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Integrated River Basin Modeling Framework to Support Payments for Watershed Services

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REPORT

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Abstract: This report is a review of hydrological and water allocation models and an evaluation of their ability to support PES-analysis (payment for environmental services) in Malaprabha River Basin, India. Important aspects that were considered during the evaluation were; (1) the models' ability to use of remotely sensed land-use and land cover information; (2) ability to use spatially distributed hydro-meteorological data; (3) reasonably comprehensive representation of surface and sub-surface interaction; (4) the user-friendliness to set up and implement the model, and (5) it should not be too demanding in terms of input data. In addition, the model should be affordable for similar implementations in developing country context or available as a public domain package. From the model inventory, there is no single model that can alone carry out the analysis. Based on this fact, a multi-tier modeling approach is recommended. It is proposed to use SWAT and SLURP as the hydrological models in the first tier, and MIKE BASIN and WEAP as the water allocation (water accounting) models in the second tier when implementing the PES-concept in Malaprabha River Basin.

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Integrated River Basin Modeling Framework to Support Payments for Watershed Services

Preface

The following report “Integrated River Basin Modeling Framework to Support Payments for Watershed Services” is an assessment of the state-of-the-art in river basin management drawing inferences from extensive literature review on water services modeling approaches inclusive of surface and subsurface hydrology, water budgeting and allocation to provide the necessary data and information to support testing of payments for ecosystem services in the *India-PES* project. The project is supported by the Royal Norwegian Embassy, New Delhi and is jointly coordinated by the Centre for Interdisciplinary Studies in Environment and Development, India and Norwegian Institute for Water Research, Norway. The report has been written and edited by Shrinivas Badiger with contributions from Tor Haakon Bakken.

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1. Introduction

In most developing countries such as India, although there is widespread consensus on the kinds of land use that support improved watershed services of different types, there is a substantial gap in the body of scientific evidence on these relationships to be carried forward in testing or implementing actual PES/PWS mechanisms. Gathering reliable hydrological evidence to quantify the value of watershed protection services is beyond the means of potential “sellers” or “buyers” of these services. In larger catchments not only are hydrological linkages between upstream actions and downstream water impacts increasingly tenuous, but perceived links by beneficiaries and service providers are less likely. Limited hydrological knowledge also makes it impossible to explore markets for “bundled” services that meet a range of needs (Landell-Mills and Porras, 2002). Policies and practices of PES/PWS with insufficient evidence of upstream-downstream relationships therefore could lead to creating allocation mechanisms that could entice the erroneous trading and diminish rather than enhance watershed services (Geoghegan, 2005). Hence investigating the contributory relationships of watershed services and their temporal-spatial trends becomes essential in exploring the markets for ecosystem or watershed services.

This review document is prepared as a component of the India-PES project. The specific purpose of the review is to provide the basis for developing a modeling framework that can contribute to identification and quantification of hydrological/watershed services at sub-system and river-basin levels under selected water resource reallocation scenarios. The framework will provide the data and information required in testing various PES/PWS scenarios, and well informed public policy decision making concerning the use and management of water resources. The identification of relevant models was based on existing literature, web-based search and experience of the authors with select models. Most models reviewed are public domain and some select commercial packages that are distributed as stand-alone models or modeling suites. They generally address one or more aspects of water resources management in small catchments and/ or a river basin context. Models specifically dealing with groundwater and aquifer dynamics are not reviewed in this report as the authors perceive them inapt for the project due to unavailability of specific data (such as hydrogeology, groundwater status and extraction) essential for such rigorous analysis. Furthermore, most groundwater management models do not deal with surface hydrology and land-use dynamics at greater detail, which are major components within the Malaprabha basin. However, certain general hydrologic models that deal with surface-subsurface interaction have been emphasized. The review also does not attempt to document agronomic models that deal with crop growth dynamics. It is implicit that hydrologic models that deal with land-use dynamics in the context of water utilization by vegetation are sufficient for the purposes of water resources analysis.

2. Selection Criteria

Data requirements, model parameters and model structure in representing critical hydrological processes are considered as key factors in selection of the modeling package. Furthermore, the model(s) should also meet the main project objective of supporting upstream-downstream hydrological linkage essential for devising PWS/PES.

The main points considered within this project will be the ability of the model to meet following set of requirements: (1) able use of remotely sensed land-use and land cover information; (2) able use spatially distributed hydro-meteorological data; (3) be reasonably comprehensive to include surface and subsurface interaction; (4) be reasonably user-friendly to set up the model and implement, and (5) be not too demanding in terms of input data. One of the less important but essential factors is that the model should be affordable for similar implementations in developing country context or available as a public domain package.

The primary goal was to identify an existing integrated hydro-economic model that implements a fairly rigorous hydrological analysis and water allocation with or without a module to assess economic implications. Due to non-availability of such a modeling package, a two level selection approach was used. At the first level a suitable hydrological model has been singled out based on the critical processes it can model more specifically, enable upstream-downstream hydrological linkage. At the second level, one of the available water accounting and allocation packages that can assess selected scenarios has been considered. The two models together will be core components of the tool box for assisting the PES/PWS implementation and/or testing.

3. River Basin Management Concepts

The river basin is characterized not only by natural and physical processes but also by structural interventions and non-structural interventions such as management policies determined by the socio-economic-institutional conditions. In Figure 1, a typical river basin system is illustrated with all the essential components such as sources/stocks and relevant flow processes including the water supply system (groundwater and surface water), the delivery system (canal network), the water users system (agricultural, municipal, and industrial), and the drainage collection system (surface and subsurface).

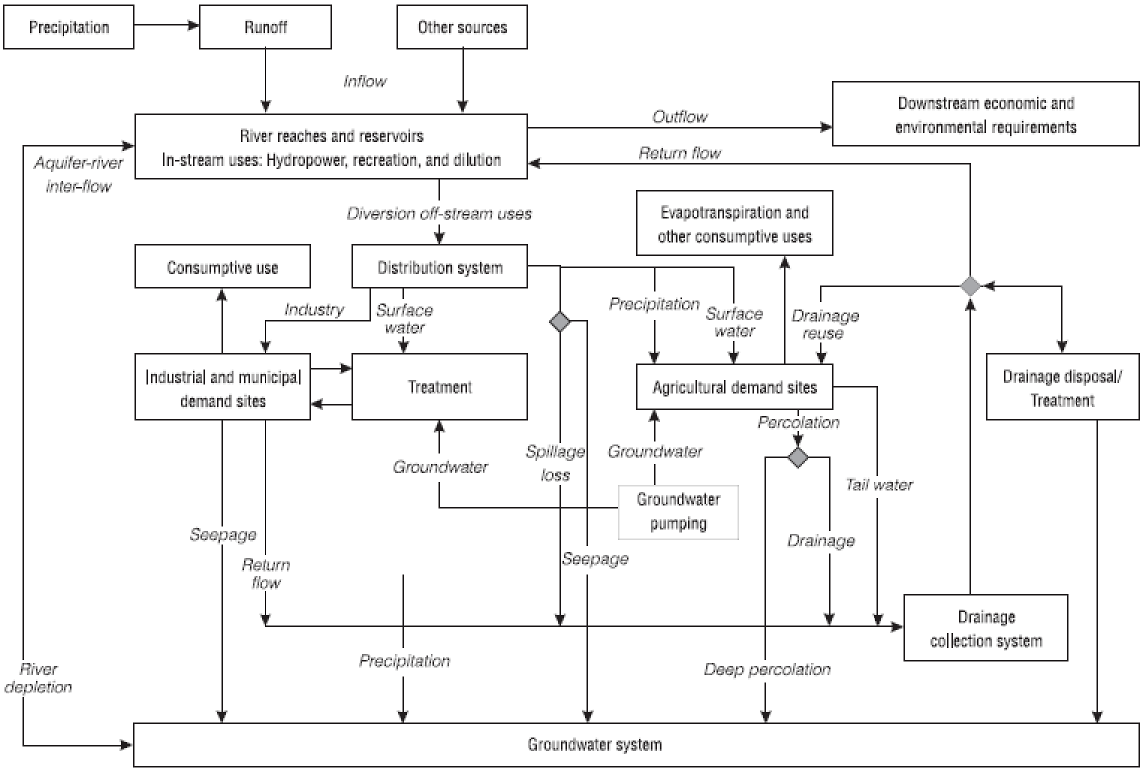

Figure 1: Schematic illustration of river basin processes (Source: Daza and Peralta 1993).

The atmosphere forms the river basin's upper bound, and mass and energy exchange through this boundary determines the hydrologic characteristics within the basin. However, the state of the basin (for example reservoir and aquifer storage) and the physical processes within the basin (for example stream flow, evapotranspiration, infiltration and percolation) are also characterized by human actions, including impoundment, diversion, irrigation, drainage, and discharges from urban areas.

The interdisciplinary nature of water problems requires innovative methods to integrate the technical, economic, environmental, social, and legal aspects into a coherent framework. Water resources development and management should incorporate environmental, economic, and social considerations based on the principles of sustainability. Therefore, water resources management modeling of a river basin system should include not only natural and physical processes, but artificial “hardware” (physical projects) and “software” (management policies) as well. The challenge is to represent critical system components and processes with adequate detail and in a meaningful manner that can address the objective of the modeling exercise, such as outcomes from a reallocation mechanism whether through an existing or additional, structural or non-structural intervention in the hydrologic system.

An ideal, complete river basin management model also needs some sub-model of human behavior in response to policy initiatives or driven by socio-economic needs. The objective function is a crucial instrument to reflect the host of rules, principles, and constraints in water resources management in a modeling framework. The essential relations within each component and the interrelations between these components in the river basin can be considered in an integrated modeling framework.

4. Catchment Hydrologic Systems Modeling

Hydrologic system modeling involves approximation of the catchment or river basin system; wherein its inputs and outputs are measurable hydrologic variables concerning processes in atmosphere, land surface, and underground, and its structure is a set of equations linking the inputs and outputs. With use of these hydrologic system models, whole temporal and spatial hydrologic system, by forecasting, reproducing and estimating flows as influenced by the behavioral rules of economic actors can be understood. Modeling within well-defined domains of the hydrologic cycle has assisted researchers, water managers and policy makers greatly in understanding hydrological pathways. Within each of the domains identified where model use is either essential or potentially useful, there are often a number of models that could be applied.

Approaches used in river basin analysis are of three prime classes viz., simulation, optimization and integrated simulation-optimization. Simulation type models are those that simulate water resources behavior based on the natural resource system under a set of rules governing water allocations and infrastructure operation, which can be broadly grouped as rainfall-runoff or hydrologic models. Representations of hydrologic processes at scales ranging from the soil profile to the cropped field and to the irrigated command area are important precursors to understanding and describing the processes at the river basin scale. These models form the core of understanding the system behaviour and have been preferred techniques to assess water resources system responses to normal, extreme, non-equilibrium conditions (like overdraft, droughts), and thereby to identify the system components most prone to failure, or to evaluate system performance relative to a set of sustainability criteria over a long time period (like climate change, or rapidly changing priority demands including increased irrigated agriculture or accelerated industrial or municipal demands).

However, water allocation decisions have wider economic implications at the sub-basin and basin level. Optimization approaches attempt to optimize resource allocations based on an objective function and accompanying constraints, and can include social value systems in the allocation of water resources. They can be hydrology-inferred or based on economic criteria of optimal water allocation. However, some optimization models contain a simulation component to characterize the hydrologic regime, and are thus usually referred to as integrated simulation and optimization models. A wide range of models of this type have been developed, often including a basin or subbasin, but mostly focusing on one sectoral water user or a few of them. Typically optimization emphasized allocation models tend to handle the hydrologic processes less rigorously than those explicitly modeling hydrologic processes. In the following sections a brief review of hydrologic systems modeling options are discussed followed by a more detailed water allocation modeling in a river basin scale.

5. Approaches to Hydrologic Processes Modeling

Surface water and groundwater numerical models are similar and yet fundamentally different. Both types of models utilize water balance concepts in accounting for the overall water budget. The primary difference between the two types of models is the relationship used to simulate momentum. Groundwater models typically utilize Darcy’s Law as the governing momentum equation whereas surface water models typically utilize the St. Venant Equations or some simplification thereof. This difference has resulted in two general categories of water flow models, groundwater and surface water separately. There are hardly any comprehensive models that treat surface and subsurface processes within rigorous analytical framework that have been extensively tested. Most models discussed below are primarily surface water models that incorporate uni-directional interaction with groundwater (from surface to groundwater). These models do not essentially allow anthropogenic disturbance of the natural groundwater flow pattern through processes such as groundwater draft. Selected models of surface-subsurface interaction are briefed at the end of distributed modeling section.

According to Singh (1995) the rainfall-runoff or broadly hydrologic models can be classified in terms of how processes are represented, the time and space scale that are used and what methods of solution to equations are used. The main features for distinguishing the approaches are: the nature of basic algorithms (empirical, conceptual or process-based); whether a stochastic or deterministic approach is taken to input or parameter specification; and whether the spatial representation is lumped or distributed. The first feature defines if the model is based on a simple mathematical link between input and output variables of the catchment or it includes the description, even if in a simplified way, of the basic processes involved in the runoff formation and development. Generally, when the observations are reliable and adequate, extremely simple statistical or parametric models are used. They vary from the empirical models that are as simple as linear regression models to the more sophisticated Artificial Neural Networks models. These models are strongly dependent on the data used for calibration and, ought to non-linear behaviour of the rainfall-runoff processes; their reliability beyond the range of observations may be uncertain. For this reason conceptual models are generally preferred (Michaud and Sorooshian, 1994). In this report the term conceptual denotes also the distributed, physically based models (fully-distributed or semi-distributed) because, even if they use parameters which are related to physical characteristics of the catchment and operate in a distributed framework, they must use average variables and parameters at grid or element scales greater than the scale of variation of the processes modeled.

Another basic distinction between models is whether stochastic or deterministic representations and inputs are to be used. Most models are deterministic so they generate a single set of output. In stochastic models, some or all of the inputs and parameters are represented by statistical distributions, rather than single values, determining a range of output sets, each of them associated with a certain probability of occurrence. Their advantage is that they provide a conceptually simple framework for representing heterogeneity when the explicit spatial or temporal detail is either not known or it is not important (Jensen and Mantoglou, 1993). This type of models has been receiving much attention as they can provide a usable quantification of the forecasting uncertainty, thus allowing decision makers to take the most effective decisions under uncertainty (Todini, 2004). Furthermore, accounting for risks in decision making may increase economic benefits of forecasts.

On the basis of the spatial representation, the hydrological models can be classified into three main categories: lumped models, semi-distributed models, distributed models. In lumped models which treat catchments as a single unit, the parameters and the input do not vary spatially within the basin. Typically these models produce net basin water budgets (stream flow, evapotranspiration and groundwater recharge). Though computationally efficient, this approach does not allow explicit account for spatial variability of parameters within the watershed. Parameters do not represent physical features of hydrological processes and the impact of spatial variability is evaluated by using certain procedures for calculating effective or representative values for the whole basin. It can be expected that their use in basins characterized by a complex orography (such as in arid and semi-arid regions of India) where high rainfall variability can be expected within the basin, they do not furnish an adequate level of reliability.

The semi-distributed and distributed models take an explicit account of spatial variability of processes, input, boundary conditions, and/or watershed characteristics. Of course, a lack of data prevents such a general formulation of distributed models, in which case these models can not be considered fully distributed. In particular, in the semi-distributed models the above quantities are partially allowed to vary in space by dividing the basin into a number of smaller sub-basins which in turn are treated as a single unit of analysis (Boyle et al, 2001). Whereas distributed models represent spatial heterogeneity with a resolution usually chosen by the user. The widespread availability of digital terrain data and the significance of topography have meant that the choice of element size and type is often dictated by the way in which (and the scale at which) the topography is represented. By far, the most common form of model construction is based on square grids especially for real-time applications where the data and computing requirements are generally not very high. These models may produce reasonable result but because of spatial disaggregation and uncertainty in parameterization, the model cannot be expected to accurately represent the watershed conditions.

Finally, according to the hydrological processes modeled, hydrological models can be further divided into event-driven models, continuous-process models, or models capable of simulating both short-term and continuous events. The first are designed to simulate individual precipitation-runoff events and their emphasis is placed on infiltration and surface runoff. The major limit to the use of event type models is the problem of unknown initial soil moisture conditions that can not be measured and may heavily condition the forecasts in real time. Continuous-process models, on the other hand, take explicitly account of all runoff components with provision for soil moisture redistribution between storm events. They are based upon equations representing the storage and the movement of water in the soil and on the surface, and their parameters are related to information provided in the form of Digital Elevation Maps (DEM), soil maps and land use maps. Generally, these models have a spatial resolution finer than the sub-catchment and so they can incorporate the spatial distribution of rainfall as furnished by interpolated rainfall surfaces or RADAR images.

6. Empirically-Based Hydrological Models

Empirical hydrological models as described earlier are simplistic representations of the hydrologic system response that use general functional (e.g. linear or non-linear regression models) relationships between input and output. The unit hydrograph model is a classic example of using a transfer function approach that efficiently relates rainfall depths to surface runoff. Classical time-series models, such as ARMA models (Box & Jenkins, 1970; Weeks & Boughton, 1987), are other examples that use historical site specific rainfall and runoff information to develop relationships. A variety of different terms have been applied to this type of modeling, including "data-based mechanistic approach" (Young and Beven, 1994). In most cases the data is allowed to determine the model form as much as possible, although mathematically, the models are simple numerically, the parameter estimation is ill-conditioned (small errors in the data can lead to large estimation errors). Simple "black-box" in-stream models are another type that greatly simplifies description of a catchment, generally using a simple analogy. Typical analogies are a simple store (bucket, representing the continuity or conservation law) and a linear reservoir, which combines a linear dynamic outflow relationship with the conservation law. Typically, models will involve some sort of filter which separates precipitation into effective (i.e. contributing to quick-flow) and ineffective elements. Conceptualizations of two pathways between input and output are then used, representing quick-flow and slow-flow processes, and these may contribute to streamflow either in parallel or in series. The IHACRES model (Jakeman et al., 1990; Littlewood & Jakeman (1994) is a well-used example of a data-based hydrological model, used for hydrograph analysis to assess impacts of land-use or climate, change and quality assurance of long, strategically important, hydrometric records. TFM (Transfer Function Model) is a similar program for the analysis of rainfall-discharge catchment data based on transfer function concepts, similar to those used in the IHACRES and the bilinear power model of Young and Beven (1994). However in such models there is no opportunity for the link between these conceptual pathways of transformation of rainfall to runoff, and the specific physical processes to be examined, let alone verified.

7. Distributed Hydrological Models

In distributed modeling the catchment characteristics are disaggregated in to a number of smaller areas, within which hydrologic processes are simulated and the output routed to the spatial point in question, in the watershed or stream. Some examples of distributed hydrological models that are public domain include the AGNPS (AGricultural Non-Point Source Pollution; Young et al., 1987) model, ANSWERS (Areal Nonpoint Source Watershed Response Simulation; Beasley and Huggins, 1982) and SWAT (Soil and Water Assessment Tool; Arnold et al., 1996). Models such as AGNPS and ANSWERS considers separate land parcels as distinct, but hydrologically connected and has been used widely in the U.S. However, many of these are event-based models except SWAT which allows continuous time-series modeling required to assess regime changes due to anthropogenic interventions. All these models treat groundwater interaction minimally to the extent of recharge and groundwater outflow to streams as base flow and barely account direct human extraction from aquifers.

The SWAT model (Arnold et al., 1996) provides continuous− time simulations with a high level of spatial detail by allowing the division of a watershed or river basin into grid cells or subwatersheds called HRUs. The water balance of each HRU in the watershed is represented by four storage volumes; snow, soil profile, shallow aquifer, and deep aquifer. SWAT operates on a daily time step and is designed to evaluate management effects on water quantity, quality and sediment in large, ungauged basins. The model is based on a command structure for routing runoff and chemicals through a watershed. The hydrology component of SWAT includes surface runoff using modified SCS curve number or the Green-Ampt infiltration method, percolation, lateral subsurface flow, groundwater return flow, evapotranspiration, and channel transmission loss subroutines. The minimum weather inputs required by SWAT are generated or measured maximum and minimum air temperature and precipitation. SWAT is one of the very few public domain packages that employ rigorous algorithms for computations while allowing some flexibility in the intensity of input data.

HSPF (Hydrological Simulation Program Fortran; Johansen et al., 1984) is a comprehensive, continuous, semi-distributed model that simulates the movement of water, sediment, pesticides, and nutrients on pervious and impervious surfaces, in soil profiles, and within streams. Similar to SWAT, HSPF requires land use data, reach data, and information on the pollutants of concern in the watershed and its reaches. The reach network is automatically developed based on the subwatershed delineation. It includes routines to simulate runoff, suspended solids, nutrients, water temperature, pesticides, biochemical oxygen demand, phytoplankton, pH, and dissolved oxygen.

HSPF is extremely data intensive and over-parameterized model that requires a large amount of site information to accurately represent hydrology and water quality processes in a watershed. WinHSPF is the new interface to HSPF within EPA’s model suite BASINS 3.0 (USEPA, 2001).

SLURP (Kite, 2000) is a GIS-based semi-distributed hydrologic model, in which the hydrologic processes and parameters are related to land cover linked variables. The model takes into account changes in the distribution and type of land cover over time and is therefore suitable for changes in crop management practices and scenario analysis of land cover change that could occur both in the catchment and command area. The SLURP model divides the watershed into hydrologically-consistent sub-units known as aggregated simulation areas (ASA). Geographic Information Systems is utilized to develop the physiographic parameters for each of the basin ASA, derived from remote sensed imagery and ground data. An ASA is a grouping of smaller areas with known physical properties and the number of ASAs used in modeling a watershed will depend on the size of the watershed and the scales of data available. At each time increment (typically 1 day), the model is applied sequentially to each element of the matrix of ASAs and land covers. Each element of the matrix is simulated by nonlinear reservoirs representing canopy interception, rapid runoff and slow runoff that include storage and flow processes both above and below the ground. Runoffs are accumulated from each land cover within an ASA using a time/contributing area relationship for each land cover and the combined runoff is converted to streamflow and routed between each ASA. Runoffs are routed through each sub-basin to the basin outlet taking account of reservoir regulation, diversions, groundwater extractions and water exports from the basin. The model has potential application in our case due to the comprehensiveness of hydrologic processes it can simulate.

The HBV model is another process-based semi-distributed model originally developed at the Swedish Meteorological and Hydrological Institute in the first half of the seventies (Bergstrom, 1976). It has gained widespread use for a large range of applications in Scandinavian environments. The HBV model describes numerically the runoff processes occurring in a natural river basin by dividing it in sub-basins as primary hydrological units, and within these an area-elevation distribution and a crude classification of land use (forest, open, lakes) is implemented. A rather undesirable feature of this model is the lack of an infiltration routine. All precipitation is assumed to enter the unsaturated zone, an assumption generally valid mostly for Scandinavian till catchments where Hortonian overland flow hardly occurs. TOPMODEL is another semi-distributed model that has been developed and applied in many environments. It is a set of programs for rainfall-runoff modeling in single or multiple subcatchments in a semi-distributed way and using gridded elevation data for the catchment area. It is considered a physically based model as its parameters can be, theoretically measured in situ (Beven and Kirkby, 1979, Beven et al., 1984). TOPMODEL is based on the variable contributing area concept, in which the major factors affecting runoff generation are the catchment topography and the soil transmissivity that diminishes with depth. TOPMODEL was originally developed to simulate catchment under humid conditions in the U.K, in the eastern USA and Scotland. The model has provided good simulation of discharge rates and dynamic saturated areas. It is suited for catchments with shallow soils and moderate topography, which do no suffer from excessively long dry periods. Its application also does not extend to catchments with important groundwater contributions and anthropogenic alterations in the hydrologic regimes. Process-based semi-distributed catchment models are simpler than fully distributed ones, and assume a similar response of many grid cells that can, therefore, be modeled in an integrated way.

One solution to integrate surface and groundwater processes in a single holistic framework is to couple the groundwater and surface water models. Typically, such models are interfaced through a relationship that accounts for water balance. Water lost from the surface water model would result in the gain of water by the groundwater model and vice versa. An example of such an interface is MODBRANCH (Swain and Wexler 1996) is a coupled surface water and groundwater model which was developed by interfacing BRANCH (Schaffranek et al. 1981), a one-dimensional numerical model capable of simulating unsteady flow in open channel networks, with MODFLOW (McDonald and Harbaugh 1988) a three-dimensional, finite-difference groundwater flow model.

The SHE (Système Hydrologique Européan) and related models are among the most widely used distributed integrated surface-groundwater models (Abbot et al., 1986). The catchment modeling area is divided into polygons based on land use, soil type, and precipitation region; the polygons are then assigned identification numbers. Model input files can be generated by overlaying the model input parameters with a grid network. The modeling system simulates hydrology components, including the movement of surface water, unsaturated subsurface water, saturated ground water, and exchanges between surface water and ground water. The model also simulates water use and management operations, including irrigation systems, pumping wells, and various water control structures. A variety of agricultural practices and environmental protection alternatives may be evaluated using the many add-on modules developed at DHI. The system has a built-in graphic and digital post-processor for model calibration and evaluation of both current conditions and management alternatives. SHE is a proprietary package currently distributed by DHI (Danish Hydraulic Institute) as MIKE-SHE (DHI, 1998) and overpriced for applications in developing country. MIKE SHE utilizes rigorous physical flow equations for all major flow processes, but also permits more simplified descriptions. MIKE SHE has undergone limited verification to test its ability to simulate single component processes and some of their interactions. Though sophisticated and flexible, its ability to simulate evapotranspiration and stream-aquifer interactions could be improved (IGWMC, 2004). Some of the model parameters are not easily available, which makes it difficult to set up the model. Model use requires a great deal of technical expertise and the learning curve is steep for new modelers (Yan and Zhang, undated).

Another model InHM, the Integrated Hydrology Model (Vanderkwaak and Sudicky, 1996), is the product of research begun at the University of Waterloo in 1993 and continued at Stanford University in 1998. Unique feature of the model is integration of surface and subsurface flow and transport processes in one coherent framework, eliminating iterative coupling between surface and subsurface models through the use of physically based first-order flux relationships. Coupling of surface and subsurface flow and transport is achieved by assembling and solving one system of discrete algebraic equations so that water and solute fluxes between continua are determined as part of the solution. The numerical model is modular in form, is tailored towards irregular geological, surficial and areal geometries, and utilizes robust and efficient discretization and solution techniques. This model has not been tested extensively, especially in large catchments.

IGSM2 is a regional scale model developed by the California Department of Water Resources (JMM, 1990, DWR, 2003a, DWR, 2003b) for the simulation of groundwater elevations, surface flows and surface-subsurface flow interactions. IGSM2 simulates groundwater elevations in a multi-layer aquifer system and the flows among these layers. The depth-integrated conservation equation is solved for horizontal flows in each layer and an approximate method is utilized to compute vertical flows among layers. The Galerkin finite element method is used to solve the nonlinear conservation equation for each aquifer layer. A mixture of confined and unconfined aquifer layers that are separated by semiconfining layers can be modeled. The changing aquifer conditions (confined to unconfined and vise versa) as well as subsidence, and effect of tile drains, injection and pumping wells can also be modeled. Stream flows, lake storages, and their interaction with the aquifer system are also modeled in IGSM2. Stream flow simulation is similar to that used in MODFLOW 2000. Conservation equations for streams, lakes and aquifer system are solved simultaneously to compute the interaction among these components accurately. The distribution of four land use types (agricultural with specified crops, urban, native and riparian vegetation) dictate the evapotranspiration, surface runoff and infiltration characteristics as well as the demand for agricultural and urban water supply. The infiltrated water is routed vertically through root and vadose zones to compute the recharge to the groundwater. Stream diversions and groundwater pumping can be specified and distributed to meet agricultural and urban water requirements, and also adjusted dynamically to balance supply and demands. DWR has now released a revised version IWFM in which agricultural and urban water demands can be pre-specified, or calculated internally based on different land use types. Water re-use is also modeled as well as tile drains and lakes or open water areas. A main feature of IWFM is a “zone budget” type of post-processor that includes subsurface flow computations across element faces. One of the major drawbacks of this package is that it does not have a user interface as it main executable runs using ASCII input data structure. Model parameters cannot be modified at ease since spatial information is provided by node and element structure defined in ASCII input files. Although the model algorithms seem to be rigorous, user ease prohibits for implementation in this project.

Several modeling suites have been developed in the past few years that allow a range of hydrological models (mostly surface water) within one package to enable testing and verification of a suitable hydrological model. These suites have the advantage of using almost same basic input data structure allowing interoperability and implementation of various hydrologic models with minimal effort. BASINS 3.0 (Better Assessment Science INtegrating Point and Nonpoint Sources; US-EPA,2004) is a multi-purpose environmental analysis system that integrates a geographical information system and state-of-the-art environmental assessment and modeling tools into one convenient package and includes SWAT and HSPF, besides several modules to deal with water quality and pollutant transport.

The Watershed Modeling System (EMRL, 1998) is a similar suite of hydrologic and hydraulic modeling packages in a comprehensive graphical modeling environment. It includes spatial tools to automate modeling processes such as automated basin delineation, geometric parameter calculations; GIS overlay computations and cross-section extraction from terrain data. The latest version WMS 7 supports hydrologic modeling with HEC-1 (HEC-HMS), TR-20, TR-55, Rational Method, NFF, MODRAT, and HSPF.

A major lacuna in many of the stand-alone hydrologic models and the modeling suites is their inability to handle surface-subsurface interaction in basins where groundwater overdraft exists.

8. Water Accounting and Allocation

Molden and Sakthivadivel (1999) have demonstrated that by using a water accounting framework, water balance information can be integrated with the various water uses within a basin. In such a framework, the different ways in which water flows into and out of basins can be assessed and potential areas of water scarcity and those where further development of water resources may be needed can be identified. Many water allocation models tend to adopt this methodology or its modified version.

WEAP (SEI, 2001) employs one such water accounting system in which it performs stock and flow balance at microwatershed, sectoral and basin scales. The program operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, a single watershed or complex transboundary river basin systems. It is the ability to simulate a broad range of natural and engineered components of these systems, including rainfall runoff, baseflow, and groundwater recharge from precipitation; sectoral demand analyses; water conservation; water rights and allocation priorities, reservoir operations; hydropower generation; pollution tracking and water quality; vulnerability assessments; and ecosystem requirements. A financial analysis module also allows the user to investigate cost-benefit comparisons for projects. A database maintains water demand and supply information to drive mass balance model on a link-node architecture consisting of sources (supply) and sinks (demand). It has the ability to calculate water demand, supply, flows, and storage, and discharge under varying hydrologic and policy scenarios. Scenario evaluations for a full range of water development and management options can be carried out taking into account multiple and competing uses of water systems.

Aquarius (Diaz et al., 1997) - AQUARIUS was developed at the Department of Civil Engineering at Colorado State University in conjunction with the U.S Forest Service. AQUARIUS is a temporal and spatial allocation model for managing water among competing uses. The model is driven by economic efficiency which requires the reallocation of all flows until the net marginal return of all water uses is equal. The model is implemented in an object oriented programming framework, where each system component (e.g., reservoir, demand area, diversion point, river reach) is an object in the programming environment. In the GUI, the components are represented by icons, which can be dragged and dropped from the menu creating instances of the objects on the screen. These can be positioned anywhere on the screen or removed. Once components are placed on the screen, they are linked by river reaches and conveyance structures. The model does not include groundwater or water quality.

The model performs optimization to identify tradeoffs between water uses by examining the feasibility of reallocating water to alternative uses. Each water use is represented by an exponential demand curve (i.e., a marginal benefit function). The model is formulated as a quadratic programming model with a linear constraint set. Costs of water use are not explicitly considered in the model. The model could be used to evaluate net benefits by subtracting costs from benefits in the individual benefit functions. From the model documentation, it is apparent that making significant modifications to the model or its structure would be very difficult. Input to and output from the model is through user entered values and ASCII text files, respectively, and there appears to be no connection to spreadsheets or databases. Although the present version of the model implements only a monthly time step, Aquarius was conceived to simulate the allocation of water using any time interval, including days, weeks, months, and time intervals of nonuniform lengths. Aquarius can be used in a full deterministic optimization mode, for general planning purposes, or in a quasi-simulation mode, with restricted foresight capabilities. The software runs on PCs under the Windows environment and is freely available. Authors have no prior experience working with this package.

Aquatool (Andreu, 2004) – Aquatool consists of a series of modules integrated in a system in which a control unit allows the graphical definition of a system scheme, database control, utilization of modules and graphical analysis of results. Modules include: surface and ground water flow simulation; single- and multi-objective optimization of water resources; hydrologic time series analysis; risk based WRS management. All documentation is in Spanish and it is hence assumed to be customized for specific environments and not suitable for implementation.

CALSIM (DWR, 2004) - The CALifornia Water Resources SImulation Model (CALSIM) was developed by the California State Department of Water Resources (DWR) and the United States Bureau of Reclamation for planning and management of the California State Water Project and the U.S. Central Valley Project. CALSIM is a hybrid linear optimization model which translates the unimpaired (i.e. natural) stream-flows into impaired stream flows, taking into account reservoir operating rules and contract water demands exerted at model nodes (Quinn et al., 2004). CALSIM uses a mixed-integer linear programming solver to route water through the river network at each time step (in contrast to the traditional Out-of-Kilter algorithm of ARSP and OASIS or the more efficient Lagrangian approach of ModSim). The model code is written in Water Resources Engineering Simulation Language (WRESL), a high-level programming language developed by the DWR, and the system of WRESL equations is solved using a proprietary solver XA (Sunset Software Inc.). The model is used to simulate existing and potential water allocation and reservoir operating policies and constraints that balance water use among competing interests. Policies and priorities are implemented through the use of user-defined weights applied to the flows in the system. Simulation cycles at different temporal scales allow the successive implementation of constraints. The model can simulate the operation of relatively complex environmental requirements and various state and federal regulations. CALSIM is in a developmental state at the present time, and it is mentioned here to illustrate the type of model and to contrast some of its characteristics with other systems.

ModSim (Labadie et al., 2000; Shannon, et al., 2000 ; Dai and Labadie, 2001; Labadie, 2004) – ModSim is a generalized river basin DSS and network flow model developed at Colorado State University with capability of incorporating physical, hydrological, and institutional/administrative aspects of river basin management, including water rights. ModSim is structured as a DSS, with a graphical user interface (GUI) allowing users to create a river basin modeling networks by clicking on icons and placing system objects in a desired configuration on the display. Through the GUI, the user represents components of a water resources system as a capacitated flow network of nodes (diversions points, reservoirs, points of inflow/outflow, demand locations, stream gages, etc.) and arcs (canals, pipelines, and natural river reaches). ModSim can perform daily scheduling, weekly, operational forecasting and monthly, long-range planning. User-defined priorities are assigned for meeting diversion, instream flow, and storage targets. ModSim employs an optimization algorithm at each time step to solve for flow in the entire network to achieve minimum cost while satisfying mass balance at the nodes and maintaining flows through the arcs within required limits. Conjunctive use of surface and ground water can be modeled with a stream-aquifer component linked to response coefficients generated with the MODFLOW groundwater simulation model (Fredrick et al., 1998). ModSim can be run for daily, weekly, and monthly time steps. Muskingum-Cunge hydrologic routing is implemented in the model.

ModSim can also be used with geographic information systems (ArcGIS) (1) to generate input data for the model based on spatial databases, (2) to provide an interface for the user to modify input parameters, and (3) to display the results of the model in a way that decision makers can view the results in an easy to understand format (Gibbens and Goodman, 2000). ModSim is well documented in both user manuals and source code comments. Model data requirements and input formatting are presented along with sample test applications useful in understanding model setup and operation. Currently, ModSim is being upgraded to use the “.NET Framework” with all interface functions handled in Visual Basic and C#. This will greatly enhance the ability of the model to interact with relational databases and all variables in the model will be available for reading or writing to a database. ModSim is in the public domain, and executable versions of the model are available free of charge for use by private, governmental, and non-governmental users. The model requires extensive prior experience to implement and is very data intensive for application in developing countries.

OASIS (Hydrologics, 2001; Randall et al, 1997) - Operational Analysis and Simulation of Integrated Systems (OASIS) developed by Hydrologics, Inc. is a general purpose water simulation model. Simulation is accomplished by solving a linear optimization model subject to a set of goals and constraints for every time step within a planning period. OASIS uses an object-oriented graphical user interface to set up a model, similar to ModSim. A river basin is defined as a network of nodes and arcs using an object-oriented graphical user interface. Oasis uses Microsoft Access for static data storage, and HEC-DSS for time series data. The Operational Control Language (OCL) within the OASIS model allows the user to create rules that are used in the optimization and allows the exchange of data between OASIS and external modules while OASIS is running. OASIS does not handle groundwater or water quality, but external modules can be integrated into OASIS. Oasis does not have any link to GIS software or databases.

RiverWare (Carron et al., 2000; Zagona et al., 2001; Boroughs and Zagona, 2002; CADWES, 2004) – The Tennessee Valley Authority (TVA), the United States Bureau of Reclamation (USBR) and the University of Colorado’s Center for Advanced Decision Support for Water and Environmental Systems (CADWES) collaborated to create a general purpose river basin modeling tool - RiverWare. RiverWare is a reservoir and river system operation and planning model. The software system is comprised of an object-oriented set of modeling algorithms, numerical solvers and language components. Site specific models can be created in RiverWare using a graphical user interface (GUI) by selecting reservoir, reach confluence and other objects. Data for each object is either imported from files or input by the user. RiverWare is capable of modeling short-term (hourly to daily) operations and scheduling, mid-term (weekly) operations and planning, and long-term (monthly) policy and planning. Three different solution methods are available in the model: simulation (the model solves a fully specified problem); rule-based simulation (the model is driven by rules entered by the user into a rule processor); and optimization (the model uses Linear Goal-Programming Optimization). Operating policies are created using a constraint editor or a rule-based editor depending on the solution method used. The user constructs an operating policy for a river network and supplies it to the model as “data” (i.e., the policies are visible, capable of being explained to stakeholders; and able to be modified for policy analysis). Rules are prioritized and provide additional information to the simulator based on the state of the system at any time. RiverWare has the capability of modeling multipurpose reservoir uses consumptive use for water users, and simple groundwater and surface water return flows. Reservoir routing (level pool and wedge storage methods) and river reach routing (Muskingum- Cunge method) are options in RiverWare. Water quality parameters including temperature, total dissolved solids and dissolved oxygen can be modeled in reservoirs and reaches. Reservoirs can be modeled as simple, well-mixed or as a two layer model. Additionally, water quality routing methods are available with or without dispersion. RiverWare does not have a connection to any GIS software; however, a hydrologic database (HDB) may be available (Frevert, et al., 2003; and Davidson et al, 2002). HDB is a relational database used by the USBR and developed by CADWES to be used in conjunction with RiverWare. HDB is an Oracle-based SQL database and includes streamflow, reservoir operations, snowpack, and weather data. RiverWare requires extensive prior experience with implementation and is proprietary software. It is assumed the costs are substantial high.

CALSIM, OASIS, RiverWare, and ModSim are similar in that they (Loucks et al., 2003) all use a high level language with syntax and logical operators. They are written to simple text files which are subsequently parsed and interpreted and are designed to be easy for planners and operators to use without the need for reprogramming. Similar to several other systems, CALSIM allows specification of objectives and constraints in strategic planning and operations without the need for reprogramming of the complex model (Loucks et al., 2003). CALSIM uses WRESL to define the objective function and constraints, similar to the OCL (Operational Control Language) used in OASIS and the Policy Editor employed in RiverWare. In ModSim, the optimization model is formulated directly through the GUI with no need for a modeling language, but with supplemental features of the optimization defined through the PERL scripting language. These various scripting languages allow planners and operators to specify targets, objectives, guidelines, constraints, and their associated priorities in ways familiar to them. CALSIM lacks a comprehensive GUI for constructing and editing the river basin system topology. The model does not link to GIS at this time.

DELFT-TOOLS (Delft Hydraulics, 2004) – Delft-Tools is a framework for decision support developed by Delft Hydraulics for the integrating water resources simulation programs. Functions of the system include scenario management, data entry, and interactive network design from map data, object-oriented database set-up, presentation, analysis and animation of results on maps. DELFT-TOOLS integrates the Delft Hydraulics models: SOBEK, RIBASIM and HYMOS. SOBEK is a one-dimensional river simulation model that can be used for flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, ground-water level control, river morphology, salt water intrusion and surface water quality. RIBASIM (River Basin Simulation Model) is a river basin simulation model for linking water inputs to water-uses in a basin. It can be used to model infrastructure design and operation and demand management in terms of water quantity and water quality. HYMOS is a time series information management system linked to the Delft Hydraulics models. Scientists in the project have no prior experience in its implementation and from the description of the model applications it seems to have been tested mostly in European contexts.

EPIC (McKinney and Savitsky, 2001) determines optimal water allocation in a river basin by multi-objective optimization in monthly time steps. Transport of conservative substances, e.g., salt, and management of generated hydroelectricity can also be optimized with the model. Water management alternatives can be developed for a time period of up to 15 years based on varying supplies and changing requirements of the water users. Models created in EPIC perform optimization calculations for operation of river networks according to a ranked list of objectives. EPIC provides an interface for automatic network and model creation, as well as data input, input of constraints on reservoirs, channel flow and salinity, setting of the objective weights and visualization of results. The modeling system generates nonlinear optimization model files for solution by the General Algebraic Modeling System. The main optimization criterion of EPIC is to minimize deficits of water delivery to users; other criteria include satisfying environmental flows, and maximizing reservoir overyear storage (McKinney & Savitsky, 2001). Policy decisions are modeled through changes in the weights on the various objective terms. A detailed description of the EPIC modeling system for river, salt, and energy management and its application to the Aral Sea basin can be found in McKinney and Kenshimov (2000) and McKinney and Savitsky (2001).

Applications of the EPIC modeling system for water management modeling have been primarily in the Aral Sea basin focusing on the Syrdarya (McKinney and Kenshimov, 2000). EPIC was used to determine water allocation tradeoffs between the needs of upstream hydroenergy production and downstream irrigation modeled on a one year basis (Antipova et al., 2002). The results were used to determine compensation for a reduction of energy production in favor of irrigation. EPIC is public domain package and has been extensively used in developing country contexts to develop water allocation scenarios as the hydrological basis for ecological impact assessment. The scientists in the project have no prior experience in its implementation, although it is potentially suitable model.

MIKE-BASIN (DHI, 2004a; DHI, 2004b) – MIKE-BASIN couples ArcView GIS with hydrologic modeling to address water availability, water demands, multi-purpose reservoir operation, transfer/diversion schemes, and possible environmental constraints in a river basin. MIKE-BASIN uses a quasi-steady- state mass balance model with a network representation for hydrologic simulations and routing river flows in which the network arcs represent stream sections and nodes represent confluences, diversions, reservoirs, or water users. ArcView is used to display and edit network elements. Water quality simulation assuming advective transport and decay can be modeled. Groundwater aquifers can be represented as linear reservoirs. Current developments are underway to utilize the functionality of ArcGIS-9 in MIKE-BASIN.

Basic input to MIKE-BASIN consists of time series data of catchment runoff for each tributary, reservoir characteristics and operation rules of each reservoir, meteorological time series, and data pertinent to water demands and rights (for irrigation, municipal and industrial water supply, and hydropower generation), and information describing return flows. The user can define priorities for diversions and extractions from multiple reservoirs as well as priorities for water allocation to multiple users. Reservoir operating policies can be specified by rule curves defining the desired storage volumes, water levels and releases at any time as a function of existing storage volumes, the time of the year, demand for water and possible expected inflows. Water quality modeling in MIKE-BASIN is based on steady, uniform flow within each river reach and a mass balance accounting for inputs of constituents, advective transport and reaction within the reach. Complete mixing downstream of each source and at tributary confluences is assumed. Non-point pollution sources are handled in the model as well as direct loading from point sources. The model accounts for the following water quality parameters: biochemical oxygen demand, dissolved oxygen, ammonia, nitrate, total nitrogen, and total phosphorus. Nonpoint loads are represented using an area loading method accounting for the nitrogen and phosphorous loads originating from small settlements, livestock and arable lands assuming certain unit loads from each category. MIKE-BASIN runs on Windows based PCs. Scientists at NIVA have extensively used MIKE-BASIN in similar environments and also possess the license for its use in the project.

WaterWare (Fedra, 2002; Jamison and Fedra, 1996) - WaterWare is a decision support system based on linked simulation models that utilize data from an embedded GIS, monitoring data including real-time data acquisition, and an expert system. The system uses a multimedia user interface with Internet access, a hybrid GIS with hierarchical map layers, object databases, time series analysis, reporting functions, an embedded expert system for estimation, classification and impact assessment tasks, and a hypermedia help- and explain system. The system integrates the inputs and outputs for a rainfall-runoff model, an irrigation water demand estimation model, a water resources allocation model, a water quality model, and groundwater flows and pollution model. The latest model seems to include economic optimization routines. There is little information about its implementation in data scarce environment and the licensing costs are exorbitant.

IQQM is an integrated quantity-quality river basin simulation model (DLWC, 1995) to model that generally runs on daily time-steps. It is designed to examine longterm river behaviour under various planning and management regimes, including environmental flow requirements for regulated and unregulated streams. It represents system behaviour through a node-link network approach, with a range of possible node and link behaviours to represent physical system components and operational requirements. The movement and routing of water between nodes is carried out in the links. One of the strengths of IQQM is the analysis of water demands and supply from an extensive and flexible range of sources, and resultant water sharing and system operation requirements (Hameed and Podger, 2001). The major processes include: (a) system inflows and flow routing; (b) on- and off-river reservoir modelling; (c) harmony rules for reservoir operation (operational management of multiple reservoirs ie, what and when to release from which reservoir); (d) crop water demands, orders and diversions; (e) town water and other demands; (f) hydropower modelling; (g) effluent outflow and irrigation channels; (h) wetland demands and storage characteristics; (i) water sharing rules for both regulated and unregulated river systems; (j) resource assessment and water accounting; and (k) interstate water sharing agreements. The model applies hydrologic flow routing for the simulation of the different ranges of flow conditions. There are a variety of options available to model the different operating procedures of both on- and off-river storages. IQQM can be configured for systems operating single or multiple reservoirs functioning in series or parallel. The irrigation module in IQQM includes features for soil moisture accounting, simulating decisions of farmers regarding area of crop to plant and irrigate, water ordering and usage, taking into account on-farm storage where appropriate, and accounting for uses related to water licenses and access rules conditions. The model can also simulate fixed demands (eg, urban water supplies and power stations), riparian and minimum flow requirements, flood plain storage behaviour, wetland and environmental flow requirements, distribution of flows to effluent streams and transmission losses. In addition, the Sacramento rainfall-runoff model as explained by Burnash et al. (1972) and climate generation model are both available as separate modules within IQQM. IQQM can also be directly linked with some of the Catchment Modelling Toolkit models such as E2 and WRAM.

9. Integrated Hydro-Economic Modeling

Agriculture in developing countries consume more than 2/3rd of the utilizable water resources and is by far the most competing user type that conflicts with other subsistence use systems. Many decisions of allocation to agriculture whether at a sub-system level or at river basin level are based on standard economic efficiency norms of water use and often overlook other non-market type uses. Important economic concepts that need to be examined include transaction costs, agricultural productivity effects of allocation mechanisms, inter-sectoral water allocations, environmental impacts of allocations, and property rights in water for different allocation mechanisms (McKinney at al., 1999). Mathematical programming models are used to allow for the joint choice of cropping patterns, water application levels, and water application technologies. Nonagricultural water uses include domestic, industrial, environmental, and in-stream demands. Due to the unique characteristics of water and the absence of markets in most cases, the value of water is often inferred, through market-based valuation techniques and non-market techniques.

Combined hydrologic and economic models are best equipped to assess water management and policy issues in a river basin setting. Integrated economic-hydrologic models can be classified into those with a compartment modeling approach and those with a holistic approach. Under the compartment approach there is a loose connection between the economic and hydrologic components, that is, only output data are usually transferred between the components. The various (sub) models can be very complex but the analysis is often difficult due to the loose connection between the components. Under the holistic approach, there is one single unit with both components tightly connected to a consistent model, and an integrated analytical framework is provided. However, the hydrologic side is often considerably simplified due to model-solving complexities. The most outstanding models using the holistic modeling approach are the Colorado River Basin Models CRS/CRM/CRIM. GIS-based decision support systems can support both modeling and analysis of river basins. Whereas GIS offer a spatial representation of water resources systems, decision support systems are interactive programs, which embed traditional water resources simulation and optimization models. Several studies have successfully applied GIS-based decision support systems in river basin models. The approaches range from loose coupling, the transfer of data between GIS and numerical models, to tight coupling, in which GIS and the models share the same database. The tightest of couplings consists of an integrated system, in which modeling and data are embedded in a single manipulation framework. It is at the basin level that hydrologic, agronomic, and economic relationships can be integrated into a comprehensive modeling framework and, as a result, policy instruments, which are designed to make more rational economic use of water resources, are likely to be applied at this level.

Improved basin-scale modeling of water policy options will be an important direction for water management research in the immediate future. Many of these integrated models are customized for specific basin applications and data driven. They are not easily applicable to other river basins and require code modifications and data customization. Efficient and comprehensive analytical tools that are generic are needed to make the rational water allocation decisions necessary to achieve sustainable water use strategies for many river basins.

10. Proposed Integrated Analysis Framework

From the field investigations carried so far in the Malaprabha sub-basin following issues and respective policy analysis scenarios have been identified where PES/PWS could be tested:

- Benefit-cost analysis (BCA) of Mandovi/Mahadayi inter-state water diversion project
- Feasibility of a market for drinking water supply services between Khanapur town and upstream land uses in Khanapur sub-catchment
- Feasibility of payments for irrigation water services in the Malaprabha command area

However, from the model inventory, there is no single model that can alone carry out the analysis of the above three policy scenarios in the PES/PWS context viz., comprehensively simulate the critical hydrologic processes, while assessing inter and intra sectoral water reallocation of existing or new resources, and quantify the range of potential economic impacts of policy-driven water reallocation scenarios.

Generally all stand-alone hydrologic models including SWAT and packaged suites of this class have the inability to treat surface and groundwater interaction adequately, more specifically groundwater extraction for agriculture. Among the few integrated surface-subsurface models, packages such as InHM and IGSM2 do not have user friendly interfaces with added inabilities to change the basin structure easily to depict temporal variations in land-water-use required for scenario assessment, and least tested in similar applications. MIKE-SHE is a well integrated surface-subsurface model, though inadequate for allocation scenario assessment, is too expensive to implement in the project. Alternatively, SLURP has reasonably good surface-subsurface integration and available at a much lower cost. Among the allocation-focused models, none except MIKE-BASIN and WEAP have the ability to model hydrologic processes. MIKE-BASIN although lacks economic tradeoff analysis does have a module based on the NAM algorithm used in the hydrologic model MIKE-11 package that can simulate hydrologic processes reasonably well. WEAP has simpler algorithms to depict hydrologic processes but has the ability to model the economic implications of reallocation, and is free for non-profit organizations (CISED is a non-profit research organization).

Hence an integrated framework consisting of hydrologic process simulation with land-use dynamics and allocation modeling is proposed. The above models could be worked within a loosely-coupled mode to meet the partial requirements of the project, namely policy scenarios (1) and (2). The integrated hydrologic-economic model combines the management of water supply systems with upstream irrigation/farming and evaluates economic tradeoffs of various reallocation options that can be tested in PES/PWS. Very few studies have attempted to integrate hydrologic system dynamics with socio-economic system, most of which are customized and basin-specific. The key contribution of this study would be development of an integration methodology that would enable rigorous hydrologic modeling with the economics and policy concerns while it is replicable in similar environments.

Proposed integrated modeling framework consists of a multi-tier modeling approach. The first tier of analysis includes a rigorous hydrologic model that will assess the stocks and flows of water resource under the reference scenario of the river basin based on existing land cover, rainfall-runoff relationship and cropping practices including existing policy instruments and under changed reallocation scenarios. Among the hydrologic models we propose to implement SWAT and SLURP. SWAT is a public domain package that is used extensively in developing contexts under moderate data availability, with which CISED has brief prior experience. SLURP is the second hydrological model which is proprietary but available at an affordable cost that has been used under data scarce conditions in developing countries such as Turkey, India and south-east Asia.

Outputs from the first tier analysis will be fed in to the second tier analysis that includes a general water accounting system with flows and stocks in a node-link network-based model. This level of analysis will include decision variables that will drive various allocation mechanisms and algorithms for prediction of future scenarios based on changing weather patterns, increasing population, changing water demands, etc. We propose to test two models in each of the first and second tier analysis. Among the water accounting and allocation models we propose to implement MIKE-BASIN and WEAP. NIVA has extensive experience in implementing MIKE-BASIN in similar projects. Although very expensive to implement in developing countries, NIVA has an existing license that could enable some advantages of the model over other water allocation models. As a second line of analysis an attempt will be made to implement the public domain package WEAP at CISED to test and demonstrate the model’s ability to carry out economic implications of reallocation scenarios effectively. There will be an attempt to test the hydrologic process modeling capabilities of MIKE-BASIN and WEAP. The integrated modeling framework would enable scenario assessment of economic impact of ongoing or potential changes in the hydrologic regime due to upstream land-cover change, changes in water use patterns and inter-basin diversions, drawing scenarios and values of water use from the PES/PWS exercise.

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