

## Water Evaluation and Planning (WEAP)<sup>1</sup>

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### Scope: questions/ challenges the tool addresses

WEAP is a modeling tool for water planning and allocation that can be applied at multiple scales, from community to catchment to basin (Yates et al., 2005a, b; Sieber, Swartz, and Huber-Lee, 2005). It has a global user base, and is available in Arabic, Chinese, English, Farsi, French, Korean, Portuguese, Korean, Spanish, and Thai. The map below shows a selection of WEAP projects from different regions of the world. A number of resources are available at the WEAP web site, <http://www.weap21.org/>.



**Figure 1**

WEAP uses scenarios as a way to evaluate different water allocation schemes, given water demand and associated priorities. It includes a hydrological model and links to the groundwater

<sup>1</sup> This tool is dedicated to Isaac Asamoah, a true friend, a wonderful collaborator and a great human being. We will miss you.

model MODFLOW and the water quality model QUAL2K. WEAP has also been linked to socio-economic models, some of which can track changes over time in livelihood assets given changes in water allocation.

### Target group of the tool

WEAP has multiple audiences, including water planners, hydrologists, agronomists, policymakers and local stakeholders. Different target groups will interact with the model in different ways. Water planners and local stakeholders can collaborate on describing an area using WEAP's schematic overview screen. However, once the system is constructed, an expert user is needed to develop a description of water supply and demand (including ecological demands). WEAP features a built-in hydrological model and can be linked to external models.

### Requirements for tool application

WEAP is a modeling tool. Although its graphical user interface makes it easier to learn than similar models, it is still a modeling tool, and is best used by someone with adequate technical expertise. Access to a good-quality computer and at least occasional access to the internet are strongly recommended. For some purposes, WEAP applications require relatively little data. If hydrology is to be modeled, however, substantial data on climate, water supply, and water use are needed.

### Tool: description and application

A project using WEAP needs to gather information on water balances within a catchment or basin, and water allocation among different uses. By setting allocation priorities, different water rights regimes can be simulated. WEAP is designed around a scenario approach, where scenarios reflect alternative changes in water allocation, water supply infrastructure, water management, land use, climate, and other water-related variables.

WEAP has been applied to two sub-projects in the Small Reservoirs Project (SRP): the Buriti Vermelho watershed in the São Francisco basin in Brazil, and the Tonga tributary of the White Volta basin. The specific application of WEAP in these two watersheds is discussed below. First, however, a general process for applying WEAP within the SRP is presented.

#### *Process for Applying WEAP to Small Reservoir Projects*

The process for developing a WEAP application for a small watershed includes these steps:

1. Problem identification
2. Scenario development
3. Initial data collection
4. Initial WEAP application development
5. Further data collection
6. WEAP application refinement
7. Scenario implementation
8. Dissemination

Note that the first few steps do not involve WEAP at all. The first step, “Problem Identification,” is particularly important, as it can determine the direction of the project, and whether WEAP or any other modeling tool is needed at all.

### *Problem Identification*

An effective modeling exercise requires considerable data, as well as the time and resources to design, implement, and test the model. This effort is often rewarded by greater insights into the nature of a problem and a better understanding of the possible consequences of different interventions. However, the nature of the problem and the purpose of the model should be very clear from the outset to ensure efficient use of project resources.

In this stage, the following questions should be answered:

1. What is the problem that the project addresses?
2. Who will use project outputs?
3. Is there a need for a future-oriented component to the project, such as a scenario? (For virtually all planning exercises, the answer to this question is “yes”)
4. Are quantitative results needed in project design or implementation?
5. Can the needed quantitative results be obtained from published studies or secondary statistics, or is a model required to generate these results?
6. If a model is needed, what are its data requirements? How much effort will be required to collect and process the data? (This can be a difficult point – it will be refined in the future.)

Depending on how these questions are answered, decisions can be taken as to whether a modeling exercise is necessary and, if it is, which tool is most appropriate. To decide if WEAP is a good choice, consider these features of WEAP:

- WEAP is built around a scenario approach
- It is easy to create new scenarios for analysis by WEAP
- Both demand and supply can be represented
- Water allocation regimes and rules can be represented
- WEAP is extensible and flexible

However, as with any water modeling framework, building a model in WEAP requires data, time, modeling skills, and patience.

### *Scenario Development*

Scenario development and analysis are a powerful way to evaluate the outcomes and consequences of different patterns of resource use and management practices. An understanding of these outcomes and consequences can be enormously useful in decision-making.

WEAP is very effective at handling scenario analysis. It is all the more important, then, to take pains when developing the scenarios to be analyzed. Scenario workshops can provide insights into the dynamics of a system – insights that can be helpful in informing model design.

Moreover, when data limitations or time constraints require that trade-offs be made in the course of model development, such insights can result in sensible choices being made about which options to choose. The best option is the one that helps to analyze the scenarios that have been developed for the project.

To take a simple example, an allocation scheme based on average flow will be inadequate in most years in a watershed with highly variable rainfall. By tying allocation rights to some measure of water availability within the system, it is possible to make a reasonable allocation in a wider range of years. A more complex example might be a payment for environmental services. If upstream communities are paid by downstream water users to maintain a certain amount of undeveloped forest land, there may be the need for a provision in the agreement for dry years, so that upstream users can have sufficient forage to maintain their livestock.

For most parts, futures techniques attempt to do one of three things: to explore the implications of a planned intervention or development; to imagine possible, but infrequent, occurrences; and to anticipate potentially surprising interactions between parts of a complex system. Before these can be represented in a model, such as in a WEAP application, it is important to think creatively about them first. A variety of techniques are available, from simple to complex.

A simple futures technique is a problem tree analysis, in which the central problem is placed in the center of the “tree”, and the causes of the problem (the “roots”) and the consequences of the problem (the “branches”) are drawn in during a brainstorming session. The problem tree can then be used to design interventions and as a starting point for representing the system in a model.

A more complicated futures technique is a cross-impact matrix. In a cross-impact matrix, a number of different interventions (if interventions are planned) or possible events are used to label both the rows and columns in a matrix. At the intersection of the rows and columns, some indication can be made of how one intervention or event affects the other. For example, the goal of an intervention might be “increasing upstream tree cover”, while an event might be “catastrophic flood”. The impact of increasing upstream tree cover is likely to be a lower chance of a catastrophic flood, which can be noted in the matrix.

A much more involved process is a Companion Modeling exercise, which could be carried out in a watershed in order to understand the interactions between different actors and how they respond to events. The result of such an exercise is greater insight into the dynamics of the community and therefore an appreciation of how the community might respond to a planned intervention.

### *Initial Data Collection*

Before any field work is done, it is a good idea to assess what data are available for a first-cut analysis. Data may be taken, for example, from official government sources, international data sets, satellite information, or from previously published studies. The goal for the initial data collection is to support the creation of an initial WEAP application. Time is of the essence at this stage. It is a good idea to provide a concrete (if incomplete) example of a model in order to assess whether it is likely to provide the needed support for decision-making. Also, it can help

prioritize resources for further data collection. It may turn out that key results are insensitive to one particular variable, in which case efforts can be focused on other variables that have more influence on the results.

#### *Initial WEAP Application Development*

Using data provided by the initial data collection step, an initial WEAP application can be created. This should not be extremely detailed – only the most important features of the area should be developed. The urge to collect more data in order to make a more detailed application should be resisted. As with the initial data collection step, time is of the essence.

However, the application should also not be misleading. For this reason, a preliminary calibration and validation step should be undertaken. With some initial effort, this step can be automated using the parameter estimation tool PEST, as discussed later in this tool description.

Once an initial, provisionally calibrated application has been created, two or three alternative scenarios can be constructed. These can then be used to review the application. The review should focus on the following questions:

1. Is the application design likely to support decision-making under this project after reasonable efforts to collect more data and elaborate the model?
2. What further data are required in order to effectively support decision-making for the project?
3. What modifications to the application must be carried out before it is useful for decision-making?

At this stage, it may be decided that further development is not necessary. Even if this is the case, there should be some useful outputs at this stage: the outputs from the scenario workshop can inform the project in many ways, while the initial data collection and basic WEAP application should support broad “what-if” questions about future developments.

#### *Further Data Collection*

If it is decided to continue with the WEAP development, in most cases there will be a need for further data collection. Most likely this will involve a combination of fieldwork and processing of existing data sets (such as delimiting a watershed more precisely using GIS data). Data may include hydrological, land use, or socioeconomic data.

#### *WEAP Application Refinement*

With the new data and insights from the model review process, the initial WEAP application can be elaborated. This will most likely involve more detailed implementation of components of the system. For example, in the initial application the outflow from a catchment may be input as data, while in the final application the catchment may be modeled in order to capture the impact of changing land use or climate. Additionally, it may be necessary to build external models that are linked into WEAP. There are many ways in which this can be done, including building models that can be called from WEAP (as a dynamic link library, or DLL), running

WEAP using an external program with the WEAP application programming interface (API), or taking the output from WEAP and running it through an external model.

The final application may take quite a while to develop, depending on the resources available to the team and the needs of the project. However, it is important to break the entire process down into steps such that a running model can be released every 1-2 months. Before each release, the model should be calibrated. As with the initial WEAP application, it is a good idea to automate the calibration step with PEST. It is not easy to set up PEST, but once it is set up, it is very easy to run.

After each release of the model, it should be reviewed, with the review addressing the same questions as for the initial application.

### *Scenario Implementation*

Once the model is reasonably well developed, it should be useful for scenario analysis in support of decision-making for the project. It is probably not necessary to wait until the final application is finished, if it is being released periodically as a calibrated model. Initial scenarios can be implemented and their implications explored. Different options can be considered in light of the scenario outputs.

For example if, under one intervention, groundwater drops rapidly in a number of different climate scenarios, then that is an indication that the way the intervention is implemented should be sensitive to inter-annual climate variability. As another example, one socioeconomic scenario may call for local electricity generation, while a planned small reservoir will reduce the potential for low-head run-of-river hydroelectric generation in a lower reach of the river. In this case, it may be desirable to consider alternative ways of achieving both off-grid electricity generation and reliable irrigation.

The scenarios do not stand by themselves. Instead, they are a prompt for reflection. They should be accompanied by discussion, interpretation, and analysis, in order to increase the likelihood that the project will succeed.

### *Dissemination*

In most studies it will be desirable to distribute the results of the analysis that underlay the study, in addition to implementing the project itself. If a WEAP application has been developed, then it can be released on the WEAP web site (<http://www.weap21.org/>). Usually, a report will also be released, containing the outputs of the analysis, including the outputs from the scenario workshop and the outputs from the WEAP model.

### *The São Francisco Basin*

The São Francisco River Basin is of great importance to Brazil, not only because of the large volume of water it conveys to a semi-arid region, but also because of its potential water resources and historic and economic contribution to the region (ANA 2006). It is the third largest basin in the country and is known as the Basin of the National Integration, as it is contained completely within Brazil. In recent years, the São Francisco River Basin has received increased attention. Running from southwest to northeast, the basin spans a range of socioeconomic conditions, land-use patterns and ecologic components. The basin covers socioeconomic conditions from wealthy industrial and urban centers, to the poverty-stricken arid northeast. Similarly, the basin traverses a range of Brazilian ecosystems, from savannah-like cerrados to coastal mangroves. Water use in the basin can be a source of conflict. For example, the São Francisco River has hydroelectric dams, which are oftentimes contested between the power sector and environmentalists.

#### *Hydrology and General Characteristics*

The São Francisco River Basin drains an area of 639,920 km<sup>2</sup> (ANA et al 2004), an area representing roughly 7.5% of Brazil (CBHSF 2006). Running in a northeast direction, the São Francisco River is 2,863 kilometers in length and spans the states of Alagoas (2.2% of the total area), Bahia (48.2%), Goiás (0.5%), Minas Gerais (36.8%), Pernambuco (10.9%) and Sergipe (1.2%), as well as the Federal District (0.2%). The basin contains 504 municipalities, representing 9% of all Brazilian municipalities (CBHSF 2006). At its mouth, the long term mean discharge of the SF River varies from 2,850 to 3,360 m<sup>3</sup>/s.

#### *Socioeconomics*

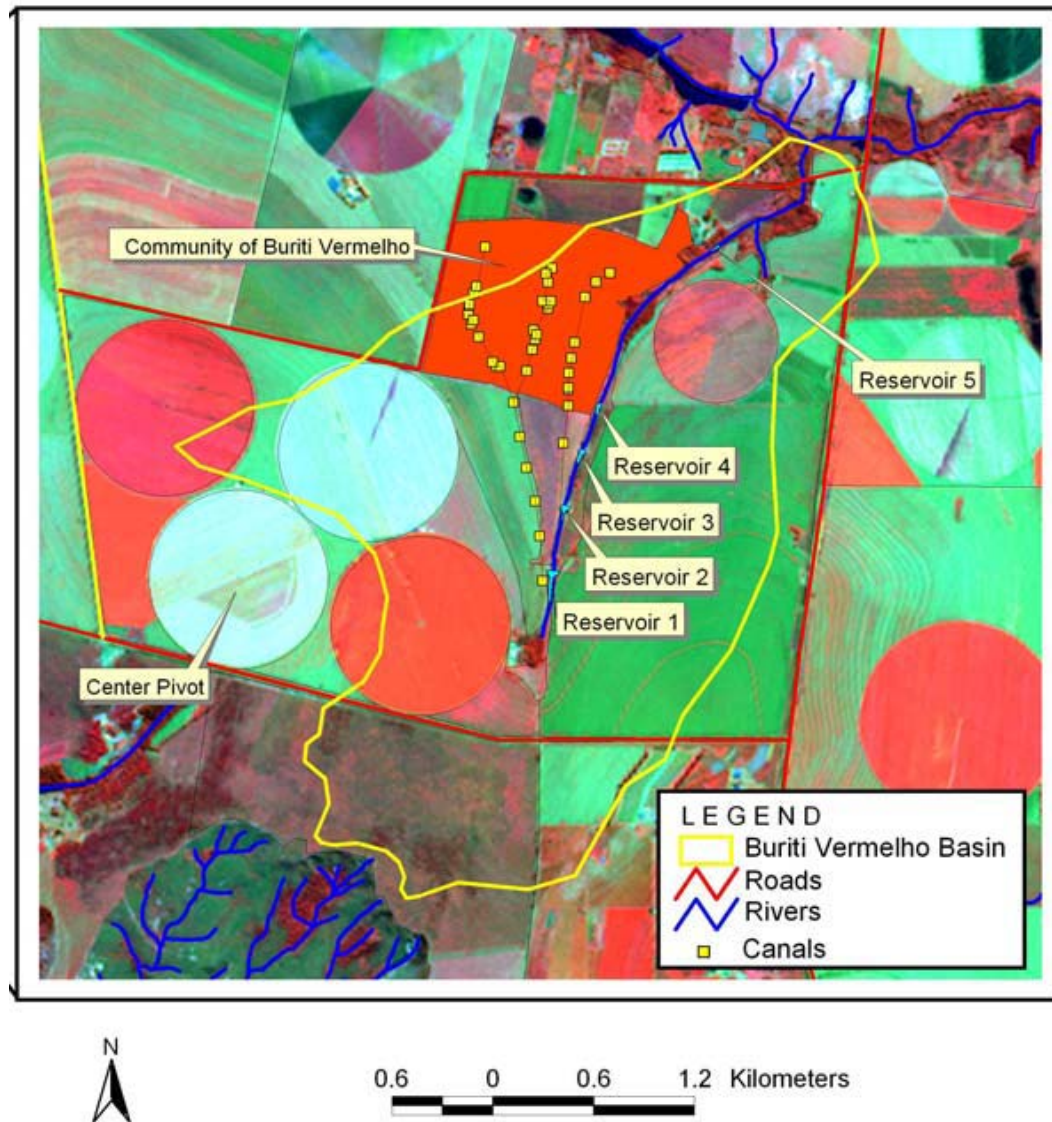
According to the GEF (2004), roughly 13.3 million people inhabit the basin. A range of socioeconomic conditions exist in the basin, from extreme rural poverty to lucrative industry and agriculture. The United Nations Human Development Index (HDI) varies from 0.823 in the upper SF to 0.538 in lower portions of the basin.

#### *Study Area*

This application focused on the Buriti Vermelho catchment, a sub catchment of the Estreito River, which is part of the Preto River Basin. The Preto River Basin provides an ideal site within which to consider the impact and potential role for small reservoirs in the broader context of livelihoods, socioeconomics and the necessary resources required to receive livelihood benefits. The drainage area of Buriti Vermelho is about 9.5 km<sup>2</sup>.

Located roughly 60 kilometers from Brasilia, the community of Buriti Vermelho has 32 parcels of land. Because some have been combined and others divided among family, there are thirty parcels functioning as independent units. Parcels range from 2 hectares to 6 hectares, averaging 3.47 hectares. Approximately 30 families live in Buriti Vermelho, with a total population of 150. Some farmers have combined several parcels into one. These farmers have either merged land with another family member or bought the right to “rent” the land from the “owner” of the contract/lease. The community of Buriti has four small reservoirs, two of which are used for

irrigated agriculture, the other two of which are not in use (Figure 2). Each of the two utilized reservoirs has one canal, which serves different parts of the community. The canal that comes from the first reservoir splits into two by the time it reaches parcels within the community (Carolina, 2006).

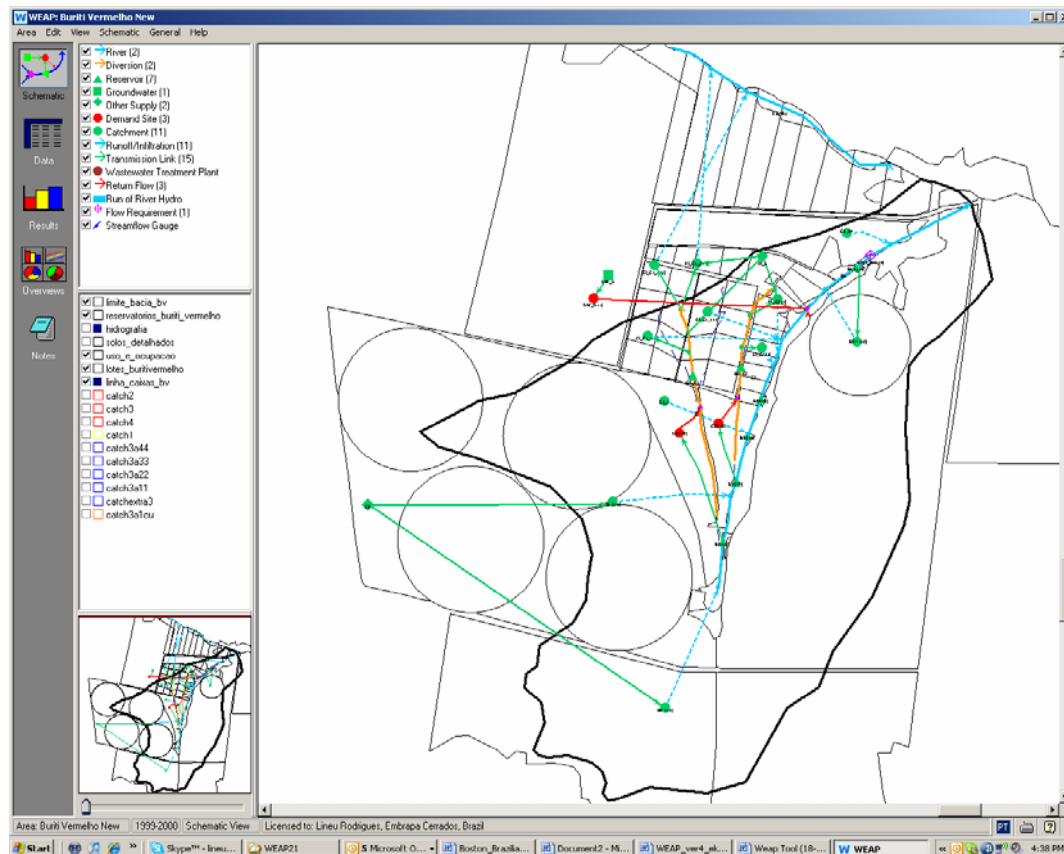


**Figure 2.** Satellite image of the community of Buriti Vermelho. The community is highlighted in a red box-like area. Small yellow boxes represent sites of diversion from main canals to individual farms. While four small reservoirs are visible, only two are in use. Center-pivot irrigated agriculture surrounds the community.

While the reservoirs in Buriti Vermelho were first built by the government starting in the late 1970s, from 1995-1996, additional funds were obtained to line the canals and repair the reservoirs. In return for the government building these reservoirs and canal systems, farmers were supposed to purchase more efficient irrigation equipment (Rodrigues et al 2004). This policy was only partially successful, as only some farmers kept these more efficient technologies. At this time, the community also decided that only those families that helped build the canal could have access to it.

Today, thirteen of the thirty parcels do not use canal water (43%). Of these thirteen, only five have rainfed agriculture, and eight irrigate with water from other sources (streams and springs). The remaining 17 parcels (57%) have irrigated agriculture. The community has a Community Association that, among other things, supports the sale of vegetable crops to nearby markets. The formal, and main source of drinking water comes from CAESB's groundwater pump, which is then stored in the communal water tank. Buriti Vermelho has an elementary school, and less than one quarter kilometer of paved road, that was built with funding obtained by the current president.

*Purpose for using WEAP/Problems to be solved*



**Figure 3:** Study Area and WEAP Application for the Buriti Vermelho, Brazil.

*Purpose*

Rural communities in the São Francisco depend on water from small multi-purpose reservoirs for their households, livestock, and irrigation schemes. The study aims to answer some of the following questions: What is the impact on income of different water management scenarios? What is the lost income due to unmet demand? What is the impact of climate change on income? How can overall vulnerability of the community be minimized? How do changes in technology uses affect water availability?

*Data Preparation*

The following steps were taken to prepare the data for this study. First, using farm level data for the entire community of Buriti Vermelho, the agricultural area was aggregated by parcel:

1. Total area of irrigated agriculture
2. Total area of rainfed agriculture
3. Type of irrigation technology used for each type of agriculture. For this, results were for all irrigated crops were aggregated, and called “vegetables”.
4. Source of irrigation

Second, after tabulating this data, aggregation was done from farm level to different “farm types”. The criteria used for aggregation was:

1. What is the source of water for irrigation?
2. Does the farm have irrigation and rainfed agriculture, or only rainfed agriculture?
3. From which canal, if any, does the farm draw water?

Following these criteria, six main groups were identified for aggregation:

1. Farmers who use water from Canal 1 for irrigated agriculture
2. Farmers who could use water from Canal 1 (due to proximity), but use water from an alternative source (e.g. stream, spring, etc) for irrigation
3. Farmers who could use water from Canal 1, but have only rainfed agriculture
4. Farmers who use water from Canal 2 for irrigated agriculture
5. Farmers who could use water from Canal 2 (due to proximity), but use water from an alternative source (e.g. stream, spring, etc) for irrigation
6. Farmers who could use water from Canal 2, but have only rainfed agriculture

*Developing the WEAP Application*

A single supply node, representing the community’s groundwater pump, is linked to one demand node that represents all of the community’s demand. Currently, the model is set up to meet all domestic demand. Runoff from this demand node goes into the Buriti stream.

The aggregated groups helped determine what catchments to delineate, but additional information was also used to establish the catchments. Parcels with significant irrigated agriculture from the canal were grouped with rainfed parcels, because future scenarios may involve some rainfed farmers switching into irrigation. It therefore makes sense to group these together. And, due to the fact that there is one set of farmers that are near to Canal 1, but fall in the Estreito Catchment (the larger basin, of which Buriti Vermelho is a part), the grouping reflects this as follows:

1. Parcels along Canal 1 (C1) that have Canal Irrigation (CI) (current or potential) or rainfed agriculture, and fall within the Buriti catchment (1), “CI\_C1\_1”
2. Parcels along Canal 1 (C1) that have Alternative Irrigation (AI), and are within the Buriti Catchment, “AI\_C1\_1”

3. Parcels along Canal 1 (C1) that have Canal Irrigation (CI) (current or potential) or rainfed agriculture, and fall within the Estreito catchment (2), “CI\_C1\_2”
4. Parcels along Canal 1 (C1) that have Alternative Irrigation (AI), and are within the Estreito Catchment, “AI\_C1\_2”
5. Parcels along Canal 2 (C2) that have Canal Irrigation (CI) (current or potential) or rainfed agriculture, and fall within the Buriti catchment (1), “CI\_C2\_1”
6. Parcels along Canal 2 (C2) that have Alternative Irrigation (AI), and are within the Buriti Catchment, “AI\_C2\_1”

The source of water for all “Alternative Irrigation” groups was delineated as one supply node. Runoff from each catchment goes to the respective catchment’s stream. It is important to note that even though the Estreito catchments currently take water from alternative sources, they could potentially access only Canal 1.

For each catchment node, data were entered by land-use type, as this is central information for the catchment. Eventually the areas under different cultivation regimes, or canal-use regimes will be switched. Data for this was obtained from field surveys, to be documented separately. Below is an outline of what was included for each crop type within the catchment land cover:

1. Rainfed crops (soy, varge, corn)
2. Rainfed orchards (distinguish that these include mango, banana)
3. Irrigated vegetables (tomatoes, bell pepper, etc)
4. Irrigated orchards (lemon, acerola, graviola, lime)

Because current flows out of the reservoir are not enough to satisfy irrigation demands, farmers have on-farm storage units in which they store canal water. When full, farmers pump water from these storage units to use for irrigation. Rather than modeling individual storage units or storage units by each aggregated catchment node, two storage units were modeled, one for each canal, treating each as a small reservoir. The size was estimated, and maximum size was set to equal the current number of canal users.

A key assumption was added regarding how many people are currently using Canal 1 (12) and how many are using Canal 2 (7). In the future, these numbers will be varied. Each storage unit along each canal was given a priority of 99.

For the storage units, a key assumption labeled “average volume of storage unit for one farm” was added and set equal to 200 cubic meters. Therefore, total storage capacity was calculated at Storage Capacity for SU\_C1 =  $200 \times 7 = 1,400$  cubic meters, and storage capacity for SU\_C2 =  $200 \times 12 = 2,400$  cubic meters.

Another important assumption is that when ‘type of irrigation used for an area that a farmer reported as irrigated’ was unknown, we split the unknown area equally into all four other irrigation types, and increased each one by the same area. However, the total area to which this was done is small. Another important consideration is that some people connected to the canal have some rainfed areas. But when rainfed areas are shown, it is assumed that all these users

are of the same type (i.e., all rainfed are of this type). This assumption may change in some scenarios.

### *Scenarios*

Scenario analysis has not yet been carried out for the São Francisco basin. The following WEAP scenarios were identified for implementation once the hydrologic component after the model is complete:

#### Changes in Irrigation Technology

1. Under a business-as-usual (BAU) scenario, increase drip by 100% in areas with irrigated agriculture
2. Under a business-as-usual scenario, increase drip by 50% in areas with irrigated agriculture

#### Changes in Types of Agriculture

1. Simulate an increase in canal users: Have rainfed agriculture shift to 100% furrow irrigation.
2. Simulate an increase in canal users, but have rainfed agriculture shift to 100% drip irrigation
3. Simulate an increase in canal users: Have groups that are currently using an alternative irrigation source shift to canal, and plant with 100% furrow irrigation
4. Simulate an increase in canal users: Have groups that are currently using an alternative irrigation source, shift to canal, and plant with 100% drip irrigation.

#### Climate

1. Simulate BAU scenario, with 0.5 degree Celsius increase
2. Simulate BAU scenario, with 1 degree Celsius increase
3. Simulate longer droughts
4. Simulate more intense rain and droughts

#### Potential Economic Scenarios

1. Water pricing scenario (i.e. energy costs increase)
2. Water trading occurs, between farmers, between community and large farmers

Note that when the variables have to do with the catchment (and therefore land cover, land type, and associated parameters), it will be necessary to adjust the parameter values in the hydrologic model in order to represent the desired scenarios.

### *Calibrating with PEST*

PEST (Doherty, 2004) is a freely-available parameter estimation tool that is currently used in many fields. It is designed to work flexibly with any computer model that can take a text file as

input and produce a text file as output.<sup>2</sup> While WEAP uses a graphical user interface (GUI), as described below it is possible to “wrap” WEAP in another program that will take a text file as input, allowing PEST to be run.

PEST was used to do a preliminary calibration of the upstream catchment in the Buriti Vermelho watershed that provided most of the flow. For this purpose, structure was removed from the WEAP application, focusing only on the catchments upstream of the first reservoir. For the preliminary calibration, the following 19 parameters were adjusted:

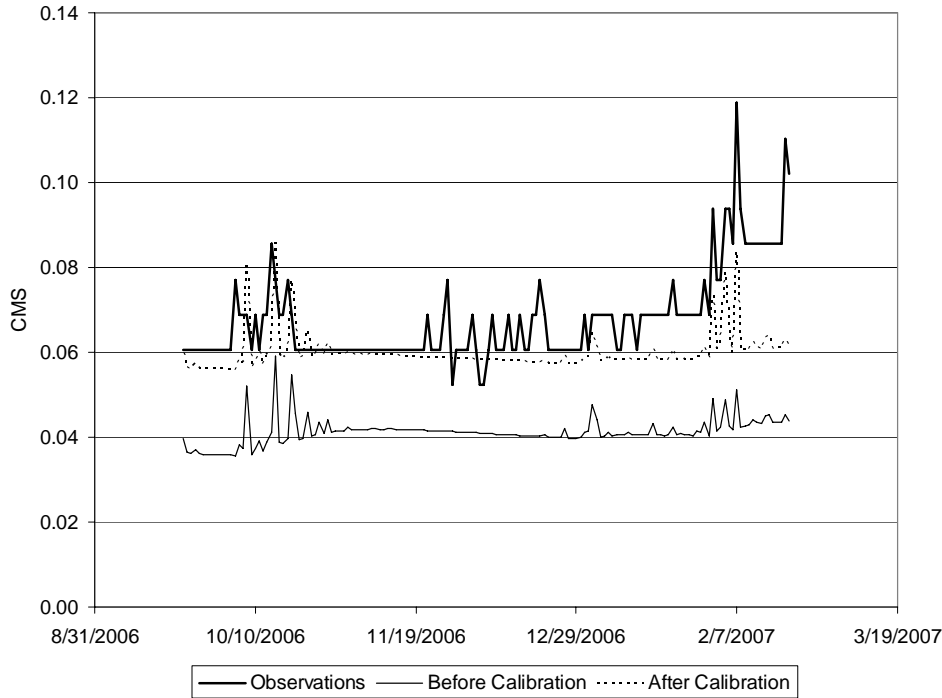
1. Deep water conductivity
2. Deep water capacity
3. Soil water capacity for the following land covers
  - a. Built areas
  - b. Cerrados
  - c. Riparian land
  - d. Upstream rainfed areas
  - e. Downstream rainfed areas
  - f. Pivot-irrigated areas
  - g. Grassland
4. The scaling factor for the leaf area index
5. The root zone conductivity for the same land covers
6. Initial soil water depth for
  - a. Irrigated land
  - b. Rainfed land

The streamflow below the catchment inflow point was then compared to an estimated value based on the flow below the reservoir. This approach was taken because a gauge was unavailable at the desired point. The preliminary calibration can then be refined once the reservoir is modeled, and the estimated flow below the reservoir (where a gauge is available) can then be compared to measured values.

To make it easier to implement PEST with WEAP, a sensible set of defaults was provided for most parameters in the PEST input files, and a template was created with prompts for application-specific variables. The template, which appears in Appendix A, was then filled in with the specific information for the Buriti Vermelho and then PEST was executed. There were some technical problems with the run, apparently related to the use of WEAP’s application programming interface (API) to repeatedly run the model. Most of these seemed to be related to problems of timing regarding opening and closing files. However, the run was completed, with the results shown in Figure 4. As seen in the figure, calibrating with PEST led to a significantly better fit between the values calculated in WEAP and the observations. The whole exercise took several hours, but in the course of the activity 19 parameters were adjusted simultaneously. The use of PEST made the work of calibration much easier than it would have been otherwise.

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<sup>2</sup> <http://www.mpassociates.gr/software/environment/pest.html>



**Figure 4:** Observed and calculated stream flow before and after calibration

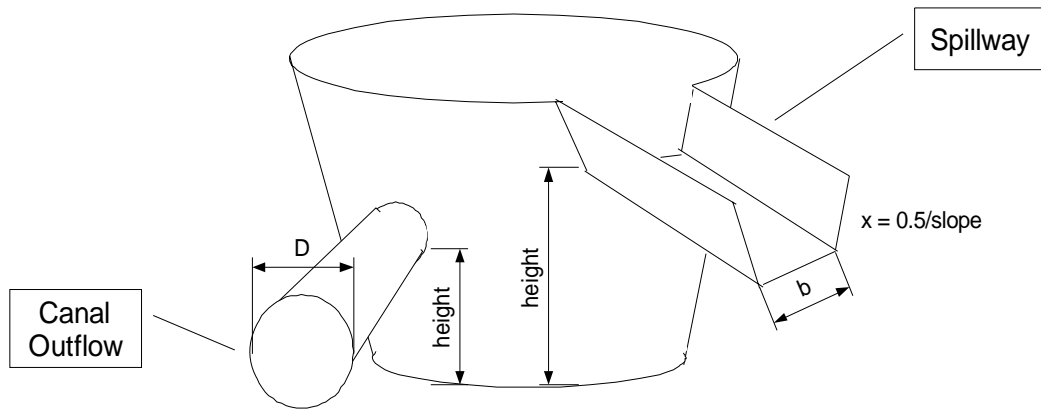
#### *A Small-Reservoir Model Linked to WEAP*

An idealized diagram of the small reservoirs that are used in the Buriti Vermelho watershed is shown in Figure 5. As shown in the figure, there is a canal outflow pipe with a circular cross-section and a spillway with a trapezoidal cross-section. The reservoir is unoperated, with the allocation of water between the canal and the spillway being determined entirely by the hydraulics of the reservoir. Flow in the canal pipe and the spillway are therefore functions of the head of water above the pipe or spillway opening, with the pipe having a  $\sqrt{h}$  dependence and the spillway having a more complicated dependence, determined by Manning's equation. The relevant equations are:

$$Q_c = \frac{1}{4} \pi D^2 C_d \sqrt{2gh}$$

$$Q_s = \frac{1}{n} \sqrt{J} (b + xh) h \left( \frac{(b + xh)h}{b + 2h(1 + x^2)} \right)^{2/3}$$

where  $Q_c$  and  $Q_s$  are the flow from the canal pipe and the spillway,  $C_d$  is the drag coefficient,  $D$  is the diameter of the pipe,  $h$  is the head in either the pipe or the spillway,  $n$  is Manning's roughness coefficient,  $J$  is the slope of the canal,  $b$  is the size of the base of the spillway, and  $x$  is the change in the horizontal distance with each increase in the head, divided by two.



**Figure 5:** Diagram of the Small Reservoir

Dynamically, the volume of water in the reservoir is related to head of water above the canal or spillway, which then determines the flow from the reservoir, which in turn causes a reduction in volume. The volume is also affected by the flow of water into the reservoir from upstream, referred to below as “base flow”.

There is no exact, closed-form solution to the dynamic equations. While sensible approximations to Manning’s equation can be introduced that allow the formulas to be integrated, the solution can be manipulated algebraically to get the head (the relevant variable) by itself on one side of the equation. For this reason, a numerical approach was followed. The numerical solution was implemented in C and a dynamic link library (DLL) was produced, which can then be called from WEAP. The program code is given in Appendix C. The functions that calculate  $Q_c$  and  $Q_s$  require each of the variables given above, the number of minutes in each time step (here, 60 minutes), the number of time steps (here, 24 – that is, one day), the initial elevation in the reservoir, the base flow, and fitted parameters for the volume-elevation curve approximated as a quadratic as inputs.

Within WEAP, the DLL is called using the following command for  $Q_c$  and a similar command for  $Q_s$ :

```
Call(unopres.dll!AveQc,
Elevation[CMS],
Base flow[LS],
60, 24,
Cd, Diameter[m], Canal 1 height[m],
b[m], x[m], Manning coefficient, slope, Spillway height[m],
800.31, -556.09, 115.36)
```

### *The Volta Basin*

The Volta River Basin in West Africa is shared by Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali and Togo, and covers an area of 400,000 km<sup>2</sup>. Ghana and Burkina Faso share 85% of the basin area, while the remaining 15% of the area is distributed among Benin, Côte d'Ivoire, Mali and Togo. The Volta River Basin has three main tributaries, namely the White Volta and the Black Volta which originate in Burkina Faso, and the Oti-Pendjari River which originates in Benin.

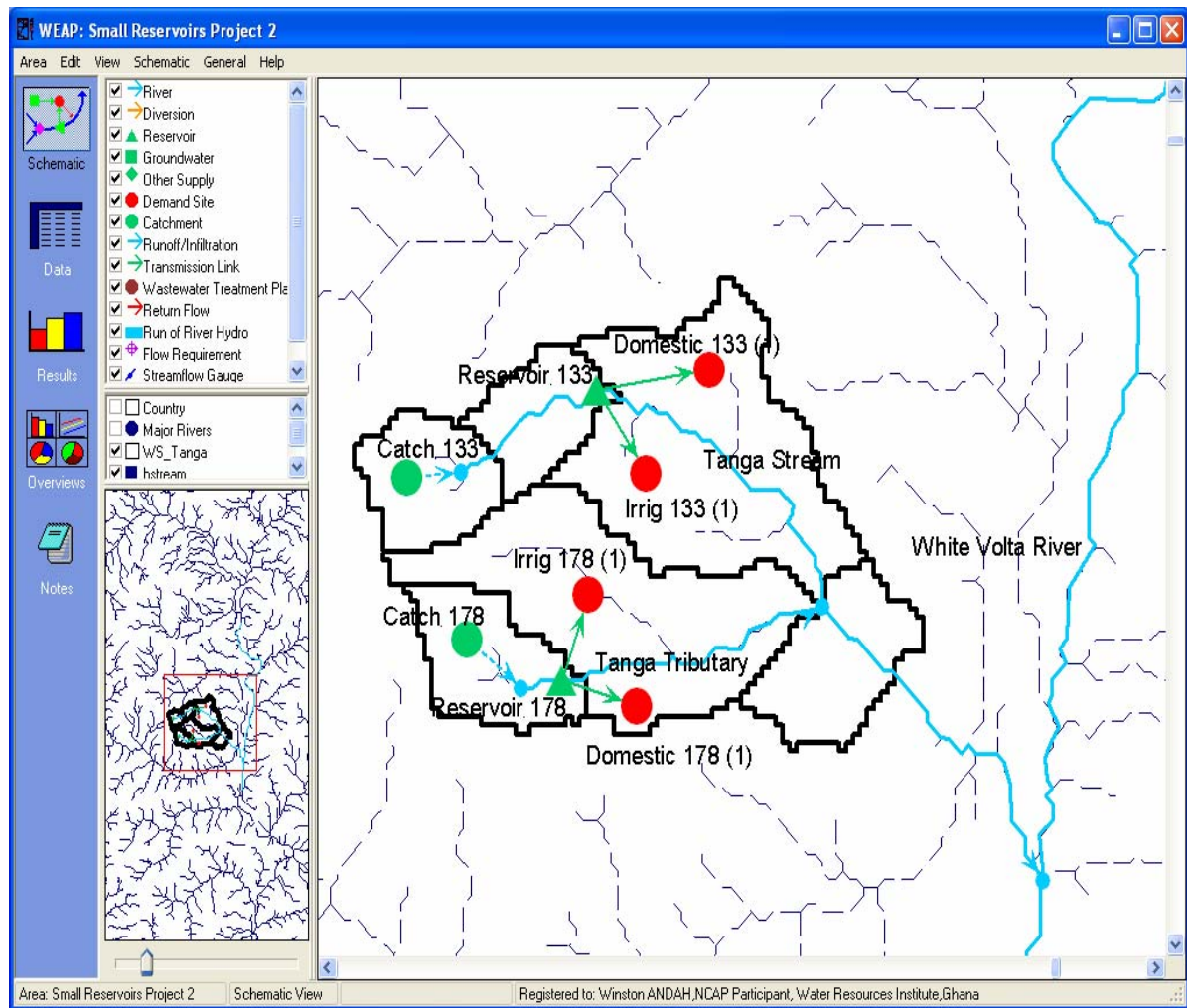
The White Volta Basin, the focus of this research, covers a total land area of 104,752 km<sup>2</sup> with 45,804 km<sup>2</sup> (43.7%) within Ghana and the remaining 58,948 km<sup>2</sup> (56.3%) outside Ghana. The White Volta basin drains the three Northern regions of Ghana, namely, the Upper East, Upper West and the Northern regions.

Tragically, Mr Issac Asamoah, a Water Resources Engineer of the Water Resources Commission (WRC) and seconded as a researcher on the Small Reservoir Project for the WEAP development for the project site passed away. At present, the WEAP application has been developed and is available, but the anticipated scenario analyses have not been carried out.

### *Study Area*

Two surface reservoirs in the White Volta Basin in Ghana in the Upper East Region were selected for the study (see Figure 6). The average rainfall of the study area is approximately 1100 mm/year. The area experiences a rainy season from late May to mid-October, and a dry season from November through early May. The annual mean temperature is 29°C with annual mean maximum temperature being 34°C. Maize, groundnut and millet, which constitute a majority of the diet of the population of the area, are the primary crops grown in the area during the wet season. Tomatoes, onions and other vegetables, such as okra and leaf vegetables for soups, are grown during the dry season in the irrigated areas. Onions provide the largest income while various other crops provide supplemental food for the households or small profits at the local markets.

The two reservoirs collect surface runoff during the wet season and water is released from the reservoirs to irrigate crops. Water from the reservoirs also serves the livestock and other basic domestic needs. The Tanga reservoir, which is part of a cascading reservoir system, is 10.6 ha (Liebe, 2002; Faulkner, 2006) and the total area under cultivation is 1.6 ha. The reservoir is located near the main junction at the market in the village of Tanga. Tanga is approximately 4.5 km south of the town of Zebilla, in the Bawku West District of the Upper East Region. The Weega Reservoir has a surface area of 11.9 ha (Liebe, 2002; Faulkner, 2006) and the total area under cultivation is 6.0 ha. It is located 3km south of the Tanga reservoir and 7.5 km south of Zebilla, near the village of Weega.



**Figure 6: Study Area and WEAP Application for the White Volta Basin**

### *Purpose*

Rural communities in the White Volta Basin depend on water from small multi-purpose reservoirs for their households, livestock, and irrigation schemes. The study is meant to develop tools for small reservoir analysis and design, and build confidence in a science-based approach to planning reservoir systems. Based on this, smallholders can realize the ultimate goal of increasing food production, reducing poverty, and improving rural livelihoods.

### *Data Preparation*

Demand sites were aggregated for water consumption in the study. Demographic and water use information were applied to construct alternative scenarios that examine how consumption of water evolves over time for domestic uses (not including drinking), irrigation and livestock. Domestic demand sites considered in the study are Tanga-Gunga, Tanga-Kpsalsako, Sitande, Weega and Tonde. Irrigation demand sites considered are Tanga and Wiiga. Table 1 indicates population and per capita water demand, irrigated areas are given Table 2.

**Table 1:** Population and Per Capita Water Demand (Faulkner 2006 & SIP 1997)

Domestic Site	Population	Per Capita Water Consumption (l/c/d)	
		2005	2030
Tanga-Gunga	655	30	40
Tanga-Ksalsako	380	30	40
Sitande	925	30	40
Wiiga	594	30	40
Toende	1006	30	40

**Table 2:** Irrigated Area (Faulkner 2006)

Irrigation Site	Area under Cultivation (ha)	Water Released for Season (m <sup>3</sup> )
Tanga	1.60	53,366
Wiiga	6.01	68,268

Catchment simulation method, thus rainfall-runoff method (FAO), was used to simulate the flows into the two reservoirs.

The following hydrometeorological data were used in the model:

- Monthly rainfall
- Monthly evapotranspiration (ET)
- Reservoir storage capacities
- Volume-elevation relationships
- Net monthly evaporation.

## Lessons learned

The project in the White Volta Basin is a typical WEAP application. It can be built using the standard techniques described in WEAP tutorials. In contrast, the São Francisco application had some unusual elements, mainly because of the unoperated reservoirs. In reflecting upon the São Francisco, the following recommendations are offered.

The recommendations all focus on the task of building an innovative application. If there are significant innovations, then it can be expected that unforeseen problems may arise. This is an unavoidable consequence of doing something new. However, the impact of the unforeseen problems can be minimized. First, any innovative extensions to WEAP or new modeling approaches should be tested on a small-scale example before investing time building them into a full application. Second, the application should be built incrementally, testing after each step. Third, and finally, bear in mind that in WEAP, only the results from the previous time step are available. In the case of the São Francisco, this meant that the model had to be implemented with an external module (a DLL).

## Recommendations

In general, for any WEAP model, ensure that the purpose of the model is clear from the start, and discuss possible scenarios before implementing the model. This way, when decisions have to be made about adding or dropping model features, there is a clear plan to use as a basis for the decision.

Second, develop the WEAP model incrementally, creating parts of the model and testing them one at a time. If possible, use a formal calibration tool like PEST. If possible, build isolated parts of the model (for example, a catchment) and calibrate them in isolation, then bring the different components together.

Third, as discussed under “Lessons Learned,” test any innovative modeling approaches on a small example first, and ensure that it can be implemented as intended within WEAP. If not, it may be necessary to modify the approach. For example, in the São Francisco application, it turned out not to be possible to implement the hydraulic reservoir model using WEAP’s built-in model-building facilities, and it became necessary to build an external model.

## Limitations of the tool

WEAP is a very flexible tool. While allowing for considerable variation in modeling approaches, it also provides a structure that allows a broad range of studies to be implemented using the built-in models. However, it does have some limitations that can make it challenging to extend into areas that do not fit the situations for which WEAP is designed.

The main limitation is on access to calculations. Internally, WEAP carries out a simultaneous water allocation calculation within each time step using a linear programming model. However, external models do not have access to this functionality, so calculations are only available from a previous time step. In cases where short-term dynamics are important, this can be a significant limitation. Additionally, some outputs, such as crop yields or soil water depth, cannot be used in calculations. Finally, there is a limited number of catchment models to choose from. This can be problematic if other aspects of a project use a different catchment model, as the parameters must be translated from one model to another, and they may focus on different aspects of the catchment dynamics.

These limitations were not serious constraints for the Volta Basin application. However, they placed noticeable constraints on the São Francisco basin application. They were overcome in two different ways: first, by building part of the model as an external model that is called from WEAP, via WEAP’s “call” function; second, by building models separate from WEAP that can take WEAP output to calculate further, downstream outputs. These models are reported as separate tools, since they are not WEAP-specific.

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## Contacts and Links

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## Appendix A: Template for running PEST

Below a template for the PEST control file is provided. Prompts are indicated by “#ID#”. For instance, #NPAR#” should be replaced by the number of parameters, and #NOBS# by the number of observations. Ellipses between #'s indicate a variable number of similar lines. For example, the lines

```
#OBSNME#    #OBSVAL#    #WEIGHT#    #OBSgrp#
#...#
```

in the template mean a variable number of lines, each of which contains an observation name, an observation value, a weight, and an observation group.

The template cannot be clearly understood without reading the PEST documentation. The prompts are meant to make it easier to find the relevant information. For example, NPAR is the identifying label used in the documentation for the number of parameters, so searching the documentation for “NPAR” will find the relevant section.

```
pcf
* control data
restart estimation
#NPAR# #NOBS# 1 0 #NOBSGP#
1 1 single point 1 0 0
5 2.0 0.4 0.02 10
5 5 1.0e-3
0.1
30 0.01 4 4 0.01 3
1 1 1
* parameter groups
WEAPvar relative 0.01 0.0 switch 2.0 parabolic
* parameter data
#FIXPARAMNAME#      fixed   factor #VAL# 0 0 WEAPvar 1.0 0.0 1
#VARPARAMNAME# none factor #INITVAL# #LBOUND# #UPBOUND# WEAPvar 1.0 0.0
1
* observation groups
#OBSgrp_1#
#OBSgrp_2#
# ... #
#OBSgrp_NOBSGP#
* observation data
#OBSNME#    #OBSVAL#    #WEIGHT#    #OBSgrp#
#...#
* model command line
cscript.exe WEAPpest.vbs
* model input/output
WEAPParam.tpl WEAPParam.dat
WEAPOutflowPIF.txt WEAPOutflow.txt
```

The other two files are the PEST Instruction File (PIF) and the Template File, which is a template for the data input file. A sample template file is provided in Appendix B.

## Appendix B: Visual Basic Script to Calibrate with PEST

This is a sample Visual Basic script that is run by PEST to execute WEAP and get outputs.

```
' Calibrate Rainfall-Runoff response of a gaged catchment using PEST
' This file is referenced by PEST to perform the following
' 0 - open WEAP, specify area
' 1 - read numbers from PEST parameter file
' 2 - change parameters in a manner identified by PEST

' **OPEN MODEL IN WEAP**
Option Explicit
Dim WEAP, WArea, WScenario, BaseYear, EndYear

WArea      = "BV_Hydro_Calibration_Pest_CAonly"
WScenario  = "Current Accounts"
BaseYear   = 2007
EndYear    = 2007
OpenWEAP

' WEAP.VERBOSE = 4

' **READ NUMBERS FROM PEST PARAMETER FILE INTO ARRAY**
Dim pestDataFile
ReDim pestParam(0)

pestDataFile = "C:\Pest\WEAPParam.dat"
PopParamArray

' **LOAD NEW PARAMETERS FROM PARAMETER ARRAY**
WEAP.BranchVariable("\Key\SM Method parameters\Deep water
capacity").Expression = pestParam(1)
WEAP.BranchVariable("\Key\SM Method parameters\soil water capacity\built
areas").Expression = pestParam(2)
WEAP.BranchVariable("\Key\SM Method parameters\soil water
capacity\cerrados").Expression = pestParam(3)
WEAP.BranchVariable("\Key\SM Method parameters\soil water
capacity\riparian").Expression = pestParam(4)
WEAP.BranchVariable("\Key\SM Method parameters\soil water capacity\rainfed
up").Expression = pestParam(5)
WEAP.BranchVariable("\Key\SM Method parameters\soil water capacity\rainfed
down").Expression = pestParam(6)
WEAP.BranchVariable("\Key\SM Method parameters\soil water capacity\pivo
E").Expression = pestParam(7)
WEAP.BranchVariable("\Key\SM Method parameters\soil water
capacity\Grass").Expression = pestParam(8)
WEAP.BranchVariable("\Key\Crop\LAI\LAI Scaling Factor").Expression =
pestParam(9)
WEAP.BranchVariable("\Key\SM Method parameters\root zone
conductivity\built areas").Expression = pestParam(10)
WEAP.BranchVariable("\Key\SM Method parameters\root zone
conductivity\cerrados").Expression = pestParam(11)
WEAP.BranchVariable("\Key\SM Method parameters\root zone
conductivity\riparian").Expression = pestParam(12)
WEAP.BranchVariable("\Key\SM Method parameters\root zone
conductivity\rainfed up").Expression = pestParam(13)
WEAP.BranchVariable("\Key\SM Method parameters\root zone
conductivity\rainfed down").Expression = pestParam(14)
```

```

WEAP.BranchVariable("\Key\SM Method parameters\root zone conductivity\pivo
E").Expression = pestParam(15)
WEAP.BranchVariable("\Key\SM Method parameters\root zone
conductivity\Grass").Expression = pestParam(16)
WEAP.BranchVariable("\Key\SM Method parameters\deep water
conductivity").Expression = pestParam(17)
WEAP.BranchVariable("\Key\irrigation\center pivot\lower
threshold").Expression = pestParam(18)
WEAP.BranchVariable("\Key\irrigation\center pivot\upper
threshold").Expression = pestParam(19)

' **RUN WEAP AND EXPORT STREAMFLOW RECORD**
CALL WEAP.LoadFavorite("Catchment 1 discharge")
CALL WEAP.ExportResults("C:\Pest\WeapOutFlow.txt", FALSE, TRUE)
WEAP.SaveArea()

' **CLOSE WEAP
SET WEAP = Nothing

' **WAIT A MILLION
Dim i
i=0
FOR i=1 TO 1000000
  i = i + 1
NEXT

Dim WEAPquery
WEAPquery = "select * from Win32_Process where Name='weap.exe'"
Do while GetObject("winmgmts:").ExecQuery(WEAPquery).Count > 0
loop

' **WAIT A MILLION
i=0
FOR i=1 TO 1000000
  i = i + 1
NEXT

''
'' Subroutines
''
'=====
' Open WEAP and run for period (BaseYear) to (EndYear)

Sub OpenWEAP
  Set WEAP = CreateObject("WEAP.WEAPApplication")

  WEAP.Verbose = 0
  WEAP.Logfile = "WEAPAutomationErrors.txt"

  WEAP.ActiveArea = WArea
  WEAP.ActiveScenario = "Current Accounts"
End Sub
'=====

'=====
' Open PEST parameter file and read (row by row) to pestParam array (skip
first line, 0)
Sub PopParamArray
  Dim fsoFileSystem      'file system object used to locate and open file

```

```

Dim tsTextStream          'text stream of file's contents
Dim dblLast              'last value from file
Dim dblCurrent           'current value from file
ReDim pestParam(0)      'dynamic array of size zero
Set fsoFileSystem = CreateObject("Scripting.FileSystemObject")
Dim paramFile
Set paramFile = fsoFileSystem.GetFile(pestDataFile)
' Read the contents of the file.
Set tsTextStream = paramFile.OpenAsTextStream(1,-2)
Dim bFirstLine,dblSum,strLine,iColumn

bFirstLine = -1 ' set equal to 1 if there is a column header line
Do While Not tsTextStream.AtEndOfStream
  'store the last value
  dblLast = dblCurrent
  strLine = tsTextStream.ReadLine
  'remove spaces
  strLine = Trim(strLine)
  'skip header row
  If (bFirstLine = 1) Then
bFirstLine = -1
  Else
    dblCurrent = CDbI(strLine)
    ReDim Preserve pestParam(UBound(pestParam)+1)      'resize array,
maintain previous values
    'Fill new array slot with current value
    pestParam(UBound(pestParam)) = dblCurrent
  End If
Loop
End Sub
'=====

```

The data file read in by this file is generated by PEST using the following template file:

```

ptf #
# DWC      #
# SWCBA    #
# SWCCE    #
# SWCRI    #
# SWCRU    #
# SWCRD    #
# SWCPE    #
# SWCGR    #
# LSF      #
# RZCBA    #
# RZCCE    #
# RZCRI    #
# RZCRU    #
# RZCRD    #
# RZCPE    #
# RZCGR    #
# DWCOND   #
# ILT      #
# IUT      #

```

## Appendix C: C Code for Unoperated Reservoir DLL, to Call From WEAP

This appendix provides C code for a model of an unoperated reservoir of the type illustrated in Figure 5. The model can be compiled into a DLL and then called from WEAP.

```

dll.h
#ifndef _DLL_H_
#define _DLL_H_

typedef struct {
    double Cd;
    double D;
    double height;
} canalInfo;

typedef struct {
    double b;
    double x;
    double n;
    double J;
    double height;
} spillwayInfo;

typedef struct {
    double a;
    double b;
    double c;
} volQuadratic;

typedef struct {
    int dur;
    int num;
} timeInfo;

#define CANAL 0
#define SPILLWAY 1

/*
    Expect these params:
    E0, BaseFlow, minutes/step, numsteps, Cd, D, canal height,
    b, x, n, J, spillway height, volume a, volume b, volume c
*/

__declspec(dllexport) double AveQc(double *Parameters, int LastIndex);

__declspec(dllexport) double AveQs(double *Parameters, int LastIndex);

double head(double elev, double height);
double Qcanal(double elev, canalInfo info);
double Qspillway(double elev, spillwayInfo info);
double Vol(double E, volQuadratic params);
double Elev(double V, volQuadratic params);
double GetAveQ(int which, double E0, double BaseFlow, timeInfo time,
    canalInfo canal,
    spillwayInfo spill, volQuadratic vol);

#endif /* _DLL_H_ */

```

*dllmain.c*

```

#include "dll.h"
#include <windows.h>
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

__declspec(dllexport) double AveQc(double *Parameters, int LastIndex) {
    timeInfo time;
    canalInfo canal;
    spillwayInfo spill;
    volQuadratic vol;
    double E0, BaseFlow;

    E0 = Parameters[0];
    BaseFlow = Parameters[1];

    time.dur = floor(Parameters[2]);
    time.num = floor(Parameters[3]);

    canal.Cd = Parameters[4];
    canal.D = Parameters[5];
    canal.height = Parameters[6];

    spill.b = Parameters[7];
    spill.x = Parameters[8];
    spill.n = Parameters[9];
    spill.J = Parameters[10];
    spill.height = Parameters[11];

    vol.a = Parameters[12];
    vol.b = Parameters[13];
    vol.c = Parameters[14];

    return GetAveQ(CANAL, E0, BaseFlow, time, canal, spill, vol);
}

__declspec(dllexport) double AveQs(double *Parameters, int LastIndex) {
    timeInfo time;
    canalInfo canal;
    spillwayInfo spill;
    volQuadratic vol;
    double E0, BaseFlow;

    E0 = Parameters[0];
    BaseFlow = Parameters[1];

    time.dur = floor(Parameters[2]);
    time.num = floor(Parameters[3]);

    canal.Cd = Parameters[4];
    canal.D = Parameters[5];
    canal.height = Parameters[6];

    spill.b = Parameters[7];
    spill.x = Parameters[8];
    spill.n = Parameters[9];
    spill.J = Parameters[10];
    spill.height = Parameters[11];

```

```

        vol.a = Parameters[12];
        vol.b = Parameters[13];
        vol.c = Parameters[14];

        return GetAveQ(SPILLWAY, E0, BaseFlow, time, canal, spill, vol);
    }

double head(double elev, double height) {
    return elev > height ? elev - height : 0.0;
}

double Qcanal(double elev, canalInfo info) {
    double hd, A, X1;
    static double g = 9.81;
    static double pi = 3.1415926535897932384626433832795;

    hd = head(elev, info.height);
    A = 0.25 * pi * info.D * info.D;
    X1 = sqrt(2.0 * g * hd);

    return 1000 * info.Cd * A * X1;
}

double Qspillway(double elev, spillwayInfo info) {
    double hd, B, A, P, R;

    hd = head(elev, info.height);
    B = info.b + 2 * info.x * hd;
    A = (info.b + info.x * hd) * hd;
    P = info.b + 2 * hd * (1 + info.x * info.x);
    R = A/P;

    return 1000 * (1/info.n) * sqrt(info.J) * A * pow(R, 2.0/3.0);
}

double Vol(double E, volQuadratic params) {
    return params.c + E * (params.b + E * params.a);
}

double Elev(double V, volQuadratic params) {
    double D;

    D = params.b * params.b - 4 * params.a * (params.c - V);
    return (-params.b + sqrt(D))/(2 * params.a);
}

double GetAveQ(int which, double E0, double BaseFlow, timeInfo time,
canalInfo canal,
    spillwayInfo spill, volQuadratic vol) {
    int i;
    double sumQc, sumQs, Qc, Qs;
    double E, V;

    sumQc = 0;
    sumQs = 0;

    V = Vol(E0, vol);

```

```

for (i = 0; i < time.num; i++) {
    E = Elev(V, vol);
    Qc = Qcanal(E, canal);
    Qs = Qspillway(E, spill);
    sumQc += Qc;
    sumQs += Qs;
    // 0.06 converts from L/s to m^3/min
    V += 0.06 * time.dur * (BaseFlow - Qc - Qs);
}

if (which == CANAL) {
    return sumQc/time.num;
} else {
    return sumQs/time.num;
}
}

BOOL APIENTRY DllMain (HINSTANCE hInst      /* Library instance handle. */ ,
                      DWORD reason        /* Reason this function is being
called. */ ,
                      LPVOID reserved    /* Not used. */ )
{
    switch (reason)
    {
        case DLL_PROCESS_ATTACH:
            break;

        case DLL_PROCESS_DETACH:
            break;

        case DLL_THREAD_ATTACH:
            break;

        case DLL_THREAD_DETACH:
            break;
    }

    /* Returns TRUE on success, FALSE on failure */
    return TRUE;
}

```