# Optimal operation of multisource water supply systems including water transfers

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**ABSTRACT**

This paper describes the application of a simulation-optimization model aimed at helping water utilities determine the best way to operate large-scale multisource water supply systems that depend on surface water and groundwater resources. The model includes a detailed simulation of the water storage in reservoirs, the groundwater flow in aquifers and the water transport in terms of quantity and quality in a discretized distribution network. The operation of the water systems is optimized in terms of reducing operating costs, satisfying demand and water quality. When applied here to the Barlavento Water System (Algarve-Portugal) the model considers the possibility of expanding the capacity of the current water system through an inter-basin transfer of surface water. Water transfers are often used for meeting growing demand and for managing the impact of drought on urban water supply systems. The results presented here highlight the potential of the envisaged inter-basin water transfer as an effective supply-side option for expanding the capacity of the Barlavento Water System, as long as interannual management of the water resources is implemented.

**KEY WORDS:** *Water management, planning, decision models.*

## INTRODUCTION

The river basin is generally accepted as the natural unit of planning for water resources management. But limited resources in a river basin might make it necessary to obtain water from sources in other river basins. In recent decades, water transfers between regions/river basins have been increasingly sought out as an additional source for urban water supply systems. Lund & Israel, 1995 discuss in some detail different forms of water transfers that include permanent transfers, contingent transfers/dry-year options and spot market transfers. Previously, Lund *et al*., 1992 had reviewed the different uses and associated benefits of water transfers: direct use to meet demand, improvement of system reliability, improvement of source water quality or satisfaction of environmental constraints.

Incorporating water transfers into system planning requires greater cooperation and coordination between all stakeholders (e.g. authorities, users, non-governmental organizations) so that conflicts can be minimized. Decision models can be of considerable help to solving this type of problem by integrating all the technical, environmental, economic, and social aspects relevant to decision making.

In this work the authors present the main features of an optimization model aimed at helping water utilities determine the best way to operate multisource water supply systems that depend on surface water and groundwater resources. The application is inspired by a real problem. The main objective was to evaluate the performance of the Barlavento Water System (Algarve-Portugal) in meeting the demand provided for the 2025 with the fulfilment of water quality objectives. The current configuration and a supply-side option for expanding the capacity of the water system by installing a conveyance system that would allow a permanent water transfer from a river basin exterior to the natural planning unit are considered here. This solution was already envisaged in the past to deal with the reduction of storage imposed by the Environmental Impact Assessment (EIA) procedure made for the Odelouca reservoir, the main source for the Barlavento Water System (BWS).

## OPTISM MODEL

The OPTISM model (Vieira *et al*., 2011) is a deterministic optimization model developed for optimizing the operation of large-scale multisource water supply systems that depend on surface water and groundwater resources. All the components of the water supply system are represented in a flow network as nodes or arcs. Mathematical functions included as model constraints simulate the water balance in the surface reservoirs, the groundwater flow in the aquifers and the water transport in the distribution network. Environmental concerns such as minimum discharges from reservoirs for downstream ecosystem maintenance and minimum piezometric levels in aquifers to prevent problems related to the over-exploitation of the groundwater resources are also introduced as model constraints.

Water quality is a crucial element when different water sources are used and especially when the water is used for drinking purposes. Water quality is explicitly specified and modelled using the multicommodity flow network approach (Yang *et al*., 2000). Under this approach water from a different source, or simply of a different quality, is regarded as a separate commodity $k$=1,…, $NK$ sharing a common distribution network. Water quality is defined in terms of volumetric blending of water from different sources. Water flows in the network are represented through the variable $x_{pq,t}^{k}$ (nonnegative flow of water identified by the index $k$ in arc $(p,q)$ from node $p$ to node $q$ in period $t$). Because water is miscible it is fair to assume that waters modelled as different commodities are perfectly mixed when the timescale used for planning purposes is longer than one day (Yang *et al*., 2000). Considering the flow of two commodities (i.e. $NK$=2) and that a node $q$ receives water only from a node $p$, the volumetric blending ratio of water type $k$=2 at node $q$ is defined as $x^2_{pq,t} / \left( x^1_{pq,t} + x^2_{pq,t} \right)$.

The decisions suggested by the resolution of the optimization model are discretized with a monthly time step over the entire period of analysis, given a time series of inflows to reservoirs and aquifer recharge. The decisions to be optimized include the volume of withdrawals from each water source, the operation of the treatment and pumping facilities and the water allocation from each source to the demand nodes. In the objective function to be minimized the operating costs are added to a set of penalty functions. The operating costs include all the abstraction, treatment and pumping costs. During the resolution of the optimization model the penalty functions minimize deviations from the planning objectives of satisfying the demand and delivering water of the appropriate quality. One last penalty function can be included to prevent unnecessary excess discharges from reservoirs. The planning objectives can be prioritized for each case with the adequate parameterization of weight factors included in the formulae of the penalty functions.

The model is nonlinear. The nonlinearities are present in the objective function and in the model constraints. The penalty functions are quadratic so that greater deviations from the planning objectives attract worse penalties. Mathematical functions most often used in optimization models to penalize failures in the satisfaction of the demand tend to prevent greater shortages. Water managers usually prefer a series of smaller shortages spread over time, since this causes less damage than one severe shortage involving the same total deficit. Quadratic functions penalize greater shortages and they spread the total deficit over a series of smaller shortages. The penalty function for controlling water quality also penalizes greater deviations from a volumetric blending ratio objective.

The model can be efficiently programmed using GAMS software (Brooke *et al*., 2008) and solved with MINOS (Murtagh & Saunders, 1998).

## CASE STUDY

The Algarve region is the southernmost administrative province of Portugal. It is characterized by a warm Mediterranean climate. A mean annual precipitation of 653 mm is referenced for the period 1941/42-1973/74 (Vieira *et al*., 2011). The precipitation regime is irregular, with intermittent periods of short, sharp floods in the winter and a long dry period in the summer.

The urban water supply to the region is guaranteed by two multimunicipal systems – Barlavento Water System (BWS) and Sotavento Water System (SWS) – managed by the same water utility – Águas do Algarve (AdA). There is a physical linkage between the two systems for transferring water in both directions. But this management option should be used only in emergency situations (e.g. droughts, accidents, maintenance). Only the BWS is analysed in this paper, and do not considering the physical linkage with the SWS. As demand is going to increase, the possibilities of transferring water from the SWS to the BWS will be reduced.

The water systems were designed in the early 1990s to satisfy demand until 2025. The initial idea was to develop water systems that relied wholly on surface waters. But a severe drought in 2004 and 2005 showed the high risk of this plan, particularly in the BWS. The situation was only not worse because groundwater was used and surface water was transferred from the SWS. The impact of the 2004-2005 drought has been well documented in other papers (Nunes *et al*., 2006; Stigter *et al*., 2009, Vieira *et al*., 2011).

Table 1. Current water sources of the Barlavento Water System (BWS).

| **Water Sources** | | |
|---|---|---|
| *Reservoirs (surface water)* | Max. storage ($\times 10^6$ m$^3$) | Max. withdrawal ($\times 10^6$ m$^3$/year) |
| **Odelouca** | 132.0 | 96.0 |
| **Bravura** | 32.5 | 6.0 |
| *Aquifers (groundwater)* | Area (km$^2$) | Max. withdrawal ($\times 10^6$ m$^3$/year) |
| **Querença-Silves** | 324.2 | 13.0 |
| **Almádena-Odeáxere** | 63.5 | 3.5 |

After this extreme situation the water managers finally realized that the urban water supply could not rely only on surface waters. Groundwater is a valuable resource and should not be disregarded, despite some limitations. Before the existence of the multimunicipal systems (i.e. until the late 1990s) the urban water supply in the Algarve depended almost solely on groundwater. Unsustainable levels of groundwater abstraction were at least partly responsible for high nitrate contamination in irrigated areas and for the displacement of the fresh water-salt water interface in some sectors of coastal aquifers. Groundwater from the most productive systems is naturally very hard since aquifer systems consist of limestone and dolomite. But laboratory studies conducted for AdA showed insignificant changes in water quality when the volumetric groundwater blending ratio was kept at ≤25% (Vieira *et al*., 2011).

The current water sources of the BWS are listed in Table 1. The maximum annual withdrawals for each water source are related to licenses/authorizations issued by the administration. The sum of the established withdrawal limits (Table 1) is more than sufficient to meet the demand up to 2025 (74.6 million m$^3$/year).

The Odelouca reservoir is the main source for the BWS. But the reservoir actually built is significantly smaller than the one initially planned. The first design of the Odelouca reservoir had a maximum storage of almost 250 million m$^3$. The reduction of the storage was only decided in 2001, when the BWS was already partly in operation. This requirement was imposed by the EIA procedure. Under this "new" circumstance a study carried out for AdA says it will be hard to meet the demand of the BWS in the long term (Hidroprojecto & Ambio, 2005). The preferred solution foreseen in that study to expand the capacity of the BWS is to transfer water from the Santa Clara reservoir. This reservoir is located to the north of Algarve, in the administrative region of Alentejo, and also in a different river basin.

The Santa Clara reservoir was completed in 1968 (maximum storage: 240.3 million m$^3$). It is used almost solely for irrigation. The historic record of exploitation of this reservoir shows that inflows are significantly higher than uses. An extended simulation analysis by Hidroprojecto & Ambio (2005) showed that it would be totally feasible to transfer up to 20 million m$^3$/year to the BWS. The planned conveyance system extends for 55 km and it would deliver

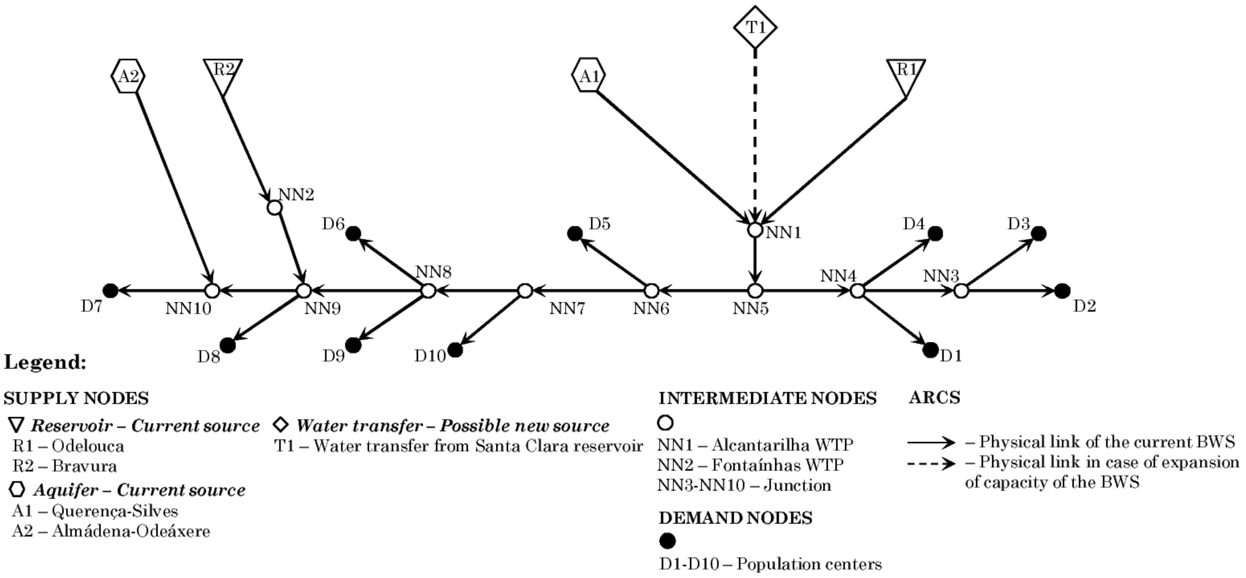

Figure 1. Network representation of the Barlavento Water System (BWS).

the water to the Alcantarilha water treatment plant (WTP). The installed capacity of the WTP is sufficient to receive the additional water.

The application of the OPTISM model presented here shows the performance of the BWS under a drought similar to the one in 2004 and 2005 and the estimated demand for 2025. The current configuration and the supply-side option of transferring water from the Santa Clara reservoir are considered.

## Input Data

Input data derived for the application of the OPTISM model presented in Vieira *et al*., 2011 were used (e.g. parameters to calculate inflows to reservoirs and aquifer recharge, minimum discharges from reservoirs for ecosystem maintenance, minimum piezometric levels in aquifers). The most significant changes in the input data were related to the network representation, the hydrologic scenario and the cost functions.

### Multicommodity flow network

The network representations of the current configuration and the possible expansion of the BWS are given in Figure 1. The link representing the water transfer from Santa Clara reservoir was not included for the selected examples that consider the current system (examples CS). In the event of expansion of capacity of the BWS (examples EXP), that link was considered in the network representation.

Different levels of hardness of the surface water and groundwater justify the description of the water transport (quantity+quality) as a multicommodity flow problem. Two distinct flows were considered ($NK$=2), one for surface/soft water and the other for groundwater/hard water. The water quality objective was to maintain the volumetric blending ratio of groundwater at the population centres ≤25%.

### Composite scenarios

The hydrologic scenario (Figure 2) reproduces the inflows and the aquifer recharge between October 2001 and September 2006. This includes the period of extreme drought in 2004 and 2005. The hydrologic scenario was combined with an annual (examples ANNUAL) and an interannual (examples INTERAN) management perspective of the water resources. Thus, two composite scenarios were defined for each configuration of the BWS.

The annual management perspective was modelled with the time horizon of each model run restricted to a fraction (1/$n$—in this case, $n$=5) of the analysis period. The system ending state from a previous model run was set to be equal to the system initial state for the next model run. The series of $n$-linked consecutive runs corresponds to the optimal operating policy of the BWS for the entire period analysed. The interannual management aspect was modelled with a single run to derive the optimal operating policy for the entire period analysed.

### Cost functions

The operating costs of each water source are as follows (includes abstraction and water treatment costs): Odelouca reservoir – 0.105 €/m$^3$, Bravura reservoir – 0.196 €/m$^3$, Querença-Silves aquifer – 0.090 €/m$^3$, Almádena-Odeáxere aquifer – 0.023 €/m$^3$ and water transfer from Santa Clara reservoir – 0.122 €/m$^3$. Pumping costs for the distribution of water to the population centres are based on a specific cost of $177.313 \times 10^{-6}$ € for the elevation of 1 m$^3$ of water at 1 m (Hidroprojecto & Ambio, 2005).

The weighting factors were parameterized so that shortages were avoided unless no more water was available. Initial failures in the satisfaction of demand should be prevented by relaxing the volumetric blending objective.

## Results and discussion

The results obtained in the two examples for the current system – CS-ANNUAL and CS-INTERAN – show failures in the satisfaction of demand (Table 2). In example CS-ANNUAL, not anticipating the serious drought, the operation of the BWS was optimized in the first three years to minimize operating costs. In this period water of the appropriate blend is always supplied to the population centres. For example, Table 3 shows the maximum volumetric blending ratio of groundwater obtained for each year at demand node D1. In the first three years only surface water from the Odelouca reservoir is used because it costs less. Surface water from the Bravura reservoir costs more and it is used only in the fourth year as the Odelouca reservoir depletes and reaches the dead storage level (Figure 3). Bravura reservoir does not reach the dead storage level in the drought period, but withdrawals are limited to 6 hm$^3$/year – this value divided by 5 (number of years of the analysis period) equals 1.2 hm$^3$/year, on average (see Table 4). The operating cost of using groundwater from the Querença-Silves aquifer is higher than the operating cost of using groundwater of the Almádena-Odeáxere aquifer. But in the first three years only groundwater from the first aquifer is used. This happens to fulfil the volumetric blending objective. While the Bravura reservoir is not used, the water leaves the Alcantarilha WTP (node NN1 in Figure 1) with a volumetric blending ratio of groundwater of 25%. In this situation the abstraction of groundwater water in Almádena-Odeáxere aquifer would cause a failure in the volumetric blending objective at demand node D7.

A more regular exploitation of the Bravura reservoir is suggested in example CS-INTERAN. The contribution of this reservoir in the five year period rises to 4.5 hm$^3$/year, on average (Table 4). Anticipating the period of drought, the Odelouca reservoir is less exploited in the first three years. Thus, the main source of the BWS starts the fourth year with a higher storage (Figure 3). Notwithstanding, failures still happen and they are spread over the first four years of the period of analysis. All resources are mobilized in this period. The abstraction of groundwater in Querença-Silves aquifer cannot exceed 13 hm$^3$/year (Table 1). Table 4 shows this same value for the period of analysis, on average. The abstraction of groundwater from the Almádena-Odeáxere aquifer is limited by imposed minimum piezometric levels at control points (Figure 4). These are selected locations for the control of piezometric levels.

Table 2. Overall satisfaction of demand.

| Scenario | Satisfaction of demand (%) | | | | |
|---|---|---|---|---|---|
| | Y1 | Y2 | Y3 | Y4 | Y5 |
| *CS-ANNUAL* | 100 | 100 | 100 | 46 | 100 |
| *CS-INTERAN* | 96 | 93 | 93 | 92 | 100 |
| *EXP-ANNUAL* | 100 | 100 | 100 | 72 | 100 |
| *EXP-INTERAN* | 100 | 100 | 100 | 100 | 100 |

Table 3. Maximum volumetric blending ratio of groundwater at demand node D1.

| Scenario | Max. vol. blending ratio $k$=2 (%) | | | | |
|---|---|---|---|---|---|
| | Y1 | Y2 | Y3 | Y4 | Y5 |
| *CS-ANNUAL* | 25 | 25 | 25 | 100 | 25 |
| *CS-INTERAN* | 51 | 51 | 61 | 83 | 32 |
| *EXP-ANNUAL* | 25 | 25 | 25 | 55 | 25 |
| *EXP-INTERAN* | 25 | 25 | 25 | 25 | 25 |

Table 4. Average water use from each source.

| Scenario | Average water use from each source ($\times10^6$ m$^3$/year) | | | | |
|---|---|---|---|---|---|
| | R1 | R2 | A1 | A2 | T1 |
| *CS-ANNUAL* | 1.2 | 52.0 | 13 | 0.5 | -- |
| *CS-INTERAN* | 4.5 | 51.6 | 13 | 1.6 | -- |
| *EXP-ANNUAL* | 1.2 | 51.9 | 13 | 0.5 | 4.0 |
| *EXP-INTERAN* | 0 | 51.4 | 12.8 | 0 | 10.4 |

Water sources: R1-Odelouca reservoir, R2-Bravura reservoir, A1-Querença-Silves aquifer, A2-Almádena-Odeáxere aquifer, T1-Water transfer from Santa Clara reservoir.

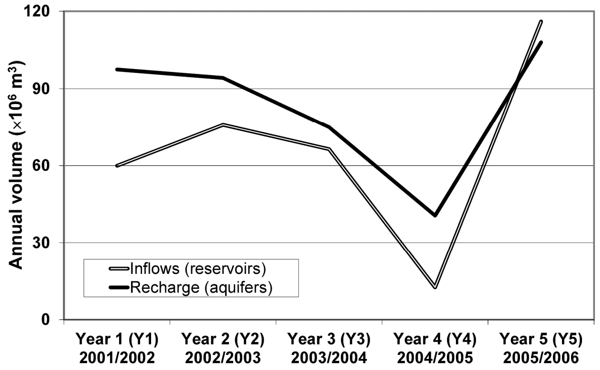

Figure 2. Hydrologic scenario (includes only water sources listed in Table 1).

With the expansion of the BWS and annual management (example EXP-ANNUAL), it is possible to reduce the impact of the drought but not to eliminate it completely. In the first three years, the optimized operation of the BWS is identical to that obtained for example CS-ANNUAL. The water transfer from Santa Clara reservoir implicates a higher operating cost and its use is avoided since cheaper sources are available and the drought is not anticipated. But in the fourth year, the water transfer is used to the maximum (20 hm$^3$/year divided by 5 equals 4.0 hm$^3$/year, on average – see Table 4).

Failures in the objectives of satisfying the demand and delivering water of the appropriate quality could be totally avoided with the expansion of capacity of the BWS and the interannual management of the water resources (see results for example EXP-INTERAN in Tables 2 and 3). The results suggest that the water transfer should be used more regularly to avoid any problems in the water supply. Table 4 indicates a use of 10.4 hm$^3$/year, on average. The Bravura reservoir and the Almádena-Odeáxere aquifer are not used due to the higher operating cost of the surface water source.

Under the interannual management perspective, the optimization model is solved with perfect knowledge of the hydrologic scenario for a period of five years. Draper, 2001, discusses the reliability of modelling with a perfect foresight assumption for extended periods, given the uncertain nature of hydrology. For water systems that rely exclusively on surface water, that author argues that foresight beyond 5-10 years may be of little value. In the selected examples, under interannual management the operation of the BWS is adjusted in the anticipation of the period of drought. But the results obtained also show that only interannual management enables a more effective combined use of the surface water and groundwater resources. Draper, 2001 uses results of optimization models to derive operating rules and concludes that an extended perfect foresight of hydrology is less significant under combined use operations.

## CONCLUSIONS

The results presented here show, for the medium-long term, potential problems in the urban water supply to the study area associated with periods of drought. The inter-basin water transfer from the Santa Clara reservoir can be an effective solution to expand the capacity of the BWS, but the interannual management of the water resources is needed. The results obtained should be seen as very preliminary. The inter-basin water transfer from the Santa Clara reservoir is of an irreversible nature and requires an initial investment of more than 28 million euros (Hidroprojecto & Ambio, 2005), too much to be dependent on a single deterministic hydrologic scenario. A multiple scenario approach could be used to deal with hydrologic uncertainty and to accomplish a more detailed analysis of the solution envisaged for expanding the capacity of the BWS.

The transfer of water resources between river basins is a category of project that must be submitted to an EIA procedure. Thus, even if a more detailed technical analysis shows the feasibility of the envisaged supply-side option for expanding the capacity of the BWS, one should always remember an EIA introduces always uncertainties for decision making.

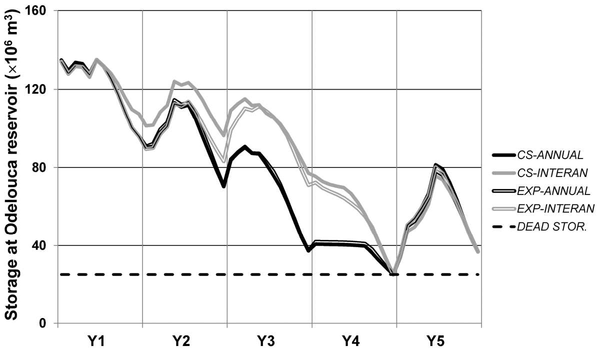

Figure 3. Storage at Odelouca reservoir.

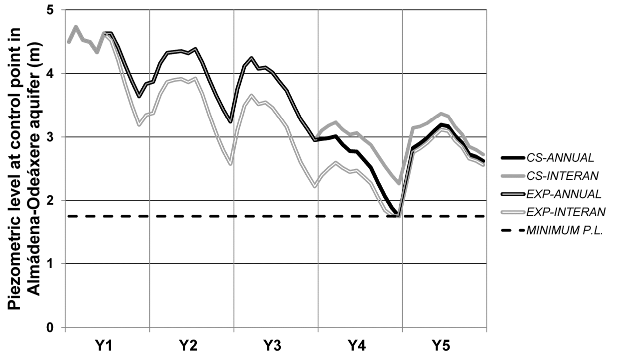

Figure 4. Piezometric level at control point in Almádena-Odeáxere aquifer.

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