in comparison to the direct use of monetary data. The shape of the penalty function determines the internal relationship within that particular objective. The magnitude determines the relationship between that objective and the others. Prioritization is based strictly on the unit cost, or slope of the penalty function compared to that of others.

3.5 Example Penalty Functions

The following example penalty functions provide an idea of what you might develop for your own model. Examples for hydropower, flood control, and environmental penalty functions are plotted in Figures 14, 15, and 16, respectively. Examples are also given for irrigation, water quality, and navigation.

Hydropower **(**Figure 14**)**
Possible Penalty Units: $ profit (negative), % of goal, % maximum power
Data to gather: turbine performance curves, generation curves, market value of power

Hydropower generation is a nonlinear function of both net head and release (flow). In order to reasonably represent this relationship, HEC-ResPRM allows users to define multiple penalty functions, each based on a different storage level. It then uses an iterative process to select the release and corresponding storage level for minimum penalty. This approach is, of course, an approximation of the actual complex conditions of power generation. All reservoir outlets in HEC-ResPRM are represented as one combined outlet. Users cannot divide reservoir releases into those that go through various gates or culverts; instead, penalty functions must be defined solely on *total* reservoir releases, with no distinction between actual route taken out of reservoir. Therefore, any time water is being released from the reservoir, it is assumed to be generating power (if you have added hydropower penalties).

Penalty functions for hydropower can be derived using the turbine performance/efficiency curves. Penalty curves are entered into the model as penalty per unit of flow. Multiple curves can be used, each based on performance at a different reservoir storage. Penalties can be assigned based on the percent of maximum power resulting at each flow level.

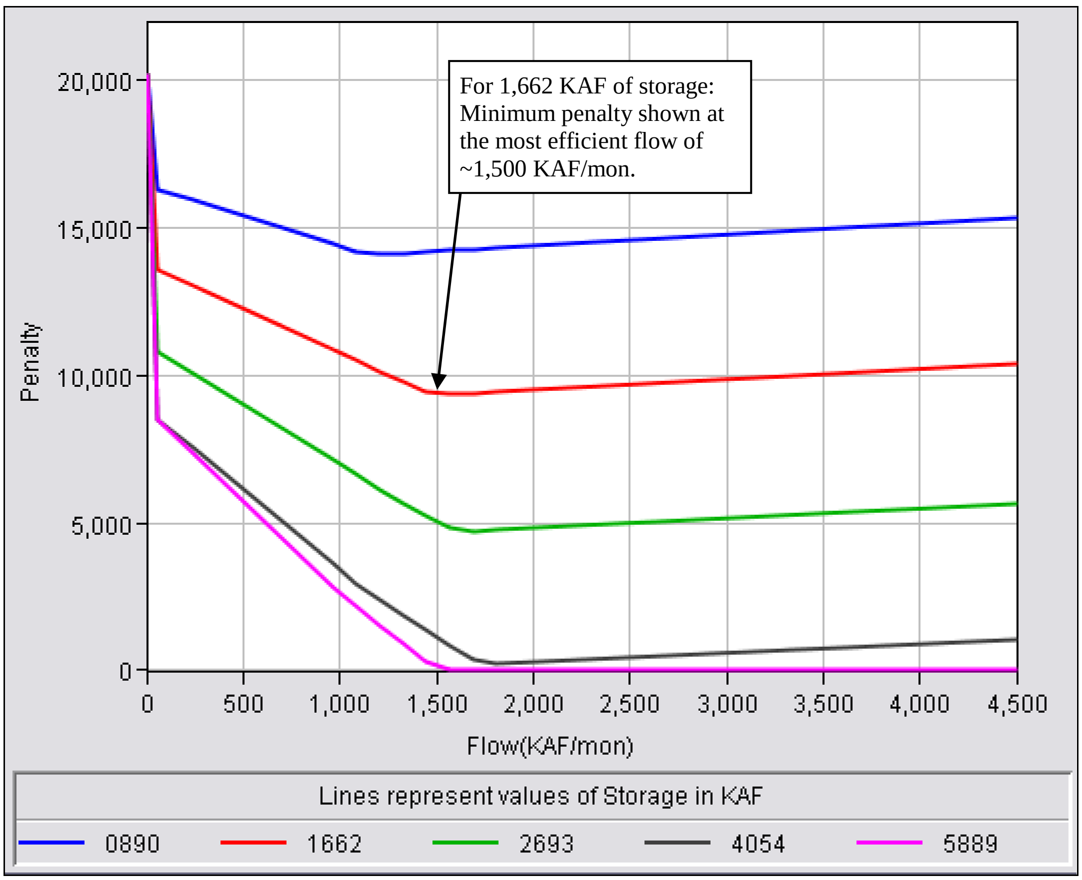


Figure 14: This plot shows a group of penalty functions that represent hydropower at a reservoir. Each curve represents the penalties for a certain reservoir storage level. Penalties at intermediate storages must be interpolated by the program.

***Flood Control* (**Figure 15**)**
Possible Penalty Units: $ damage, buildings affected
Data to gather: Stage-damage relationships, Stage-discharge relationships, survey of land use and property value, channel capacities, infrastructure capacities

Flood control penalties are used to discourage inefficient use of flood control storage and damaging flows in the system. Flood costs include damage to property, infrastructure, and agriculture, as well the risk to lives. Rating curves and stage-damage relationships can be used to develop flood control penalties. If economic data are unavailable, development of flood control penalties can involve estimating low and high flood threshold levels, and assigning a smaller unit cost to the lower levels. Penalty function unit values change based on the infrastructure inundated (i.e., stage-damage curves).

***Environmental/Ecological* (**Figure 16**)**
Possible Penalty Units: % habitat loss, miles of shoreline habitat, % population loss, % of maximum benefit
Data to gather: relationship of storage/elevation/flow to species of interest or other goal, seasonality, life cycle, etc.

Irrigation Diversions
Possible Penalty Units: $ crop lost, % target met
Data to gather: crop types, crop value, water needs, damage/loss related to meeting less than irrigation target, planting-harvesting seasonality, etc.

Water Quality, In-stream Minimum Flows
Possible Penalty Units: fine for noncompliance, % target met
Data to gather: cost of not meeting target, seasonality, etc.

Transportation/Navigation
Possible Penalty Units: navigation-days, lost transport $
Data to gather: typical navigational use rates, locks capacities, etc.

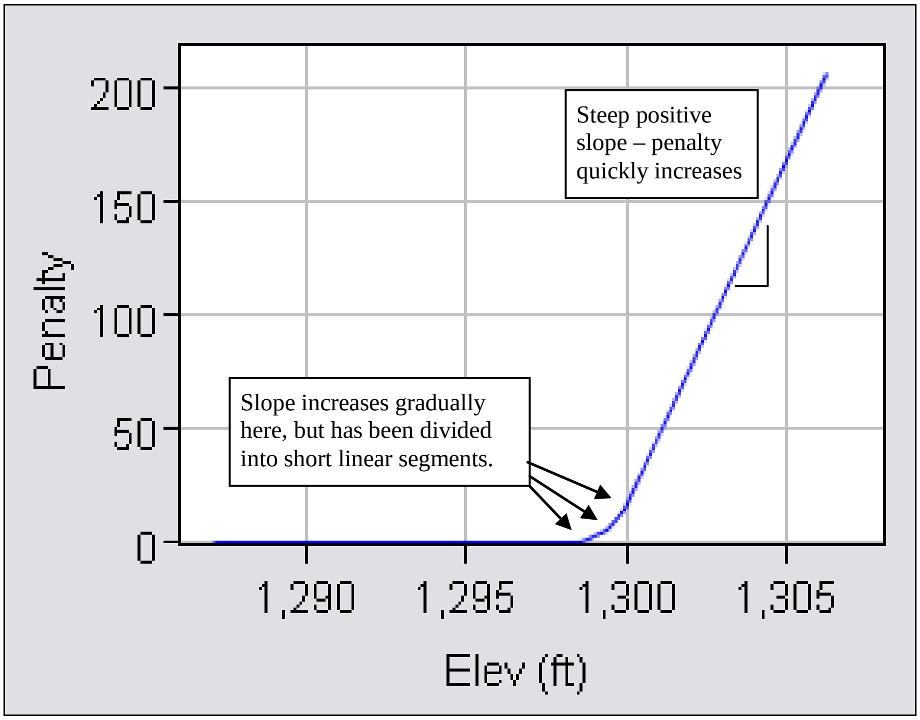


Figure 15: This penalty function for Flooding shows a steep increase in penalty once reservoir elevations rise above 1300 ft.

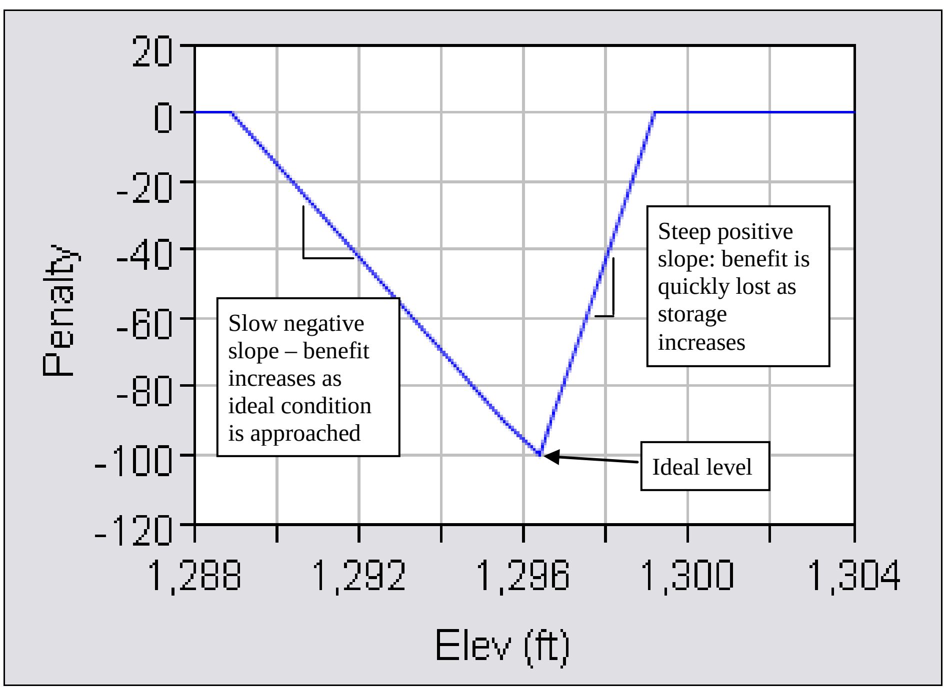


Figure 16: This Environmental Penalty has a narrow range of elevations at which the maximum benefit can be gained. The effect of lower-than-ideal elevations is less severe than higher ones.

CHAPTER 4

Basic Modeling Procedure

This section details the basic steps for developing a simple water resources system optimization model, using an example project called "Blue River Demo." The cases described in this and the following chapters are intended to serve as tutorials to demonstrate key features of HEC-ResPRM and techniques for using it. They do not aim to capture a real system or purport to apply completely realistic penalty curves. However, this guide should provide you with the procedural know-how to create models with your own well-researched penalty curves.

4.1 Steps for Developing a HEC-ResPRM Optimization Model

Once you have prepared your model data, you can begin building the HEC-ResPRM model. The steps of the basic modeling procedure in HEC-ResPRM are summarized below.

Set Up the Watershed
- Create/Open a Watershed
- Add Input Data Files
- Draw a Stream Alignment
- Create a Configuration
- Add Project Elements to the Configuration

Develop a Network
- Create/Open a Network
- Add River Reaches
- Specify Inflow Time-Series – Part I
- Create Penalty Functions for Reaches, Reservoirs, and Diversions
- Set Flow and Reservoir Capacity Constraints

Define Alternatives
- Create an Alternative
- Specify Inflow Time-Series – Part II: Identify Time-Series Data Records from DSS
- Specify Compute Options

Perform an Optimization
- Create/Open an Optimization
- Select/Activate Alternatives
- Compute
- View and Analyze Results
- Manage Optimization Data

4.2 Setting Up the Watershed

In this section concerning the **Watershed Setup Module** you will learn to:

1. Create/Open a Watershed
2. Add Map Files
3. Draw a Stream Alignment
4. Create a Configuration
5. Place Project Elements into the Configuration

1. Create/Open a Watershed.

To create a watershed, in the **Watershed Setup Module**, choose **New Watershed** from **File** menu. The new watershed screen will appear, as illustrated in Figure 17. Enter a name for your watershed and a detailed description in the appropriate fields. *Name the Demo watershed "Blue River Demo."* From the **Location** list, select where you want your watershed stored. [If the **Location** list is empty, press **Cancel**, and go back to page 2-6 to see how to add a Watershed Location.] Use the Units list to select the unit system that the watershed will use for entering, displaying, and storing data. The available unit systems are US Customary (English) and the International System of Units (SI). *The Demo watershed uses English units.* Then select a Time Zone. The watershed time zone is always specified as some offset from GMT, which does not recognize Daylight Savings Time. This feature will not affect your HEC-ResPRM model, so you may choose any Time Zone for the Demo. It is used for modeling with other HEC software. When you have completed all fields, press OK.

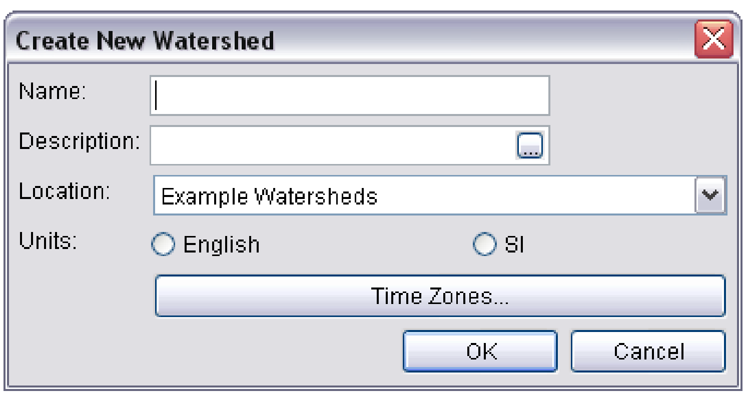


Figure 17: Dialog for creating a new HEC-ResPRM Watershed: The Watershed name, description, location (directory), unit system, and a time zone must be defined.

2. Add Input Data Files to the Watershed Directory.

When a watershed is created, a directory tree is automatically built by the system. All watershed data should be located in this directory structure. This directory organization enables you to easily share your watershed with others by zipping up the main directory (named after your watershed). It will be entirely self-contained, so the next user will not have to obtain extra data files and redefine the input pathnames for the model. Input data folders, **Maps** and **Shared** are created in the main watershed folder and should be used as described below.

The **Maps** subdirectory is used to store GIS files and images relating to your watershed. These can be used as background maps to give viewers a frame of reference when looking at the watershed. This step is optional, but can be helpful: Using a file system viewer (like Windows Explorer), copy the files you will use as background maps into the maps directory of your watershed:

<watershed location>\<watershed name>\maps

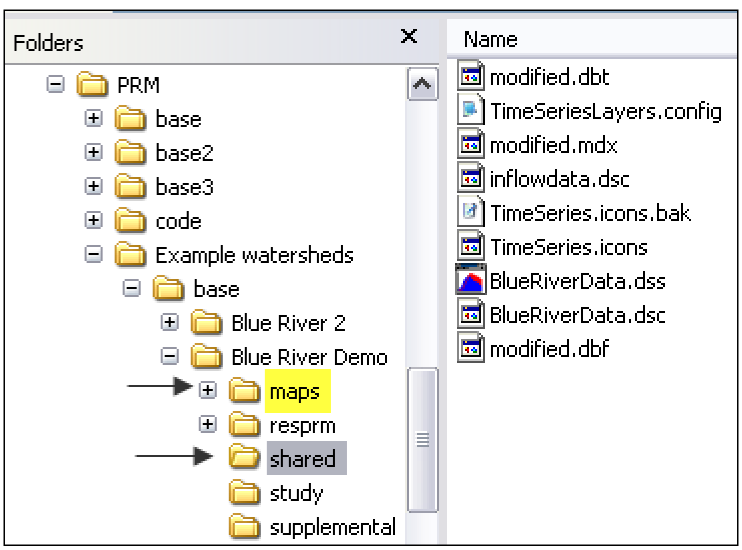


Figure 18: Once you have created and saved a watershed, HEC-ResPRM will create a directory structure to hold project data. You should add the input data files to the maps and shared directories.

The supported types of map files include DLG (USGS Digital Line Graphs), SHP (ArcView® shapefiles), DXF (Autocad® Digital Exchange Format), DEM (USGS Digital Elevation Models), IMG (Raster Image), ASC (ArcInfo® ASCII grid), JPEG, and NET (ASCII NetTIN).

Input time-series are stored in the **Shared** subdirectory. Add your HEC-DSS data files to this directory (similarly to how you added the map files). *Note that time-series data used by your model must be in DSS format. If you are unfamiliar with the HEC-DSS software, please refer to the HEC-DSSVue User's Manual.*

To display a map in the watershed, go to **View, Layers…** This will open the Layers Editor. First, make the layers editable by selecting **Allow Layer Editing** from the **Edit** menu. This is illustrated in Figure 19. Then, from the **Maps** menu, select **Add Map Layer**. This will open another window from which you can select the map file you want to view. You can also change the order of appearance of individual map layers. Note that it is not necessary to use a background map. However, it is convenient to have the map as a guide when creating stream alignments and locating other system elements.

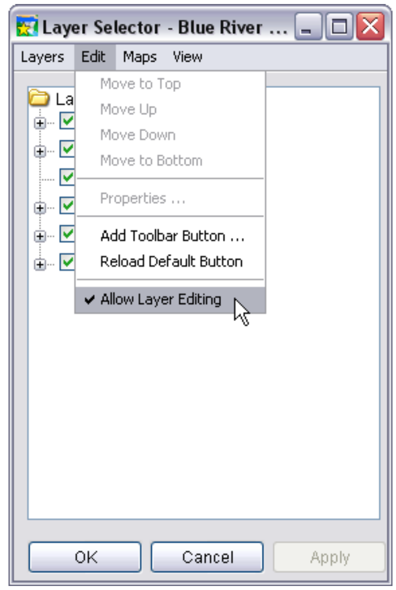


Figure 19: Turn on Layer Editing to work with background maps.

To **Zoom** in or out on the map area, select the zoom tool  on the left side of the window. To zoom in, click and drag over the desired viewing area. To zoom out, right-click until the desired viewing area is visible. Alternately, to zoom out to the original display, go to **View, Zoom to All**.

The Demo watershed map files are City.shp, MyRiver.shp, and MyReservoirs.shp. The input DSS file is BlueRiverData.dss.

3. Draw a Stream Alignment.

The stream alignment forms the "backbone" of your model, providing the structure or shape of your river system, over which all model elements are added (reservoirs, stream reaches, diversions). The next step is to create a stream alignment, on which stream reaches and reservoirs can later be located. It may be useful to view a background map in order to draw the stream alignment. First, ensure that the Watershed Setup Module is the active module. If it is not, select it from the Module list.

Make the Configuration Editable. Before you can begin editing, you must ensure the Configuration is editable. To do so, select **Allow Editing** from the **Edit** menu (or press the "yellow lock" button ). This option turns on (or off) the ability to make changes to the Configuration. The locked position  indicates that you have locked the watershed so that only you can edit it. This is useful for other Res software that is used by multiple people over a network.

Create a Stream Alignment Element. Each branch of the stream alignment must be created *from upstream to downstream*. Select the stream alignment tool  from the tool bar along the left side of the map region. Hold down the control (**CTRL**) key while clicking to place successive points along the stream alignment (Figure 20). To terminate the stream element, release the **CTRL** key and click to place the last point of the stream. You will be prompted to name the stream alignment. *For the demo model, name the stream alignment "Blue River."* Once the stream alignment is finished it becomes orange with tick marks, and its name is displayed. Alternatively, if you have an existing ResSim model of your system, you can use its stream alignment in HEC-ResPRM. To do this, make a copy of your ResSim watershed and put it in the HEC-ResPRM directory. Open the ResSim watershed in HEC-ResPRM. You will still have to build a new Network and Alternatives (described later).

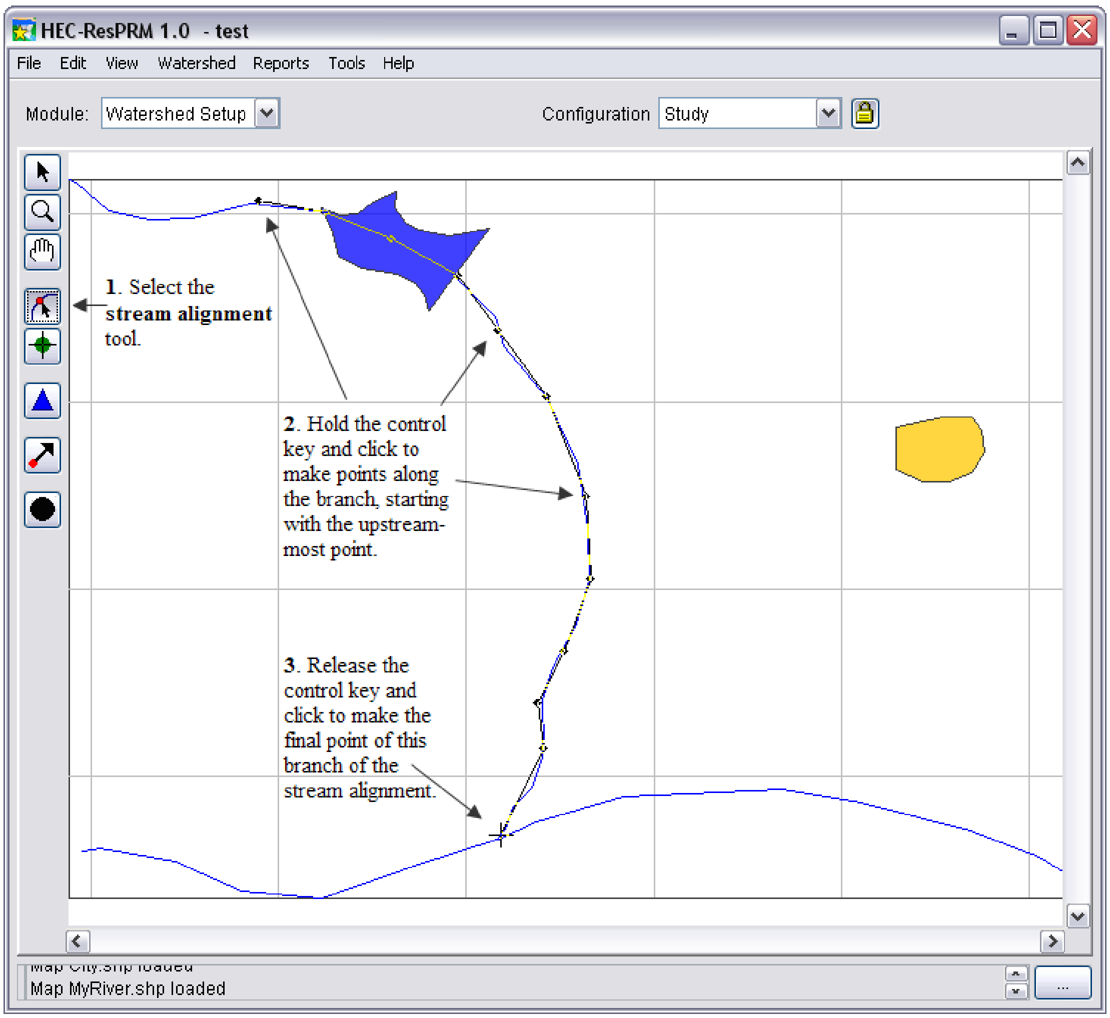


Figure 20: Draw one or more branches of the stream alignment as depicted.

Create a Multi-branched Stream Alignment. *(optional)* Additional branches can be added to the stream alignment, but in the example case, the full model can be represented with a single branch. Should you wish to explicitly model a multi-branched river system, you can connect tributary branches to a previously drawn branch of the stream alignment. To draw the new tributary, follow the same procedure as above. The new stream's final point is placed on top of the main branch, at the stream junction. If you have placed the last point of your tributary close enough to the main stem, you will be prompted to confirm that you would like to connect the two stream segments. Once you confirm the connection, a special stream junction node (light green) will be created at the junction of the two stream alignments. *Note that any time you create a junction in your stream alignment, you should follow up by placing a computation point on top of the junction.* The computation point tool will also prompt you to confirm that you want the point at the junction of the two streams. Once the computation point has been properly placed there, HEC-ResPRM will be able to correctly identify and model the connectivity of those rivers.

Edit a Stream Element. *(optional)* Select the stream alignment tool  and double click on the stream element to be edited. The stream will become red, and blue dots will appear where each stream point was originally defined. Each element point can be moved to realign the stream by positioning the cursor over the point and holding down the left mouse button and dragging. New points are added to a stream by clicking on the stream while holding down the **CTRL** key. Remove points from a stream by clicking over an existing point while holding down both the **SHIFT** and **CTRL** keys. An entire stream can be deleted by right-clicking on it and selecting **Delete Stream Element** from the shortcut menu. Streams can be renamed by right-clicking on the stream and selecting **Rename Stream Element**.

Define Stationing. *(optional)* The green dots at the end of each stream in the alignment are Stream Nodes. Their purpose is to define the stationing along the stream. By default, the most downstream node will get a stream station of zero, and the node at the upstream end will get a stream station value determined by the length of the stream line in the coordinate system of the map region. However, these default values can be changed to more accurately describe the stream. Using the stream node tool  right-click on a stream node and select **Edit Node**. In the editor that appears, uncheck the "Use Default Stationing" box, then update the value of the station to represent the appropriate real-world station value of that representative point. Stationing along a stream will be determined proportionally based on the station values of the bounding nodes. Interior stream nodes can be added to a stream to more accurately define distances along a stream and to locate known river station landmarks. To do so, select the stream node tool, then while holding down the **CTRL** key, click those locations on a stream where you want to place a stream node. *Note: Do not change the stream stationing after adding reservoirs. This makes it very difficult to get all elements back in their proper places in the map.*

4. Create a Configuration.

Before adding reservoirs and diversions to your stream alignment, a **Configuration** should be defined. A Configuration identifies a set of projects that you want to model together in your watershed. If more than one set of projects will be considered in a study, then more than one Configuration can be used. For example, you may wish to create two different optimization runs on the same watershed, but one may have a diversion that is not present in the other. When you add projects to your Configurations, a special superset (named Study) is developed by the program to contain all projects from all

Configurations in the watershed. If multiple programs (e.g., HEC-ResSim, HEC-HMS, HEC-FIA, HEC-RAS, etc.) are going to be applied to your watershed, then Configurations should be developed by the whole modeling team before the models for an individual program are produced.

Create the Configuration. From the **Watershed** menu, select **Configuration Editor**. From the **Configuration** menu in the Configuration Editor (Figure 21), select **New**. In the new configuration window, enter a **Name** and **Description** for the Configuration, select a time step from the **Time Step** list (not used by HEC-ResPRM) and press **OK**. Then, click **OK** in the Configuration Editor.

The Configuration you will make for the Demo model will be BasicConfig and will contain the projects present at the time of the study. Later, the study will be expanded to include a proposed new project. At that point you can create a second configuration to represent the system with this project, or you can take the shortcut that will be described.

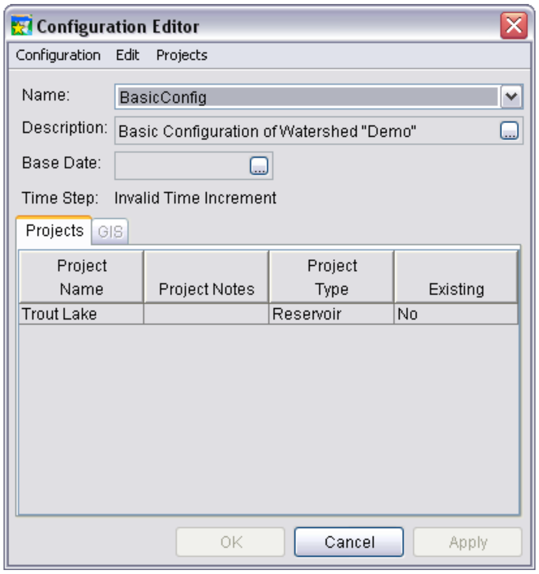


Figure 21: Configuration Editor: You are required to enter a time step, but this will not affect HEC-ResPRM's operation. Any time step selected will be indicated as invalid.

The Configuration time step is only used for real-time models that are operated as part of the Corps Water Management System (CWMS) Software package. Since HEC-ResPRM is not a real-time model, this time step will not affect your optimization models. You are required to enter a time step for HEC-ResPRM because the Watershed Setup Module is a generic feature that is shared with other HEC software (ResSim, CWMS). *HEC-ResPRM 1.0 runs only on a monthly time step*; selecting a different time step in the **Configuration Editor** does not change the HEC-ResPRM run time step.

Shared components of the Res interface: The Watershed Setup Module interface is shared with several other HEC software packages. This means that the Configurations and Stream Alignments created in the Watershed Setup can be opened in some other software, but it also means that some of the settings were designed for HEC-CWMS or HEC-ResSim and are not used by HEC-ResPRM. Features/settings including the Watershed time zone, Configuration time step, and the process of locking the Configuration before editing have no effect on HEC-ResPRM modeling.

5. Place Project Elements into the Configuration.

The next step is to place projects (reservoirs or diversions) into the watershed. The projects you place will be added to the active Configuration (identified in the Configuration field at the top of the main screen).

Draw Project Elements. Verify that you have selected the appropriate configuration *(BasicConfig)* to which you will be adding projects. (See the dropdown menu in the upper right of the main screen.) Select the appropriate tool (either the reservoir or diversion) to add projects. Each project, when placed, will create one or more computation points on the stream alignment, in addition to a symbol for that type of project.

- **Reservoirs.** A reservoir can be added to the system anywhere on the stream alignment and forms a "reservoir reach" that follows the selected segment of the stream alignment. When using the reservoir tool  to place reservoirs, hold down the **CTRL** key to place the *upstream* point(s) of the reservoir, then release the **CTRL** key and place the *downstream* point. A **Name New Reservoir** window will appear so that you can name the reservoir. In the case of a reservoir, two computation points are added: one just upstream and one just downstream of the reservoir reach. These computation points should be renamed something more descriptive than their default names. You can also reshape the blue triangle to better represent the pool of your reservoir. For the Demo project, add a reservoir on the upper section of the Blue River stream alignment. Name your reservoir "Trout Lake."
- **Diversions.** *(optional)* To work on diversions, start by clicking the diversion tool . To create a diversion, hold down the **CTRL** key and click on the stream alignment where the diversion starts. Proceed as when drawing stream alignments.
- **Computation points**. *(optional)* The computation point tool , gives access to computation point properties. Be sure to rename all computation points associated with project elements so they can easily be identified from a list when the map region is not visible. To rename a computation point, right-click on the computation point, select **Rename** from the shortcut menu and enter a new name in the **Rename** window as shown in Figure 22. To move a computation point, double click to select it then drag it to its new location.

> ☆ **Using Computation Points to Ensure Stream Connectivity:** As was mentioned in the section on drawing stream alignments, you should add a computation point to every stream junction. The program will ask where the point should be located, and you should select the junction of your streams. By indicating this location, you will ensure that HEC-ResPRM will have the proper connectivity later, when you add the actual stream reaches to the alignment (in the Network Module).

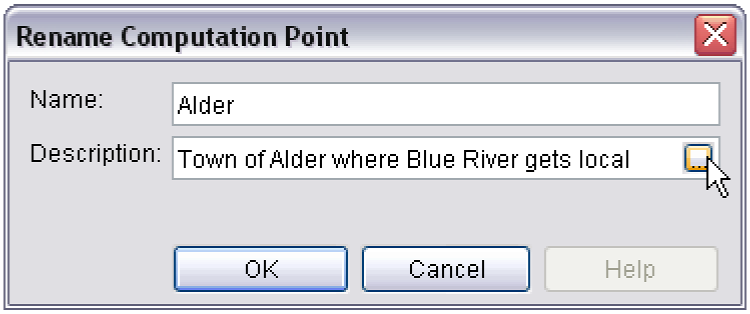


Figure 22: Rename computation points, so that they are meaningful to your study. A long description can be added and viewed by clicking on the ellipses button (…).

Save the Configuration. When you are finished adding elements to the Configuration, be sure to save it. Select **Save Configuration** from the **Watershed** menu to save. A simple Configuration of the Blue River Demo watershed (named "WithDiversion") is shown in Figure 23. It contains two project elements, a reservoir and a diversion. You can now build more Configurations, if desired, or move on to the Network Module, where you will connect your projects with stream reaches and add penalty functions.

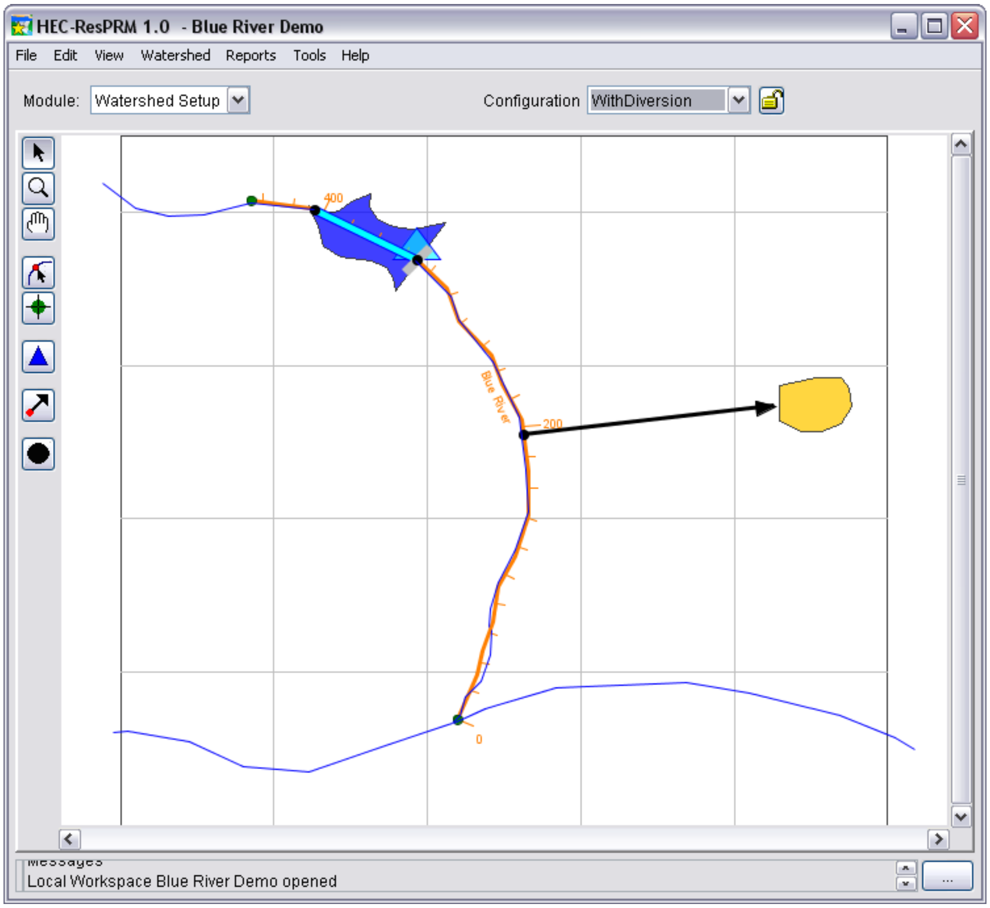


Figure 23: This Configuration includes a reservoir and a diversion. It was named "WithDiversion" to differentiate between it and a configuration that does not have the diversion. This Configuration is not part of the Demo.

Naming Convention Tip: Although HEC-ResPRM will allow you to give elements long names, the PRM engine only considers the first ten characters. For reservoirs that generate hydropower, PRM only uses the first eight characters, and adds a "_P" to the end of the name to represent the power. It is helpful to keep this naming convention in mind to be sure that all your elements have unique names when truncated to ten or eight characters. If they are not unique, you will be warned when you attempt to run the model. You should also keep this in mind when you are working with HEC-ResPRM output, because the DSS records are stored using the truncated versions of the names.

4.3 Developing a Network

With a stream alignment in place and one (or more) configurations defined, you are finished with the **Watershed Setup Module**, and can move on to the **Network Module**. Here, a **Network** of reservoirs, stream reaches, and diversions can be created. A network is created based on a selected Configuration of projects on your stream alignment and includes river reaches that connect the projects. In this section you will learn to:

1. Create/Open a Network
2. Add River Reaches
3. Specify Inflow Time-Series – Part I: Locations
4. Add Reservoir and Reach Constraints
5. Create Penalty Functions

To begin, select **Network** from the **Module** dropdown list in the upper left of the HEC-ResPRM interface.

1. Create/Open a Network.

From the **Network** menu, select **New**. The Create New Reservoir Network window will appear (Figure 24). Specify a name and description for the Network. *For the Demo model, the Network is named "Base2004" because it represents the baseline configuration of the system in 2004.* Then, select the Configuration on which this Network will be based (for example "BasicConfig") and click **New**.
Project elements that were part of the configuration on which the new Network is based are automatically created as elements in the Network. Reservoirs and diversions transfer directly. Computation points (black circles) appear as Junctions (red circles), as depicted in Figure 25.

Figure 24: Create New Reservoir Network and name it "Base2004."

2. Add River Reaches.

The next step is to connect the project elements with river reaches to produce a complete water resource system network schematic. Although your stream alignment shows where rivers exist, water conveyance will not occur in HEC-ResPRM until stream reaches have been drawn. All junctions and elements need to be connected by stream reaches, which can be created along any segment of the stream alignment.

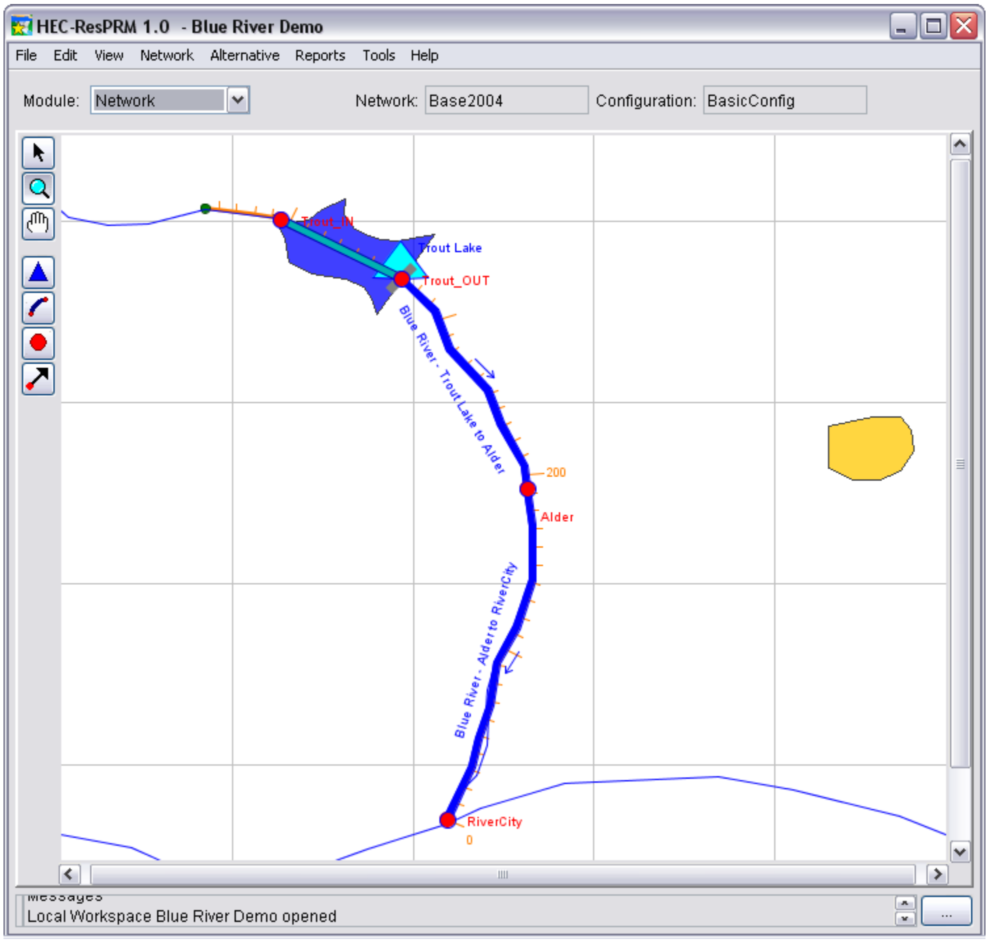
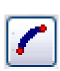


Figure 25: New Network based on the Configuration "BasicConfig": Note that in the Network stream Reaches have been laid on top of the Stream Alignment created in the Watershed Setup, and Junctions (red circles) have replaced the Stream Nodes and Computation Points.

Select the routing reach tool . Hold down the **CTRL** key and click anywhere on the stream to place the upstream end of the reach. Release the **CTRL** key and click on the stream to place the downstream end of the reach. River reaches begin and end at junctions (red dots). If you start or end a reach where there isn't already a junction, one will be created for you. Tributary river reaches must enter the main stem at a junction. Once a reach is drawn, you will be prompted to name it. You can always rename it by right-clicking on it at a later time.

In the demo example (Figure 26), *"Blue River – Trout Lake to Alder"* connects junctions that already existed (*"Trout_OUT"* at the reservoir and *"Alder"* downstream). *"Blue River – Alder to River City*" begins at "*Alder*" and terminates at "*River City*." Since no junction already existed there, the "*River City*" junction was automatically created at the endpoint when the reach was drawn.

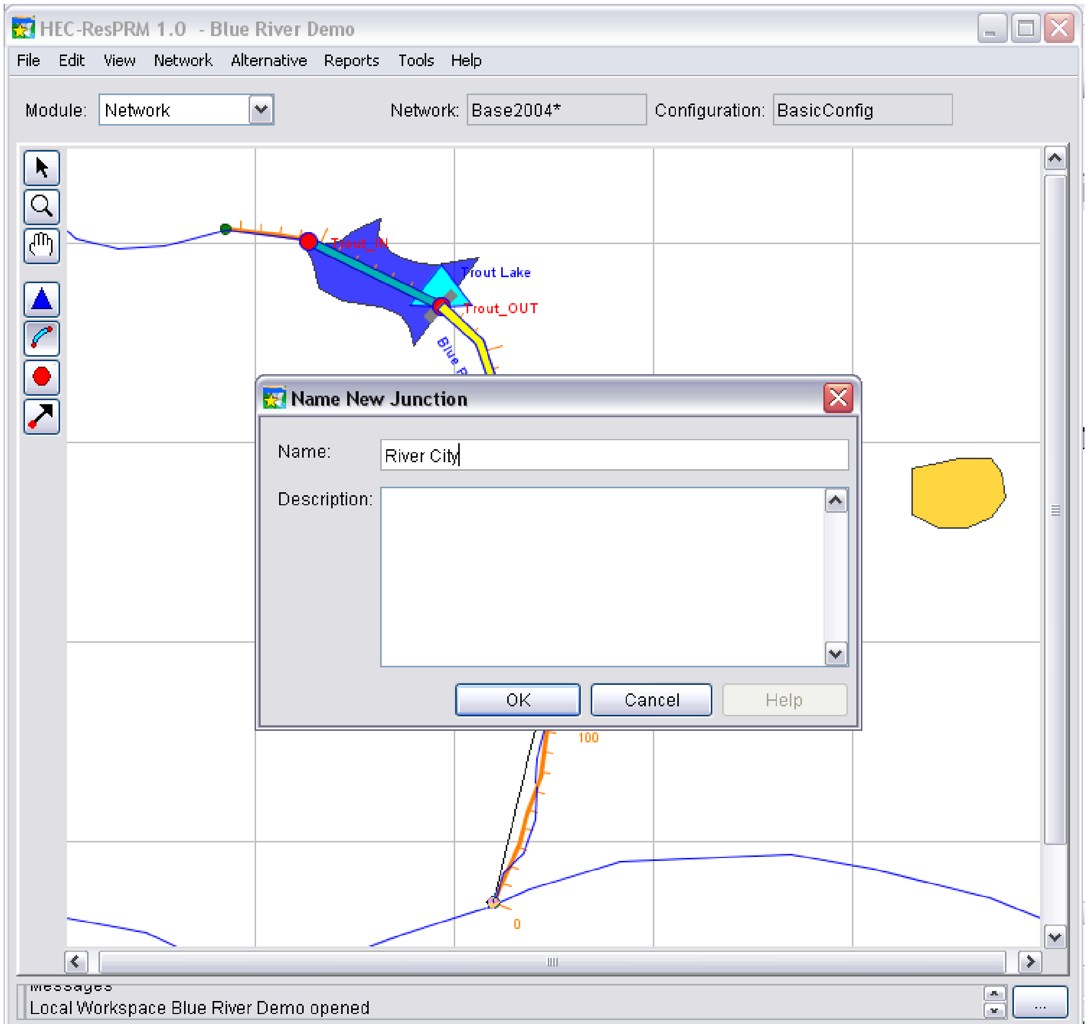
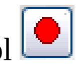
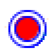


Figure 26: The stream reach tool was used to draw a reach from the Junction "Alder" to the end point of the Blue River (the downstream boundary for this model). This reach started at an existing junction, but since it ended on a point with no existing junction, it first prompts the user to name the new downstream junction. After the junctions have been named, HEC-ResPRM prompts the user to name the stream reach, itself.

Adding Inflows Tip: Inflow is mandatory for any headwater junction, but it can also be added to intermediate junctions, if there is local inflow that you want to capture in your model.

3. Specify Inflow Time-Series – Part I: Locations.

With the network schematic now complete, inflow time-series must be specified at all the network's upstream-most locations (i.e., headwater nodes). Local inflows can also be added to intermediate junctions. Adding inflows to your model is a two step process; the first step, described here, is to indicate the junctions at which the inflows occur. This indication is accomplished by modifying the junction properties.

Edit Junction Properties. With the pointer tool  or the junction tool  selected, right-click on desired junction and select **Edit Junction Properties**. The Junction Editor will appear (Figure 27). Select the **Local Flow** tab and input a name and multiplication factor for each external flow time-series entering the junction. The name entered should clearly identify the node because it needs to be recognizable later in the process. *In the case of the Demo Network, which only has one upstream node, enter a local inflow called "TroutLake_Inflow" at the inflow junction to Trout Lake ("Trout_IN"). Set the factor to 1.* The Factor column is used to indicate a value by which the inflow is multiplied. This value is typically one, but if losses or gains occur, it can be less than or greater than one, respectively. Once an inflow time-series has been specified at a junction, the junction icon changes from a red circle to a red circle surrounded by a white halo . (See upstream-most node in Figure 27 for an example.)

To edit junction properties for other junctions without exiting the Junction Editor window, click **Apply** and then select another junction from the **Name** list or use the navigator buttons located in the upper right portion of the window. Alternately, click **OK**, then right-click and **Edit** another junction.

For building the Demo example model, add time-series "Alder_Inflow" at the inflow junction to the Alder junction (Figure 27). This inflow represents the incremental streamflow generated by runoff in the watershed area between computation points "Trout_OUT" and "Alder."

The section entitled "Specifying Inflow Time-Series – Part II" (pp. 4-28) will specify the location of the file which contains the time-series. This will be done in the Alternative Editor.

4. Add Reservoir and Reach Constraints.

Having created all the project elements and connected them with reaches, you can now start editing the reservoir and reach data. In the example, begin by adding physical constraints. Reservoir storage and release, and flow in reaches and diversions, are physically limited by infrastructure capacity. It is appropriate to include them in HEC-ResPRM models as constraints. Constraints *may* also be used in certain situations to represent management constraints, such as environmental minimum flows. If a model is over-constrained, however, it may become infeasible (no solution exists). Therefore, the recommended approach to adding constraints is to use them only when absolutely necessary (e.g., physical constraints such as a maximum storage to prevent the dam from overtopping). It is generally best to represent management restrictions with penalty functions that impose very high penalty values on flow or storage values outside the range of acceptable operations. This strategy will allow for what would normally be unacceptable operations; however, the associated penalty would be so great that the operations would be avoided when at all possible.

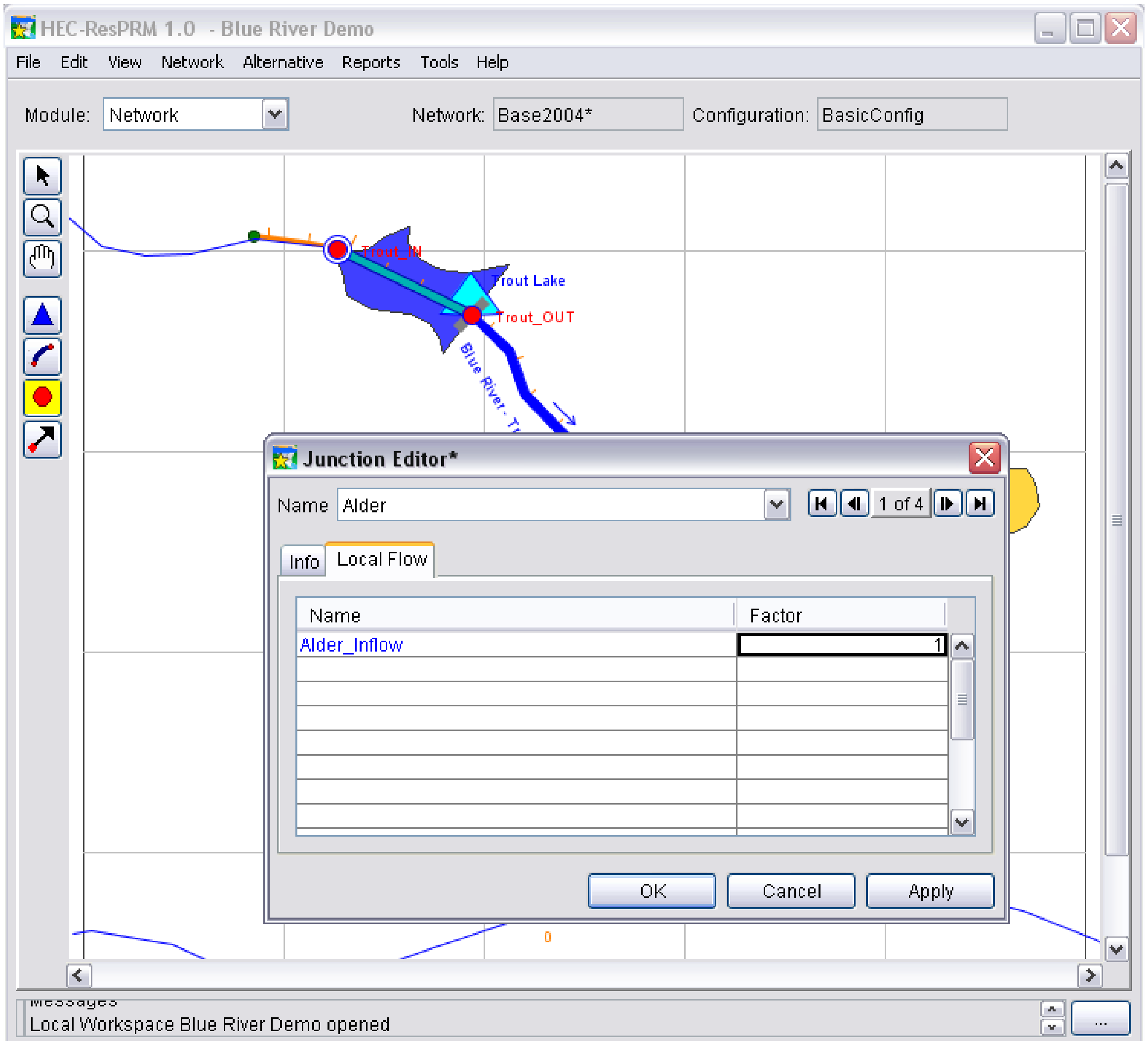
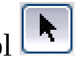


Figure 27: Inflows are added using the Local Flow tab of the Junction Editor. An inflow has been added to the upstream junction of Trout Lake, as indicated by the white ring around the junction.

To input minimum and maximum constraints on project elements in HEC-ResPRM, you must use the Edit Properties option. For the example problem, you will add constraints to storage at Trout Lake reservoir.

Open the **Reservoir Editor** by right-clicking on the reservoir with the arrow tool  or the reservoir tool . Select **Edit Reservoir Properties** from the dropdown menu. (You can also access this Editor by selecting **Reservoirs…** from the **Edit** toolbar.) Select the **Constraints** tab (Figure 28). Constraints can be either constants, monthly constants, or a time-series. If the **DSS Time-Series** radio button is selected, you will be prompted later on (in the Alternative Editor - next section) for the location of the time-series file and its DSS path. For the Demo model, select "Storage" in the **Constraint Type** selector. *Enter a minimum storage of 10 KAF and a maximum of 600 KAF.* You can also add release constraints, but this model does not require them.

To add constraints to reaches or diversions, go to the **Constraints** tab of the respective element editors. Reach and Diversion Editors can be accessed with the same procedure used for accessing the Reservoir Editor.

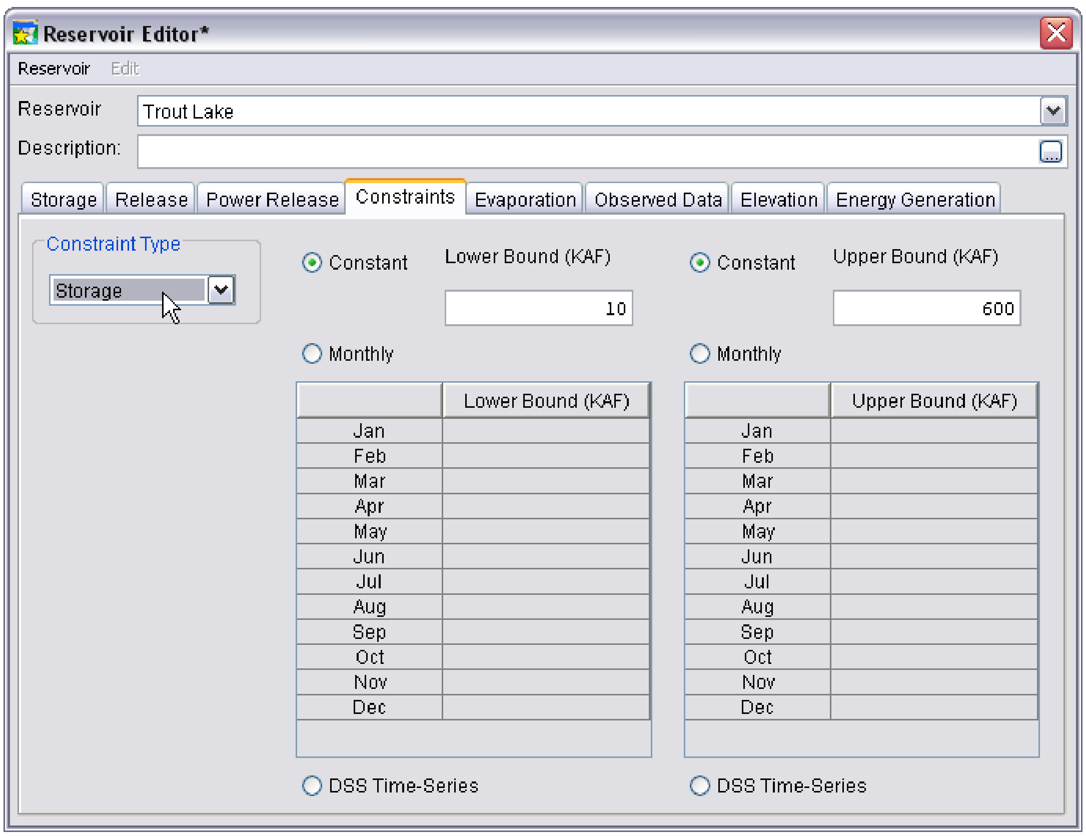


Figure 28: Storage capacity constraints for the "Trout Lake" reservoir of the Demo model.

5. Create Penalty Functions for Network Elements.

Given the inflows of water into the water resources system, HEC-ResPRM solves for the optimal allocation of water over time. Penalty functions quantify the harm (or benefit) done by allocating water to a certain place at a certain time. Penalty functions in HEC-

ResPRM are entered into a table of flow or storage vs. penalty. One objective at one location is represented with a set of monthly penalty functions, which may be the same all year or vary by season. Benefits are represented as negative penalties. An example of a flow penalty function can be seen in Figure 33.

In HEC-ResPRM, **Penalty Functions** are grouped into **PenaltySets** and **Composite Penalties**. Each **PenaltySet** is intended to represent one particular interest and consists of 12 individual **Penalty Functions** – one for each month. The **Penalty Functions** may vary based on the season selected for each month. If a penalty applies consistently all year, a single "**all year**" season can be applied to every month. (This is the default setting.) Monthly seasons can be automatically generated and applied to the months using the **Create Monthly Seasons** option on the **Seasonal** menu of the Reservoir (or Reach) Editor toolbar. Alternatively, you can create your own seasons, such as a wet and dry, and then apply them to the appropriate months. If your PenaltySet does have multiple seasons, don't forget to enter the Penalty data for each season by highlighting the desired season in the selector at the bottom left panel and then adding the data in the Penalty Function table.

Composite Penalties also consist of 12 individual monthly penalty functions. The Composites are the sum of the individual monthly PenaltySets and are defined based on which PenaltySets are selected in the Editor. For example, you may have a Composite called "FloodComp," to which you have added the PenaltySets "FloodBuildings," "FloodErosion," and "FloodAgriculture," which are three different PenaltySets that represent the cost of flooding to different interests in the watershed. The January "FloodComp" penalty function would be the sum of January penalties for "FloodBuildings," "FloodErosion," and "FloodAgriculture."

A single reservoir, or a single river reach, may have several competing purposes. Each interest will be associated with different penalties. For example, a full reservoir is beneficial for recreation and water supply but could be dangerous for flood control. Because a single water body will often be the object of different, (often competing) interests, HEC-ResPRM is equipped to store multiple PenaltySets. When optimizing the system, HEC-ResPRM combines these separate penalties into a composite penalty function (referred to in ResPRM as a **Composite**). Composites must be specified for each reservoir storage and reservoir release link in a ResPRM model. The program creates a Default Zero Penalty Composite at each reservoir storage and release location, so that you may run your model even if you do not wish to apply value to all locations. Composites can also be defined for stream reaches, if you wish to apply PenaltySets to flows there.

HEC-ResPRM Penalty Functions: Because HEC-ResPRM uses linear optimization, penalty functions must be piece-wise linear (i.e., they must have linear segments). The network flow solver requires the penalty functions to be convex, which allows the solver to find a global solution. (Refer to Chapter 3.) You may also use non-convex penalty functions, if you turn on the Restricted Basis Entry option. If you use the Restricted Basis Entry option, you are not guaranteed a global solution.

PenaltySets are created on the Storage, Release, and/or Power Release tabs of the **Reservoir Editor**. Figure 29 shows the layout of the storage tab of the reservoir editor with an active Composite. The **Reservoir Selector** allows you to quickly switch between editing different reservoirs without having to select them from the map.

The **Composite Selector** allows you to select a Composite to view or edit. The upper left panel is a **Penalty Selector** which lists the active Composite in bold. Below this is a listing of all storage PenaltySets for the current reservoir. Add one or more PenaltySets to your Composite by checking the box in this column.

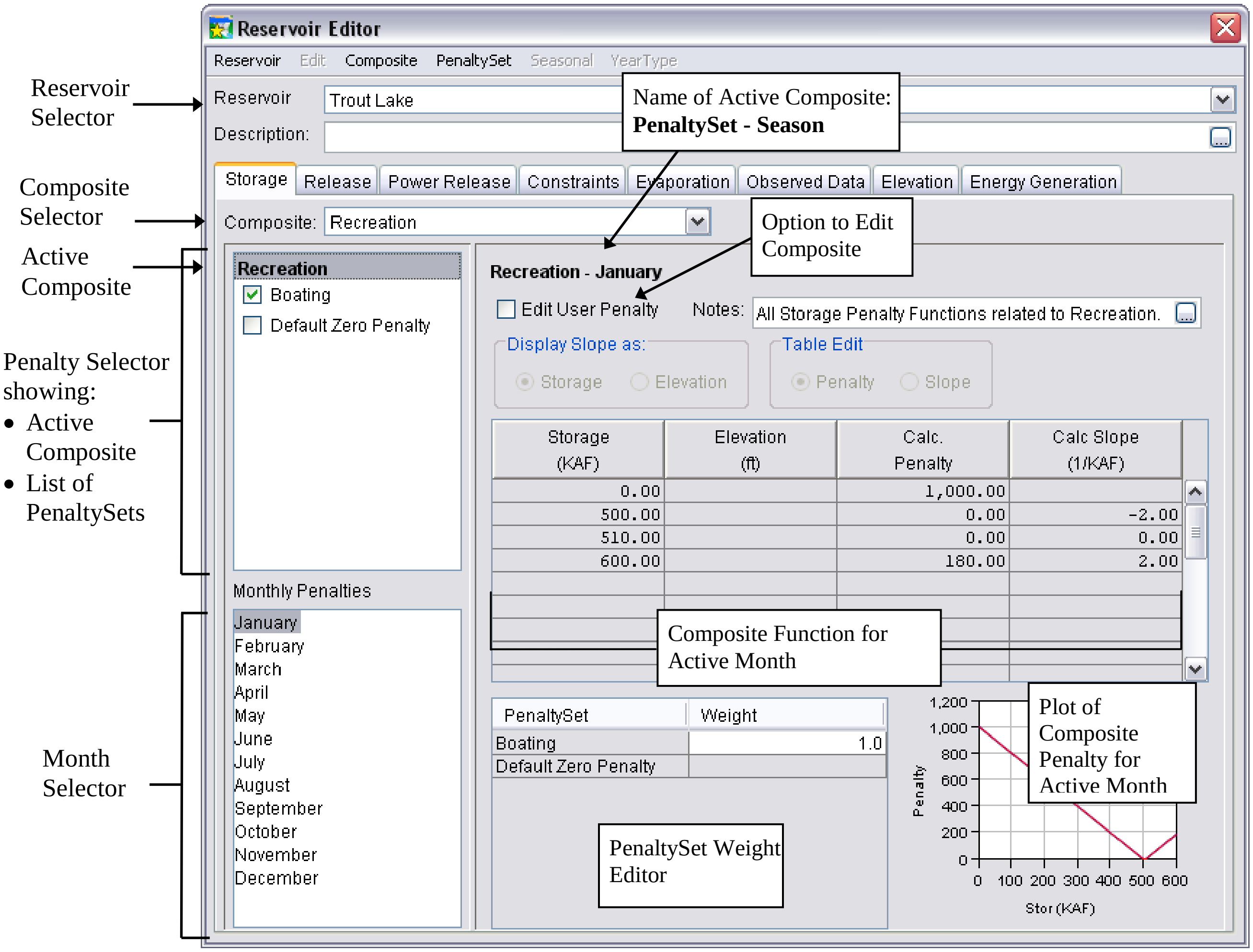


Figure 29: Storage tab of the Reservoir Editor with the Composite Penalty Function "Recreation" active.

In the bottom left panel, **Monthly Penalties**, you can select each month to view the total (composite) storage Penalty that will be applied for that month. The main panel shows the name of the Composite and the active month in bold text. The main table holds the penalty function data and a plot of the penalty can be seen in the lower right corner of the editor.

The values of the monthly Composite Penalty Functions are the weighted sum of the selected monthly PenaltySets. Because the Composite is strictly a sum, it is not normally editable, but the **Edit User Penalty** checkbox allows you to override the Composite values with your own "User" values.

The **PenaltySet Weight Editor** at the bottom middle allows you to apply weights to the various PenaltySets that contribute to your composite.

Figure 30 shows the layout of the storage tab of the reservoir editor with a PenaltySet active. The editor looks much like it does when the Composite is active, with the differences noted below.
The bottom left panel, **Seasonal Penalties**, holds a list of **Seasons** that have been defined (or the default, "all year") instead of a listing of months. A list of months is contained in a table in the bottom middle of the Editor. The second column of this table has dropdown selectors that allow you to group each month into a season.

The main panel lists the active PenaltySet and season in bold, and the penalty function is added to the main table.

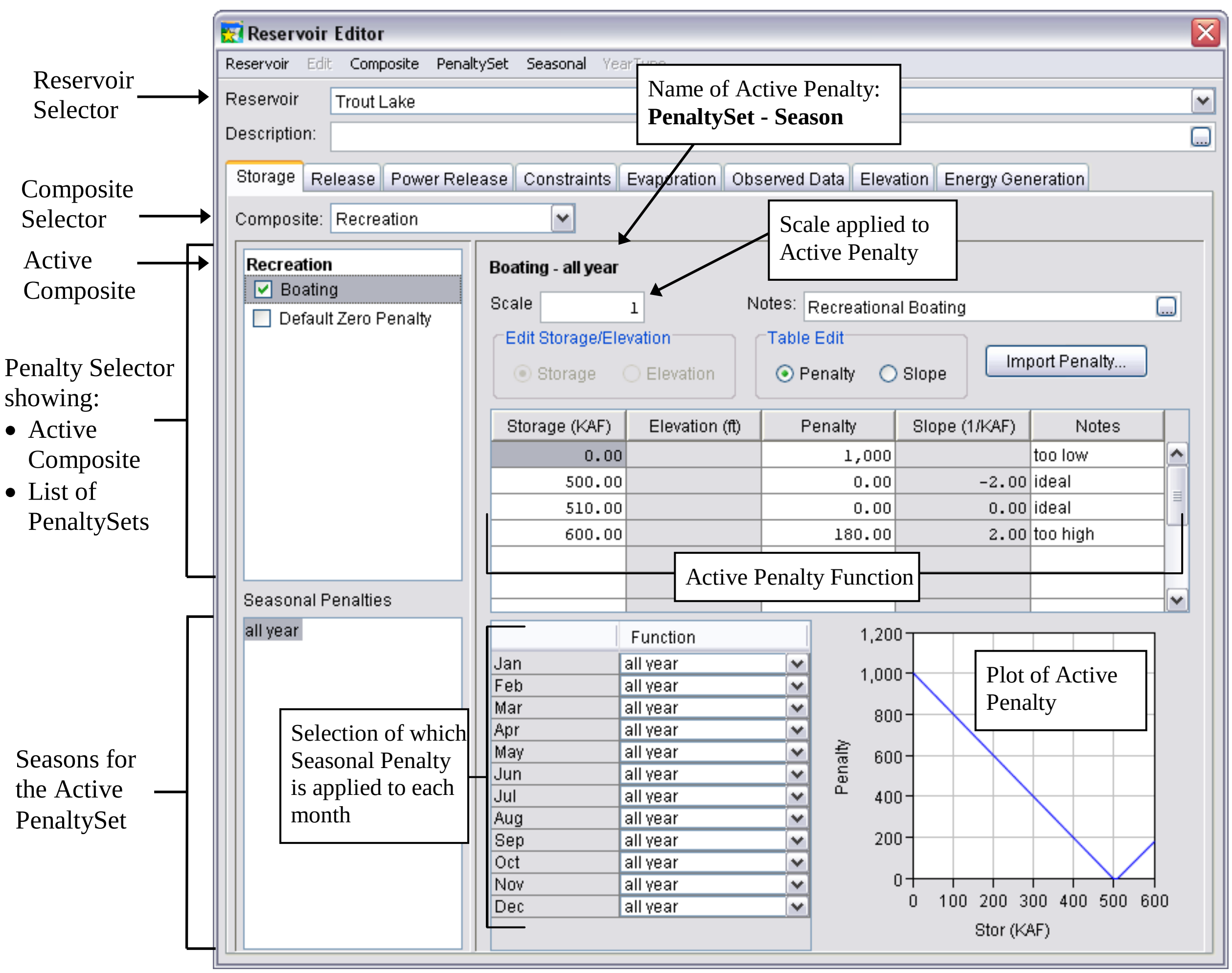


Figure 30: The Reservoir Editor Storage tab with a PenaltySet selected looks like this.

> **HEC-ResPRM Editing Composite Penalty Functions:** Composite Penalties are not normally directly editable. The concept behind the Composite is that it is the sum of all contributing PenaltySets, so, to change its data you must adjust the individual penalties. You can, however, use the "Edit User Penalty" option to make direct adjustments, when necessary. This option will rarely be necessary, but it may be useful, for example, as a temporary test when calibrating a model.

The **Scale** is a weight applied to the active PenaltySet.

The **Edit Storage/Elevation** radio buttons allow you to choose to enter your penalty function values in terms of storage or elevation. The **Table Edit** radio buttons allow you to enter your penalty function values in terms of penalty or slope.

The **Import Penalty…** button opens a **DSS Selector**, allowing you to add your penalty function directly from a DSS record.

- **Construct a Composite Storage Penalty Curve**. With the reservoir tool  or the arrow tool selected, right click on the desired reservoir and select **Edit Reservoir Properties**. Select the **Storage** tab in the **Reservoir Editor** (Figure 29). In the Demo example we will first add a recreation penalty function to the "Trout Lake" reservoir.

  Select **New** from the **Composite** Menu. You will be prompted in a separate window to name the Composite (Figure 31).

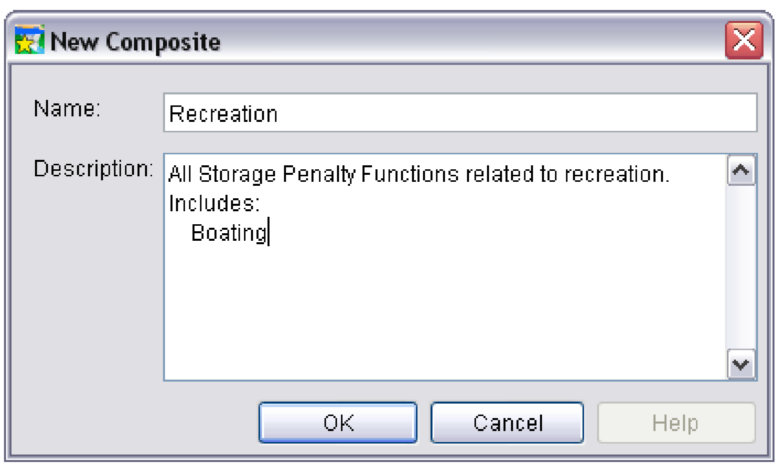


Figure 31: Name the Composite penalty function "Recreation."

Once the composite penalty function is named, the Reservoir Editor shows a data table and a data plot section. To have penalty values show up in the table, you must have at least one **PenaltySet** to add to the **Composite**. By default, the **Default Zero Penalty** is available, but you will want to create one or more new PenaltySets that represent the interests you are modeling.

Red PenaltySet Warning: If a PenaltySet is colored red in the Penalty Selector, you have not completely or correctly filled in the data. Click on that PenaltySet to make it active, then check to make sure the data tables are filled out for all seasons, and that there is a season selected for every month.

Construct a PenaltySet. For the Demo model, we are going to create a **PenaltySet** for recreational boating interests on Trout Lake. Select **New** from the **PenaltySet** Menu. A window will prompt you to name the PenaltySet you are about to create (Figure 32).

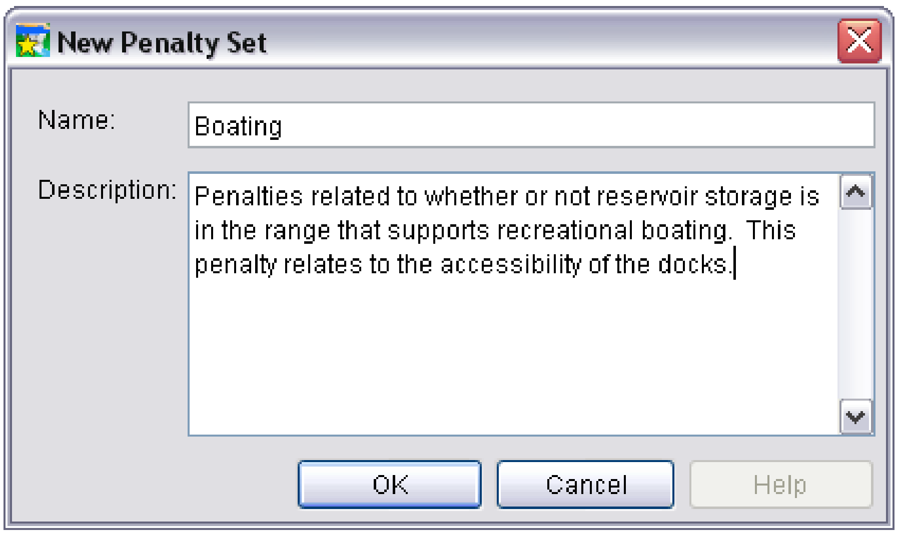


Figure 32: Name the new PenaltySet "Boating" and add a description.

Once named, the PenaltySet will appear as one of the PenaltySets available to be added to the Composite. You will see that the penalty function table has become editable. By default, the same penalty function applies all year, but you can also vary the PenaltySet by season. In the lower left of the Reservoir Editor, notice the "Seasonal Penalties" panel. The Seasonal Penalties panel lists any seasons that you have defined, or the default "all year" season. Each seasonal penalty function can be viewed or edited by selecting the season in the Seasonal Penalties panel. In the lower middle of the Reservoir Editor, is a listing of the months of the year. In the column labeled "Function," dropdown menus allow you to choose which of the Seasonal Penalties you wish to apply to that month. You will work more with seasonal penalties in the next example.

Now you are ready to enter the values of the PenaltySet into the data entry table. The Demo example recreation penalty (Table 1), compiled by a local expert, reports the number of leisure visits per month lost due to inappropriate reservoir levels. The penalty function shows that the best reservoir storage is between 500 and 510 KAF – between those storage levels the penalty is zero. Above or below those levels the penalty increases linearly as the elevation gets further from this ideal, no-penalty range.

The recreational boating activity at Trout Lake occurs all year. Therefore this PenaltySet will consist of a single "all year" penalty, applied to all months. *Enter the values of Table 1 into the penalty table as shown in Figure 33.* As you enter penalty table values into the Reservoir Editor, a plot of the penalty function is created in the lower right of the Editor. (Double-click the plot to enlarge.)

Table 1: Recreation penalty function at Trout Lake.

Storage (KAF)	Penalty	Notes
0	1,000	No recreation (no water!)
500	0	Lower limit of ideal conditions
510	0	Upper limit of ideal conditions
600	180	Docks are too low

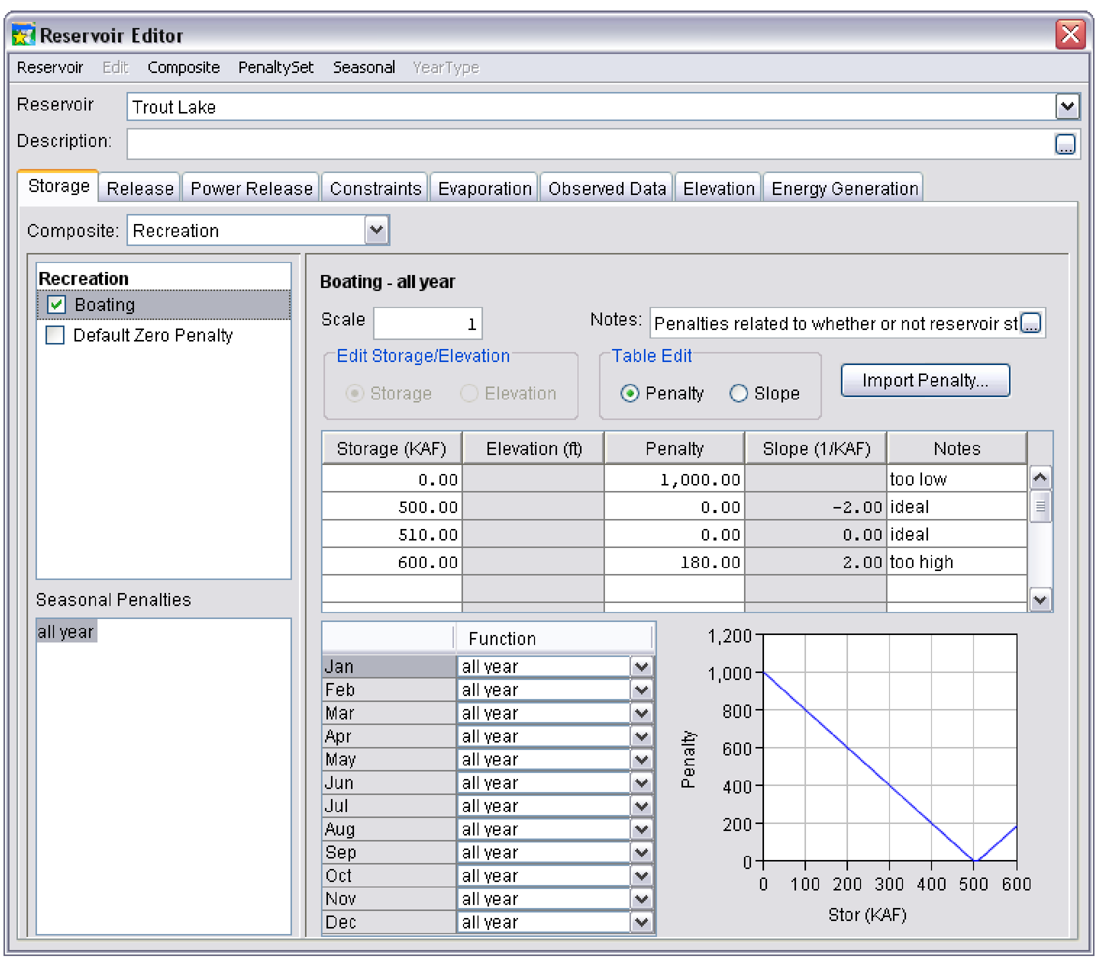


Figure 33: Entering the Boating penalty function as part of the Recreation Composite Penalty function.

Entering a Penalty as a Function of Elevation: The default way to add a storage penalty at a reservoir is to enter it as a function of storage. If, on the other hand, you have developed your penalty as a function of reservoir level (elevation), you can enter the penalty in terms of elevation. In order to do this, select the Edit Storage/Elevation radio button for Elevation. Now the elevation column is editable. Because PRM does its internal calculations based on storage, you must be sure to enter the reservoir's storage-elevation relationship on the **Elevation** tab of the Reservoir Editor.

Check the box to the left of the PenaltySet name (*in this case, "Boating"*) to include this PenaltySet in the Composite. Now if you click on Composite "Recreation" in the Penalty Selector, you'll see that the Boating PenaltySet has been incorporated. *This means that when you run an optimization that uses the Recreation Composite, the Boating penalty will be used in the calculations.* You can click on each month in the Monthly Penalties panel to see the penalty applied for that month, but since the same penalty was applied to all months, they should be the same. To save your changes select **Save** from the **Reservoir** menu.

You have now completed the steps necessary to implement a penalty function, which in HEC-ResPRM requires a Composite and a PenaltySet. To run an optimization with HEC-ResPRM, each reservoir must have a storage and release penalty, even if that penalty is zero. You will now add a penalty function for the release from the "Trout Lake" reservoir into the "Blue River – Trout Lake to Alder" river reach. This river segment hosts rafting activity during the summer months. The penalty function represents loss of monthly rafting parties due to inappropriate flow (Table 2). A typical month sees 60 rafting parties, so the maximum penalty for low flows is 60. Some rafting may occur at very high flows, but this rafting is risky and can result in injuries or loss of life. A higher penalty is given to high flows, in order to discourage flows that might result in excessively dangerous rafting conditions.

Table 2: Recreation penalty function for the releases from Trout Lake.

Release (KAF/mo)	Penalty	Notes
0	60	Too low for rafting
30	0	Ideal rafting conditions
40	0	Ideal rafting conditions
200	480	Rafting may occur but is high risk

To enter a release (flow) penalty function, select the **Release** tab of the Reservoir Editor and follow the same procedure as for the reservoir storage penalty. First create a composite penalty; then create the PenaltySet that will belong to it. Because rafting on Blue River occurs only during the summer months, you must build seasonal penalty functions. The storage penalty was applied equally all year so this step was not necessary.

Release Flow Penalties vs. Reach Flow Penalties: When a penalty represents a flow objective just downstream of a reservoir, it can be applied to either the reservoir release or to the stream reach below the reservoir. They are effectively the same thing, as long as there is no local flow at the reservoir's dam. Just be sure not to double-count the penalty by applying it in both places!

Name your release Composite "Recreation" and your PenaltySet "Rafting." Check the Rafting box in the Penalty Selector to add it to the Recreation Composite. Then, create new seasons by selecting **New** from the **Seasonal** menu. Create a "Recreation Season" and a "NonRecreation Season" (Figure 34). In the Monthly Assignments section of the Reservoir Editor, select the appropriate season for each month (Figure 35). Finally, fill in the table of penalty values for each season. The values from Table 2 are applied to the Recreation Season and you can copy the Default Zero Penalty values for the NonRecreation Season.

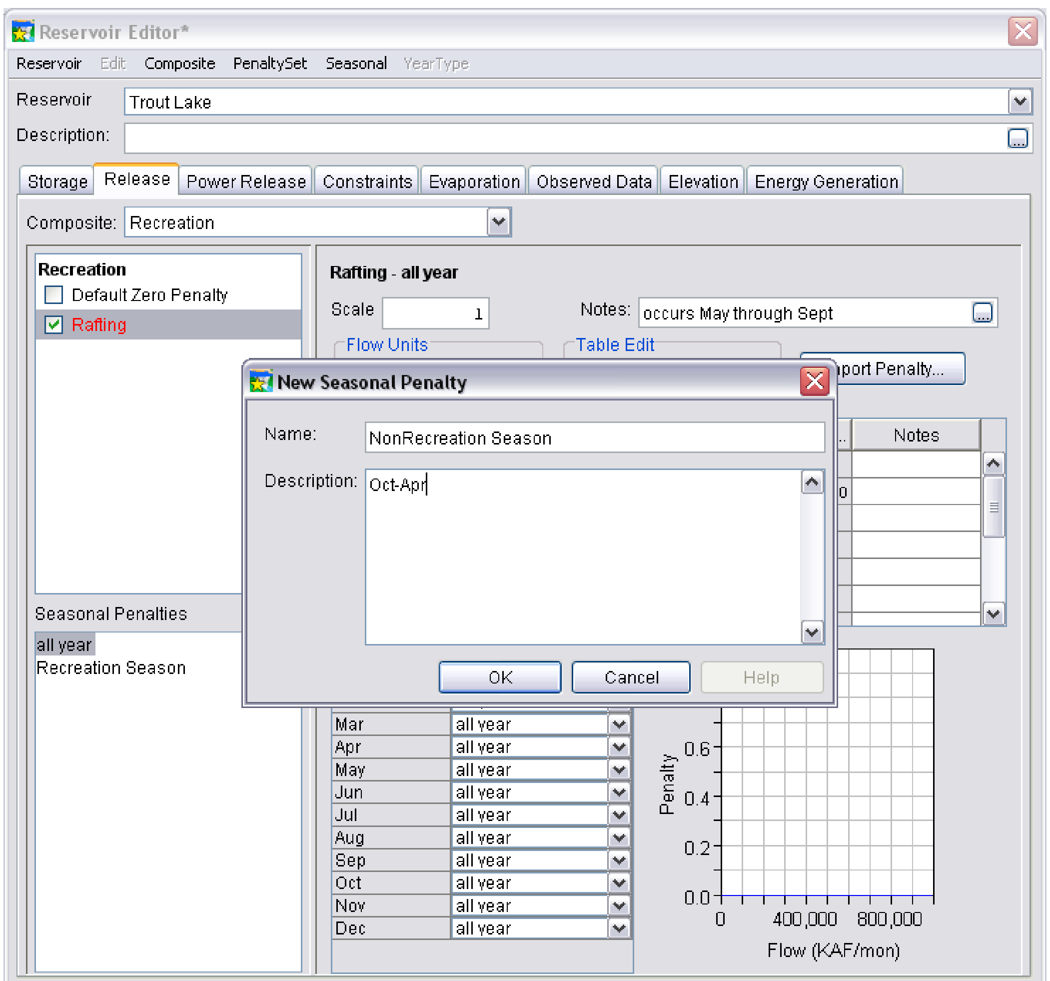


Figure 34: Zero-valued seasonal penalty function for the months outside the recreation season.

The **Release** tab of the Reservoir Editor for the "Trout Lake" reservoir should appear as it does below in Figure 36. In the right hand column of the penalty table there is a "**Notes**" column where the modeler can write comments ("metadata") for him/herself and future model users.

	Function
Jan	NonRecreation Se...
Feb	NonRecreation Se...
Mar	NonRecreation Se...
Apr	NonRecreation Se...
May	Recreation Season
Jun	Recreation Season
Jul	Recreation Season
Aug	Recreation Season
Sep	Recreation Season
Oct	NonRecreation Se...
Nov	NonRecreation Se...
Dec	NonRecreation Se...

Figure 35: Select which season to apply to each month.

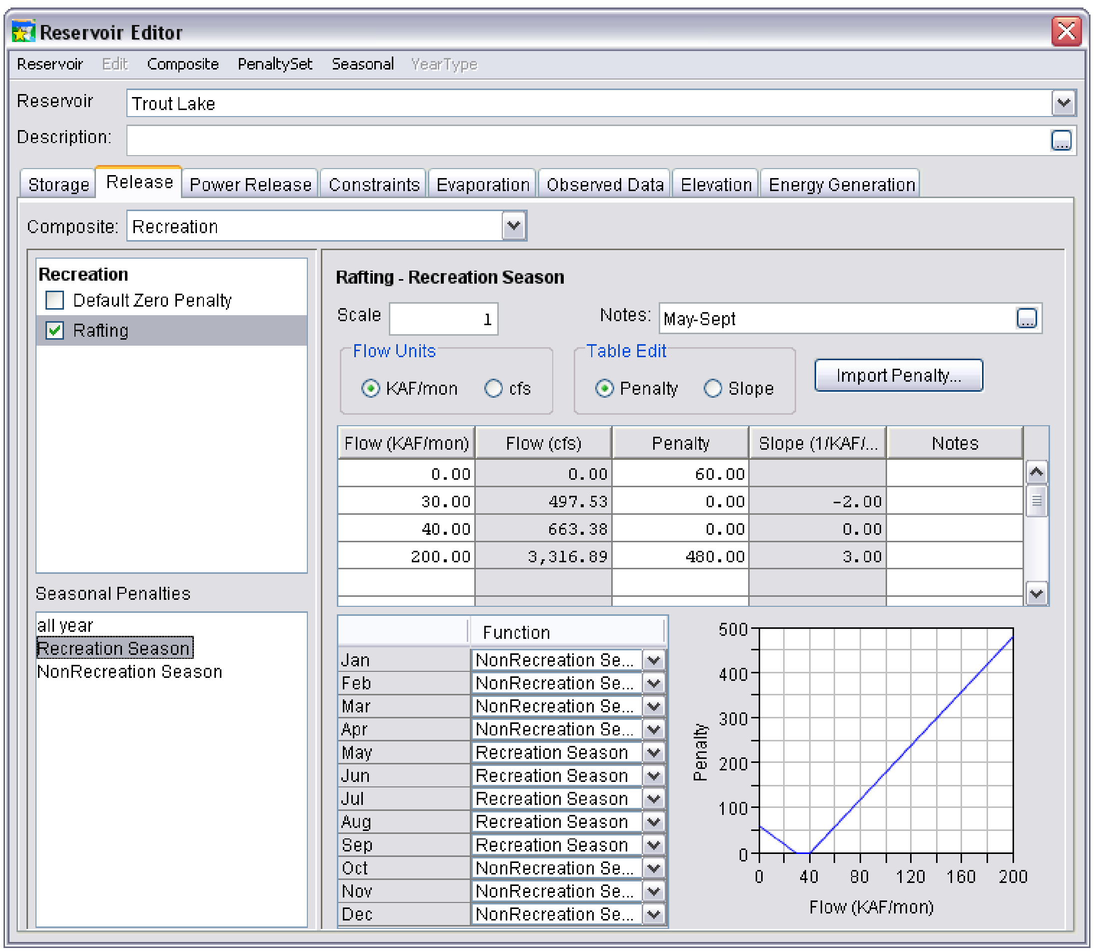


Figure 36: Currently displayed is the Recreation Season penalty function for the Rafting PenaltySet.

Because we may want to run a model without considering the reservoir release penalty of Trout Lake, it is useful to have a Composite and PenaltySet with no penalties. HEC-ResPRM creates a default zero penalty Composite and PenaltySet for both Storage and Release (Figure 37).

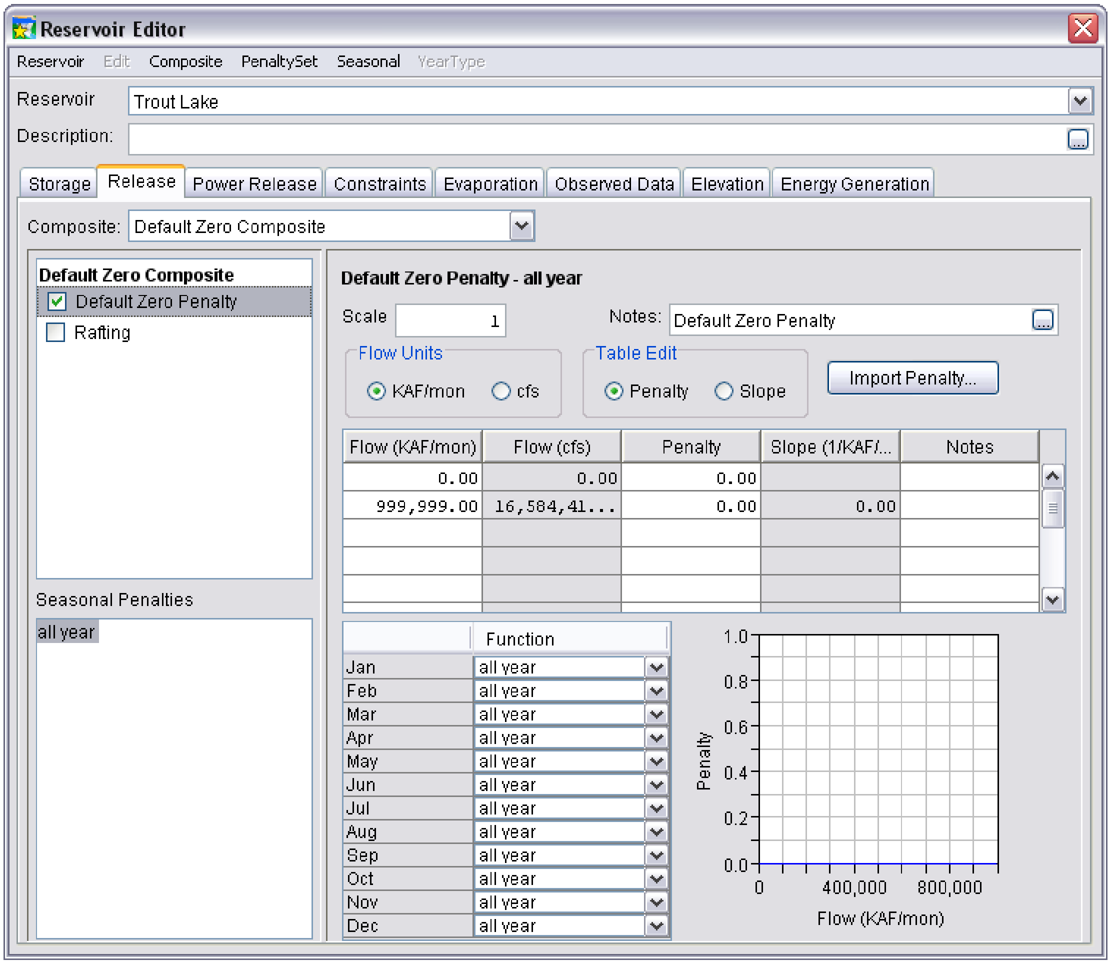


Figure 37: Only the Default Zero PenaltySet should be checked for the Default Zero Composite.

Mandatory Penalty Functions: Two Composite Penalty Functions are mandatory at all reservoirs: one Composite for the Reservoir Release and one for the Reservoir Storage. All other penalty functions in the network are optional. By default, null-value penalty functions are automatically created for these two locations. Using the "Default Zero Penalty" Composites allows you to make optimization runs without putting a penalty value function at every Reservoir Release and Storage.

4.4 Defining Alternatives

For most planning or modeling studies, several different alternatives are evaluated to determine the best option. These alternatives may differ based on the role of different objectives, operational strategies, included projects, etc. HEC-ResPRM is set up to accommodate the need to model and compare these types of variations in alternatives. An **Alternative** in HEC-ResPRM is a group of data that includes a Network, a selection of Composite Penalties and settings, and a variety of compute settings. Optimization runs are performed on these Alternatives.

Before optimizing, several selected characteristics of the model must still be specified by creating an **Alternative**. Think of an Alternative as a specific case (instance) of the Network that you will optimize.

In an Alternative you *must* specify:

- which Network to base the Alternative on,
- which Composite Penalty functions are to be used at each location,
- the starting and ending storage levels of all reservoirs, and
- the directory and path of the DSS files that contain inflow or constraint time-series.

The Alternative Editor has seven tabs for data entry:

- **Penalty Assignments**, for applying Composite Penalties,
- **Initial Solution**, for providing an initial solution,
- **Reservoir**, for setting initial and ending storage values,
- **Time-Series**, for mapping input DSS time-series,
- **Observed Data**, for adding observed data to graphs,
- **Compute Options**, for changing compute settings, and
- **DSS Output**, for changing the default output.

This manual only covers the **Penalty Assignments**, **Reservoir**, **Time-Series**, and some features of the **Compute Options** tabs. Data used by the other tabs is optional and its description is outside the scope of this Quick Start Guide. For more information on Initial Solution, Compute Options, and DSS Output, see the HEC-PRM User's Manual. For more information on Observed Data, see the HEC-ResSim User's Manual.

The following steps will be taken to build an Alternative:

1. Create an Alternative.
2. Assign Composite Penalty Functions.
3. Define Initial and Ending Reservoir Storages.
4. Specify Inflow Time-Series – Part II: DSS Paths.

1. Create an Alternative.

To create an Alternative, from the **Alternative** Menu (in the Network Module) select **Edit**. The HEC-ResPRM Alternative Editor window will appear.

- Select a Network (*"Base2004" for the Demo watershed*).
- From the **Alternative** menu on the Alternative Editor Toolbar, select **New**.
- In the New Alternative window (Figure 38) enter a name for the Alternative in the Name box. Your alternative name must be ten or fewer characters long. *For the Demo watershed, use "RecAlt."* Entering a description in the Description box is optional, but can be helpful. Select a Network from the list *("Base2004" for the Demo)* and click **OK**.

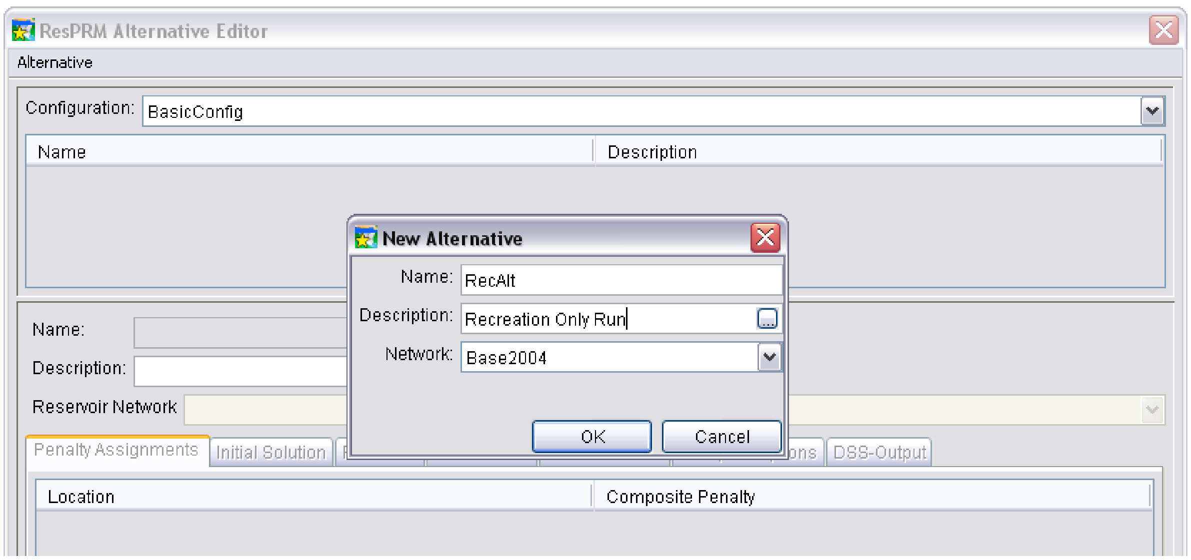


Figure 38: The upper portion of the Alternative Editor when creating a New Alternative: Select the Network your Alternative will be built from, then name the Alternative and provide a description.

2. Assign Composite Penalty Functions.

After you have named an Alternative, the Alternative Editor initially displays the **Penalty Assignments** tab. (Your new alternative will not show in the upper panel list until you have saved it.) The elements of the network are listed in the left-hand column entitled "Location." Because reservoirs can have three different types of penalty functions (storage, release, hydropower), they are listed three times. For each element that has a Composite, select one from the drop-down list in the right-side column of the table (Figure 39). In the case of the Demo example, the end result is displayed in Figure 39. Note that reservoir storage and release elements must have a Composite, even if it is the Default Zero Composite, while all others may use "None."

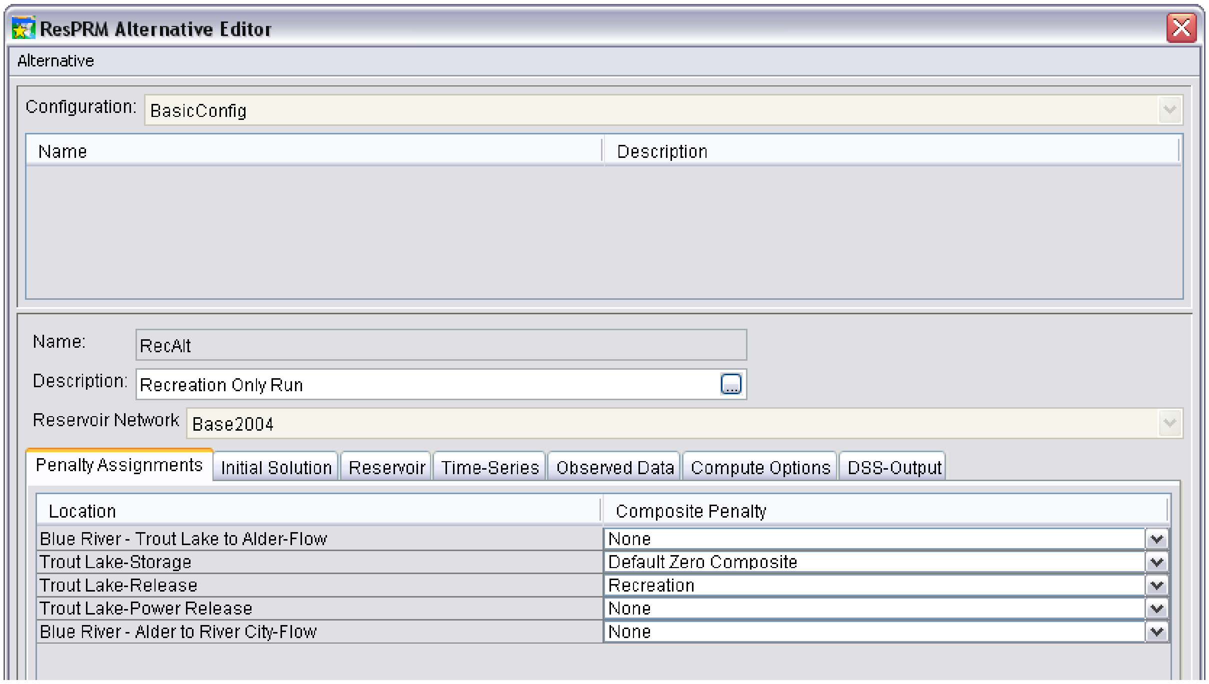


Figure 39: Select one Composite (or None) for each Location on the Penalty Assignment tab of the Alternative Editor.

3. Define Initial and Ending Reservoir Storages.

Now select the **Reservoir** tab, and define initial and ending reservoir storage volumes (Figure 40), which will occur at the beginning and end of the Optimization time window. This ensures that the reservoir starts the optimization with a specified amount of water and that it doesn't drain the reservoir at the end of the time window. In the Demo, the "Trout Lake" reservoir is set to start and end at 500 KAF.

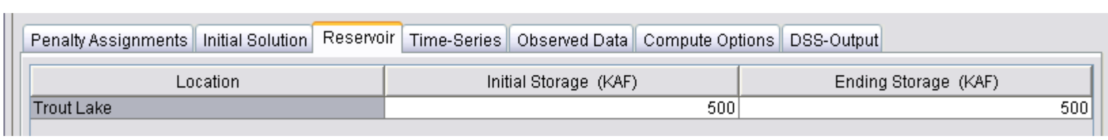


Figure 40: The initial and ending reservoir storages are set on the Reservoir tab of the Alternative Editor.

4. Specify Inflow Time-Series – Part II: DSS Paths.

Inflow time-series must be provided at upstream nodes and other nodes that receive inflows. As described in the section "Specifying Inflow Time-Series – Part I." (p. 4-13), this is a two-step process. The first step consisted of identifying those nodes with which an inflow time-series would be associated. In the second step, considered here, you must specify the DSS file and pathname that contains the time-series. If you declared a constraint of type time-series or an evaporation, you will specify that DSS file and pathname here as well. To specify time-series, select the **Time-Series** tab of the **Alternative Editor** (still in Network Module). The first column titled "Location" shows the name you gave your inflow time-series. The second column tells you the type of data HEC-ResPRM expects (evaporation, local inflow, etc.). Subsequent columns indicate the pathname for the DSS record. These will be populated when you select data from a DSS file.

For the Demo, select the row of Location “TroutLake_Inflow,” which represents the upstream node for Trout Lake. Click the button **Select DSS Path…** (Figure 41).

The Select Time-Series Path window will appear. Select **File > Open** from the menu and open the “BlueRiverInflows.dss” file from the “…/Base/BlueRiverDemo/shared/” directory. Select the second time-series record (Part B = TROUT LAKE, Part C = FLOW-IN) and press the **Set Pathname** button.

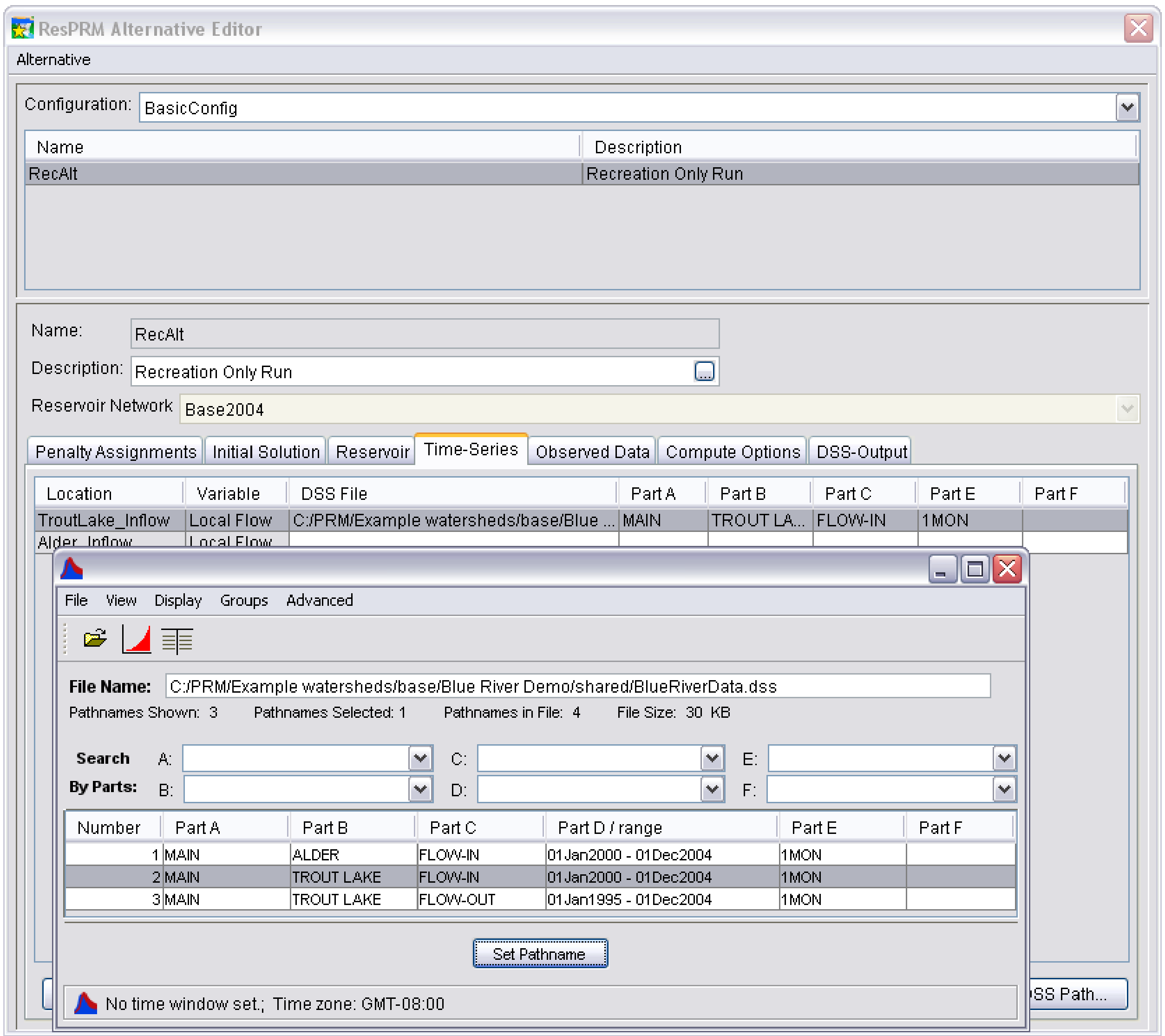


Figure 41: A DSS record is chosen as the inflow to Trout Lake. Inflow DSS paths are set on the Time-Series tab of the Alternative Editor.

DSS Data Units and Time Step: Be sure that the time-series data is in the correct units and has the right time step. For British units, this means flows are in thousand acre feet per month and for SI units, million cubic meters per month. Time step should be monthly. If your time-series data are in the wrong units or time step, they must be corrected in HEC-DSS before you use them in HEC-ResPRM.

We've given the reservoir a time-series of inflows, but the Demo example has a second inflow at the "Alder" junction. Repeat this procedure for the "Alder_Inflow" row in the **Time-Series** tab of the Alternative Editor. The pathname to associate with this inflow has a Part B of "ALDER" and a PART C of "FLOW-IN."

We can display the contents of the DSS time-series by selecting one or several location rows and selecting either the **Plot** or **Tabulate** buttons. This opens a window displaying the time-series in either graphical or tabular form (Figure 42).

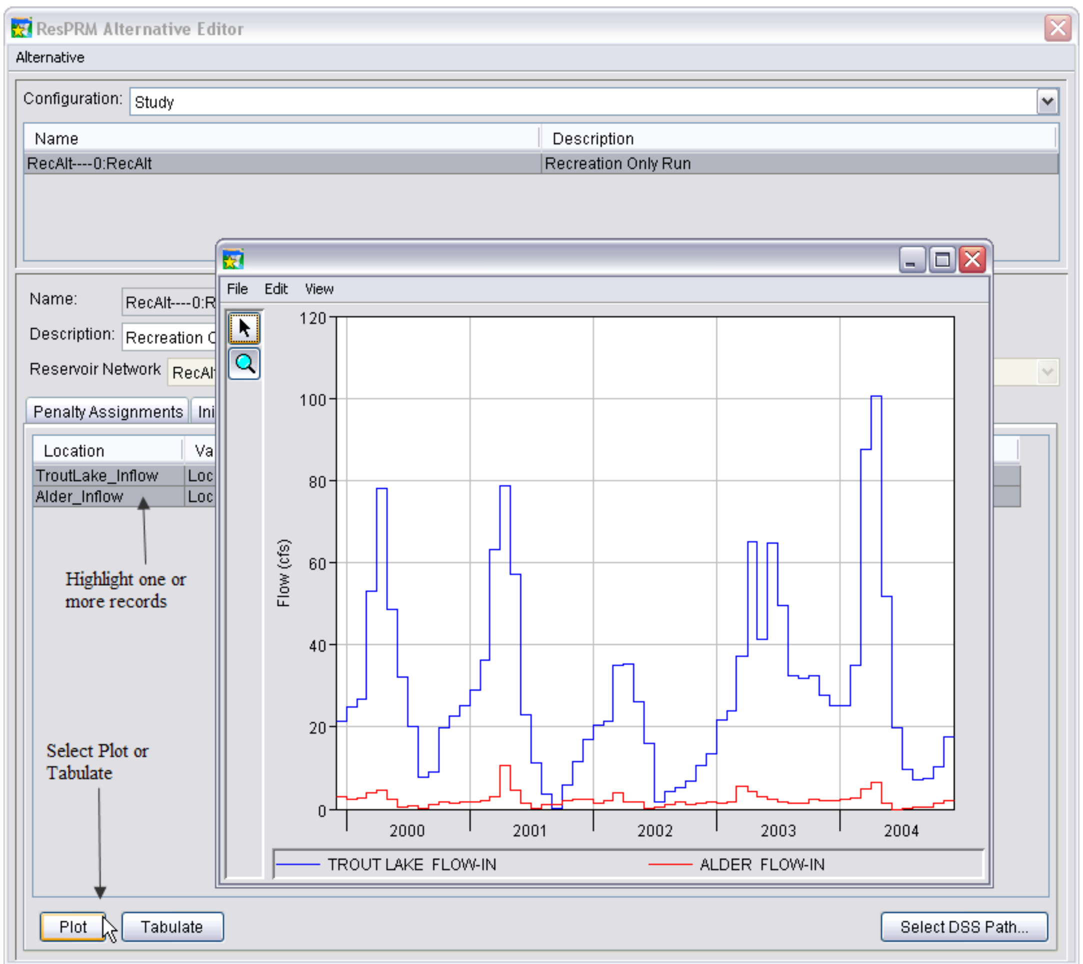


Figure 42: Inflow time-series can be plotted or tabulated from the Time-Series tab of the Alternative Editor.

4.5 Performing an Optimization

Having built a Network and an Alternative in the **Network Module**, you are ready to perform an optimization in the third and final module: the **Optimization Module**. In this module you will run optimizations on selected Alternatives and view and compare results. The following steps will be taken:

1. Create/Open an Optimization
2. Set the Active Alternative
3. Compute.

1. Create/Open an Optimization.

Be sure your Network is saved, then, from the Module list, select Optimization. To create an Optimization, select New from the Optimization menu. The window illustrated in Figure 43 will open.

- Enter a name for the Optimization in the **Name** box. A name is generated by default based on the start date and current time. You should change this to something more fitting. A good name gives some indication of the time period used (e.g., “Drought Period,” “Period of Record,” or “1950s”). For the Demo example, name the Optimization “Early2000s.” (See Figure 43.)
- Enter a **Start Date** & **Time** and an **End Date** & **Time**. To run the Demo example use 01Jan2000 and 31Dec2004, respectively. *Note that it is often easier to type the dates (in DDMmmYYYY format) than to use the calendar selector.*
- Select one or more applicable **Alternatives** for the Optimization (in the Demo example you only have one: “RecAlt”) and click **OK**.

When the Optimization is built, HEC-ResPRM makes copies of all the input data (the Network, Alternative, and DSS Time-Series) and puts them in a new subdirectory of your watershed, named after your Optimization. *Note that runs of your Optimization will access these copied files, not the original Network, Alternative, and time-series files, so they will not see changes in the base files unless specifically instructed (Section 5.2).* It also creates a new DSS file for each alternative in the Optimization. These DSS files hold the composite penalty functions for the system, and each is named after its alternative and the network the alternative was based on.

2. Set Active Alternative.

In the Demo example you only have one Alternative so far, so you can skip this step. If several Alternatives have been created, right-click on the desired Alternative in the Optimization Control Panel, and select **Set as Active**.

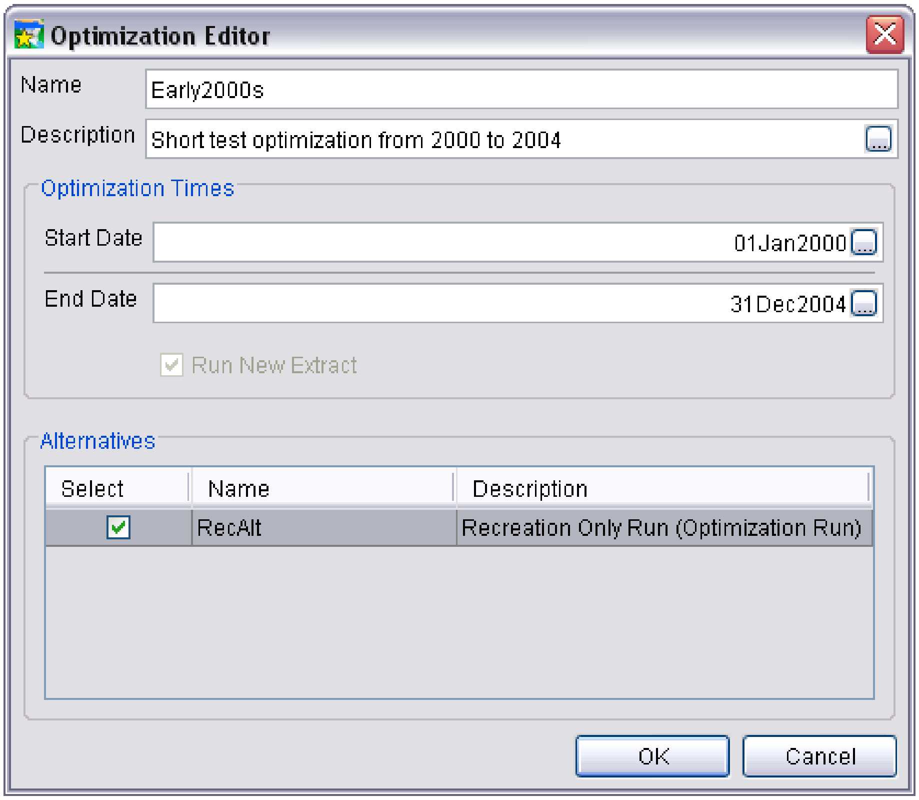


Figure 43: Select the time window and Alternatives and update the input DSS records (Run New Extract) in the Optimization Editor. (When initially building a new Optimization, the "Run New Extract" option is mandatory, and cannot be unchecked.)

3. Compute.

Click on the "Compute {Name of Alternative}" button 

in the control panel of the Optimization Module's main window to perform the computations. A compute window will appear showing status messages and program progress. If HEC-ResPRM doesn't compute automatically (for example, if no changes were made to the active Alternative), you can force recomputation by holding the Ctrl key while clicking the Compute button. (Alternatively, the option to always force a recompute can be set on the Optimization tab under **Options** on the **Tools** menu.) When the computation is finished, a "Compute Complete" message will appear and the status bar will read 100%. Click **Close** to close this window. *Note: Clicking **Close** before the compute is complete may not stop the compute process.*

4.6 Viewing, Interpreting, and Organizing Results

Once you have a successful Optimization run, you can view and compare results in the HEC-ResPRM interface. The following steps are described in this section:

1. View Results
2. Interpret Results

1. View Results.

Model results can be accessed and visualized in three different ways:

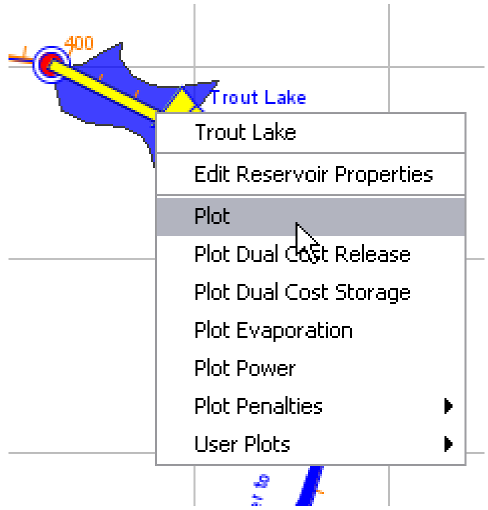
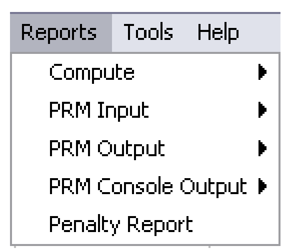


Figure 44: Right-click on network element to plot.

- **Plots.** On the model schematic you can right-click on a model element to get a menu list. Included on the list are several plot options. Select the **Plot** option (Figure 44) to display the default time-series graph. The plotted results can be tabulated by selecting **Tabulate** from the plot's **File** menu. Note that time-series graphs of Shadow values (**Dual Cost)** and **Penalties** are also available. (See next section.)

- **DSS Viewer**. When **Hec-DssVue** is selected from the **Tools** menu, a DSS file is opened that contains the results of the Optimization. A list of pathnames is provided, and a screened list can be obtained by selecting a pathname part from the lists in the **Search by Parts** section of the window. To learn more about the pathnames for various results, consult the HEC-PRM User's Manual. To select records to be displayed, highlight the pathnames and click on the **Select** button. After one or more records are selected, the buttons for plot and tabulate become active. Click either button to generate the associated output. To learn more about using DSS, consult the HEC-DSS User's Manual.



- **Summary Reports.** The **Reports** menu of the Optimization Module contains a list of Summary Reports. Most summary reports show various input and output files for the DOS-based HEC-PRM software engine. Each alternative is listed for each category under the Reports menu. Under **Compute** is the compute log for the most recent run of each alternative. This is the information that shows up in the Compute window when you run an alternative. **PRM Input** and **PRM Output** contain the *.pri and *.pro files, respectively, for each alternative. These are the files sent to and received from HEC-PRM for an optimization run. **PRM Console Output** shows the compute messages from HEC-PRM for each alternative. The *.pri and *.pro files, in particular, can be helpful when troubleshooting problems with your model. Consult the HEC-PRM User's Manual to learn more about these files.

  The **Penalty Report** summarizes the total numeric penalty attributed to each PenaltySet and Composite. If you have created **Penalty Groups**, you can also view the total penalty for each group. *For the Demo model, this report is not yet available because no Penalty Groups have been specified.* This practice is useful for multi-objective modeling.

2. Interpret Results.

A quick survey of Demo model results helps interpret HEC-ResPRM output. The plot in Figure 45 is accessed by right clicking on Trout Lake and selecting Plot. The graph in the top viewport shows storage volume and the graph in the bottom viewport shows reservoir inflow and outflow (release). Storage generally stays within the 500 to 510 KAF range, and releases are usually below 40 KAF/month except when higher releases are necessary to prevent reservoir storage from reaching excessive levels.

To understand these optimal results, refer back to the relevant penalty functions. For the Demo model, the storage and release Recreation Composites are made up of the Boating and Rafting PenaltySets at Trout Lake. No penalty is incurred for storages within the 500 to 510 KAF range, and no flow penalties are incurred within the 30 to 40 KAF/month range. Penalties incurred during the model run are visualized by right clicking on "Trout

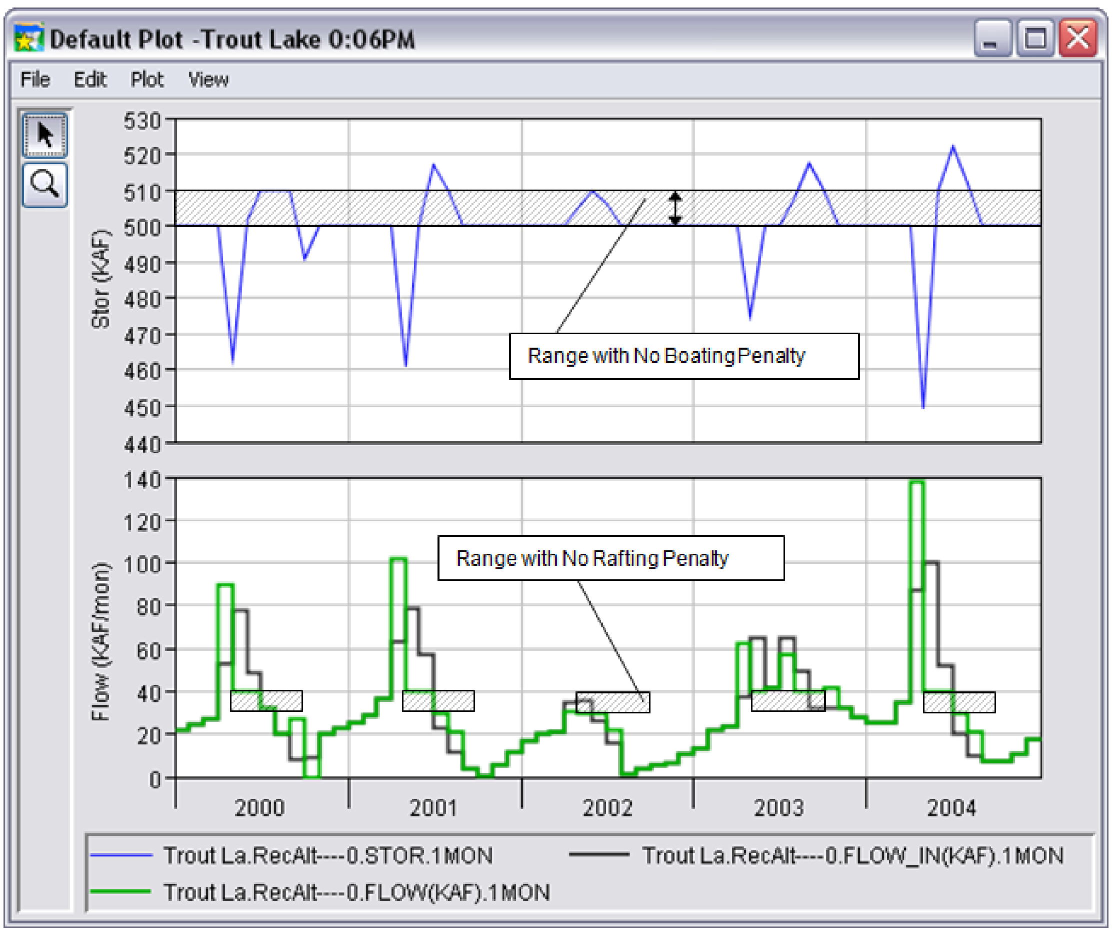


Figure 45: Time-series plot of reservoir storage (top), inflow (bottom-grey), release (bottom-green).

Lake" and selecting **Plot Penalties**. (Different plots are available; see an example in Figure 46.) Time-series plots of penalties are helpful to interpret HEC-ResPRM results. *Note that penalty plots show units of K$-Release and K$-Storage by default, under the assumption that you entered your penalty functions in terms of $1000. Plots should be re-interpreted if you are using other units. In the Demo example, units are recreational-visits.*

Another important concept in results interpretation is awareness of the perfect hydrologic foresight associated with multi-period deterministic optimization such as in HEC-ResPRM. In Figure 45, Trout Lake is "pre-releasing" to avoid high penalties resulting from high storage levels. Releases are large the month before a high inflow. Otherwise stated, when HEC-ResPRM finds the optimal release in January 2000, it has full knowledge of all inflows throughout the network until December 2004. This foresight occurs because the optimization solves a single multi-period problem (rather than month by month as it would in simulation). Perfect foresight will influence different models and different PenaltySets to varying degrees. The current example is a case of strong bias; in other cases it is negligible. You should be aware of how perfect foresight affects the results of your specific model. An annual run mode is available in HEC-ResPRM, which reduces foresight from inter-annual to intra-annual only.

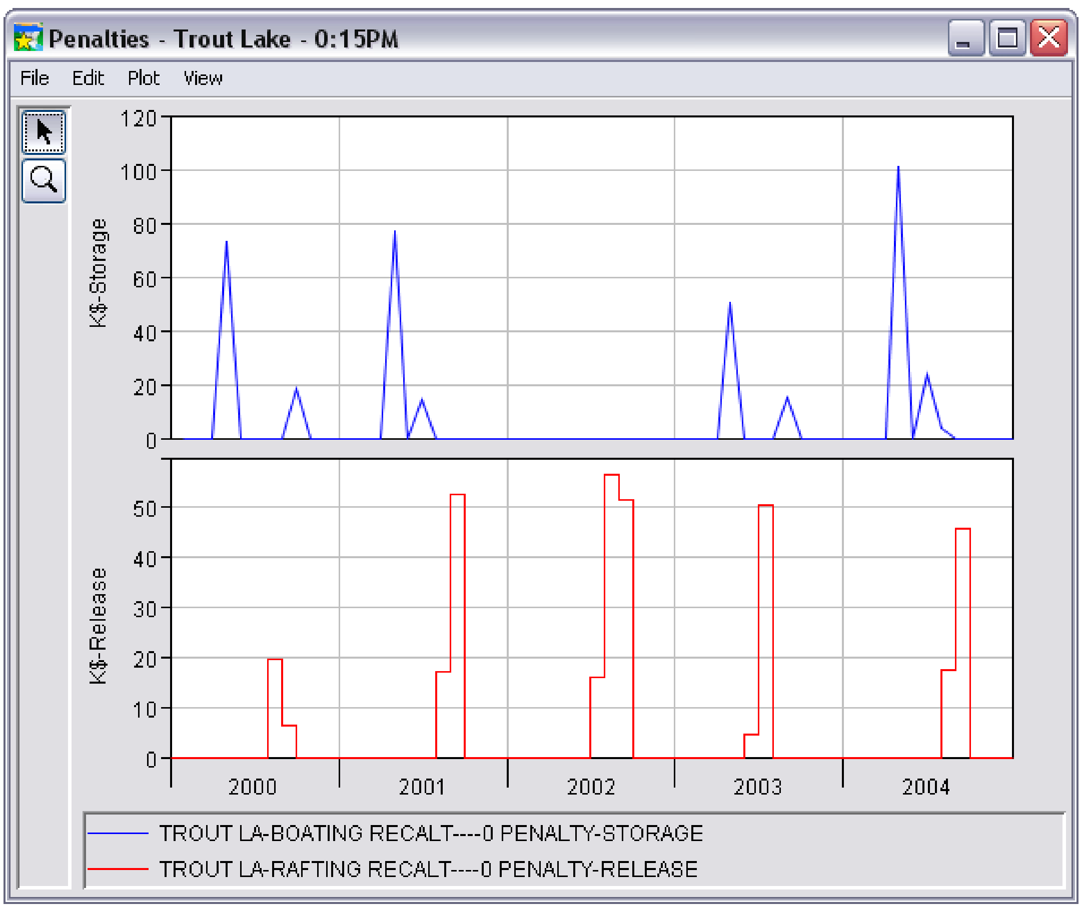


Figure 46: The Penalties plot shows the time-series of penalties generated by storage and release from reservoir Trout Lake.

Interpreting the Plot Legend: Plots in HEC-ResPRM come directly from the DSS output file. The legend names are based on the DSS pathnames of the data. They take this form: *{Element Name}.{Alternative Name and Number}.{Data Type}.{Time Step}*. Note that the program has truncated the name "Trout Lake" to 8 characters, "Trout La." The Alternative name always has 11 characters – The first 10 are the user-defined name with dashes to fill in for names shorter than ten. The last character is a number. In HEC-ResPRM 1.0, this number is always 0. The data type varies depending on what you have plotted, and the time step is always 1 month for this version of HEC-ResPRM.

Finally, HEC-ResPRM offers an option to **Plot Dual Costs** for each Network element. These plots show marginal value information, or quantify the change in the objective function value that would occur if a constraint were relaxed by one unit. Since HEC-ResPRM has two constraint types (capacity constraints and mass balance constraints), there are two types of information given in the plots:

- The **marginal cost** of a link capacity constraint tells how much more or less penalty that link would generate if its capacity constraint were relaxed by 1 (e.g., if a canal supporting a maximum of 10 flow units/month were upgraded to 11). Since HEC-ResPRM minimizes penalties, a negative dual cost indicates a benefit. Capacity constraint dual costs are labeled "MARG_COST" in HEC-ResPRM.
- The **dual cost** (or shadow value) of a node's mass balance constraint indicates how the objective function would change if the continuity equation were relaxed by 1 unit (e.g., if you injected a supplementary unit of flow at the node). Mass balance constraints in HEC-ResPRM are labeled as "DUAL_," with "ORIG" indicating the value of injecting a unit of flow at the starting node of a link and "TERM" at the terminal node of a link. For storage nodes, where storage is a link over time, "ORIG" refers to the beginning of the time period and "TERM," the end of the time period.

You can now interpret the graph of dual costs of storage link "Trout Lake" (Figure 47). Since the capacity constraints on storage are never reached (the dam is never full or empty), the effect of changing these constraints is null and thus the shadow value is zero. (See MARG_COST_S in Figure 47.) The "DUAL_ORIG_S" shadow value is sometimes non-zero since adding a unit of storage (at the beginning of a period or the end of the previous one) often changes the penalty incurred (Figure 47 and Table 3). HEC-ResPRM tends to produce negative shadow values when "Trout Lake" storage levels are low and positive ones when levels are high. Because HEC-ResPRM optimizes by minimizing rather than maximizing, a negative shadow value implies a benefit; a positive one implies a penalty. See any optimization text to learn more about dual costs. *Note that the plotted units for marginal cost and shadow values are $/KAF, but the true unit is determined by the unit of your penalty function. If your penalty functions were based on something besides dollars, then interpret the "$" as whatever unit you actually used. In this case, the $ should be replaced with recreational visits (rafting or boating).*

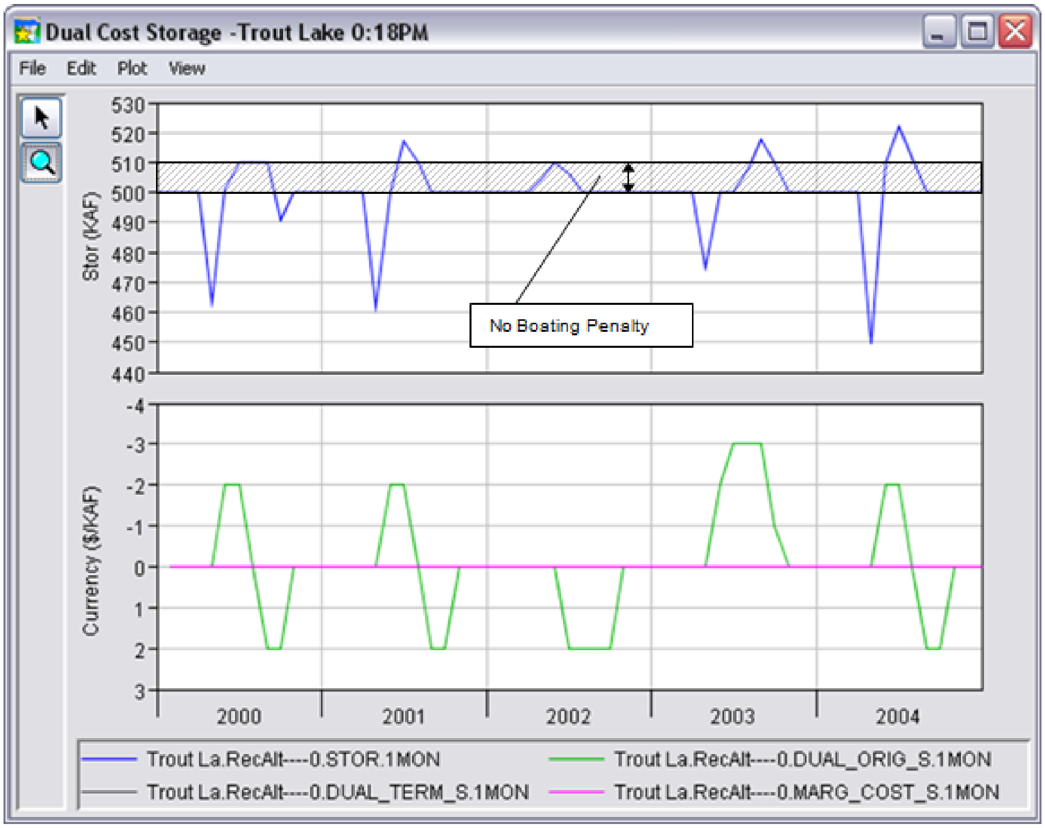


Figure 47: The Dual Cost Storage plot at "Trout Lake" shows the time-series of reservoir storage along with the dual cost and marginal cost values.

Table 3: Release, storage, penalties, and shadow values of mass balance equation at the "Trout Lake" reservoir. (This table was created independently, using results of HEC-ResPRM.)

Date	Inflow	Release	Release Penalty	Storage	Storage Penalty	Dual_Orig_S
3/31/00	26.76	26.76	0	500	0	0
4/30/00	53.14	89.69	0	463.45	73.1	0
5/31/00	78	40	0	501.45	0	-2
6/30/00	48.55	40	0	510	0	-2
7/31/00	32.24	32.24	0	510	0	0
8/31/00	20.19	20.19	19.62	510	0	2
9/30/00	7.81	26.84	6.32	490.97	18.06	2
10/31/00	9.03	0	0	500	0	0
11/30/00	19.78	19.78	0	500	0	0

Units for Penalty Plots and Dual Cost Plots: Penalty and Dual/Marginal Cost results are saved in default units that assume the user entered penalty functions with penalties in units of $1000. If your penalty functions were entered in other units, simply re-interpret the graphs accordingly.

CHAPTER 5

Expanding the Model

The previous section described the Demo model with only two simple penalty functions, both representing recreation. This leaves many basic features of HEC-ResPRM unused. Most HEC-ResPRM models will have several different objectives that express competing needs in the watershed. In this section you will consider a case in which a water resources system is managed for several different interests (multi-objective framework), all expressed in monetary units. You will also learn how to update your model by making changes in the Network and Optimization Modules, and you will learn how to keep the data in both modules in synch with each other. As you now have some familiarity with data entry in HEC-ResPRM, many intermediate screen captures are omitted.

Expanding a Multi-objective Model
- Update and Add New Penalties
- Create a New Alternative
- Update and Run the Optimization
- Interpret Results

Managing Optimization Data
Adding a New Project
- Update and Add New Penalties
- Create a New Alternative
- Update and Run Optimization
- Interpret Results

5.1 Expanding a Multi-objective Model

The Blue River Authority – a watershed management group – has decided to develop a full system model for several of the main objectives on the Blue River. In order to develop their model, they first consulted with local businesses, landowners, scientists, park rangers, and other stakeholders to determine the important objectives in the watershed. Once they had clearly defined objectives, the Blue River Authority got help from economists in developing penalty functions that accurately reflect the value of the objectives (including recreation) in terms of dollars. A little research will help you find a variety of ways to estimate monetary values for nonmonetary objectives. Expressing all objectives in the same units (typically dollars) makes it much easier to interpret results.

Begin with the recreational model created in Chapter 4. The process for developing the expanded model will follow these steps:

1. Update and Add New Penalties.
2. Create a New Alternative.
3. Update and Run the Optimization.
4. Interpret Results.

1. Update and Add New Penalties.

You will be making changes to existing penalties and adding new ones. You can test small changes to existing PenaltySets in the Optimization Module, but for more extensive changes, and for making new Composites, you must be in the Network Module. Go to the Network Module and make sure the "Base2004" Network is open.

You will first update the existing penalties based on economic data the study team has collected. The objectives to be modeled in this study are recreational boating and rafting, flood reduction, and water quality. Begin by creating a copy of the Boating PenaltySet at the reservoir. In the Storage tab of the **Reservoir Editor**, under PenaltySet, select **Save As…**. Save the copied PenaltySet with the name "Boating$." You will use the "$" to represent penalty curves in monetary units. Select the "Boating$" PenaltySet and edit it to reflect the new economic information shown in Table 4. Enter your economic penalties in terms of $1000. Some PRM results are, by default, displayed under the assumption that they were entered in $1000. If you entered the penalties in different units, you will have to reinterpret some results graphs based on the actual units.

Table 4: Economically-based penalty curves for recreational boating.

Storage (KAF)	Penalty	Notes
450	0	All docks out of water, assume no boating
500	-$55,000	Monthly benefit for full recreational use
510	-$55,000	Monthly benefit for full recreational use
600	0	Docks are too low, assume NO rec. boating

Next, create a new PenaltySet for the reservoir storage flood objective. Call it "Flood$." The penalty information for flooding around the reservoir is shown in Table 5. The slope of the penalty function changes at 580 KAF, where the density of affected structures increases.

Table 5: Economically-based flood penalties for reservoir storage.

Storage (KAF)	Penalty	Notes
0	0	No flooding
535	0	No flooding
580	$80,000	Docks, marina, a small building affected
600	$250,000	A few waterfront cottages, roads affected

Create a new Composite to which you will add your economic penalty functions. Call the Composite “AllComp$,” because you will add all economic penalty functions to this Composite. Check the boxes for the “Boating$” and “Flood$” penalty functions.

Now you will adjust the flow penalties on the reservoir Release tab. The adjusted rafting penalties are shown in Table 6. Copy the Rafting PenaltySet and save it as “Rafting$.” Adjust the recreation season penalties, and remember to enter them in terms of $1000. Next, add a new PenaltySet called “Flood$” for flooding along the Blue River from Trout Lake to Alder. Penalties are shown in Table 7. Create an “AllComp$” Composite for the reservoir release and add the “Rafting$” and “Flood$” PenaltySets.

Water quality issues are of concern on the lower stretch of the Blue River. The Water Authority is fined up to $25,000 when flows from Alder to River City drop below 15 KAF/month. Add a penalty to this river reach to reflect this information. See Figure 48 to see what the Reach Editor should look like when you are done.

Table 6: Economically-based penalty for rafting on Blue River from Trout Lake to Alder.

Flow (KAF/mo)	Penalty	Notes
0	0	Too low for rafting
30	-$30,000	Ideal rafting conditions
40	-$30,000	Ideal rafting conditions
200	0	Assume NO rafting

Table 7: Economically-based penalty for flooding on Blue River from Trout Lake to Alder.

Release (KAF/mo)	Penalty	Notes
0	0	No Flooding
100	0	Two-year return period – no flooding
200	$50,000	Floods some agriculture
250	$150,000	Floods many agricultural fields, roads

Penalty Function Extrapolation: What happens if a recreation season flow exceeds the range given in the penalty function (200 KAF/month in this case)? The penalty will increase, because HEC-ResPRM extrapolates linearly when penalty function ranges are exceeded.

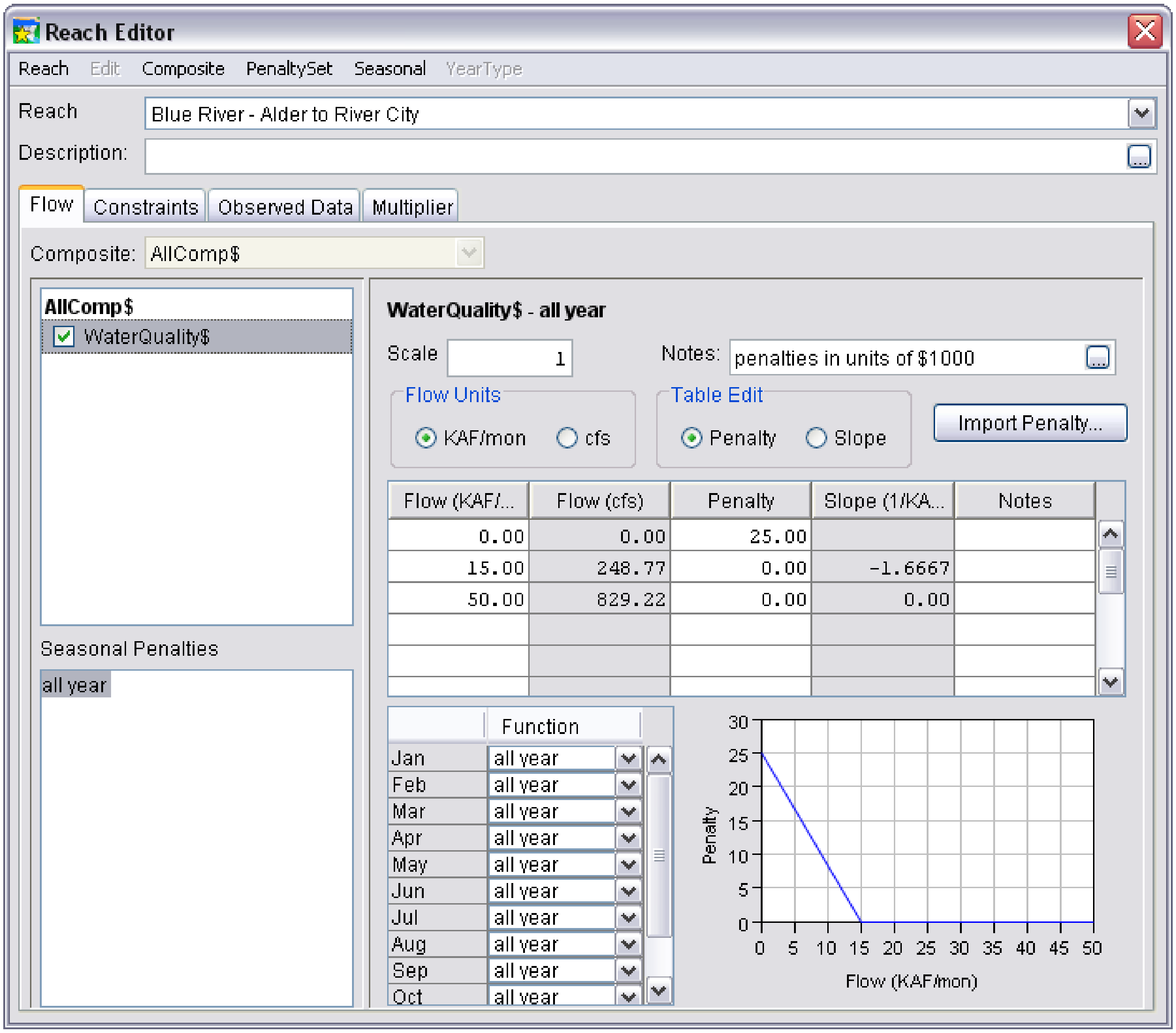


Figure 48: Flows below 15 KAF/month are fined up to $25,000. It was assumed that the fine would increase linearly from 0 at 15 KAF/month to $25,000 at 0 KAF/month. All flows above 15 KAF/month incur no penalty. The 50 KAF/month value was chosen arbitrarily to show this.

2. Create a new Alternative.

Now that you have made the necessary penalty updates, you will want to make a run using the new Composite Penalties. Build a new Alternative called “AllPenalty.” Since this Alternative is based on the same Network used for the RecAlt, a new Alternative can be built quickly with the **Save As...** option. This will allow you to avoid having to re-enter DSS paths and initial and ending storages. Open the **Alternative Editor**, highlight the RecAlt Alternative in the upper panel, and select **Save As…** from the Alternative menu. Give the Alternative a name of ten or fewer characters (in this case, “AllPenalty”) and a fitting description. Once the new “AllPenalty” Alternative exists, you need to select the correct Composite Penalties (as in Figure 49). All other settings are unchanged from the “RecAlt” Alternative.

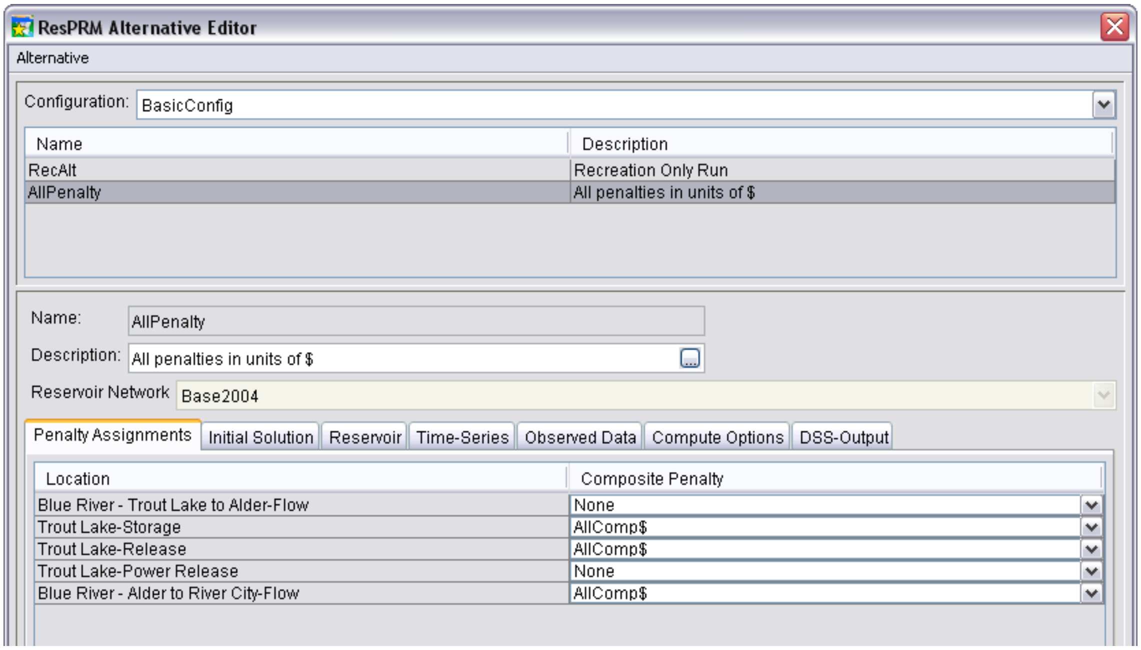


Figure 49: Alternative "AllPenalty" has the “AllComp$” Composite Penalties selected for “Trout Lake” Storage and Release, and for “Blue River – Alder to River City” Flow.

3. Run model and interpret results.

To run the Optimization, make sure you save the changes you made in the Network, and then switch to the **Optimization Module**. Select the **Edit** from the Optimization menu and the Optimization Editor will appear (as in Figure 43). Add a check mark next to the “AllPenalty” Alternative to add it to this Optimization. (Note that if you had made changes to the DSS input records or added new ones, you would want to check the Run New Extract box. This would bring the new or updated DSS data into the file that is used to run the Optimization.) The **Optimization Control Panel** in the right hand side of the Optimization Module should now show two Alternatives in the “Early2000s” Optimization. Right-click on “AllPenalty” and make it the active Alternative (Figure 50). Click the **Compute** button to run the multi-objective optimization alternative.

Results for the “AllPenalty” Alternative, can be viewed by checking the box in the Optimization Control Panel. Uncheck the RecAlt box, so that you are only seeing the results from one Alternative at a time. Plot the Trout Lake results by right-clicking on Trout Lake in the map and selecting Plot (Figure 51). In the upper plot, the blue line is storage for “AllPenalty.” For the most part, the storage is staying between 500 KAF and 510 KAF, maximizing benefit for boating recreation. Flood penalties are not incurred until storages exceed 535 KAF, and the reservoir maintains its storage below that. The bottom panel of the “Trout Lake” graph shows the inflow (FLOW_IN) and outflow (FLOW). Rafting benefits are highest between 30 and 40 KAF/month and only occur during the rafting season, the months of May – September. These flows are only met about 30% of the time. This suggests that the system either could not physically meet the rafting needs, or that the overall value of rafting is not as great as that of the competing objectives. Flood penalties do not occur on flows below 100 KAF/mon.

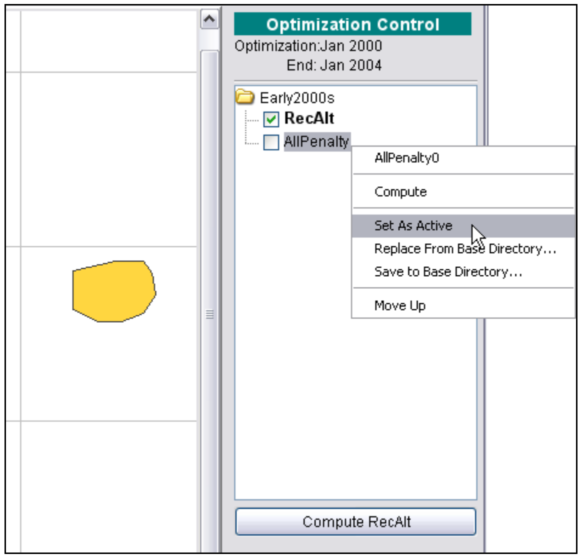


Figure 50: Right-click on the "AllPenalty" and set it as the active Alternative.

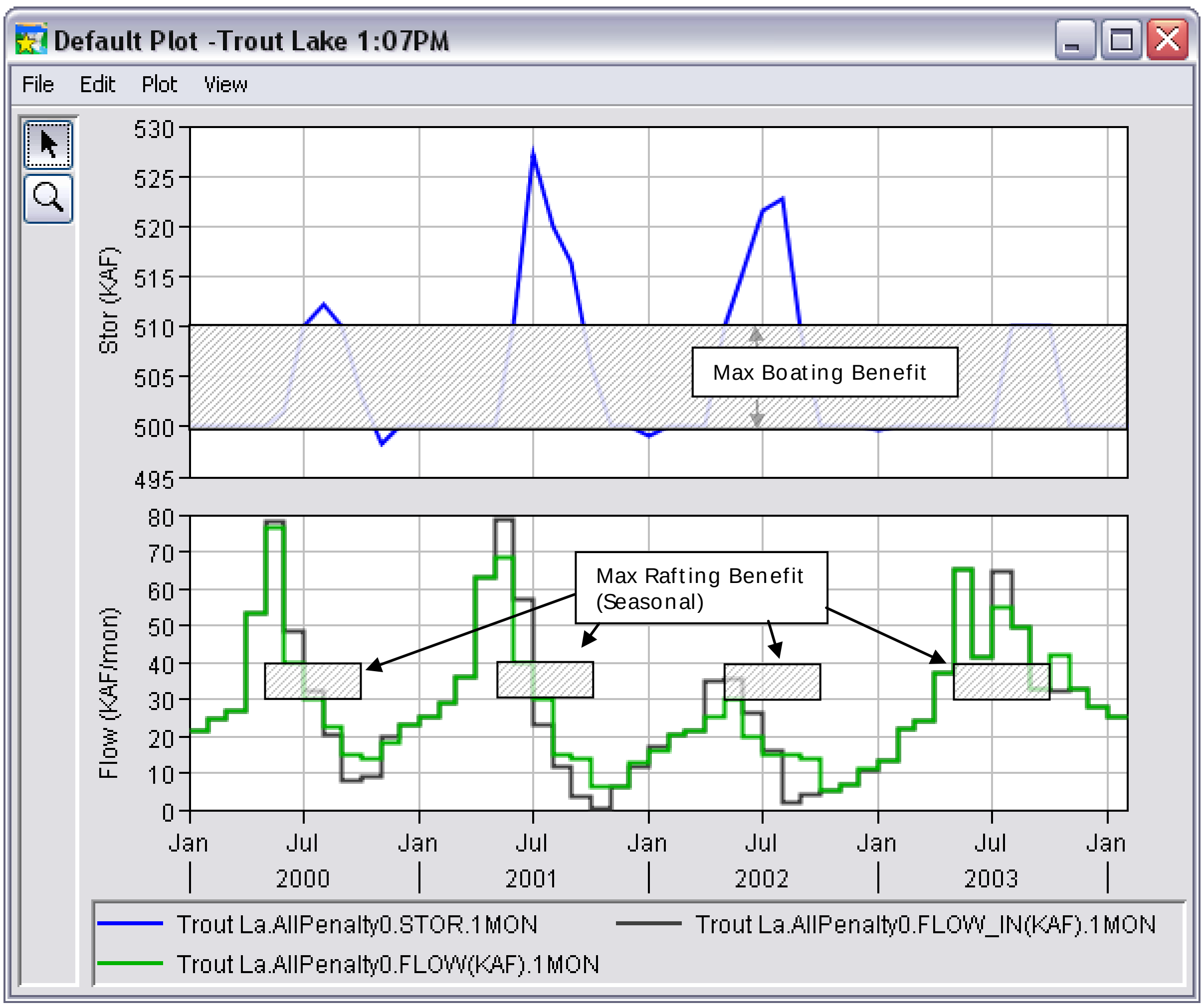


Figure 51: Most of the time Trout Lake storage levels remain in the best range for boating, but the best rafting levels are met less often.

Penalty plots can confirm your analysis of the storage and flow plots. Right-click on "Trout Lake" reservoir again, and select **Plot Penalties** -> **Penalty Sets…**. By default, the active PenaltySets for this alternative will be checked. These are the penalties that determined the optimal flows and storages. If you would like to see what kind of penalties other PenaltySets would accrue for these flows and storages, you can select those PenaltySets. However, keep in mind that PenaltySets that were not active during the run (not part of the active Composites), were not considered in the optimal results. The PenaltySet Plot, shown in Figure 52, confirms that no flood penalties were accrued for storage or reservoir release, and that boating benefits (negative penalties) were not always maximized, while rafting benefits were often not maximized.

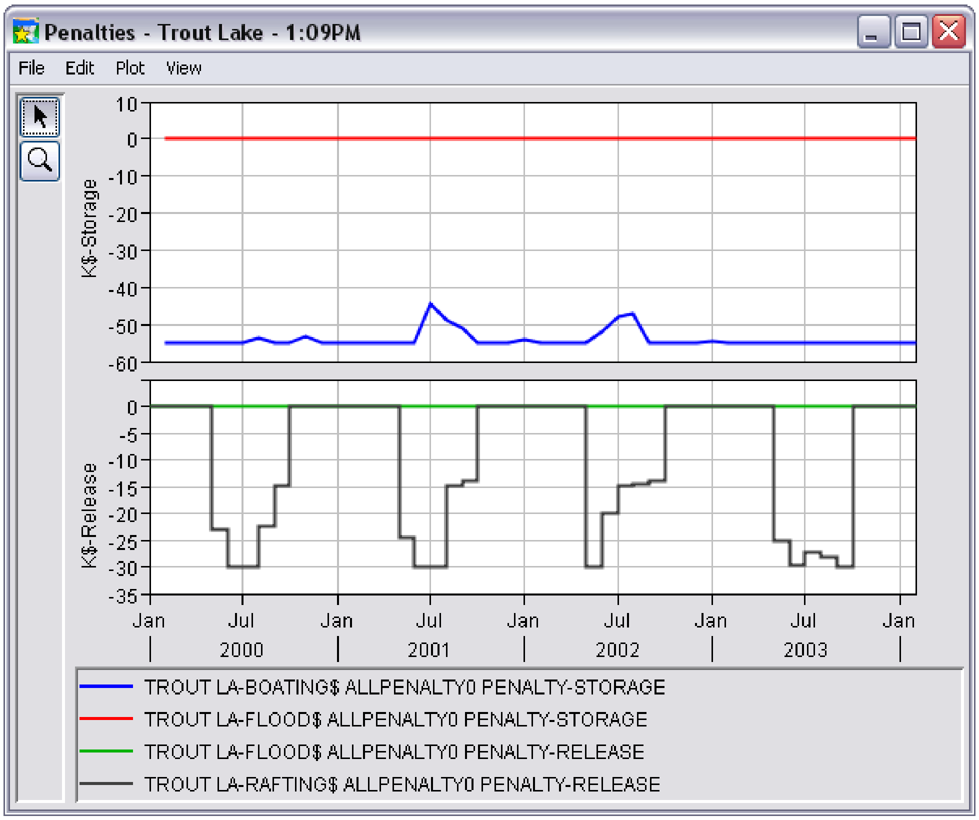


Figure 52: No flood penalties are incurred, but rafting and boating do not always reach the maximum benefits of $55,000 and $30,000, respectively.

Next, take a look at the lower reach of the Blue River, where the water quality objective takes effect. Plot the default results plot on the reach as in Figure 53. There are two occasions on which the flows drop below the minimum level. Take a look at the penalties incurred by plotting the PenaltySet on this reach. Since the penalty functions are the actual dollar value, you can compute the total water quality fines paid by the Water Authority over the four-year period by adding the monthly penalties. Select Tabulate from the File menu of the plot (Figure 54). Copy the list of monthly penalties and add them in a spreadsheet program. Total fines in four years are $54,167.

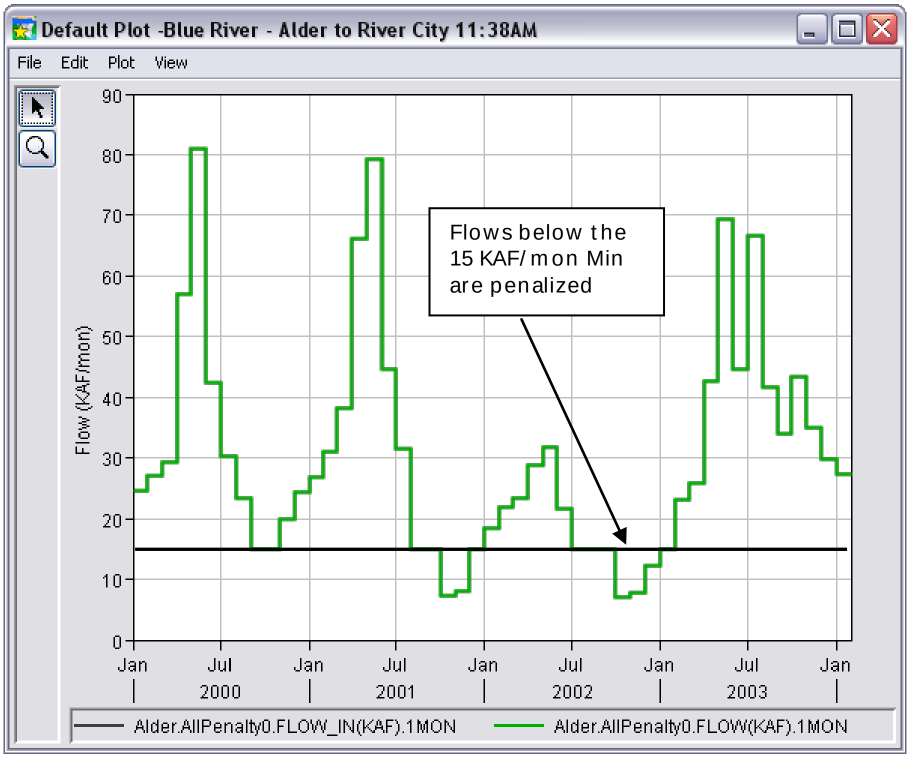


Figure 53: Flow on the "Blue River – Alder to River City" reach drops below the water quality minimum of 15 KAF/month twice.

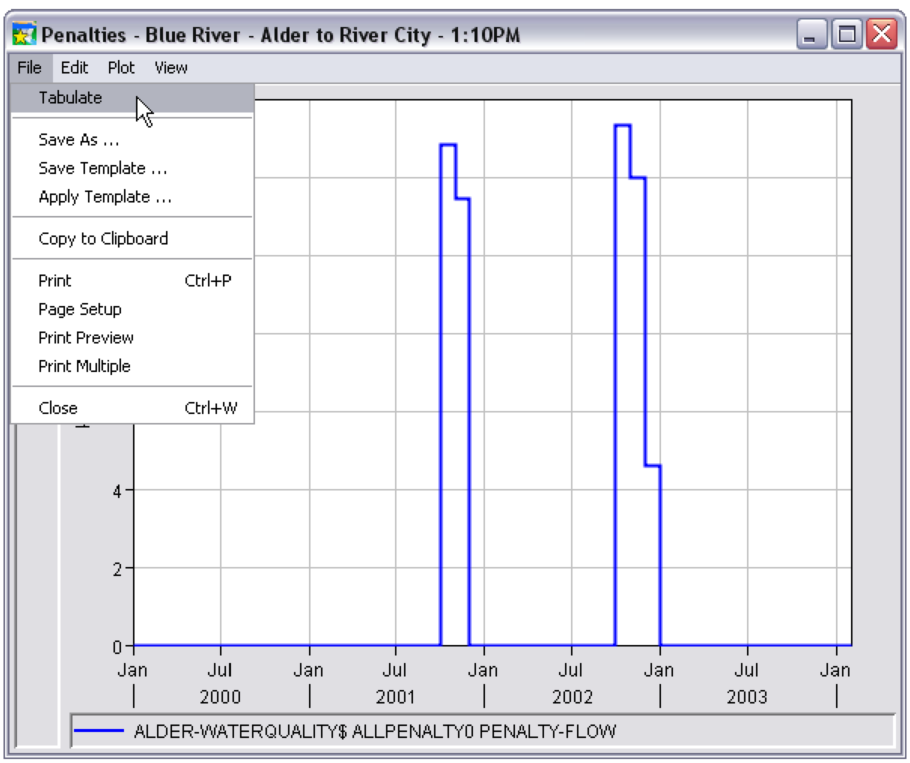


Figure 54: Penalty results can be quickly tabulated using the menu option.

5.2 Managing Optimization Data

The **Optimization Control Panel** located on the right hand side of the Optimization Module allows for managing different Alternatives and their results. You can choose which Alternative(s) to visualize by checking the box(es) next to the Alternative name(s). If the intention is to run an Alternative, or to make temporary changes to its Network, the Alternative must be active. To activate an Alternative, right-click on the Alternative name and select **Set As Active**.

Remember that in the HEC-ResPRM file system, each Alternative added to an Optimization consists of a copy of its Network file and a copy of its Alternative data. The original Alternative and Network files are saved in a base directory, with all Network Module files, and the Optimization Module copies are saved in the individual Optimization directory. If the Optimization contains more than one Alternative based on the same Network, then there exist multiple copies of the same Network. Figure 55 shows the directory structure with an Optimization directory open.

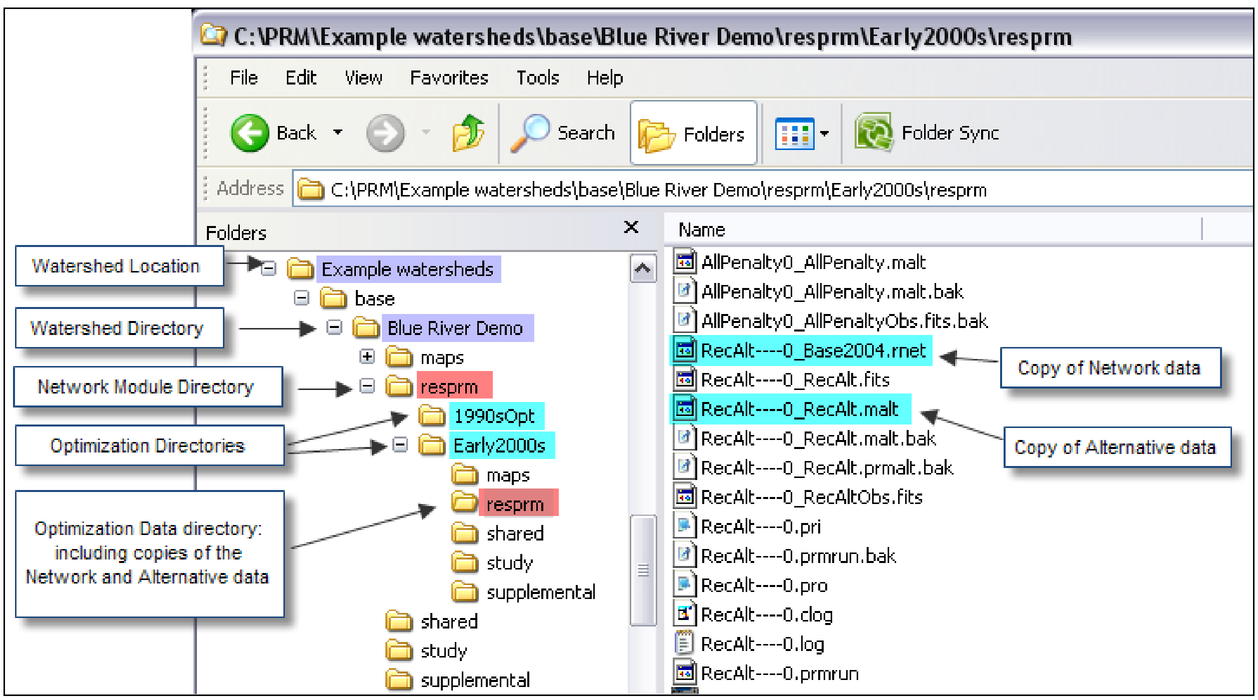


Figure 55: The watershed directory structure has one HEC-ResPRM directory for storing Network Module data files. Subdirectories in that HEC-ResPRM directory include one named for each Optimization. In these Optimization subdirectories are HEC-ResPRM subdirectories, which include copies of all Network and Alternative data in addition to Optimization-specific data.

Generally, any changes you wish to make to your Alternative or its Network should be done on the base copy, in the Network Module. Sometimes, however, you may wish to test a quick change and run the optimization immediately, without going back to the Network Module and then synching your changes with your Optimization. For these situations, the Optimization Module permits some temporary changes to any Alternative and its Network. This allows you to test the effects of minor changes by making them in the *Optimization's copy of the Alternative/Network*, while maintaining an unchanged base directory version (in the Network Module). Once you are finished testing, however, it is important to synch your Optimization with the base directory, so that the Optimization copy and the original version (in the Network Module) are the same. You may choose to save your changes or revert back to the original version of the Alternative/Network.

There are two main operations involved in managing Alternative/Network data in the Optimization Module. If you have made changes to your Alternative's settings or its Network in the Optimization Module, you can either save your changed version to the base directory or you can replace the edited version with the original from the base directory. It is helpful to think of the Network Module files as the base directory files. If you have multiple Alternatives in your Optimization, and you made Network changes that you like to one of them, the process of synching your files takes two steps. First, right click on the Alternative with the changes you want to keep and select **Save to Base Directory**. Now the Network and Alternative in the Network Module will match your Optimization version. Next, you will want to update your other Alternatives in the Optimization with the new Network data. Right-click on one of the other Alternatives in the Control Panel and select **Replace from Base Directory**. A menu will appear that will allow you select all of the Alternatives that need to be updated.

An additional issue that comes up when dealing with Optimization data, is that of keeping the input DSS files current. When you make changes to the input DSS files (on the Time-Series tab of the Alternative Editor), these changes do not affect your optimization runs until you have updated the optimization input DSS file. An input DSS file belongs to each Optimization and holds copies of all input time-series data for all Alternatives. If you have changed the source file names or paths in the Alternative Editor, update the Optimization input DSS file by selecting **Optimization → Edit** from the Optimization Module. Check the box next to "Run New Extract" and select "OK." This will bring updated DSS records into your Optimization's input DSS file.

Try working with Optimization Module management options now with the Blue River Demo Model. The Department of Environmental Quality thinks penalties for violating minimum flow laws are too lax. Legislation may be going through to support higher penalties, up to a maximum of $50,000/month. The Water Authority Board would like see what the effects could be if fines are raised.

Test this in the Optimization Module by editing the Water Quality Penalty temporarily. First change the penalty at zero flow from 25 to 50 (thousand dollars). Save your edits and then re-compute the optimization. At the higher penalty, is the minimum flow ever violated? Figure 56 shows that the flow remains at or above the minimum of 15 KAF/month. Figure 57 shows the effects that meeting water quality goals had on the other objectives.

You do not want to save the changes you have made, so right-click on the "AllPenalty" Alternative and select **Replace from Base Directory**.

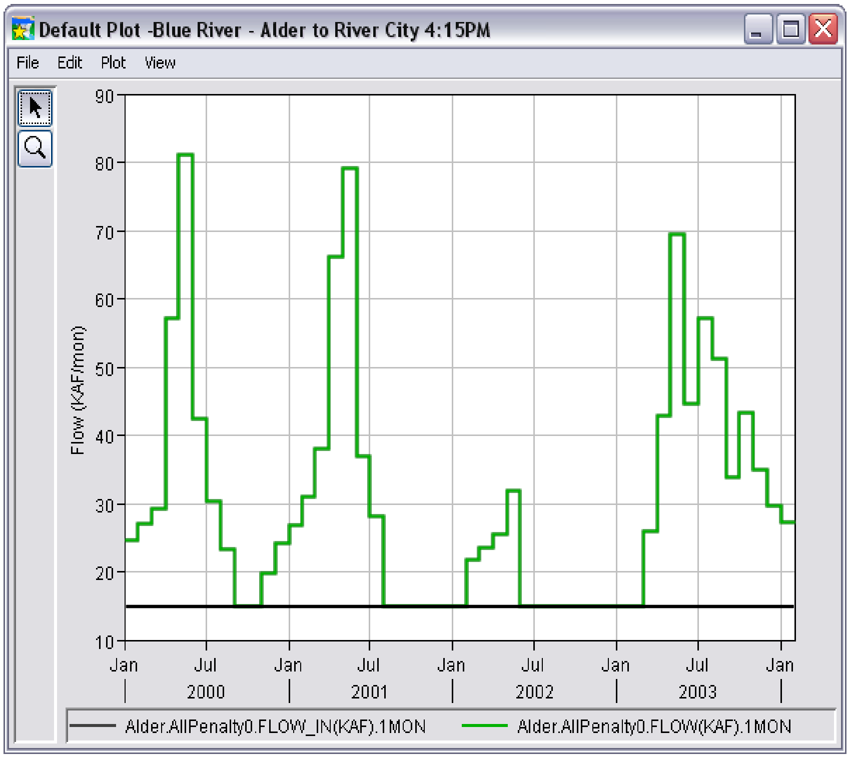


Figure 56: The minimum flow of 15 KAF/month is never violated at the higher penalty level.

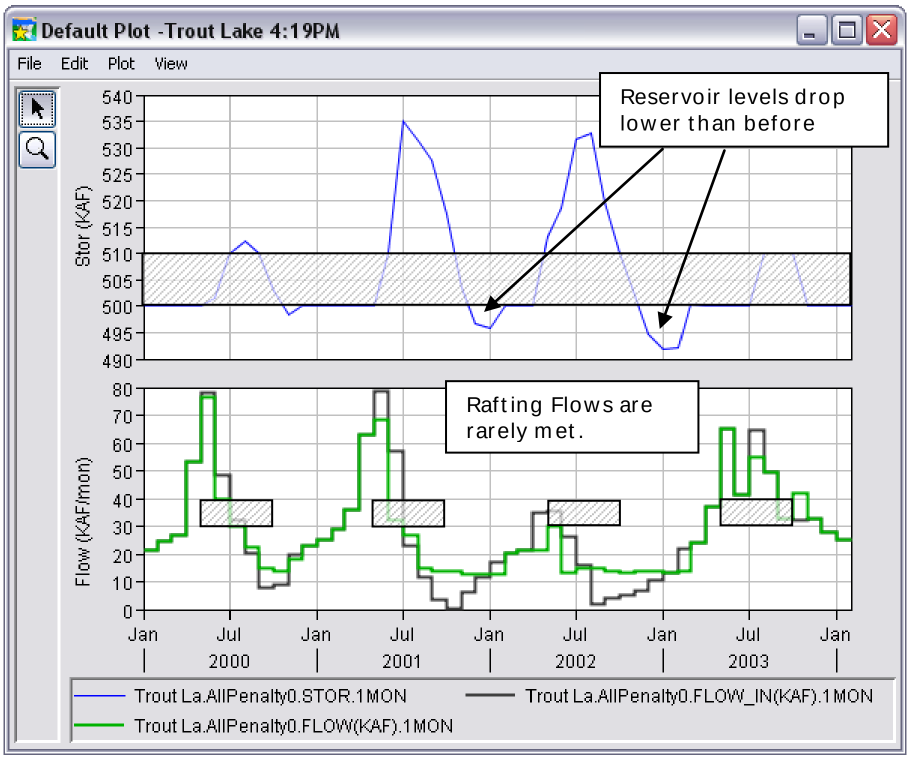


Figure 57: The plot of "Trout Lake" storage and releases show that other objectives suffer when more water is sent to meet minimum flows downstream.

Optimization Data Management Summary: Because the **Res** file system consists of a directory tree that involves copies of files in different Modules, any changes to Network or Alternative data in one Module must be kept in synch with the copies in other Module. To summarize, these options help you keep your data copies in synch:

To update Network/Alternative changes (access by right-clicking on an Alternative in the Optimization Panel):

- **Save *to* Base Directory**. When you edit data in the Optimization Module, your changes apply only to an individual Alternative/Network that is saved in your Optimization directory. Any new Optimizations (different Time Windows) you build will be based off the Network in the base directory. Therefore, if you want your changes to be available for subsequent Optimizations, you will need to *save* the data *back to* the Base directory. This will make your changes available in the Network Module.
- **Replace *from* Base Directory**. If, while editing Optimization data, you need to revert to the original Alternative data, you can *replace* the changed data in your Optimization directory with data *from* the Base directory. This will make your *original data* (from the Network Module) available in the Optimization Module, overwriting any changes you made to the selected Alternative within the Optimization Module.

To update DSS changes:

- **Extract New Data**. If you have changed an input DSS filename or path in the Alternative editor, the changes will not affect your optimization until you have updated input file for your Optimization. Do this by editing your Optimization and selecting the box next to Extract New Data.

5.3 Adding a New Project

The Blue River Water Authority is considering making some changes to the operations on Trout Lake. Population growth around Trout Lake has created more competition for available water. A nearby community, Dry Town, would like a contract for making water withdrawals to serve its expanding population. Dry Town proposes to make constant withdrawals from the river at Alder. The Authority is not certain that such a contract is feasible, particularly considering the potential threat to minimum water quality flows downstream of Alder. Once made, the contract should not be broken, because Dry Town will construct a new development, contingent on the reliability of this source of water. Water managers want to know how this will affect the other objectives on the Blue River. You will model the system with the proposed new project (diversion) to see how it affects overall operations and whether all system goals can be met. The following steps will be taken:

1. Add a New Project in the Network Module.
2. Add Penalties and Create a New Alternative.
3. Run the Optimization and Analyze Results.

1. Add a New Project in the Network Module.

Now you are going to add a new project (in this case, a diversion) to your watershed. As you learned earlier, each HEC-ResPRM Configuration is a grouping of projects to be modeled. You can make a new Configuration in the Watershed Setup Module and add a diversion to it. Some HEC software uses Configurations to organize model runs with and without certain projects, (e.g., HEC-FIA). This would necessitate the creation of a new Network based on your new Configuration, and all the Network data would have to be populated (drawing stream reaches, adding penalties and constraints, etc.). Alternatively, if you do not need to compare with- and without-project conditions, you can simply add the new project to your current Configuration.

It is very useful to build separate Configurations for different groupings of projects when you are using several different models in a shared environment (e.g., HEC-CWMS or HEC-WAT), and your modeling team wants to have different Configurations. HEC-ResPRM, however, is typically only used in conjunction with ResSim, and for these software, multiple Configurations are not often used. A shortcut, which you will use for this project, is to add the diversion in the Network Module. This avoids the work of building a new Network, because you can simply make a copy of one you've already created, and add your new project(s) to that.

Select the Network Module using the Module Selector. Make a copy of the "Base2004" Network by using the **Save As…** option on the Network menu. Name the new Network "Div2004." Next, use the Diversion Tool  to draw a Diversion from Alder towards the yellow circle (representing the Dry Town development) on the background map, and name it "DryTownDiv."

Figure 58: Save a copy of the existing Network using the Save As… option.

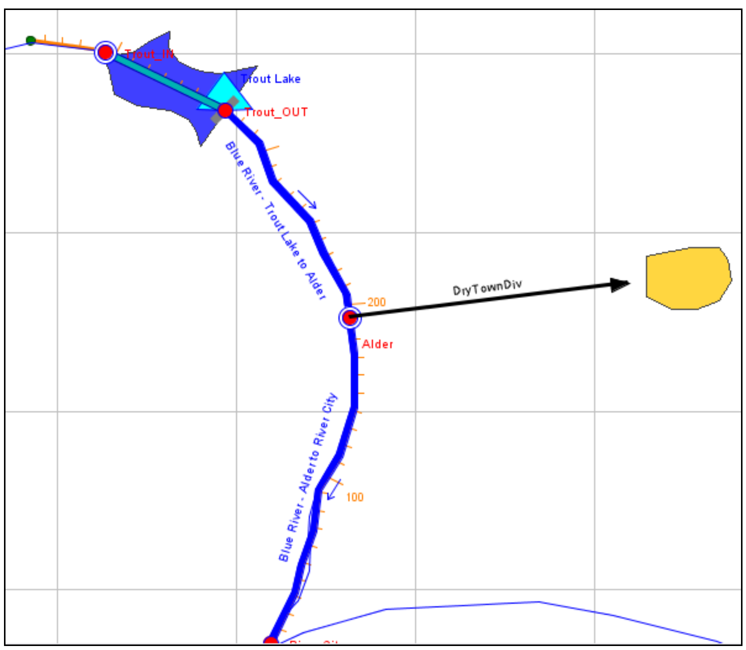


Figure 59: The new Network includes a Diversion.

2. Add Penalties and Create a New Alternative.

In the Network Module, right-click on the Diversion "DryTownDiv" and select **Edit Diversion Properties**. In the Flow Tab of the **Diversion Editor**, create a new Composite called "AllComp$" and a new PenaltySet called "DryTown$." Ideally, Dry Town would like a fixed (non-interruptible) contract for 2 KAF/month, but they are willing to pay $1000 per KAF diverted, up to 2 KAF/month. The infrastructure on the diversion cannot handle any more 2.5 KAF/month. Create the penalty function to reflect this objective (Figure 60). On the Constraints tab of the Diversion Editor, set a maximum flow of 2.5.

The Water Authority would like to see how this withdrawal will affect other objectives and whether or not $1000/KAF is a sufficient price to make a fixed contract. If the optimal results show 2 KAF/month always being delivered to Dry Town, then the Water Authority is willing to make the contract at the proposed rate. (*Obviously, in real-life such a study would be done on much more than four years of data!)* Such results would indicate that the unit price of $1000/KAF is sufficient to outweigh any conflicts the withdrawal might have with other interests in the watershed, assuming the water authority compensates these other interests accordingly.

Having updated the Network to reflect the new project and associated penalties, open the Alternative Editor to create a new Alternative. Because this Alternative will be based on a new Network, you must create a new Alternative (as opposed to using Save As). Name your new Alternative “DTDiv” for Dry Town Diversion, and be sure to select the “Div2004” Network as your base. Next populate the Alternative data: select “AllComp$” for all available Composite penalties, enter 500 KAF and initial and ending storages, and enter the same DSS input records as you used in the previous Alternatives. (*Hint: As a shortcut, you can select and copy the Time-Series fields from another Alternative and paste them into your new one*.) Save your new Alternative and go to the Optimization Module to run the model.

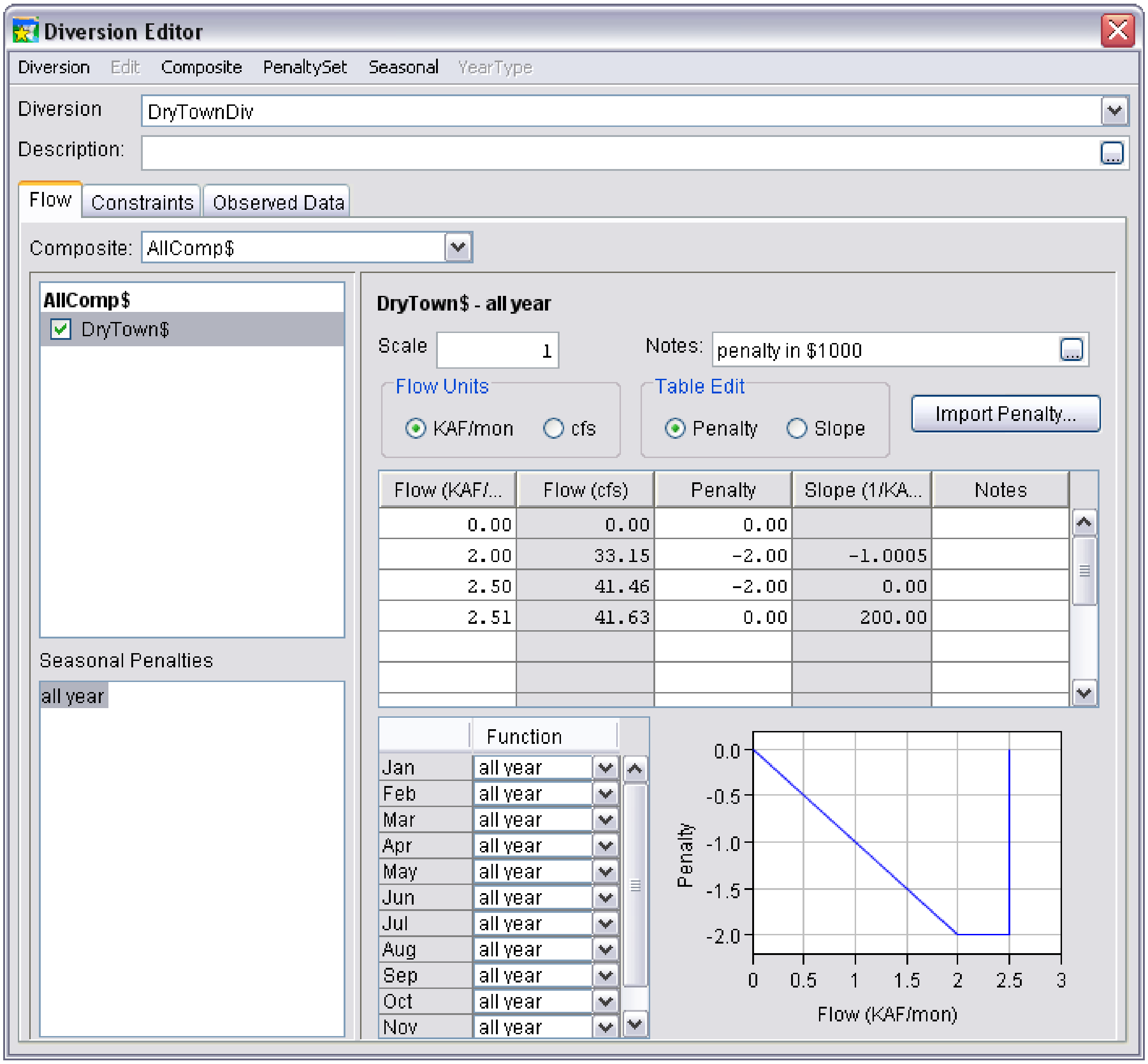


Figure 60: The "Dry Town" diversion PenaltySet shows a benefit of $1000/KAF up to 2 KAF. Beyond 2.5 KAF, the benefit rapidly decreases. Since PRM extrapolates the ends of its penalty functions, any diversion greater than 2.5 KAF will incur a penalty at a rate of $200,000/KAF.

3. Run the Optimization and Analyze Results.

Edit the "Early2000s" Optimization by right-clicking on the folder in the Optimization Control Panel. Check the box next to "DTDiv" and click "OK" to add this Alternative to your Optimization. Now make the DTDiv Alternative active and run the optimization.

Once the run is complete, make sure the only selected checkbox in the Optimization Control Panel is the one for the DTDiv Alternative, and take a look at the results. There are several occasions on which the 2 KAF/month is not met at the Dry Town diversion. These coincide with times when the minimum flows in the "Blue River -

Alder to River City" reach are not being met. This suggests that water is short at these times and comes at a higher cost. You can plot both the reach and diversion together (Figure 61) by holding the shift key while highlighting the elements in the map; clicking the right mouse button; and selecting **Plot**.

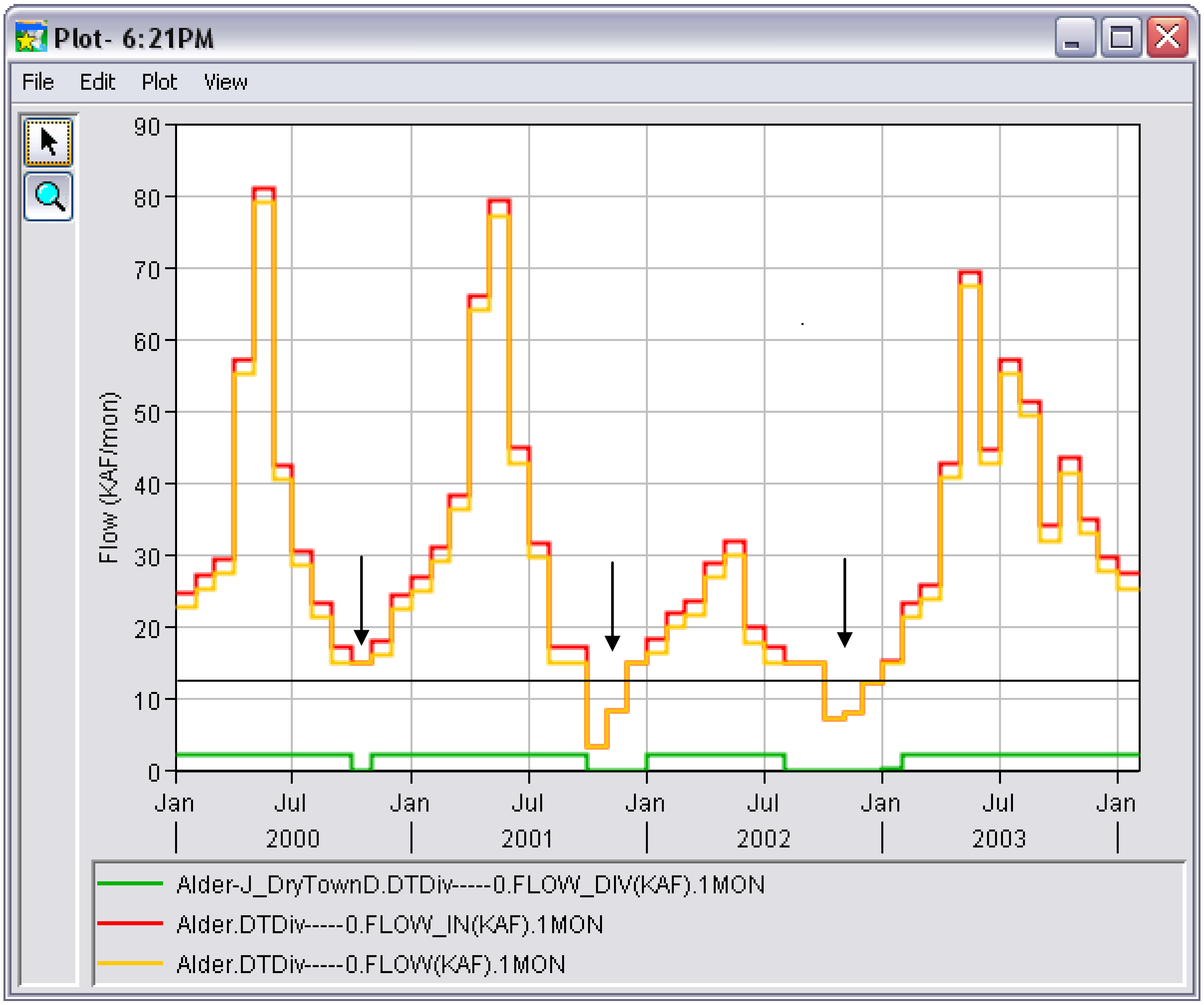


Figure 61: The green line shows the flow diverted to Dry Town. Months when the 2 KAF desired diversion were not met coincide with times when minimum in-stream flows were missed or barely met on the Blue River (yellow line).

CHAPTER 6

Trade-off Curve Analysis

One use of HEC-ResPRM is in the derivation of trade-off curves. A trade-off curve demonstrates the value of one objective in terms of another. Examining trade-off curves can be especially helpful when considering objectives that do not have the same unit of cost. For example, some environmental or social values are not easily measured in dollars. Stakeholders and water managers can more easily visualize the significance or value of such objectives by measuring their marginal cost in terms of the value (monetary or otherwise) of other objectives. In this demo, you will build a trade-off curve between all economic objectives and flows for fish. The following steps will be considered:

Establishing a Basic Trade-off Model

- Adjust Penalties
- Implement Scaling
- Create a New Alternative

Building a Trade-off Curve

- Build Penalty Groups
- Make the Trade-off Runs
- Analyze the Trade-off Curve

6.1 Establishing a Basic Trade-off Model

While you can build trade-off curves for almost any model, there are a few considerations that can make the results more useful and easier to interpret. A trade-off, by definition, is a dual-variable system, so trade-off curves are easiest to interpret when looking at only two objectives at a time. However, you can group objectives together by type and then look at the trade-off between the two groups. A trade-off graph is also easiest to analyze when penalty units translate to reality well. You can use non-monetary units, but they should be quantifiable in a way understandable to experts (e.g., miles of habitat, % achievement, navigable days are better than something more nebulous). You will now make some adjustments to the Blue River Demo model to facilitate making straight-forward trade-off curves.

1. Adjust Penalties.
2. Implement Scaling.
3. Create a New Alternative.

1. Adjust Penalties.

The Blue River Authority has been asked to manage operations to support a population of rare fish that currently lives only in the Blue River. This species does best when minimum Blue River flows are about 335 cfs with higher (about 750 cfs) flows in the late spring/early summer. To translate these interests to your model, you will build new penalty functions on both reaches of the Blue River.

Work with the “Div2004” Network. You can assume the Authority made the interruptible contract with “Dry Town,” so you do not need to change the penalty functions there. Open the Reach Editor for “Blue River – Alder to River City” and add a new PenaltySet to reflect the desired flows for fish. Name the PenaltySet “Fish” and using the Seasonal menu, rename the “all year” season to “Normal Conditions.” (By using the Rename option, your new season will automatically apply to every month of the year.) Add another season called “Wet Season” and apply it to April, May and June. (See Figure 62 for an example.)

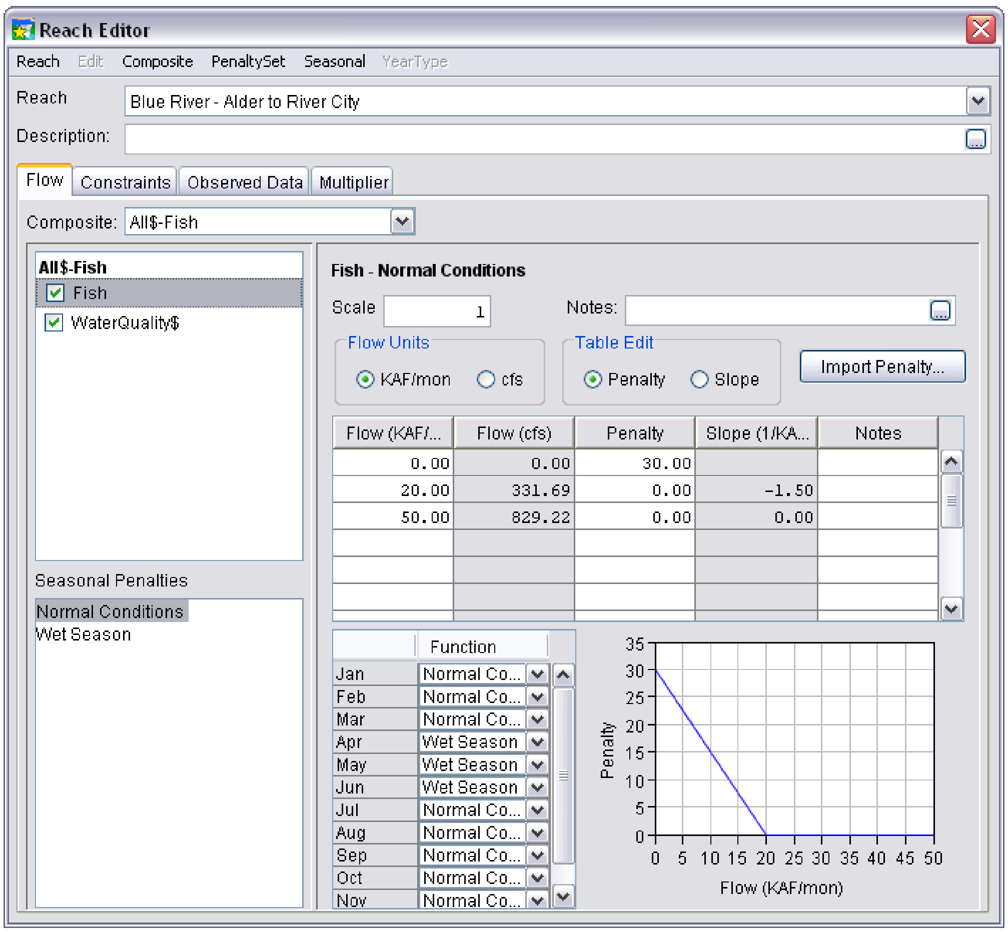


Figure 62: The PenaltySet that represents the fish objective has two seasons; the “Normal Conditions” penalty function is visible above.

The penalties for each season will be in units of days the minimum flow is not met. This is roughly approximated by assigning a penalty of 30 (days per month) to a flow of 0, and assigning a penalty of 0 to the goal flow. One additional point, at any flow higher than the goal flow, should be added and set to a penalty of 0 in order to be sure that extrapolation occurs correctly. (This creates a unit penalty of 0 for all flows above the target amount.) The 335 cfs and 750 cfs minimum flows are approximated as 20 KAF and 45 KAF, respectively. Add the PenaltySets accordingly.

Next, create a new Composite penalty function named “All$-Fish” and add the “Fish” and “WaterQuality$” PenaltySets. Complete the same steps to model the fish objective on the “Blue River – Trout Lake to Alder” branch as well. Again, note that since there is no inflow between the reservoir and “Alder,” penalties to flow on the “Blue River – Trout Lake to Alder” act the same as penalties to “Trout Lake” release. In the prior examples, you added penalties on the reservoir release, but here you will add the penalties to the reach. This choice is arbitrary.

2. Implement Scaling

In HEC-ResPRM, **Scale** allows intra-objective weighting; affecting the relative influence of penalty functions (usually of a single objective type) at different locations. Scale factors can be used in a variety of situations. A few simple examples follow. If two areas of similar importance are modeled to contain significantly different numbers of similar magnitude penalty functions, the composite penalty functions for those areas will likely be undesirably unbalanced. PRM will operate the system to favor the area with the composite penalty function of the highest magnitude. Scale is used in this case to balance the effect of disparate numbers of penalty functions between regions. Suppose two river reaches are equally important, but an erosion study relating flow to erosion has resulted in one data point on the first branch and three data points on the second. Penalty functions based on this study can be added to the model – one penalty function for the first reach and three for the second. If the scale of the latter group is set to 1/3, then PRM will treat both areas as equals. This scaling allows a more objective comparison between the branches.

You will now use scaling in the Demo model to reflect the relative species populations in the two stream reaches. Only 1/4 of the fish population of “Blue River” live in the reach from “Trout Lake” to “Alder.” The other 3/4 live in the reach from Alder to River City. Therefore, you should make the penalties reflect the relative importance of the two reaches. Take the total fish penalty, and apply 1/4 of it on the upper reach and 3/4 of it to the lower reach. Add a Scale of 0.5 to the Fish PenaltySet on the “Blue River – Trout Lake to Alder” reach. Add a Scale of 1.5 to the “Blue River – Alder to River City” reach. Since the scale applies to the whole PenaltySet, you do not need to set it for each season. You will be able to see the effects of the scale on your Composite penalty.

Figure 63 shows that when a specific PenaltySet is selected (here Fish) a scale factor can be input (but not a weight). Because Scale is assigned at the PenaltySet level, all Composites are affected by the Scale factor of a particular PenaltySet. Weights are different; they are assigned at the Composite level. A single PenaltySet in different Composites can have different weights but not different scale factors. You will learn about using Weights in the next section.

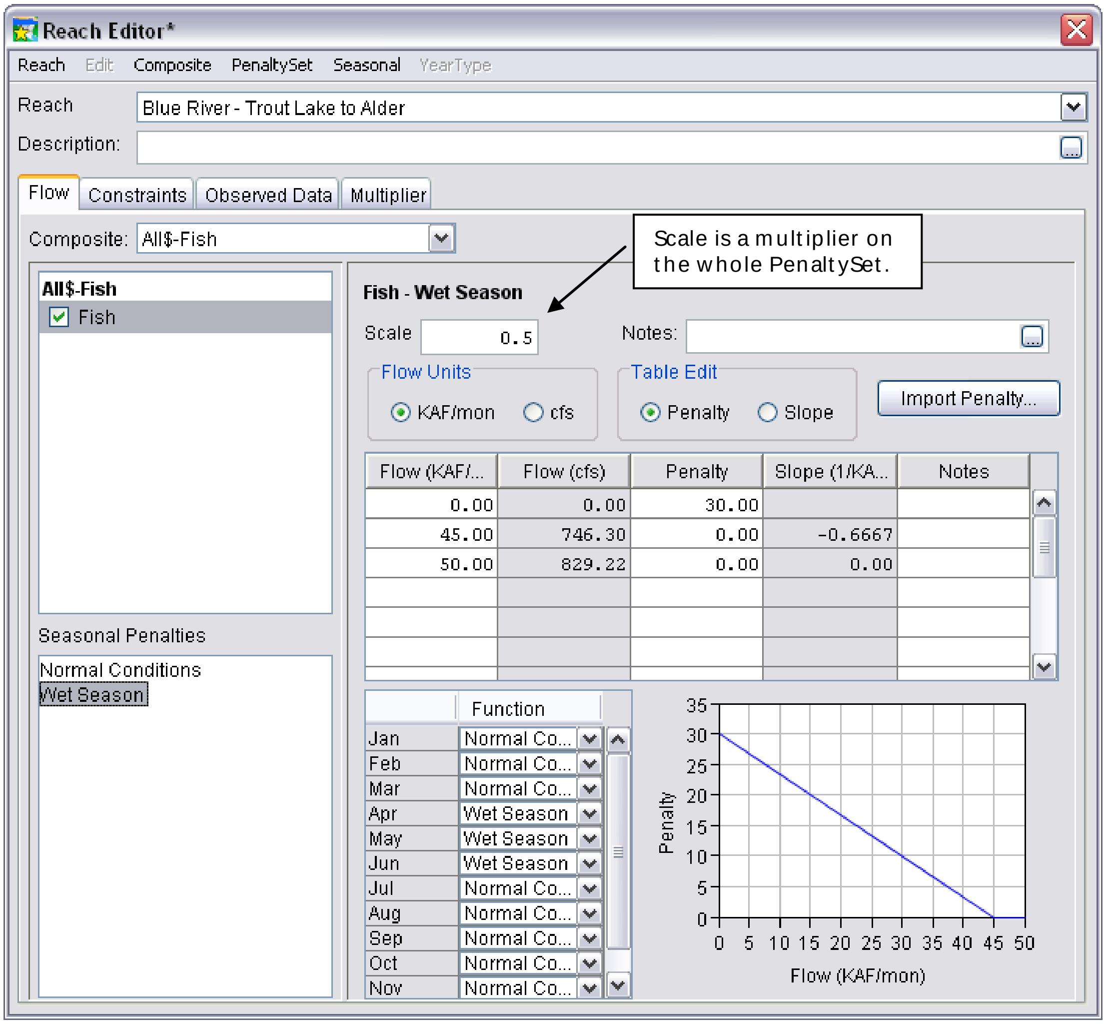


Figure 63: A Scale of 0.5 is applied to the fish PenaltySet at "Blue River – Trout Lake to Alder."

Scale and Weight: The impact of a PenaltySet on the objective function (overall optimization problem) can be adjusted in two ways. One is weighting, the other is scaling. Each approach has the same effect on the objective function (acts as a coefficient multiplier on the unit cost), but each is used for a different modeling technique. **Scale** is used to adjust the relative importance of PenaltySets, typically of the same type, while **Weight** is used to build trade-off curves and is assigned separately to different Composites. The Penalty reports show total penalties *including* Scale, but *without* the effect of Weight. Both are optional and independent of each other.

3. Create a New Alternative.

Open the Alternative Editor and save the "DTDiv" Alternative as "All-Fish." This Alternative will be used to make trade-off runs between all economic penalties and the fish penalty, and is named accordingly. You will use the "AllComp$" Composites for "Trout Lake" storage and release and the "DryTownDiv" flow. For each reach of the "Blue River," select the "All$-Fish" Composite.

6.2 Building a Trade-off Curve

The method for developing a trade-off curve using HEC-ResPRM is to change the relative weights (or importance) of the objectives, make a run, calculate the (unweighted) penalties incurred for each objective, and then repeat the process. Weights change the relative influence of each objective (represented by penalty functions) on optimal results; they involve inter-objective trade-offs. In this example, you will build a trade-off curve between all economic objectives and the fish flow objective. The following steps will be taken:

1. Build Penalty Groups.
2. Make the Trade-off Runs.
3. Analyze the Trade-off Curve.

1. Build Penalty Groups.

To build trade-off curves, it is useful to be able to quickly assign weights to a group of several PenaltySets at once. This is done with the **Penalty Manager** (Figure 64), accessible from the Edit Menu of the Network or Optimization Module. The Penalty Manager has two tabs, the Grouped tab for creating and editing PenaltySet groups, and the Sorted tab for viewing all weights, sortable by element, parameter, Composite, PenaltySet or Weight.

To build a trade-off between economic interests and the fish interest, build a **Penalty Group** for each. In the Network Module, open the Penalty Manager and select **Add…** from the **Group** menu. Name the new group "All$," and add all the economic PenaltySets that are being used for this Alternative. That includes all PenaltySets that are members of the "AllComp$" Composite for "Trout Lake" storage and release, "DryTownDiv" flow, and the "WaterQuality$" PenaltySet belonging to the "All$-Fish" Composite on the "Blue River." (Remember, it was the "All$-Fish" Composite, rather than the "AllComp" Composite that was used on the "Blue River – Alder to River City" flow.) It can be useful to sort the PenaltySets by Composite or PenaltySet; click on column headers to do so. To start, set a weight of 1 to your Group. That will not change their effect on the objective function.

Next, make a Penalty Group for the fish objective. Call the Group "Fish" and add the "Fish" PenaltySets belonging to the "All$-Fish" Composites on both reaches of the "Blue River."

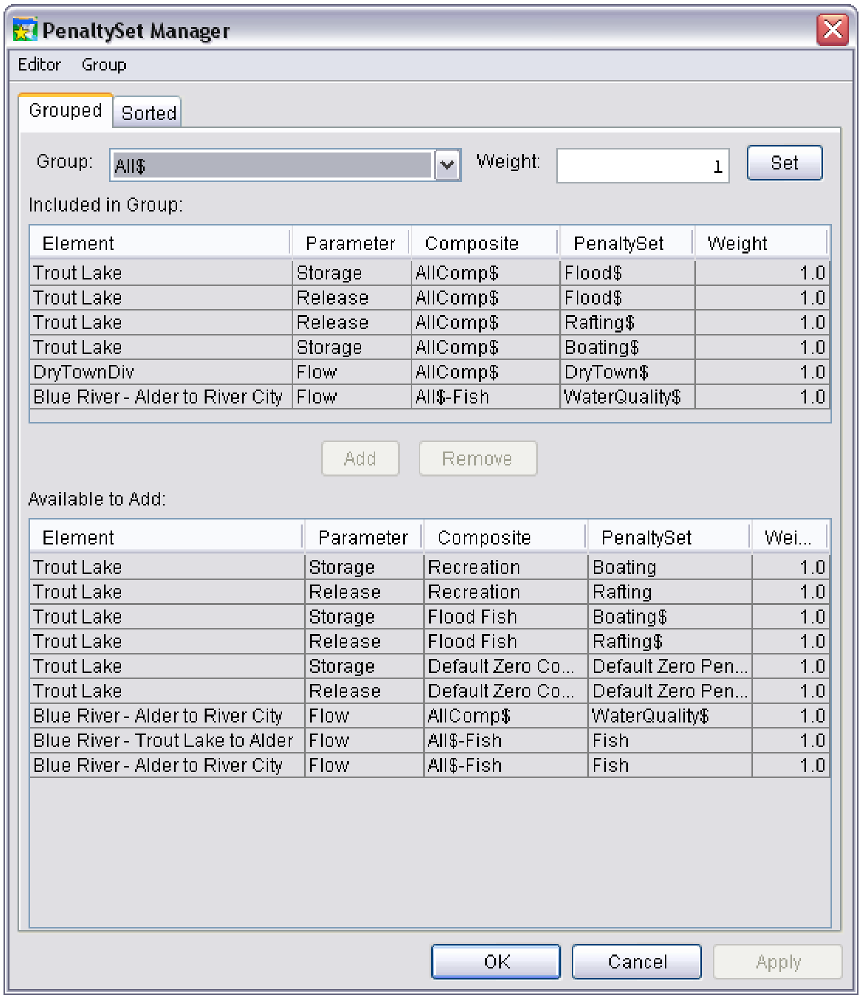


Figure 64: Here, the Grouped tab of the PenaltySet Manager shows a Group called "All$" with the weight set at 1.0.

2. Make the Trade-off Runs.

Having set up Penalty Groups, you can now progress to the Optimization Module to make your model runs. (Be sure to save the Network first.) In the Optimization Module, add the new Alternative, "All-Fish," and compute it.

Use the **Penalty Report** feature to get the total cumulative penalty for each group you established in the PenaltySet Manager. Be sure that only the "All-Fish" Alternative is checked, then select Penalty Report under the Reports menu. The Groups tab shows **Total Penalties** for each Group. These are the actual cost (based on the penalties) of the flows generated in the run. In other words, the weights are not considered when these penalties are calculated. However, PRM used the weighted penalties when it calculated the optimal solution. Then, the optimal solution (flows and storages) was used to calculate penalty based on the unweighted penalty functions.

The other tab of the Penalty Report, entitled "PenaltySets," contains the cumulative penalties incurred by all PenaltySets (not summed by group). At least one group must have been established (in the PenaltySet Manager) for the Penalty Report to be available.

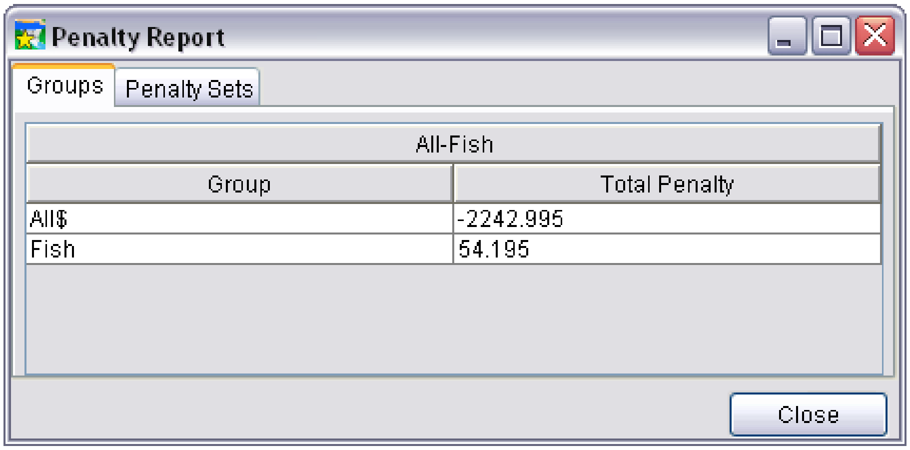


Figure 65: The Penalty Report shows the Total Penalties for each Group. Here, the Weights used were 1.0 on "Fish" and 0.1 on "All$."

Since you created your Penalty Groups with weights of 1, the first run is essentially an unweighted run. Next you will want to make runs with different weights (or importance) on the objectives. Using the Penalty Manager (accessible in the Optimization Module), adjust the weights one at a time to change their relative influence on the objective function. Armed with the PenaltySet Manager (to set weights in an efficient manner) and the Penalty Report (to read the total penalty incurred by a group of PenaltySets) you can quickly generate a trade-off curve. Each set of weights (and associated total cumulative penalty) produces one point on the trade-off curve. You currently have a single point on trade-off curve, with both weights equal to 1. Weights of 0 and 1 can be used to generate the extreme points of the trade-off curve (i.e., set the weights on Fish = 0 and All$ = 1 to generate one end of the curve; vice-versa for the other end of the curve). Table 8 shows a list of weights that were used to create a trade-off curve and their associated penalties.

Table 8: These weights were used to establish the economic objectives vs. fish objectives curves, and each objective resulted in the shown penalties.

Weights		Penalties	
Fish	**All$**	**Fish**	**All$**
1	0	0.00	-1007
1	0.1	10.84	-2243
1	0.25	23.28	-2704
1	0.5	39.59	-2934
1	0.75	53.63	-3053
1	1	57.20	-3071
0.75	1	62.50	-3095
0.5	1	68.06	-3113
0.25	1	79.16	-3134
0	1	88.27	-3141

3. Analyze the Trade-off Curve.

Figure 66 shows the trade-off curve for economic vs. fish objectives, generated by optimizing ten different pairs of weights. The trade-off, or cost to one objective of an improvement to the other, is the slope at any point along the curve. The end points show the minimum possible cost to each of the objective groups (produced by setting the Weight on the other group to 0). For typical trade-off curves, those endpoints are associated with a very high cost to the other objective.

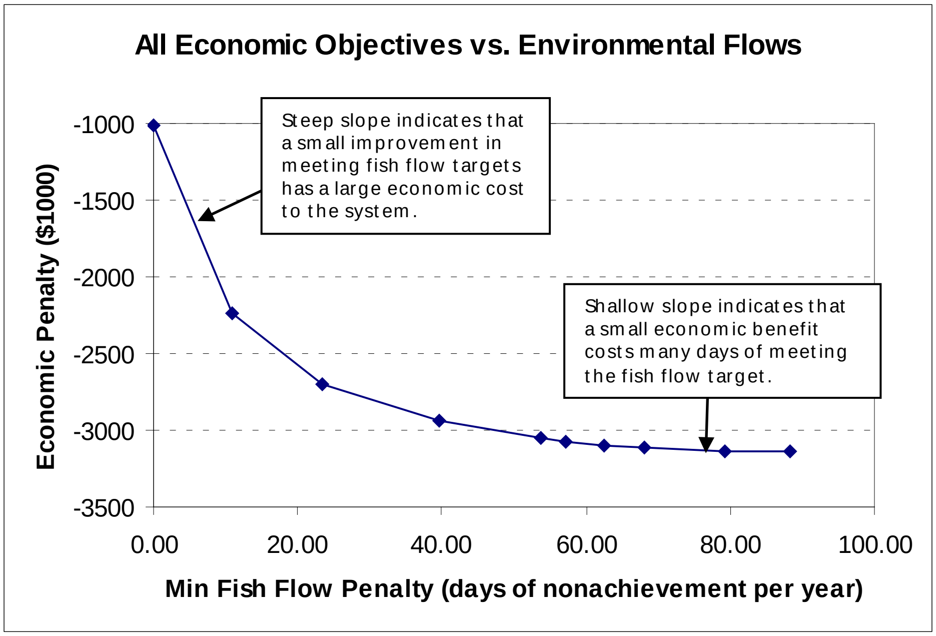


Figure 66: Trade-off curve between Recreation and Navigation objectives in the Demo problem. This was generated by evaluating ten different pairs of weights.

The trade-off curve is a very useful tool for understanding the relationships between various system objectives. This is a major step in the analysis and may be an end in itself. The trade-off curve can be used to demonstrate objectives' costs in a very visual way. It can be used to compare objectives that share units such as dollars, but it is especially helpful when evaluating objectives that are not tied to an economic value. After developing trade-off curves for your model, you may have stakeholders and policy makers select ideal points on the trade-off curves – points that best reflect the joint interests and values (economic, political, social, etc.) of the system. Then, using the weights implied by the chosen points, the optimization model is run one last time, and model results are analyzed to derive operating rules that reflect the chosen trade-off.

CHAPTER 7

Conclusions

HEC-ResPRM is a reservoir system operations optimization model developed to assist reservoir operators with decision-making by demonstrating the optimal possibilities for reservoir management in a system. HEC-ResPRM can be used in conjunction with ResSim, or alone, to improve and analyze reservoir operations. As an optimization model, HEC-ResPRM offers an idea of the best outcome that can be expected for the system or any particular operating strategy.

This Quick Start Guide is designed to demonstrate the process used to create a reservoir optimization model using HEC-ResPRM and to highlight some features of the software. Additional features of the software will be explained in future documentation, including a User's Manual.

7.1 Model Verification and Results Application

Once a model has been set up and run, it should be calibrated to fine-tune the network, penalty functions, and other features. Sensitivity analysis can be performed by adjusting the demands, turning on and off constraints, changing the shape or magnitude of the penalty curves, or changing initial and ending reservoir levels. Calibration can consist of repeated runs, which provide successive improvement of the model.

The model verification begins with the basic model. The results can be reviewed to determine where changes in the model might be desirable. The user should identify the locations and times that penalties occur and then determine why they occurred and where the trade-offs were. If these penalties are not realistic, some of the penalty functions need to be adjusted in order to deter these kinds of infringements. Whether the behavior is reasonable should be determined at all reservoirs, nodes, and other locations. Then, constraints can be adjusted as needed.

After the model has been fine-tuned, tests can be run on the performance under various inflow conditions. For example, a series of wet years could be run to see how the optimal results differ from average conditions. To cover a wider range of possible conditions, synthetic streamflow time-series can be constructed using the statistical information provided by the available historical record. Such an investigation could result in a recommendation for refined operations during wet years.

Operational guidelines can be inferred using the results of runs for different time-series. Then the rules can be tested in ResSim, or HEC-ResPRM can test rules by making them constraints rather than penalty curves to encourage the desired behavior. Regression Analysis can be used with various data sets to derive rule systems or more information for rule development and improvement. For example, the relationship between individual reservoir storage versus total reservoir storage can help to determine which reservoirs are more optimally used for storage and which should be drawn down first under demand.

7.2 Caveats

A large part of the work involved with HEC-ResPRM actually occurs before and after building the model. Development of penalty curves and results interpretation are important and should not be overlooked, as they are a major part of the study effort.

Certain phenomena cannot be captured by this model. Short floods, for example, are easily missed with the monthly time step. This fact must be considered when analyzing results. There are ways to examine short-duration floods, such as those that would occur due to rainstorms. The approach would use the statistical analysis to determine the magnitude and frequency of daily peaks that are associated with certain magnitude monthly flows. Then penalties associated with monthly flows can be increased accordingly. Most likely, some other model or combination of models would be more appropriate for situations where short-term flooding is a significant consideration.

An obstacle encountered in network flow modeling is the problem of non-convexity. When non-convex penalty functions are added to the model, the solver cannot ensure a global optimum. The HEC-ResPRM solver uses an approach called Restricted Basis Entry to enable it to selectively choose which variables can enter the basis, allowing it to solve non-convex problems. However, a global optimum is not guaranteed. Users can improve the chances of reaching a global optimum by attempting several runs for the same alternative using different starting solutions. (See HEC-PRM manual for discussion of starting solutions.) Another approach is to simplify the system representation to the extent that all penalty functions used are convex. While this is not as accurate, it may at times be more useful to have a model of a simplified system that can be easily run. In optimization modeling there is always a tradeoff between the degree to which a system must be simplified to easily model it and the loss of accuracy caused by adjustments to the solver in order to solve more complex problems.

7.3 Future HEC-ResPRM Development

HEC-ResPRM is still a relatively young software tool. New features are being actively developed and existing features improved. Everything covered in this document and all features active in the software have been tested extensively, but undetected problems may still surface. If a bug or suspect behavior is noted, please refer to HEC's website (www.hec.usace.army.mil/software/HEC-ResPRM/BugReport/) for guidance on how to report bugs.

Features being investigated for future versions of HEC-ResPRM include the following: channel routing and other types of solvers, including Mixed Integer Programming, which will allow more flexible models with the use of side-constraints.

CHAPTER 8

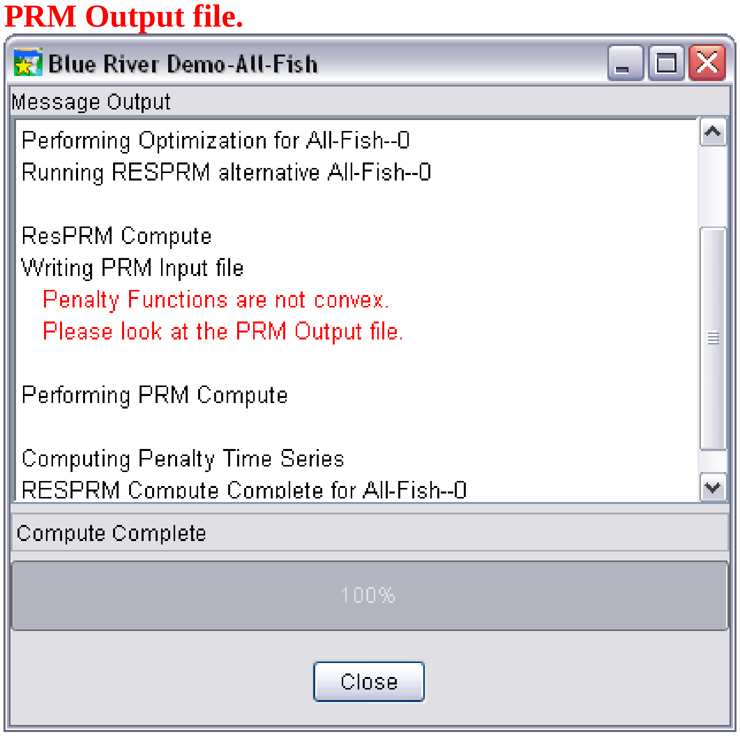
Troubleshooting Help

Below are some common questions and pitfalls that the new HEC-ResPRM user may encounter.

I made changes to my Network (Penalty functions, Weights, etc.) or DSS Time-Series, but my optimization results are the same. Why?
Once changes have been made in the Network Module, they must be synched with the copy of the Network that exists in the Optimization you are running. This is accomplished in the Optimization Module with a "Replace from Base" for general Network changes. See Section 5.2.

If you have made changes to the DSS records or path, you must update the Optimization DSS time-series. This is accomplished with "Extract New Data" in the Optimization Editor. See Section 5.2.

My model won't run. I get the error: Penalty Functions are not convex. Please look at the PRM Output file.



Your penalty functions are not convex. See Section 3.3.

Restricted Basis Entry is an option that can be used to solve models that must use non-convex penalty functions. Access this option in the Alternative Editor, on the Compute Options tab. Under the Solution Algorithm section, select 1 for “Whether or not Restricted Basis Entry is Used.”

My model won’t run. I get the error: The solution is infeasible.
This error suggests that there is either too much or too little water to meet the constraints of the model at some point in the run. Possible causes of an infeasibility include constraints that are too restrictive and inadequate/excessive inflows, withdrawals, or starting/ending conditions. Check the upper and lower bounds on reservoirs (release and storage) and reaches. Make sure the time-series data is realistic. If you are using evaporation, check the coefficient. Try changing the starting and ending conditions.

In the Watershed Setup, I can’t make changes to my Configuration. Why?
Is the lock turned on for editing?  The lock indicates that you have locked the Configuration to be edited by you alone. This concept is used in other HEC software that are edited by multiple users in a network environment. Since HEC-ResPRM is not network software, the concept is not meaningful to this program. However, because the Watershed Setup Module is shared among different HEC software, its application still applies in HEC-ResPRM. See Section 4.2, Step 4.

Why do I have to choose a Time Zone?
See Section 4.2.

I selected an hourly time step when I made my Configuration. Why does the Optimization Module run on a monthly basis?
The Configuration time step is only used for networked HEC software. It does not apply to HEC-ResPRM, but since the Watershed Setup interface is shared with other software, HEC-ResPRM users must still select a time step.

I can’t add anything to my Network. Why?
Do you have a Network open? If not, you need to either create one or open an existing Network.

I can’t create a new Watershed. Why?
You must be in the Watershed Module and have a Watershed Location (directory) named. See Section 4.2.

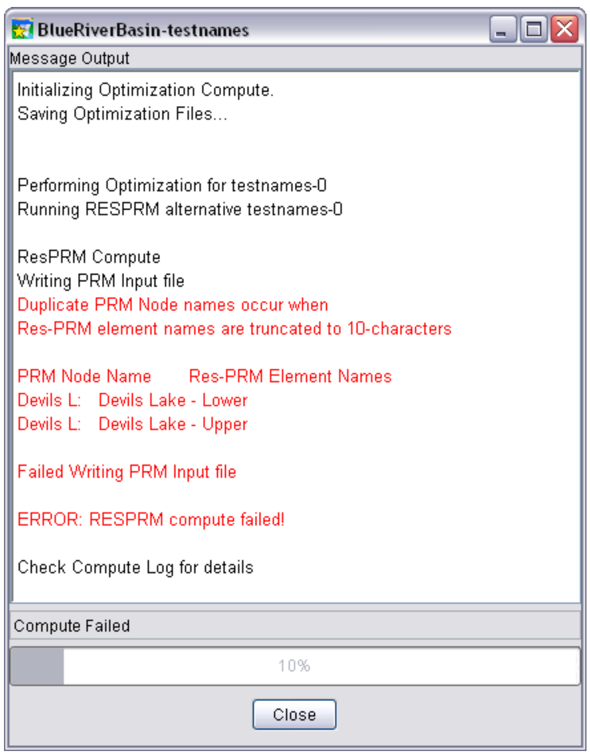
I can add reservoirs and diversions in the Network Module. I thought this step was part of the Watershed Setup Module. What’s the point?

Good question! The user has the flexibility to make project changes in either the Watershed Setup Module (Configurations) or the Network Module (Networks). There are advantages and disadvantages of either tack, but it is important to choose one and be consistent in its application.

If you are modeling with and without project conditions you can set up two different Configurations in the Watershed Setup. For each Configuration, you can create one or more Networks. Alternatively, you can create a basic Configuration with all shared projects, and then build a Network based on that. When you want to make a model with an added project, you can save a copy of the Network, and then edit the network to add your new project.

The latter approach has the advantage that if, at some point, you wish to change the Configuration, you can apply that change to all Networks by "Updating from Configuration". One disadvantage of having multiple Configurations, though, is that you must build each Network independently. See Section 5.3 for an example.

My optimization won't run. I get an error related to Res-PRM Element Names, similar to the one below:



What gives?
HEC-ResPRM creates input files that it feeds to the PRM engine. Elements names for PRM can be no longer than ten characters. Reservoirs that operate for hydropower can have names of only eight characters because PRM expects an "_P". So, HEC-ResPRM truncates any names longer than ten (or eight) characters. Should the truncated versions of two elements be duplicates, the optimization will not run and HEC-ResPRM will give the warning above. It is up to the user to rename the elements in the Network module and then update the simulation module (Replace from Base Directory). Output datasets that are generated by HEC-ResPRM will be saved as DSS

records with "B-parts" that correspond to the truncated names. Keep this in mind when naming your reservoirs, diversions, reaches, and junctions.

There is no Save As… menu option for Watersheds. What is the best way to copy an entire HEC-ResPRM Watershed under a new name?
If you would like to create a copy of your watershed, you should do so by copying the files directly, using a tool such as Windows Explorer. First save and close your watershed. Then go to the Watershed Location, under the base directory, where your project is stored. Copy the directory (and all subdirectories and files) that has the name of your watershed. Paste the copy of the watershed and rename it as desired. Under the new Watershed directory, rename the workspace file ({watershedname}.wksp) to match your new Watershed name. Then, edit the workspace file using a text editor and change the WorkspaceName on the first line of the file.

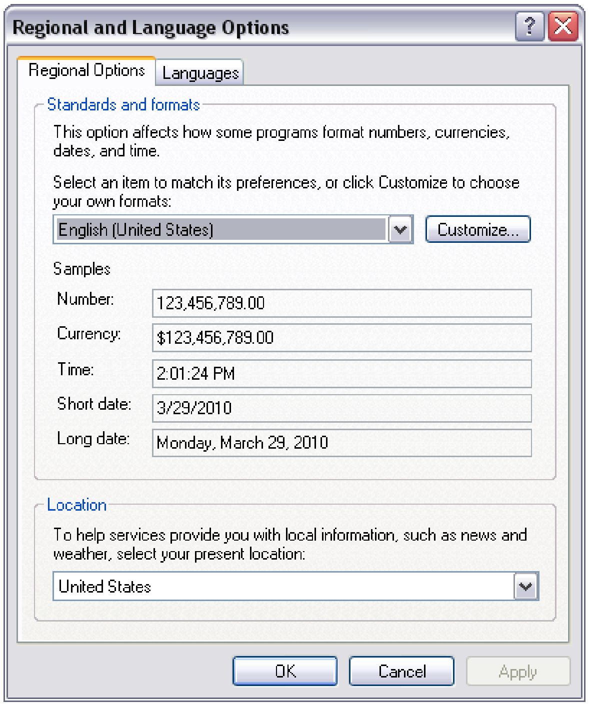
If you would like to give a copy of your watershed to someone else, you should zip the Watershed file. Be sure that all your input files are located in the proper folders (shared, or maps).

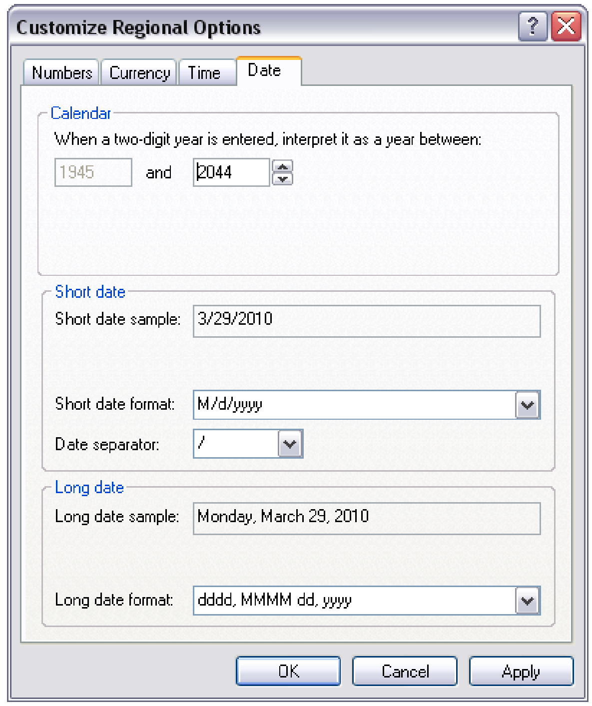
I tried to change the default stream stationing, and all my reservoirs stacked on top of each other in the map! What can I do?
It is not recommended that you change the default stream stationing. If you wish to set your own stream stationing, it is best to do so before adding project elements like reservoirs and diversions. You can recheck the default stream stationing option, but it is possible to irrevocably jumble your network this way. The best thing to do is start over if this occurs.

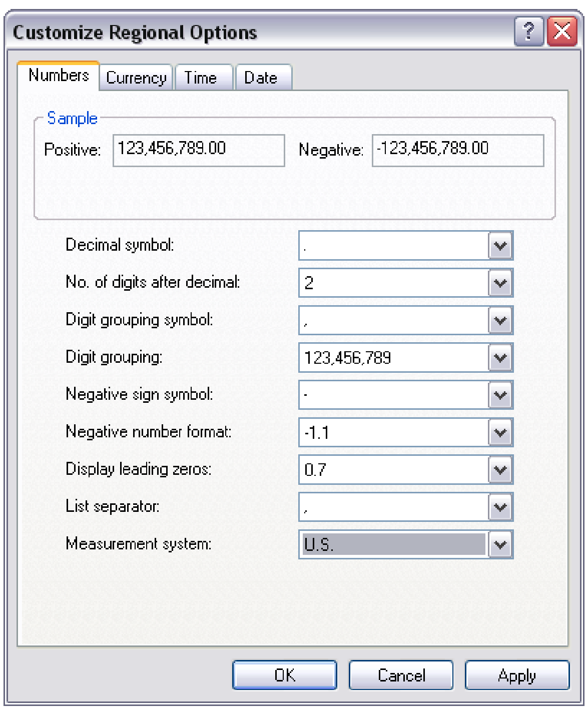
In the optimization editor, you can change the end date but not the start date. Why?
A defining aspect of the Optimization is the start date, so this is unchangeable. If you would like your optimization to start at a different date, you should make a new Optimization.

I want to enter my penalty in terms of Elevation, but the Edit Storage/Elevation radio button is grayed out. What went wrong?
PRM does its optimization calculations in terms of storage. In order to make penalty calculations using Elevation data, the program needs to have the relationship between Storage and Elevation. Go to the Elevation tab of the Reservoir Editor and fill in the Elevation-Storage-Area information. (Area information is optional, unless you are using evaporation.)

I can't select dates as expected. What's wrong?
Make sure you are running an English-language version of Windows. HEC-ResPRM will not run for other languages, though you can run HEC-PRM. In Windows, go to the Control Panel. Then select Regional and Language Options. Make sure your settings match the screens below.







What's in the *.pri and *.pro files?

Any HEC-ResPRM user should have a fundamental understanding of HEC-PRM. When running optimizations, you should be familiar with the *.pri and *.pro files. These will help you determine whether or not your model is set up as desired, and to troubleshoot any errors you might see. Coupled with this Quick-Start Guide, you should read the HEC-PRM User's Manual. This manual will help you interpret the *.pri and *.pro files, among other things.

*.pri file

Comments: Name of Alternative
Description of Alternative
F-part based on Alternative Name

```
..        RecDiv----0:RecDiv
..        Recreation Only Run with Diversion
ZW        F=RecDiv----0
..
..
```

Name of Source Node and Sink Node (fixed in HEC-ResPRM)

```
IDENT     S_SOURCE  SINK
```

Time Window (set when making a new Optimization)

```
TIME      JAN2000  DEC2004
```

Compute Options (set in Alternative Editor)

```
..
J1                        1.0       1.0        1         4
J2      .5       .01       .0
J4      .0        .0
JJ      .0        .0       .0        0         0
```

Time-series Output to Write to DSS (set in Alternative Editor DSS-Output tab)

```
..
ZWTS   FLOW_IN STOR EVAP(KAF) FLOW_IN(KAF) ENERGY_GEN DUAL_COST ELEV
ZWTS   FLOW_LOC(KAF) FLOW(KAF) FLOW
```

Frequency Output to Write to DSS (set in Alternative Editor DSS-Output tab)

```
ZWFRQ    -ALL
```

Reservoir Node is named after the Reservoir "Trout Lake" truncated to 8 char.
Identifies Node name, Beginning Storage, Conversion Factor for calculating Evap (even though Evap is not calculated), Ending Storage.
The Beginning and Ending storage a clues that tell you this is a Reservoir Node.
The next line is the Reservoir Description

```
..
NODE      TROUT LA      500.0       .1     500.0
ND        Trout Lake on the Blue River
```

Node below reservoir. This node connects the Reservoir release with the downstream reach.

```
NODE      TROUT_OUT
ND        Trout Lake Outflow
```

Node

```
NODE      ALDER
ND        Town of Alder
```

Node

```
NODE      RIVER CITY
ND
```

Dummy Node Automatically created when the Diversion was created.
Description created by program

```
NODE      J_DRYTOWND
ND        Dummy downstream node for Diversion DryTownDiv
```

Link/Arc that connects the Source to the Sink

```
LINK      DIVR      S_SOURCE  SINK      1.0       0.0
LD        Continuity Link
```

Link/Arc that connects the Source to the Trout Lake (inflow)

Inflow Pathname for getting DSS Time-series

```
LINK      INFLOW    S_SOURCE  TROUT LA
LD
IN        A=MAIN     B=TROUT LAKE    C=FLOW-IN    D=     E=1MON     F=
```

Link/Arc for Storage in Trout Lake (automatically created for any reservoir)

Lower and Upper Storage bounds (Set on the Reservoir Editor constrain tab)

```
LINK      RSTORAGE  TROUT LA  TROUT LA                           10.0     600.0
LD
```

DSS paths for monthly Storage Penalties

```
PS        MO=JAN     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=JAN     F=
PS        MO=FEB     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=FEB     F=
PS        MO=MAR     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=MAR     F=
PS        MO=APR     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=APR     F=
PS        MO=MAY     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=MAY     F=
PS        MO=JUN     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=JUN     F=
PS        MO=JUL     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=JUL     F=
PS        MO=AUG     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=AUG     F=
PS        MO=SEP     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=SEP     F=
PS        MO=OCT     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=OCT     F=
PS        MO=NOV     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=NOV     F=
PS        MO=DEC     A=RecAlt----0:Base2004    B=Trout Lake    C=STOR-PENALTY    D=Recreation    E=DEC     F=
```

Link/Arc for Release from Trout Lake (automatically created for any reservoir)

```
LINK      RRELEASE  TROUT LA  TROUT_OUT
LD
```

DSS paths for monthly Release Penalties (Set on Release Tab of Reservoir Editor)

```
PQ        MO=JAN     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=JAN     F=
PQ        MO=FEB     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=FEB     F=
PQ        MO=MAR     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=MAR     F=
PQ        MO=APR     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=APR     F=
PQ        MO=MAY     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=MAY     F=
PQ        MO=JUN     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=JUN     F=
PQ        MO=JUL     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=JUL     F=
PQ        MO=AUG     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=AUG     F=
PQ        MO=SEP     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=SEP     F=
PQ        MO=OCT     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=OCT     F=
PQ        MO=NOV     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=NOV     F=
PQ        MO=DEC     A=RecAlt----0:Base2004    B=Trout Lake    C=FLOW-PENALTY    D=Recreation    E=DEC     F=
```

Link/Arc for Channel from Trout Lake to Alder

```
LINK      CHANNEL   TROUT_OUT ALDER
LD        Blue River - Trout Lake to Alder
```

Link/Arc that connects the Source to Alder (Local Inflow)

Inflow Pathname for getting DSS Time-series

```
LINK      INFLOW    S_SOURCE  ALDER
LD
IN        A=MAIN     B=ALDER    C=FLOW-IN    D=     E=1MON     F=
```

Link/Arc for Channel from Alder to River City

```
LINK      CHANNEL   ALDER     RIVER CITY
LD        Blue River - Alder to River City
```

Link/Arc from River City to the Sink Node

(Automatically created at last node in network)

```
LINK      CHANNEL   RIVER CITYSINK
LD        Dummy reach connecting River City to SINK
```

Link/Arc from Alder to DryTown Diversion

Min and Max Flow

```
LINK      CHANNEL   ALDER     J_DRYTOWND                          2.0       2.0
LD        DryTownDiv:  Diversion from Blue River to Dry Town
```

Link/Arc for DryTown Diversion to Sink

```
LINK      CHANNEL   J_DRYTOWNDSINK
LD        Dummy reach connecting J_DryTownD to SINK

STOP
```

*.pro file

```
: WARNING: FILE GENERATED -- HEC-ResPRM\AllPenalty0.pro
```

This gives information about the version of HEC-PRM that was used to compute the Optimization run.

```
                     Reservoir System Operation Optimization
                      Version   1.020.12;  January 20, 2005
                       IBM-PC Compatible  (Compaq Fortran)
                        Run date 24MAR10   time 10:38:42



                                   HECPRM




                         U.S. Army Corps of Engineers
                         Hydrologic Engineering Center
                          609 Second Street, Suite B
                            Davis, California 95616
                                (916) 756-1104
```

This gives the date that the run was made.

```
 Start of data processing.
 March 24, 2010   10:38:42
```

DSS file with Input Time-series

```
    -----DSS---ZOPEN:  Existing File Opened,  File: C:\PRM\Example watersheds\base\Blue River Demo\HEC-
ResPRM\Early2000s\simulation.dss
                       Unit: 71;  DSS Versions - Software: 6-MN, File: 6-QF
```

DSS file with Input Penalties

```
    -----DSS---ZOPEN:  Existing File Opened,  File: C:\PRM\Example watersheds\base\Blue River Demo\HEC-
ResPRM\Early2000s\HEC-ResPRM\AllPenalty0_Div2004.dss
                       Unit: 72;  DSS Versions - Software: 6-MN, File: 6-QF
```

DSS file to which Results are written

```
    -----DSS---ZOPEN:  Existing File Opened,  File: C:\PRM\Example watersheds\base\Blue River Demo\HEC-
ResPRM\Early2000s\result.dss
                       Unit: 73;  DSS Versions - Software: 6-MN, File: 6-QF
 found it HECPRM.ERR


 SUP_DIRECTORY:    C:\PRM\Example watersheds\base\Blue River Demo\HEC-ResPRM\Early2000s\HECPRM.ERR
 NC_SUP_DIRECTORY:       75




 WR_SPLY............     F
 WR_ARC.............     F
 WR_OLD_ARC.........     F
 WR_MCS.............     T
 WR_OARC............     F




==================================================================================================================
===================
```

```
=========================================================================================================================
===================

=========================================================================================================================
===================

=========================================================================================================================
===================

=========================================================================================================================
===================
```

Compute Time Window (a date at the end of the month is inclusive of the full month)

```
 Time Window: 31JAN2000 to 31DEC2004
```

Basic information on Network

```
 Ú-------------------------------------------------------------¿
 ³                                                             ³
 ³             Dimensions allocated for this Job               ³
 ³                                                             ³
 ³ Number of Nodes...................................       8 ³
 ³ Number of Reservoirs..............................       1 ³
 ³ Number of Links...................................      12 ³
 ³ Number of DSS Pathnames...........................      26 ³
 ³ Number of Time Periods............................      60 ³
 ³                                                             ³
 ³ Number of Time-Series Buffer......................     150 ³
 ³ Number of Paired Data Buffer (Retrieval)..........     700 ³
 ³ Number of Paired Data Buffer (Storage)............    1400 ³
 ³ Number of Penalty Categories......................       0 ³
 ³ Number of Text Input Lines........................       1 ³
 ³                                                             ³
 À-------------------------------------------------------------Ù



 Begin Processing of this Time Window
 ----------------------------------------------------------------------------------------------------

.
.
.
.


 VVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVV
 VVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVV
 VVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVVV
 Start Checking for Errors in the Network.
 ----------------------------------------------------------------------------------------------------



 Number of arcs to process:        475
 ------------------------------------------------------------------------------------------------------------------------
-----------------------------
    Arc # From Node    To Node       Date                         Unit Cost    Amp.         Lower Bound
Upper Bound                Flow
 ------------------------------------------------------------------------------------------------------------------------
-----------------------------


 Node Information, number of nodes:      303
```

Important that all arcs be filled in correct order. If they are not, it means that you have non-convex penalty functions, and you should turn Restricted Basis Entry on in the Compute Options tab of the Alternative Editor.

```
 Print any Error Messages for Nodes (Always nodes 1 & 2)
   Ixnode Idnode                 e(ixnode)         bt(ixnode)  Period
 ------------------------------------------------------------------------------

Check for incorrect arc fill order
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 All arcs are filled in the correct order.



 ----------------------------------------------------------------------------------------------------
 Completed Checking for Errors in the Network.
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
 ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^

 Network printed, compute cost.
 March 24, 2010   10:38:42
 Elapsed Time is         0 seconds or
                      0.00 minutes or
                     0.000 hours.
```

Total Penalty

```
 Total Penalty at zero flow..........     1500.000000             1500.0
 Fixed Cost..........................     0.000000000                0.0
 Cost in the arcs (network cost).....    -1500.000000            -1500.0
 Fixed Cost Cumulative New...........     0.000000000                0.0
 Total Cost..........................   -0.4547473509E-12            0.0
```

Was an Optimal Solution found? How many iterations did the solver need to converge on a solution?

```
 Status at completion of job.............OPTIMAL
 Number of solver iterations.............       329
 Number of nodes.........................       302
 Number of arcs..........................       471


    -----DSS---ZCLOSE Unit:  71,   File: C:\PRM\Example watersheds\base\Blue River Demo\HEC-ResPRM\Early2000s
               Pointer Utilization:  0.25
               Number of Records:      2
               File Size:     27.1  Kbytes
               Percent Inactive:   0.0

    -----DSS---ZCLOSE Unit:  72,   File: C:\PRM\Example watersheds\base\Blue River Demo\HEC-ResPRM\Early2000s
               Pointer Utilization:  0.26
               Number of Records:     92
               File Size:     84.4  Kbytes
               Percent Inactive:   0.0

    -----DSS---ZCLOSE Unit:  73,   File: C:\PRM\Example watersheds\base\Blue River Demo\HEC-ResPRM\Early2000s
               Pointer Utilization:  0.25
               Number of Records:    191
               File Size:    214.9  Kbytes
               Percent Inactive:   0.3
```

When the run was made and how long it took

```
 End-of-Run
 March 24, 2010   10:38:52
 Elapsed Time is        10 seconds or
                      0.17 minutes or
                     0.003 hours.
```

CHAPTER 9

Recommended Reading for the HEC-ResPRM User

The uninitiated HEC-ResPRM user will require more than just this Quick-Start Manual to get started in the modeling process. It is recommended that you have a solid background in water resources and optimization in general. A familiarity with other HEC software can also be helpful. The following list provides a starting point from which to build your knowledge base.

General Water Resources Optimization:

Bhaskar, N.R. & Whitlatch E.E. (1980). “Derivation of Monthly Reservoir Release Policies,” *Water Resources Res*., **16**(6), 987-993.

Cohon, J. L. (1978). *Multiobjective Programmingand Planning*, Academic, New York.

Cohon, J. L. & Marks, D.H. (1975). “A review and evaluation of multiobjective programming techniques,” *Water Resources Research*, **11**(2), 208-220.

Dantzig, G. B. (1963). *Linear Programming and Extensions*. Princeton University Press, Princeton, NJ.

Draper, A. J. & Lund J. R., (2004). “Optimal Hedging and Carryover Storage Value,” *J. of Water Resour. Plng. and Mgmt.*, **130**(1), 83-87.

Harboe, R. (1992). “Multiobjective decision making techniques for reservoir operation,” *Water Resources Bulletin.* **28**(1), 104-110.

Hillier, F. S. & Lieberman G. J. (1986). *Introduction to Operations Research*. Holden-Day, Inc., Oakland, CA.

Hollinshead, S. P. & Lund J. R. (2006). “Optimization of Environmental Water Account Purchases with Uncertainty,” *Water Resources Res*., **42**(8), W08403.1-10.

Israel, M. S. & Lund, J. R.. (1999). “Priority Preserving Unit Penalties in Network Flow Modeling *J. of Water Resour. Plng. and Mgmt.*, **125**(4), 205-14.

Jenkins, M. W., et al. (2004). "Optimization of California's water system: results and insights," *J. of Water Resour. Plng. and Mgmt*, **130** (4), 271–280.

Jettmar, R.U. & Young G.K. (1975). "Hydrologic Estimation and Economic Regret," *Water Resources Res.*, **11**(5), 648-656.

Karamouz, M., & Houck, M. H. (1982). "Annual and monthly reservoir operating rules generated by deterministic optimization." *Water Resour. Res.*, **18**(5), 1337–44.

Karamouz, M., Houck, M. H., & Delleur, J. W. (1992) "Optimization and simulation of multireservoir system." *J. of Water Resour. Plng. and Mgmt.*, **118**(1), 71–81.

Ko, S-K., Fontane, D., & Labadie, J. (1992). "Multiobjective Optimizaiton of Reservoir Systems Operations," *Water Resources Bulletin*, **28**(1), 111-127.

Labadie, J. W. (2004). "Optimal Operation of Multireservoir Systems: State of the Art Review." *J. of Water Resour. Plng. and Mgmt.*, **130**(2), 93–111.

Lee, S., Hamlet, A. F., Fitzgerald, C. J., & Burges, S. J. (2009). "Optimized Flood Control in the Columbia River Basin for a Global Warming Scenario." *J. of Water Resour. Plng. and Mgmt.*, **135**(6), 256-71.

Loucks, D., Stedinger, J., & Haith, D. (1981), *Water resource systems planning and analysis*, Prentice-Hall, Englewood Cliffs, N.J.

Lund, J. R., & Ferreira, I. (1996). "Operating rule optimization for Missouri River reservoir system." *J. of Water Resour. Plng. and Mgmt.*, **122**(4), 287–295.

Lund, J. R. & J. Guzman, (1999). "Some Derived Operating Rules for Reservoirs in Series or in Parallel," *J. of Water Resour. Plng. and Mgmt.*, **125**(3), 143-153.

Needham, J., Watkins, D., Lund, J. R., & S. Nanda. (2000). "Linear Programming for Flood Control on the Iowa and Des Moines Rivers," *J. of Water Resour. Plng. and Mgmt.*, **126**(3), 118-127.

Watkins, D. W., & Moser, D. A. (2006). "Economic-based optimization of Panama Canal system operations." *J. of Water Resour. Plng. and Mgmt.*, **132**(6), 503–512.

Young, G., (1967). "Finding Reservoir Operating Rules," *Journal of Hydraulics Division*, **93**(6), 297-321.

HEC-PRM Network Flow solver

Dr. Paul Jensen wrote the solver that HEC-PRM uses. More about the technique used by the solver can be found in this book.

Jensen, P.A., and Barnes, J.W. (1980). *Network Flow Programming*. John Wiley & Sons, New York, NY.

Dr. Jensen's homepage is also full of useful information about optimization.
http://www.me.utexas.edu/~jensen/ORMM/

USACE HEC-PRM Project Reports

Several US Army Corps of Engineers studies have been conducted using HEC-PRM. Project reports include some theory as well as information on how projects were conducted. These reports are available on-line from the HEC website.

http://www.hec.usace.army.mil/publications/pub_download.html

See:

- **PR-15**, Missouri River System Analysis Model - Phase 1
- **PR-16**, Columbia River System Analysis Model - Phase 1
- **PR-17**, Missouri River Reservoir System Analysis Model - Phase II
- **PR-18**, Developing Operation Plans from HEC Prescriptive Reservoir Model Results for the Missouri River System: Preliminary Results
- **PR-22**, Operating Rules from HEC-PRM Results for the Missouri River System: Development and Preliminary Testing
- **PR-26**, Preliminary Operating Rules for the Columbia River System from HEC-PRM Results
- **RD-40**, Developing Seasonal and Long-Term Reservoir System Operation Plans Using HEC-PRM
- **RD-43**, Application of HEC-PRM for Seasonal Reservoir Operation of the Columbia River System
- **TP-136**, Prescriptive Reservoir System Analysis Model - Missouri River System Application
- **TP-146**, Application of the HEC Prescriptive Reservoir Model in the Columbia River System

HEC User's Manuals

These are also available on the HEC website. See:

HEC-ResSim User's Manual
http://www.hec.usace.army.mil/software/hec-ressim/documentation.html

HEC-DSS User's Manual
http://www.hec.usace.army.mil/software/hec-dss/hecdssvue-documentation.htm

This HEC-ResPRM Quick-Start Guide and the HEC-PRM User's Manual are located on the HEC-ResPRM homepage.

CHAPTER 10

Glossary

This glossary is a collection of definitions of important terms used in this User's Guide or other reference material that you may consult when working with HEC-ResPRM.

arc	An element of a network that connects two nodes. An arc can be a water conveyance such as a reach of a stream or pipe, or simply a zero-length connector between two physically adjacent nodes. It can also be a conveyance in time, for example, reservoir storage is represented with an arc that connects the reservoir at time, t, to the reservoir at time, t +1.
computation point	A location in a watershed where time-series information can be exchanged between different models.
concave	Curve like the inner surface of a sphere, which means the slope decreases from one segment to the next for a piecewise linear function. A function *f(x)* is said to be *concave* if *–f(x)* is a *convex* function.
Configuration	In the *Res* environment, a selection of *projects* located on the *Stream Alignment*.
constraint	Any restriction the decision variables must satisfy. Generally expressed as an inequality.
continuity	The principle requiring that the sum of all flows entering a node minus the change in storage to equal the sum of all flows leaving that node. See also *mass balance.*
control point	A *node* having physical characteristics of interest. Often, some *constraint* is imposed on flow from a *control point*.
convex	Curved like the exterior surface of a sphere. A *convex function* is a function with value at the midpoint of any interval less than the average of the values at the ends of the interval. In this case, the slope increases from one segment to the next for a piecewise linear function.

data mining	Practice of systematic analysis of complex information structures to discover patterns, correlation, and trends.
data visualization	Graphical presentation of information directed toward discovery of patterns, correlation, and trends.
decision support system	Any computer program(s) that encapsulates data analysis and visualization functionality, which permits the user to obtain advice or to draw conclusions in the real world.
decision variable	A quantity in a mathematical program that may be adjusted by the *solver*. Convertible to and from a quantity that is meaningful in the real world.
economic efficiency	A characteristic of a solution that has low economic cost
feasible solution	A solution that satisfies all *constraints.*
foresight	The use of definitive knowledge of a future state of the system while computing or forecasting a future state.
global optimum	A solution that is optimal among all possible solutions.
HEC-DSS	Hydrologic Engineering Center Data Storage System. A non-relational database widely used by the Corps of Engineers, particularly optimized for rapid storage and retrieval of time-series.
HEC-ResSim	Hydrologic Engineering Center Reservoir Simulation Software widely used by the Corps of Engineers, Runs reservoir simulation for complex systems based on user-defined storage pool guide curves and rules.
incommensurable	Having no common measure or standard of comparison.
incremental flow	See *local flow.*
infeasible	A solution that does not satisfy at least one constraint.
junction	A point in a stream network where two tributary streams meet or where a diversion begins or ends.

linear program (LP) A *mathematical programming* problem that can be expressed as follows (the so-called standard form):

minimize $\boldsymbol{c}x$

subject to $\boldsymbol{A}x = \boldsymbol{b}$

$x >= 0$

where x = the vector of variables to be solved for, **A** = a matrix of known coefficients, and **c** and **b** = vectors of known coefficients.

linear programming matrix The matrix of coefficients **A** in a *linear program.*

local flow Flow into a system between adjacent junctions, usually added to the system at the downstream junction.

local optimum A solution that is optimal among all neighboring solutions. It may or may not also be the *global optimum*. A problem can have multiple local optima.

logical constraint A constraint in a *linear program* (LP) that is added by the solution algorithm to expedite solution. The standard form of an LP requires nonnegative decision variable values. Logical constraints can be used to permit general bounds on decision variables at a cost of additional variables.

mass balance Equations that ensure mass (water volume) is conserved at a particular point. In LP, done with continuity constraints.

multiple optima A case where more than one optimal set of decision-variable values exists.

network A collection of connected *arcs* and *nodes*. In the *Res* environment, it is the collection of data built in the Network Module (physical and model data added to a *Configuration*).

network flow programming A special case of general linear programming, represented by *nodes* linked by *arcs.*

node The junction of two or more *network arcs*. An element of a *network* where mass is conserved, connected to other nodes by *arcs*. The node may represent a system reservoir, demand point, channel junction, diversion point.

objective function A linear combination of decision variables, the value of which represents the desirability (or undesirability) of a particular set of values of the decision variables. The goal of mathematical programming is to find the set of decision-variable values that minimizes or maximizes the objective function.

operation rule An expression of how a reservoir is to be operated to meet specified conservation or flood control goals.

optimal solution The set of decision variables representing a feasible solution to a mathematical program for which the objective function is at its minimum or maximum value.

optimality tolerance The magnitude of the change in the value of the *objective function*, between successive evaluations, below which the *decision variables* are considered to be *optimal.*

parameter A variable, in a general model, whose value is adjusted to make the model specific to a given situation. A numeric measure of the properties of the real-world system.

penalty function An *objective function* that imposes cost for certain ranges of values of certain *decision variables.*

penalty manager An editor used to create and manage groups of PenaltySets, so that weights can be applied to multiple PenaltySets at one time, from one screen.

penalty weight A multiplier applied to change the weight or effect of a penalty on the objective function. In HEC-ResPRM, multiple runs are made, with slightly adjusted penalty weights to build trade-off curves. Penalty Reports display calculated penalties without the effect of weights.

persuasion penalty A non-economic cost or benefit associated with a decision variable in the objective function of a mathematical program to drive the solution towards a solution that is intuitively optimal, even if not economically optimal.

physical constraint A constraint that is based on physical laws; an inviolable constraint.

piecewise linear function Representation of a nonlinear function with a set of successive, connected linear segments.

project In HEC-ResPRM, this can refer to elements such as reservoirs or diversions. It can also be used to refer to a HEC-ResPRM Watershed – all the files and subdirectories involved in the main watershed directory, located under the "base" directory.

Res The Grapical User Interface and environment that supports some of HEC's Next Generation software, including ResSim and HEC-ResPRM.

reservoir regulation manual An official publication that specifies how controlled releases will be made from a particular reservoir or reservoir system, given storage, inflow, and downstream requirements.

rule curve Operational guidance on the amount of water to be stored in a reservoir. A graphical or tabular representation of this guidance.

scale In HEC-ResPRM, a multiplier applied to change the effect or weight of a PenaltySet on the objective function. Scale is typically used to balance the relative effects of penalties of the same type. Penalty Reports display calculated penalties including the effect of scales.

solver A computer program that implements the algorithms required to determine a solution to a mathematical programming problem.

storage allocation A method to distribute reservoir inflows and outflows among two or more storage zones, or among two or more reservoirs.

storage zones A representation of allocation of storage in a reservoir for specific purposes.

stream reach Any facility, channel, or stream bed that transfers water between junctions.

suboptimal solution The set of decision variables that represents a feasible solution for which the objective function is near, but not equal, its maximum or minimum value. Also, a feasible solution that appears optimal but has not been proven so.

watershed Projects or models in HEC-ResPRM, including all files for all modules.

CHAPTER 11

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