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Water reservoir engineering and management

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ABSTRACT

This work aims to develop a practical system to store water in times of abundance and reuse it in times of scarcity. The proposed system uses natural caves, caverns, or empty underground spaces from mining or oil or gas extraction to store water. The geological structure of the water reservoir should be a non-porous substrate to avoid leakage. Water collection comes from dam discharge during thaw times or river flooding, raising the basins or reservoirs level above their capacity limit. The system engineering requires water pipes to the storage location, which reduces the system viability to the nearby area where natural caverns or empty underground spaces exist; nevertheless, the pipeline network can cover long distances if necessary using abandoned pipelines or building new ones parallel to the existing network. The collected water is recovered by pumping and distributed to water-scarce areas through the pipeline network. The simulation shows that the process is feasible and reliable regarding water supply. The system is scalable to small underground spaces or artificial containers. The simulation provides the underground reservoir autonomy as a function of engineering design parameters, fluid characteristics, environmental conditions, and human water demand. The simulation concludes that the underground reservoir has an autonomy of 1 to 37 days depending on rainfall average rate, human water and energy demand, and population.

Keywords: Water reservoir. Water management. Pipeline engineering.

INTRODUCTION

Water shortage represents a severe problem today in many areas around the world [1]. This problem does not derive from water scarcity but from time and geographical irregular distribution [2]. Indeed, the water mass on the planet remains constant, but it is irregularly distributed [3]; therefore, while specific zones suffer from drought, others are submitted to regular flooding [4-5].

The advent of increasingly intense climate change that affects practically the entire planet has altered the water cycle, generating natural disasters, like flooding or drought, at regular intervals [6-7]. The most relevant consequence is the water shortage affecting agriculture and human and other species' lives [8-9]. Recent reports from FAO and OMS reveal that one-third of the world population does not have access to water, while another third uses polluted water for drinking and culture [10].

Water shortage provokes the desertification of large areas on the planet. On the other hand, human action removing the vegetal substrate generates flooding when raining due to the lack of soil water capacity retention [11]. Permanent and appropriate soil hydration avoids eutrophication and promotes agriculture and human settlements. The terrain desertification is responsible for people migration, increasing population density in migratory confluence zones, and creating a higher water demand with the subsequent water scarcity problem [12-13].

In global terms, there is no easy solution for water scarcity, either in time or geography distribution; nevertheless, some practical measurements may partially solve the consequences of a permanent drought or periodical flooding [14]. If the water shortage is a time problem, the simplest solution is storing water in periods of abundance and using the stored water when drought occurs. If water scarcity derives from irregular geographical distribution, it is necessary to transport as much water as needed, using new or existing infrastructure, like pipelines, hydraulic ducts or similar [15].

Water is easy to manage and transport; it is clean and does not contaminate the environment in case of spillage. Besides, transporting water does not require specific security measurements since it does not explode, ignite, or generate toxic emissions; however, due to its high density and compressibility, transported flow is heavy and requires a solid duct structure to stand for.

In heavy rainy periods, some areas cannot absorb all falling water, draining the excess to rivers and lakes. If a damp interrupts the river flow, the continuous water supply increases pressure on the dam until it reaches the breaking point. Before that, the operator opens the spillway gate to release pressure.

Water from the spillway gate currently runs to the river and flows until reaching the ocean or another dam, and may not contribute to raindrops in this area. However, if we canalize water to an underground storage system, it may be recovered afterward and be used for human needs, agriculture, and animal watering. This configuration avoids flooding upstream and downstream of the dam for good river basin design.

Store water may be canalized to regions suffering from drought if the appropriate pipeline infrastructure is built like in the case of carbon dioxide or biomass [16-18]. Although is some regions of the planet this may represent a titanic challenge, thus, not feasible and economically reliable, in some others, the existing infrastructure favors water transportation instead of rejecting or dismantle the pipeline [19].

Coexistence of geological appropriate terrain for water storage and dam facilities does not always happen; in that case, two solutions arise, carrying water from dam facility to a nearby region where natural or artificial underground empty space exists, or vice versa, bring the water discharged from a surrounding dam to the area where the geological cavity suitable for water storage is located [20,21].

In this work, we design and analyze the characteristics of an underground water storage system based on collected water flow from dam discharge. The study represents a novelty in the field of water resource management. Although the idea is not new

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because it was mentioned in the past as a solution for solving water scarcity, no scientific or technical studies have been made, and the feasibility has not been simulated until now.

ENGINEERING DESIGN AND OPERATION

The proposed system has two configurations: an underground reservoir (Figure 1) and an underground river (Figure 2). The first configuration consists of a water dam, a pipeline, and an underground reservoir; the second configuration replaces the underground reservoir with an underground river and the pipeline by a duct. The pipeline in the first configuration and the duct in the second one travel across a variable orography terrain with alternating flat, uphill, and downhill segments.

Both configurations operate on the same basis, storing the discharge water in an underground reservoir or underground river. The water discharge, which corresponds to the excess in the water reservoir, is canalized through the spillway gate to a pipeline or a duct and carried to the underground reservoir or the underground river. A pumping system guarantees the water flow and recovery when a water shortage occurs.

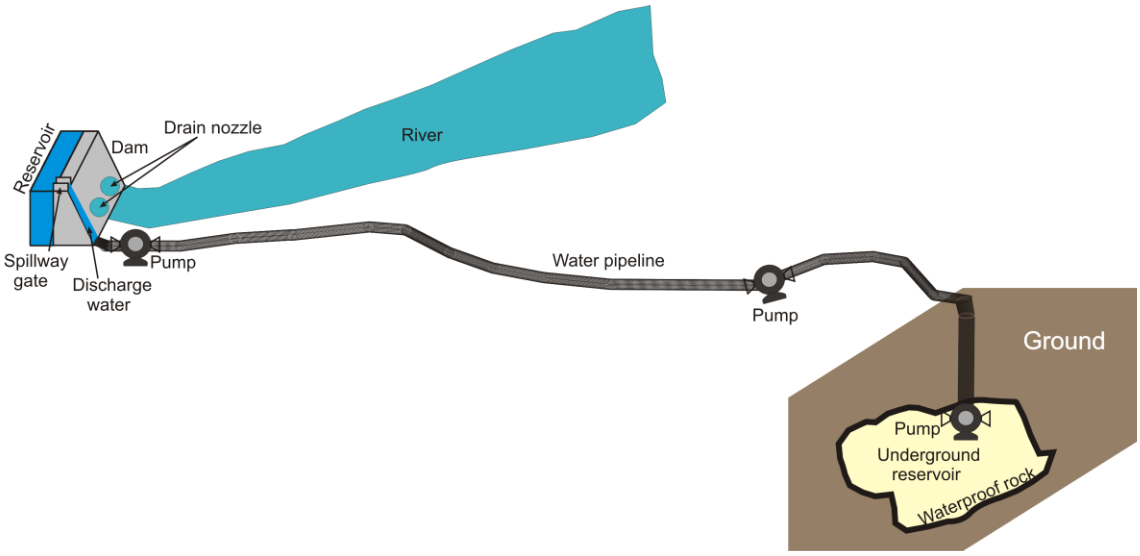

Figure 1 Schematic view of the underground reservoir configuration

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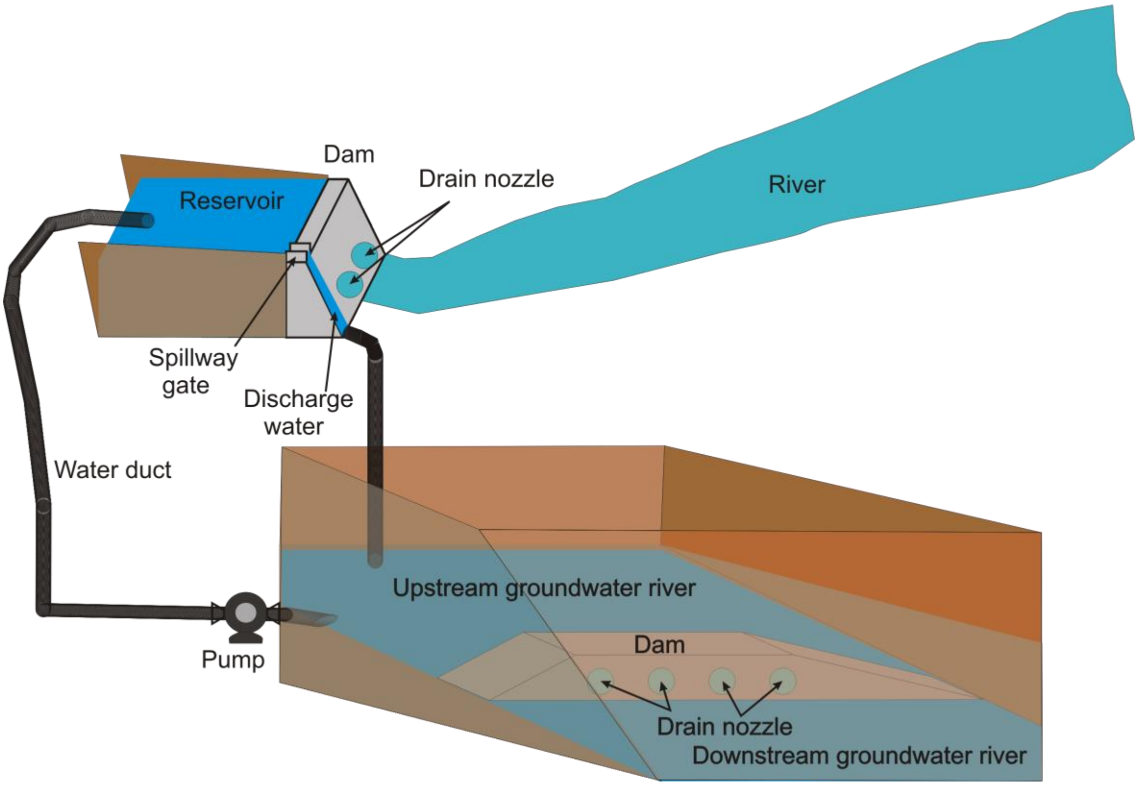

Figure 2 Schematic view of the underground river configuration

The underground river configuration requires the building of an underground dam to retain water for storage. This process is engineering feasible although complex and expensive.

Available water for discharge depends on the water dam balance, which is the difference between water inflow and outflow; the water inflow comes from the rivers' flow and runoff from the river basin that feeds the reservoir. The water output corresponds to the ecological flow and the water for the hydroelectric plant turbines if the dam had this type of plant.

THEORETICAL APPROACH

The water inflow is a function of the zone rainfall, whose value changes according to the period of the year. The estimation of the mean precipitation can be obtained from deterministic and stochastic weighting methods [22]; considering the terrain water absorption, the net water contribution from rainfall is expressed by:

$$\dot{V}_w = f\,\dot{V}_{rf} \qquad (1)$$

f represents the terrain absorption factor, which is the fraction of rainfall, $\dot{V}_{rf}$, absorbed by the ground, and S is the river basin surface.

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The ecological water flow depends on the human population and people activities like agriculture, industry, cattle raising, and similar; mathematically:

$$\dot{V}_{eco} = w_{hr} N \tag{2}$$

N is the inhabitants number and w_{hr} is the human rate water consumption.

The water for electric generation at the hydroelectric power plant is given by:

$$\dot{V}_{el} = \frac{P_t}{\gamma H} \tag{3}$$

P_t is the generated power, Υ is the water specific weight, and H is the hydraulic height.

Therefore, the net available water for discharge is:

$$\dot{V}_w^{net} = f\,\dot{V}_{rf} - w_{hr} N - \frac{P_t}{\gamma H} \tag{4}$$

Considering there is no leakage during transportation, the water storage to human needs ratio is defined as:

$$R_w = \frac{\dot{V}_w^{net}}{w_{hr} N} = \frac{f\,\dot{V}_{rf}}{w_{hr} N} - \frac{P_t}{\gamma H w_{hr} N} - 1 \tag{5}$$

Equation 5 gives a practical way of determining the autonomy of the underground water reservoir if human consumption rate remains constant. If water and energy human demand changes with time, equation 5 should transform into:

$$R_w = \frac{f}{N} \sum_{i=1}^{n} \left(\frac{\dot{V}_{rf}}{w_{hr}} \right)_i - \frac{1}{\gamma H N} \sum_{i=1}^{n} \left(\frac{P_t}{w_{hr}} \right)_i - 1 \tag{6}$$

n represents the underground water reservoir autonomy in days. We consider the human population does not change.

The analysis of the underground water reservoir autonomy evolution is complex since it depends on three independent variables, rainfall, water human demand, and power requirements. The last two variables may be connected in some way, but many times they evolve independently; therefore, we should analyze the underground water reservoir autonomy as follows:

a) Constant rainfall rate and invariable power requirement

In this case, we observe that the underground water reservoir autonomy lowers as the daily water human needs increase. Nevertheless, the autonomy dependence on water demand is not linear since the second term in equation 6 decreases with water demand rising for constant power demand; therefore, because it is a negative term, the detraction lowers, and the ratio lowers too, but in a smaller amount.

b) Constant power requirement and water demand

The underground water reservoir autonomy increases with the rainfall rate, independent of the power requirement and water demand. In this case, the dependence of underground water reservoir autonomy with rainfall rate is linear as the second term in equation 6 only modifies the ordinate at the origin.

c) Constant water demand and rainfall rate

In this situation, the underground water reservoir autonomy lowers as power requirement increases. As in the previous case, the dependence of underground water reservoir autonomy with power requirements is linear since the first term is constant, thus only modifying the ordinate at the origin.

Three additional configurations arise from the analysis of underground water reservoir autonomy: constant rainfall rate, constant power requirements, and constant water demand. The analysis for these three configurations is even more complex due to the dependence on two independent variables.

d) Constant power requirement

If water demand and rainfall increase at the same rate, the underground water reservoir autonomy also increases since the first term in equation 6 remains constant while the second reduces. If both decrease, the underground water reservoir autonomy also decreases.

The underground water reservoir autonomy may increase or decrease if water demand rises quicker than the rainfall rate, depending on the power requirement value and on how much faster water demand rises regarding rainfall rate. For water demand and rainfall rate decrease, the underground water reservoir autonomy trend is the opposite.

e) Constant rainfall rate

The analysis of the underground water reservoir autonomy is similar to case d) by replacing power requirement by rainfall rate and reversing the autonomy trend with water demand dependence.

f) Constant water demand

The underground water reservoir autonomy depends on the evolution of rainfall rate and power requirement and their ratio to water demand; therefore, it is complicated to set up a specific trend if the involved parameters and their evolution are not known.

Analysis of the underground water reservoir power requirement

Water transportation from one place to another requires a pumping process to win the pipeline resistance. According to fluid mechanic principles, energy losses due to fluid transportation along a duct is expressed as:

$$h_L = f\,\frac{L_{eq}}{D_H}\frac{v^2}{2g} \tag{7}$$

f is the friction factor, or Darcy factor, L_{eq} is the equivalent duct length, D_H is the duct hydraulic diameter, and *v* is the fluid speed.

Applying continuity equation:

$$\dot{V}_w^{net} = \frac{\pi}{4}D_H^2 v \tag{8}$$

Combing equations 4, 7 and 8:

$$h_L = \frac{8\,fL_{eq}}{\pi^2 g}\frac{\left(f\,\dot{V}_{rf} - w_{hr}N - \frac{P_t}{\gamma H}\right)^2}{D_H{}^5} \tag{9}$$

From Bernoulli's equation, considering the water velocity is null at the dam and the underground water reservoir, the required power for underground water storage at z-depth, if no pressure change occurs, is:

$$P_t^p = \gamma\dot{V}\,h_L - \gamma z\dot{V} \tag{10}$$

Replacing h_L from equation 9 in equation 10:

$$P_t^p = \frac{8\,fL_{eq}\gamma\dot{V}}{\pi^2 g}\frac{\left(f\,\dot{V}_{rf} - w_{hr}N - \frac{P_t}{\gamma H}\right)^2}{D_H{}^5} - \gamma z\dot{V} \tag{11}$$

Equation 11 allows determining the power for storing water in an underground reservoir as a function of the fluid properties, river basin characteristics, and human water consumption.

SIMULATION

We simulate for specific given data to evaluate the performance of the proposed system. To this goal, we consider a river basin of 500 m wide and 20 km long for a total surface of 10 km^2. We obtain the new area for larger river basins by applying a scale factor.

Annual average rainfall in the world largely varies from heavy rainy areas to extremely dry or desert zones [23]. Since we promote a system for dry, heavy-dry, or dessert zones, we select a maximum annual rainfall of 800 mm, used as a reference value. The simulation runs for the 100 mm to 800 mm range in 100 mm step. We consider that the rainfall remains constant over the year.

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We use a friction factor of 0.02 since it corresponds to a standard duct mostly used in carrying water ducts [24]. Water density is 1000 kg/m^3. Since we consider the duct full of water, the hydraulic and geometric diameter match. We use a geometric diameter of 40” (1 m). The simulation runs for 100 m, 250 m and 500 m for the average depth for the underground water reservoir.

First simulation runs for the following conditions: 1 million people, 100 m depth underground water reservoir, and power generation rate: 20, 50 and 100 kW/person. Figure 3 shows the results from the simulation under above mentioned conditions.

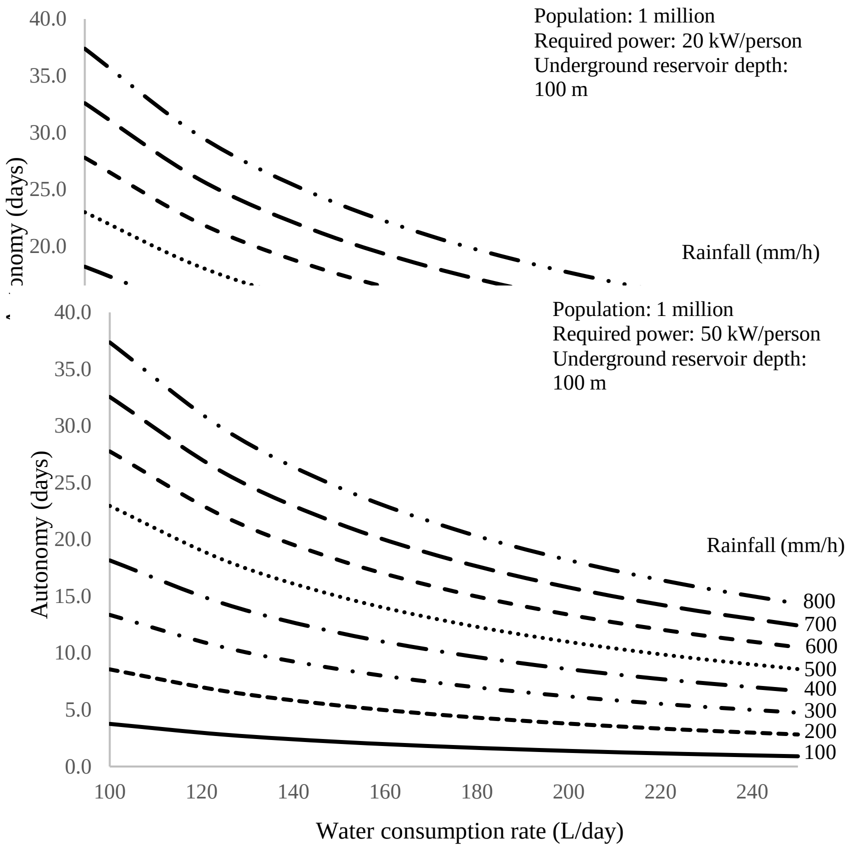
Comparing the three drawings, we realize that the underground water reservoir autonomy evolves in the same way regardless of the electrical power generated in the hydroelectric power plant, with little difference in autonomy values for the same rainfall rate.

The underground water reservoir autonomy evolution follows a potential fit no matter the rainfall rate according to the following expression:

$$R_w = a\left(w_{hr}\right)^b \tag{12}$$

The coefficients *a* and *b* follows a polynomial fitting curve of the type:

$$\begin{aligned} a &= 2x10^{-7}\left(w_{hr}\right)^4 - 4x10^{-4}\left(w_{hr}\right)^3 + 0.2857\left(w_{hr}\right)^2 - 84.983\left(w_{hr}\right) + 10843 \\ b &= 2x10^{-11}\left(w_{hr}\right)^4 + 3x10^{-8}\left(w_{hr}\right)^3 - 3x10^{-5}\left(w_{hr}\right)^2 + 0.0089\left(w_{hr}\right) - 2.1939 \end{aligned} \tag{13}$$



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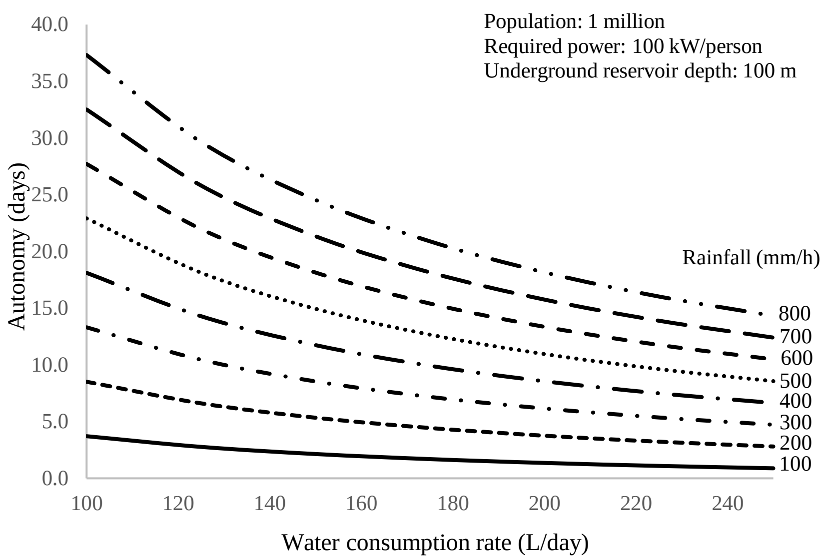

Figure 3 Underground water reservoir autonomy (simulated results)

Repeating the simulation for 250 m and 500 m underground water reservoir depth, the results shown in Figure 3 are almost identical within 99.5% accuracy.

Figure 3 shows that the minimum autonomy is 0.91 days, corresponding to a water consumption rate of 250 liters per day per person, and a rainfall of 100 mm. The maximum autonomy is slightly higher than 37 days for minimum water rate consumption of 100 liters per day and person and rainfall rate of 100 mm.

CONCLUSIONS

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This work studies and analyzes an underground water reservoir system as a solution for areas suffering from water scarcity, water supply shortage, or drought periods. The proposed system uses water discharge from dams to store water in natural or artificial waterproof underground reservoirs.

The water storage system requires hydraulic engineering consisting of a pipeline or duct from the bottom side of the dam spillway gate to the underground storage. The engineering design includes a pumping system to compensate for the mechanical losses and to extract water when necessary.

The simulation runs on the engineering design, resulting in the calculation of the underground reservoir autonomy as the relevant parameter of the system. The simulation determines the autonomy as a function of engineering design parameters, fluid characteristics, environmental conditions, and human water demand.

The system autonomy follows a potential function that depends on the water human consumption, including residential, commercial, industrial agricultural, and cattle raising needs. The simulated results show a 1 to 37-day autonomy range depending on rainfall average rate, human water and energy demand, and population.

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