

OPTIWAM: An Intelligent Tool for Optimizing Irrigation Water Management in Coupled Reservoir–Groundwater Systems

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Abstract An approach based on a real coded Genetic Algorithm (GA) model was used to optimize water allocation from a coupled reservoir-groundwater system. The GA model considered five objectives: satisfying irrigation water demand, safeguarding water storage for the environment and fisheries, maximizing crop water productivity, protecting the downstream ecosystem against elevated soil salinity and hydromorphic issues, and reducing the unit cost of water. The model constraints are based on hydraulic and storage continuity requirements. The objectives and constraints were combined into a fitness function using a weighting factor and the penalty approaches. The decision variable was water allocation for irrigation demand from reservoir and groundwater. The irrigation water demands around the reservoir were estimated using the Food and Agriculture Organization (FAO) Penman-Monteith method in the water evaluation and planning (WEAP) software. The deterministic GA model was coded using Visual Basic 6 and a new tool for irrigation water management optimization (OPTIWAM) was developed. To validate the applicability of the deterministic model for the operation of coupled reservoir-groundwater systems, the Boura reservoir (in the center-west region of Burkina Faso) and the downstream irrigation area were used as a case study. Results show that the proposed methodology and the developed tool are effective and useful for

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determining optimal allocation of irrigation water. Furthermore, the methodology and tool can improve water resources management of coupled reservoir-groundwater systems.

Keywords Irrigation · Water resources · Allocation · Optimization · Genetic algorithms

1 Introduction

In many regions in the world, particularly in developing regions such as Africa, availability and access to freshwater largely determines patterns of economic growth and social development (Odada 2006). Thousands of small reservoirs dot the landscape of rural sub-Saharan Africa (Venot and Krishnan 2011) and provide water for multiple uses including agriculture, livestock watering, fisheries, households and others (Faulkner et al. 2008; Andreini et al. 2009; Boelee et al. 2009; de Fraiture et al. 2014).

Reservoirs in West Africa were developed mainly to provide water for irrigation to increase crop production (Venot and Cecchi 2011). In Burkina Faso, the agriculture sector contributes about 35 % to the country's gross domestic product (FAOSTAT 2013) and more than 65 % of total water consumption is related to irrigation and agricultural development (MAHRH 2003). The development of irrigation has increased agricultural production and crop diversification, enhancing income generation, favoring labor creation, and promoting settlement of the rural population. Because water supply is inadequate in the semi-arid areas of West Africa, irrigation is used to supplement water supply for crops during the dry season.

Although reservoirs are initially designed for irrigation, aquaculture is subsequently introduced into these infrastructures. Fish production is also an important para-agricultural activity in rivers in West Africa. Fisheries are conceptually non-consumptive users of water, although water requirements to maintain fisheries have been estimated for different fishery cultures (Mdemu 2008; Tran et al. 2011a). Thus, maintaining the volume of water in the reservoirs is important for sustaining fisheries and also providing habitat to other aquatic life.

In addition, reservoirs play an important role in the sustainability of groundwater in arid and semi-arid areas. The seepage from reservoirs can be considered as a major source of recharge for aquifer systems. Groundwater is hydraulically connected to surface water in many regions of the world (Owor et al. 2011; Levy and Xu 2012). To withdraw groundwater, structures such as boreholes and hand-dug wells are used in West Africa although their usage is limited by cost. Because groundwater is generally less prone to pollution than surface water, it is mainly used for domestic water supply and watering livestock. The use of groundwater for irrigation is limited but can be considered as an alternative. Despite difficulties, agricultural groundwater development has had a long and varied tradition throughout Sub-Saharan Africa (SSA). Giordano (2006) estimated the total area irrigated by groundwater in SSA to be 1–2 million ha. Villholth (2013) updated the estimate of the current extent of groundwater irrigation in SSA. The total irrigated area using groundwater is significantly higher than the earlier estimate of 6 % proposed by Giordano in 2006. Laube et al. (2008) estimated that about 100–200 ha of land are cultivated with groundwater in the dry season in the Upper East Region in Ghana.

The spatial and temporal variability in rainfall, global climate change, land degradation and high population growth rates put immense pressure on water resources in West Africa (Descroix et al. 2009; Favreau et al. 2009; Karambiri et al. 2011). Clearly, surface water resources are very vulnerable to droughts. Lack of efficient management tools and procedures for assessing sustainable use of water resources in reservoirs exacerbates the situation (Tendai 2005).

A United Nations Environment Programme (UNEP) study (2002) revealed that, in the next decades, water demand will rise to levels that will make providing water for human use more difficult. It is clear that wise management is required to address the many challenges that confront the sustainability of water resources in West Africa. To secure water supplies in anticipation of the negative impacts of predicted climate change in the coming years, it is necessary to develop decision support systems for optimizing water allocation. There is an immense need to formulate strategies to utilize the available resources effectively and efficiently (Jothiprakash and Shanthi 2006; Suiadee and Tingsanchali 2007).

During the last several decades, various optimization techniques have been developed and used for solving water resources problems. Some state-of-the-art reviews of these techniques were provided by Yeh (1985), Labadie (2004), Rani and Madalena (2010) and Singh (2012). In recent years, the research community focused on soft computing techniques, such as Evolutionary Algorithms, and more specifically Genetic Algorithms (GAs). GAs have proven to be effective and suitable for solving optimization problems (Momtahan and Dariane 2007; Consoli et al. 2007; Azamathulla et al. 2008). GA models were also successfully applied to solve different optimization problems for reservoir operation by Jian-xia et al. (2005), Reddy and Kumar (2006), Li and Wei (2008), Jothiprakash and Shanthi (2009), Jothiprakash et al. (2011), Yang et al. (2013).

Yang et al. (2009) integrated multi-objective GA, constrained differential dynamic programming and groundwater simulation model to solve a water resources planning problem for the combined use of surface water and groundwater in southern Taiwan. Safavi et al. (2010) employed artificial neural networks (ANN) as a simulator and GA as an optimizer in the optimal operation of surface water and groundwater resources for the Najafabad plain in west-central Iran. (Chen et al. 2013a, b) proposed a hybrid approach consisting of GA and ANN for optimizing the combined use of surface water and groundwater resource management. Their results indicate that adding a groundwater system to a surface water system can significantly decrease the shortage index. RezapourTabari and Soltani (2013) applied a non-dominated sorting GA (NSGA-II) and a sequential GA (SGA) to determine the optimal trade-off between different management objectives for the combined use of surface water and groundwater. Safavi and Esmikhani (2013) developed a support vector machines (SVMs) model as a simulator of surface water and groundwater interaction model while GA was used as the optimization method. Noori et al. (2013) formulated a GA for optimal operation of a multipurpose multi-reservoir system. Nouri (2014) developed a multi-sexual GA to optimize the daily management of a hydraulic system in Tunisia. Recently, Fallah-Mehdipour et al. (2015) developed and applied a fixed length gene genetic programming (FLGGP) algorithm coupled with GA to derive the optimal operation of an aquifer- reservoir system.

Applications using GA approaches have covered many objectives such as: satisfying water demands (Zahraie and Hosseini 2009; Chang et al. 2010; Wang et al. 2011; Louati et al. 2011), maximizing the crop yields or maximizing the hydropower generation (Kumar et al. 2006; Chen et al. 2013a, b), maximizing the net benefit of water use (Suiadee and Tingsanchali 2007), minimizing water costs and use (Nouri 2014), and incorporating socio-economic and environmental aspects (Chang et al. 2010; Cai et al. 2013).

The novelty of this research is the integration of conflicting objectives of water management for irrigation in the problem formulation. The proposed methodology incorporates hydraulic, agronomic, environmental and economic objectives for management of a coupled reservoir-groundwater system. The approach based on a deterministic GA, allowed the

development of a decision support tool called OPTIWAM (OPTimizing Irrigation WATER Management).

The paper is organized as follows: Section 2 introduces the general conceptual model within a management area and presents the connectivity between different sub-systems. Section 3 presents the water management problem formulation, gives an overview of the main computational steps of the genetic algorithm for solving the problem, and provides detailed information on the case study and on the determination water demand for irrigation. Subsequently, the developed tool, OPTIWAM, is used to obtain the optimal solution for the reservoir-groundwater system. Section 4 shows the results and includes discussion about the findings of this study, as well as future research directions.

2 General Conceptual Model for Water Management

The general conceptual model is based on a single framework where sources, demands and transmission links are present. In the general conceptual model proposed (Fig. 1), sources are represented either by rectangles (groundwater: G) or by triangles (reservoir surface water: S) with indexes “gw” or “sw”. Demand sites “D” are represented by circles with index “d”. Connections between the model nodes (water sources and demand sites) are ensured by percolation and supply links represented by dotted and continuous lines, respectively.

It is assumed that within any given water management area, multiple sources with different water storage capacities can be used to satisfy the water requirements of demand sites. For groundwater sources, the storage capacity corresponds to the maximum water volume of the aquifer. However, of interest is the recharge to aquifer (dotted lines) which occurs via infiltration “ $V_{inf}(d, gw)$ ” from the surface water source and deep percolation from the

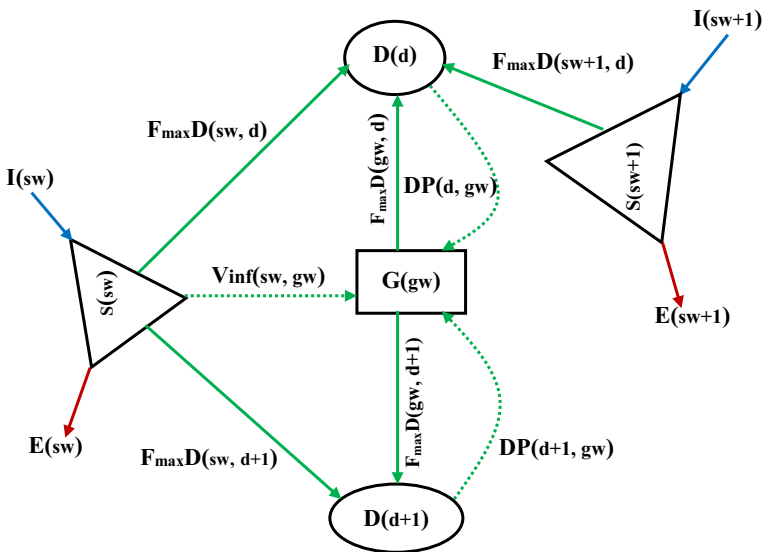


Fig. 1 Connectivity between water sources and demand sites within a management area (Adapted from Nouri 2014)

agriculture fields “ DP (d, gw)”. For surface water sources, the storage capacity is the maximum water volume that can be stored in the reservoir. This capacity is usually defined by the topography and the principal spillway level.

In the water management area, each surface water source “sw” can be supplied by inflows “ I (sw)” and is subjected to water losses “ E (sw)” due to net evaporation. In the proposed conceptual model, water transfer between surface water sources was not considered because such transfer is negligible for independent reservoirs.

It was also assumed that each of the demand sites should be supplied by at least one water source through a supply link (solid lines) that can be a pipe or a natural or artificial channel. Each supply link from source “se” to demand site “D(d)” is characterized by its maximum supply capacity “ $F_{max}D_{se,d}$ ” and its unit supply cost “ $P_{t_{se,d}}$ ” which depend on the infrastructure (pipelines, pumping stations and outlet capacities) and on the operating rules, respectively. The index “se” indicates that the relative information is valid for both water sources.

To model each reservoir “sw”, maximum and minimum storage capacities, “ V_{max_sw} ” and “ V_{min_sw} ” respectively, are needed. These parameters are obtained from the continuous elevation-volume curve.

Initial conditions of the sources must be specified at the beginning of the modeling, in particular, the initial amount of water stored “ V_{ini_sw} ”. For each demand site “d”, it is necessary to specify the required water volume “ D_d^t ”.

The decision variable is the water supplied by each water source “se” to each demand site “d” at any time interval t : “ $F_{se,d}^t$ ”, over the management period “0-T”.

3 Optimization Model Development

3.1 Mathematical Model Formulation

3.1.1 Objective Functions

In this study, water resources management is formulated as a constrained multi-objective problem with five objectives. The first objective is to satisfy water needs of demand sites “d” at every time interval “ t ” of the management period “0-T”. This objective is expressed by minimizing the following unmet demand function “ f_{DNS} ” (Pilpayeh et al. 2010; Jothiprakash et al. 2011; Giuliani et al. 2014)

$$f_{DNS} = \sum_{t=\Delta t}^T \sum_{d=1}^{ND} \left(\frac{\sum_{sw=1}^{N_{sw}} F_{sw,d}^t + \sum_{gw=1}^{N_{gw}} F_{gw,d}^t - D_d^t}{\sum_{sw=1}^{N_{sw}} F_{max}D_{sw,d} + \sum_{gw=1}^{N_{gw}} F_{max}D_{gw,d}} \right)^2 \tag{1}$$

where Δt is the time step. The time step depends on the dynamics of the managed system and the management objectives. For short-term operation, the time step can be hourly or daily, while for long-term operation, the time step can be monthly or yearly. “ND” is the number of demand sites, “ N_{sw} ” and “ N_{gw} ” are the number of surface water sources and aquifers in the management area, respectively.

The second objective is to guarantee water supply for the ecological system and for fisheries throughout the study period. This objective is expressed by minimizing the deviation to the full storage function “ f_{NR} ” (Pabiot 1999; Tran et al. 2011b).

$$f_{NR} = \sum_{t=\Delta t}^T \sum_{sw=1}^{Nsw} \left(\frac{V_{sw}^t - V_{max_sw}}{V_{max_sw}} \right)^2 \tag{2}$$

where “ V_{max_sw} ” and “ V_{sw}^t ” are respectively the maximum storage capacity and the storage at the end of time period t corresponding to the surface water source “sw”.

The third objective is to improve water productivity (WP) throughout the management period. Water productivity is represented by crop production per unit volume of water that is supplied from the sources (Playán and Mateos 2006; Mdemu et al. 2009). This objective is expressed by minimizing the water productivity losses function “ f_{WP} ” as follows:

$$f_{WP} = \left(\frac{WP_{max} - WP}{WP_{max}} \right)^2 \tag{3}$$

where “ WP_{max} ” is the maximum water productivity.

Water production functions can be computed on the basis of evapotranspiration or consumptive water use or on the basis of applied irrigation water. “WP” and “ WP_{max} ” are given by the following Eqs. (4) and (5)

$$WP = \frac{\sum_{d=1}^{ND} \sum_{cp=1}^{Ncp} \omega_{cp} \times Y_{d,cp} \times A_{d,cp}}{\sum_{t=\Delta t}^T \sum_{d=1}^{ND} \left(\sum_{sw=1}^{Nsw} F_{sw,d}^t + \sum_{gw=1}^{Ngw} F_{gw,d}^t \right)} \tag{4}$$

$$WP_{max} = \frac{\sum_{cp} \omega_{cp} \times Y_{max,cp}}{T \sum_{t=\Delta t}^T \sum_{cp=1}^{Ncp} ETM_{cp}^t} \tag{5}$$

$$\sum_{cp=1}^{Ncp} \omega_{cp} = 1 \tag{6}$$

where

“ $Y_{d,cp}$ ” is the crop “cp” yield at site “d” [kg/ha] over the management period, “ $Y_{max,cp}$ ” is the potential crop yield [kg/ha], “ ω_{cp} ” is the weighting coefficient associated to the crop “cp”; “ $A_{d,cp}$ ” is the cultivated area for crop “cp” at site “d” [ha] and “ ETM_{cp}^t ” is the crop evapotranspiration during the time period “ t ” [mm].

To account the response of crop yield to irrigation, a water production function (Rao et al. 1988) was adapted from the method proposed by Fang et al. (1989).

The fourth objective is to protect the downstream ecosystem against soil salinity and hydromorphic issues by maintaining the groundwater level. This objective is expressed by minimizing the deviation function “ f_{Env} ” between the total inputs (reservoir infiltration and deep percolation from the plots) and the total water withdrawal from the aquifers throughout the management period.

$$f_{Env} = \left(\frac{\sum_{t=\Delta t}^T \left(\sum_{d=1}^{ND} \sum_{gw=1}^{Ngw} F_{gw,d}^t - \left(\sum_{sw=1}^{Nsw} V_{inf_sw}^t + \sum_{d=1}^{ND} i_d \times (1-\alpha_d) \times BP_d^t \right) \right)}{\sum_{t=\Delta t}^T \left(\sum_{sw=1}^{Nsw} V_{inf_sw}^t + \sum_{d=1}^{ND} i_d \times (1-\alpha_d) \times BP_d^t \right)} \right)^2 \tag{7}$$

where “ $V_{inf_sw}^t$ ” is the volume of reservoir infiltration into the aquifer during the time period “ t ”; “ i_d ” is the fraction of water losses in the plots by deep percolation, “ BP_d^t ” is the water requirement for demand site “ d ” during the time period “ t ” and “ α_d ” is the irrigation efficiency for demand site “ d ”.

The fifth objective is minimizing the unit cost of water over the management area throughout the study period. The sum of all the costs of water supplied to demand sites was computed. The total cost was then divided by the total volume of water supplied and standardized by the maximum unit cost of water (Cai et al. 2003; Gartley et al. 2009; Nouri 2014). The unit cost is expressed by the following equation:

$$f_c = \frac{\sum_{t=\Delta t}^T \sum_{d=1}^{ND} \left[\sum_{gw=1}^{Ngw} (Pu_{gw,d} \times F_{gw,d}^t) + \sum_{sw=1}^{Nsw} (Pu_{sw,d} \times F_{sw,d}^t) \right]}{\sum_{t=\Delta t}^T \sum_{d=1}^{ND} \left(\sum_{gw=1}^{Ngw} F_{gw,d}^t + \sum_{sw=1}^{Nsw} F_{sw,d}^t \right)} \times Pu_{max} \tag{8}$$

where “ $Pu_{sw,d}$ ” is the unit cost of surface water supply “sw” to the demand site “ d ”, “ $Pu_{gw,d}$ ” is the unit cost of aquifer supply “gw” to the demand site “ d ”, and “ Pu_{max} ” is the maximum unit cost of the sources.

3.1.2 System Constraints

The model must respect the following constraints:

Hydraulic constraints (physical restrictions)

The hydraulic constraints are the minimum and maximum values for acceptable active storage in the surface water sources “sw”, and the maximum flow capacities of transmission links from sources to demand sites in any time period. These constraints are given by Eqs. (9) and (10a and 10b):

$$V_{min_sw} \leq V_{sw}^t \leq V_{max_sw}, \quad \forall sw \wedge \forall t \tag{9}$$

$$0 \leq F_{sw,d}^t \leq F_{max} D_{sw,d}, \quad \forall sw \wedge \forall d \wedge \forall t \tag{10a}$$

$$0 \leq F_{gw,d}^t \leq F_{max} D_{gw,d}, \quad \forall gw \wedge \forall d \wedge \forall t \tag{10b}$$

Storage continuity constraints

For any water sources “se” and time period “t”, the continuity equation is stated as:

$$V_{se}^t = V_{se}^{t-\Delta t} + I_{se}^t - O_{se}^t, \quad \forall se \in \{sw, gw\} \wedge \forall t \quad (11)$$

where “ V_{se}^t ” and “ $V_{se}^{t-\Delta t}$ ” are the storage volumes of source “se” at the end of time period “t” and “(t-Δt)”, respectively, “ I_{se}^t ” is the total inflow into water source “se”, during the time period “t”, and “ O_{se}^t ” is the total outflow from the water source “se”, during the time period “t”.

To model reservoir operation, net evaporation losses are considered as a storage function by assuming a linear relationship between the reservoir surface area and the initial and final storages (Ahmed and Sarma 2005; Moradi-Jalal et al. 2007; Celeste and Billib 2009; Regulwar and Kamodkar 2010), and we also assume a non-linear relationship between storage volume and reservoir seepage losses formulated according to Pabiot (1999).

At time “t=0” of the management period, surface water sources are characterized by their initial storage volumes “ $V_{ini_sw}^0$ ”. Equation (12) expresses this initial condition:

$$V_{sw}^0 = V_{ini_sw}, \quad \forall sw \quad (12)$$

where “ V_{sw}^0 ” is the water volume in source “sw” at time “t=0”.

The water resources management problem formulated in this study can be summarized as follows:

$$\left\{ \begin{array}{l} \text{Minimize } (f_{DNS}, f_{NR}, f_{WP}, f_{Env}, f_c) \\ F_{se,d}^t \\ \text{Subject to} \\ V_{\min_sw} \leq V_{se}^t \leq V_{\max_sw} \quad \forall d \wedge \forall t \wedge \forall se \in \{sw, gw\} \\ 0 \leq F_{se,d}^t \leq F_{\max_se,d} \\ V_{se}^t = V_{se}^{t-\Delta t} + I_{se}^t - O_{se}^t \\ V_{sw}^0 = V_{ini_sw} \end{array} \right. \quad (13)$$

The present problem formulation combines conflicting objective functions dealing with the social, economic and environmental aspects of water resources management. A genetic algorithm approach is proposed to solve this optimization problem and to identify optimal water supply from sources to demand sites.

3.2 Model Solving by Genetic Algorithm

3.2.1 Overview of Genetic Algorithms

A genetic algorithm (GA) is a search procedure based on the mechanisms of natural selection and natural genetics (Holland 1975). GAs are meta-heuristic techniques for searching over the solution space of a given problem in an attempt to find the best solution or set of solutions (Forrest 1993). The structure of GAs differs from traditional optimization methods and search procedures in four ways:

- Typically uses a coding of potential solutions, not the solutions themselves;
- Searches the solution space from a population of solutions, not a single solution, including discontinuities that can cause difficulties for calculus-based methods;
- Works directly with the objective function, thus requiring no additional knowledge about its derivatives;
- Uses probabilistic, not deterministic, search rules (Goldberg 1989).

A GA starts with an initial population of randomly generated solutions (chromosomes) with respect to the problem constraints. Each chromosome, representing a solution to the problem, is formed by a set of genes. Each gene represents a decision variable value of the problem (real coded solutions).

Each solution in the population is evaluated by maximizing a fitness function. After evaluation, the chromosomes with the best fitness function value are copied into the next generation (elitist evolution strategy). The number of these chromosomes depends on the crossover rate and the population size.

To form the next generation, the crucial mechanism of the “survival of the fittest” is applied to the chromosome based on the tournament selection method (Goldberg and Deb 1991). This method gives the opportunity to weak solutions, with some good genes, to participate to the creation of the next generation.

The arithmetic crossover, which operates on two selected chromosomes (parents), produces two new individuals (offspring) with the crossover rate (P_{cros}). Mutation is an important process that permits new genetic material to be introduced to a population, maintaining diversity and preventing premature convergence to local optima. Mutation alters one individual, parent, to produce a single new individual, offspring with a mutation rate (P_m). In this study a random mutation operator was used. After mutation, the new population is evaluated.

This process (elitism-crossover-mutation-evaluation) is repeated until the optimal values of the decision variables are found. When the maximum number of generations is reached or when no improvement in the maximal fitness function is observed, resulting in stagnation, the iterative process is stopped.

To enable accessibility of the proposed tool for stakeholder system the multi-objective problem formulated above was transformed into a single objective one using the weighting factor approach (Elferchichi et al. 2009). Each stakeholder can act on the optimization results by changing the weight of the objectives, giving them more or less importance according to his or her priorities. This leads to the formulation of a global objective function to be minimized. A single objective GA is thus used to generate the optimal releases from the reservoir-groundwater system, while respecting the system constraints.

3.2.2 Fitness Function and Violations

In single objective GA approaches, the purpose is to maximize a fitness function used to evaluate a solution. Thus, minimizing the objectives was transformed into maximizing the fitness function. The fitness function that integrates the five objective functions and their associated constraints can be expressed by Eq. (14):

$$Fitness(s) = \sum_j p_j \times F_j(s), \quad j \in \{DNS, NR, WP, Env, c\} \quad (14)$$

with $\sum_j p_j = 1$; $p_j > 0$

$$F_j(s) = \frac{1}{1 + f_j(s)} \tag{15}$$

where “ $F_j(s)$ ” is the fitness function corresponding to the objective function “ $f_j(s)$ ” and “ p_j ” is the weighting coefficient associated to the fitness function “ $F_j(s)$ ”.

In the fitness function, the objective function “ $f_{NR}(s)$ ” taking into account the violations of acceptable volumes in surface water sources is given in Eq. (16):

$$f_{NR}^p(s) = f_{NR}(s) \times (1 + \text{ViolVmaxMax}(sw)) \times (1 + \text{ViolVminMax}(sw)) \tag{16}$$

where:

“ViolVmaxMax (sw)” is the maximum violation of the maximum acceptable volume in the reservoir “sw” expressed by Eq. (17):

$$\text{ViolVmaxMax (sw)} = \text{Max}\left(0, \frac{V_{sw}^t - V_{\text{max}_sw}}{V_{\text{max}_sw}}\right) \quad \forall t \in \{1, \dots, T\} \tag{17}$$

“ViolVminMax (sw)” is the maximum violation of the minimum acceptable volume in the reservoir “sw” expressed by Eq. (18):

$$\text{ViolVminMax (sw)} = \text{Max}\left(0, \frac{V_{\text{min}_sw} - V_{sw}^t}{V_{\text{min}_sw}}\right) \quad \forall t \in \{1, \dots, T\} \tag{18}$$

The violation functions used in Eqs. (17) and (18) are bounded by 0, if there is no violation, and 1, when the violation is the maximum.

3.3 Case Study

3.3.1 Study Area Description

The study was conducted on the Boura reservoir (latitude 11.05° and longitude -2.49°), located in the center-west region of Burkina Faso near the border with Ghana. The Boura dam, built on the Kabarvaro River (tributary of Black Volta River) in 1983, is the single perennial surface water source in the Boura district that covers 1145 km². The reservoir was equipped with irrigation infrastructure in 1985. The catchment area of about 150 km² is located in a region defined by the latitude range 10.94°–11.07° and longitude range (-2.50°)–(-2.37°) lying the center-west region of Burkina Faso and upper west region of Ghana (Fig. 2).

The main features of the Boura reservoir are shown in Table 1. The maximum and minimum storage volumes of the reservoir are 4.2 and 0.34 million cubic meters (MCM), respectively. The catchment receives an average annual rainfall of 920 mm but exhibits a strong inter-annual variability over the period 1961 to 2010. Generally, the maximum inflow occurs during the month of July or August. The main purpose of the Boura reservoir is to satisfy agricultural water demands. The crop growing periods are classified into two categories: the wet period (June–October) and the dry period (November–May).

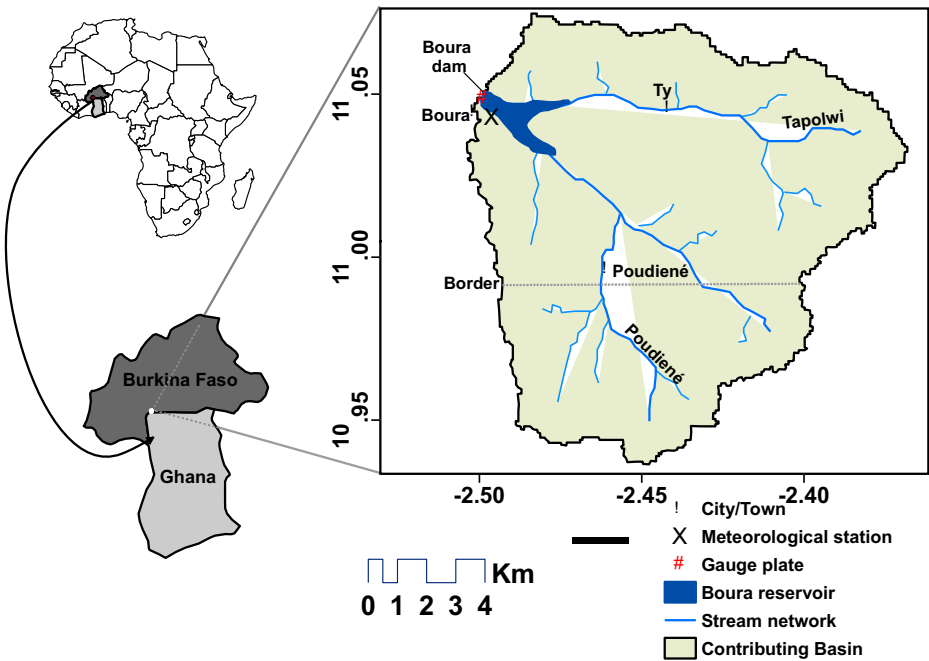


Fig. 2 Location of the Boura dam catchment with the hydrological monitoring system (Fowe et al. 2015)

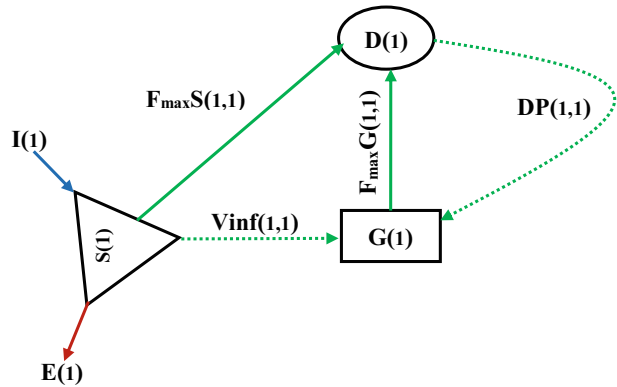
The conceptual model of the case study is presented in Fig. 3. The case study includes two water sources (S(1) and G(1)) and a single demand site D(1). The source S(1) is supplied by runoff $I(1)$ from the catchment while G(1) receives water from deep percolation from the plots DP(1,1) and reservoir seepage $V_{inf}(1,1)$. The demand site D(1) is gravity-fed by the upstream

Table 1 Morphometric characteristics of the Boura dam and its contributing catchment

Feature	Value
Full supply capacity (MCM)	4.2
Reservoir surface area (ha)	200
Length of dam wall (m)	750
Maximum height of dam wall (m)	6.25
Dam crest elevation (m)	276.25
Crest width (m)	3.5
Full supply level (m)	275
Spill length (m)	35
Minimum operation level (m)	272
Catchment area (km ²)	150
Maximum elevation (m)	349
Minimum elevation (m)	270
Global slope index (m/km)	4
Specific elevation (m)	37.24

Adapted from ONBI (1982, unpubl)

Fig. 3 Conceptual model of the case study



surface water $S(1)$ and is supplied by pumped water from $G(1)$. The aquifer $G(1)$ is considered an unlimited water source. This study is only concerned by changes of level in $G(1)$ due to reservoir seepage and deep percolation from irrigated plots.

Three main crops are cultivated in site $D(1)$: rice (during the dry and wet seasons), maize and tomatoes during the dry season.

Water losses from $S(1)$ are mainly caused by seepage and net evaporation. From monitoring data on site, the volumetric loss rate ranged between 3,425 and 9,743 m^3 per day depending on the month.

The maximum water supplied $F_{\max}S(1,1)$ and $F_{\max}G(1,1)$ from transmission links $S(1)$ – $D(1)$ and $G(1)$ – $D(1)$ are 350,000 and 100,000 m^3 per month, respectively. The unit supply costs from the surface water and aquifer sources are 8×10^{-3} and 50×10^{-3} USD per m^3 , respectively.

The above model was tested with data collected on-site for a period of one year (from November 2012 to October 2013).

3.3.2 Irrigation Water Demand Estimation

The irrigation water demands were computed using the WEAP-MABIA software package. Effective rainfall was estimated based on the rainfall amount (a fraction of 80 %).

The crop data (crop coefficients and duration of the development stages) and the soils profiles were obtained from WEAP-MABIA (“CropLibrary” and “SoilProperties”), data collected on-site, and from other studies (PCD 2007, *unpubl.*). Taking into account the water losses during conveyance and application to the field, the monthly water irrigation demands for agricultural fields as calculated by WEAP are shown in Table 2. Within the management period, the monthly water demand of $D(1)$ fluctuates between 3,761 and 266,744 m^3 per month. Average demand over the study period is estimated at 106,500 m^3 per month.

4 Results and Discussion

OPTIWAM was implemented for the Boura irrigation scheme to find the optimal monthly values of the 24 ($2 \times 1 \times 12 = 24$ where 2, 1 and 12 indicate respectively the number of water sources, demand site and months in the management period) decision variables for the water

Table 2 Monthly irrigation demand, net evaporation and reservoir inflows over the management horizon

Month	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul	Au	Sep.	Oct
Irrigation demand [$\times 10^3 \text{ m}^3$]	3.8	5.4	168.6	228.0	266.7	202.1	121.0	81.7	12.6	40.5	52.2	95.5
Runoff [$\times 10^3 \text{ m}^3$]	0.0	0.0	0.0	0.0	0.0	11.2	3.5	77.8	1741.0	500.3	718.9	10.4
Net evaporation [mm]	148.4	142.1	163.4	171.6	189.0	141.3	197.5	146.8	-63.9	-46.2	30.8	109.1

supplied from the sources over a one year planning horizon. The chromosome length was equal to 24 genes.

A sensitivity analysis was performed to identify the best GA parameters. Initial tests converged to a population size of $NS=50$, a maximum number of iterations $NMG=1000$, a crossover rate of $P_{cros}=0.8$, a mutation rate of $P_m=0.01$, a percentage of elitism of $P_e=20\%$, and tournament size equal to 2.

The trend of the GA convergence with respect to above mentioned values of parameters is shown in Fig. 4. The best value of the fitness function is improved by the GA until the maximum value (0.7701371) is obtained. As shown, the performance reaches the level of 95 % of the maximum possible fitness within 150 and 200 generations.

The aquifer balance and the demand satisfaction were the first objectives achieved (less than 250 generations). The water productivity and the cost reduction were the most difficult objectives to achieve.

The water allocation pattern for the best solution is given in Fig. 5. A comparative graph of the water demand and the optimal water allocation for a deterministic yearly inflow shows that

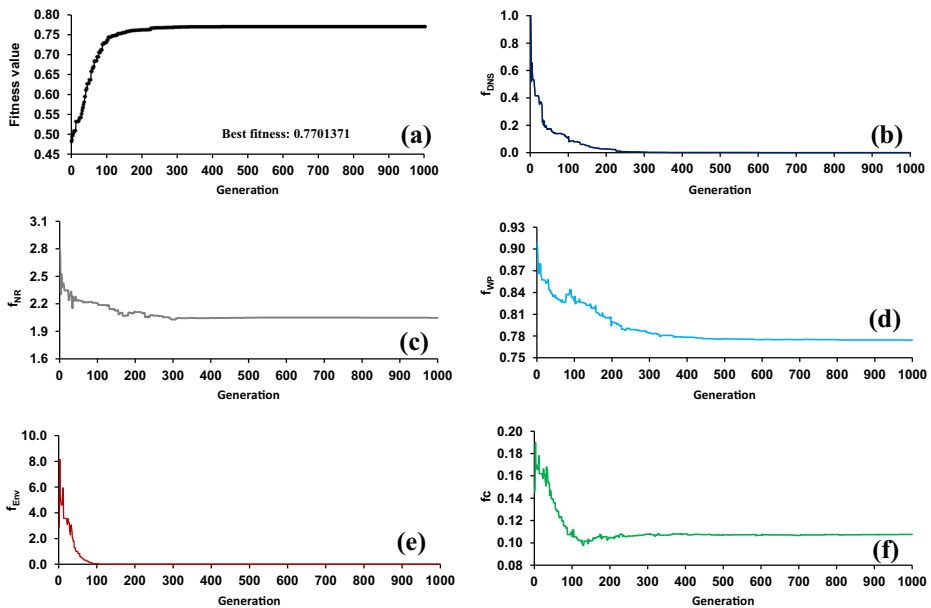


Fig. 4 Fitness function (a) and objective functions ((b) demand satisfaction, (c) Ecological reserve, (d) water productivity, (e) Aquifer balance and (f) cost reduction) curves over iterations

the demand is almost satisfied. The high water allocation is related to the peak of dry season (through February until the end of April) which is quite compatible with the high demands of water during this period.

The monthly relative errors “ $RE=100*(F_{tot} - D)/D$ ” (%) between of the water demand (D) and the water supplied (F_{tot}) are computed for the twelve months of the study period. The minimum value of RE is estimated at -6.06% in May. Water supplied to site D(1) is greater than the water demand at the beginning and at the end of the water year with a maximum RE of 3.53% in November. There is high reliability in meeting the irrigation demands. Acceptable flow rate error in hydraulic systems is usually around $\pm 2\%$ (USBR and USDA 2001), thus the model can be considered as efficient and robust in terms of satisfying demand.

The optimal percentage of the relative contribution of S(1) and G(1) to satisfying demand for the optimal solution depends on the month. Except for November and July, low contribution percentages are observed for source G(1). These low percentages are mainly due to the fact that there is still more water available into the reservoir, and the unit water cost of G(1) is relatively high. The source S(1) provided more than 80% of the total water demand of D(1) over the study period.

The yields computed for different crops at the optimization time period are shown in Table 3. By assuming that all others agricultural inputs were optimal, the crop yields throughout the growing period will be affected by water deficits ($F_{tot} < D$). The yield losses are more pronounced for maize (4.5%).

The water productivity values for rice fall within the range ($0.4\text{--}1.6\text{ kg m}^{-3}$) proposed for Asia case study conditions (Tuong and Bouman 2003) and were comparable to those (0.56 kg m^{-3}) obtained in the upper east region of Ghana (Mdemu et al. 2009). The values of water productivity for maize obtained in this study were comparable for those ($0.4\text{--}0.7\text{ kg m}^{-3}$) reported in Tanzania (Igbadun et al. 2006) and were greater than those proposed in Burkina Faso (Some et al. 2006). Crop water productivity for tomatoes (2.28 kg m^{-3}) was very similar to that of the Dorongo irrigated scheme (2.58 kg m^{-3}) in Ghana (Mdemu et al. 2009).

The operating rule curves (normal and observed) obtained for Boura reservoir are shown in Fig. 6. The observed storage is the operating rule curve without taking into account the aquifer in the management strategy. It can be observed that the new management strategy with the addition of the aquifer source allows more water to be stored in the surface water source. An

Fig. 5 Optimal monthly water supply computed by OPTIWAM and water demand

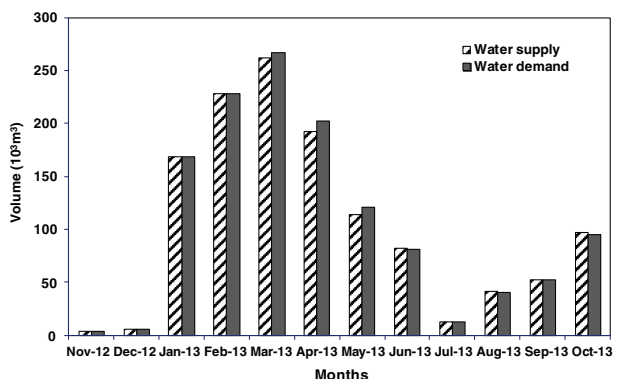


Table 3 Optimal crop yields and losses during the optimization horizon

Crops	Crop yield [kg ha ⁻¹]	Potential yield [kg ha ⁻¹]	Cultivated areas [ha]	WP [kg m ⁻³]	WPmax [kg m ⁻³]	Yield loss [%]
Dry rice	6924	7000	68	0.49	0.70	1.10
Wet rice	7000	7000	40	0.98	1.00	0.00
Maize	4776	5000	8	0.49	0.53	4.50
Tomatoes	21646	22000	4	2.28	3.05	1.60

additional water volume of about 0.7 MCM is preserved in the surface reservoir at the end of management period. The maximum storage is observed at the start of September and consequently reduces to a minimum in June at the start of next rainy season. The storage decrease is due to water withdrawals, net evaporation, and the lack of inflow into the reservoir during this period. The increase from June through September in storage is mainly due to a significant inflow into the reservoir while the water demand is low. No violations of the minimum and maximum storage capacities were observed. This indicates that, with the amounts of water supplied, optimal sources management was reached. This illustrates that, with knowledge of initial storage data, optimal monthly water supply can be achieved.

The optimization processes are considered for three scenarios of initial storage representing wet, dry and very dry seasons in the study area with initial storage Vmax, 75 % Vmax and 50 % Vmax respectively (Vmax=4.2 MCM). As shown in Fig. 6, changes in the initial storages affect the reservoir storage volume at the end of each month. The minimum and maximum reservoir storages respectively in June and September decrease when the initial storage is low. There is difficulty in meeting irrigation demands especially in dry and very dry seasons.

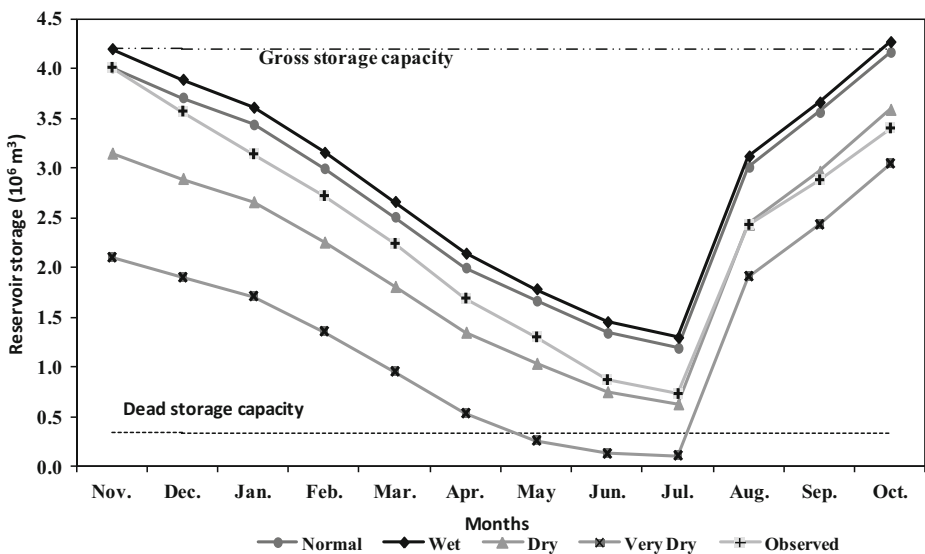


Fig. 6 Changes in water storage volume during the optimization period for different initial storages and observed storage

Reliability is a measure of the frequency of the reservoir without violations of the acceptable limits of reservoir over the management period (T).

$$\text{Reliability}[\%] = 100 \times \left(1 - \frac{n_f}{T}\right) \quad (19)$$

where n_f is the total number of time steps with violation.

Table 4 shows the reliability obtained for wet, dry and very dry seasons estimated as 92, 100 and 75 %, respectively. For the dry season in June, the minimum storage is very close to the dead storage. In the wet season, the violation of the maximum permissible volume of the reservoir is observed in September. Three violations of the dead storage capacity are observed in April, May and June in the very dry season (Fig. 6).

Figure 7 shows the optimal monthly water supply computed by OPTIWAM for Wet (a), Dry (b) and Very Dry (c) scenarios. This graph shows that it would be difficult to satisfy water demand from March to June in the very dry scenario with the current uses. The result shows that, when the initial storage is very low (pessimistic scenario 3), there is no water supplied from the surface reservoir between May and July; therefore only the aquifer satisfies water demands.

This study combines modeling of the hydraulic, agronomic and environmental processes for the optimal management of a coupled reservoir-groundwater system. The proposed approach integrates field data with irrigation water demand computed by WEAP. This methodology enables the identification of realistic optimal solutions for system operations.

The proposed tool constitutes a first step. Improvements can be added in terms of problem formulation and resolution methodology. Multi-objective resolution is a promising option leading to more flexible decision making at the governmental level. Accurate input data are required to guarantee the best quality of the outputs.

More functionality can be also added allowing the tool to communicate with the WEAP-MODFLOW framework. This makes it possible to profit from the capabilities of a suite of tools to compute water demand and surface water-groundwater interactions (Droubi et al. 2008).

5 Conclusions

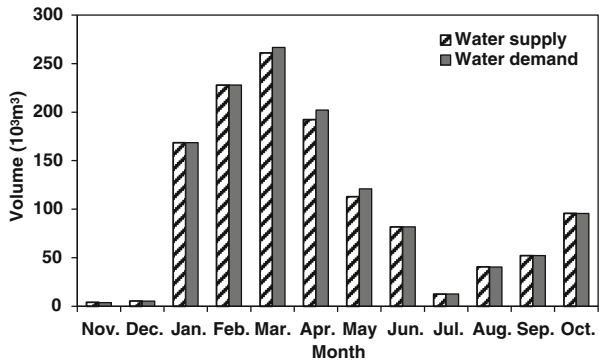
The purpose of this study is to derive an optimal reservoir-groundwater system management by quantifying the water allocation from different sources. The proposed multi-objective problem integrates demand satisfaction, ecological needs, water productivity, aquifer water

Table 4 Indicators of reliability in rule curves during the management horizon

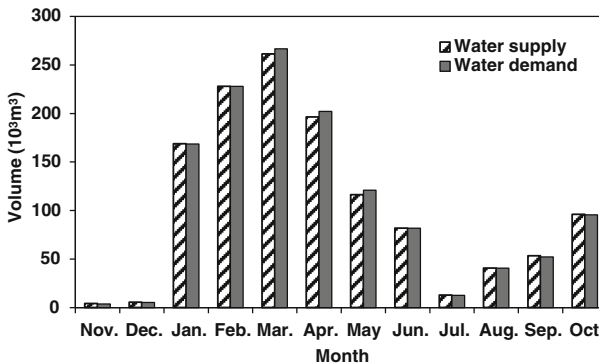
Scenario	NMVmin ⁱ	NMVmax ⁱⁱ	Reliability [%]
Wet	0	1	92
Dry	0	0	100
Very dry	3	0	75

ⁱ Number of minimum storage violation

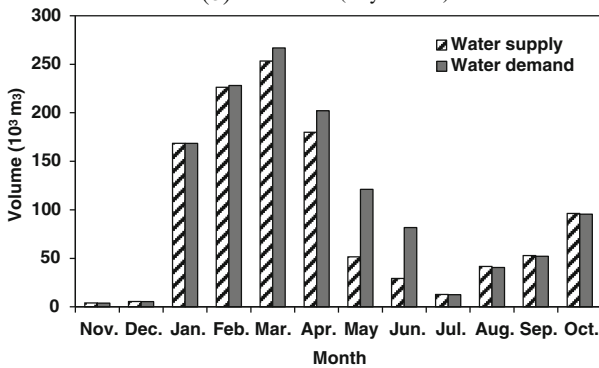
ⁱⁱ Number of maximum storage violation



(a) Scenario 1 (Wet season)



(b) Scenario 2 (Dry season)



(c) Scenario 3 (Very Dry season)

Fig. 7 Optimal monthly water supply computed by OPTIWAM for different initial storages scenarios and water demand

balance, reduction of the unit water cost and compliance with hydraulic and storage continuity constraints. A GA model using the sum weighting method was used to solve the problem and to recommend optimal water management.

A case study was used to test the developed optimization tool. Irrigation water demands were estimated from water requirements of the irrigated areas. The water losses by evaporation and seepage were determined from storage volumes using deterministic models previously

fitted to measured data. Results demonstrated the robustness of the tool to identify optimal solutions and its computational efficiency.

The model results for irrigation water supply are very close to the irrigation demand. Minimum storage is observed at the start of the rainy season and maximum storage is observed when the rainy season reaches its peak. These types of rule curves are expected in the actual operation of the reservoir.

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