Design of a climate-dependent water reuse project

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Abstract Reclaimed water storage is imperative in water reuse management. Climate is a primary factor controlling reclaimed water storage design by its significant influence on irrigation water needs as well as on stored water quality. This study presents a modelling approach that has been applied to assist the design of a climate-dependent water reuse project on an Atlantic island. Models for predicting irrigation water needs and water quality in tertiary lagoons were coupled with a technical–economic model to design reclaimed water storage facilities. Three scenarios corresponding to different augmentation of current reclaimed water reuse were investigated. According to the modelling, the storage sizes to meet the water quantity required for irrigation increased with water deficit – the difference between evapotranspiration and precipitation. The size of tertiary lagoons to meet required water quality was found to be larger than the size to meet required water quantity. To meet both quantitative irrigation needs and <1,000 FC/100 ml irrigation and disposal regulation, extending the tertiary lagoon system would be more cost-effective than storage calculated to meet only quantitative irrigation needs supplemented with UV disinfection. The reliability of reclaimed water storage design was estimated with 40 years historic climatic records.
Keywords Climate; irrigation; modelling; storage lagoon; water reuse

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Introduction

Water reuse has constituted an increasingly important component in integral water resources management. It provides an attractive option for conserving and extending available water supplies. In addition, water reuse is an effective solution to pollution control by reducing sewage discharge into the environment. Reclaimed water storage has become a significant design consideration in water reuse management (US EPA, 1992) and is necessary to match wastewater supply to seasonal variation in water demand and avoid the discharge into the environment during critical periods. Moreover water storage can improve stored water quality and be used as treatment facility to meet water reuse and discharge guidelines.

Storage has always been an important issue in surface water management. Various models have been developed to help with the design and operation of reservoirs. Mujumdar and Ramesh (1997) developed a short-term real-time reservoir operation model for irrigation of multiple crops. Reservoir releases and irrigation allocation were optimised through the integration of reservoir operation and allocation models. Ziari *et al.* (1995) evaluated the economic feasibility of on-farm runoff impoundments for supplemental irrigation with a non-linear mixed integer program. Yao and Georgakakos (1993) used a set control approach to discuss the uncertainty in reservoir management. Ward and Lynch (1997) applied an empirical trade-off model to compare the economic performance of multiple use and a dominant use of reservoir systems. The economic, technical and environmental aspects of storage reservoirs were discussed by Crommelinck (1998), and Van Breemen and Waals (1998).

Unlike surface water reservoirs, reclaimed water reservoirs are not only storage systems but also treatment processes. Many studies have addressed the pollution abatement performance of reclaimed water reservoirs. Juanico and Shelef (1991; 1994) developed multiple regression models for the forecasting of BOD and COD removal in stabilisation reservoirs under Israeli climatic conditions. Liran *et al.* (1994) investigated the effect of operational parameters on bacterial removal in stabilisation reservoirs for wastewater irrigation. Juanico (1996) discussed the effect of the operational regimes of batch stabilisation reservoirs for wastewater treatment, storage and reuse. Maynard *et al.* (1999) reviewed the removal mechanisms and performance of tertiary lagoons which were used often for reclaimed water storage. Mara and Pearson (1999) proposed a hybrid waste stabilisation pond-wastewater storage and treatment reservoir system to produce microbiologically safe effluent for both restricted and unrestricted crop irrigation.

Few previous studies integrated the impact of water reuse on stored water quality, the reliability of reclaimed water supply, uncertainty and economic aspects in storage design. By far the largest application of reclaimed water is agricultural irrigation. The primary factor controlling agricultural water reuse is climate. Agricultural water requirements depend strongly on evapotranspiration (ETP) and rainfall. Meanwhile, climate has significant effects on the quality of water stored in reservoirs. Firstly, variation of solar intensity and temperature directly influences stored water quality. Secondly, water quality can deteriorate because of short hydraulic retention time due to high agricultural water abstraction. In addition, storage design and operational regime significantly affect stored water quality. In this study, we present a modelling approach assisting the design of reclaimed water storage with consideration of the impact of climate.

Project description

This approach has been applied to a water reuse project design on a French island, Noirmoutier, where the sole fresh water resource is potable water conveyed from the continent. In Noirmoutier the main activities are tourism, agriculture, salt production, shellfish farms and fishing. Population increases from 9,000 local residents in winter to 90,000~130,000 in summer. Reclaimed water irrigation has been carried out for years, providing a reliable alternative water resource and preserving the sensitive aquatic environment. There are two wastewater treatment plants (WWTP) in Noirmoutier, one in the north and the other in the south. Treated effluent is stored in four tertiary lagoons (196,000 m^3) at the northern WWTP and in two lagoons (90,000 m^3) at the southern WWTP. Stored water is pumped for crop irrigation from March to September. The excess water is discharged into the sea. The microbial criterion allowing water reuse for agricultural and landscape irrigation and disposal into the sea is β1,000 FC/100 ml.

The climate is dry in summer and rainy in winter. The average annual precipitation is 606 mm (Table 1). ETP is more than precipitation from April to September, corresponding to the irrigation period. The peak period of temperature and solar intensity is from May to August.

Part of the cultivated area is irrigated with costly potable water that farmers would like to displace by reclaimed water. Moreover because of agricultural development, reclaimed water resources in the south will not meet increased demand. Therefore, the lagoon system in the northern WWTP is intended to be enlarged to meet these demands. A runoff impoundment of 24,000 m^3 located near the final lagoon can be renovated and used as an additional tertiary lagoon and the original final lagoon can be enlarged. Three scenarios based on the local situation were investigated. We supposed that fields irrigated with reclaimed water would increase by 51% (scenario CI 2) and 77% (scenario CI 3), with slight differences in the respective cultivation schedules. Scenario CLI 4 assumed that, in order to minimise sewage discharge, about 100,000 m^3/year reclaimed water would be reused for landscape irrigation in addition to CI 3 agricultural irrigation. The aim of the design was to determine the volume of the enlargement needed to meet the water quality and quantity required in each scenario. The lagoons are supposed to be operated continuously in series. When the last lagoon is empty, water is withdrawn from the preceding one, and so on.

Methods

As can be seen from Table 1, water demand is highly dependent on climate. For each scenario, the minimum size of the tertiary lagoon system necessary to meet quantitative irrigation needs, and qualitative irrigation and disposal regulations was determined with the daily meteorological precipitation, ETP, temperature and solar intensity data for the 10 year period 1990–1999.

Two models calculating irrigation needs and faecal coliform contents in lagoon effluents were calibrated with field monitoring data and then coupled with a technical economic model to design this climate-dependent water reuse project. This was used to identify the size of the lagoon system and resolve the technical–economic issues of water storage.

An accurate prediction of irrigation needs is important to water resources management. To capture the influence of climatic variation on agricultural water requirements, an operative model developed by Maihol *et al.* (1997) was adapted to predict the irrigation needs. It took into account crop, climate and soil factors. Water needs were calculated on a daily basis with a three-reservoir model, the capacities of which varied with the development of crop root. The dominant crop in Noirmoutier is potato. Seven varieties of potatoes are classified in four groups according to the dates of planting: Pot1 (1–10 February), Pot2 (11–28 February), Pot3 (1–31 March), and Pot4 (1–30 April).

As reused water comes mainly from treated domestic sewage, pathogenic issues are of great concern. Faecal coliform was chosen as an indicator to represent the water quality in tertiary lagoons because it is easy to analyse and widely used in water reuse guidelines. A non-steady state model was developed to predict on a daily basis the microbiological quality during storage (Xu *et al.*, submitted). This model allowed for the variation of water quality, inlet flow rate, irrigation withdrawal, volume and depth of lagoons, and climatic conditions (precipitation, ETP, solar intensity and temperature). Inlet water quality was assumed to depend on the season but not on the year, which actually was a simplification. It was also assumed that the hydraulic regime of each lagoon was a completely stirred tank reactor pattern and that faecal coliform decay followed first order kinetics in each lagoon.

The technical–economic model simulated the main water volumes and flows in the integrated hydrologic cycle, including potable water importation and supply, potable and

Table 1 Wastewater reuse and mean annual meteorological data for Noirmoutier

Year	Reused volume (m^3)	Period of irrigation	Annual precip. (mm)	Annual ETP (mm)	Mean temp.(°C)	Mean solar intensity ($J/cm^2/day$)
1990	320,000	1/4 to 22/10	503	1,002	13.9	1320.0
1991	310,000	18/4 to 30/9	544	707	12.4	1327.9
1992	246,500	14/4 to 28/9	566	697	12.8	1269.4
1993	164,000	–	626	934	12.5	1258.8
1994	212,460	–	788	951	13.7	1318.4
1995	323,000	4/4 to 16/10	723	1,072	14.0	1367.2
1996	229,180	1/4 to 29/9	634	954	12.9	1337.6
1997	301,546	28/3 to 30/9	515	1,073	14.1	1341.6
1998	174,901	1/5 to 30/9	636	959	13.2	1196.5
1999	85,242	1/4 to 14/9	805	954	14.1	1114.0

non-potable water needs and consumption, wastewater collection, treatment and disposal, water storage, transportation and reuse (Xu *et al.*, 2001). The model was composed of two sub-models according to the location of the wastewater treatment plants, one for the north of the island and one for the south. The two sub-models were linked by potable water supply and reclaimed water transportation whenever a reclaimed water deficit occurred in the south. Microeconomic criteria, payback time and water lifecycle costs, were calculated through basic cost-benefits analysis. The coupling of the three models allowed identification of the size of the lagoon system and helped discussion of the technical-economic issues of water storage.

The size of the lagoon system appeared to be fairly well represented as a function of annual precipitation and ETP (Figures 2 and 4). For each scenario and each objective, this function was discretised in a matrix form. Thus it was easy, though not very precise, to extend the results obtained from the daily meteorological data of the 10 year period 1990–1999 to the period 1961–2000 using only annual precipitation and ETP records.

Results and discussion

Impact of climatic variation on irrigation needs

Theoretical irrigation needs of potato fields vary greatly with the date of planting and water deficit EPT-P (Figure 1). Summer potato "Pot4" needs more water than other varieties of potatoes as it grows in a hot and dry period. In addition, irrigation needs depend greatly on yearly climatic conditions. A large amount of water was needed by all varieties of potatoes in the dry years 1990, 1995 and 1997. Theoretical total irrigation need in the dry year 1997 was twice that of wet year 1999.

Storage design to meet water quantity requirement

The technical–economic model permits the calculation of the minimum size of reclaimed water storage necessary to match landscape and agricultural irrigation needs. In order not to spoil pumped water with sludge deposited in the bottom of the lagoons, it is assumed that pumping stops when the water depth is less than 0.3 m. Figure 2 illustrates calculated storage size as a function of annual rainfall and ETP. Storage size increases with declining precipitation and rising ETP as a result of high irrigation needs. Within a 40 year period, the existing lagoon system could meet most irrigation needs except 3, 6 and 10 dry years for scenarios CI 2, CI 3 and CLI 4, respectively. Wastewater disposal to the sea can be avoided in summer owing to irrigation reuse. The reduction of discharge is important in protecting the tourist sea sites.

Meeting quantitative irrigation needs does not mean that the quality of reused and dis-

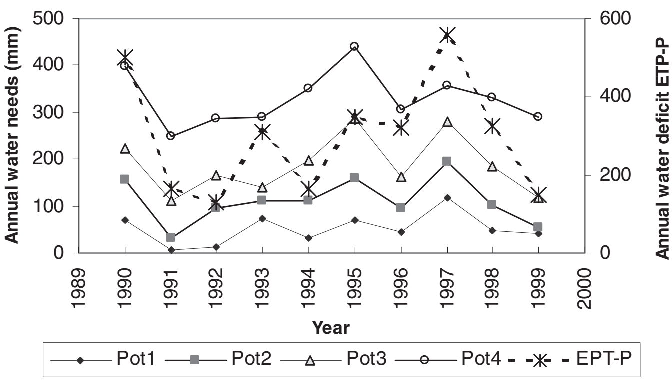

Figure 1 Impact of climate on annual water needs for different potatoes

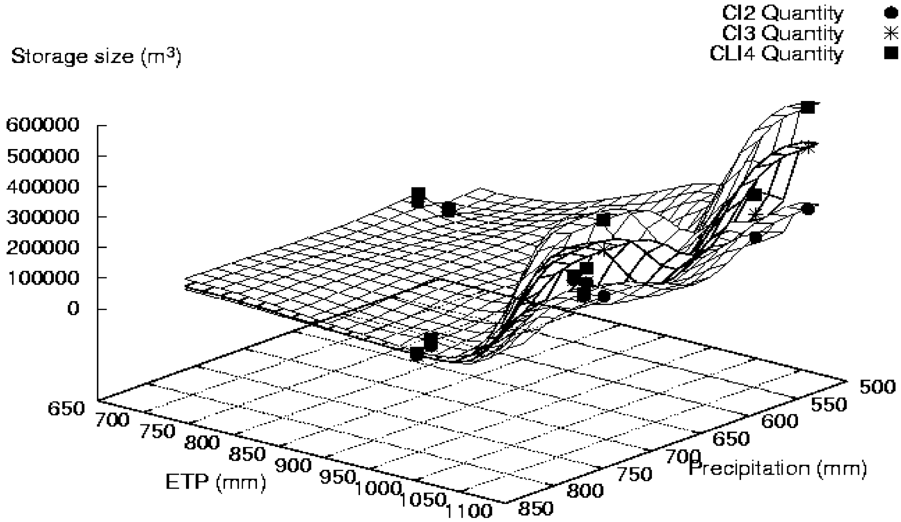

Figure 2 Storage size required to meet quantitative irrigation needs as a function of annual precipitation and ETP for CI 2, CI 3 and CLI 4 scenarios (dots represent the values calculated for the 10 year period 1990–1999)

charged water complies with health regulations, particularly at the end of the irrigation season. Figure 3 describes the variation of faecal coliform concentration in the final effluents of lagoons in dry (1997), moderate (1998) and wet (1999) years for scenario CI 2. The size of the tertiary lagoons is calculated to meet irrigation needs in 1997, the second driest year of the 40 year period. FC numbers decrease gradually from winter to the middle of the irrigation period due to long effluent retention time and increasing solar intensity and temperature. In the late period of irrigation, water quality deteriorates due to short retention time caused by irrigation abstraction, and high inlet flow rates and bacterial contents. In the dry year, even though UV radiation is very strong and favours the disinfection in the lagoons, water quality can not comply with health regulations – 1,000 FC/100 ml – as a result of too short retention times. Simulation shows that there is no obvious difference in water quality in wet and mild years due to a long enough retention time.

Storage design to meet water quality requirement

The correlation of storage sizes with annual precipitation and ETP to meet the water quality requirement follows the same tendency as that required to meet the water quantity requirement. But, for given values of rainfall and ETP, the storage sizes to meet the water quality requirement are always larger than those required to meet the quantity requirement for all scenarios. Figure 4 is an instance for scenario CI 2. Over a 40 year period, the existing lagoon system could meet both water quality and quantity requirements for only 26, 21 and 17 years for scenarios CI 2, CI 3 and CLI 4.

The storage design should take into account the economic issues and storage safe yield. Figure 5 presents the probability of reclaimed water supply meeting water quantity and quality requirements throughout the year as a function of the investment in extending the storage for each scenario. For a given year, the quality requirement is said not to be satisfied if effluent FC content exceeds 1,000/100 ml one day or more in the year. It is evident that reducing the risk of supply failure requires higher investment and that the investment would increase with the irrigation needs.

To date, water reuse agreements generally avoid a guarantee on continuous delivery for irrigation supply. However, in order to promote water reuse, reliability of reclaimed water

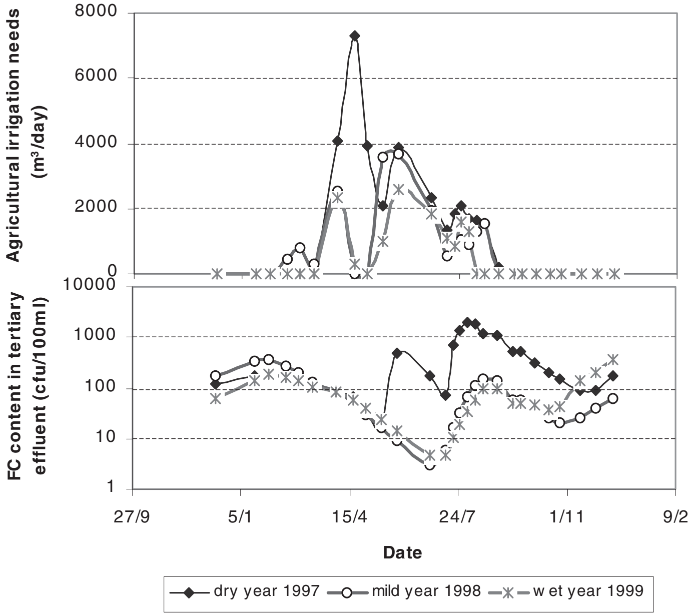

Figure 3 Simulation of effluent water quality and irrigation needs under various climatic conditions (scenario Cl 2)

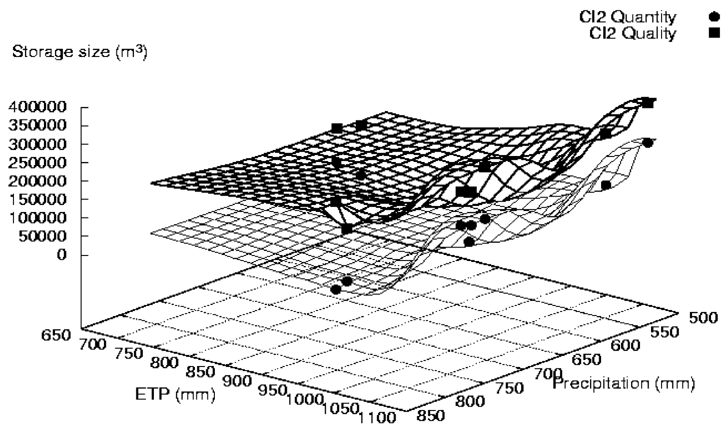

Figure 4 Comparison of storage sizes to meet water quantity and quality requirements (scenario Cl 2)

supply becomes important. To guarantee crop harvest, farmers expect a reliable and safe supply so they expect large reservoirs for reducing the risk. On the other hand, potable water is an alternative source when reclaimed water shortage occurs, despite its high price. Decision makers should trade off the supply reliability and the investment in reservoir construction and conveying potable water as an emergency supply.

In order to meet water quality requirements, other disinfection technologies can be employed instead of extending tertiary lagoons. At present UV disinfection is widely used to remove micro-organisms from reclaimed water. Table 2 compares the investments for two reclamation and storage alternatives: (i) extending the tertiary lagoon system to meet water quality requirements and (ii) UV disinfection in addition to storage meeting water quantitative requirements. Because of the high suspended solids content in the effluent of lagoons, sand filtration is required prior to the UV system. The economic evaluation indicates that a supplementary UV system is more costly than extending the tertiary lagoon sys-

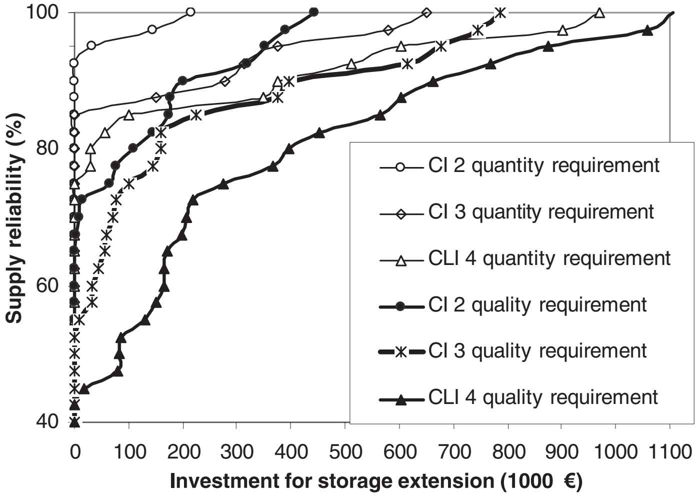

Figure 5 Supply reliability vs the investments for storage extension. Supply reliability is defined as the percentage of years during which quantitative and qualitative requirements would be met every day

Table 2 Estimation of lagoon sizes to meet water quality and quantity requirements and corresponding investments (calculated to meet 1-in-20 year high need)

Scenario	Volume of tertiary lagoons (m^3)		Additional investments for providing qualified reclaimed water (1,000 €)	
	To meet water quantity requirements	To meet health regulations	Lagoon system	Lagoon + filtration + UV
CI 2	259,000	367,000	391	1,352
CI 3	460,000	522,000	745	1,843
CLI 4	590,000	659,000	1,059	2,178

tem due to the high additional investment for filtration, UV equipment, pumps and a one-day post-storage lagoon.

Conclusions

This study presents a modelling approach to assist reclaimed water storage design. Three models were coupled to calculate the storage size of a tertiary lagoon system to meet the water quality and quantity required in different reuse scenarios using 40 years of historic climatic records. The sizes of tertiary lagoons to meet required water quality would be larger than the sizes to meet required water quantity. Stock sizes would increase with water deficit, irrigation demand and supply reliability. With appropriate design, a tertiary lagoon system can provide reliable and cost-effective reclaimed water meeting both irrigation needs and 1,000 FC/100 ml irrigation and discharge guidelines. The application of this methodology to the Noirmoutier case study demonstrates that it is a useful tool to storage design and decision making. It accounts for the impact of climate, water reuse and discharge guidelines, irrigation needs, investments related to the treatment and storage system and the reliability of reclaimed water supply.

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