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TECHNICAL ARTICLE

Improvements in Mero River Basin Water Supply Regulation Through Integration of a Mining Pit Lake as a Water Supply Source

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Abstract Seasonal increases in demand puts a strain on water supplies in the city of La Coruña (northwest Spain) and its surroundings during times of drought. Exploitation of Meirama Lake, a pit lake forming in a former lignite mine, could supplement the Abegondo-Cecebre reservoir, the city's main water supply. We analysed the hydrochemistry and the Mero River basin regulations to determine whether the water quantity and quality could meet the needs during periods of increased demand and drought, and still satisfy ecological conditions required by law. Our results indicated that joint use of the two reservoirs is feasible. The local administration is implementing the recommendations by building a tunnel to tap into the pit lake.

Keywords Beneficial use · Fluvial hydrodynamics · Solute transport · Water quality

Introduction

Water resource managers attempt to minimize conflicts among users, preserve the environment as much as possible, and satisfy all users at a minimum cost. Several European directives address mine restoration policies, with a goal of minimizing negative impacts and adding social and environmental value where possible (EC 2000, 2004, 2006, 2008, 2009; EPLWG 2004). In line with these directives, studies have been conducted to determine if pit lakes could be restored to provide environmental benefits (Brinker et al. 2011; Castendyk and Eary 2009; Hirji and Davis 2009; Nixdorf et al. 2005; Younger and Wolkersdorfer 2004). In this paper, we present a study on increasing a metropolitan area's water supply in northwestern Spain during times of drought by using water from a lake that is developing in an old mining pit, taking both water quality and water demand requirements into account.

Electronic supplementary material The online version of this article (doi:10.1007/s10230-015-0378-9) contains supplementary material, which is available to authorized users.

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Location

The area of study is located in Galicia, in northwest (NW) Spain (Fig. 1). The river basin's hydrographic demarcation is defined as the land and marine area made up of one or more neighbouring river basins together with the transitional waters, coastal waters, and groundwater basins (Galician-Coast 2011). The boundary separating the waters of the 'Galician Coast' and the waters of the 'North Demarcation (Miño)', runs from south to north along the Galician Dorsal. The Mero-Barcés River basin analysed in this study is the responsibility of Aguas de Galicia, the public institution in charge of the Galicia Coast Demarcation.

The average altitude of the area across the Mero-Barcés River basin varies from 40 to 200 m (Delgado et al. 2011; Padilla et al. 2007). The area of study is 246 km^2, consisting of the Barcés River basin (84 km^2), Mero River basin (120 km^2), and the headwaters of the Mero River basin (42 km^2).

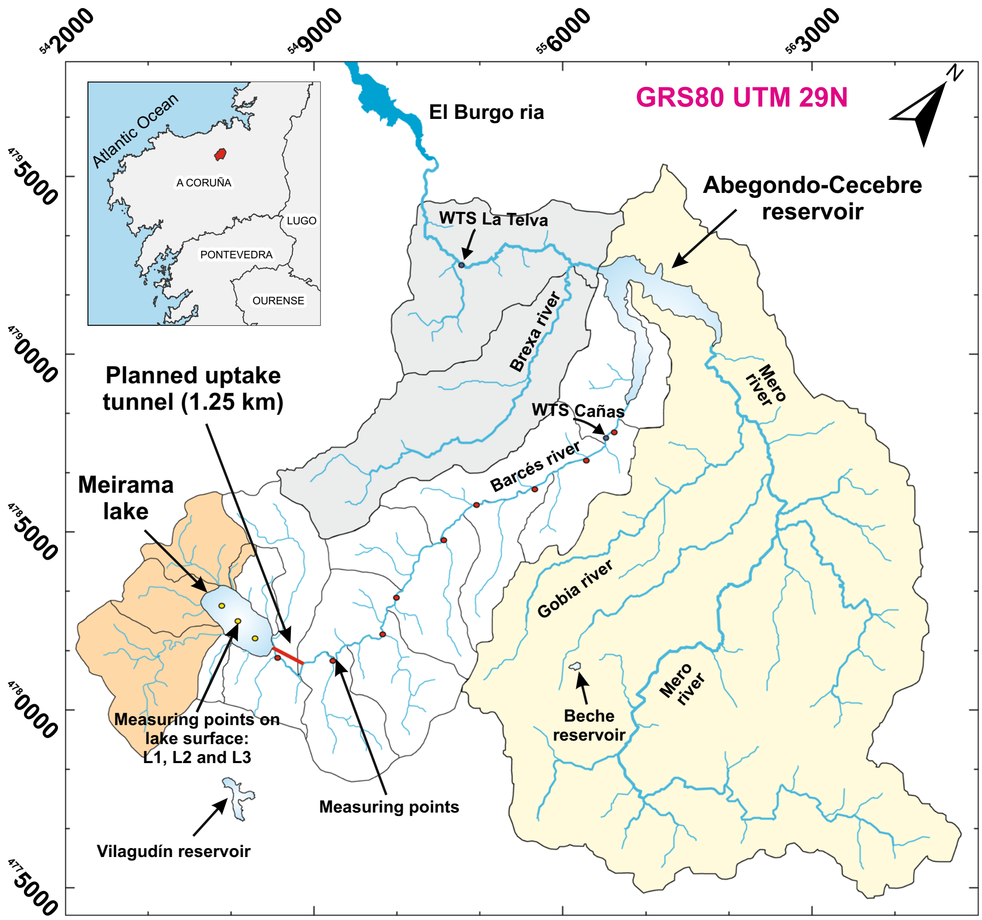

Fig. 1 Location of Mero-Barces basin

Stresses on the Water Supply

Water management must consider water sources, ecological flows, flood control, and variability in demand for urban, industrial, and agricultural needs. The water supply for the city of La Coruña (urban and industrial uses) comes from the Abegondo-Cecebre reservoir. The reservoir supplies the municipalities of La Coruña, Sada, Culleredo Bergondo, Oleiros, Arteixo, Cambre and Carral. The Barcés and Mero Rivers both feed into the Abegondo-Cecebre reservoir. At full capacity, the reservoir volume is 22,000,000 m^3 (20,610,000 m^3 of useful volume) with a maximum depth of 15 m and an average depth of 6 m. The Abegondo-Cecebre reservoir discharges at an average rate of 3149 L/s.

Water treatment stations (WTS) are located above and below the reservoir. Above the reservoir, in the Barcés River, is the 'Cañas' WTS, which partly satisfies the water supply for the village of Carral. Below the reservoir, the water flows down the Mero towards the 'La Telva' WTS (Fig. 1), which supplies La Coruña and surrounding municipalities.

Although the basin has a relatively high precipitation (1450 mm/year), droughts can occur when the rains stop for several consecutive months. This occurred in 2010 and triggered water restrictions, indicating that the reservoir was not large enough for drought conditions. In addition, the summer population is expected to grow. To assess future monthly demands on reservoir supplies, the urban evolution of the area supplied by the Cañas and La Telva WTS was predicted through 2023, taking into account its seasonal peak in population (Supplemental Fig. S1). The current population of La Coruña is about 245,000 and the wider metropolitan area is about 420,000. The area is expected to see seasonal summer increases in population, peaking in August at nearly 680,000 people. To assess the supply that would be needed to meet monthly demand (urban, industrial), the rate of water treatment at the WTSs was determined as 220 L/d/inhabitant. At the Cañas WTS, the water is treated at an average rate of 20 L/s to serve about 7800 inhabitants; by 2023, the average rate would need to increase to 53 L/s. The average rate at La Telva is currently 1124 L/s; by 2023, the La Telva WTS discharge would need to be 1323 L/s.

Table 1 Total population and mean monthly discharge expected at Cañas and La Telva WTSs in 2023

Month	$Discharge_{Cañas}$ 2013 (L/s)	$Discharge_{Cañas}$ 2023 (L/s)	$Discharge_{Telva}$ 2013 (L/s)	$Discharge_{Telva}$ 2023 (L/s)
October	18	43	1098	1100
November	19	43	1051	1150
December	18	43	1086	1103
January	17	43	1010	1090
February	16	45	1060	1120
March	15	53	1033	1160
April	16	52	1079	1200
May	16	53	1113	1400
June	28	61	1192	1550
July	29	75	1262	1650
August	25	66	1306	1770
September	22	53	1194	1580

Within the province of A Coruña, the population density is highest (6471 inhabitants per km^2) in the capitol city of the same name, distantly followed by the municipalities of Oleiros, Cambre, Sada, Culleredo Bergondo, and Arteixo with population densities closer to 200 inhabitants per km^2, according to A Coruña's General Plan of 2013. Seasonal populations vary and can stress the water supply during drought conditions. During summer, the population in coastal regions increases, as does the per-capita consumption, but water sources are at a minimum. Natural population (census) increases are projected to be low at about 0.26 %, taking into account trends in fertility, mortality, and migration ratios within the area. Therefore, the seasonal influx is likely to be more important than future growth (Table 1).

In addition to supplying water for urban and industrial demands, the Abegondo-Cecebre reservoir is used to regulate droughts and flooding (Hernández et al. 2012). Its operating policy requires that the reservoir should only be filled to 72 % of its total capacity (14,840,000 m^3) from November to March when floods are most likely to occur, to retain enough capacity to accept excess water. After March, management is focused on filling the reservoir as much as possible in order to meet the demands that occur in the summer. So if it does not rain for a period of seven consecutive months before summer, supply problems will occur.

Lastly, ecological flow (environmental flow rate) is required by Water Planning Regulations and is defined as the flow required to achieve a good ecological potential, so that fish life can be maintained in a natural way (HPI 2008; NHP 2005; PWR 1986). The distribution of minimum flows has been estimated from the time series of daily flows for the Mero River, and shows that the peak ecological needs are from November to April (Table 2). The same values were applied to the Barcés River for the most conservative approach in regulation analysis.

Table 2 Mean monthly values of the ecologic discharge for the Barcés and Mero rivers

Month	Q_{eco} (L/s)
October	200
November	300
December	400
January	400
February	500
March	400
April	300
May	240
June	200
July	200
August	170
September	200

In summary, the increasing seasonal demands and situations of drought, as recently happened in 2010, when it rained less than 1200 mm, will require that the capacity of the Abegondo-Cecebre reservoir be increased or supplemented with an alternative reservoir.

Meirama Lake

Meirama is an open pit mine located in the headwaters of the Barcés River watershed, where lignite was extracted for nearly 30 years (1980–2007). The pit void is about 146,000,000 m^3 with an area of 1.88 km^2. It has been filling since 2008 with water diverted from the Pereira and Porta Antiga rivers (Delgado et al. 2010, 2013; Juncosa et al. 2008) at an average rate of 18,250,000 m^3/y. About one-third of the 100 km^2 Barcés River watershed drains into the pit. When the water reaches the overflow elevation (171 m above sea level, or masl), the maximum depth will be 205 m; this should occur in May 2016. When full, the

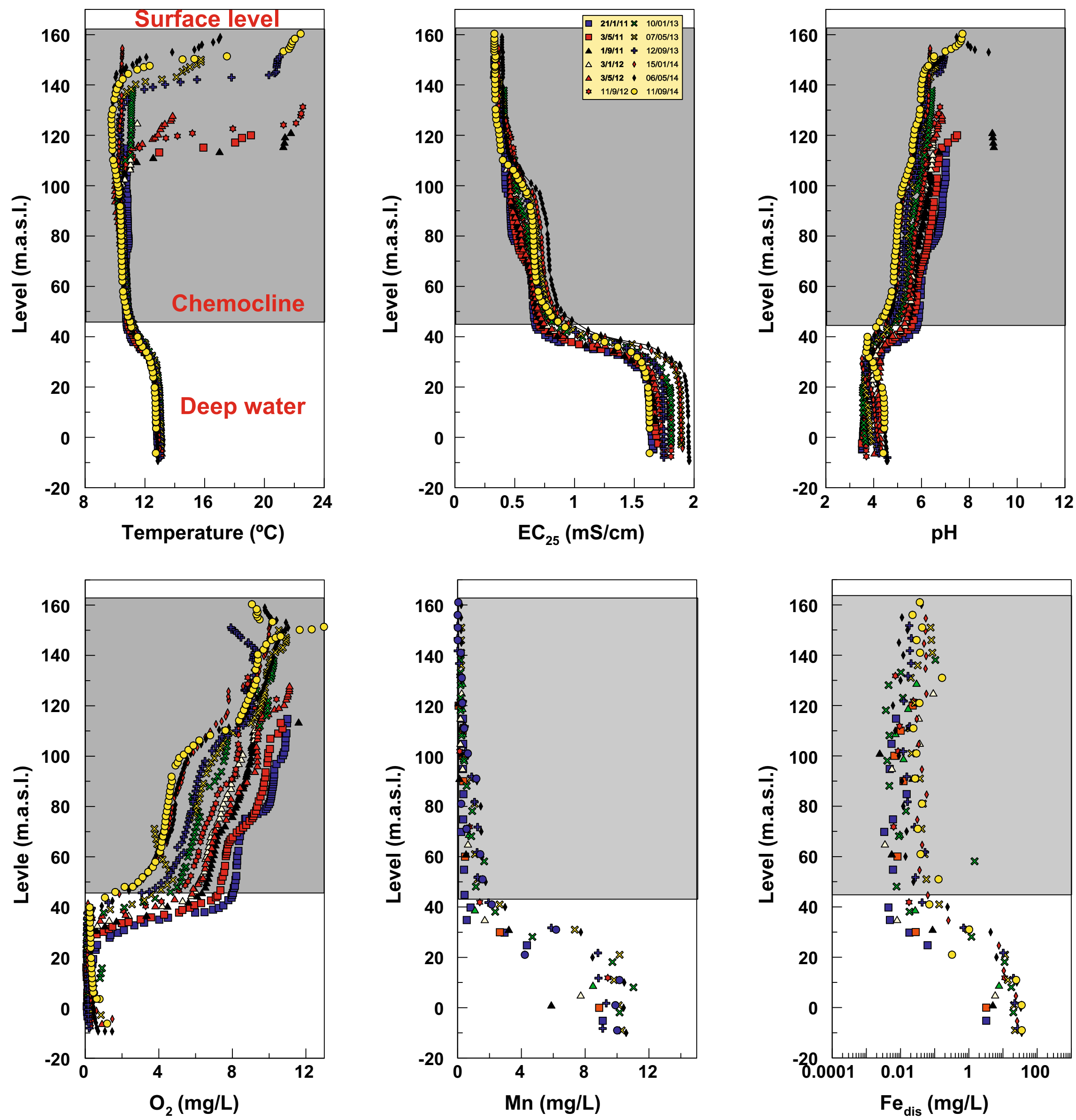

Fig. 2 Temperature, specific conductivity, pH, dissolved oxygen concentration, manganese, and dissolved iron in the middle of the lake (maximum depth) along the monitoring campaigns so far carried out. The *grey band* corresponds to the chemocline

pit lake will be larger than the Abegondo-Cecebre reservoir and could augment water supplies to municipalities downstream.

The lake stratifies during periods of higher temperatures (May through November) and is thermally homogenous in cold seasons (January through March). The thermocline develops at a depth of 25–45 m, depending on the year (Fig. 2).

Chemical stratification exists all year, although it shifts slightly seasonally. Higher concentrations and acidity levels occur at depths greater than about 125 m depth (25–40 masl) for all species and compounds. Vertical profiles of pH, dissolved oxygen (DO), temperature, specific conductivity, dissolved manganese, and dissolved iron are shown as examples (Delgado et al. 2014). The pH and DO decline while specific conductivity, dissolved Mn, and Fe increase, suggesting a shift in redox potential (Fig. 2). The chemocline has remained stable as the pit lake fills.

Water quality was measured in the upper 15 m of the pit lake, since that is the depth that water would be discharged by tunnel to the Barcés River if the pit lake were to be used as a supplemental water source. The volume of water in the upper 15 m is 24,000,000 m^3, slightly more than the 22,000,000 m^3 of the Abegondo-Cecebre reservoir when full. In addition to the parameters shown in Fig. 2, analysis was conducted for dissolved Al, total Fe, dissolved trace elements (As, Se, Cr, Ni, Cd, Pb, Zn, Hg), sulfate, sulfide, ammonia, total nitrogen, total phosphorous, and TSS (Supplemental Table S1). The mean values were all within regulatory limits, perhaps due to the influence of and buffering by the Pereira River, which provides most of the water filling the pit void. However, Fe, Mn, and Ni approach regulatory limits seasonally in winter (Supplemental Fig. S2); therefore, our study focused on these species.

Methods

The Meirama pit sits at the headwaters of the Barcés River. Once the lake fills, it will overflow into and be diluted by the Barcés River before entering the Cañas WTS and the Abegondo-Cecebre reservoir 16 km away. Although it was clear that it will have enough volume to serve as a supplemental water source, more needed to be understood about its recharge and changing water quality, before it enters the Barcés River and how it will change with mixing.

Modeling the Hydrologic Inputs

A joint hydrodynamic model for surface and groundwater flow was developed with the MELEF code (Padilla et al. 2007) to assess the filling of the pit lake and contributions of different catchments to the Barcés River under wet, average, and dry year scenarios. The model was calibrated with water quality records as the pit lake has filled over time (Supplemental Fig. S3), and with 38 years of precipitation records and air temperatures. The average annual rainfall throughout the basin is about 1450 mm. An estimated 22 % of the rainfall is lost through evapotranspiration in the basin and free surface evaporation (Padilla et al. 2007). The pit lake's hydrodynamics and hydrochemistry is being monitored as it fills (Delgado et al. 2008a, b).

Catchments along the Barcés River basin, which accounts for approximately one third of the total Mero River basin, will contribute water along the river path between the pit lake and the reservoir (Fig. 1). Based on 141 measurements of surface flows captured at several rivers and streams (2006–2012), a small fraction of water infiltrates into the ground and the rest flows as surface runoff. It is estimated that about 85 % of the stream flow comes from rainfall and the rest comes from the aquifer (García-Rádade et al. 2014; Padilla et al. 2007). These measurements were used to calibrate the model.

Once the model was calibrated, contributions of the pit lake to the Barces River were estimated with three different scenarios (Fig. 3): a rainy year (90th percentile of rainfall data), an average year (50th percentile), and a dry year (10th percentile). The average year has a mean annual rainfall of 1400 mm, while the rainy year totals 1817 mm, with a return period of 8 years, an acceptable recurrence frequency, and is more likely than the dry scenario. In a dry year, the annual rainfall rate is 876 mm, considerably less than the 1200 mm of 2010, with a return period of 38 years.

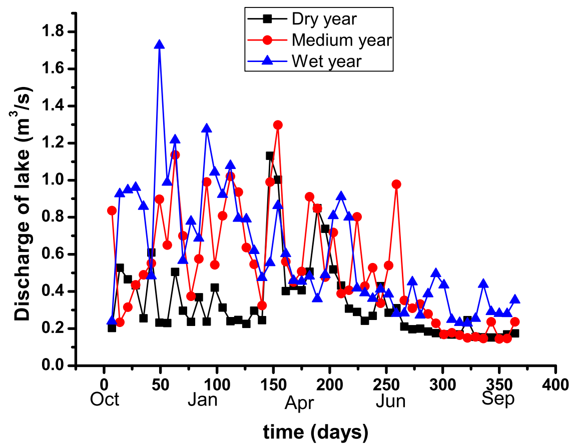

Fig. 3 Predicted mine pit lake discharges to Barces River if discharge flows are not regulated

Modelling Water Quality

A conservative transport model was developed to determine the water quality once the pit water mixes with the river (Supplemental Fig. S4). The model considers changes in Fe, Mn, and Ni concentrations due to transport processes and dilution. These were examined for a range of wet and dry years. It was developed as a steady state model because the residence time in the basin is small (<6 h) and the time being assessed is annual.

Input data to the model included chemical water quality measured at several discharge points along the Barcés River for the three scenarios (wet, average, and dry year). The transport of the Fe, Mn, and Ni was modelled assuming that concentrations of these elements fluctuate harmonically and seasonally in the first 15 m in depth of the lake as these elements can reach concentrations values very close to the allowed limits (Supplemental Fig. S2).

Water flow and turbulence, which affects solute transport, is controlled by the discharge volume, river width, terrain, and river bottom type. The Barcés River, at elevations of 180–90 m, is less than four meters wide, on average, with a rocky bed, boulders, coarse sand, and gravel. As it drops below 90 m, it widens to 6–8 m across. Areas with shallow slopes accumulate sand and muddy fine-grained sediments. Where slopes are steeper, the flow is more turbulent and the riverbed consists of coarse sand with boulders.

The MELEF hydrodynamic model (Padilla et al. 2007), which was used to analyse flow dynamics, considers three different processes or mechanisms: (a) advection, (b) molecular diffusion, and (c) mechanical dispersion (Supplemental Fig. S5, Table S2; Juncosa et al. 2010a). Of these, transport occurs primarily by advective flow. FREECORE^{2D}, which was developed from the FLOWDECAY code (Juncosa et al. 2010b) was used to assess solute transport.

Modelling Water Volume in the Pit and Reservoir

Once the chemical quality analysis was carried out, a model was developed to assess the joint operation of the lake and the reservoir under the three precipitation scenarios to determine the best policy of regulating water flow and recharge to meet demands, including flood and drought requirements. Scenarios simulated an inter-annual series of precipitation. The worst scenario modelled a dry year followed by two average ones. Additionally, the following requirements were applied:

- To limit erosion of the riverbed, the discharge from the lake, together with that from the Pereira and Porta Antiga rivers, was not allowed to exceed 1.34 m^3/s. These discharge values are based on historical discharges that occur in the rainy scenario.
- Both the ecological flow and the amount of water required at the Cañas WTS should be met.
- Seasonal demand requirements should be met.
- The flows being discharged at the Barcés River take into account the underground flow and surface runoff from the different sub-basins.
- Water quality standards should be met at the pit lake, rather than downstream after dilution. This is a priority. Therefore, both the Pereira and the Porta Pereira Antiga rivers, at certain times, are diverted to fill the pit in order to maintain water quality by renewing the surface water (to avoid eutrophication) and prevent discharges of poor water into the Abegondo-Cecebre reservoir.
- The obligatory discharge from the Abegondo-Cecebre reservoir to prevent floods was minimized, maximizing its water supply capacity.

When the pit lake releases water, it will quickly travel from the lake to the Abegondo-Cecebre reservoir in less than 6 h.

Results

Water Quality

Concentrations of Ni and Mn in river water at the Cañas WTS and at the inlet to the Abegondo-Cecebre reservoir vary inversely with the volume discharged from the Meirama pit lake, while Fe concentrations are less affected by pit lake discharge (Supplemental Fig. S6, S7, and S8). The pit is made up of schists and granites and is the primary source of Ni and Mn to the river. Thus the distribution of the concentrations along the Barcés River decreases as the flow rate increases due to dilution by river water. In winter and spring, when the volume of water contributed by natural streams is low, the concentrations of Ni and Mn at the Cañas WTS and at the inlet to the Abegondo-Cecebre reservoir increase.

However, Fe follows the opposite trend: concentrations increase with higher flow rates. This is attributed to the Fe concentrations of the natural rivers and streams that contribute to the Barcés River, which are higher than those discharged from the Meirama lake. In this sense, the lake discharge dilutes the basin's Fe concentrations.

The dilution intervals for Ni and Mn are independent of the type of year being considered (dry, average, or wet); the values follow the same trends over time, regardless of the kind of year, and quantitatively fall within very defined margins. Graphs of water quality over time indicate that Ni and Mn concentrations increase from March to June, while Fe concentrations decrease.

All species will become even more diluted in the Abegondo-Cecebre reservoir. Therefore, the only critical point is whether water quality standards will be met at the Cañas WTS water intake. Given that these standards are met at the pit lake and are modelled to be met at the reservoir, and do not vary substantially in wet and dry years, it appears that they will be met at the Cañas WTS. As a result of this analysis, a tunnel is now being constructed that will intersect the mine pit 15 m below the overflow level (156 masl), to draw water from the lake as a supplemental water source.

Maintaining Pit Lake and Reservoir Volume

The model assumes a steady state in the Abegondo-Cecebre reservoir, so that at the end of the hydrological year, the reservoir volume should be 13,000,000 m^3. Maintaining the seasonal volume of water in the reservoir in order to meet demands and ecological flow is critical. From November to May, the reservoir needs to act as a flood regulator, accepting floodwaters that come from the headwaters; from May to November it needs to be full to supply increased seasonal demands from residential and industrial consumers. If needed, the mining lake can be reduced in volume down to 9,520,000 m^3, which would keep the water surface above the height of the tunnel, in order to provide water to fill the reservoir. Models were run to examine volumes in the pit lake and reservoir under wet, average, and dry year scenarios. The worst case situation

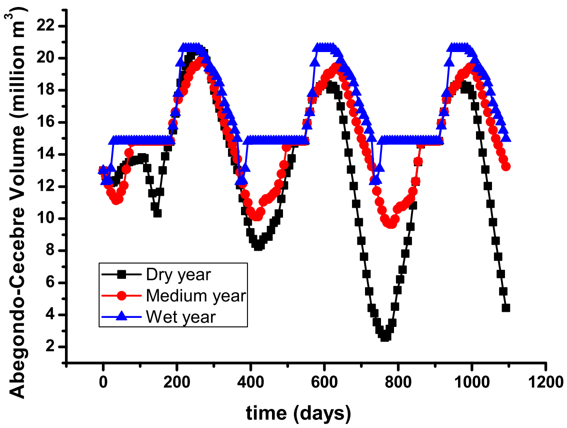

Fig. 4 Modelled water volume over time in the Abegondo-Cecebre reservoir in rainy, average, and dry hydrological years. Inter-annual regulation

would occur in a dry hydrological year, when demand is high and inputs are low (Fig. 4 and Supplemental Fig. S9).

Discussion

River diversions into and away from the pit can be used to maintain pit and reservoir volumes. The timing of diversions would differ for dry and average scenarios; no stream diversion is necessary for the wet scenario.

In the inter-annual regulation model, an average year was used as a reference to build the rainfall series. At the beginning of summer during an average year, about 9,300,000 m^3 would be discharged from the pit lake to raise the level of the Abegondo-Cecebre reservoir to the level at which it can meet demands. Over the following year, the water level in the lake would recovered due to underground, runoff, and direct rainfall contributions, contributions from smaller streams, and diversions of the Pereira and Porta Antiga streams from December to late January into the pit void. This ensures that the Abegondo-Cecebre reservoir would maintain a capacity of 72 %, as required to save room for potential flood waters. From February to mid-May, the mine lake is recharged entirely by groundwater, runoff, rainfall, and minor streams, while the Pereira and Porta Antiga are allowed to run into the Barcés River. The mine lake will fill again by May, discharging then in order to avoid overflowing. Water quality will be dominated by natural waters that have flowed into the pit lake.

The “dry scenario” inter-annual model assumes a dry year followed by two average years; the probability of two consecutive dry (<876 mm) years is very small. Under this scenario, the Abegondo-Cecebre reservoir may actually go below the desired 72 % full mark in winter, and need to be supplemented to meet demands. In order to maintain the desired level, the Pereira and Porta Antiga streams would have to be diverted towards the pit void, to prevent overfilling the reservoir, or toward the Barcés to prevent lowering the reservoir too much. From December to January, stream flows would be redirected towards the Barcés to feed the Abegondo-Cecebre reservoir. This would ensure that demands for flood control and water supply can both be satisfied without the Abegondo-Cecebre reservoir emptying any further. From January to February, the flow in the Pereira and Porta Antiga rivers would be redirected to the pit lake. From February to March, they would be redirected alternately to the Barcés and back again to the pit void. From April through November, they would be directed back to the pit to keep good quality water in the pit lake; the pit will overflow into the Barces River.

In the case of a rainy year series followed by average years, the inter-annual model implies that the mine lake overflows fairly continuously, remaining completely full. At the Abegondo-Cecebre reservoir, the days of surplus overflow are increased, achieving, as in the previous cases, 100 % supply and regulation guarantees and a steady cyclical regime in the evolution of stored volume. In this case, it is not necessary to divert the Pereira and Porta Antiga rivers.

Conclusion

A former lignite mine is filling up and creating a pit lake, the Meirama Lake. The water quality in the upper layers of the lake meet water quality requirements, so that the pit lake can be used as a supplemental water supply, augmenting the Abegondo-Cecebre reservoir to fulfill increasing seasonal demands for water in A Coruña and surrounding areas during periods of water shortage.

Models were developed to determine flow volumes and water quality under inter-annual recharge scenarios, and examining volumes and water quality under wet, dry, and average precipitation years. Joint management of the Abegondo-Cecebre reservoir and the Meirama Lake can be manipulated by seasonal and inter-annual regulation of recharge to the pit lake and discharge of the pit lake and the reservoir to ensure a sufficient volume of water as well as to ensure water quality requirements are met. With joint management, water demand needs, flood control, minimum erosion and ecological requirements can be met. Water volume at the pit lake can be regulated by diverting streams into and out of the pit void seasonally.

Although water quality standards should be met as water leaves the pit lake, the critical point is at the Cañas WTS, which provides drinking water. Water quality will be met there. At the Telva WTS, the water comes from the reservoir, and the reservoir will have diluted any elevated metals.

In order to use the lake as a regulatory reservoir, a tunnel is being built 15 m from the peak to take advantage of the water volume above the 15 m level (from 156 to 171 masl), some 24,000,000 m^3. This is a greater capacity than that of the Abegondo-Cecebre reservoir itself, currently the source of water for most of the area. Thus, this work has demonstrated how a closed mine can be used as sustainable water resource, taking into account water quality and quantity.

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