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WEAP21 – A Demand-, Priority-, and Preference-Driven Water Planning Model
Part 1: Model Characteristics

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Abstract: *The Water Evaluation and Planning Version 21 (WEAP21) Integrated Water Resource Management (IWRM) model seamlessly integrates water supplies generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements and is governed by the natural watershed and physical network of reservoirs, canals, and diversions. This version (WEAP21) extends the previous WEAP model by introducing the concept of demand priorities and supply preferences, which are used in a linear programming heuristic to solve the water allocation problem as an alternative to multi-criteria weighting or rule-based logic approaches. WEAP21 introduces a transparent set of model objects and procedures that can be used to analyze a full range of issues faced by water planners through a scenario-based approach. These issues include climate variability and change, watershed condition, anticipated demands, ecosystem needs, the regulatory environment, operational objectives, and available infrastructure.*

Keywords*: Integrated Water Resources Management, physical hydrology, decision support systems, priorities, preferences and equity groups.*

Introduction

Water resources planning, once an exercise based primarily on engineering considerations, increasingly occurs as part of complex, multi-disciplinary investigations that bring together a wide array of individuals and organizations with varied interests, technical expertise, and priorities. In this multi-disciplinary setting, successful planning requires effective Integrated Water Resource Management (IWRM) models that can clarify the complex issues that can arise (Loucks, 1995). Effective IWRM models must address the two distinct systems that shape the water management landscape. Factors related to the bio-physical system, namely climate, topography, land cover, surface water hydrology, groundwater hydrology, soils, water quality, and ecosystems shape the availability of water and its movement through a watershed. Factors related to the socio-economic management system, driven largely by human demand for water, shape how available water is stored, allocated, and delivered within or across watershed boundaries. Increasingly operational objectives for the installed hydraulic infrastructure constructed as part of the management system seek to balance water for human use and water for environmental needs (Biswas, 1981; Jamieson, 1986, Bouwer, 2000; Zalewski, 2002; Westphal et al., 2003).

To capture the first set of factors, it is necessary to develop a better understanding of how the natural hydrologic system behaved prior to the onset of the dramatic hydrologic manipulations that characterizes many of our water resource systems today (Muttiah and Wurbs, 2002). This type of analysis relies upon the use of hydrologic modeling tools that simulate physical processes such as precipitation, evapotranspiration, runoff, and infiltration (see Figure 1a, pre-development). Following the construction of hydraulic structures such as dams and diversions (see Figure 1b, post-development), factors related to the management system must also be considered. These systems were put in place to govern the allocation of water between competing demands, be they consumptive demand for agricultural or urban water supply or non-consumptive demand for hydropower generation or ecosystem protection.

The water management literature is rich with IWRM models that have tended to focus either on understanding how water flows through a watershed in response to hydrologic events or on allocating the water that becomes available in response to those events. For example, the US Department of Agriculture's Soil Water Assessment Tool (SWAT, Arnold and Allen [1993]), includes sophisticated physical hydrologic watershed modules that describe, among others, rainfall-runoff processes, irrigated agriculture processes, and point and non-point water watershed dynamics, but a relatively simple reservoir operations module (Srinivasan et al., 1998; Ritschard et al., 1999; Fontaine et al., 2002). The RiverWare™ DSS is a state-of-the-art hydrologic and hydraulics operations model, which can be used to develop multi-objective simulations and optimizations of river and reservoir systems such as storage and hydropower reservoirs, river reaches, diversions, and water users, but requires upstream flows derived from a physical hydrologic model (Zagona et al., 2001).

The US Geological Survey's Modular Modeling System (MMS, Leavesley et al. [1996]) has provided a framework for integration with RiverWare, utilizing such models as the Precipitation Runoff Modeling System (Leavesley et al., 1983) that can supply boundary flows to RiverWare. Similarly, The US Army Corp of Engineers, HEC-ResSim (USACE, 2003) is a reservoir simulation model that can describe operating rules such as release requirements and constrains, hydropower requirements, multiple reservoir operations, etc., but it too requires prescribed flows from other models. The MODSIM DSS (Labadie et al., 1989) is a generalized river basin network flow model which can simultaneously incorporate the complex physical, hydrological, and institutional/administrative aspects of river basin management, including water rights, but boundary flows must be prescribed.

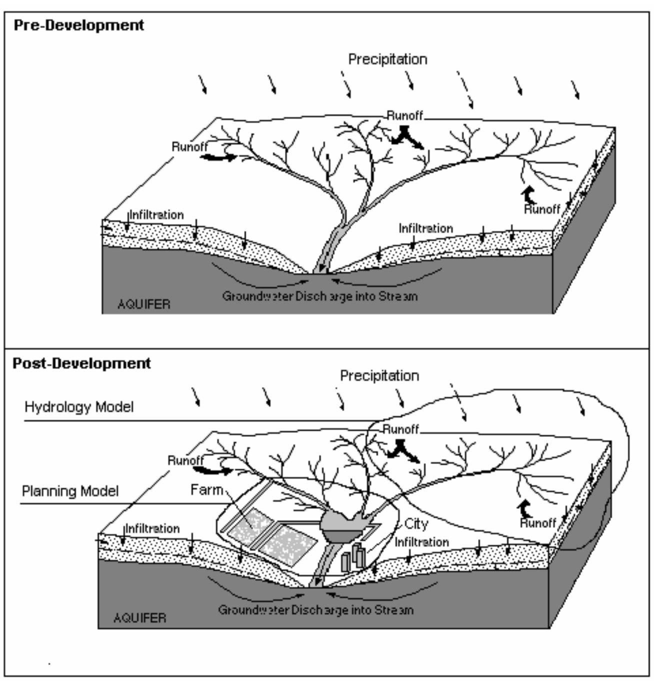

Figure 1. Characterization of (a) pre- and (b) post-watershed development that highlights the implications of water resource infrastructure on the hydrologic cycle

The MULINO DSS (Giupponi et al., 2004) is a multi-sectoral, integrated, and operational decision support system for sustainable use of water resources at the catchment scale, with a focus on the DSS as a multi-criteria decision aid. Similar to RiveWare, MULINO can accommodate a physical watershed hydrology model that is external to the system, linked through appropriate input-output procedures. WaterWare (Jamieson and Fedra, 1996; Fedra and Jamieson, 1996) is a sophisticated water resource DSS that includes dynamic simulation of physical models of water quality, allocation, rainfall-runoff, groundwater, and water management elements including demand/supply, cost-benefit analysis, and multi-criteria analysis. While WaterWare provides integration between the physical hydrology and the management system, application of the model requires a rather sophisticated level of user and hardware support.

The Water Evaluation and Planning Version 21 (WEAP21) IWRM model attempts to address the gap between water management and watershed hydrology and the requirements that an effective IWMR be useful, easy-to-use, affordable, and readily available to the broad water resource community. WEAP21 integrates a range of physical hydrologic processes with the management of demands and installed infrastructure in a seamless and coherent manner. It allows for multiple scenario analysis, including alternative climate scenarios and changing anthropogenic stressors, such as land use variations, changes in municipal and industrial demands, alternative operating rules, points of diversion changes, etc. WEAP21's strength is addressing water planning and resource allocation problems and issues, and importantly, is not designed to be a detailed water operations model, which might be used to optimize hydropower based on hydrologic forecasts, for example.

WEAP21 – A Demand-, Priority-, and Preference-driven Approach

The Water Evaluation and Planning (WEAP) model has a long history of development and use in the water planning arena. Raskin et al. (1992) first applied it to a study on the Aral Sea, but that version of WEAP had several limitations, including an allocation scheme that treated rivers independently, gave priority to demands on upstream sites over downstream sites, and assured demand sites that preferred groundwater to surface water were last in line in getting surface water allocations. Given these deficiencies, WEAP21 introduces major advances including a modern Graphic User Interface (GUI), a robust solution

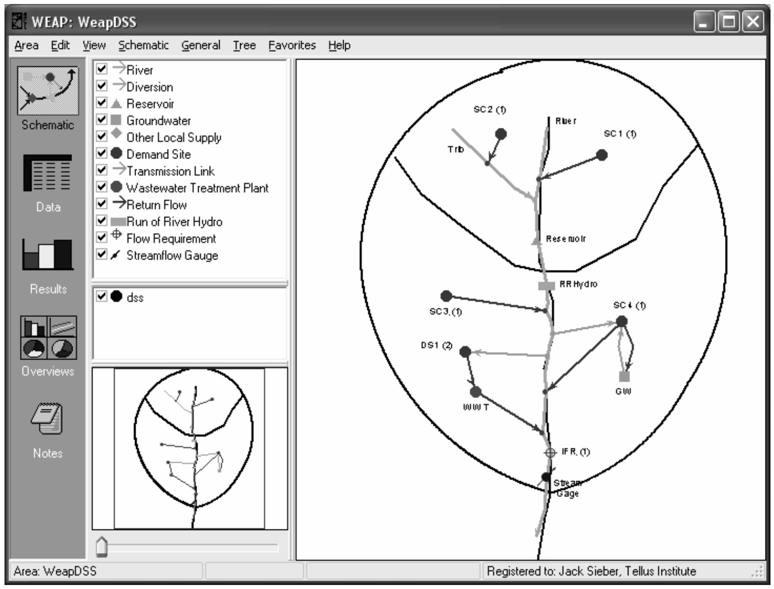

Figure 2. An example of a simple watershed, sub-divided into four catchments (SCs) using the WEAP21 graphical user interface model building tools.

algorithm to solve the water allocation problem, and the integration of hydrologic sub-modules that include a conceptual rainfall runoff, an alluvial groundwater model, and a stream water quality model.

WEAP21 data objects and the model framework are graphically oriented, with the software built using the Delphi Studio® programming language (Borland Software Corporation), and also utilizing MapObjects® software libraries from the Environmental Systems Research Institute (ESRI) to allow for spatial referencing of watershed attributes (e.g. river and groundwater systems, demand sites, wastewater treatment plants, watershed and political boundaries, and river reach lengths). WEAP21 model simulations are constructed as a set of scenarios, where simulation time steps can be as short as one day, to weekly, to monthly, or even seasonally with a time horizon from as short as a single year to more than 100 years.

The *Current Accounts* tool provide a snapshot of actual water demand, pollution loads, resources, and supplies for the system for the current or a baseline year. Scenarios are alternative sets of assumptions such as different operating policies, costs, and factors that affect demand such as demand management strategies, alternative supply sources and hydrologic assumptions, with changes in these data able to grow or decline at varying rates over the planning horizon of the study. Among others, the scenarios are evaluated with regards to supply sufficiency, cost, and average cost of delivered water, the meeting of in-stream flow requirements, hydropower production, and sensitivity of results based on uncertainty of key variables. These could include reductions in water demand due to demand side management, assumptions of rates of growth, incorporation of technical innovation, changes in supply, etc.

The advancements of WEAP21 have been based on the premise that at the most basic level, water supply is defined by the amount of precipitation that falls on a watershed or a series of watersheds with this supply progressively depleted through natural watershed processes, human demands and interventions, or enhanced through watershed accretions. Thus, WEAP21 adopts a broad definition of water demand, where the watershed itself is the first point of depletion through evapotranspiration via surface-atmosphere interactions (Mahmood and Hubbard, 2002). The residual supply, after the satisfaction of evaporative demands throughout the watershed, is the water available to the management system, which is typically the head flow boundary condition of a water planning or operations model. In addition to streamflow generated via hydrologic simulation, the user is free to prescribe time series of head flows for the surface water system and groundwater recharge for focusing solely on water management.

Figure 2 is a screenshot from the WEAP21 interface of a stylized water resource system, showing the drag-and-drop template from which demands and water resource objects can be created (demands, sub-catchments, rivers, reservoirs, transmission links, in-stream flow requirements, etc.) and placed on the interactive workspace. The dark, dashed line segment on the lower portion of the river indicates the river length that is hydraulically connected to the local groundwater aquifer, GW. DS is a conventional demand site, WWT is a wastewater treatment plant, IFR is an in-stream flow requirement, RR HydPwr is a run-of-the-river hydropower object.A WEAP21 study

Table 1. Description of the base-year land use categories for the four SCs, given as a percentage of their total area, where only SC4 has irrigated land cover types.

Base-Year 2000	*Irrigated*	*SC1*	*SC2*	*SC3*	*SC4*
Total Area (km^2)		250	330	350	320
Deciduous	No	35	40	15	
Evergreen	No	25	20	20	
Grassland	No	20	30	55	35
Shrub	No	20	10	10	20
Pasture	Yes				10
Grains	Yes				10
Orchards	Yes				5
Vegetables	Yes				10
Rice	Yes				10
TOTAL		100%	100%	100%	100%

begins by dividing the watershed into a number of irregular sub-catchments (SCs) based on watershed boundaries, climatological regions, land use categories, or combinations thereof. When combined, the sub-catchments account for the total study area of the encompassing watershed. This hypothetical watershed has been divided into four sub-catchments, where each is fractionally subdivided into several land cover classes, which combine to account for a total catchment area of 1,250 km^2 (Table 1).

A conceptual model of the hydrologic cycle is defined for each sub-catchment using a semi-distributed water balance approach that yields streamflow and groundwater recharge throughout the watershed (Yates, 1996; Yates and Strzepek, 1998). Each sub-catchment is represented by the dark circles with gray insets, with arrows originating from each of the SCs that link its hydrologic output to a stream or a groundwater aquifer. So in the case of SC1, generated runoff goes to the river while for SC2, the flow goes to the tributary. Watershed demand in these sub-catchments is estimated by the hydrologic model as evapotranspiration by trees, grasslands, and shrubs.

The SC4 sub-catchment also applies the surface hydrology model, but is linked to an alluvial groundwater aquifer, represented by the small rectangle and the fact that a return flow arrow is drawn from SC4 to the groundwater object. SC4 can draw water from either the surface supply or from the groundwater aquifer. Note that the surface supply is labeled with a "1," which indicates it is the preferred source to meet SC4's demand, while groundwater has a value of "2," indicating it is a secondary supply. The watershed's demand in SC4 is both through evapotranspiration by grasslands and the irrigated demand for pasture, grains, orchards, vegetables, and rice (Table 1). In addition, the node DS1 (represented by a single dark circle) is a municipal center that draws water from the river, returns it to a waste water treatment plant, and then to the river. The river's main stem includes a reservoir object, a run-of-the-river hydropower object, an in-stream flow requirement, and a stream gage.

The Bio-physical System: the Physical Hydrology Module

The WEAP21 model includes an irregular-grid, water balance model that can account for hydrologic processes within a watershed system and that can capture the propagating and non-linear effects of water withdrawals for different uses. Our approach is informed by Beven (2002), who challenges the trend towards physically-based modeling systems. He argues that watershed scientists increasingly attempt to apply first-principle fluid dynamics models in a manner similar to atmospheric scientists and oceanographers without achieving marked improvement over reduced form representations of the hydrologic cycle. Beven (2002) points out that, in hydrology, the small-scale flows are largely dominated by the local geometry and local boundary resistances of the individual flow paths rather than the dynamics of the fluid itself and that these geometries cannot be known in significant detail. Beven (2002) concludes with a call to differentiate between physically based in the sense of being based on defined assumptions and theory, and physically based in the sense of being consistent with observations.

The physical hydrology component of WEAP21 has been developed to account for two different hydrologic realities. The first is the notion that precipitation in sub-catchments located in the upstream portions of watersheds, with complex topography, steep slopes, and abrupt hills and valleys, contributes to groundwater baseflows that serve a gaining stream year-round, with a relatively short time lag (Winter et al., 1998; Winter, 2001; Eckhardt and Ulbrich, 2003; Burness et al., 2004). Conversely, sub-catchments located in lower portions of watersheds with flatter terrain tend to contribute to alluvial aquifers that are directly linked to the river system to which they can contribute flow (gaining streams) and from which they can receive seepage (losing streams), depending on hydrologic conditions. These groundwater systems can also provide storage from which users can draw water to satisfy demands (Figure 3). This schematic shows a watershed broken into two sub-catchments. SC-1 is a headwater catchment, without surface-groundwater interaction and applies the two "bucket" water balance model. SC-2 is characterized as being in a valley area, where the surface hydrology applies the single bucket water balance with recharge to an underlying alluvial aquifer which as groundwater-surface water interaction.

Surface Water Hydrology

The physical hydrology model consists of several conceptually simple components that are combined to be computationally efficient, but with enough specificity to capture important hydrologic process and address key water resource issues. For a given time step, the hydrology module is first run to update the hydrologic state of

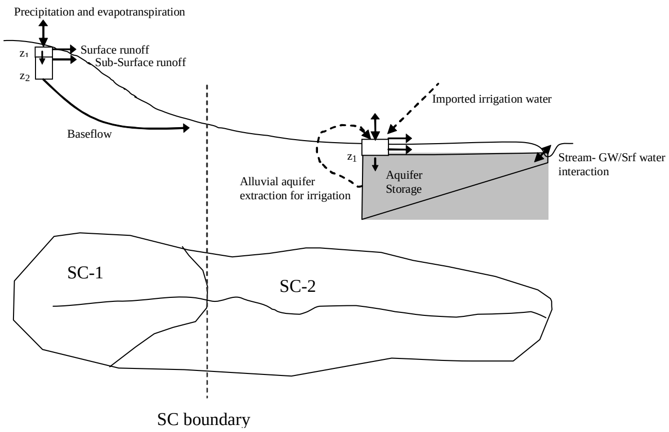

Figure 3. Physical hydrology component of WEAP21 with two different hydrologic realities.

the watershed, and thus provides mass balance constants used in the linear allocation problem in a second procedure within the same time step.

A one dimensional, 2-storage soil water accounting scheme uses empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff or interflow, and deep percolation (Yates 1996). Figure 4 shows the components of this conceptual model that allow for the characterization of land use and/or soil type specific impacts on runoff and groundwater recharge. A watershed is first divided into sub-catchment (SC's) and then further divided into *N* fractional areas, where a water balance is computed for each fractional area, *j* of *N*. Climate is assumed uniform over each fractional area where a continuous mass balance equation is written as

$$Sw_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j}-2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{\frac{LAI_j}{2}} - f_j k_j z_{1,j}^2 - (1-f_j)k_j z_{1,j}^2 \qquad (1)$$

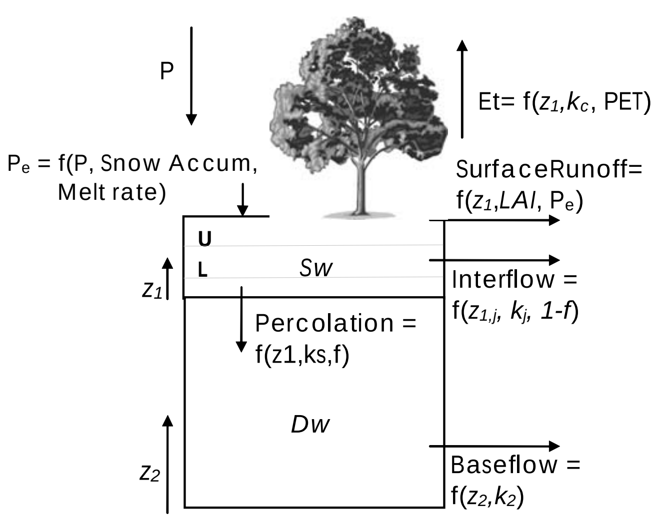

Figure 4. Schematic of the two-layer soil moisture store, showing the different hydrologic inputs and outputs for a given land cover or crop type, j

with the relative soil water storage, $z_{1,j}$ given as a fraction of the total effective storage and varies between 0 and 1, where 0 represents the permanent wilting point and 1 field capacity. The total effective storage of the upper layer is approximated by an estimate of the soil water holding capacity (Sw_j in mm) prescribed for each land cover fraction, *j*.

WEAP21 includes a simple temperature-index snowmelt model which computes an effective precipitation P_e. The model estimates snow water equivalent and snowmelt from an accumulated snowpack in the sub-catchment, where m_c is the melt coefficient given as

$$m_c = \begin{cases} 0 & T_i < T_s \\ 1 \quad \text{if} & T_i > T_l \\ \dfrac{T_i - T_s}{T_l - T_s} & T_s \le T_i \le T_l \end{cases} \qquad (2)$$

with T_i the observed temperature for period *i*, and T_l and T_s are melting and freezing temperature thresholds, with the melt rate is given as

$$m_i = \min(Ac_i m_c, Em) \qquad (3)$$

Snow accumulation, Ac_i is a function of m_c and the observed total precipitation, P_i

$$Ac_i = Ac_{i-1} + (1-m_c)P_i - m_{i-1} \qquad (4)$$

where *Em* is the available melt energy converted to an equivalent water depth/time. The effective precipitation, P_e is then computed as

$$P_e = P_i m_c + m_r \qquad (5)$$

The second term in Equation 1 is evapotranspiration from the fractional area, *j* where *PET* is the Penman-Montieth reference crop potential evapotranspiration given in mm/day and k_c^j is the crop/plant coefficient for each fractional land cover. When the model is run with longer time steps, *PET* is scaled to an appropriate depth/time (Allen et al. 1998). The third term represents surface runoff, where *LAI* is the Leaf and Stem Area Index (LAI), with the lowest LAI_j values assigned to the land cover class that yields the highest surface runoff response, such as bare soils. The third and fourth term are the interflow and deep percolation terms, respectively, where the parameter k_j is an estimate of the upper storage conductivity (mm/time) and f_j is a quasi-physical tuning parameter related to soil, land cover type, and topography that fractionally partitions water either horizontally, f_j or vertically ($1-f_j$). The surface and interflow runoff contributions from the upper store, *Ro* from each sub-catchment at time *t* is

$$Ro(t) = \sum_{j=1}^{N} A_j \left(P_e(t) z_{1,j}^{\frac{LAI_j}{2}} + f_j k_j z_{1,j}^2 \right) \quad (6)$$

where A_j is the contributing area of each land cover class, j. For sub-basins without a modeled aquifer (Figure 3), a mass balance for the second store is given as

$$Dw \frac{dz_{2,j}}{dt} = (1 - f_j) k_j z_{1,j}^2 - k_2 \, z_{2,j}^2 \quad (7)$$

where the inflow to this deep storage is the deep percolation from the upper storage given in Equation 1, and k_2 is the conductivity rate of the lower storage (mm/time) which is given as a single value for the catchment, and *Dw* is the deep water storage capacity (mm). Equations 1 and 7 are solved using a fourth-order runge kutta algorithm (Chapra and Canale 1998). Baseflow is simply

$$Bf(t) = \sum_{j=1}^{N} A_j (k_2 \, z_{2,j}^2) \quad (8)$$

When an alluvial aquifer is introduced into the model (Figure 3), the second storage term is dropped and recharge from the subcatchment is the percolation term from the top store to the aquifer, *P* (Vol/time)

$$P = \sum_{j=1}^{N} A_j (f_j k_j z_{1,j}^2) \quad (9)$$

Groundwater-Surface Water Interaction

Surface water and groundwater are dynamically linked, for when groundwater is depleted, a stream contributes to aquifer recharge (a losing stream), while a stream is considered to be gaining when there is substantial recharge to the aquifer across the watershed and flow is from the aquifer to the stream. Irrigated agriculture can complicate the picture even further, since water can be drawn from the stream, pumped from the local aquifer, or even imported from outside the basin, and thus both depletes and recharges the aquifer (Liang et al., 2003; Winter, 2001).

Capturing these dynamics is important, and the groundwater module implemented in WEAP21 allows for the dynamic transfer of water between the stream and the aquifer (Figure 5). In WEAP21, the aquifer is a stylized wedge that is assumed symmetric about the river, with total aquifer storage estimated under the assumption that the groundwater table is in equilibrium with the river. Thus the equilibrium storage for one side of the wedge, GS_e is given as,

$$GS_e = h_d * l_w * A_d * S_y \quad (10)$$

where h_d (m) represents the normal distance that extends horizontally from the stream, l_w (m) is the wetted length of the aquifer in contact with the stream, S_y is the specific yield of the aquifer, and A_d is the aquifer depth at equilibrium. An estimate of the height which the aquifer lies above or is drawn below the equilibrium storage height is given by y_d, so the initial storage *GS* in the aquifer at *t=0*, is given as,

$$GS(0) = GS_e + (y_d * h_d * l_w * S_y) \quad (11)$$

The vertical height of the aquifer above or below the equilibrium position is given as

$$y_d = \frac{GS - GS_e}{(h_d * l_w * S_y)} \quad (12)$$

and the more the aquifer rises relative to the stream channel, the greater the seepage back to the stream and vice versa, where total seepage, *S* from a side of the river (m^3/time) is defined by

$$S = (K_s * \frac{y_d}{h_d}) * l_w * d_w \quad (13)$$

where K_s (m/time) is an estimate of the saturated hydraulic conductivity of the aquifer, and d_w (m) is an estimate of the wetted depth of the stream, which is assumed time invariant. The wetted depth, together with the wetted length, approximates the area through which river-groundwater exchanges can take place, and the saturated hydraulic conductivity controls the rate at which water moves towards or away from this area. Once seepage is estimated, then half of the aquifer's total storage for the current time step is given as

$$GS(i) = GS(i-1) + (1/2\, P - 1/2\, Ex - S) \quad (14)$$

where *E* is the water withdrawn from the aquifer to meet demands, and *R* is the watershed's contributing recharge (Equation 8), and total aquifer storage is simply *2GS(i)*.

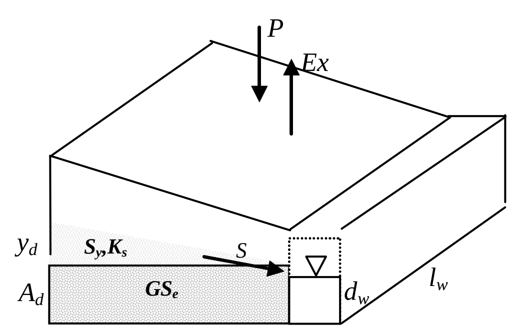

Figure 5. Schematic of the stylized groundwater system, and its associated variables

Irrigated Agriculture

Demand associated with irrigated agriculture shares the same surface hydrologic model as the watershed demand associated with evapotranspiration from natural land cover. A sub-catchment can be designated as containing irrigated land cover fractions, which are then assigned upper and lower irrigation thresholds, U_j and L_j for crop *j* (Figure 4). These thresholds dictate both the timing and quantity of water for irrigation, as crop evapotranspiration and percolation deplete the available water from the upper zone storage, $z_{1,j}$. These thresholds are designated by the dashed lines of the top soil moisture storage prescribed for each agricultural type as shown in Figure 4. When the relative soil moisture, $z_{1,j}$ drops below L_j, this triggers an irrigation demand for the fractional area, $ID_j = Cp_j * A_j \left[(UT_j - z1_{1,j}) * Sw_j \right]$, where Cp_j is an time-varying, integer variable, used to prescribe the cropping pattern for each crop *j*, using a WEAP21 GUI tool. The total irrigation demand for each sub-catchment is simply, $TID = \sum_{j=1}^{N} ID_j$.

Sub-catchments with irrigation require a water source to meet that demand and these sources are identified in WEAP21 by using the drag-and-drop capability to link the water sources to the appropriate irrigation demand location. In the example given in Figure 2, both surface and groundwater sources are available to meet the irrigation water requirements of SC4. The surface hydrology of SC4 is linked to the river via the return flow arrow from SC4 to the river. Also, the SC4 sub-catchment includes an alluvial groundwater system that is recharged from SC4 and dynamically linked to the lower river reaches, the extent of which is expressed through the wetted length variable, l_w.

Surface Water Quality

The WEAP21 model includes descriptive models of point source pollutant loadings that can address the impact of wastewater on receiving waters. The water quality parameters are currently limited to conservative constituents that decay according to an exponential decay function, dissolved oxygen (DO), Biological Oxygen Demand (BOD) from point sources, and in-stream water temperature. The water quality of reservoirs is currently not modeled. The first-order DO and temperature models are patterned after Chapra (1997), where water quality is simulated for select rivers, chosen by the WEAP21 user interface. Mass balance equations are written for each stream segment of the selected rivers, with hydrologic inflows from rivers and groundwater sources automatically input to simulate the water balance and mixing of DO and BOD concentrations and temperature along each reach. The river network is the same for the water resources and the water quality simulation and assumes complete mixing.

A heat balance equation is written for each node on the river, and the reach control volume is defined by its length, a constant cross-section, and the assumption of constant volume and steady state within a time step. The water quality equations are solved from upstream to downstream, by first computing the mixing from all tributaries, return flows, and groundwater sources, *j* and for each constituent (*T*, *DO*, and *BOD*), *x* at node *i*, as follows

$$x_i = \frac{\sum_{j=1}^{n} Q_j x_j}{\sum_{j=1}^{n} Q_j} \tag{15}$$

A heat budget is then computed for each control volume (Chapra, 1997: 451), given by

$$\frac{dT}{dt} = \frac{Q_i}{V} T_i + \frac{Rn}{\rho C_p H} + \left(\frac{\sigma (T_{air} + 273)^4 a \sqrt{e_{air}}}{\rho C_p H} \right) - \frac{Q_i}{V} T_{i+1} - \frac{\varepsilon \sigma (T_{i+1} + 273)^4}{\rho C_p H} - \frac{f(u)(T_{i+1} - T_{air})}{\rho C_p H} - \frac{g(u) D}{\rho C_p H} \tag{16}$$

where the first term on the right-hand side of Equation 16 is the upstream heat input to the stream segment with constant volume, *V* (m^3), expressed as a relationship of flow, Q_i (m^3/time), and temperature, T_i, at the upstream node. The second term is the net radiation input, R_n, to the control volume with the density, *r*, the specific heat of water, C_p, and the mean water depth of the stream segment, *H* (m). The third term is the atmospheric longwave radiation into the control volume, with the Steffan-Boltzman constant, *s*, the air temperature T_{air}, and *a*, a coefficient to account for atmospheric attenuation and reflection (Chapra, 1997). The fourth term is the heat leaving the control volume, while the fifth term is the longwave radiation of the water that leaves the control. The sixth and seventh terms are the conduction of heat to the air and the removal of heat from the river due to evaporation. The terms *f(u)* and *g(u)* are wind functions, and *D* is the vapor pressure deficit. The temperature, T_{i+1} is solved for the downstream node with a fourth-order Runga-Kutta and is the boundary condition temperature for the next reach after mixing is considered (Equation 15).

With T_i computed for each reach segment, the BOD-DO model is then solved from upstream to downstream. First, the oxygen saturation OS_i for each segment is estimated as a function of water temperature, $OS_i = 14.54 - (0.39T_i) + (0.01T_i^2)$ and an analytical solution of the classic Streeter-Phelps model is used to compute oxygen concentrations from point source loads of BOD (Tchobanoglous and Schroeder, 1985: 338)

$$O_i = OS_i - \left(\frac{k_d}{k_a - k_r}\right) \exp^{-kr(L_i/v_i)} - \exp^{-ka(L_i/v_i)} BOD_i - \left((OS_i - O_i)\exp^{-ka(L_i/v_i)}\right) \tag{17}$$

where k_d=*0.4*, k_a = 0.95, and k_r = 0.4 are the decomposition, the reaction, and the re-aeration rates, respectively (1/day); L_i is the reach length (m); v_i the velocity of the water in the reach given as $v_i = Q_i / A_i$ (m/s), with A_i is an assumed constant cross sectional wetted area of the reach (m^2); O_i is the oxygen concentration (mg/l); and BOD_i is the concentration of the pollutant loading (mg/l). Chapra (1997) describes stream bed and settling velocity effects on the reaction rate coefficients of BOD. If the depth of the water, $H < 2.4$ m then $kr_{bod} = 0.3 * (H / 2.4)^{-0.434}$ else it is given as $kr_{bod} = 0.3$ /day. The total removal rate of BOD is affected by the depth of the river and the water temperature, so $kr_{bod} = kr_{bod} + (0.25 / H)$ and then $kr_{bod} = kr_{bod} * 1.047^{(T_i - 20)}$. The BOD removal is given as

$$BOD_i = BOD_i * \exp^{kr_{bod}(L/v)} \quad (18)$$

The Management System: the Allocation Module

The starting point in a WEAP21 water management analysis is the development of watershed demands. Each demand is assigned a user-defined priority given as an integer from 1 (highest priority) to 99 (lowest priority). Each demand is then linked to its available supply sources, with each supply source preference set for each demand site (e.g. does the site prefer to get its water from a groundwater or surface water source?). The supply-demand network is constructed and an optimization routine allocates available supplies to all demands. Demands are defined by the user, but typically include municipal and industrial demand, irrigation demands from portions of the watershed, and in-stream flow requirements.

Water Demands

Demand analysis in WEAP21 that is not covered by the evapotranspiration-based, physical hydrology module is based on a disaggregated, end-use approach that determines water requirements at each demand node. Demographic and water-use information is used to construct scenarios that examine how total and disaggregated consumption of water evolve over time. These demands scenarios are computed in WEAP21 and applied deterministically to the Linear Program (LP) allocation algorithm. Demand analysis is central to integrated water planning analysis with WEAP21, since all supply and resource calculations are driven by the allocation routine which determines the final delivery to each demand node, based on the priorities specified by the user.

WEAP21 provides flexibility in how data are structured and can range from highly disaggregated end-use oriented structures to highly aggregated analyses. Typically, a demand scenario comprises several sectors including households, industry, ecosystems, and agriculture, and each can be broken down into different sub-sectors, end-uses, and water-using devices. However, if the physical hydrology module is used, agricultural and urban turf watering demands are not included in the disaggregated demand analysis but are derived from soil moisture fluctuations.

The structure of demand data can be adapted to meet specific purposes, based on the availability of data, the types of analyses the user wants to conduct, and their unit preferences. In most cases, demand calculations are based on a disaggregated accounting for various measures of social and economic activity (e.g., number of households, water use rates per household, hectares of irrigated agriculture, industrial and commercial activity, and water use rates) and are aggregated and applied in the allocation scheme at the demand site level. Activity levels are multiplied by the water use rates of each activity and each can be individually-projected into the future using a variety of techniques, ranging from applying simple exponential growth rates and interpolation functions, to using sophisticated modeling techniques that take advantage of WEAP21's built-in modeling capabilities via a spreadsheet-like expression builder.

Figure 6 shows an example WEAP21 dialogue box for "South City" which has been broken into single and multi-family residences, with projected growth in each category out to 2008. Here, a growth function has been used with an estimated 3 percent population growth rate, combined with a technical innovation scenario that shows a declining per-unit use of water per-household due to implementation of water saving devices and a gradual shift from multi-family to single-family housing.

In-stream Flow Requirements

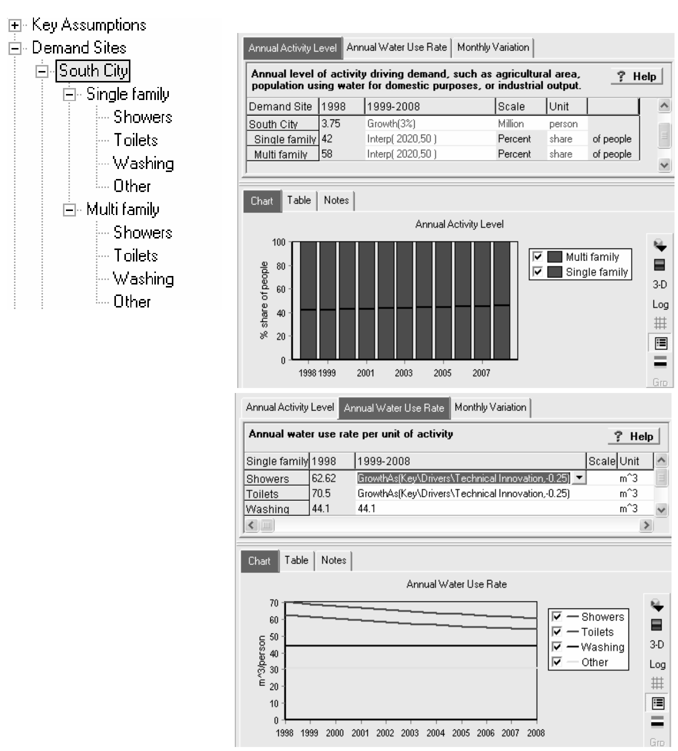

Figure 6. The WEAP21 demand model builder graphical user interface

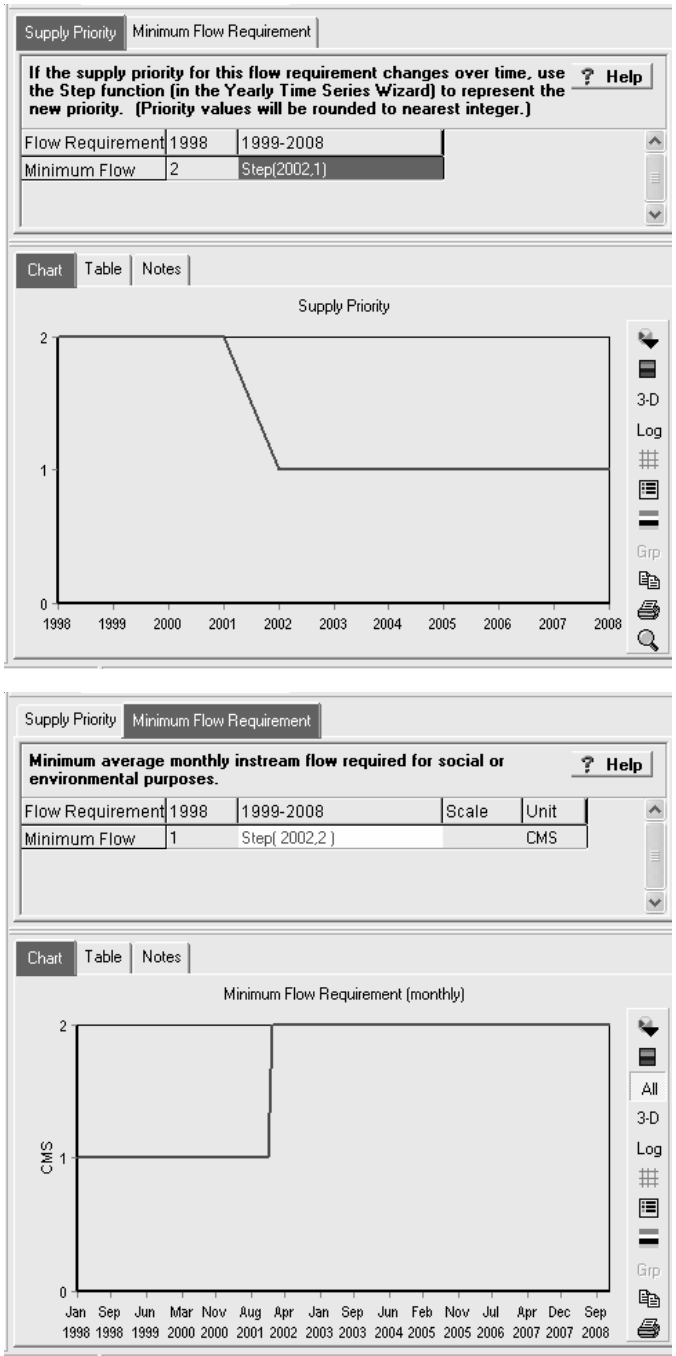

Figure 7. WEAP21's GUI for specifying in-stream flow requirements. The upper panel shows the supply priority of in-stream flow, while the lower panel is the actual in-stream flow requirement in m^3/s that abruptly changes over time as a result of regulatory requirement

In-stream flow requirements are used to represent established or new regulatory requirements of minimum flows in a river. These data objects are placed on the river and are assigned a priority and minimum flow value that must be maintained during a specified period. In-stream flow requirements can vary in time, so one can characterize a temporally changing regulatory environment, making it possible to make the in-stream flow requirements a higher priority and simultaneously raise the minimum standard of flow at any given time in the simulation. Figure 7 illustrates this, where the in-stream flow priority has changed from a 2 (lower priority) to a 1 (highest priority) in 2005, while the minimum in-stream flow requirement has been raised from 1.0 cubic meters per second (cms) to 2.0 cms in the same year.

Surface Reservoirs

Reservoirs represent a special object in the WEAP21 model in that they can be configured to store water that becomes available either from the solution of the physical hydrology module or from a user-defined time-series of streamflows. A reservoir's operating criteria determines how much water is available in the current time step for release to satisfy downstream demand and in-stream flow requirements, hydropower generation, and flood control requirements and how much if any should be carried over until a later time-step. If the priority assigned to storing water in a reservoir is less than downstream demands or in-stream flow requirements, WEAP21 will release only as much of the available storage as is needed to satisfy demand and in-stream flow requirements, taking into consideration releases from other reservoirs and withdrawals from rivers and other sources.

In WEAP21, a reservoir is stratified according to water storage volumes as shown in Figure 8, where: 1) the flood control storage (S_f) defines the zone that can temporarily hold water but must be released before the end of the time step. In effect, it is always vacant, as additional flows that would lead to reservoir storages above the flood control storage are spilled; 2) the conservation storage (S_c) is the storage available for downstream demands at full capacity, where all water in this zone can be drawn from; 3) the buffer storage (S_b) is a storage that can be controlled to uniquely meet water demands during shortages; when reservoir storage falls within the buffer storage, water withdrawals are effectively conserved via the buffer coefficient, b_c, which determines the fraction of

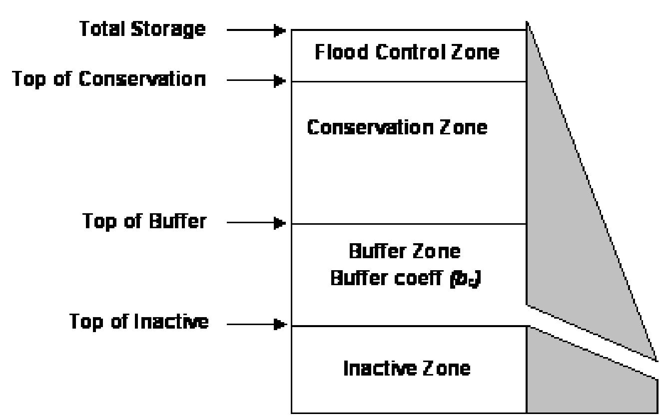

Figure 8. The different reservoir storage volumes used to describe reservoir operating policies

storage available for reservoir release; and 4) the inactive storage (S_i) is the dead storage that cannot be utilized. All these storages parameters can vary in time and can be used to define water conservation and flood storage/release targets. The amount available to be released from the reservoir, S_r is the full amount in the conservation and flood control zones and a fraction (defined by b_c) of the amount in the buffer zone, $S_r=S_c+S_f+(b_c*S_b)$..

The LP Allocation Routine

WEAP21 calculates a water and pollution mass balance for every node and link in the system at each time step. Each period is independent of the previous, except for reservoir storage, aquifer storage, and soil moisture. Thus, all of the water entering the system in a given time period is either stored in the soil, an aquifer, a river, a tributary, a reservoir, or leaves the system by the end of that period. Point loads of pollution into receiving bodies of water are computed, and in-stream water quality concentrations of conservative and first-order decay constituents, Biological Oxygen Demand (BOD), dissolved oxygen (DO), and water temperature are calculated as above.

All flows are assumed to occur instantaneously and a demand site can withdraw water from the river, consume some, return the remainder to a wastewater treatment plant, which then returns it to the river, all in the same time step. Given there is no routing, the analyst should choose a model time step at least as long as the residence time of water corresponding to the period of lowest flow. Larger watersheds should adopt longer times steps (e.g. one month for example), while smaller watersheds can apply shorter time steps (e.g. 1-day, 5-day, 10-day, etc.) as all demands can be satisfied within the current time step.

Demand Priorities and Supply Preferences

A standard linear program (Berkelaar et al., 2004) is used to solve the water allocation problem whose objective is to maximize satisfaction of demand, subject to supply priorities, demand site preferences, mass balances, and other constraints. The constraint set is iteratively defined at each time step to sequentially consider the ranking of the demand priorities and supply preferences. The approach has some attributes of a more traditional dynamic programming algorithm, where the model is solved in sequence based on the knowledge of values derived from the previous variables and equations (Loucks et al., 1981; Nandalal and Sakthivadivel, 2002).

Individual demand sites, reservoirs, and in-stream flow requirements are assigned a unique priority number, which are integers that range from 1 (highest priority) to 99 (lowest priority). Those entities with a Priority 1 ranking are members of Equity Group 1, those with a Priority 2 ranking are members of Equity Group 2, and so on. The LP constraint set is written to supply an equal percentage of water to the members of each Equity Group. This is done by adding to the LP for each demand site: 1) a percent coverage variable, which is the percent of the total demand satisfied at the given time step; 2) an equity constraint that equally satisfies all demands within each Equity Group in terms of percentage of satisfied demand; and 3) a coverage constraint which ensure the appropriate amount of water supplied to a demand site or the meeting of an in-stream flow requirement.

The LP is solved at least once for each Equity Group that maximizes coverage to demand sites within that Equity Group. When solving for Priority 1, WEAP21 will suspend (in the LP) allocations to demands with Priority 2 and lower. Then, after Priority 1 allocations have been made that ensure equity among all Priority 1 members, Priority 2 demands are activated (but 3 and lower are still not set).

Similar to demand priorities, supply preferences apply an integer ranking scheme to define which sources will supply a single demand site. Often, irrigation districts and municipalities will rely on multiple sources to meet their demands, so there is a need for a mechanism in the allocation scheme to handle these choices. To achieve this effect in the allocation algorithm, each supply to the same demand site is assigned a preference rank, and within the given priority, the LP algorithm iterates across each supply preference to maximize coverage at each demand site. In addition, the user can constrain the flow through any transmission link to a maximum volume or a percent of demand, to reflect physical (e.g., pipe or pump capacities) or contractual limits, or preferences on mixing of supplies. These constraints, if they exist, are added to the LP. The general form of the allocation algorithm is as follows,

For each $p=1$ to P — for each demand priority

For each $f=1$ to $F \in (D_k^{p,t-n})$ — for each supply preference to demand, k

maximize (Coverage to all demand sites $k \in N$ with priority p)

$Z = C_p$

subject to

$\sum_{j=1}^{n} x_{j,i}^{p} - \sum_{r=1}^{m} x_{i,r}^{p} + S_i^{t-1} = S_i^{t}$ — mass balance constraint with storage for node i to node r

$\sum_{j=1}^{F} x_{j,k}^{p} = \mathbf{D}_k^{p,t-n}$ — demand node constraint for demand k from j sources

$\sum_{j=1}^{F} x_{j,k}^{p} = \mathbf{D}_k^{p,t-n} * c_k^p$ — coverage consraint for demand k from j sources

$\sum_{j=1}^{m} x_{j,k}^{p} \geq \mathbf{D}_k^{p,t-n} * c_k^p$ — coverage constraint for ifr and reservoirs k from j sources

$c_k^p = C$ — equity constraint for demand site k with priority p

$c_k^p \geq C$ — equity constraint for ifr and reservoirs with priority p

$0 \leq c_k^p \leq 1$ — bound for demand site coverage variables (not ifr or reservoirs)

$x_{i,l}^{>p} = 0$ — for demand sites l with priority $> p$

$x_{i,k}^{p} \geq 0$ — for demand sites k with priority $= p$

$x_{i,k}^{f} \geq 0$ — for demand sites k with preference $= f$

$x_{i,k}^{>f} = 0$ — for demand sites k with preference $> f$

Solve LP, then

1. Evaluate shadow prices (h_k^p) of each equity constraint, is $h_k^p > 0$?
2. If so, set $x_{j,k}^p$ and c_k to optimal values from solution
3. Remove equity constraints with $h_k^p > 0$

Next iteration for current priority, p

4. Set $x_{i,k}^f$ to optimal values

Next f

Next p

where p are the demand priorities, f are the supply preferences for each demand k, of N total demand sites. The constants $D_k^{p,t-n}$ are determined for each demand site k with priority p and can: 1) be built *a prior* using the built-in WEAP21 demand model builder; 2) be based on results computed from previous time steps, n; or 3) be computed for the current time step in the case of irrigation demands. The $x_{j,i}^{p}$ terms define the flows from nodes j to i with priority p, S_i^t are the reservoir storages at site i for time t, C_p is the total coverage for priority p, and c_k^p is the percent coverage for individual demand sites. For the given priority, supplies to each demand site, k are established incrementally based on their preference rank, with $x_{j,k}^{>f}$ set equal to zero and values of $x_{j,k}^{f}$ fixed to their optimal solution upon improvement of total coverage, C_p at each iteration for the current priority, p.

Upon solution of the LP, the shadow prices on the equity constraints are examined and if non-zero for demand site k, then the water supplied for this demand site is optimal for the current constraint set. The supply $x_{j,k}^{p}$ is set from the optimal solution of the current LP, its equity constraint removed, and the LP is solved again for the current Equity Group and the equity constraints re-examined. This is repeated until the equity constraint for each demand site returns a positive shadow price, and their supplies $x_{j,k}^{p}$ set. The LP then iterates across the supply preferences, and this too is repeated until all the demand sites have an assigned water supply for the given Equity Group. The algorithm then proceeds to the next Equity Group. Once all Equity Groups are solved at the current time step, the algorithm proceeds to the next time step where time dependent demands and constraints are updated, and the procedure repeats.

A series of stylized examples are presented to illustrate the robustness of the solution algorithm in solving allocation problems. We begin with a simple example described by Figure 9a, where there is tributary inflow between the withdrawal points for Demand Site A and Demand Site B, both members of the same Equity Group since each has a Priority 1 ranking. Although the allocation LP is written to satisfy all demands with the same priorities at an equal percentage, there are certainly examples where a demand site with the same priority has access to more water than other sites, or in the case of reservoirs and in-stream flow requirements, can have a coverage fraction greater than 1.0. Here, the tributary can fully supply water to B, so A should get the maximum allotment from the upstream source of 60 units.

This problem has a simple solution, which could be achieved by simply eliminating the equity constraints and maximize the sum of the coverage, $c_{\mathrm{A}}^1 + c_{\mathrm{B}}^1$. However, a general algorithm is needed that could handle more complex allocation problems. Thus, at the end of the first iteration (note there is no iteration on supply preference, since both A and B draw water from only one source), $x_{1,\mathrm{A}}^1 = 60$, $x_{1,\mathrm{B}}^1 = 40$, $c_{\mathrm{A}}^1 = c_{\mathrm{B}}^1 = 67\%$. However, demand B should be able to withdraw its full requirement, even though A cannot. The shadow price on the equity constraint for Demand A is, $h_{\mathrm{A}_1}^1 = 1$ and the LP allocation iterates after fixing the supply $x_{1,\mathrm{A}}^1$ to 60 units and removing demand A's equity constraint. The final solution is $x_{1,\mathrm{A}}^1 = 60$ units, or 67 percent of its total requirement from R1, while demand $x_{1,\mathrm{B}}^1 = 60$ units and is 100 percent satisfied, receiving all its water from T1. No water exits R1 through Node 3.

Supply preferences are illustrated by extending the previous example, where demand A can draw water from the surface supply or from a new groundwater source (Figure 9b). In this case, the demand site's preferences are to first draw from the groundwater supply constrained at 40 units, and then draw from the surface supply if needed (Preference 2). Since the groundwater water is given a preference of 1, the demand site should draw all 40 units from it, and make up the 50 unit shortfall from the surface supply. The final solution is $x_{1,\mathrm{A}}^1$ can supply 40 units from source GW, 50 units from R1, while 10 units flow to the Node 2 tributary from R1. Demand B gets 60 units from R1 and is 100 percent satisfied. Ten units exit the system through Node 3.

The example is again extended by placing an in-stream flow requirement (*ifr*) below the demand B diversion at

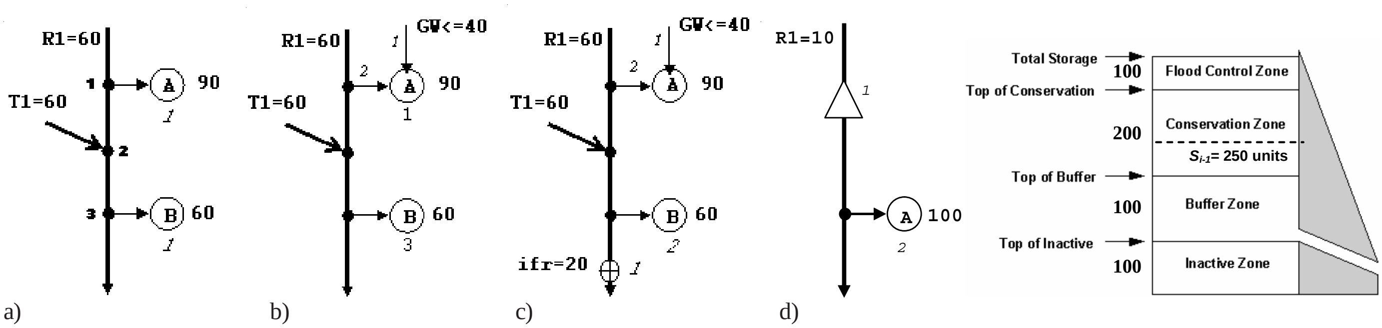

Figure 9. a) Two demand sites, A and B are members of the same Equity Group indicated by the "1" below each symbol. The numbers near each object represent 1) the water supply available from the river, R1 and the tributary T1; and 2) the demands for A and B; b) Same as a, but demand site A now has a secondary source, labeled GW which is its preferred source indicated by the 1 along its transmission link, with its secondary source from R1; c) Same as b, but with the addition of an in-stream flow requirement (ifr) with priority 1; d) A reservoir example, with a priority 2 water storage target, and a demand site (A) with a priority 1 demand. The stylized reservoir on the right illustrates reservoir storage volumes (top of conservation storage = 400 units; top of buffer storage = 200 units)

Node 3, where a 20 unit *ifr* is imposed (Figure 9c). The *ifr* joins Equity Group 1, and demand B is demoted to Priority 2 and becomes the exclusive member of Equity Group 2. In this case, the LP will iterate among Equity Groups, with demand A being 100 percent satisfied from 40 units of the GW source and 50 units of the R1 source. The total volume available at Node 3 is 70 units, 60 from T1, and 10 from R1. To meet the *ifr* at 100 percent, 20 units must pass through Node 3, and so demand B can draw only 50 units from R1 and, therefore, only 83 percent of its demand is met.

The final example illustrates the solution of a demand site supplied by a reservoir, with an assumed operating policy to meet downstream demands (Priority 1) and conserve water by reducing delivers from the reservoir. Demand site A has a demand of 100 units, with the physical reservoir volume capacities given in Figure 9d. The reservoir has an inactive pool of 100 units, a buffer pool of 100 units, a conservation pool of 200 units, and a flood control zone of 100 units. Thus, the total storage volume of the reservoir is 500 units. For the current time step, inflow to the reservoir is 10 units with an assumed initial storage volume of 250 units (S_{i-1}) which is just above the buffer storage zone. The buffer coefficient, b_c is set at 0.05, which means that if the reservoir's storage level drops into the buffer zone (< 200 units), then reservoir water available for release to meet downstream demands will be limited to 5 percent of the current buffer storage.

After solution of the current time step, demand site A is supplied 65 units of water or 72 percent of its demand and the reservoir storage is 195 units. Thus, the 10 units of inflow to the reservoir are passed through it, the full 50 units are drawn off the conservation pool released downstream to meet demand at A, and water available for release from the buffer zone is limited to 5 units, or 5 percent of the 100 units of the full buffer storage. The final storage in the reservoir for the current time step is 195 units. For the next time step, if it is assumed that the demand is again 90 units, with an inflow of 10 units, then 10 units are allowed to pass through the reservoir, and only 5 percent of the 95 units of buffer storage are released for a total downstream delivery of 14.75 units or 14.75 percent of total demand at A.

Summary

IWRM tools that aid the water resource planning and management processes have become more common, but often generic tools that can be applied to different basin settings are difficult to use because of the complex operating rules that govern individual water resource systems (Watkins and McKinney, 1995). Integrated water resource planning models that can simultaneously aggregate and process hydrologic and management elements are needed to help decision planners evaluate the tradeoff landscape under different hydrologic realities and management objectives. These IWRM tools must be useful, easy-to-use, and adaptive to new information and stakeholder priorities. The Water Evaluation and Planning (WEAP21) model described in this paper is one such tool, and this paper introduces the WEAP21 model user interface, its capability to build complex, distributed physical hydrology and demand models of agricultural, municipal/industrial, and environmental demands at a variety of spatial and temporal scales, and with cascading levels of detail.

The WEAP21 IWRM incorporates a demand priority and supply preference approach to describing water resource operating rules, as system demands drive the allocation of water from surface and groundwater supplies to the demand centers. The water allocation problem is solved at each time step using an iterative, linear programming approach that introduces the concept of Equity Groups. The objective function in the LP is formulated so that demand centers with the same priority (i.e. an Equity Group) are equally supplied as a percentage of their total demand, although flexibility is also introduced in the LP to ensure that demand sites in the same Equity Group with access to differing amounts of water can take advantage of their strategic position.

In order to demonstrate the suite of functionality in the WEAP21 model, a companion paper applies the model to two sub-catchments of the Sacramento Watershed of Northern California, USA. The case studies are used to illustrate and demonstrate the capabilities of the WEAP21 model in reproducing watershed hydrologic process, the relevance of the water allocation algorithm in managed watersheds, and to illustrate the WEAP21 potential use in ecosystem service evaluation.

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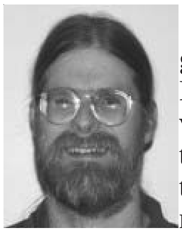

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