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Water resource management through systemic approach: the case of Lake Bracciano

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Water is a common good which is fundamental for life and it is only apparently ~~(though in most cases perceived to be)~~ an unlimited resource. In fact, natural water resources are becoming scarce, both due to global climate change but also due to an irresponsible behavior of human beings. Lakes are perhaps among the most delicate aquatic systems~~. In fact,~~ due to their limited size~~, if compared to seas and oceans, and to the slow replacement of their water, these systems are very exposed to external agents, which can interfere with the equilibrium of lakes' ecosystems~~. The objective of this paper is to propose a System Dynamics simulation model, employed in a real case study regarding the city of Rome and one of its water reserves, the Bracciano Lake, for the evaluation of environmental impacts resulting from different water exploitation/use strategies and policies, under different climatic and context scenarios. The results indicate that, as the system is currently exposed to a high risk of ecological disaster, the situation might worsen, and the disaster effectively happen; especially if meteorological conditions, like the one experienced in 2017, will occur again in the near future. However, according to certain policies and contextual situations, the risk can be avoided and ultimately mitigated. Nevertheless, models like the one presented in this paper may help water agencies and municipal administrations to explore policies and find solutions to address this fundamental problem, that may become even worst over the next years, given the potential severe consequences deriving from the current global warming trends.

Keywords: Water resource management; Sustainability; Policy Evaluation; Model-based Governance; System Dynamics; Modelling & Simulation

Introduction

Although there are some countries where water scarcity is a long-established problem – ~~—~~ for example, in most African countries, for both geographical and notorious economic factors (Mekonnen & Hoekstra, 2016; Gann et al., 2016) – ~~,~~ climate change has harmed water availability in many parts of the world (Gosling and Arnell, 2016; Vörösmarty et al., 2000; Arnell, 1999). In California, for example, despite a recent respite, the long-running drought costed the agricultural sector ~~an estimated~~about $2.7 billion in 2015, and the state expects ~~to experience~~more chronic water shortages in the future (Thompson, 2015). Another example occurred in Sri Lanka, where the worst drought in 40 years affected more than 1 million people by acute water shortages (Bacchi, 2017).

According to the European Environment Agency (2008), water scarcity is defined as a situation where "insufficient water resources are available to satisfy long-term average requirements". Similarly, Van Loon and Van Lanen (2013) considered that "water scarcity represents the overexploitation of water resources when demand for water is higher than water availability". Estrela and Vargas (2012) noted that "drought is a natural hazard that results from a deficiency of precipitation from expected or normal, which can translate into insufficient amounts to meet the water demands of human activities and the environment."

As stated during the 23rd Conference of the United Nations Framework Convention on Climate Change (UNFCCC), on 16-17th November 2017: "Around 40% of the world's population will face water shortages by 2050, accelerating migration and triggering conflict, while some regions could lose up to 6% of their economic output, unless the water utilization is better managed."

The Intergovernmental Panel on Climate Change (IPCC, 2015) reported that unabated climate change has the potential to strongly impact freshwater resources with wide ranging consequences for societies and ecosystems. Furthermore, there are other dynamic factors that must be considered within water scarcity issue, including economic growth, technological progress, national water endowment, structure of production (at sectoral level), international trade, and population growth (Distefano and Kelly, 2017).

Nowadays, one of the most challenging problem that Italy is facing is certainly the water crisis that periodically damages ~~almost all of~~most of the country's regions, from north to south. The decrease of rainfall index in 2017 was 47.4% compared to the historical average. In the north, rainfall scarcity reached alarming 72.3% of the average value, causing, ~~according to~~as said by the biggest stakeholders' association in italian agriculture, Coldiretti, the worst water crisis of the decade. Two-thirds of the crops along the Italian peninsula were dried up and the damages ~~caused~~ to the plantation and livestock amount to more than 2 billion of Euros (source: Repubblica, 2017, August 29. *Allarme siccità: piogge e consumi d'acqua in Italia*).

The case ~~we~~ analysed in this study concerns~~is~~ the water crisis that afflicted the metropolitan area of Rome during the summer of 2017, which has ~~strongly~~ heavily upset the hydrogeological equilibrium of the nearby Bracciano lake, that serves as a potable water reservoir for the city of Rome (the lake supplied also some small towns in the vicinity, but the data about them is not very reliable and their volume are very low compared to the one of Rome). On November 2017, in fact, Lake Bracciano reached the level of 193 cm below its "hydrometric zero" ~~point~~ (that is, 43 cm below the ~~maximum limit~~threshold beyond which the ecological system can be considered at risk). For this reason, the municipality of Lazio region has forbidden further water withdrawals, carried out by the local Water Agency, that manages all the phases of the technological water cycle (withdrawals, transport, distribution, collection and purification), until the lake reaches~~ed~~ back ~~to~~ its safe ~~operating~~ water level, i.e. 161.90 cm (source: ANSA). This drastic decision had far-reaching consequences on water availability for Rome citizens.

This study aims to address the issue of water scarcity in this specific geographical area, ~~taking into account~~considering different stakeholders' perspectives (public administration, water system operator and general population), ~~and putting considerable~~

~~weight~~ with particular attention to the sustainability perspective. We choose for our analysis a systemic approach, ~~in particular~~ the System Dynamics methodology. This approach was chosen due to the intrinsic complexity ~~which is part~~ of water crisis problems ~~and~~ caused by the presence of multiple perspectives (demographic, environmental, economic) that interact ~~each other~~ and produce emergent and unpredictable behaviours ~~sometimes~~.

The paper is divided in 6 sections: in the (next) second section the most important studies in the past, which have dealt with water issues in the chosen geographical area, will be showed. Section 3 is a literature review of papers that analyse ~~some~~ water scarcity issues around the world through systemic approaches. Section 4 will be dedicated to the description of the used methodology (System Dynamics) and to the development of a qualitative model (Causal Loop Diagram) and its quantitative transformation (Stock & Flow diagram) describing the system. In Section 5, we will carry out scenario analysis based on the Stock & Flow diagram, showing also its ~~simulation and~~ validation with real data. Finally, we will explain simulation results and related conclusions ~~of our model~~ as well as expose its limits and future research directions.

Research background

This work will present a model for analysing the water balance of the Lake Bracciano, located near Rome, in Italy. In highly populated areas like that one, with lakes and other water reserves, the human influence on the hydrogeological system can be critical, representing the most important factor to be considered in the definition of the balance between inflows and outflows of water in the impacted basin.

Lake Bracciano is a sub-circular volcanic lake belonging to the Sabatino Volcanic District. The following Table 1 summarizes its characteristics (source: Barbanti and Carollo, 1969).

[Table 1 near here]

By considering the pure hydrogeological aspects of this system, there are two important studies that we have ~~taken into account~~considered in order to understand which are the hydrogeological factors ~~that define~~defining the equilibrium of Lake Bracciano's area. The reason why we choose only these two works is twofold: on the one hand, they specifically addressed the issue of Lake's water level fluctuation, describing its factors and causes; on the other hand, the studies are both ~~relatively~~ quietly recent, so they provide ~~with~~ reliable information, which will ~~be~~ constitute ~~the~~ fundamental basis ~~of the~~for the model's development.

The first study was made by Taviani and Henriksen (2015), who developed a ground-water/surface-water model to test the vulnerability of Lake Bracciano to climatic and water-use stresses. Through this study, the authors have, somehow, identified the potential incoming of water shortage ~~that was likely to occur shortly~~ and tried to early address the issue ~~beforehand~~ by developing an inflow-outflow ~~specific~~ model, which depicts the dynamics of the water system.

The model is conceptualised in Figure 1, below.

[Figure 1 near here]

The work performed by Taviani and Heriksen ~~led to~~raised two important points:

1. The importance of withdrawals made by agency for public supply. In fact, eliminating those outflows may lead the lake to ~~discharge~~ overrun its threshold~~over the lake outlet~~, at least during the winter season, causing damages to the surrounding areas.
2. The groundwater system tends to offset a declining net precipitation trend for a short period of time, but the combination of precipitations ~~lower than~~

~~average~~below the average ~~precipitation~~ and ~~increased~~ excessive water use for long periods may cause lake levels to drop significantly.

Another more recent study made by many researchers (Rossi et al., 2018) performed some analyses for assessing the water level of the lake in relation to climatic factors and withdrawals for human demand, giving an important overview of Lake Bracciano's actual state of health.

As stated in this paper, the Lake Bracciano crisis ~~appears~~ seems to have started in 2015 and in the last 3 years scarce precipitation and increased withdrawals have prevented the recovery of the Lake. If weather conditions and withdrawals will continue in the future, causing the same drop in level as experienced in 2017, this will lead to a 13.5% reduction in the surface area of the lake bed responsible for self-purification (the average lake water level for 2000–2014 corresponding to an 8% reduction), with significant drawback for the whole area surrounding the lake (Rossi et al., 2018). The equilibrium of Lake Bracciano may change irremediably.

Finally, another very important contribution in Rossi et al. (2018) has been to highlight the need to develop predictive models for water resources, that could help policy makers to safeguard the environmental balance, even in the presence of climatic adversities, thus implementing a model-based strategy (Armenia et al., 2018b). This is also one of the reasons that led us to consider, for this study, ~~building~~ the development of a simulation model, based on a System Dynamics approach~~, about Lake Bracciano~~.

Literature review

Water crises has been extensively studied in the past, also by making use of modelling and simulation approaches. In this work, we will make use of the System Dynamics modelling and simulation approach.

System Dynamics consists in an iterative process to define a dynamic hypothesis, develop a formal model, test and validate it, and formulate and evaluate different intervention policies (Coyle, 1996; Richardson and Pugh, 1981; Sterman, 2000). The method was developed in the 60s by Jay W. Forrester (1961) to study complex business problems and it was later expanded to study problems associated with the dynamics of growth and decline in urban centers (Forrester, 1969), in the world as a whole (Forrester, 1971; Meadows et al., 1972), as well as modern problems such as climate change (Gohari et al., 2017; Duran-Encalada et al., 2017). The features of system dynamics modelling include the possibility to account for non-linearities, information feedbacks, time delays, and dynamic complexity (O'Connor and McDermott, 1997).

A brief literature review on system dynamics concerning the phenomena of water scarcity was conducted. The most recurring elements in all the analyzed studies (presented in the following Table 2) are:

- water pollution,
- resilience of systems with increasing demand,
- infrastructures' efficiency,
- alignment of conflicting interests of distinct stakeholders.

[Table 2 near here]

Model description

As showed in our literature review above, some aspects about the phenomenon of water crises has thus been already studied in the past through systemic approach. This work aims, by means of that approach, at addressing a relevant problem that ~~emerged~~ arose in the last years, providing a top-down view of the ~~specific~~ case study of Lake Bracciano.~~,~~ ~~which~~ The lake faced an extreme water shortage during the summer of 2017 due to climatic conditions and increasing consumption demand (Armenia et al., 2018). Although the problem appears to be softened and mitigated thanks to the prohibition of further withdrawals issued by institutions at the end of 2017, it is very likely it will reappear again in the future, therefore a prevention analysis made by a modelling approach could be very useful ~~and this model can be of help in those situations~~.

As a first ~~phase~~ step of our research project, we modelled our case study of Lake Bracciano by means of a causal loop diagram (CLD). A CLD is generally useful for defining the problem's scope, boundaries and perspectives from a qualitative point of view, hence providing a wider understanding of the issues ~~at stake~~under investigation.

A CLD is defined as an oriented di-graph, composed by a combination of nodes and links (which are arrows with a positive or negative sign). The nodes represent the variables that constitute the considered system, whereas the links express the causal relationship between two variables. As mentioned, links can be of two types:

- Positive (+): when the independent variable (arrow tail) changes, then the dependent variable (arrow head) changes in the same direction.
- Negative (-): when the independent variable (arrow tail) changes, then the dependent variable (arrow head) changes in the opposite direction.

Also, it is possible to indicate a time delay between two variables with two small lines in the middle of the link that connects them.

This type of representation will then allow the identification of closed cycles inside the diagram, that provide useful information about the circular causality of the system. In fact, some system variables are often "chained" together in loops, called "feedback loops". Those loops are structures of variables and links capable of reinforcing or balancing themselves, causing a change in the variables' behaviours inside them, which then will either tend to grow or to seek for a certain goal.

There are two types of feedback loops: reinforcing feedback loop and balancing feedback loop (indicated by + and – inside the loop). The total polarity depends on the polarity of the links inside the loop. If the number of negative links is even, the total polarity is positive (reinforcing feedback loop), vice versa the total polarity is negative (balancing feedback loop).

In a Reinforcing feedback loop the effects of a small disturbance on one or more variables inside the loop cause an overall increase in the magnitude of the perturbation. This type of loop often produces exponential growth, increasing oscillations, chaotic behaviour or other divergences from equilibrium. Conversely, balancing feedback loop tends to promote a settling to equilibrium, reducing the effects of possible perturbations which affected one or more variables inside the loop.

Through a first analysis it was possible to identify effectively the problem scope (variables and relations), allowing for qualitative insights and considerations.

Figure 2 illustrates the proposed causal loop diagram, in the next paragraphs the model development process will be illustrated and explained.

[Figure 2 near here]

~~It is possible to analyse the above CLD, by examining its various sections, still by keeping in mind the fact that they are tightly interconnected and interdependent.~~

Let's start our analysis by examining the central role played by the need for drinking water. Generally, water is retrieved from springs or basins, then conveyed to water purification plants and, subsequently, distributed~~ in homes~~ for domestic use. According to the European Union consolidated legislation, and in order to be considered drinkable, water must be colourless, tasteless, odourless, clear and fresh. Furthermore, it cannot contain more than a certain amount of mineral salts which are important to cell physiology (among these, calcium and magnesium should not prevail because they would be too heavy for human digestion). Also, water has to be totally free of pathogens and substances harmful to the organism and even non-pathogens are allowed only in small quantities. The law sets precise and impassable limits also for several other elements.

The Lake Bracciano has a "self-purification" capability that is associated with the volume of water and its surface. In addition, the "self-purification" factor can be an indicator of the general health of the lake. The lower the self-purification percentage, the more the deterioration of the ecological state of the lake (Ostroumov 2010, 2017; Rossi, 2006). In Figure 3~~5~~ it is possible to see the short-term solution often set to counter the problem of water treatment. A decrease in the effectiveness of the lake's self-purification due to the lowering of the hydrometric level of the lake, brings to a higher need of drinkable water, hence leading the local Water Agency to invest into structures and facilities for water treatment/purification. This approach, however, does not take into consideration a long-term dynamic, that will be explained during the description of the CLD.

[Figure 3~~5~~ near here]

In this model, the Financial Resources of the Agency is impacted, on a side, by the level of investments on infrastructure and on purifiers for water treatment and, on the other side, by the water price and public demand. Another variable that deserves attention is represented by the penalties or fines that could arise in case the agency's conduct is leading to environmental damages.

The agency's financial resources are not unlimited. So, the agency has the difficult task to choose on which aspects it is necessary to invest for increasing the service quality. So far, the Agency seems to have~~s~~ overlooked the situation of infrastructure, focusing on treatment/purification or shareholders' remuneration through dividend (source: Borsa Italiana Spa - Dati sociali). Only recently it has started some important renovation works.

As there is always the risk of incurring in heavy penalties for failing to meet the standards of water quality, the agency tends to invest on purifiers, increasing their number and improving their purifying capabilities. Once investments in purifiers are made, any resources used to deal with the problem of water loss inevitably decrease.

~~[Figure 6 near here]~~

Our model also addresses demographic aspects~~ (Figure 7)~~. The water consumption of a population can be distinguished by the type of users:

- domestic users (such as private homes);
- non-domestic users such as industries, farms and public buildings or public services (schools, hospitals, prisons, offices, public watering, fountains, hydrants, washing, sewers, etc.).

In this specific case, the water extracted by Lake Bracciano is used only for domestic demand.

The level of demand heavily drives the amount of withdrawal that the Agency carries out over time from the basin. For this reason, one of the most important levers to control the consumption (and therefore the withdrawals) is represented by the water price. By setting an optimal level of price, and following a raise in water consumption awareness that grows in users' perception due to the fact that their water bill is much higher, much water could be saved.

~~[Figure 7 near here]~~

To conclude the model ~~presentation~~description, it is necessary to account for the Agency's water withdrawal. This important aspect is of course affected by the total demand which arises from the consumers' needs. However, demand also needs to be related to the efficiency of water infrastructures (i.e. the rate of water loss during transport/distribution). In Italy, there is a water leakage of almost 9 billion litres/day due to losses recorded along the water supply-chain network (in Italy there are around 474.000 Km of aqueducts). Every 100 liters of water that flows inside the aqueducts, almost 40 liters are lost due to the obsolescence of the distribution network, representing one of the highest average loss percentages in Europe (Fontana et al., 2011). The infrastructures around Lake Bracciano makes no exception to this situation.

This kind of inefficiency produces a very harmful impact, that has the potential for current and future consequences in terms of water scarcity.

In fact, water scarcity often occurs when certain weather-climatic conditions (i.e. decreases in precipitation) and actions of anthropic nature, (i.e. withdrawals by water agencies due to water demand) happen at the same time. As weather-climatic phenomena cannot be controlled (not at least within the scope of this analysis) but only predicted, the withdrawals can be done instead according to a careful consideration of targets of efficiency and optimization of water resources.

~~[Figure 8 near here]~~

~~All these sections create the overall model showed below (Figure 9).~~

~~[Figure 9 near here]~~

Following the description and systemic understanding of the model and its interconnected variables (hence of the scope of this study), we moved forward with the development of a quantitative simulation model, a ~~that is a co called~~ Stock and Flow

Diagram (SFD), which can be simulated ~~and that helps~~helping in the observ~~e~~ation of the expected dynamics found ~~expected~~ during the description of the Causal Loop Diagram. The SFD also includes important hydrogeological variables (rainfalls, run-off, etc.) that need to be accounted for in order to produce a ~~veritable and~~ reliable analysis.

The Stock and Flow Diagram has a twofold objective: the first is to predict the possible evolution of the lake's level over the next few years, making some assumptions on environmental parameters; the second is to identify the best policies for mitigating possible and periodical water crisis.

[Figure 4~~10~~ near here]

As can be seen in the model (Figure ~~4~~~~10~~), there are three main Stocks that represent three important dimensions which in turn, directly or indirectly, determine the dynamics of the model:

- "**Lake level**" at the top left: it represents the fundamental core of the study and depicts the level (and therefore the health) of the lake over time.
- "**Population**" at the bottom: a level that controls the increase (or decrease) in population over the months, which drives the total water consumption.
- "**Water losses in infrastructure**" at the top right: it considers the water losses due to the obsolescence of water supply system, that affect the withdrawals.

The availability of the water resource is strongly linked to the meteorological and climatic conditions that influence the aquifer's supply. There is no tributary river, therefore the level of the lake considerably oscillates according to the main source of water, that is rain, which affects also the amount related to runoffs and infiltrations phenomena, described below. In fact, to give as more reliable results as possible, we considered in this model also other important factors which affect the water balance:

- **Runoffs** (inflow). Phenomenon of flowing rainwater on the surface of the ground that occurs when it cannot deeply penetrate due to infiltration capacity that characterizes the ground itself exceeds. The average value of the period considered corresponds to 109 mm / year.
- **Infiltration** (inflow). Physical phenomenon for which the water present on the surface of the ground penetrates inside and in part goes to feed the underlying aquifers, the average value is equal to 254 mm / year.
- **Evaporation** (outflow). This element was calculated starting from the Visentini equation:
    - EV_m= b* i_m^{a1}* t_m^{a2}

- Where a_1, a_2 and b are experimental coefficients; i_m is the Thornthwaite monthly solar index and t_m the average monthly temperature. These variables, for central Italy, were quantified on experimental data basis.

The information reported in this paper, related to precipitation and temperature, are available on the website of the Information System of the Regione Lazio's hydrographic office. In particular, the graph below (Figure 5~~11~~) shows the average of rainfalls detection from the rain monitoring centres of Bracciano. As can be seen in figure 5~~9~~, the recorded average cumulative value in 2017 was equal to 504.8 mm, about 40% lower compared to the historical period average. In fact, considering the period 2012-2017, the average annual rainfall recorded on basin was equal to 880 mm.

[Figure 5~~11~~ near here]

Runoffs and infiltration are correlated to rainfall, so their monthly values can be calculated ~~straightforward~~accordingly.

In our model we considered mainly the role of domestic demand of water.

The water consumption of the city of Rome is higher than the real needs of the city's population. Agency data and ISTAT (National statistics institute) data show that the average per capita consumption of daily water per inhabitant in Rome is quite high: about 161 liters of consumption per capita per day, equal to 58.8 m^3 of average annual consumption. Unfortunately, the demographic growth and economic development leads to an increase in the demand for water, producing conflicting tensions between urban and economic expansion on the one hand, and water and environmental security on the other. For this reason, the demographic variable was included in the model as an exogenous variable which, in relation to the consumption per capita, leads the withdrawals by the agency. The consumption per capita is represented as a parameter and it is treated as a manifestation of possible price strategies (that discouraged the consumption of consumers).

The central area of Lazio is rich in water, but large amounts of resources are wasted due to the losses that occur on the distribution networks, often due to their obsolescence. According to the latest surveys, over 38% of "real losses" occur with respect to the quantity of resources fed into the network. Generally, the losses occur in various part of the water infrastructure, even far away from the lake. There could be a small part that returns to lake, but there are no evidences or specific studies that quantify~~ied~~ it. Anyway, the water losses are critical in our model and represent a dimension which could be improved with investments made by the Agency.

Before simulating the model, it is important to evaluate its likelihood~~, that is to~~ through a validat~~e~~ion process~~ it~~. The simulation of a basic scenario (base run) was performed in order to test how the numerical model was properly calibrated. The validation is based on the comparison of the model's outputs with the time series data, collected from the “real world” and between years 2012 and 2017.

In the following image (Figure 6~~12~~) we can see the two time-series representing respectively:

- the hydrometric level of Lake Bracciano, on real data;
- hydrometric level of Lake Bracciano estimated with the model subject to validation.

[Figure 6~~12~~ near here]

The average error was calculated as the average of all deviations of the two distributions. This error is equal to 0.019583 m, which can be considered a small value. Furthermore, an F-test and a T-test were carried out. For the F-test, which verifies that two groups of variables have similar variance, the two-tails probability that the variances of real and simulated data are not significantly different is equal to 0.619, so it can be said that the two variances are quite different. Conversely, T-test aims to verify whether the mean value of two groups is similar. The F-test is preparatory to T-test, in fact it defines the type of T-test to be carried out (in this case dissimilar variance). The results of T-test said that the two-tails probability that the means of real and simulated data are not significantly different, is equal to 0.884. This value can be considered acceptable, as we are talking about a simulation model, which cannot consider the totality of factors that affect the level of a lake. For these reasons, the model can be considered acceptable and valid.

Scenario analysis

As mentioned before, our intention is to shed light on one or more optimal policies~~y~~ of intervention for a ~~good~~ better management of water resources, by conducting some scenario analysis. The scenario analysis allows to describe the evolution of the system, assuming different values of some key variables or activating some policy feedbacks. In the next subsections, resilience of the water system is analyzed in different scenarios, each of which are different for the set of policies adopted to face the crisis periods. In all scenarios, we consider a time interval of five years and a time step of one~~a~~ month.

Clearly the combinations of possible values, also in relation to the same number of variables, are unlimited. For this reason, the number of scenarios has been reduced, considering the most representative ones. In the next paragraphs they will be explained in detail.

- Scenario 1.1 recreates the situation of drought for the only first year without specific policies;
- Scenario 1.2 recreates the situation of drought for the only first year with external policy (State's support) to improve water infrastructures;
- Scenario 1.3 recreates the situation of drought for the only first year with internal price strategy;
- Scenario 2.1 recreates the situation of drought for the first two years with external policy (State's support) to improve water infrastructures;
- Scenario 2.2 recreates the situation of drought for the first two years with internal price strategy.

Scenario 1.1

The first scenario describes the Business-As-Usual situation. BAU is the situation of the water system of Lake Bracciano on 2017. Currently, after some political and judicial events that took place at the end of 2017, the agency does not take out water from the lake.

Through this scenario we want to describe the evolution of the system in the next 5 years if the block currently underway is revoked with the advent of the new year, 2019, maintaining constant data input on prices and efficiencies of the infrastructure. For this reason, the initial data entered in the model are those relating to the current state. They are shown below:

- Lake level: 161,47 m
- Water price: 1,62 EUR/m^3
- Population of Rome: 2.873.000
- Percentage of water lost in infrastructure: 38%

Regarding the climatic data, we hypothesize that, during the 5 years of simulation, in the first year there is a drought like the one recorded in 2017, while the remaining 4 years are equal to 2014, which was quite generous in terms of rainfall. Figure 13 shows the rainfall values of this simulation.

[Figure 7~~13~~ near here]

Figures 8~~14~~ and 9~~15~~ show the results related to monthly withdrawals and the consequent evolution of the lake level over months.

[Figure 8~~14~~ near here]

[Figure 9~~15~~ near here]

The increasing trend of the withdrawals over time is mainly due to the obsolescence of the infrastructures, in fact, without maintenance interventions and with a constant demand, the agency is forced to extract more and more water to meet the consumers' need, facing with the losses incurred in the infrastructure.

In the figure 9~~15~~ it can be seen how the level of the lake reaches and exceeds 160 m (red bold line~~)~~, that is ~~limit~~ threshold ~~beyond~~ under which the lake would lose almost entirely its biological balance, compromising its self-purification capacity), starting from the fourth year, for then arriving in the fifth year to an even more serious situation.

It is necessary to consider the lake acts as a big ecosystem-filter. So, if the self-purifying capacity is lacking, the water to be used must be treated, and this also leads to an increase in management costs and, naturally, less resources in infrastructure maintenance that exacerbates the problem.

Scenario 1.2

The second scenario differs from the first one only in adding an external policy. We have hypothesized an external economic aid over time by the state, supporting the agency for restructuring the water infrastructure for the achievement, and maintenance, of an objective value of 35% of water losses.

Figures 10~~6~~ and 11~~7~~ show the results related to the monthly withdrawals and the consequent evolution of the lake level, given the new policy.

[Figure 10~~6~~ near here]

[Figure 11~~7~~ near here]

Due to the new policy, the agency's withdrawals decrease over time due to the increase in efficiency of the water infrastructure. The level of the lake ~~in turn~~ benefits from this effect in turn, in fact the limit of 160 m is only touched during the fifth year. Unfortunately, this does not seem to be enough to avoid the overrun, which would probably occur during the sixth year (not ~~considered~~ recorded in the ~~simulations~~graphs) due to the descending trend easily recognizable in the graph. Furthermore, the 160 meters altitude represents an ideally catastrophic border, this implies that if the level is between 160 and 160.5 m for a few consecutive years, the lake can be considered in high risk, indicating a situation of ~~serious~~ real emergency (Rossi et al., 2018).

Scenario 1.3

In this last scenario we have considered the variable relating to the price applied by the agency in a dynamic way, contrary to what was done in the other scenarios where it was constant.

A monitoring feedback cycle has been added and then activated by the agency, which updates its price based on the expected costs due to the different health conditions of the lake over time. If the lake was too close to a dangerous situation, the price applied would increase (with some delay due to the time for analyzing the data by the agency and for updating the charges), determining in turn a decrease in consumption by the population (also affected by a delay in adaptation to the new, more expensive charge). Figures 12~~8~~ and 13~~9~~ show the results related to the monthly collection and the consequent evolution of the lake level, given by the new price control feedback.

[Figure 12~~8~~ near here]

[Figure 13~~9~~ near here]

The graphs show a clear improvement compared to ~~past~~ previous scenarios. This price adjustment strategy has led to change the habits of consumers toward ~~who changed their consumption to~~ more efficient regimes of consumption;~~,~~ on the other hand the higher price allowed the Agency to achieve additional resources for investment in the infrastructure, reaching higher levels of efficiency (20% of losses) at the end of the fifth year.

This type of situation makes State’s intervention (as described in scenario 1.2) completely unnecessary because the Agency is always able to allocate resources for the continuous improvement and maintenance of its water network. In fact, by activating both the external aid and the price feedback, there is no significant change in results.

The benefit of the situation described above can also be understood by comparing the minimum values of the third (160.35 m) and fifth year (160.38 m), denoting that Lake’s level is growing considering the long term.

Scenario 2.1

In this scenario we hypothesized a situation of great stress for the system, foreseeing in the first two consecutive years of simulation the same climatic situation recorded in 2017, so two years of severe drought instead of just one (Figure 14~~20~~). This type of scenario may seem extreme, but in fact, with the climate change we are experiencing in recent years, it is not too far from the possible reality, unfortunately.

[Figure 14~~20~~ near here]

We apply these elements of severe drought to the situation in which the State supports the maintenance activities as described in scenario 1.2.

As shown by the F~~f~~igures 15~~21~~ and 16~~22~~, although at the beginning the captions decrease thanks to the joint investments of the agency and the State, two years of severe drought appear to be too exhausting for the system, leading to collapse already at the end of the second year, with no possibility of recovery in the following years.

[Figure 15~~21~~ near here]

[Figure 16~~22~~ near here]

Scenario 2.2

In this last scenario, we considered the same stress situation of scenario 2.1, but including the price monitoring feedback cycle described in scenario 1.3.

Figures 17~~23~~ and 18 ~~24~~ show the results related to the monthly collection and the consequent evolution of the lake level.

[Figure 17~~23~~ near here]

[Figure 18~~24~~ near here]

As can be seen by graphs, two consecutive years of drought are too much oppressive for Lake's water balance, in fact, even if the Agency try to contrast the extreme situation with adaptive price strategy and maintenance of infrastructure, the severity of drought ~~unavoidably~~ brings inevitably the system to collapse during the summer months.

The only way to avoid permanent damage for the balance of the ecosystem seems to stop the withdrawals until the climatic conditions ~~are~~ become favourable again.

Figure 19~~25~~ and 20~~6~~ show, in aggregate form, the scenarios explained in this section, which are divided based on the hypothesis on climatic condition: scenarios 1.1, 1.2 and 1.3 are relative to one-year of drought; scenarios 2.1 and 2.2 are relative to two-years of drought.

[Figure 19~~25~~ near here]

[Figure 20~~6~~ near here]

We also simulated for additional 5 years each scenario. It is interesting to note that results from scenario 2.2 indicate that the level returns permanently over the threshold of 160 m starting from the 8th year (i.e. 2027). Anyway 8 years may be a long time for recovery and the lake probably cannot get over it, but we think that this "catastrophic" scenario deserves a separate complex study, which would consider also the flora and fauna system in details. Maybe, this leaves room for another paper in the future.

Finally, the following Table 3 summarizes the main results of the different scenarios.

[Table 3 near here]

Discussion

The model presented in this study captures the main dynamics observed in the recent water crisis occurred on 2017 in the city of Rome, with severe consequences on water balance of one of its basins, Lake Bracciano. The episode revealed an underlying vulnerability of basin that could lead to emergency situations if the extreme climatic conditions, due to climate change, will become more ~~accentuated~~ severe over time.

The results of the simulations suggest that the first level of sustainability of the water supply of the region depends, besides climatic conditions, on how the water agency responds to ~~the~~ potential crisis, on how it succeeds in ~~balancing~~ developing new ~~the~~ policies that ~~act~~ may influence ~~on~~ the supply and demand of water. The model showed that implementing a simple control feedback which acts on water charge makes the withdrawals less copious. So, the benefit on long term is worthwhile, because Lake may ~~satisfy~~ fulfill the need of the population it serves, without risks for the ecosystem.

Also, it is precisely in these kinds of situations that the Agency should intervene to increase (and maintain) the efficiency of the infrastructure, reducing losses and improving service. Given that the total loss in the Rome's distribution network can be estimated at around 6.5 m^3/s, this amount of waste of resource should be avoided, at least mitigated, especially during ~~situations~~ conditions of water scarcity. The model showed that making the water more expensive has benefits also on the availability of resources for investments, that may be allocated for the improvement and maintenance of infrastructure, which is critical for ~~the~~ dimensioning the~~of~~ withdrawals.

Unfortunately, the model lacks in some specific data. It does not consider unregulated withdrawals performed by the citizens of surrounding areas of the Lake. This type of water extraction is very variable and ~~difficult~~ hard to quantify because it is not tracked~~. It is nevertheless important because~~ , but it may ~~further~~ lower the Lake's level values even further compared to the ~~ones~~ results emerged from the simulations ~~performed~~ showed in this paper.~~.~~

Another limit is represented by the exclusion of water sewage system, that could deeply affect the general health condition of the Lake. In fact, when the level of water is high the consequences of inefficient water sewage system are slight, but the combination of an inefficient water sewage and low water level could heavily worsen ~~heavily~~ the basin's health condition, undermining the ecosystem.

Furthermore, the model does not consider the fluctuations due to seasonality of demand. In fact, during the summer the water usage is higher compared to colder seasons.

The strength of the model presented in this paper is twofold:

First, it could be an easy-to-use tool for administration and Agency to build, experiment and evaluate different strategies and policies. Such a tool could on the one hand ~~could~~ safeguard the environment, preventing irreparable damages to the delicate ecosystem of Lake and~~,~~ ~~that may lead to~~guaranteeing harmless ~~the impossibility of further~~ water extractions~~ of water~~ in the future; on the other hand, it allows to quantify the right amount of withdrawals to meet the consumers' demand, considering the average consumption per capita and the water losses due to obsolescence of infrastructures and avoiding waste.

The second important strong point of this type of model is that it can be easily replicated in other geographical areas and contexts. The scalability is a real added value for this topic, because at national level the issue regarding water scarcity and drought is increasingly frequent and severe in terms of environmental impact and water availability among population; the climate change makes more complex the challenge for the coexistence of these two aspects (environment protection and population needs) and the only way for making it happens is to ~~create~~ develop new management tools, ~~that could~~

~~manage the increasing complexity,~~ helping the policy-makers to plan and implement effective strategies for a more sustainable world.

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Water resource management through systemic approach: the case of Lake Bracciano

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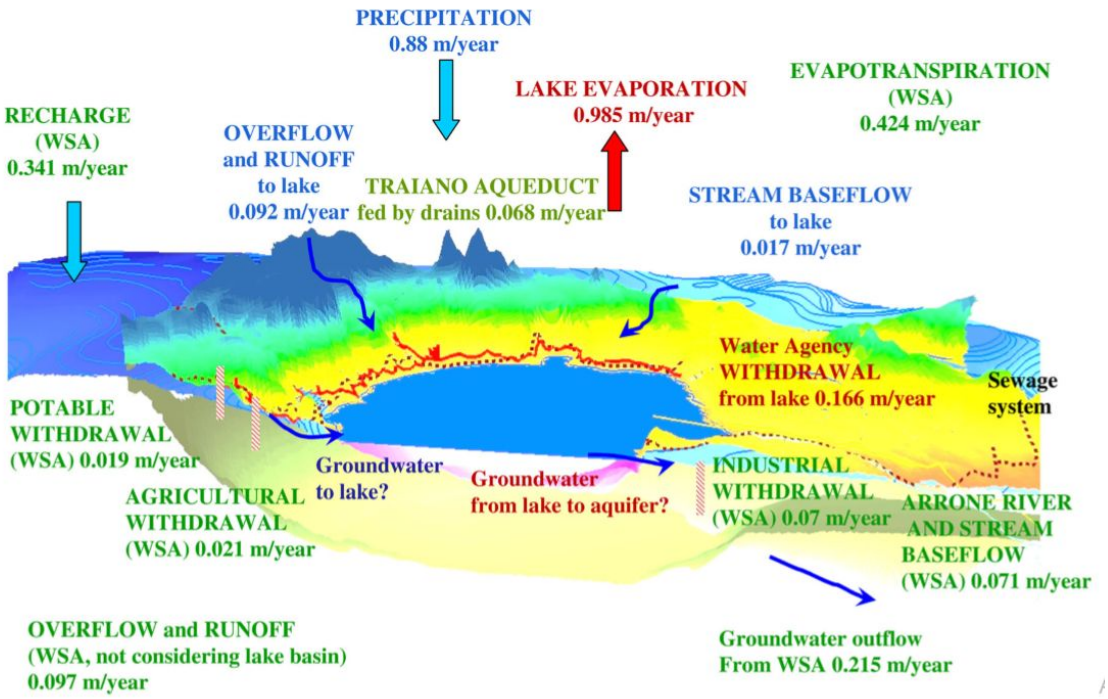
Paper's figures list



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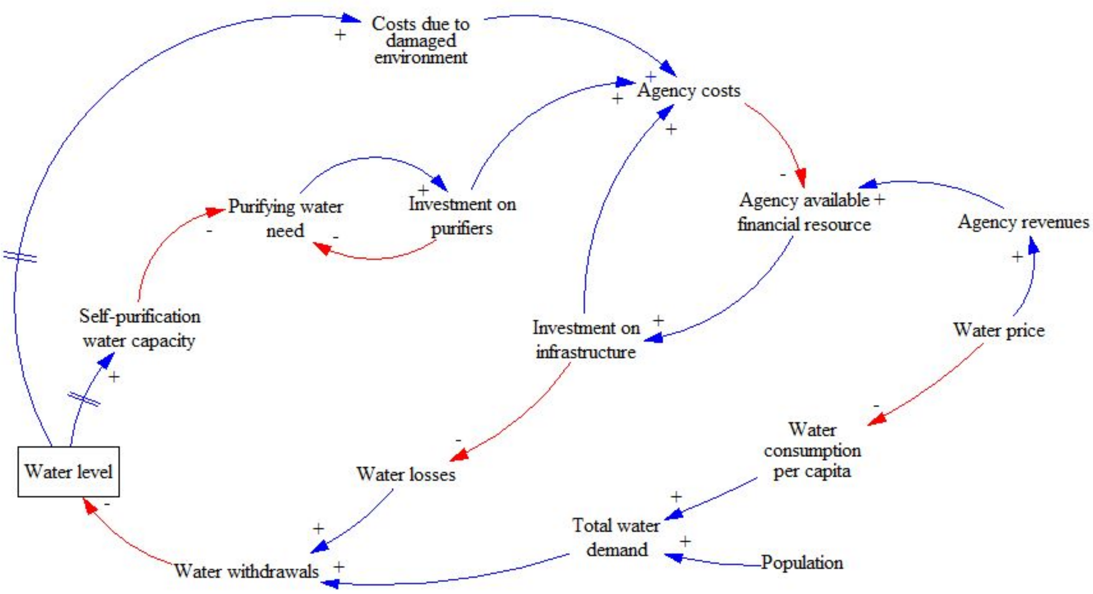

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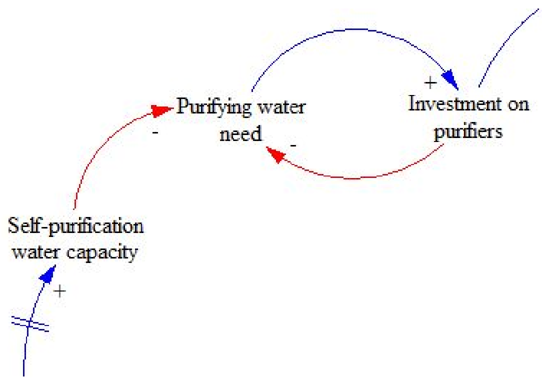

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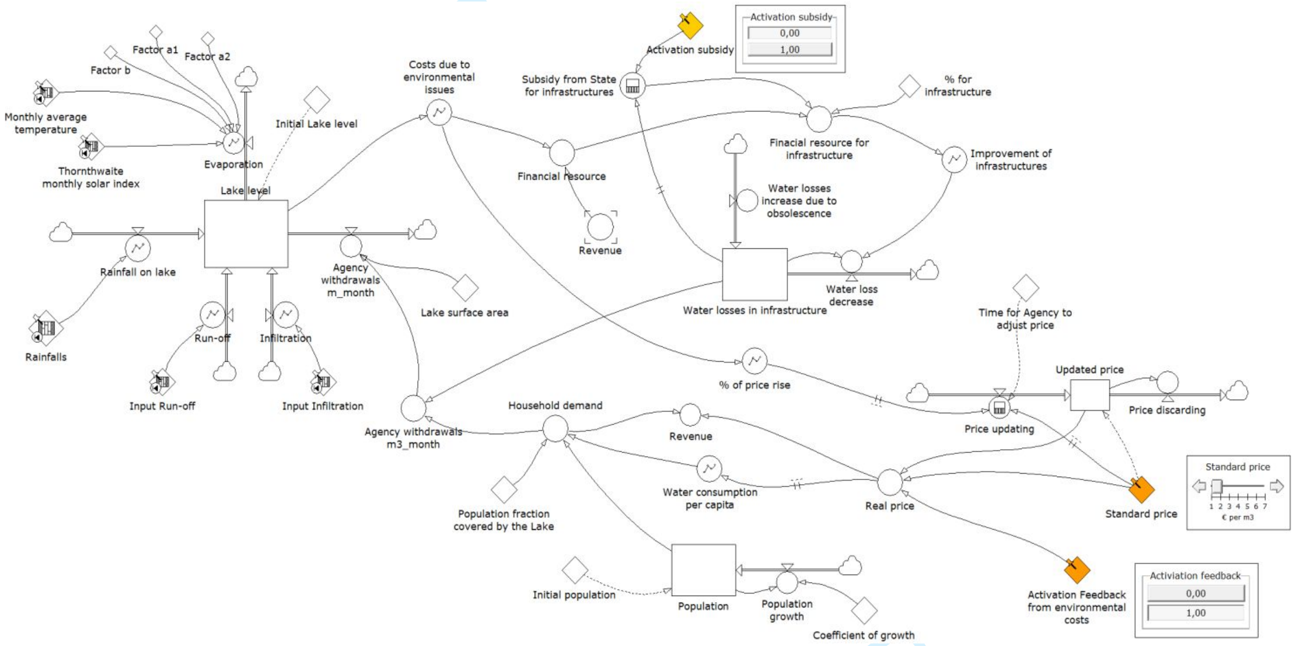

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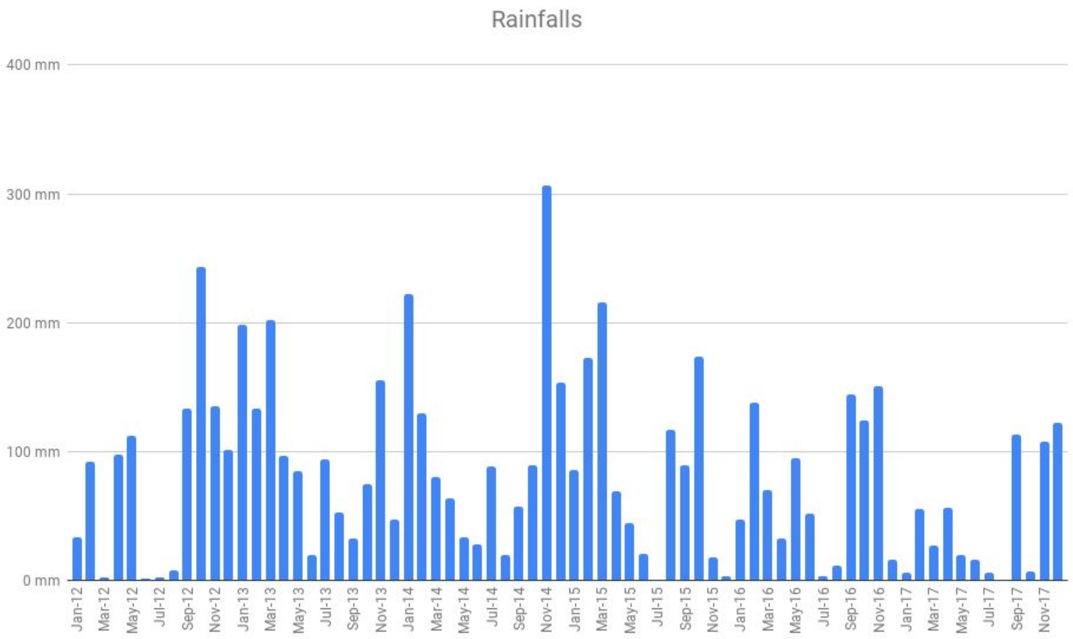

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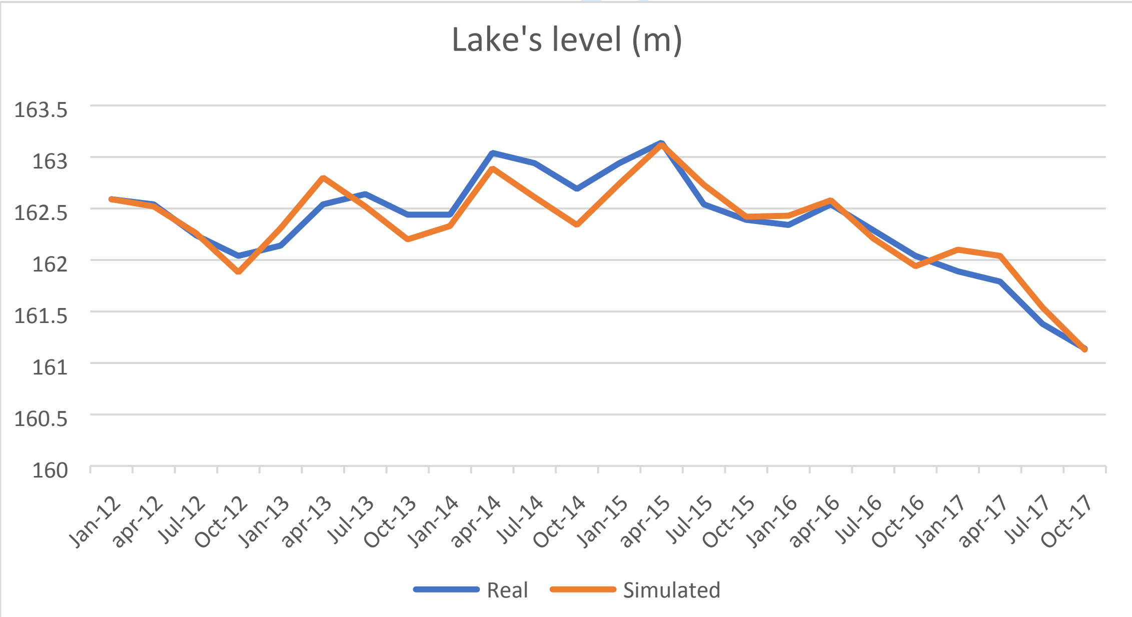

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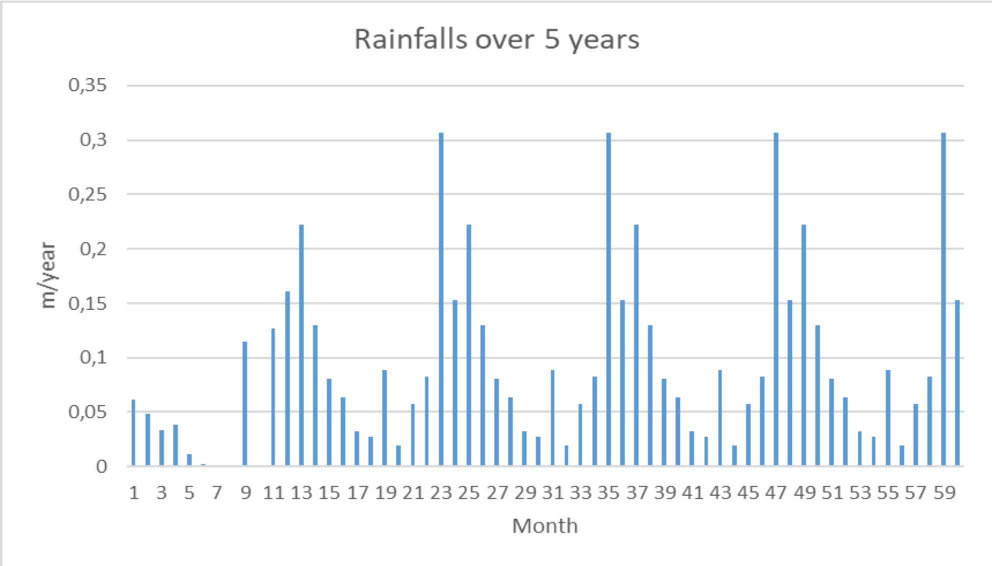

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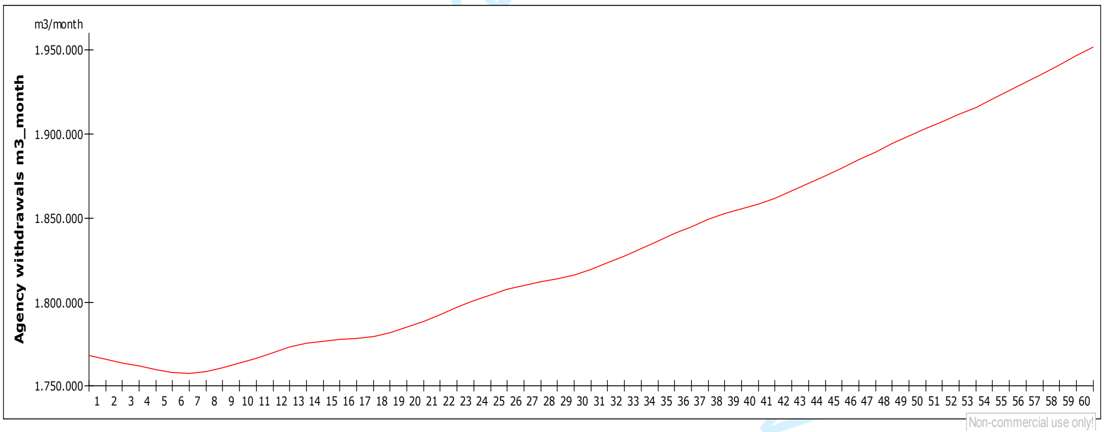

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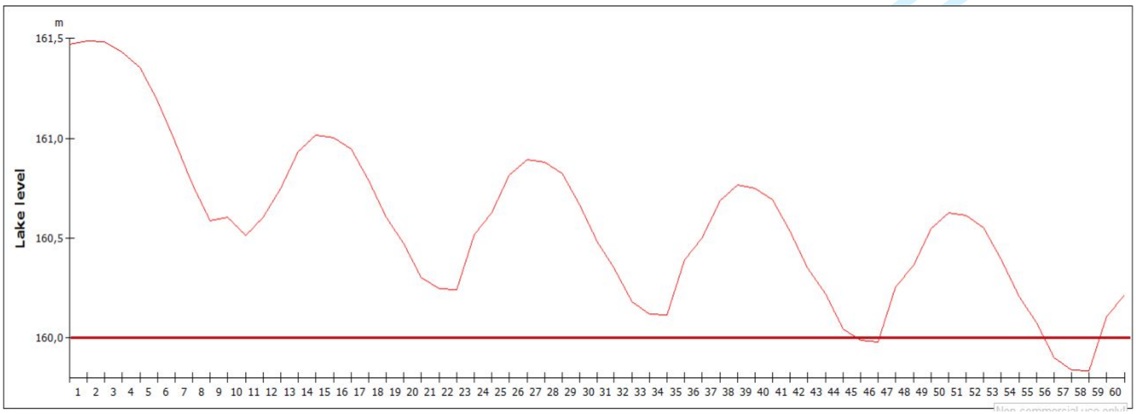

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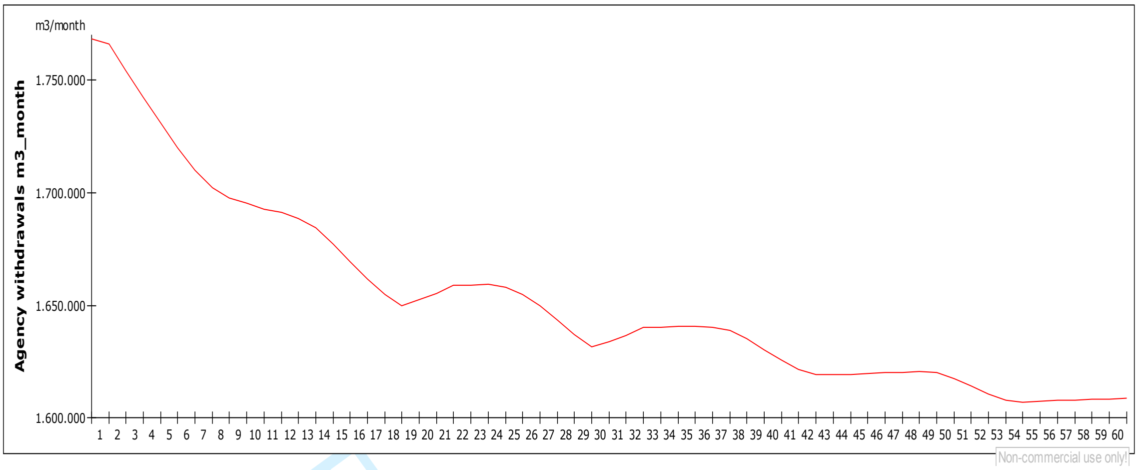

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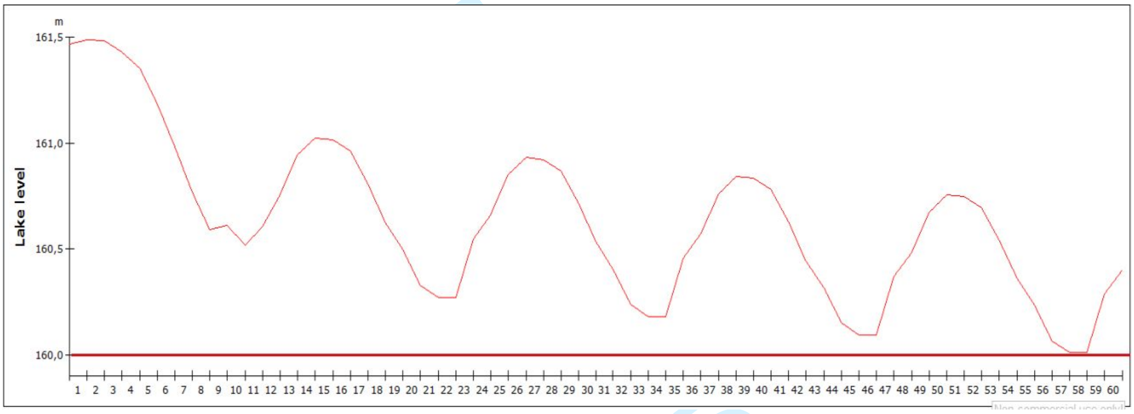

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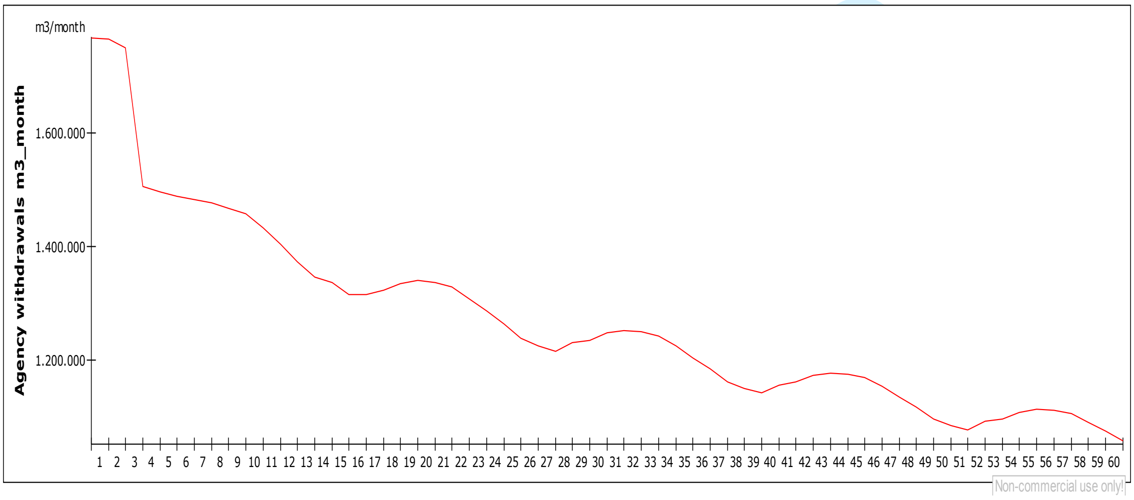

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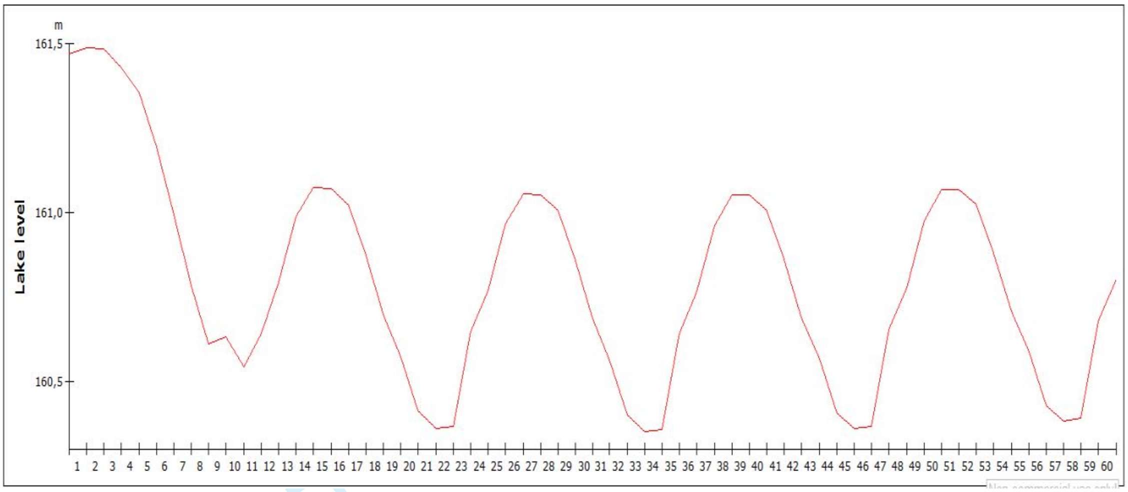

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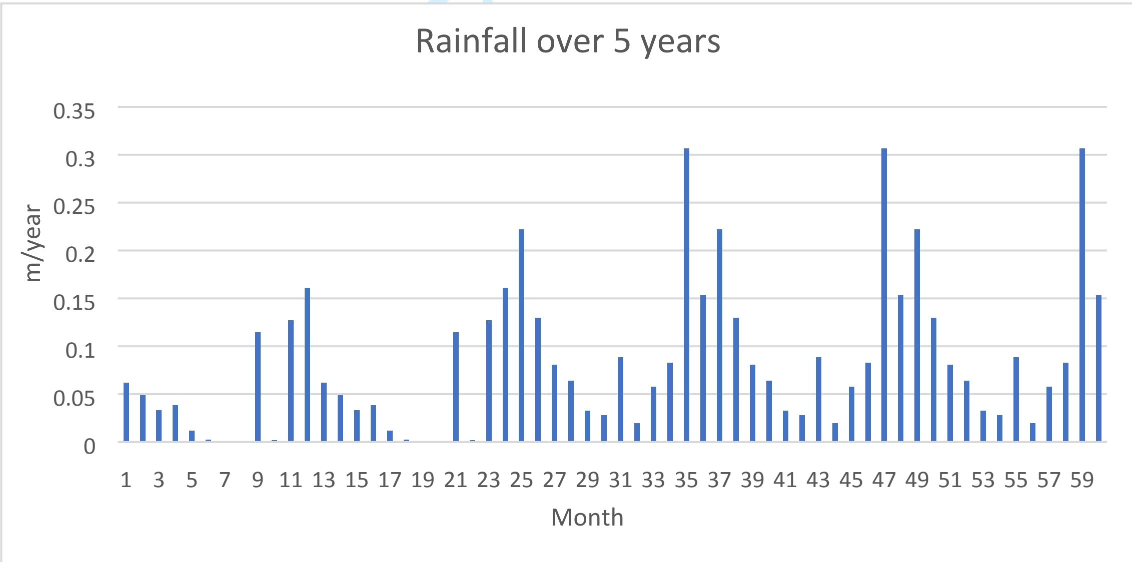

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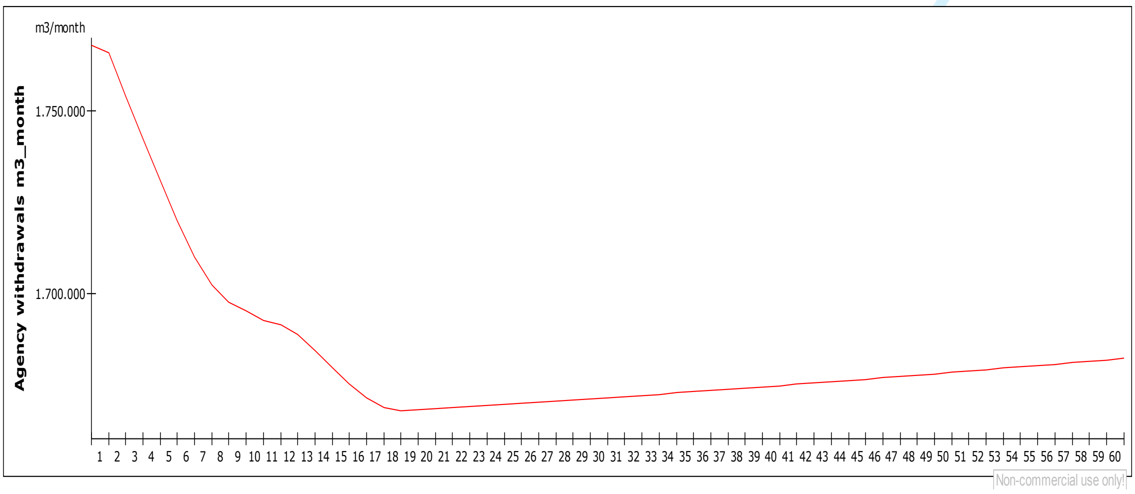

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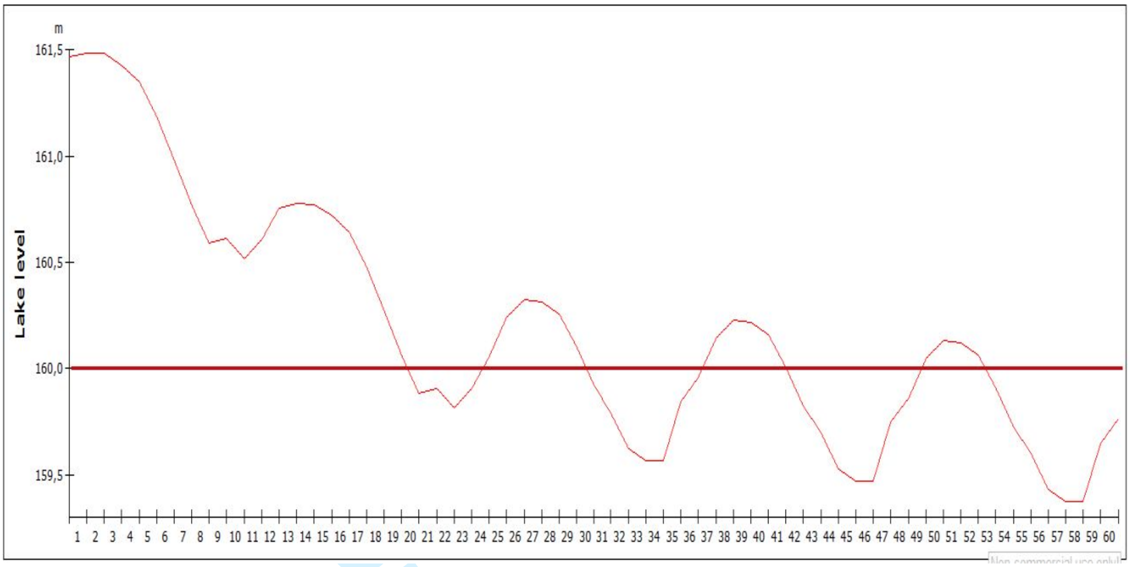

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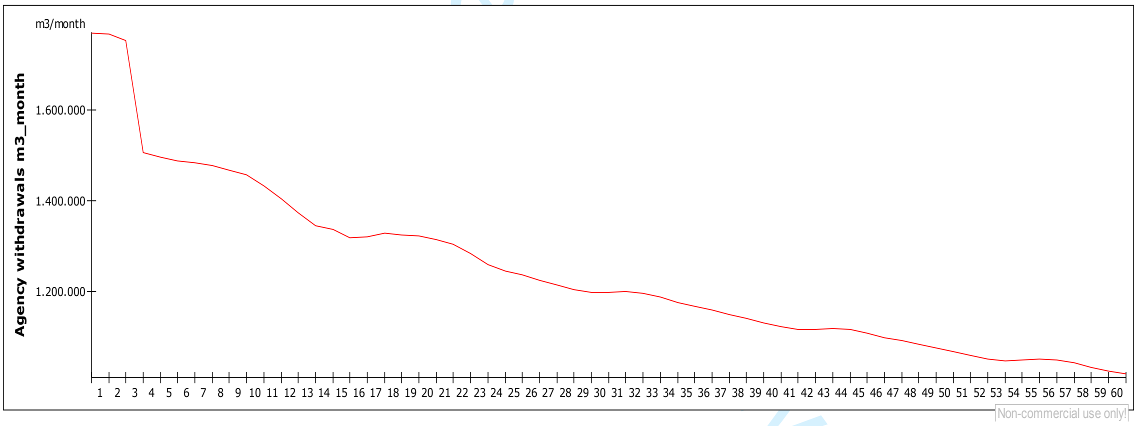

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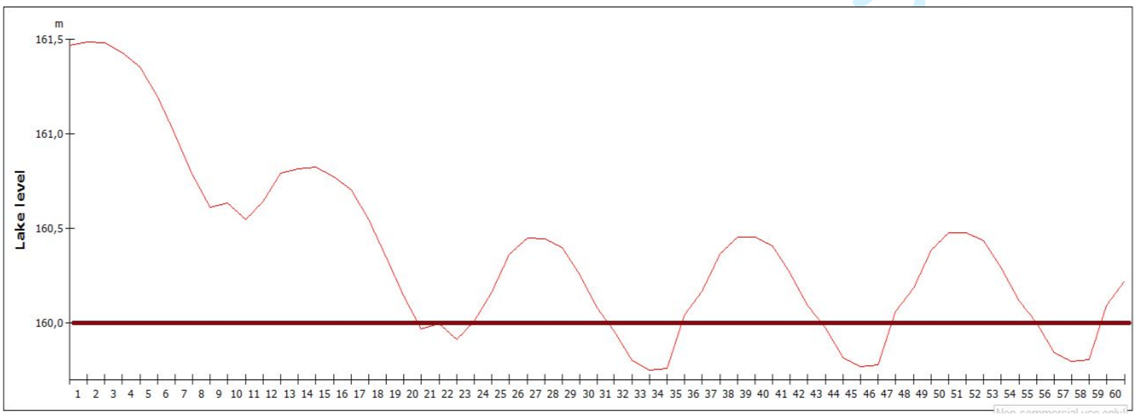

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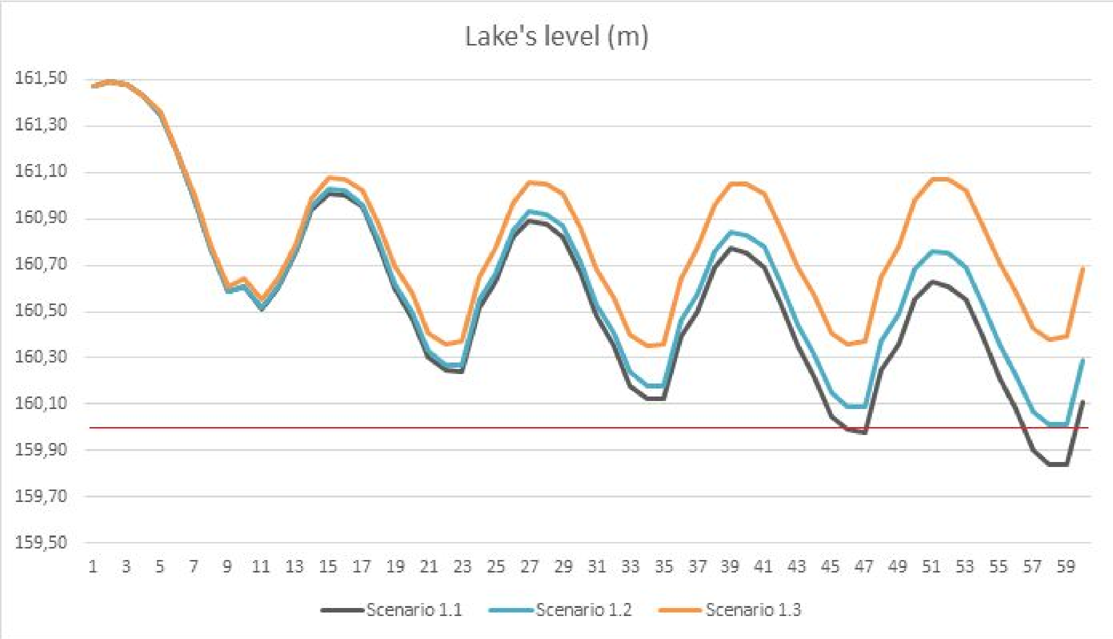

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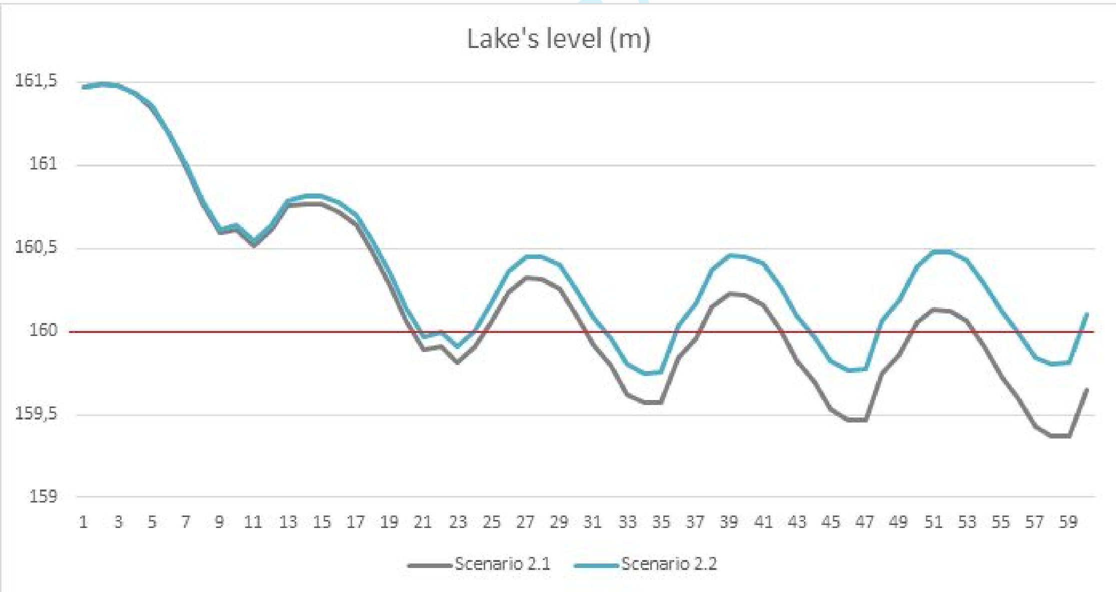

Figure 20

Water resource management through systemic approach: the case of Lake Bracciano

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Paper's tables list

Table 1

Location	32 km northwest of Rome
Surface area	57.58 km^2
Circular perimeter	31.981 km
Elevation (hydrometric zero of the lake)	163.04 m a.s.l.
Max depth	165 m
Total volume	5.13 × 109 m^3
Shoreline Development ratio	1.2

Table 2

Author/s	**Year**	**Main topic**	**Brief description**
Guo, H. C., Liu, L., Huang, G. H., Fuller, G. A., Zou, R., & Yin, Y. Y.	2001	Pollution	Proposed a model for one major water system in China, emphasizing the aspect of pollution for water supply effectiveness.
Simonovic, S. P.	2002	Pollution	Tried to envisage future trends of water supply in the world, identifying water pollution as one of the main problems.

Xu, Z. X., Takeuchi, K., Ishidaira, H., & Zhang, X. W.	2002	Sustainability	Evaluated the sustainability of the Yellow River basin in China, which was under pressure due to high demand by population as well as agriculture and industry.
Sánchez-Román, R. M., Folegatti, M. V., & Orellana-González, A. M.	2009	Sustainability	Described scenarios for the Piracicaba-Capivari-Jundiaí basin, in Brazil, predicting the deterioration of its sustainability.
Santos, J. R. D., Franco, E. F., Carvalho, H. C., Armenia, S., Pompei, A., & Medaglia, C. M.	2018	Sustainability	Analyzed the impacts that different intervention policies to addresses the water supply crisis experienced by the metropolitan region of São Paulo during 2013 to 2015 and evaluate how resilient the water supply system is.
Rehan, R., Knight, M. A., Haas, C. T., & Unger, A. J. A.	2011	Infrastructure	Argued in favor of proactively rehabilitating the physical infrastructure, which allows the system to achieve financial sustainability and withdrawals optimization.
Kotir, J. H., Smith, C., Brown, G., Marshall, N., & Johnstone, R.	2016	Infrastructure	Assessed through SD possible evolutions of the Volta River Basin in Ghana. the model results suggested to invest in water infrastructure, building large and small-scale reservoirs, and provide the agricultural activities with an appropriate infrastructure.
Stave, K. A.	2003	Aligning stakeholders' interests	Developed a model to clarify the problem of water scarcity in Las Vegas (USA), in which she illustrated how system dynamics modeling represents a very powerful tool for allowing people to align their mental models along a shared reasonable one.
Winz, I., Brierley, G., & Trowsdale, S.	2009	Aligning stakeholders' interests	Emphasized the advantages of using System Dynamics and participatory procedures to address the complex problem of water management.
Beall, A., Fiedler, F., Boll, J., & Cosens, B.	2011	Aligning stakeholders' interests	Described a participatory modeling process that proved to change perceptions of key social actors in the Palouse Basin (USA) regarding the sustainability of that water system, in particular in a business-as-usual scenario.

Table 3

		Year in which level reaches 160 m	Trend beyond 5 years of simulation
One-year drought	No specific policies	Beginning of last quarter of 2021	Lake's level decreasing – no recovery
	Water infrastructure improvement	Beginning of last quarter of 2022	Lake's level decreasing – no recovery
	Price strategy	Never	Almost stationary
Two-year drought	Water infrastructure improvement	Beginning of last quarter of 2020	Lake's level decreasing – no recovery
	Price strategy	Beginning of last quarter of 2020	Lake's level stops decreasing – potential recovery from 2027