Mathematical simulation of the Alqueva irrigation system

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Abstract

The current dissertation evaluates the performance of the Alqueva Multiple Purposes Project, in what concerns the fulfillment of water demands. Two scenarios are considered; the original project with 120 000 ha of irrigated land and an expansion project to 160.000 ha.

The data used in the Alqueva Project characterization was gathered from non-technical reports and official documents of EDIA, SA, while the runoff series were obtained from SNIRH and existing hydrological studies.

The development of this study was supported by the mathematical simulation model MIKE HYDRO BASIN, developed by Danish Hydraulics Institute (DHI). This software is a multipurpose decision support tool for integrated river basin analysis, planning and management. The application of this software required the definition of operation rules adequate to the Alqueva project operation, while attending to the program limitations. These limitations are discussed in a particular chapter, specially the fact that MIKE HYDRO BASIN is not able to take cycles into account.

The results obtained demonstrate a good performance throughout the system, which satisfies the hydro-agricultural demands, both for the original project and for the expansion solution.

Keywords: Alqueva Multiple Purposes Project, MIKE HYDRO BASIN, Water Resources planning and management, Hydro agricultural demands.

Introduction

The integrated management of the water resources appears has a demand originating in the various water uses along with the human interactions arising from it.

This document aims to evaluate the extent to which the initial project of irrigation associated with the Alqueva (whose implementation is not yet completed), is able to support the water needs for the agriculture sector in the surrounding area. It also aims to study a potential expansion of the irrigated territory from the Alqueva reservoir. Thereby, two situations were defined as object of study: the first one will have an irrigation area of 120 thousands ha; the second one with a 40 thousands increase. The purpose of this reasoning is to evaluate the degree in which the agricultural and urban needs are being satisfied, based on the Danish MIKE KYDRO BASIN software.

Alqueva Multiple Purposes Project

The Alqueva Multiple Purposes Project (EFMA, Portuguese acronym), located in Alentejo, south of Portugal, is a system that ensures the transportation and storage of water. It includes a set of 69 dams and reservoirs; 382 km of primary network for the connection between the system's main dams; a 1620 km extension of pipelines on the secondary network; 47 pumping stations; and 5 hydropower plants.

A scoping area of EFMA is formed by the hydrographical region of Guadiana river (RH7) and the east hydrographical region of Sado river (RH6). Being the area located in Alentejo, the climate presents a high temperature amplitude during the year, with an annual average between 9,1 °C and 24,4 °C in January and July, respectively. The average annual rainfall in this region varies between 400 mm in dry years and 750 mm in wet years, approximate values.

Originally, the EFMA was divided in three subsystems: Alqueva, Ardila and Pedrógão, whose distribution and area are represented in Figure 1.

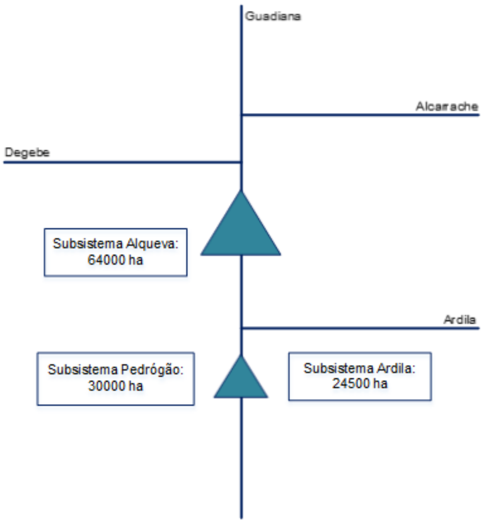

Figure 1 – Simplified scheme of the Alqueva Multiple Purposes Project.

The motorization of the agricultural area of EFMA is assigned to the Conselho para o Acompanhamento do Regadio de Alqueva (CAR Alqueva), which has representatives from other entities, including DGADR, DRAP Alentejo and EDIA, SA.

CAR Alqueva is responsible for the water usage management, encouraging irrigation and establishing some cooperation among the farmers.

The exploitation of the hydropower plants of Alqueva and Pedrógão is entitled to EDP (Portuguese main energy supplier), upon a contract signed on October 2007.

Hydrography

The Guadiana River rises in Spain and enters the Portuguese territory in Elvas, and then runs into the Atlantic Ocean between Vila Real de Santo António and Ayamonte (Spain). It has a total length of, approximately, 820 km. Its main tributaries are the Alcarrache, Degebe and Ardila rivers, appropriately identified in Figure 1.

Besides comprehending the river basin of Guadiana River, the EFMA also comprehends the river basin of the Sado river. The Sado river flows entirely in Portugal into the Atlantic Ocean, with its source in Serra da Vigia and the mouth in the district of Setúbal.

Figure 2 illustrates the allocation of hydrographic basins and sub-basins that form the EFMA. By this figure, obtained from a Geographical Information System, it has been possible to determine the areas of the hydrographical basins upstream of each river section, namely dams included in EFMA's infrastructure system and/or confluences with the top tributaries of the Guadiana and Sado rivers. (Ferreira, 2014)

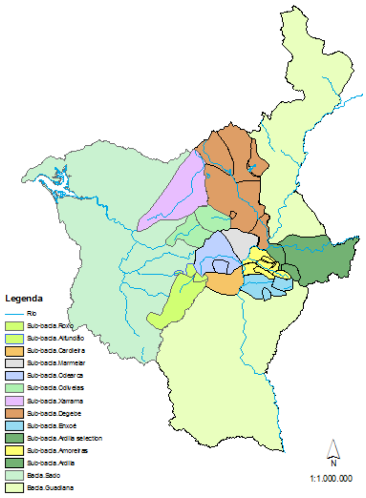

Figure 2 – Hydrographical sub-basins of the EFMA area (Ferreira, 2014)

Runoff

The estimations of the runoff which flown into the EFMA were made taking into account the SNIRH records. We used hydrometric stations registrations located near the EFMA and also existing studies of EDP (1988) and COBA (1985).

The development of the present study has adopted a runoff register EDP-Alqueva-R=4800/V=7000 as representative of the Guadiana river runoff upstream of Alqueva basin, and it has been completed with the runoff register observed in Ponte Mourão. These series are represented in Figure 3.

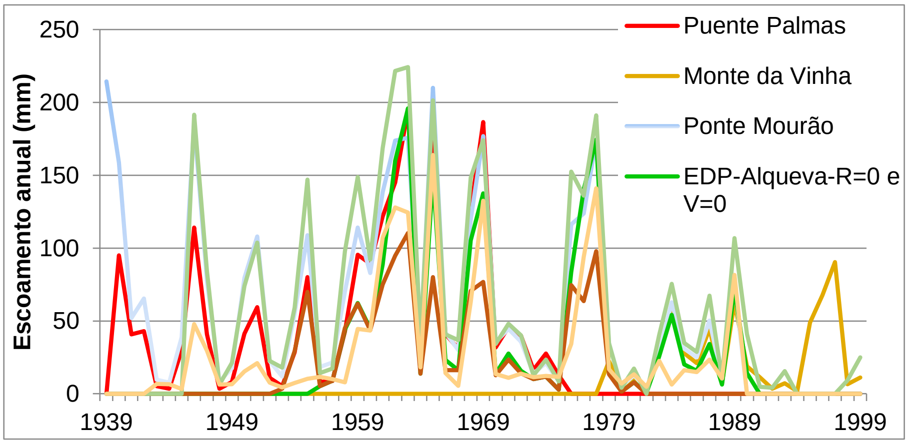

Figure 3 – Annual runoff according studies and hydrometric stations (Ferreira, 2014)

Evaporation

Evaporation is responsible for a substantial loss of water, and it varies with atmospheric temperature, wind, relative humidity, etc. Table 1 represents the monthly evaporation rate of the Alqueva and Pedrógão reservoirs (Oliveira, 1994). The values shown have been considered for all the reservoirs that form the EFMA.

Table 1 – Distribution of the monthly evaporation rate in EFMA (mm)

Out.	Nov.	Dez.	Jan.	Fev.	Mar.	Abr.	Mai.	Jun.	Jul.	Ago.	Set.
97	50	26	33	44	87	116	168	204	167	244	164

Infrastructures

EFMA consists mainly of dams, reservoirs e distribution networks. In order to characterize the EFMA, we have used data from the *Carta Global do Empreendimento de Fins Múltiplos de Alqueva* (EDIA, S.A, 2013), in the *Story Map*[1] application, as from the Reading of non-technical reports (RNT) e and the *Comissão Nacional Portuguesa das Grandes Barragens* (CNPGB)[2] digital platform.

Of the three subsystems represented in Fig.1, only the Alqueva subsystem is being exploited, having been completed in 2011. Regarding the Ardila subsystem, the conclusion of the reservoirs of Caliços and Pias is foreseen until 2016, and Furta Galinhas reservoir the following year; in the Pedrógão subsystem, only the São Pedro reservoir is completed. (Tables 2, 3 e 4)

Table 2 - Characteristics of the storage infrastructure of the Alqueva subsystem

Reservoir	Conclusion year	River stream	Total Vol. (hm^3)	Usef. Vol. (hm^3)	APA (km^2)	NPA (m)	NMC (m)	NmE (m)	Watering block	Reservoir downstream
Alqueva	2002	Guadiana	4150	3150	250	152	154.7	135	-	Álamos
Vigia	1981	Degebe	16.725	15.58	2.62	224	224.75	199	-	-
Monte Novo	1982	Degebe	15.28	14.78	2.77	196	196.8	171	-	-
Álamos	2000	Degebe	17.6	4.4	19.5	227.5	228.1	225	-	Loureiro,
Loureiro	2000	Degebe	6.98	2.48	0.92	222	223.1	219	Monte Novo	Alvito, Monte Novo, Vigia
Alvito	1977	Odivelas	132.5	130	14.8	197.5	198,85	172	Vale de Gaio, Alvito Pisão, Beringel Beja, Loureiro Alvito, FFV	Vale de Gaio, Odivelas, Cinco Reis, Pisão, Penedrão
Vale De Gaio	1949	Xarrama	63	58	5.5	40.5	42.5	11	-	-
Odivelas	1972	Odivelas	96	70	9.73	103	104.55	91.3	Associação de Regantes	-
Cinco Reis	2011	Roxo	3.73	1.38	0.4	204	206	198	Cinco Reis Trindade	-
Pisão	2007	Alfundão	8.8	6.69	2.02	155	156	150	Pisão Alfundão	-
Penedrão	2010	Alfundão	5.2	3.6	0.9	170	170.5	167	Ervidel	Roxo
Roxo	1968	Roxo	96.3	89.5	13.78	136	137	124.5	Aljustrel, Rio de Moinhos, Sines	-

Table 3 - Characteristics of the storage infrastructure of the Pedrógão subsystem

Reservoir	Conclusion year	River stream	Total Vol. (hm^3)	Usef. Vol. (hm^3)	APA (km^2)	NPA (m)	NMC (m)	NmE (m)	Watering block	Reservoir downstream
São Pedro	2014	Odearca	10.83	10.16	1	142.5	143.5	131	-	Almeidas, Amendoeira
Almeidas	-	Odearca	0.5	0.45	0.1	194	195	190	São Matias I	-
Amendoeira	-	Odearca	1	0.8	0.2	194	195	187.5	-	Magra
Magra	-	Odearca	3	3	0.28	194	195	187.5	S. Pedro-Baleizão, Baleizão-Quintos	-

[1] www.edia.pt

[2] http://cnpgb.apambiente.pt/

Table 4 - Characteristics of the storage infrastructure of the Ardila subsystem

Reservoir	Conclusion year	River stream	Total Vol. (hm^3)	Usef. Vol. (hm^3)	APA (km^2)	NPA (m)	NMC (m)	NmE (m)	Watering block	Reservoir downstream
Pedrógão	2005	Guadiana	106	54	11.04	84.8	91.8	79	Pedrógão	São Pedro, Amendoeira
Amoreira	2005	Amoreiras	10.7	9	1.49	135	136.5	125	Orada Amoreira, Amoreira-Caliços, Caliços Moura	Caliços
Caliços	-	Amoreiras	0.8	0.6	0.24	193.35	194.25	190	-	Pias, Furta Galinhas
Furta-Galinhas	-	Ardila	3.75	3	0.8	225	226.01	219	Caliços Machados	-
Pias	-	Amoreiras	5.4	4.2	1.3	182.5	183.52	177.5	Pias	-
Brinches	2005	Rib. de Pias	10.9	9.57	1.41	135	136,33	121.25	Brinches, Brinches Enxoé	Serpa, Laje, Enxoé
Enxoé	1985 (restr. em 1998)	Enxoé	10.4	9.5	2.05	175	177.1	160.75	-	-
Laje	2008	Enxoé	4.17	3.37	0.67	177.5	178.9	170	-	-
Serpa	2008	Enxoé	10.18	9.92	1.52	123.95	125.2	105	Serpa	-

Hydrological Demands

Table 5 and Table 6 present the water demands calculated for urban and agricultural consumption. The urban needs are constant in the two simulated situations

Table 5 – Annual flow for urban supply (dam^3)

Month	Monte Novo	Alvito	Sines	Associação Regantes
Total/Year	9662.4	3272.4	10009	10000

Table 6 – Hydrological demands on project and expansion situation (dam^3)

Subsystem	Project	Expansion
Alqueva	266714	279361
Ardila	120663	125622
Pedrógão	93031	94947

Ecological Issues

The environmental flow values are those indicated in Table 7 and their establishment aims to ensure the ecosystem that naturally settled downstream of a dam.

Table 7 – Volume for ecological preservation (dam^3)

Reservoir/Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.
Álamos	34.3	33.2	34.3	68.6	64.2	68.6	24.9	25.7	24.9	1.1	1.1	1.1
Loureiro	10.2	29	62.7	122.4	122.3	110.1	35.5	15.8	2.1	0	0	0
Res. R4 /MNV	29.5	36.2	29.4	25.6	23.2	17.9	16	7.9	1.8	1.6	8.3	23.4
Alvito	62.4	178.8	390.5	763.1	765	685.7	222.4	97.5	12.2	0.8	0	2.9
Pisão	187	147.7	317.9	140.3	156.3	84.6	34	6.2	0	0	0	1
Roxo	126.7	544.3	562.5	562.5	508.8	376.9	151.9	41.2	6.7	2.9	3.7	8
Odivelas	227.7	453.6	1031.2	1499.9	1354.8	1499.9	777.6	289.3	59.6	61.6	61.6	59.6

MIKE HYDRO BASIN

MIKE HYDRO BASIN is a software developed by Danish Hydraulics Institute (DHI). It is a multipurpose tool suitable for integrated analysis, planning and watershed management. It is applicable to integrated management of water resource studies, to solve water allocation problems to different sectors, to improve operations associated with dams and hydroelectric power plants, and it assesses the performance of the water supply and irrigation system as well as crop productivity (DHI, 2011). This software requires the user to specify the system's operating rules thus constituting a model with a supply-driven type of rules.

Application of MIKE BASIN HYDRO to the case study

The model under consideration was adopted for the software according to Figure 4. We have characterized watersheds, dams and irrigation areas with the data collected for this purpose. Watersheds are defined by entering the corresponding runoff series, and irrigation areas are characterized based on their water requirements. The definition of reservoirs involves the introduction of supply priorities by Water Supply Fraction file, which define the system's operating rules. These rules are based on the following concepts:

• Supply fraction: fractions that establish the relationship between the decline in water level in a reservoir and the small percentage of supply;

• Storage demand: amount of water that is supplied among reservoirs as required.

System performance evaluation

The performance indicators allow to evaluate the system's strength and sustainability; the indicators used to measure this development were the monthly and annual guarantee, the monthly coverage, among others.

Figure 4 and Figure 5 summarizes the results obtained for each watering block in both analyzed situations.

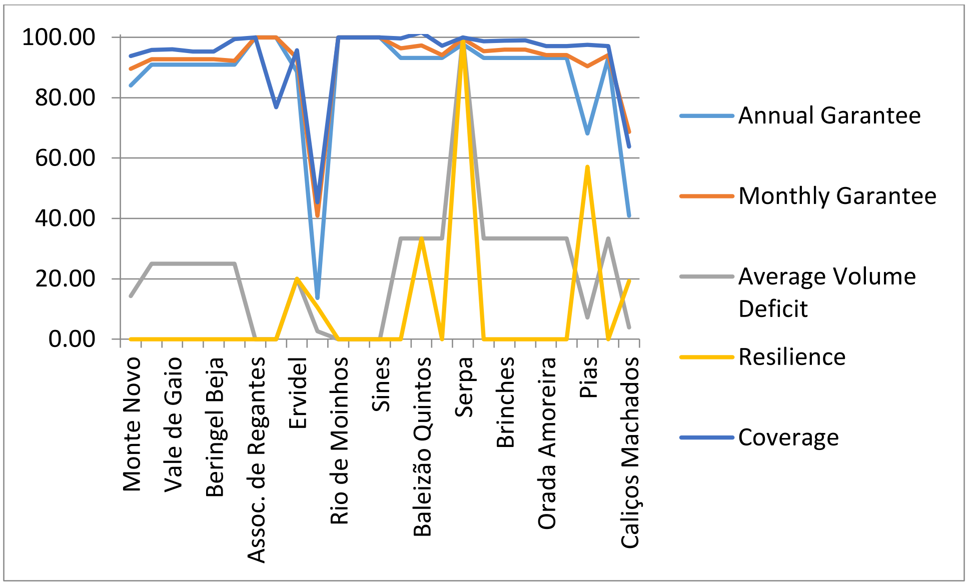

Figure 4 – Results obtained in the project situation (%)

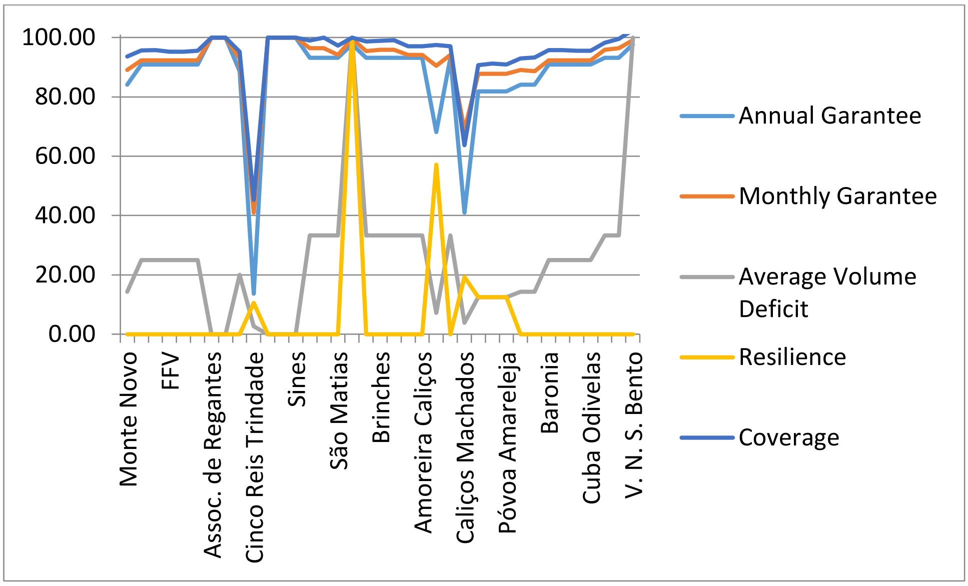

Figure 5 - Results obtained in the expansion situation (%)

Potentialities and limitations of HYDRO MIKE BASIN

The software's main deficiency regards the non-acceptance of cycles which is reflected in the effectiveness of water allocation between reservoirs.

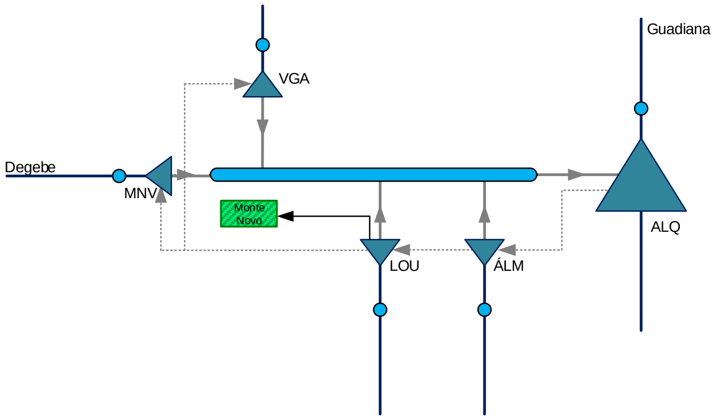

Figure 6 – Cycle created in Alqueva subsystem

In Figure 6, the cycle occurs in the Degebe river. In this particular case the Alqueva dam (ALQ) supplies the Alamos dam (ALM), which supplies Loureiro (LOU), Monte Novo (MNV) and Vigia (VGA), while the tributaries of reservoirs converge in river Degebe, which again returns the discharged flows to Alqueva. The solution regarding this cycle was to remove the connections from Loureiro to Monte Novo reservoir and to Vigia reservoir and to interrupt the connection to Degebe river of the streams in which the Loureiro dam and Alamos dam are inserted.

Another obstacle observed in building the model is the non-acceptance of bidirectional flows, as shown in Figure 7. The problem detected in the simulation originates in a creation of cycles.

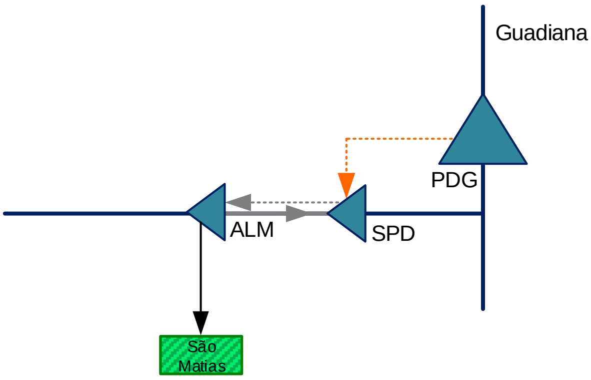

Figure 7 – Bidirectional runoff in Pedrógão subsistem

This error in the model does not enable the supply of Almeidas dam (ALM) by the São Pedro dam (SPD) and hence the adequate supply of São Matias irrigation block was not possible. The solution was to remove the link between São Pedro and Almeidas and to allocate the supply of this irrigation block to the dam of São Pedro.

Alqueva Multiple Purposes Project performance

This thesis analyzed two scenarios. The first scenario assumes an irrigated area of 120 000 ha, corresponding to the area planned in the initial design of the EFMA; the second scenario considers an increase of 40 000 ha of irrigated area. The tested simulation period is 44 years, from 1946 to 1989/90.

In what concerns the model, the main difference between the scenarios is the number of water users. From the first scenario to the second, 12 supply points were added with the water requirements shown in Table 6. Table 8 shows the storage volume of all the reservoirs, irrigation areas and water needs operating in each simulated situation, average values.

Table 8 – General characteristics of the scenarios

Characteristics	Project	Expansion
Total stored Volume (hm^3)	4790	4790
Total Useful Stored Volume (hm^3)	3664	3664
Water area of Alqueva subsystem (ha)	57928	83428
Water area of Ardila subsystem (ha)	30979	43879
Water area of Pedrógao subsystem (ha)	24154	29814
Total watering area of EFMA (ha)	113421	157121
Agricultural demands of Alqueva subsystem (hm^3)	26.25	38.90
Agricultural demands of Ardila subsystem (hm^3)	12.10	17.0
Agricultural demands of Pedrógão subsystem (hm^3)	9.30	11.20
Total agricultural demands of EFMA (hm^3)	47.6	67.1
Urban demands of EFMA (hm^3)	20	20

To fully understand the previously reported results, it is also important to analyze Alqueva storage volume variation, in order to fully contextualize the examination of the previously reported results.

Figure 8 compares the volume variation stored in Alqueva during the simulation period, respectively in the design and expansion situations. These values allow a more immediate identification of the existing drought in dry years, even though the operating rules have been established according to the water level and not according to the stored volume. It is also possible to observe the importance of minimum reached values facing the working volume of the 3,150 hm3 reservoir.

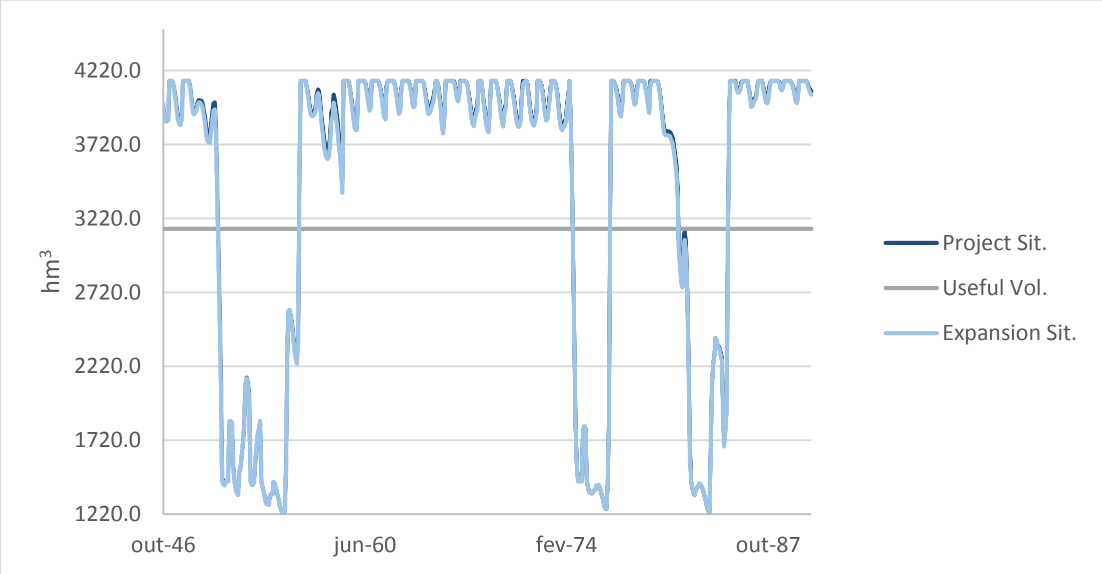

Figure 8 – Stored volume in Alqueva reservoir, project and expansion situations.

Table 9 sums up the global balance of EFMA, regarding project and expansion situations respectively. Average values take into account the affluences to the system, as in runoff series, and also the water losses through evaporation, allocation to water users and returns to natural runoff of the watershed.

Table 9 – Medium annual balance on EFMA (hm^3)

Situation	Input	Output			Total
-	Afluences	Downstream	Consumption	Evaporation	-
Project	5.79	4.76	0.11	0.81	1.71
Expansion	5.79	4.79	0.15	0.79	0.06

Figure 9 shows the variation of monthly guarantees in the watering blocks that are common to both situations. As expected, monthly guarantees in the expansion situation are inferior to those in the situation project for its water demands are much higher.

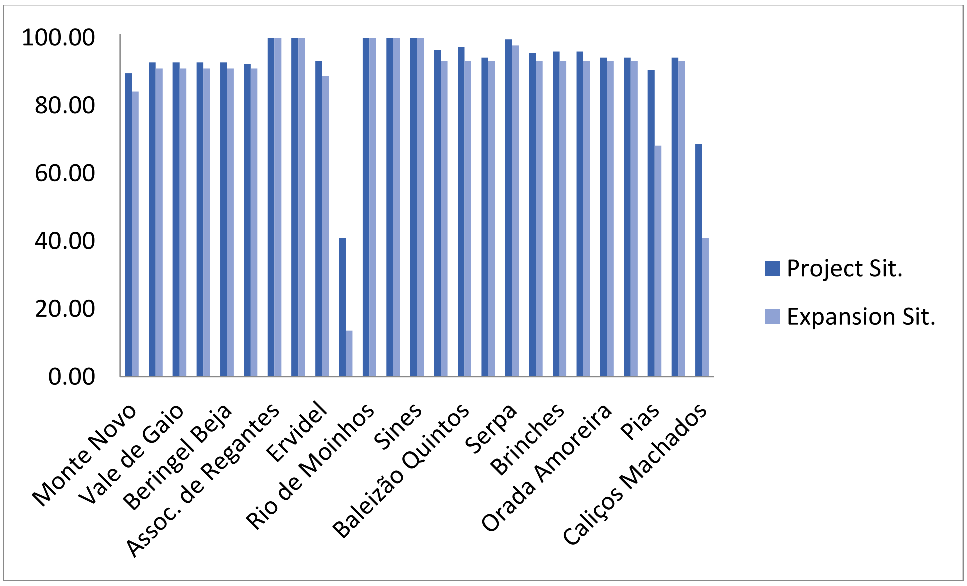

Figure 9 – Annual Guarantee regarding project and expansion situations, common water users.

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