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# Integration of economic and hydrologic models: Exploring conjunctive irrigation water use strategies in the Volta Basin

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ABSTRACT

We describe the development, calibration and preliminary application of a dynamically coupled economic–hydrologic simulation–optimization model ensemble for evaluating the conjunctive use of surface and groundwater in small reservoir-based irrigation systems characteristic of the Volta Basin, Africa. We focus on a representative small reservoir-irrigation system located in the Antakwidi catchment in Ghana. The model ensemble consists of the physical hydrology model WaSiM-ETH and an economic optimization model written in GAMS. Results include optimal water storage and allocation regimes for irrigated production, given conjunctive surface water and groundwater systems. The goal of our research, conducted within the GLOWA Volta project, is to develop a decision support system for improving the management of land and water resources in the face of potential environmental change in the Volta Basin.



## 1. Introduction

The potential regional impacts of global environmental change present extraordinary challenges for users and managers of water resources. This is particularly true in regions already subject to water stress, regions possessing weak or inadequate water management infrastructure, and regions anticipated to exhibit high local sensitivity to broad scale changes in climate. The Volta River Basin, occupying over 400,000 $km^2$ within the sub-humid to semi-arid West African savanna zone, is characterized by these and other vulnerabilities, including low incomes and rapidly expanding population.

Volta Basin inhabitants are overwhelmingly rural, and small-scale rainfed agriculture is the dominant economic activity, employing roughly two in three Basin residents. Agricultural productivity is low, however, at roughly 1 metric ton of cereal yield equivalent per hectare, reflecting erratic and unreliable precipitation and low levels of fertilizer use—less than 3 kg N per ha in Ghana or roughly 20% of the Sub-Saharan Africa (SSA) average of 12.6 kg $ha^{-1}$, and far below the world average of nearly 100 kg $ha^{-1}$. Both factors are exacerbated by the extremely low percentage of cropland within the basin and surrounding region for which supplemental irrigation is available. Less than 1% of agricultural lands in Ghana and Burkina Faso are irrigated, as compared to roughly 4% throughout SSA and 20% worldwide (World Bank, 2004). Given extreme unreliability of rainfall, irrigation development is seen as an obvious strategy to increase agricultural productivity and food security. With annual population growth rates

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around 2.5%, national planning studies predict that water demand for irrigation within the basin will increase considerably in the near future (MoWH, 1998; Andah and Gichuki, 2003). Volta Basin rural residents also suffer from limited development of domestic water infrastructure, particularly in Burkina Faso, where only 37% of the population has access to improved water supply and 27% to improved sanitation (World Bank, 2004).

One response to the problems associated with inadequate irrigation and rural domestic water supplies has been the utilization of small reservoirs in Northern Ghana and throughout Burkina Faso. Several hundred have been constructed over the last 4 decades by government agencies and NGOs. These multipurpose structures impound the transient rainy season runoff from small catchments to provide rural communities with seasonal storage for small-scale irrigation and water for domestic purposes, livestock and aquaculture. The reservoirs begin filling with the onset of the rainy season, and provide supplemental irrigation during the rainfed cropping season (April to September) and primary water supply for a second, irrigated cropping season (October to February). In many locations, these reservoirs are completely dry prior to the onset of the following year's rains. Small reservoirs appear to have many desirable features, including relatively low capital investment requirements and a scale of construction and operation consistent with local, decentralized management. They are often described as significant local sources of groundwater recharge, although there is little empirical research documenting small reservoir–groundwater interactions.

Many questions arise concerning the relative benefits of an irrigation development strategy based on extensive construction of small reservoirs. Low-relief terrain settings dictate that these reservoirs typically have high surface area-to-volume ratios. Large open water areas are exposed to steep humidity gradients during several months of the year, leading to high evaporation rates. Numerical simulation suggests that evaporative losses (roughly 30% of annual water budgets) can easily exceed potential withdrawals for irrigation (around 10%). Additionally, reservoir siltation due to erosion within reservoir catchment areas can reduce storage capacity significantly during relatively short time spans, necessitating premature rehabilitation. Additional questions can be raised concerning the optimal density of small dam development, specifically the impacts of small dam ensembles on downstream flows, and the potential for negative health and environmental externalities (Van de Giesen et al., 2004; Amerasinghe et al., 2001).

Groundwater can serve as a substitute for stored surface water, and potentially as a complementary source of irrigation water at suitable locations within the Volta Basin, and the conjunctive use of surface water and groundwater is an important area of irrigation research (O'Mara, 1988). Annual groundwater extraction via boreholes, hand dug wells, and piped systems has increased substantially over past decades, although present levels of groundwater utilization are estimated to remain within sustainable limits throughout much of the basin, and specifically at between 5% and 10% of recharge in the Upper East Region, containing our research site (Martin and Van de Giesen, 2005). Groundwater is used preferentially for rural water supply, however, so that strategies promoting groundwater irrigation must be evaluated carefully to eliminate the possibility of conflict with critical domestic uses.

We describe the development, calibration and preliminary application of a dynamically coupled economic–hydrologic simulation–optimization model ensemble designed to evaluate the conjunctive use of surface and groundwater in small reservoir-based irrigation systems characteristic of the Upper Volta Basin. We focus on a representative small reservoir-irrigation system located in the Antakwidi catchment within the Upper East Region of Ghana. The model ensemble consists of the physical hydrology model WaSiM-ETH and an economic optimization model written in GAMS.

The dynamic linkage of hydrologic and economic models is appropriate because decisions concerning the quantity and timing of surface and groundwater abstractions, respectively, act in turn to modify the hydrologic boundary conditions constraining such decisions. Furthermore, the dynamics of hydrologic processes cannot be simulated accurately within the economic optimization model itself without a substantial increase in model complexity, increasing the burden on nonlinear optimization solvers. Of particular interest is the impact of groundwater extraction for irrigation on depth to water table, since village bore- and dug wells are of restricted depth, at least over the short term, and irrigation development strategies must not succeed at the expense of vital access to water for domestic purposes.

This study was intended as a ''proof of concept'', specifically, a means of testing and evaluating an approach to integrating hydrologic and economic optimization models with respect to feasibility, as distinct from producing a specific set of empirical research results that can be held up to examination in their own right. Therefore, we focus more on the methodology rather than specific results. We begin by presenting some general features of the study area, and discussing selected research literature. We then discuss the coupled hydrologic–economic model configurations followed by selected results of the conjunctive use optimization. In conclusion, we propose future extensions of the modeling work within the framework of the Glowa Volta Project.

## 2. Study area: the Volta Basin and Atankwidi catchment

The Volta Basin is located in West Africa between 5°30N–14°30N and 2°00E–5°30W (Fig. 1). The basin encompasses the majority of Ghana (70% of land area) and Burkina Faso (63%) and lesser portions of Togo, Benin, Mali and Cote d'Ivoire. It is a low-relief basin with elevations ranging from sea level to 920 m (mean elevation 257 m) and correspondingly low channel grades. The lower Volta Basin is fed by three major tributaries. To the west, the Black Volta (147,000 $km^2$) drains western Burkina Faso and small areas within Mali and Cote d'Ivoire; the White Volta (106,000 $km^2$) drains much of northern and central Ghana and Burkina Faso, and to the east, the Oti (72,000 $km^2$) drains the northwestern regions of Benin and Togo.

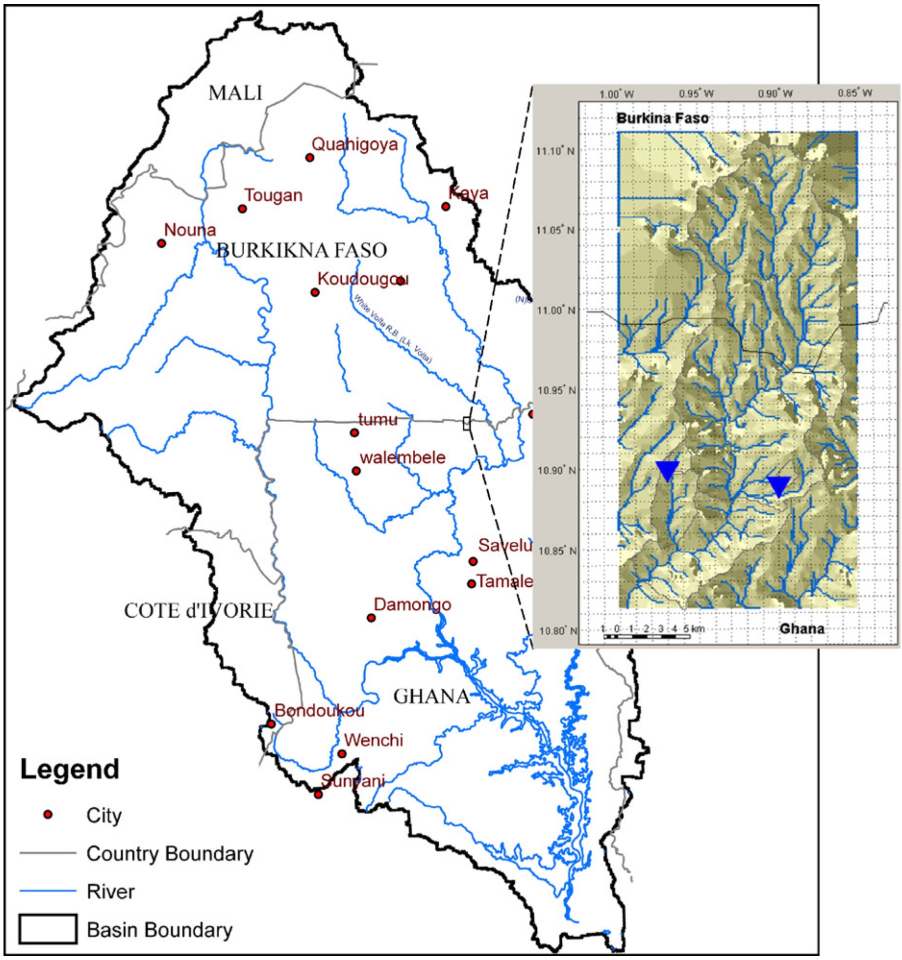


**Fig. 1 – Volta Basin (source: Andah and Gichuki, 2003) with Atankwidi catchment (flows gradients detail map) and reservoirs indicated.**

The Atankwidi is a tributary to the White Volta, flowing south from Burkina Faso into the Upper East Region of Ghana between Navrongo and Bolgatanga. The Atankwidi Catchment (Fig. 2), 276 $km^2$ in area, is typical of agricultural catchments found in the Upper East Region (UER), which is situated in the transitional area between the northern Guinea and the Sudan savanna zones. Within the transition zone, vegetation is characterized by open woodland savannas associated with perennial grasses in the south, and increasingly with annual tussock grasses in the northern zone (Iloege, 1980; Windmeijer and Riesse, 1993). Annual precipitation is around 990 mm distributed over pronounced rainy (April to October) and dry (October to March) seasons, and annual average temperatures are above 18 °C (Martin, 2005). Monthly rainfall exceeds potential evaporation for 2–7 months per year.

The UER contains the highest levels of groundwater use per $km^2$ within the Volta River basin. Geology consists of Brimian rocks of Paleoproterozoic age, which are part of the West African Man Shield (Martin and Van de Giesen, 2005). Formations that are found within the catchment are Birimian metasediments, granitoids (granodiorites, granite and gneiss) associated with the Birimian and intrusive Bongo granite. Granitoids make up the largest part of the study area. Outcrops of the potassium-rich pink Bongo granite are found in the northern and eastern part of the catchment. Soils in the catchment typically consist of sandy loam to sandy clay loam with high clay contents in the upper part of the profile and an increasingly coarse texture with depth. Weathering on average reaches a depth of 30–40 m. The main groundwater bearing zone is the lower weathered zone, where the fresh rock is only moderately weathered. Groundwater potential in the region is estimated at good to moderate (Martin and Van de Giesen, 2005).

The village of Kandiga (pop. 6000), which lies within Atankwidi catchment, consists of a central complex and peripheral settlements. Kandiga is the seat of the District Chief Executive. It has a large secondary school, health clinic, Women's Development Association and a tree-planting club that promotes tree planting to improve soil fertility. Groundwater pumping was introduced with the help of the NGO Water Aid, which provided pumps and training. Management and maintenance are performed by the local community (Shao and Biglobosa, 2002). Rural households are organized by compounds occupied by extended families engaged in mixed livestock and cultivation. The land is generally not privately owned; it is communally owned with the earth priests (*Tindaana*) exerting authority superimposed on government land tenure regulations. Some farmers are engaged in off-farm activities including trading, clothes-making and cash-crop cultivation, such as

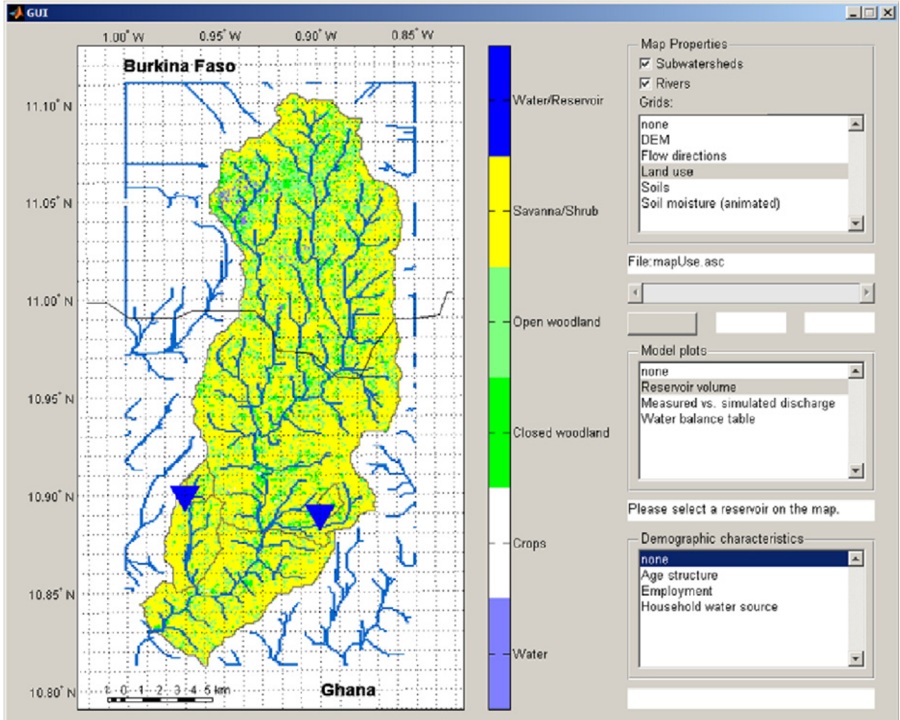


**Fig. 2 – Atankwidi catchment detail, with reservoirs indicated.**

shea-butter, to supplement their farm income. Livestock is used as a store of value: farmers sell cattle during or following bad harvests to finance food purchases. Stocking rates of livestock are much higher than the national average in Kassena-Nankana district where Kandiga is located. This hedging strategy to insure against bad harvests contributes to land overgrazing.

There were two small reservoirs in the catchment in 2004, the year the study was undertaken; one of which is used for irrigation (Kandiga Reservoir or Reservoir 1, see Fig. 2). The surface area of the Kandiga reservoir is 8 ha when full. Reservoir 2 has a surface area of 7 ha and is used mainly to provide drinking water for cattle. Kandiga Reservoir (Reservoir 1), built in the early 1990s with donor funds, is typical of the small reservoirs distributed throughout the mid- and upper regions of the Volta Basin (Fig. 3). These reservoirs consist of earth-fill dams roughly 2.5–10 m in height and 100–750 m in length with passive spillways, capable of storing maximum volumes of $10^4$–$10^7$ $m^3$ and serving irrigation perimeters of between 5 and 20 ha (LACOSREP, 2004). The irrigation perimeters are equipped with small networks of distribution channels, typically lined with concrete and controlled via manually operated gates. Water is diverted from the reservoir to the channel network via one or more submerged conduits running beneath the dam and controlled by valves located on the downstream toe of the dam (Fig. 4).

## 3. Modeling objectives and approach

The task of achieving efficient, sustainable water management within Atankwidi catchment reflects, in microcosm, the broader challenges of integrated water resources management within the Volta Basin. While water is not absolutely scarce in a climatic sense (at least in most years), the spatial and temporal variability of rainfall and runoff result in a situation in which water supply represents the binding constraint to improved agricultural productivity, household income, health and well-being in many regions. During the dry season, irrigated agriculture competes with domestic, livestock, aquaculture and occasionally other sources of demand for available water resources. The water management challenge involves the strategic allocation of stored surface water and groundwater to meet these competing objectives in a manner that is sustainable, and which reflects the hierarchy of value of water in its respective uses. In this study, water for domestic purposes (drinking, food preparation, bathing, washing, sanitation) is assumed to hold the highest priority, intrinsically.

The development of a coupled hydrologic–economic model ensemble is intended to support the following activities, among others:

- Dynamic coupling of a distributed physical model and an economic optimization model.
- Optimization of cropping strategies and associated irrigation schedules at existing small reservoir locations.
- Cost-benefit analysis of small multipurpose reservoirs.
- Evaluation of the optimal (maximum) density of small reservoir development.

### 3.1. *Approaches to the integration of economics and hydrology*

The integrated model complex described here is designed to possess both simulation and optimization capabilities. The

**Fig. 3 – Kandiga Dam, reservoir and spillway.**

simulation capabilities are required to predict the response of the subcatchment hydrologic system to a given pattern of water storage, allocation and transfer decisions with sufficient accuracy to allow quantification of likely costs, benefits and impacts on each competing user community and on the physical environment. The optimization capabilities are required to reduce the number of alternatives requiring detailed simulation by identifying configurations of cropping and irrigation scheduling, reservoir operation, groundwater abstraction and possibly other policy-related parameters that lead to desirable outcomes (McKinney and Savitsky, 2003).

In recent years, a number of integrated water resources management studies have been conducted in which economic optimization models have been linked with models of surface water and groundwater hydrology. In one modeling format ("unified"), the technical, economic and hydrologic model components are integrated in a unitary body of code, such as GAMS (Brooke et al., 1998). Studies employing this modeling approach include Rosegrant et al.'s (2000) study of the Maipo Basin, Chile, Cai et al.'s (2003a,b) studies of the Syr Darya Basin in Central Asia, Ringler and Cai's (2003) study of the Mekong Basin, and Rodgers and Zaafrano's (2003) study of the Brantas Basin, Indonesia.

In an alternative approach, economic optimization models are coupled with engineering hydrology and possibly other simulation models and run as ensembles. Recent examples of studies employing coupled model ensembles for integrated analysis at basin-scale include Draper et al. (2003) and Jenkins et al.'s (2004) California water management study, Quinn et al.'s (2004) study of climate change and water resources in the San Joaquin River Basin, California, Letcher et al.'s (2002) IWRAM project to evaluate the impacts of climate, commodity prices and government policies on agricultural output and water supply within the Mae Chaem catchment, Thailand, and Barth et al.'s (2004) DANUBIA project.

Each approach has advantages and disadvantages. The unified approach reduces model integration and data management tasks by eliminating the need for model interfaces. As a consequence, however, the representation of many hydrologic (and possibly other) processes must be greatly simplified to avoid over-taxing optimization algorithms. Cases in which

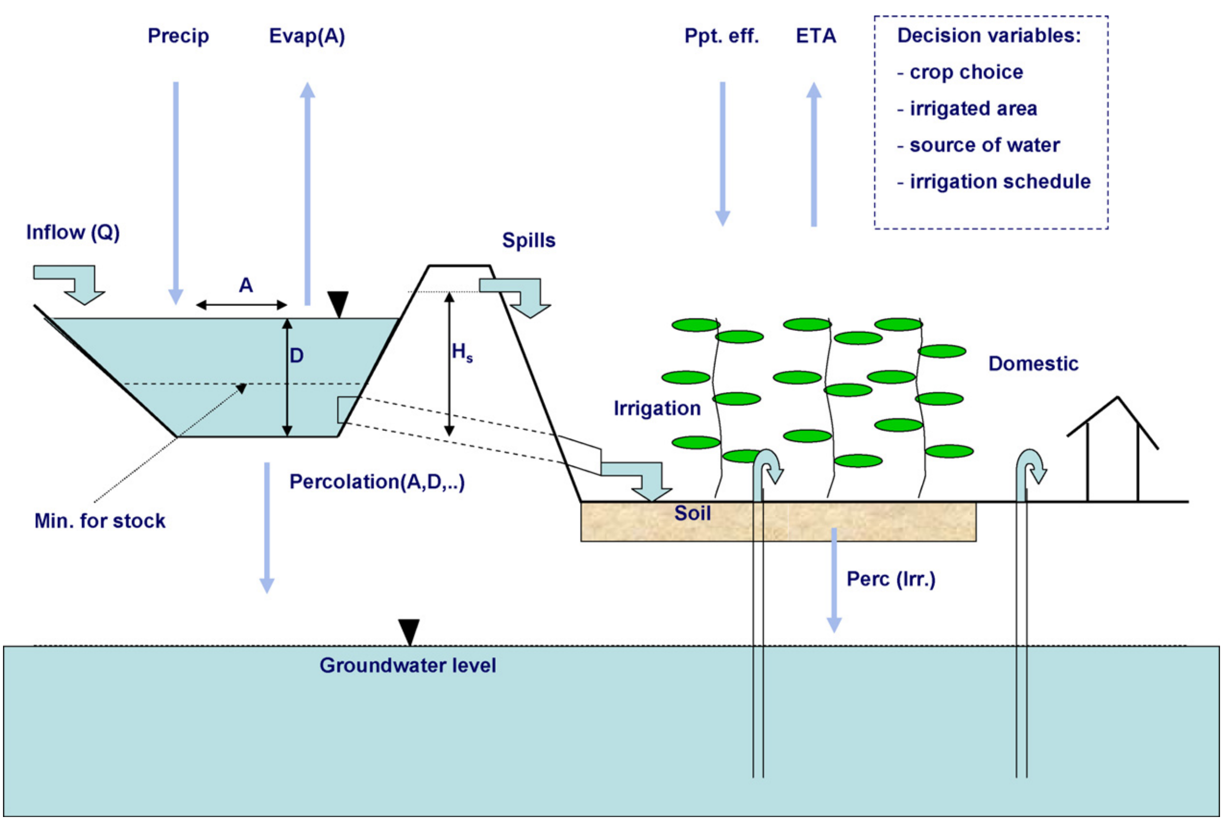


**Fig. 4 – Schematic of Atankwidi small reservoir conjunctive use problem used for the economic model.**

physical systems can be described realistically only by functions that are not continuously differentiable, or which contain abrupt thresholds, pose particular problems for nonlinear solvers. This can result in overly simplistic treatments of hydrologic processes such as groundwater flow and soil moisture storage. The unified modeling approach in any event requires an external source of hydrologic data to provide boundary conditions such as the time series of inflows to each river reach, because land surface hydrologic processes, including rainfall-runoff dynamics, cannot realistically be incorporated within the optimization framework itself.

The use of coupled model ensembles greatly enhances the modelers' ability to simulate hydrologic, terrestrial and socioeconomic processes at finer levels of detail, and likely with enhanced accuracy, but model coupling introduces the need for significant software engineering tasks required to enable inter-operability. Having selected the coupled approach, our primary research task is to develop the interface between the physical hydrology and economic optimization models in a manner that minimizes redundancy, allowing GAMS to take full advantage of WaSiM's simulation capabilities. This challenge embodies both a research task, which is to determine an efficient allocation of computational effort between these models, and a software engineering task.

### 3.2. *WaSiM-ETH—physical hydrology*

We chose WaSiM-ETH (Schulla and Jasper, 1999), developed at the Swiss Federal Institute of Technology (ETH), because the model has been successfully calibrated and applied within the framework of the GLOWA—Volta project in the Volta basin at full basin scale (400,000 $km^2$), sub-catchment scale (100,000 $km^2$) and at small watershed scale (300 $km^2$) (Jung, 2006; Wagner et al., 2006; Martin, 2005). It is a distributed, physically based combined hydrologic surface, subsurface and groundwater model. It is spatially differentiated and supports both continuous and event-based rainfall-runoff simulations. Temporal resolution can range from minutes to daily time intervals. Spatial dimensioning is represented via a grid system consisting of equal-sized orthogonal cells and spatial resolution can range from 1 m to many kilometers.

The model domain can be subdivided into sub-basins, which can be extracted automatically from a digital elevation model (DEM) using a digital terrain analysis tool. It is also possible to subdivide the model domain into other zones of interest, e.g. into different land-use regions, or into upper and lower sub-watersheds, as in this study. In either approach, the basic subdivision is defined on a rectangular grid which may contain variably sized cells, similar to the spatial structure of climate models, i.e. grid cells show only small changes in width from row to row. WaSiM ETH permits the simulation of regulated reservoirs, river branching and artificial abstractions including irrigation. In simulating irrigation, the model allows users to specify whether water is taken from groundwater (from a lower layer within the same cell where irrigation is applied) or from surface water (the reservoir). The respective surface water and groundwater balances are then re-calculated to account for the impact of irrigation.

The input data files are shown in Fig. 5. Spatial data requirements include a digital elevation map (DEM), land-use and soil types, formatted to conform to the model spatial grid resolution. Meteorological data are managed via text files. The minimum meteorological data set includes precipitation (mm) and temperature (°C) by time interval. In this study, WaSiM-ETH was run using the optimum meteorological configuration, which includes global radiation ($W/m^2$), relative sunshine duration (%), wind speed (m/s) and relative humidity (%), supporting the calculation of potential evapotranspiration via the Penman–Monteith method. All meteorological data are interpolated to pixel level using one of several possible interpolation methods, including inverse distance weighting, altitude-dependent regression, bilinear interpolation, or Thiessen polygons.

The structure of WaSiM-ETH is modular, and alternative calculation methods are often available to model a given

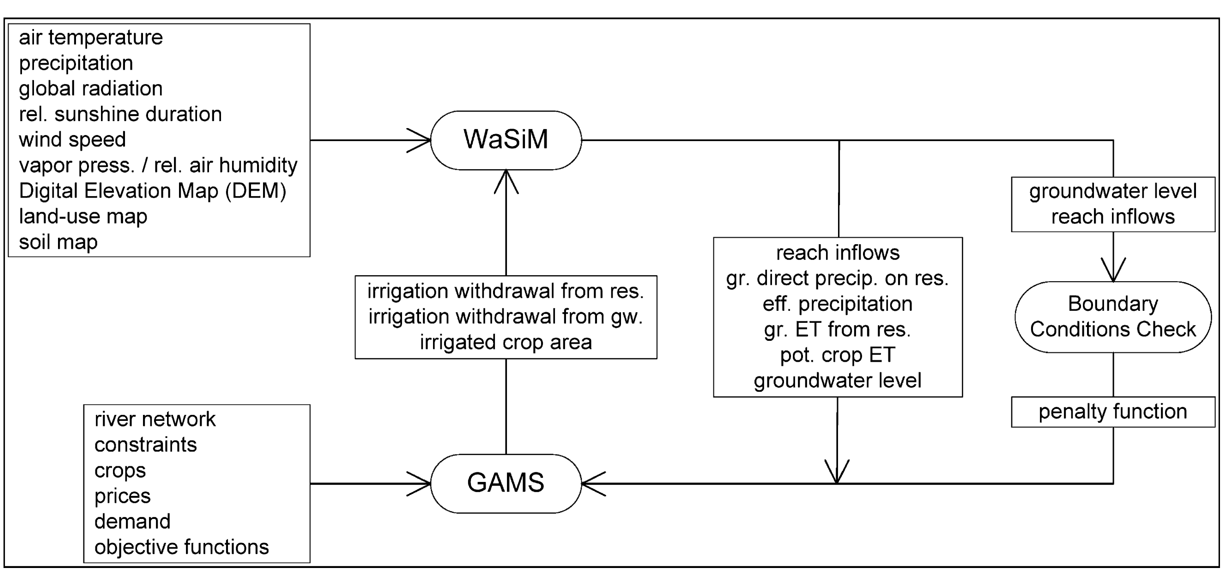


**Fig. 5 – Schematic of the input files required for the hydrology and economics models and the data exchange between them.**

hydrologic process. In this study, the following specification options were used in calibrating and validating the model:

- Meteorological data at hourly time intervals were used, and Inverse Distance Weighting was used for spatial interpolation.
- Potential evapotranspiration was calculated using the Penman–Monteith approach (Monteith, 1975; Brutsaert, 1982).
- Actual evapotranspiration was calculated via a simple reduction function of potential evaporation. Actual evaporation was estimated by reducing potential evaporation based on soil moisture storage below a specified threshold, set at 0.6 mm following Menzel (1997).
- Infiltration was simulated using an approach following Peschke (1977, 1987) based on the Green and Ampt (1911) model.
- Richards' equation was used to model soil water dynamics.
- A two-dimensional groundwater model utilizing an implicit finite difference scheme was dynamically coupled to the unsaturated zone.

The interface between the model and the user is the WaSiM-ETH control file, which contains all information required for the model run: (a) parameters controlling the model run, (b) file- and path names controlling input and output operations and (c) hydrologic model parameters, property tables and statistic model parameters. The control file is subdivided into separate sections, each responsible for a sub-model or for a separate theme such as interpolation of parameters or land use table. A more detailed description of WaSiM-ETH computational methods appears in the model handbook (Schulla, 1997).

### 3.3. *GAMS—economic optimization*

The conjunctive use economic optimization model developed for this study is coded in GAMS (General Algebraic Modeling System; Brooke et al., 1998), which was developed in the 1980s to facilitate development of increasingly complex operations research models, and has been used widely in the water resources and agricultural economics research communities. GAMS is a file-oriented system, which simplifies interface and data exchange with other applications, and provides seamless access to a wide range of large-scale linear, nonlinear and mixed-integer optimization solvers.

The conjunctive use—small reservoir prototype model, like all GAMS models, consists of sets (indices or model objects), data (scalars and exogenously determined parameters), variables (decision and state), variable bounds and constraints, equations, and other statements controlling the flow of calculations and passing instructions to the solver. Each member of a given set shares a common set of behavioral rules, equipping GAMS with object-like capabilities. For example, all members of a set of river reaches can be described in terms of the same generic water balance equation, although descriptive parameter values are reach-specific. This makes it relatively easy to add new model elements, or change the characteristics of existing elements without modifying the system of variables and equations comprising the model.

Our prototype optimization model is a greatly simplified representation of the Atankwidi catchment. The model contains two small reservoirs and an irrigation system associated with one of them (Reservoir 1, Kandiga) overlying a shallow aquifer (Fig. 4). Water from the Western tributary is captured and stored in Reservoir 1, which has a total (live + dead) capacity of roughly 40,000 $m^3$. Inflow to the reservoir in excess of full capacity is spilled through a passive spillway, and flows downstream to the confluence of reaches. Water can be withdrawn for irrigation through a conduit located below the dam and controlled by a valve. The irrigation system consists of 10 ha of irrigable command area, and contains soils assumed suitable for the cultivation of the dominant crops grown in the region, including rice, maize, tomatoes and onions. Irrigation water can also be extracted from the underlying aquifer, although at a variable cost assumed equal to the cost of electric power needed to pump one cubic meter of water from groundwater depth to surface. Pumping costs are thus directly proportional to the vertical distance to water table. The aquifer is recharged locally, via percolation from the small reservoir, irrigation system conveyance losses, deep percolation from irrigated areas, and by diffuse recharge due to its position in the local groundwater flow field.

The model includes an objective function, water balances for the reservoir, river network and irrigation system, and a crop-water production function. The model also includes physical and economic constraints, such as a limit on the maximum extent of irrigable area. Constraints on water allocation patterns are imposed to maintain seasonally determined minimum reservoir levels for stock watering, and by maximum depths to groundwater (corresponding to existing well depths) to ensure the reliability of domestic water supply. The constraint for livestock watering reflects the priority that the local population places on maintaining livestock, as revealed in household surveys. The maximum depth—domestic water supply constraint (wells cannot dry out) is motivated by the priority placed on domestic uses, consistent with the treatment of domestic water supply as a social, rather than an economic good.

The objective function in the model describes the sum of net benefits of available stored water ($Z$), consisting of returns to irrigated crop production, a proxy measure of the value of water stored for in-reservoir uses, and costs associated with pumping groundwater:

$$Z = \sum_{cp}(P_{cp}Y_{cp} - AC_{cp})A_{cp} + \sum_{pd}(RS_{pd}\,SP_{pd}) - \sum_{pd}CGW_{pd}$$

Net benefits from irrigation are calculated on a per hectare basis as physical yield in t $ha^{-1}$ ($Y_{cp}$) multiplied by the farm-gate price of the respective commodity in dollars per tonne ($P_{cp}$), less the average costs of production ($AC_{cp}$), which consist largely of labor, low levels of fertilizer use, herbicide, and traction. Per-hectare net benefits are multiplied by the number of hectares harvested ($A_{cp}$).

Water stored in the reservoir is used also for other purposes, such as stock watering and brick making (consumptive uses) and informal fisheries and clothes washing (non-consumptive uses). Reliable economic data are not available to evaluate the explicit value of a unit of water used for these purposes. Hence, we assign a single unit benefit (SP) to the volume of water held in storage for each time period ($RS_{pd}$). We use an initial value of SP of \$5.00 per 10,000 $m^3$ in storage, per week. We also examine the impacts on management decisions of SP values ranging between \$3.00 and \$100.

Groundwater extraction costs ($CGW_{pd}$) were evaluated using a proxy measure, which is the market cost of electricity required to lift one cubic meter of water the required distance, times the volume lifted. In the UER, most farmers lift water manually (by bucket) from open dug-wells. The use of electricity as a proxy measure allows us to make explicit the costs involved in lifting water over variable distances, and to impose practical limits on the volume of extraction from any well during a given period.

Choices regarding crops and planting dates are two important decision variables. Economically important local crops include irrigated rice, tomatoes and onions grown in the dry season and wet rice in the rainy season, which typically requires supplemental irrigation. The model operates at weekly time steps, and the simulated cropping calendar begins with the onset of the rainy season, so that week 1 corresponds to April 1–7 and week 52 to March 24–30 of the following year. Crop choice determines the economic productivity of water, and total returns to irrigating households. Long-season crops generally have larger water requirements and place greater restrictions on subsequent planting decisions. The option to use staggered planting dates reflects the differing water requirements at each stage of crop development. Many crops have relatively low water requirements during the initial and final stages, but demand increases as the crop canopy develops. Optimal strategies may involve staggered plantings to ensure that the entire crop does not reach maximum water (and labor) demand at the same time. Crop yield as a function of water supply (direct precipitation + irrigation) is simulated using the standard FAO yield coefficient method (FAO 56):

$$Y_C = Y_C{}^P\left(1 - k_c\left(1 - \frac{ETA}{ETC}\right)\right)$$

$Y_C$ is observed (simulated) yield, $Y_C^p$ is yield potential, assuming water is not limiting, $k_c$ is the empirical FAO crop-water response coefficient, ETA is actual crop evapotranspiration and ETC is potential crop evapotranspiration. ETC is determined by environmental controls, including radiation, temperature, humidity, and wind speed; and by crop type and developmental stage.

Decision variables include the allocation of land to each crop in each season, planting dates, and the amounts of surface water and groundwater diverted for irrigation in each period. The volume of water in the reservoir is described using a conventional control volume approach (Fig. 4):

$$S_t = S_{t-1} + P_t + Q_t - E_t - RP_t - G_t - I_t$$

$S_t$ is storage at the end of period t, $P_t$ is direct precipitation during period t, $Q_t$ is inflow from the catchment, $E_t$ is surface evaporation, $RP_t$ is overflow spillage, $G_t$ is percolation to groundwater and $I_t$ is abstraction for irrigation. Among these, only $I_t$ is a decision variable. $P_t$ and $Q_t$ are exogenously determined (boundary conditions). The remaining terms ($E_t$, $RP_t$, $G_t$) are functions of reservoir storage and are dependent on decisions regarding $I_t$. Evaporation ($E_t$), in particular, is strongly dependent on storage through the areal extent of reservoir surface area, which is related to storage via a surface area-to-volume curve based on Liebe (2002) and applicable to small reservoirs in this region.

### 3.4. Physically based approach to model integration

Measured data on climate and hydrology within the Atankwidi catchment are scarce, and are limited in most cases to a small number of sites and a few recent years. We use meteorological and hydrologic data collected primarily through GLOWA Volta project activities during 2001 through 2005 (Martin, 2005). The physical hydrology model (WaSiM-ETH) is calibrated and validated using existing data, and is then used to generate time series of surface discharge, groundwater levels and other required hydrologic data at locations and/or time periods for which measured data are absent or inadequate. Long-term meteorological data are available for Atankwidi in the form of MM5 mesoscale climate simulations covering the entire Volta Basin (Jung, 2006). This model-generated data provide the boundary conditions for the economic optimization model. Once the optimal solution is obtained, the values of decision variables are passed back to the hydrologic model, which is re-executed. The output is examined to determine whether the original boundary conditions are still valid, and in particular, if groundwater levels have fallen below acceptable bounds. If conditions have been violated, restrictions on groundwater extraction are tightened, and the optimization model re-executed. The process is illustrated in the dataflow diagram (Fig. 5).

## 4. Model results

### 4.1. Results of WaSiM-ETH model

The model WaSiM-ETH was successful in simulating the catchment hydrology. Although comparison between the daily measured and simulated runoff at the catchment outlet (Fig. 6) shows that some of the peaks in the hydrograph do not match, the total volume of measured runoff (98 mm) was very close to the total volume of simulated runoff (114 mm) for the rainy season (Table 1). The coefficient of determination ($R^2$) was 0.72 (see Fig. 7), indicating a reasonably good calibration. The Nash–Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970) of 0.2 was calculated after taking out one outlier point. Although data from five rain gauges were incorporated to calculate the spatial precipitation field over the 273 $km^2$ catchment, rainfall variability within the catchment confounded efforts to improve the calibration. The model performance is likely to improve with a longer time series of data.

According to the water balance calculations, annual total runoff was 14% of the annual total Rainfall (Table 1). The average estimated potential ET is 2503 mm for the year and 1095 mm for the rainy season. The simulated actual ET values are 953 mm for the year and 630 mm for the rainy season. These high values (total 2004 rainfall was 973 mm) are typical for the semi-arid climate of the Volta Basin. A previous study

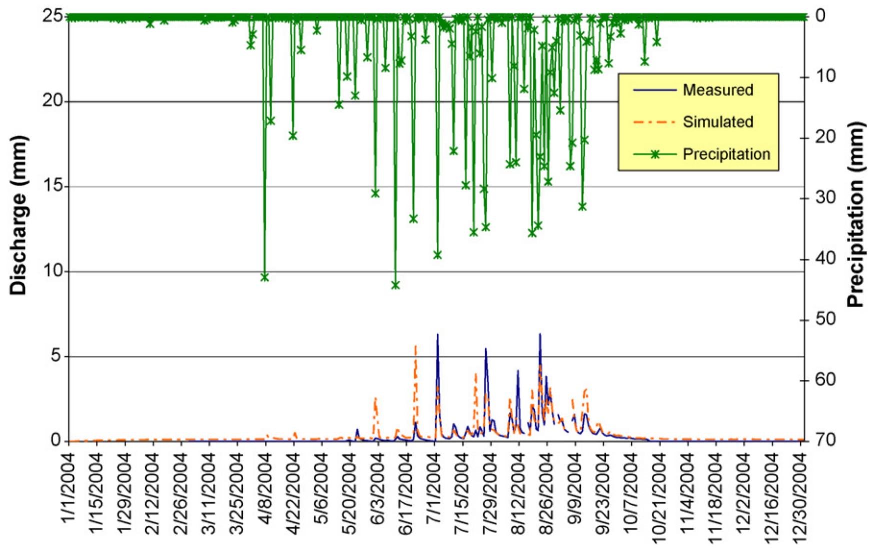


**Fig. 6 – Measured and simulated runoff from the outlet of the Atankwidi watershed.**

**Table 1 – Water balance calculations for the Atankwidi catchment using the WaSiM-ETH model precipitation–evaporation-groundwater recharge-Runoff = *E***

| | Rainy season (1.04–30.09, 2004) | Yearly (2004) |
|---|---|---|
| Precipitation (mm) | 945.6 | 973.3 |
| Actual evapotranspiration (mm) | 629.7 | 953.3 |
| Potential evapotranspiration (mm) | 1095.2 | 2502.8 |
| Simulated runoff (mm) | 113.6 | 140.9 |
| Measured runoff (mm) | 97.5 | N/A |
| Groundwater recharge (mm) | 31.6 | −10.2 |
| Error (mm)* | 170.7 | −110.7 |

* *E* = sum of errors in water balance calculations.

of the annual water balance in the Upper East Region (Andreini et al., 2000) based on historical data showed that up to 90% of total catchment rainfall is accounted for by ET. The mean annual daily temperature for 2004 was 27.6 °C and average relative humidity was 42%. During the rainy season, mean temperature was 28.2 °C and relative humidity was 66%. Water balance calculations indicate that there is positive groundwater recharge during the rainy season (32 mm) although there is a net negative recharge over the entire year (−10 mm). Therefore, a complete shift from using surface water to groundwater might not be sustainable, assuming that 2004 conditions are typical. However, 2004 was a drier than normal year, and the use of supplemental groundwater irrigation is a good strategy to reduce the risk and vulnerability associated with sole dependence on surface water for irrigation,

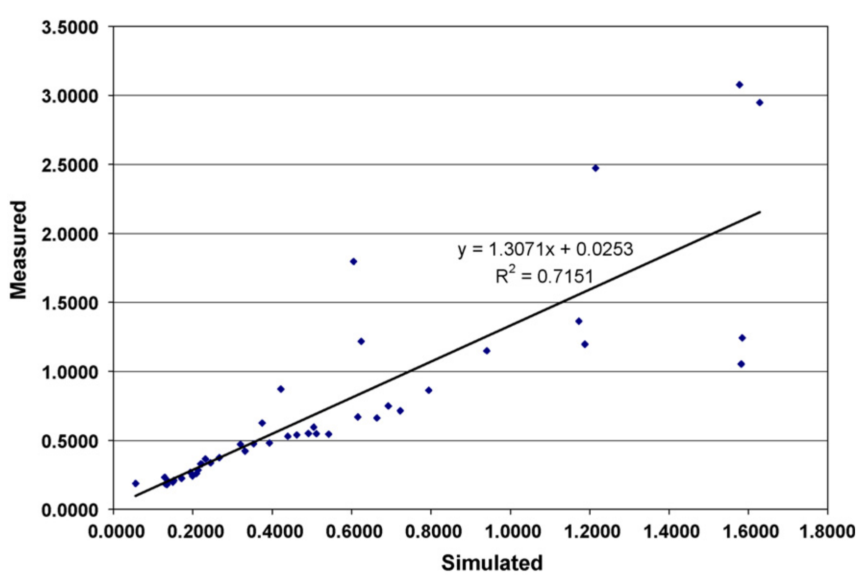


**Fig. 7 – Measured and simulated daily outputs (mm/day).**

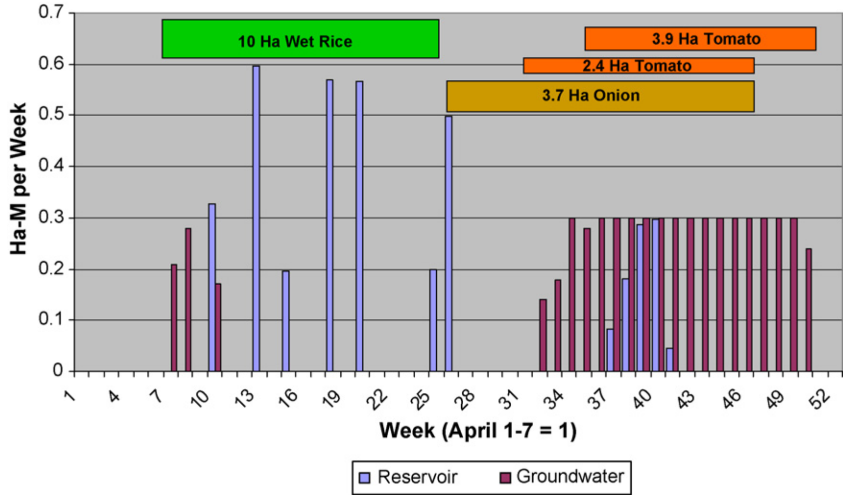


**Fig. 8 – Optimized pattern of surface and groundwater extraction.**

particularly during intermittent periods of surface water scarcity. ET losses can also occur in the dry season due to transpiration from plants, particularly trees with deep root systems. These results suggest that to increase water retention and water use within the catchment, management strategies must focus on reducing losses through ET and increasing groundwater recharge.

The errors (and variation in errors) in the hydrological model, presented in Table 1 are +18% during one rainy season and −11% during one calendar year. As the model was calibrated using runoff, the errors could be due to under-estimates in groundwater recharge and the re-charge of soil moisture storage during the rainy season. However, during the dry season, capillary rise from groundwater resources to soil moisture, and hence to evapotranspiration, seems to be underestimated. At the same time, the model may be over-estimating evapotranspiration during the entire calendar year. The implications of these results for the optimization model are that there may be underestimation of available groundwater. The main goal of the study was to test the model integration concept. Therefore, it was decided that the simulated water balances were acceptable to run the optimization model.

### 4.2. *Results of the water optimization model*

Using WaSiM-ETH output as input data, the optimal cropping pattern was determined in GAMS using nonlinear optimization. The optimal strategy, defined as the decision set that maximizes the objective function, involves the use of direct precipitation, in conjunction with periodic reservoir diversions, to grow a wet season rice crop; followed by a dry season crop consisting of a mix of onions and tomatoes, planted at staggered intervals. The dry season crops utilize reservoir storage initially, but are primarily irrigated via groundwater. The staggered cropping calendar offsets the water-intensive periods of specific crops, improving overall water use efficiency.

The optimal strategy involves planting the entire 10 ha command area with wet (paddy) rice in week 7 (May 13–19) when precipitation is sufficient to ensure adequate soil moisture and begin filling the reservoir. This 140 day crop is harvested in week 26 (September 23–29), near the end of the rainy season. In week 27, 3.7 ha of onions are planted (150 day crop), followed by 2.4 ha of tomatoes in week 32 (120 day crop), and an additional 3.9 ha of tomatoes in week 36, for a total of 10 ha of dry season crops. The optimal cropping and irrigation schedules are shown in Fig. 8. The profits from irrigated agriculture ($18,943) dominate the objective function value ($19,433), with in-reservoir storage uses contributing an additional $572 and implicit pumping costs reducing benefits by $82 (Table 2). Agricultural profits are equivalent to roughly $950 ha$^{-1}$ per crop season, or $1895 ha$^{-1}$ per year. The assumed value of water for in-reservoir uses (SP) has little impact on the optimal cropping strategy. As indicated in Table 2, varying SP between $3 and $100 per 10,000 m$^3$/week has only a minor impact on net revenue from irrigated cropping, groundwater extraction costs and mean storage levels. An important reason for this is the high level of evaporative losses from the reservoir as the dry season progresses. Irrigated agriculture effectively competes with the atmosphere for available reservoir resources, and little is gained by holding water in reserve, only to be lost subsequently to non-productive evaporation.

The extent to which this strategy results in optimal use of reservoir water depends critically on the actual pattern of rainfall and reservoir inflow. Thus our results are to some degree contingent upon the 2004 climate and reported input and output prices. Assuming that long-term climate and hydrology data are available, an exceedance probability-based approach is clearly preferable. The basic strategy identified, dictated broadly by the seasonality of rainfall, runoff and storage, is likely to be successful over a wide range of annual conditions, with modest adjustments in times of planting.

The water budget in the small reservoir is summarized in Table 3. Irrigation diversions are small, relative to both reservoir spills and to water surface evaporation, highlighting the relative inefficiency of these structures as sources of irrigation water. It is typical in reservoir optimization schedules to enforce a constraint that ending storage equals

**Table 2 – Objective function values and sensitivity analysis**

| Unit value in-reservoir storage (USD/$10^4$ $M^3$) | Net value irrigated cropping (USD) | Total value in-reservoir storage (USD) | Cost ground-water pumping (USD) | Objective function value (USD) | Mean period storage ($10^4$ $M^3$) |
|---|---|---|---|---|---|
| 3 | 18943.9 | 341.9 | 80.7 | 19205.2 | 2.2 |
| 5 | 18943.1 | 572.4 | 81.8 | 19433.7 | 2.2 |
| 10 | 18943.1 | 1,151.4 | 86.4 | 20008.1 | 2.2 |
| 15 | 18943.1 | 1,727.1 | 86.4 | 20583.8 | 2.2 |
| 20 | 18942.9 | 2,303.1 | 86.4 | 21159.5 | 2.2 |
| 25 | 18942.9 | 2,878.9 | 86.4 | 21735.3 | 2.2 |
| 50 | 18942.9 | 5,757.7 | 86.4 | 24614.2 | 2.2 |
| 75 | 18792.3 | 8,872.1 | 85.5 | 27579.1 | 2.3 |
| 100 | 18792.3 | 11,829.4 | 85.5 | 30536.5 | 2.3 |

**Table 3 – Water budget in the reservoir 1**

| | Volume ($M^3$) | Percent of input |
|---|---|---|
| Inputs | | |
| Initial reservoir storage | 24000.0 | 6.3 |
| Inflows | 279600.0 | 73.7 |
| Direct precipitation | 75800.0 | 20.0 |
| Total inputs | 379400.0 | |
| Outputs | | |
| Evaporation | 111000.0 | 29.3 |
| Percolation to groundwater | 16000.0 | 4.2 |
| Spillway discharge | 214000.0 | 56.4 |
| Diversions for irrigation | 38500.0 | 10.2 |
| Reservoir end storage | 0.0 | |

or exceeds beginning storage, although in this year (2004), rainfall was abnormally low, and the reservoir nearly dried out by year's end, independent of the pattern of irrigation withdrawal. Under these circumstances, the stock watering constraint must be relaxed during months of zero storage to allow for a feasible solution. In practice, when reservoirs dry out, livestock are watered from dug-outs, or are moved to areas of perennial storage. The study site was visited in 2005 and it was observed that farmers had decided to not plant any crops that year. We were told that the reason for this was because in 2004, the water in the reservoir ran out before harvest and as a result, the harvest was very low, confirming the accuracy of water balance simulations. Had farmers used supplemental irrigation from groundwater, as recommended in this modeling exercise, this harvest losses would have been minimized.

## 5. Further research applications

The modeling exercise described above involved a single recent year (2004), as the primary focus of the study was to develop a methodology for coupling the economic and hydrological models. To provide sound guidance for water management decision-making, however, a wider range of climatic conditions must be modeled. Extended simulations involving many years will allow us to address a wider range of issues, such as the return on investments in small reservoirs over their design lifetime (20–30 years) and management protocols for drought years. Multi-year simulations would also enhance the performance of WaSiM-ETH, as initial conditions for each year would be linked to climate, and to decisions taken in previous years.

WaSiM-ETH is a useful tool for simulating a wide range of hydrologic variables required for optimization studies in a data-scarce environment. However, several aspects of WaSiM's specification restrict its suitability in particular applications. WaSiM currently does not possess the capacity cannot be used to model a storage reservoir as such—reservoirs are presently simulated by ponding water on a pixel or pixels, by introducing a clay layer in the soil model. The impact of reservoir retention is simulated by applying an abstraction rule (a volume-runoff-table for each reservoir) or by applying a single linear storage approach to uncontrolled reservoirs in the routing model. As a consequence, explicit stage-storage-area relationships, essential in predicting evaporative losses accurately, cannot be specified. In the context of this study, GAMS was used to simulate reservoir behavior in part to overcome this limitation.

To identify optimal cropping strategies that are robust to climatic variation, the economic optimization model must also be expanded to optimize over many years and the treatment of non-water resource constraints must be improved. In its current form, the objective basis for optimization is limited primarily to market valuation of crop production, based largely on crop-water response. Current GAMS development work focuses on improving the framework of economic analysis by expanding the production function to include a more detailed representation of a farm economy, including additional resource constraints, such as family labor.

One potentially important modification, currently under development, involves the addition of soil moisture accounting within the optimization model. Crop-water supply and use are mediated by the volume of water stored in the root zone. Explicit simulation of moisture storage will allow a wider and more realistic set of water management options to be explored, including deficit irrigation strategies.

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