Technical-economic modelling of integrated water management: wastewater reuse in a French island

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Abstract An integrated technical-economic model is used to address water management issues in the French island of Noirmoutier. The model simulates potable water production and supply, potable and non potable water demand and consumption, wastewater collection, treatment and disposal, water storage, transportation and reuse. A variety of water management scenarios is assessed through technical, economic and environmental evaluation. The scenarios include wastewater reclamation and reuse for agricultural and landscape irrigation as well as domestic non potable application, desalination of seawater and brackish groundwater for potable water supply. The study shows that, in Noirmoutier, wastewater reclamation and reuse for crop irrigation is the most cost-effective solution to the lack of water resources and the protection of sensitive environment. Some water management projects which are regarded as having less economic benefit in the short-term may become competitive in the future, as a result of tightened environmental policy, changed public attitudes and advanced water treatment technologies. The model provides an appropriate tool for water resources planning and management.
Keywords Irrigation; technical-economic model; water management; wastewater reuse

Introduction

Because of the increasing scarcity of water resources, and the significant benefits of water for society, economy and environment, integrated water resources management plays an important role in human sustainable development, but it is complex and the application of computational models has become essential in modern integrated water management (Wavern, 1999; Beck, 1999). In an attempt to optimise water planning and management, an integrated technical-economic model is applied to the management of water and wastewater at the scale of an hydrologic unit. The technical sub-model focuses on water engineering systems, the key to the integral hydrologic cycle, including potable water production, distribution and consumption, and wastewater collection, treatment, disposal and reuse. Combined with the economic sub-model, it allows assessing water management schemes, taking into account economic and technical criteria and environmental impact.

Noirmoutier, an island located off the Atlantic coast, represents a typical insular micro-environment. Its main activities are agriculture, salt production, shellfish farms, fishing, and tourism. Thus its aquatic environment is very sensitive to water pollution, and the discharge of treated water into the sea is periodically forbidden in order to protect the aquatic industries and littoral areas. On the other hand, fresh water resources are virtually negligible in the island. The main supply is potable water conveyed from an hinterland reservoir 70 km away and sold at a high price.

Wastewater irrigation has been implemented for years in Noirmoutier; currently, reclaimed wastewater accounts for 80% in the agricultural irrigation in the North, and 100% in the South. It manifests the unique advantages of preventing coastal area contamination by reducing wastewater disposal to the sea while increasing available water resources. After a secondary treatment, wastewater is stored in shallow reservoirs and

constitutes a reliable water supply for irrigation. Water demand varies with season and is expected to rapidly increase with agricultural development. In the near future, wastewater resources are predicted to become insufficient for agricultural needs in the southern part of Noirmoutier.

Several potential water management alternatives, aimed at addressing water deficits in Noirmoutier, are envisaged and simulated in the model. The economic, environmental and technical benefits are analysed, especially for wastewater reclamation and reuse scenarios. The technical-economic model provides an integrated method to facilitate preliminary planning of water resources management.

Site description

Potable water consumption

The island suffers from seasonal water stress due to irrigation and tourism. The island population increases from 9,000 local residents in winter up to 90,000~130,000 in summer, caused by a high number of visitors. Annual potable water consumption is about 1.2 M.m^3, of which household consumption represents up to 83%; tourism 2% (about $8,000 \text{ m}^3/\text{year}$), while the consumption of landscape irrigation and agriculture is similar and about 7.5% each. Potable water consumption increases at an annual rate of 2%, while water consumption per subscriber keeps relatively constant at around $100 \text{ m}^3/\text{year}$. Monthly variation of potable water consumption (Figure 1) shows that the demand reaches peak points in July and August, passing $11,000 \text{ m}^3/\text{d}$ and being more than five times higher than winter demand ($1,800 \text{ m}^3/\text{d}$).

Wastewater treatment and reuse

Two wastewater treatment plants (WWTP), La Salaisière (in the North) and La Casie (in the South), treat municipal sewage collected from the four communities of the island. Monthly wastewater volumes received by the WWTPs are shown in Figure 2. The collection of run-off water by the sewage network can be deduced from the high volumes received during the winter season. Average sewage flow rates in La Salaisière and Casie WWTPs are $8,000 \text{ m}^3/\text{d}$ and $1,500 \text{ m}^3/\text{d}$, respectively. La Salaisière secondary effluents are stored in a series of 4 reservoirs, with an overall storage capacity of $220,000 \text{ m}^3$, making water available for irrigation and improving the microbiological quality of the stored water. Stored water that cannot be used for irrigation is disposed of to the sea. The volume of water stored in La Salaisière reservoirs is reported in Figure 3, together with flow rates of inlet raw sewage, pumped wastewater for irrigation and wastewater discharged into the sea. Between May and July, most of the stored water is used for irrigation and no water is discharged into the sea. Primary effluents of La Casie WWTP are stored in $90,000 \text{ m}^3$ stabilisation ponds.
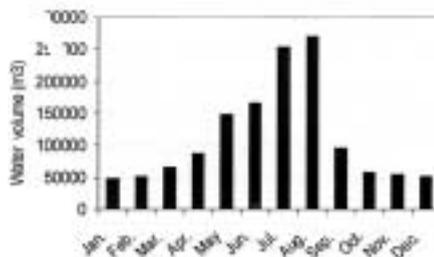
Figure 1 Potable water Consumption in Noirmoutier
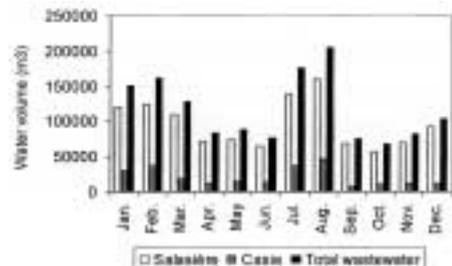

Figure 2 Sewage flow variation in La Salaisière and La Casie WWTP
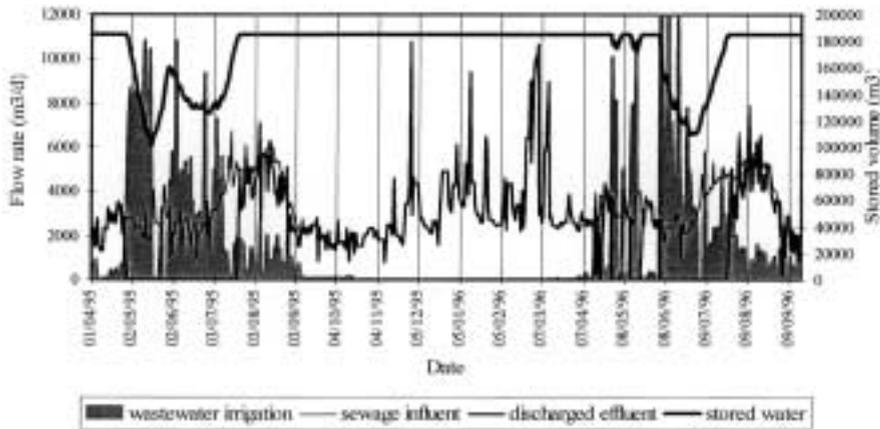
Figure 3 Hydraulic variation in La Salaisière WWTP in 1995 and 1996

At present, from 150,000 to 300,000 m³/year of wastewater stored at La Salaisière WWTP are utilised to irrigate 2.70 km² potato fields, while at La Casie about 30,000 to 50,000 m³/year are used to irrigate an area of 0.35 km² potato fields. In France, wastewater reuse for irrigation is encouraged after appropriate treatment, subject to reclaimed wastewater quality and irrigation conditions complying with public health and environmental requirements. The microbiological water quality characterised as faecal coliform content in the final reservoir and in discharged effluent is presented in Figure 4. Compared with French regulations for wastewater irrigation (CSHPF, 1991), in most cases, irrigation water quality met the class A criteria (helminth egg content < 1 per litre, faecal coliform content < 1,000/100 ml), which is required to protect not only irrigation operators and livestock, but also consumers of food crops which can be eaten raw.

There is no French or European microbiological regulation governing the quality of wastewater discharged to the sea, but bathing waters and shellfish breeding areas, which are not very far from the discharge point, must comply with European Directives. Compared with European Bathing Water Regulation (EEC, 1976), coastal water quality is quite good in Noirmoutier. But the quality of wild shellfish in some areas did not meet the European criteria. The European Union prescribes that less than 300 faecal coliforms are allowed in 100 ml of intervalvular fluid and flesh of the shellfish (EEC, 1979). Unfortunately, the impact of the discharged water quality on that of receiving water bodies is not identified. Therefore, the safe ways to control the water quality of receiving water are to diminish wastewater disposal and to improve discharged water quality.
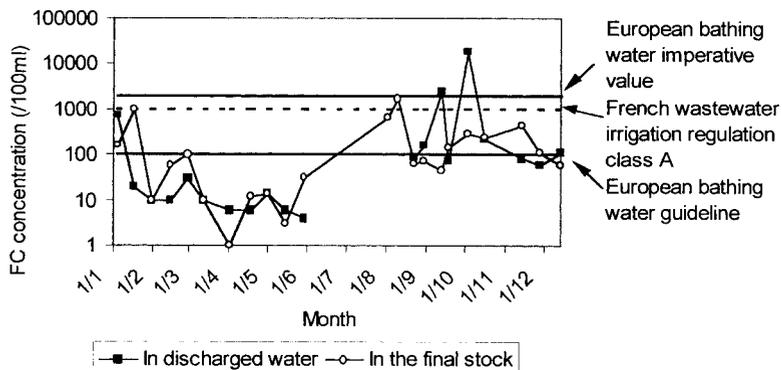
Figure 4 Monthly variation of microbiological characteristics of effluent quality in Salaisière

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Water prices in Noirmoutier

The 4 communities of the island have constituted an association which is in charge of water supply and wastewater collection, treatment, reuse and disposal. This association purchases the potable water and sells it to the consumers. It also sells treated wastewater to the farmers. Prices listed in Table 1 vary with the quantity, quality and usage of water.

Principles of modelling

The model is constructed with the "STELLA" software which offers a flexible and practical tool to build a conceptual framework and a dynamic system to simulate integrated water management (Valette, 1999). The model can be divided into two components.

- A physical model simulating (i) current equipment and its functioning; (ii) potential alternatives and scenarios envisaged to improve water management in Noirmoutier island. Water volumes and flows in the integral hydrologic cycle are calculated according to appropriate time steps. The model can include water production, supply, consumption, wastewater treatment and disposal, groundwater recharge, rainwater runoff and evaporation, etc. Even though some elements or functions are not strictly necessary in the case of Noirmoutier, they may be key parameters in other cases.
- An economic analysis completing the physical simulation.

To avoid taking just a single viewpoint of the water management alternatives, several aspects are considered in their evaluation : (i) basic economic analyses of the costs (investment, maintenance and operation costs) and benefits of installation and running of water and wastewater supply and treatment systems; (ii) island water supply autonomy and (iii) environmental impact.

Physical simulation

The model of Noirmoutier is composed of two sub-models according to the WWTPs' location, one for the North of the island and one for the South. The two sub-models are linked by potable water supply and reclaimed water transportation to compensate water deficit in the South.

Water sources in Noirmoutier are considered as (i) *existing* imported potable water, stored treated wastewater, collected storm water and rain water falling into the reservoirs; (ii) *potential* desalinated sea water or brackish groundwater. Main water consumption is classified into three groups: (i) domestic consumption plus hotels, restaurants and a few enterprises and services; (ii) urban landscape and park irrigation; (iii) crop irrigation, mainly for potato fields.

Economic analyses

The economic sub-model is designed to estimate the economic efficiency of investments. Economic efficiency is evaluated by: (i) marginal cost analyses and (ii) water cost estimates. Economic analyses are developed based on capital investments and annual operation & maintenance (O&M) costs. Capital investments consist of individual water treatment unit, transport and the construction of storage facilities. O&M costs comprise

Table 1 Average water prices in Noirmoutier (including the cost of subscription and meters)

	Potable water (Euro/m³)			Reclaimed water (Euro/m3)
Purchased	Sold			Sold
	Domestic, hotel, etc.	landscape	agriculture	Agricultural irrigation
0.60	4.57*	0.67	1.54	0.23–0.3

Note: * including the price for sewage treatment and disposal : 2.21 Euro/m³

personal salaries, management expenses, operating fees (energy consumption and chemical costs), maintenance costs (equipment repair and replacement). Cost data vary with treatment capacity, market prices for construction, energy, chemicals and equipment, management and operation conditions, as well as with water quality (Adham, *et al.*, 1996; Jolis, *et al.*, 1996; Asano, 1998; Dorau, 1998).

Marginal cost analyses. Marginal cost analyses distinguish the benefit-cost margin from additions to or changes in the project. Benefit-cost margin is the difference between annual income (revenues from the water users) and annual cost (O&M cost and the cost of buying potable water from the hinterland). In addition, potable water and reclaimed water are sold to the subscribers as a beneficial product. The investment will be paid back in a certain number of years, i.e. the payback time *C*, by the benefits. In the model, it is assumed that sunk costs, i.e., costs that occurred in the past, should not influence decisions on future actions (Asano, 1998). Thus payback time *C* is calculated as:

C = Incremental capital investment/Incremental margin

where incremental capital investment is the additional investment related to added equipment and systems for the considered project; and incremental margin is the difference between the considered new scenario and the current situation.

Water cost estimates. The costs of a water project will be paid generally by users in the form of charges. It is necessary and important to consider the users' view of water costs. Lower cost will encourage users to accept the implementation of the project. On the other hand, the water system must be seen as a whole; some users may be affected by the variation of water costs even though they do not participate in the project directly. Water costs help to estimate the economic feasibility of different scenarios. In the model, life cycle costs are used to describe cost estimation over a specific time period (20 years in this study). Life cycle costs of a scenario combine amortised capital investment with annual O&M costs associated with pipelines, treatment plants, pumping stations and storage.

In Noirmoutier, capital investment for the water projects comes from four sources with different rates of contribution according to the extent of benefit to the public: subsidies from the Agriculture Ministry, Water Agency, County, and investment from the community association. Subsidies, which do not need paying off by the community association, are deducted from the true capital investment in the calculation of water costs. Only the loans are supposed to be paid in 20 years at 8% annual interest. Unlike the basis for marginal cost analyses, continuing debt payments for past investments are included in the water costs. For example, consumers will pay the remaining debt obligation for the potable water distribution network regardless of which future action is taken. Taking into account the different construction time of existing equipment and pipelines, different charge rates are developed to calculate the repayment of the remaining capital investment. For example, the potential scenarios will have a 100% charge rate while existing potable water supply system will just have a 15% charge rate.

$$\text{Water cost} = \frac{\left(\sum_{i=1}^{m} \text{loans in capital investment}_j \times \text{charge rate}_j\right) \times \text{capital recovery factor} + \text{annual O \& M cost}}{\text{Annual water volume}}$$

$$\text{Capital recovery factor} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

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where i: interest rate, 8%; n: years of payment, 20 years; j: item of equipment or facility relating to water projects.

Water supply autonomy

The autonomy degree of water supply, i.e., the ratio between the volume of indigenous available water supply and the volume of water demand, which increases with new available water resources, should influence the policy of the community association, because more autonomy reduces its dependency on hinterland potable water supply and increases its latitude for negotiation.

Environmental impact

Even though water reuse is well known for its beneficial impact on environment, it is difficult to measure the benefits of improved water quality and guarantee of public health. Since the discharged water quantity is directly related to environmental quality, we consider the effluent discharge percentage as a relevant indicator.

Model simulations, exploitation and discussion

To optimise water management, the model permits very detailed analyses on several options (Table 2) : (i) irrigation at the actual situation and with increased water demand; (ii) further wastewater reuse for landscape irrigation and domestic non-potable water reuse in order to meet the "zero discharge" goal; (iii) seawater or groundwater desalination to reduce the dependence of the island on imported potable water.

Table 2 Summary of criteria of different water management scenarios in Noirmoutier

Criteria/Scenarios	S1	S2	S3	S4	S5	S6	S7
Economic analyses							
Payback time *C* (year)	– 20.92	14.49	14.90	27.26	21.34	14.87	
Incremental capital investment (1000 Euro)	0	1586	2130	3740	11331	3026	2898
Incremental margin (1000 Euro/year)	0	76	147	251	416	142	195
Specific water cost (Euro/m³)							
Imported potable water	1.56	1.58	1.58	1.62	1.84	–	–
Wastewater treatment	1.54	1.54	1.54	1.54	1.54	1.54	–
Reclaimed water for agriculture	0.26	0.31	0.29	0.29	0.29	0.26	–
Reclaimed water for landscape irrigation	–	–	–	0.96	0.96	–	–
Reclaimed water for non potable dom. reuse	–	–	–	–	1.29	–	–
Desalinated water from sea or aquifer	–	–	–	–	–	2.76	2.59
Environmental impact							
Percent of effluent discharged into the (%) sea	69	55	44	37	9	69	69
Autonomy criteria							
Global degree of water autonomy	0.25	0.34	0.39	0.44	0.79	1	1
Degree of potable water autonomy	0	0	0	0	0	1	1
Degree of non potable water autonomy	0.69	0.87	0.89	1	1	0.69	0.69

Notes about scenarios:
S1: current situation: 20% crop irrigation water is potable water in the North
S2: 100% crop irrigation water is reclaimed water; transporting reclaimed water from North to South to meet agricultural water demand increased by 51%
S3: 100% crop irrigation water is reclaimed water; transporting reclaimed water from North to South to meet agricultural water demand increased by 77%
S4: landscape irrigation in addition to 77% increased agricultural demand
S5: landscape irrigation and domestic non-potable reuse in addition to 77% increased agricultural demand
S6: current wastewater reuse situation, but desalinating seawater to replace imported potable water
S7: current wastewater reuse situation, but desalinating brackish groundwater to replace imported potable water

Wastewater reuse

Due to the insufficient water resources in the South and abundant wastewater in the North, the model simulates the enlargement of reclaimed water reservoirs and the extension of the distribution network to convey reclaimed wastewater from North to South to meet agricultural water demand (scenarios S2 and S3). To maximise the elimination of effluent discharged into the sea, the surplus treated effluent is simulated to be further reused for the landscape irrigation and domestic non-potable reuse (S4 and S5). For domestic non-potable reuse, the simulation is based on these hypotheses: (i) because of the water deficiency and of the smaller population in the South, wastewater urban non-potable reuse is performed only in the North; (ii) in order to ensure reclaimed water quality, microfiltration plus UV irradiation is required after the present treatment processes but only for the effluent devoted to domestic reuse; (iii) reclaimed water is pumped to a storage tower and then distributed to the consumers by dual water supply network; (iiii) reclaimed water is estimated to reduce the domestic water demand by 40% (Law, 1996).

With the increasing degree of wastewater reclamation and reuse, the capital investments grow and the incremental benefit-cost margins rise gradually. Meanwhile payback times for crop irrigation decrease with more treated water reused (scenarios S2 and S3). In contrast, payback times for further water reuse are prolonged owing to added equipment and distribution systems, particularly for S5 in which dual distribution system is constructed for non-potable domestic reuse. On the other hand, scenario S5 is an attractive one, with a greatly increased degree of water autonomy and a very high reduction of effluent discharge. Considering the increased water source and the positive impact on the environment, complete wastewater reuse may become competitive in the future due to increasingly demanding environmental policy, changes in public attitudes, and the advancement of water technologies.

In order to identify the financial feasibility of a project, subsidies are not incorporated into capital investments in the calculation of payback time. Otherwise, subsidies would lower the true capital cost for a project and shorten the payback time. On the contrary, we suppose a 50% subsidy rate for the new water projects in the water cost estimates. It is obvious that the life cycle water costs would be abated greatly by an increased rate of subsidy. It is conceivable that the scenarios with high capital cost but that have non monetary factors which are beneficial to the public (such as S5) might be affordable with the help of subsidies. Nevertheless, the subsidies depend on local and governmental policies.

However, incremental margin and payback time depend greatly on water prices. In this part of the study, reclaimed water prices were supposed to be 0.53 and 3.81 Euro/m^3 for crop or landscape irrigation and domestic non potable wastewater (including the price for sewage treatment and disposal), respectively. These assumed prices are just used to compare the economic feasibility of scenarios, and not to represent real water prices. Payback time decreases reasonably with the rise of reclaimed water prices. For example, payback time for S2 abates from 45 to 21 years, corresponding to agriculture reclaimed water prices augmented from 0.3 (in actual situation) to 0.53 Euro/m^3 (in simulated scenarios). Meanwhile, the rise in reclaimed water price is to offset the rise of potable water cost. It is seen in Table 2 that potable water costs increase because the reuse of wastewater lowers the use of freshwater. It is considered that reclaimed water revenues should make up for the difference. However, the price of reclaimed water is one of the key concerns for wastewater reuse. From the consumers' viewpoint, the reclaimed water is obviously expected to cost less than potable water, and a lower price is clearly better. From the community association's viewpoint, the revenues should be able to cover water reuse project costs. It is essential to negotiate a price based on complementary social and economic analyses, so the price may be accepted by all water users and by the community association.

Desalination of seawater and brackish groundwater

Seawater and brackish groundwater are considered as alternative water resources in Noirmoutier, so water desalination by reverse osmosis (RO) is evaluated in the model (S6 and S7). Compared with imported potable water, economic analyses show that desalinating seawater and groundwater is not cost-effective because of high capital investment and O&M costs. Water costs are estimated as 2.76 Euro/m^3 for seawater and 2.59 Euro/m^3 for groundwater, which are higher than purchased potable water from the continent. However, the autonomy degrees of potable water supply are increased in the island. In addition, with the expectation of declined RO capital and O&M costs, seawater or groundwater may become a competitive potential water resource to substitute or compensate for imported potable water in Noirmoutier.

Conclusions and perspectives

The Noirmoutier application allowed us to verify the chosen approach of the technical and economic model to address water management issues. With the check of a technical model, integrated water management was simulated based on the actual situation and potential scenarios. Evaluations within alternative water projects demonstrated that water reuse for crop irrigation was the most attractive way to solve water scarcity in Noirmoutier and to protect the sensitive environment. Treated wastewater is the resource most easily accepted by the farmers for its low price. In an attempt to reduce significantly the pollutants discharged into the coastal areas, wastewater reclamation and reuse for domestic non-potable application were simulated. Despite economic assessment showing that domestic reuse was not a cost-effective option due to the long dual distribution system and relatively high reclaimed water cost, it might be desirable and affordable by subsidies in view of its beneficial non monetary impact.

The technical scenarios we mentioned just above have not yet exploited completely all the technical-economic issues that should accompany engineering projects. So what presently remains to be done is systematically to exploit the model and to evaluate in more depth the environmental, social and economic issues of water reuse and other improvements on water management. The main purposes and long term objectives of the research are to develop a comprehensive modelling tool for the implementation of sustainable integrated water management and to identify the optimal water management scenario based on water reuse according to local conditions.

Acknowledgement

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