Using reservoir trophic-state indexes in optimisation modelling of water-resource systems

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ABSTRACT

Water quality is an important factor to consider when attempting to reconcile mathematical optimisation modelling with the physical reality of water-resource systems. In particular, when the greater part of water resources in supply systems comes from artificial reservoirs, as in Mediterranean regions, a simplified approach based on the attribution of the trophic state of reservoirs can be developed to consider water quality in the optimisation model. Experimental studies have demonstrated that a measure of the trophic state can be given by the Trophic-State Index (TSI), which is evaluated by chlorophyll-concentration. When certain families of microscopic phytoplanktonic algae produce algal toxins during eutrophication, limitations on resource use based solely on TSI values may be insufficient. In this paper, a linear optimisation model is presented that includes quality indexes estimated based on both TSI and concentration density of the most toxic species of algae in reservoirs. The application of the optimisation model to a multi-reservoir system, located in Sardinia, Italy, highlights the impacts of using different water-quality indexes on the results of the optimisation model.

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1. Introduction

The use of mathematical models to simulate and assess water quality in the management and planning of alternatives in complex multi-reservoir systems is limited. Assaf and Saadeh (2008) used the Water Evaluation and Planning System (WEAP) simulation model (Sieber and Purkey, 2007) to set up a water-quality management Decision Support System (DSS) for the identification of cost-effective management alternatives based on selected environmental indicators. Schlüter et al. (2005) discussed previous experiences of optimal policy selection based on environmental criteria using an optimisation model compared to a simulation model. In their opinion, the optimisation model was better able to allocate the resource and achieved higher potential water savings than the simulation model. Additionally, an optimisation model can more easily be extended to include economic aspects into the objective function. Optimisation models can provide effective tools for an integrated and flexibly fashioned system analysis, and managers can potentially benefit from the use of optimisation models to define an optimal policy satisfying economic, environmental and social criteria. A key aspect for an effective application of optimisation models to real-world water systems is to incorporate both water-quantity and water-quality issues into the model.

The use of optimisation models usually requires significant simplifications of water-quality classifications. For complex water systems where reservoirs are the primary water source, a simplified approach to incorporating water quality into the mathematical optimisation model can be achieved by considering only the trophic state of the reservoirs. This is frequently the case for water systems in the Mediterranean region, as examined in this work. In recent years, the Trophic-State Index (TSI) (Carlson, 1977) appears to have attained general acceptance as a reasonable indicator for classifying water stored in reservoirs. TSI can be easily used to insert management constraints on water-use possibilities, to predict short-term trophic evolution in different climate scenarios and to check relationships between parameters.

Nevertheless, the sole use of TSI does not provide information on algal composition, nor does it allow us to establish the specific type of algae within algal blooms. Several families of microscopic phytoplanktonic algae produce algal toxins during reservoir eutrophication phenomena. Toxic algal blooms are a growing problem worldwide. Monitoring the toxicity of the blooms showed that almost half are indeed toxic (Sivonen et al., 1990). As toxins cannot be eliminated during standard water-purification processes, special filters or costly treatments are needed to prevent these algae from entering the supply network. In such cases, modelling
limitations on resource use based solely on TSI values may be insufficient.

When considering a single reservoir, several optimisation models have been utilised for comprehensive modelling of optimal management based on trophic conditions (Kularathna and Somlyódy, 1994). However, to date, few studies have been presented in which an optimisation model characterising eutrophication status has been used for determining control policies in complex water systems (King et al., 2002; Hermans et al., 2003; Sechi and Sulis, 2007a).

The challenge is to develop an optimisation model that can consider multiple types of water-quality impairments from multiple reservoirs that serve multiple competing users having different water-quality requirements. The goal in using the model is to identify optimal water-allocation alternatives and provide a more realistic assessment of the reliability of water supplies of adequate quality. The proposed approach uses linear optimisation modelling of complex multi-reservoir and multi-use water systems based on the TSI with additional consideration of algal composition in the reservoirs. In particular, the density of cyanobacteria is considered, as this prokaryotic blue-green algae is found in surface waters worldwide and the risk posed by these organisms to human health is perhaps significant but largely unexplored. To evaluate how the proposed quality-index evaluation affects the optimal water allocation, the model was applied to the Flumendosa-Campidano water system located in South Sardinia (Italy), and the results were compared with those obtained by Sechi and Sulis (2007a).

The paper is organised as follows: first, several indexes of trophic status and the alga characterization are presented: the optimisation model proposed in Sechi and Sulis (2007a,b) is then briefly recalled, and a modified quality evaluation combining the Trophic-State Index and cyanobacterial density is described; finally, the model application and results in the Flumendosa-Campidano water system are illustrated.

2. Considering reservoir trophic conditions in the optimisation model

Modelling water quality on the basis of trophic conditions must take into consideration complex phenomena including chemical, physical, morphological and biological features (Brylinsky and Mann, 1973). This modelling requires great effort to understand how these factors are related after arranging them in a model using analytical relations. Many authors (e.g., Sakamoto, 1966; Smith, 1982; Smeltzer et al., 1989; Walker, 1991, 2000) have analysed the interactions among a large number of variables to capture this complexity, while also reducing the dimension of the model. To assess the eutrophication rate, primary productivity is frequently measured. Experimental studies in lakes have shown that nutrients (nitrogen and phosphorus) play an important role as factors influencing phytoplankton production. An indirect measure of phytoplankton production is provided by chlorophyll-a (Chl-a) concentration. Chl-a is a simpler and more useful estimator than cell number or cell volume. Sakamoto (1966), Carlson (1977), and Smith (1982) have described a log-linear relationship between Chl-a and total phosphorus (TP) concentrations.

The Water Framework Directive (WFD) created a new legislative framework to achieve sustainable management of surface water resources based on changes in the structure of the biological communities. The WFD necessitates that the quality status of surface water bodies is assessed using biological quality indicators. Currently, intensive research is being carried in Europe to develop indexes and classification metrics that can be used in assessment and comparison of water quality targets across Europe. Italian legislation defines the quality evaluation (QE) index in reservoirs based on a limited number of parameters (Chl-a, TP, Secchi disk — SD — transparency and hypolimnion oxygen), and the following classification metric of reservoir water quality:

- QE = 1 → excellent;
- QE = 2 → good;
- QE = 3 → acceptable;
- QE = 4 → poor;
- QE = 5 → bad.

TSI can be used for characterising a trophic state of reservoirs and can be evaluated using Chl-a, TP and SD measurements through semi-empirical relationships. According to Carlson (1977), averaging TSI values makes no sense as, when available, Chl-a is a better predictor than TP and SD.

In Sechi and Sulis (2007a) a single approach (SA) was adopted to evaluate the QE index on the basis of TSI(Chl):

\[
QE = F_1(\text{TSI}(\text{Chl}))
\]  

(1)

Columns 1 and 2 of Table 1 show this relationship between QE and TSI(Chl).

Periodically, the microscopic algae yield blooms, giving a unique colouring to the reservoir. Freshwater harmful algal blooms (HABs) can occur anytime water use is impaired due to excessive accumulations of algae. Several types of algae may cause HABs, including cyanobacteria. Cyanobacterial blooms (CHABs) may or may not be toxic, but refer to the overabundance of the cyanobacterial population. There is growing evidence that the temporal and spatial incidence of CHABs is increasing. Since the first report of toxic cyanobacteria in the late 19th century, all continents except Antarctica have reported CHABs. Cyanotoxins are natural toxins that are sometimes produced by cyanobacteria. According to their effects, cyanotoxins are classified as hepatotoxins, neurotoxins, skin irritants and other toxins (World Health Organisation — WHO, 1998). Most poisoning involves acute hepatotoxicity caused by cyanotoxins referred to as microcysts.

Even if cyanotoxins are clearly hazardous to human health and ecosystem sustainability, the degree of risk they present is unclear. UNESCO (2005) adopted the microcystin concentration threshold of 1 µg/L (acute intoxication risk) for consumption of drinking water from eutrophic reservoirs with CHABs. International guidelines also recommend a threshold of 1 µg/L for the chronic hazard from water consumption of over long periods (Ueno et al., 1996). A density of 100 × 10^6 cells/L of cyanobacteria can produce microcystin concentrations from 10 µg/L to 20 µg/L equivalent to 10—20 times the precautionary threshold value recommended by UNESCO. On the assumption that a three-stage water-purification system in a municipal water supply should remove the 90% of cyanobacteria and microcysts, as reported by Begliutti et al. (2007), a threshold value for urban and irrigation uses of 100 × 10^6 cells/L was adopted in this paper. This value is, of course, influenced by a lack of concern and the absence of clear legislatice standards. Research is needed to provide water-system managers with cost-effective alternatives for reducing the risks through prevention and mitigation measures.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Relationships between TSI values, density of cyanobacteria and QE values.</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE</td>
<td>TSI (Chl)</td>
</tr>
<tr>
<td>1</td>
<td>&lt;30—40</td>
</tr>
<tr>
<td>2</td>
<td>40—50</td>
</tr>
<tr>
<td>3</td>
<td>50—70</td>
</tr>
<tr>
<td>4</td>
<td>70—80</td>
</tr>
<tr>
<td>5</td>
<td>&gt;80</td>
</tr>
</tbody>
</table>

The first report of cyanobacteria was in 1879 in the Mediterranean region (Sakamoto, 1966). The green alga is found in surface waters in the Mediterranean region (Sakamoto, 1966). Chlorophyll-a is a simpler and more useful estimator than cell number or cell volume. Sakamoto (1966), Carlson (1977), and Smith (1982) have described a log-linear relationship between Chl-a and total phosphorus (TP) concentrations.

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Considering the water quality and potential use degradation due to cyanotoxins, a combined approach for classifying the quality of stored water in reservoirs was developed in this work using both TSI and concentration density values for the most toxic species of algae. In fact, TSI does not provide enough information about the consequences of algal blooms, and more detailed analyses on toxic algal classification are necessary. Analyses of TSI values and cyanobacterial concentrations ($D(\text{cyano})$) highlight the complementary nature of information provided by these indicators (Begliutti et al., 2007).

By adopting this combined approach (CA), the QE index is evaluated as:

$$QE = F_2(TSI(\text{Chl}), D(\text{cyano}))$$  \hspace{1cm} (2)

Table 1 shows the relationship between TSI values from Chl, cyanobacterial concentrations and QE values. In particular, when the cyanobacterial density is lower than $100 \times 10^6$ cells/L, the QE index is based on the TSI(Chl), whereas when cyanobacterial density is higher than $100 \times 10^6$ cells/L, the water must be considered unsafe for human consumption due to the toxic effects of this high cyanobacterial density; thus, the QE value is assumed to equal 5, regardless of the TSI(Chl) value.

3. Multi-reservoir water-system optimisation model

The optimisation model represents the water-resource system in a single period (static representation) by a direct network (or basic graph) consisting of nodes and arcs. A dynamic multi-period network can be generated by replicating the basic graph for each period $t$ in the time horizon $T$ and then connecting the corresponding reservoir nodes for different consecutive periods by additional arcs carrying water stored at the end of each period; we call these inter-period arcs (Pallottino et al., 2005; Sechi and Zuddas, 2007). For more details on the quality optimisation model, the reader is referred to Sechi and Sulis (2007a) and Sulis (2006). Here a general presentation of the quality model is briefly recalled, and additions and improvements are thoroughly presented, specifically on the combined approach evaluating QE.

The Objective Function (OF) in the optimisation model incorporates construction costs, Operation—Maintenance—Repair (OMR) costs and costs depending on water-quality upgrades by purification processes. Optimisation model constraints express the relationships between system variables and limits of their attributions (namely, continuity constraints at the nodes, functional constraints on the arcs and bounds on the flow and project variables) (Labadie, 2004). Moreover, the set of constraints in the model includes water quality, limiting the possibility of using reservoir-stored water for downstream uses. In all types of constraints, both flow (resource transfer in the network) and project (new works and facilities in the network) variables may appear as well.

Model linearity implies that only one of the two terms can be a variable in the product between the quality index $QE$ and a flow variable $x$, whereas the other is constrained by pre-assigned values. The model can be represented in the following compact structure:

$$L \leq Y \leq U$$  \hspace{1cm} (7)

$$QE = F_2(TSI(\text{Chl}), D(\text{cyano}))$$  \hspace{1cm} (2)

$$x_j = F_4(QE)$$  \hspace{1cm} (8a)

where $Y$ indicates the set of project variables (new works and facilities in the system) and $\gamma$ indicates associated construction costs; $[x_u,x_d]$ are the subsets of flow variables $x$ related to costs $c_p$, which represent OMR costs to assure the efficiency of the system, and to costs $c_c$, which represent purification costs. In particular, the purification costs can be fixed or dependent on water-use requirements (costs of quality protection and management). Constraint (4) represents the continuity equations at the nodes, in which the vector $b$ represents input or output at the nodes. Constraint (5) expresses the relationship between the flow and project variables; the subsequent two constraints ((6) and (7)) are the bounds attributed to the two sets of variables.

For each reservoir, equation (2) models the dependency of QE on TSI(Chl) and $D(\text{cyano})$ measured in the time horizon $T$. The model could also be used as a predictive screening-level model to evaluate the impact of different planning alternatives on water uses. In such a case, other exogenous variables, particularly future scenarios of hydrological inputs to reservoirs, could be inserted in relation (2) (Sechi and Sulis, 2007b). Constraint (8a), in general terms, limits the possibility of releasing water $|x_j|$ from reservoirs $j = 1,...,J$ to downstream uses. Considering the simple system schematisation in Fig. 1, for each arc outgoing from the reservoir $j$ towards a downstream node $k$, the model imposes the condition that:

$$QR_k = \min QR_d; \quad d = \text{demand nodes downstream of node } k \quad \hspace{1cm} (9)$$

$$I \leq x \leq u \quad \hspace{1cm} (6)$$

$$F_3(Y,x) \geq 0 \quad \hspace{1cm} (5)$$
2. at each time \( t \), the water-quality value, \( \text{QE}^t_{jk} \), of releases from the reservoir \( j \) must achieve the water-quality standard of the related designated uses:

\[
\text{QE}^t_{jk} = \text{QR}_k \tag{10}
\]

In particular, this last quality constraint (10) in reservoir \( j \) must ensure that water released from the reservoir \( j \) at time \( t \) meets the quality standards of the downstream nodes (Fig. 1). Then, the quality constraint \((8a)\) can be written in the following complete form:

\[
\text{QE}^{t-1}x_j^{t-1} + \sum_{i=1}^{J} \text{QE}^t_{ij}x_{ij}^t \leq \text{QE}^t_jx_{jk}^t + \sum_{k=1}^{K} \text{QE}^t_{jk}x_{jk}^t, \quad j = 1, \ldots, J \tag{8b}
\]

where \( x_j \) flow variable representing volume stored; \( x_{ij} \) flow variables indicating water incoming from node \( i \), \( i = 1, \ldots, I \), where \( I \) is the number of nodes sending water to reservoir \( j \); \( x_{jk} \) flow variables indicating water outgoing towards node \( k \), \( k = 1, \ldots, K \), where \( K \) is the number of nodes receiving water from reservoir \( j \); \( x_{ij,l} \) flow variable representing the sum of losses \( l \) from reservoir \( j \).

In equation \((8b)\), the linearity implies that only flow values \((x)\) are variable, whereas \( \text{QE} \) are constrained by the sampled values or by equation \((10)\). It considers the water stored in the reservoir as a whole (complete mixing condition) and implicitly considers linear approximation in the use of quality indexes. No stricter water-quality constraint has been assumed, as we need to assume the simplification of non-diffusive and conservative water-quality processes.

To provide a user-friendly tool for water-system modelling, the proposed optimisation model was implemented in WARGI-DSS (Sechi and Zuddas, 2000; Manca et al., 2004). WARGI-DSS generates a standard-data-format MPS (Mathematical Programming System) file to feed to the solver. The standard data format allows the use of any solver, generally the most efficient or the most

![Fig. 2. The Flumendosa-Campidano water system.](image-url)
readily available in the work environment. In the present work, WARGI-DSS was linked with a CPLEX (2006) solver.

4. Model application to the Flumendosa-Campidano water system

Application of the optimisation model to a real multi-reservoir system considering quality constraints was carried out in the Flumendosa-Campidano (Sardinia, Italy) water system. The Flumendosa-Campidano water system extends over southeastern Sardinia, reaching to the centre of the Island. The hydrology is typically Mediterranean, with the alternation of several drought years with years marked by intense rainfall. This multi-reservoir and multi-use water system is the most extensive and complex on the Sardinian island. In the absence of natural lakes and significant aquifers, 10 reservoirs have been built to meet competitive water requirements during the last century. All reservoirs are used for urban water, industrial and irrigation uses. Pressure pipelines and open channels supply downstream demands. The average total annual inflow to reservoirs and intake nodes is approximately $438 \times 10^6 \text{m}^3/\text{yr}$, with 85% occurring during the rainy season (November–April). A network representation of the system is shown in Fig. 2 including 10 reservoir nodes, 9 diversion nodes, 22 demand nodes and 59 links. Urban, industrial and irrigation demands are, respectively, $116 \times 10^6 \text{m}^3/\text{yr}$, $19 \times 10^6 \text{m}^3/\text{yr}$ and $224 \times 10^6 \text{m}^3/\text{yr}$. A detailed description of the main characteristics of the system is also available in the reports of the European Project SEDEMED (2007), where the Flumendosa-Campidano was used as test case for dealing with problems related to water-system management under drought conditions.

Since the early 1990s, the Regional Water-System Management Board (Ente Acque della Sardegna – ENAS) has conducted an intensive monitoring program to identify water-quality status in the most important reservoirs in the system, particularly in the following four reservoirs, whose main characteristics are shown in Table 2: Flumendosa, Mulargia, Is Barrocus and Cixerri. Measurements of the main chemical and biological parameters suggest that reservoir eutrophication is the major water-quality problem in almost all reservoirs of the system. Eutrophication is caused by the excessive proliferation of planktonic algae due to high loads of TP from point and diffuse sources in the catchment area. Samples for Chl-a, TP and SD were taken monthly from January 1994 to December 2003 at multiple depths from the water surface using a vertical sampler. The temporal evolution of monthly Chl-a density values is shown in Fig. 3 over that period. TSI values calculated from Chl-a samples using equation (1) are presented in Sechi and Sulis (2007a) where the statistics for TSI(Chl) values are also reported. Briefly, Flumendosa and Mulargia had an intermediate trophic level between oligotrophy and mesotrophy, whereas Cixerri and Is Barrocus were in a state between eutrophy and hypertrophy.

Regarding phytoplankton compositions, algal species in the four reservoirs mostly belonged to five classes: Cyanophyceae, Chlorophyceae, Bacillariophyceae (Diatoms), Cryptophyceae and Conjugatophyceae. Once a month, cell-density values were determined from 1996 to 2005 at each reservoir. As extensively reported in Begliutti et al. (2007), the phytoplanktonic composition of the four reservoirs was dominated by cyanobacteria throughout almost the whole period under study. In particular, the phytoplanktonic composition can be summarised as follows:

<table>
<thead>
<tr>
<th>Flumendosa</th>
<th>Mulargia</th>
<th>Is Barrocus</th>
<th>Cixerri</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total catchment basin [km$^2$]</td>
<td>1004.51</td>
<td>1183.16</td>
<td>93.00</td>
</tr>
<tr>
<td>Reservoir surface at maximum level [km$^2$]</td>
<td>9.00</td>
<td>12.40</td>
<td>6.30</td>
</tr>
<tr>
<td>Elevation at maximum level [m asl]</td>
<td>269.00</td>
<td>259.00</td>
<td>414.55</td>
</tr>
<tr>
<td>Elevation at maximum regulation level [m asl]</td>
<td>267.00</td>
<td>258.00</td>
<td>413.00</td>
</tr>
<tr>
<td>Volume at maximum level [10$^6$ m$^3$]</td>
<td>316.40</td>
<td>347.70</td>
<td>14.04</td>
</tr>
<tr>
<td>Volume at maximum regulation level [10$^6$ m$^3$]</td>
<td>292.90</td>
<td>320.70</td>
<td>11.96</td>
</tr>
</tbody>
</table>

Table 2
Main characteristics of reservoirs in the Flumendosa-Campidano system.
1) Marked predominance of cyanobacteria in 1999 and from 2001 to 2005 in the Flumendosa reservoir;
2) Domination of cyanobacteria during almost the entire period under study, apart from the years 1998 and 1999 (which also recorded the lowest total algal density values) at the Mulargia reservoir;
3) High variable composition in the Is Barrocus reservoir where in only five out of the 10 years under study were cyanobacteria the dominant class, with percentage values always higher than 64% of total density;
4) Cyanobacteria were the only algae in the Cixerri reservoir.

The phytoplankton composition in the reservoirs emphasises the importance of cyanobacteria as a limiting factor for water use in the Flumendosa-Campidano system. The cyanobacterial cell-density values provided by ENAS are reported in Figs. 4 and 5 and together show how the density of the cyanobacteria changed over time in each reservoir. The trend in the density of cyanobacteria in the Flumendosa reservoir was increasing from 1996 onward, and the annual mean values of cyanobacterial density peaked in 2002 at \(28 \times 10^6\) cells/L. The phytoplanktonic composition of the Mulargia reservoir was higher than \(100 \times 10^6\) cells/L for three consecutive years (2000–2002). The Is Barrocus reservoir displayed a more variable trend, and the maximum cyanobacterial density values were recorded in 2005. Mean annual values of cyanobacterial density in the Cixerri reservoir showed a downward trend after 2000, when they peaked at more than \(700 \times 10^6\) cells/L, and reached their lowest levels in 2005 with \(15 \times 10^6\) cells/L.

Generally, over the annual cycle, cyanobacteria adapted very rapidly to unfavourable habitat conditions that change seasonally (temperature and nutrient loading). Once cyanobacteria reached high biomass, exceeding the maximum density value of \(100 \times 10^6\) cells/L, the reservoirs showed low resilience to return to a safe density.
These data highlighting cyanobacterial density in the reservoirs confirm the necessity of modelling the attribution of QE values considering their concentrations. Therefore, the combined approach (2) evaluates monthly QE values in each reservoir based both on TSI(Chl) and D(cyano) values.

Table 3 shows the comparison among the frequency distribution of historical QE in the five classes obtained using only TSI(Chl), (single approach – SA) and using both TSI(Chl) and D(cyano) values (proposed combined approach – CA). Particularly for the Cixerri reservoir, the differences are remarkable; considering TSI(Chl) water-quality characteristics in the reservoir rendered the water unsuitable for designated uses for only one month out of 96; the use of cyanobacterial concentrations affected the water safety usage during 38 months (+39%). In contrast, in the Flumendosa reservoir the acceptability of water for consumers largely depended only on the TSI(Chl) value and the QE frequency distribution remained the same whether using D(cyano) values or not.

Considering this optimisation modelling approach in a predictive management assessment, the historical QE series can be used to calibrate multiple linear regressions to evaluate the seasonal dependencies of QE, mainly from hydrological data (Sechi and Sulis, 2007b).

When assigning the water-quality standard values that must be guaranteed for demands during the optimisation horizon (QRd in Fig. 1), according to ENAS requirements they were assumed to equal 1 for urban use (QRu = 1), 3 for industrial use (QRI = 3), and 4 for irrigation (QRA = 4). The Flumendosa-Campidano optimisation was developed on a time horizon of seven years (between 1996 and 2003) and a unit-time period equal to one month, in accordance with the available database provided by ENAS.

In order to highlight the impact on water usage when considering cyanobacterial density as a limiting factor, the optimisation was preliminarily implemented considering only the single approach (1) and results were then compared when the optimisation model was implemented using the combined approach (2). Two indexes were used to quantify the main results and performances of the optimisation models: time reliability (expressed as a percentage value of the months in which the deficit is equal to or less than predefined thresholds) and volumetric reliability (expressed as the deficit rate on the demand value for the entire period of analysis).

A comparison of system-performance levels shows that the high concentration of cyanobacteria included in (2) seriously reduced water availability in the reservoirs. Table 4 shows a significant reduction in time reliabilities (−11.67% and −11.69%) and in volumetric reliability (−11.25%) of the urban supply. Cyanotoxins cannot be eliminated by water-purification processes in the plants located in the Flumendosa-Campidano system. In the event of heavy cyanobacterial blooms, toxic cells and free toxins have been found in end-user water supplies. The industrial supply is not affected by toxic algae, at least when considering industries in Southern Sardinia. A comparison between the performance index values in SA and CA (Table 4) also illustrates the increase in the

![Graph showing releases from reservoirs](image-url)
deficit when the cyanobacterial density is considered as a limiting factor for water use in agriculture.

Fig. 6 compares mean monthly water releases from the four main reservoirs over the observed period. As expected, a significant reduction in releases appeared in reservoirs where the cyanobacterial concentration significantly affects the safety of urban and irrigation water consumption. In particular, this was evident in the Cixerri and Is Barrocus reservoirs, where algal blooms occur frequently during the spring and summer seasons. High density values of toxic cyanobacteria caused reductions of 47.1% in Cixerri and 42.7% in Is Barrocus of the total water release in the spring and summer seasons. The release reduction was required because the cyanobacterial density exceeded the maximum water-quality value for downstream use. In this application, the behaviours of releases from the Flumendosa and Mulargia reservoirs were very similar in both approaches.

5. Summary and conclusions

In optimisation modelling of a complex multi-reservoir water system in a fully integrated fashion, determining the effects of different water-quality indicators is critical. The proposed approach for classifying water in reservoirs uses both TSI(Chl) and concentration-density values of the most toxic species of algae (cyanobacteria). TSI(Chl) alone does not provide enough information about the consequences of algal blooms on water safety for human consumption (direct or indirect) and toxic algae analyses are therefore necessary. Although toxic algae in reservoirs have not been adequately addressed by legislation regulating the use of water for various purposes, toxic algae are a common problem impairing the quality of water resources and represent an essential factor in limiting the range of water-use options. Since toxic algal blooms occur each year in seven regions out of twenty in Italy, and the toxins produced are carcinogenic risk substances, a limiting factor for water use must be adequately established based on the density values of the various toxic algal species. WHO guidelines suggest a threshold value, above which the presence of cyanobacteria in reservoirs becomes critical, particularly for urban supply, irrigation and recreational uses, and treatment processes become inadequate to bring toxic cells and released toxins to levels below these limits, causing acute, sometimes lethal effects.

This paper shows how a combined TSI(Chl) and toxic algal classification can provide a simple approach for mathematical optimisation modelling of complex multi-reservoir water systems. Although the present case study only considered cyanobacteria, since this is the most toxic algal group in the Flumendosa-Campidano water system, this approach is independent of the number and type of toxic algae considered. The application of the optimisation model to Flumendosa-Campidano provided a means to analyse the impact of cyanobacteria on water-allocation policy for different water uses. The results obtained highlight the fact that system performances are seriously affected by the presence of these toxic algae in reservoirs. Particularly during the spring and summer, the combined approach reduced the water availability in the system due to high cyanobacterial density, making the satisfaction of competitive water needs during periods of scarcity even more difficult.

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