Genetic algorithm-based optimization of water resources allocation under drought conditions

Z. Rao, D. Debski, D. Webb and R. Harpin

ABSTRACT

The efficient allocation of increasingly scarce water resources is a growing challenge worldwide, particularly during times of drought. This paper describes the development and application of an innovative technique to optimize the allocation of raw water supply to the city of London, UK during a period of drought in 2006. Using genetic algorithms, an optimization tool was developed to derive near-optimal operating strategies for the water company's multiple reservoir system for different projected rainfall scenarios and also to test the robustness of drought contingency strategies for operating the reservoirs down to a lower level under a severe drought condition. The project demonstrated that this approach is rigorous yet practical, the optimization technique is robust and effective and that optimal water allocation is an efficient measure to overcome water scarcity under drought conditions and mitigate consequent impacts. The potential application of genetic algorithms to the day to day operation of a complex water resource system represents a step-change in the industry's approach to managing such systems.

Key words | drought mitigation, genetic algorithm, simulation based optimization, water resources allocation

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INTRODUCTION

Pressures on water resources worldwide are set to increase and competing demands create a need for improved analytic techniques to better understand and manage water resources for sustainable development. The complexity of the problems, the large number of possible measures, multiplicity of their combinations, nonlinearities and uncertainties make intuitive solutions impossible. Efficient management of a complex water supply system, when operating under water scarcity conditions, requires adoption of modelling tools to help decision makers identify actions able to mitigate the impacts of drought on users.

The use of computer models in water system operations has evolved considerably over the past few decades. Simulation models are widely used by water authorities in the planning of multireservoir water supply systems. The simulation models allow the water supply planners to analyse 'what if' scenarios associated with decisions regarding the water supply system. The driving force for these models is the operating rules. Therefore, it is necessary to use optimal and realistic operating rules, taking into account actual performance parameters in simulation models to adequately capture system behaviour during a period of drought.

Over the past 30 years, various forms of mathematical models and optimization techniques have been used for deriving optimal operating rules (Wurbs 1993; Labadie 2004), including US Army of Engineers' HEC-3 (US Army Corp. of Hydrologic Engineering Center (HEC-3) 1974) and HEC-5, WASP (Kuczera & Diment 1988), WATHNET (Kuczera 1993), ACRES (Sigvaldason 1976) and its latest version ARSP. As a result, optimal water resources allocation, in particular with increasing pressure on this scarce commodity in many parts of the world, is gradually being adopted by the water industry as a means of

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mitigating water shortage under drought conditions. The ability of genetic algorithms (GAs) to be linked directly with trusted simulation models is a great advantage (Jamieson & Rao 2003) to the success in the implementation of water system optimisation tools.

This paper describes the development and application of an innovative technique to optimize the allocation of raw water supply to the city of London, UK during a period of drought in 2006. Using genetic algorithms, an optimization tool was developed to derive near-optimal operating strategies for the water company's inter-connected, pipes, aqueducts, multiple reservoir system for different projected rainfall scenarios and also to test the drought contingency strategies for operating the reservoirs down to a lower level under a severe drought condition. The project demonstrated that this approach is rigorous yet practical, the optimization technique is robust and effective and that optimal water allocation is an efficient measure to overcome water scarcity under drought conditions and mitigate consequent impacts. The potential application of genetic algorithms to the day to day operation of a complex water resource system represents a step-change in the industry's approach to managing such systems.

THE COUPLED SIMULATION–OPTIMIZATION APPROACH

Reservoirs regulate surface flow for allocation of water resources to meet the temporal variability of demands for multiple uses. A decision-making procedure is needed for system operation to balance demand and supply for optimal economic and social benefits. Operating rules are used to guide water managers when it is not possible to satisfy ideal storage levels and downstream releases. Ideal storage volumes in individual or multiple reservoirs are typically defined by rule curves. When conditions are not ideal, operating rules define what should be done for various combinations of system states and hydrological conditions. The purpose of operating rules is to distribute any necessary deviations from the ideal conditions in a way that minimizes the total perceived discomfort to all water users in the system.

The operating rules can be found from optimization and simulation and various models based on these methods have been proposed and reviewed by many authors (Yeh 1985; Simonovic 1992; Wurbs 1993; Labadie 2004). In general terms, simulation methods for the analysis of water systems behaviours are often the only methods for dealing with large and complex systems that cannot be reproduced by experiment or by analytical solutions. Unfortunately, in complex systems, the alternative number is quite large and the 'trial and error' process of simulation becomes very time consuming. The process of employing optimization to reduce the range of designs and policies requiring simulation and more in-depth evaluation is often called "preliminary screening" (Loucks & van Beek 2005). Most of the approaches involving the combined use of optimization and simulation can be classified according to the mathematical method adopted (linear, dynamic, nonlinear, or heuristic programming), the operating rule that users can parameterize in simulation and to the kind of links between optimization and simulation modules (optimization embedded in simulation, simulation as a submodel of a main optimization model, or "optimization and simulation in parallel" are some examples).

Despite the potential use of optimization in efficient space and time exploration, full integration between simulation and optimization has not as yet been implemented with the specific aim of defining drought mitigation measures in a proactive approach. For the optimization of water allocation during drought conditions, the objective is typically to maximize the total storage volume at strategic reservoirs, subject to all operational constraints, including minimum and maximum storage levels for reservoirs and hydraulic capacities of the pipe mains and tunnels/aqueduct, whilst meeting water demands at all water treatment works. The decision variables which are to be optimized are the typically the daily flow abstracted from each pumping station to the reservoirs and the supply from each reservoir to the treatment works.

The inputs include time-series data of total available abstractions from a river, demands for all the water treatment works and inter-basin transfers. Operational parameters, such as the initial storage levels/volumes and duration of the simulation are entered or modified when setting up the model runs whilst most of the constraint data, such as reservoir drawdown curves and hydraulic capacities of the links (pipes, aqueducts/conduits), are built into the model. The main simulation results include storage profiles for each of the reservoirs together with time-series data of their inflows and outflows and the flows and composition of water to each of the treatment works.

APPLICATION TO LONDON STORED WATER SYSTEM

The prolonged period of low rainfall in the UK over 2005–2006 resulted in a depletion of the stored water system which supplies the city of London's water treatment works with over 2,000 Ml/d of raw water. In early 2006, as part of the drought action plan, a simulation–optimisation model was developed to review the operation of this large-scale stored water system, support the water company's contingency planning and assist in developing operational and business strategies for a prolonged drought event.

The approach and methodology were applied to the Lower Thames stored water system which comprises 10 raised storage reservoirs, supplied with raw water abstracted from the River Thames by 5 pump stations. The reservoirs supply 4 water treatment works (WTWs) via a complex interconnected system of tunnels and pipe mains.

London stored water system

The London Stored Water System comprises the Thames Valley Stored Water System in the west of London and the Lee Valley Stored Water System in the east of London.

The Thames Valley System comprises 10 raised storage reservoirs, supplied with raw water abstracted from the River Thames by 5 pump stations. The reservoirs supply 4 water treatment works (WTWs) via an interconnected system of tunnels and pipe mains. Figure 1 illustrates the system and normal supply routes schematically.

The Lee Valley System comprises 13 storage reservoirs which are supplied with raw water abstracted from the River Lee by 2 pump stations and a gravity aqueduct. These reservoirs are also supplied with groundwater pumped from boreholes and water abstracted from the River Thames and transferred via the Thames-Lee-Tunnel. The reservoirs supply 2 treatment works via a system of tunnels and pipe mains. A third treatment works (Hornsey) is supplied directly from the River Lee (New River) and boreholes. Raw water is also supplied to Essex & Suffolk Water Company from the reservoirs via the Lower Hall pump station.

Drought contingency planning

The prolonged period of low rainfall over 2005–2006 resulted in a depletion of the stored water in the Lee Valley stored water system early in 2006. Storage in the Thames Valley stored water system (which supplies the west London WTWs) was also low. As part of the action plan, a modelling and optimization model was developed to review the operations of the Thames Valley and Lee Valley stored water systems in support of the water company's contingency planning and in assistance of their developing the operational and business strategies for a drought event.

The main objectives of the drought mitigation planning were set to

- ensure that the system is operated most efficiently over the dry months;
- ensure reservoir levels are high enough to drive the required flows;
- increase the security of supply during the drought and
- maintain good quality of raw water to all treatment works.

As part of this study, two optimization–simulation models for both the Lee Valley and Thames Valley raw water reservoirs systems were developed to derive a strategy for operating reservoirs down to a low level and for testing the operating control strategies associated with different rainfall scenarios.

The main operational objectives were set to maximize the total storage volume in the reservoirs of strategic importance, having regard to the maximum and minimum operational storage levels of all reservoirs and the capacity of the pipe mains, aqueducts and tunnels in the system. All the daily river flows and demands for the whole simulation period are taken from the outputs of the water company's hydrological model which is currently used to assess the London stored water system's balance of demand and supply based on different rainfall (river flow) and demand scenarios. This model lumps all the reservoirs in the Thames

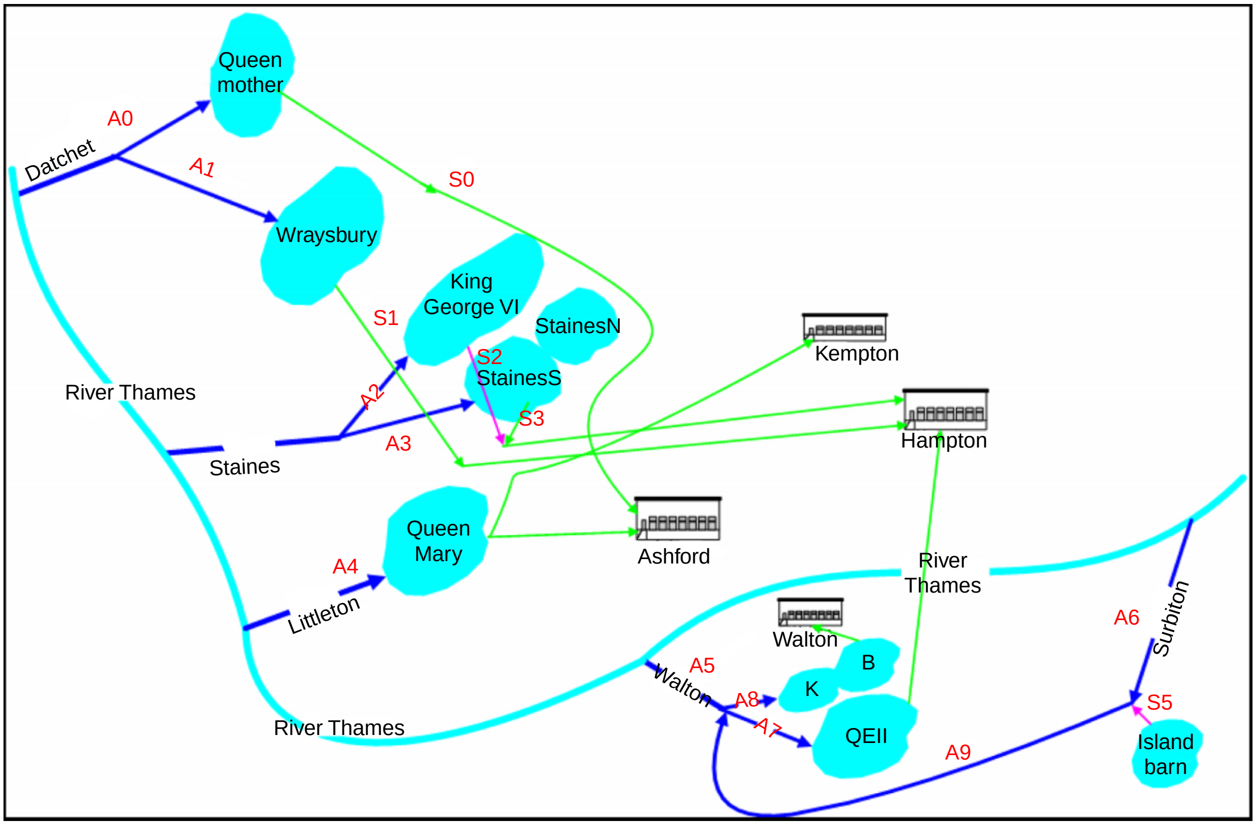

Figure 1 | Schematic of the London stored water system and optimization model.

Valley into two reservoirs (Thames North and Thames South reservoirs), so is unable to evaluate detailed operation each individual reservoir.

Operational optimizaton model

In this study, the operational control of the Thames Valley stored water system was formulated as an optimization problem whose objective is to maximise the storage volume at Queen Mary reservoir at any day because this reservoirs has the largest storage volume. Consideration was given to all operational constraints, including minimum and maximum storage levels for all reservoirs in the Thames Valley and hydraulic capacities of the pipe mains and tunnels/aqueduct whilst meeting water demands at all water treatment works (Ashford, Kempton, Hampton and Walton) and the interaction between the abstractions and hydraulic relationships which governs flows in the distribution network.

The decision variables are the daily abstracted flow to and discharge from each reservoir. Table 1 lists all decision variables used for the Lower Thames system and Figure 1 shows their relationship.

In its general form, the optimization model for operational control of a multi-reservoir system can be mathematically described as follows:

$$\text{Maximize} \sum_{i \in M} V_{1i}, \quad M \in N \tag{1}$$

Subject to

(1) Reservoir mass balance (rainfalls to and evaporations from reservoir surface are omitted)

$$V_{1i} = V_{0i} + A_{ji} - S_{iw}, \quad i = 1, \ldots, N; \quad j = 1, \ldots, P;$$
$$w = 1, \ldots, W$$

(2) Reservoir capacity

$$V_i^{\min} \le V_{1i} \le V_i^{\max}, \quad i = 1, \ldots, N$$

Table 1 | List of decision variables

Variable	Description
A_{0t}	Abstraction to Queen Mother from River Thames at day t
A_{1t}	Abstraction to Wraysbury from River Thames at day t
A_{2t}	Abstraction to KGVI from River Thames at day t
A_{3t}	Abstraction to Staines N + S from River Thames at day t
A_{4t}	Abstraction to Queen Mary from River Thames at day t
A_{5t}	Abstraction at Walton PS from River Thames at day t
A_{6t}	Abstraction at Surbiton PS from River Thames at day t
A_{7t}	Abstraction to K&B at day t
A_{8t}	Abstraction to QEII at day t
A_{9t}	Inflow to K&B & QEII from Surbiton & Island Barn at day t
S_{0t}	Outflow from Queen Mother to Ashford WTW at day t
S_{1t}	Outflow from Wraysbury to Hampton WTW at day t
S_{2t}	Outflow from KGVI to Hampton WTW at day t
S_{3t}	Outflow from Staines NS to Hampton at day t

(3) Pumping station capacity

$$0 \leq \sum_i A_{ji} \leq \mathrm{PC}_j, \quad j = 1, \ldots, P$$

(4) Total available abstraction from the river

$$\sum_j \sum_i A_{ji} \leq \mathrm{RQ}$$

(5) Hydraulic draw-down limit from each reservoir

$$\sum_w S_{iw} \leq f\left(\frac{1}{2}(V_{1i} + V_{0i})\right), \quad i = 1, \ldots, N$$

(6) Hydraulic capacity for each route

$$\mathrm{RC}_r^{\min} \leq \sum_w \sum_{i \in R} S_{iw} \leq \mathrm{RC}_r^{\max}, \quad r = 1, \ldots, R$$

(7) Supply to each treatment works

$$\sum_i S_{iw} \geq \mathrm{WD}_w, \quad w = 1, \ldots, W,$$

where V_{0i}, V_{1i}, $V_i^{\min}$, $V_i^{\max}$–the initial, ending, minimum and maximum storage volumes at reservoir i, $i = 1, \ldots, N$;

A_{ji}–the abstraction flow from pumping station j to reservoir i;

S_{iw}–the discharge from reservoir i to treatment works w;

PC_j–the pumping capacity at pumping station j;

WD_w–the water demand at treatment works w, $w = 1, \ldots, W$;

RQ–the total available abstraction from the river;

$\mathrm{RC}_r^{\min}$, $\mathrm{RC}_r^{\max}$–the min and max flow limits for route r, $r = 1, \ldots, R$;

M–the total number of reservoirs of strategic importance;

N–the total number of reservoirs;

P–the total number of pumping stations;

W–the total number of treatment works;

R–the total number of supply route.

Optimizing operating strategy using genetic algorithms

Genetic algorithms (GAs), whose name recalls the strong operational similarity with the biological behaviour of living beings, are stochastic optimization search methods that belong to and within soft computing technologies. GAs are a particular class of evolutionary algorithms, categorised as

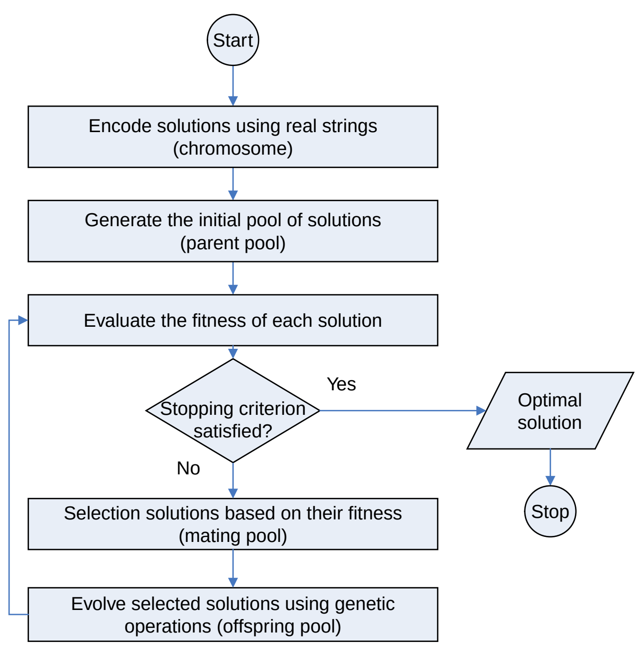

Figure 2 | Flow chart of problem solving using genetic algorithm.

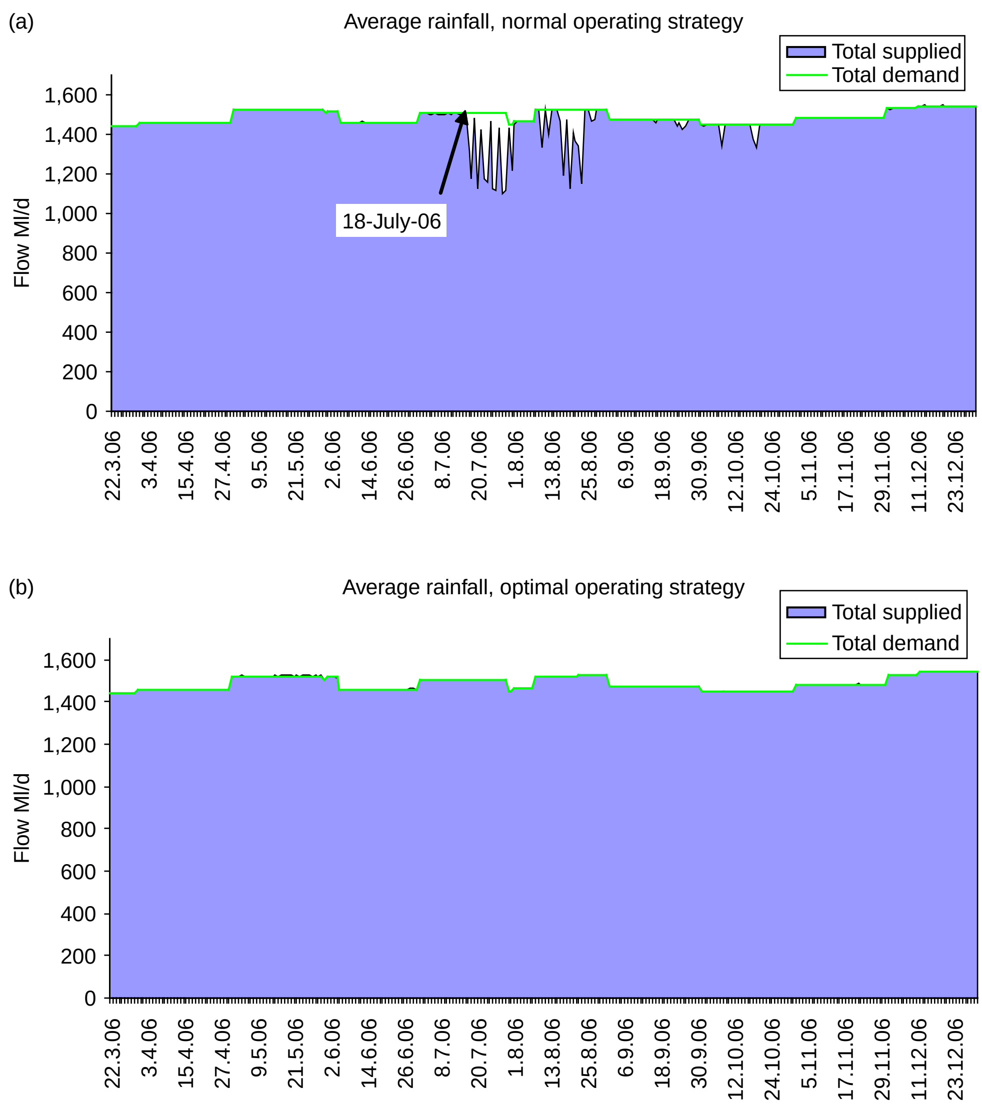

Figure 3 | Comparison of the system demand and supply resulted from two operating strategies for the predicted average rainfall scenario.

global search heuristics. They can be applied to many complex problems that are difficult to solve using traditional techniques such as linear and non-linear programming or methods based on gradient calculations.

The possible solution of the problem is defined as a 'chromosome'. This is subdivided into 'genes'. A GA starts with an initial population of random generated chromosomes with respect to the problem constraints. Then, new populations are generated and evaluated through iterative, random and probabilistic mechanisms ruled by the four fundamental operators of parent selection, crossover, replacement and mutation. By using the GA approach, the objective function is translated into a positive fitness function that measures the suitability of a chromosome and its performance to satisfy the objective of the problem to be optimized.

In this study, a real-coded GA was used. This approach, instead of using a binary-coded GA, is more appropriate for real values (i.e. the daily abstracted flow to the discharge from each reservoir) as it avoids transformation of real values into binary values and then, after crossover and mutation, retransformation of binary values back into real values. This coding/decoding process consumes large computer memory and requires long computation time, especially when studying large hydraulic systems.

The structure of the solution for the investigated system is a sequence of real values of flows (chromosome). Therefore, the solution represents the daily abstractions discharges for all the reservoirs that should guarantee the optimal reservoir operation, i.e.

$$\text{Chromosome}: \quad (A_{11}, A_{12}, \ldots, A_{PN}, S_{11}, S_{12}, \ldots, S_{NW})$$

The initial population of chromosomes (abstractions and discharges) was randomly generated under the constraints of minimal and maximal values for each of the decision variables A_{ji} and S_{iw}. Each chromosome is evaluated on the basis of the value of the fitness Function (1).

The rule of elitism of one chromosome was then applied to guarantee the convergence of the algorithm by avoiding the fittest chromosome disappearing through crossover and mutation operations.

The parents' selection phase was obtained on the basis of the tournament selection method. The crossover operator then combines two chromosomes (parents) to produce two new chromosomes (children). Then, the mutation operator was applied by modifying 1% (probability of mutation equal to 0.01) of the chromosomes.

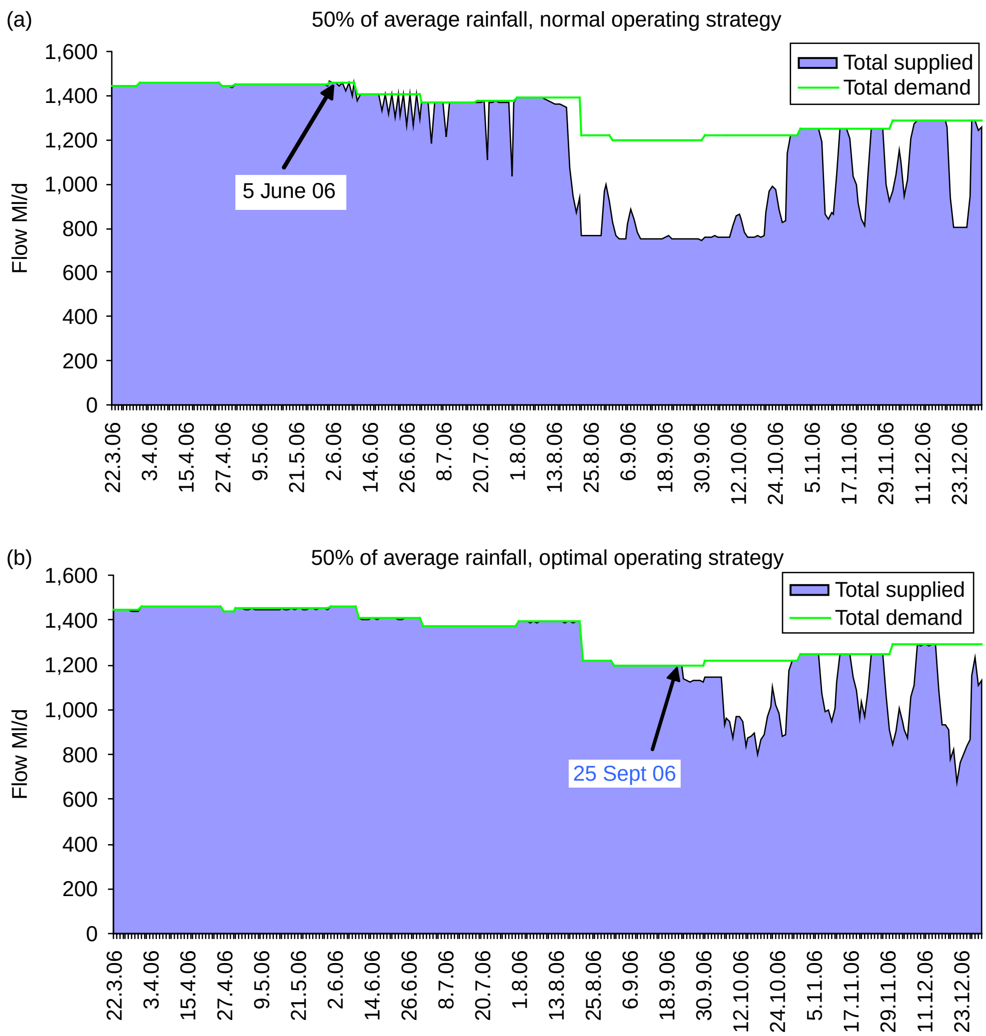

Figure 4 | Comparison of the system demand and supply resulted from two operating strategies for 50% of the predicted average rainfall scenario.

Each of these chromosomes was modified by randomly altering the value of one gene.

With the above procedure, the successive population contained chromosomes with higher fitness values. The procedure was then repeated until the criterion of convergence was reached, i.e. the optimal solution was obtained (Figure 2).

Optimal operational strategies

The simulation–optimization model was used to derive the optimal control strategy for the London stored water system for the period from 22 March to 31 December 2006 based on two predicted rainfall scenarios: average rainfall scenario and 50% of the average rainfall scenario representing a severe drought.

For each scenario run, the model produces detailed information on the daily abstraction to and supply from each reservoir, daily storage for all reservoirs and composition of supply to all treatment works based on the optimal operational strategy. The simulation results also identify the failure date when the system fails to meet demand in full due to shortage of raw water.

The simulation results for the operations of the Thames Valley stored system indicate:

- Under the average rainfall scenario, the existing operational strategy is inadequate and needs to be adjusted to the changes of river flows. Otherwise, the system may fail to meet the full demand as early as in the middle of July due to the hydraulic constraints of the system. However, this short period of failure can be avoided by deploying the optimal operating strategy as shown in Figure 3.
- Under 50% of the average rainfall scenario, the total available water is less than the total demand and the total storage will fall below critical level of the total storage. The optimal operational strategy would prolong the supply of the raw water and delay the failure date from 6 June to 25 September as shown in Figure 4. Compared with the failure date by adopting the normal operating rule, it can be seen that the operating strategy adopted for the stored water system has a significant impact on the management of water resources and security of the supply.

CONCLUSIONS

A coupled, genetic algorithm based optimisation simulation model has been successfully applied to a large complex multi-reservoir water resources system during a period of drought.

The results of the simulation–optimization technique provided effective support to the water company in planning reservoir operation and usage restrictions (e.g. hosepipe ban) to meet demands and limit the impact of the drought. The tool allowed the effectiveness of a number of potential measures, together with the impacts of planned and emergency essential maintenance work to be tested.

As the result of this development, operators at the water company can simulate the operations of the water abstraction and distribution system under different scenarios for the purposes of testing the management strategy before its implementation.

The model can also be used for optimizing the short-term (weekly) production plans, including configuration of abstraction and supply routes and percentage of abstraction/supply for each route, etc. by taking account of scheduled maintenance plans, such as tunnel inspections and responding to unscheduled failures or outages.

This innovative approach provided the water company with confidence that the management strategies adopted would ensure that standards of supply were met and that the available raw water was allocated efficiently between storage reservoirs. The generalized tool can be applied to any system configuration and to optimise the long-term or the short-term operating strategies of similar multi-reservoirs systems.

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