Pergamon

Wat. Sci. Tech. Vol. 39, No. 5, pp. 211–218, 1999

0273–1223/99 $19.00 + 0.00

PII: S0273-1223(99)00104-3

A COST-SUSTAINABILITY ANALYSIS OF URBAN WATER MANAGEMENT

J. Icke*, R. M. van den Boomen* and R. H. Aalderink**

* *Witteveen+Bos Consulting Engineers, P.O. box 233, 7400 AE Deventer, The Netherlands*
** *Wageningen Agricultural University, Department of Environmental Sciences, Aquatic Ecology and Water Quality Management Group, P.O. Box 8080, 6700 DD Wageningen, The Netherlands*

ABSTRACT

A simple model for the urban water cycle is presented, based on mass balances for water and phosphorus. This model is used for the evaluation of the sustainability rate of the urban water cycle. This type of model is to be used in an early stage of town planning, to compare several possible measures. In general, contributing to achieving a more sustainable urban water management. A sensitivity analysis was performed to rank the management options and additional measures to their contribution to the sustainability rate of the urban water cycle. A module for the calculation of cost was linked to the model, revealing the relation between cost and the sustainability rate for a wide range of scenarios. The results show that an improved separated sewer system and the use of a local ground water source have the biggest impact on the sustainability rate. A slightly positive correlation between investment cost and the sustainability rate was found as well. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Modelling; sustainability; cost; urban water management; phosphorus.

INTRODUCTION

In The Netherlands several plans for new building sites are made, or will be made in the near future. At many locations initiatives are taken aiming for a more sustainable urban water management. Examples of such new towns are Vathorst (Amersfoort), Leidsche Rijn (Utrecht) en IJlanden (Hoofddorp).

During the initial phase of town planning, town-planners, architects and water managers are expected to evaluate the possibilities and the potentials of the water system and to integrate the urban water cycle in the town plan. A wide spectrum of management options and additional measures is available, ranging from re-use of water in households to the treatment of urban run off in helophytefilters. Prior to the making of a detailed town-plan water and mass balances for phosphorus and pollutants are often applied to make an inventory of the functioning of the proposed water system and effectiveness of the proposed measures. As a result of this first inventory, a program of design demands is made. In accordance with these design demands a detailed town plan is made.

In this paper an extended mass balance model is presented for water and phosphorus in the urban area. The model is characterised by a high level of aggregation, covering the major components of the urban area. In order to compare the different scenarios for the urban water system that are proposed, a so-called sustainability rate has been defined. A simple module for the calculation of the cost is linked to the model, based on expert opinion. This facilitates balancing the sustainability rate against the cost.

As input for the model geographical, hydrological and urban building characteristics are used of Leidsche Rijn; one of the largest building areas in The Netherlands at the moment. It is to be expected that in the year 2015, this urban area will have a population of 100,000 inhabitants. The total area comprises 10,000 hectare, including a recreational lake and a large central park.

Several design demands have been formulated. Firstly the phosphorus concentration in the water system should be less than 0.05 mg P/l. Phosphorus is generally regarded as being the controlling nutrient for eutrophication in shallow Dutch surface waters. Furthermore, the town should be self sufficient in water. It should only be necessary in dry years to take in water from the Amsterdam-Rhine channel, a nearby shipping channel containing water of rather poor quality. Under average Dutch meteorological conditions, the precipitation surplus occurring during winter could be stored in the groundwater or the surface water, thus preventing the intake of water during average summers. However, the groundwater level and the surface water level should fluctuate no more than 30 cm. An extensive network of canals will be constructed in Leidsche Rijn. This canal system can be used for urban drainage. Infiltration devices and helophytefilters are proposed to serve as natural treatment systems for urban run off.

METHODS

A definition of sustainability

An operational definition of the sustainability rate of the urban water cycle was defined. A set of seven goal variables was selected. The goal variables are regarded to be representative for the impact of the urban area on the surroundings, the quality of urban waters and the accumulation of pollutants in the urban area. In Table 2 an overview of the selected goal variables is given. In the most sustainable situation the values of these goal variables should be minimized. The 'sustainability rate' can be calculated, being the sum of the scaled and weighted goal variables.

The goal variables are scaled according to the difference between their minimum and maximum values, thus scaling all goal variables between 0 and 1. The sustainability rate is the sum of these scaled goal variables of sustainability. Each scaled goal variable is multiplied by a weighing factor. The sum of these weighing factors equals 1.

$$S = 1 - \sum_{i=1}^{7} (f_i \cdot G_{s,i})$$

where:

S	sustainability rate	(-)
f_i	weighing factor for goal variable i	(-)
$G_{s,i}$	scaled goal variable i	(-)

Given the hydrological and geographical boundary conditions, the most sustainable urban water system has a sustainability rate that equals 1. In the least sustainable condition the sustainability rate equals 0. It should be noted that the sustainability rate is a relative value, indicating whether the possibilities of the urban water system are fully used.

In this study, all weighing factors are of the same value (1/7). In specific cases, other goal variables for sustainablity might be defined and a distinction might be made between the importance of the goal variables by assigning different values to the weighing factors.

Model description

The water and mass balance model provides the link between control variables (the management options and the additional measures) and goal variables for sustainability. Examples of control variables are the chosen types of sewer system, drinking water source and waste water treatment plant. In Table 2 a complete overview of the control variables and the goal variables is presented. The outline of the model used is presented in Figure 1.

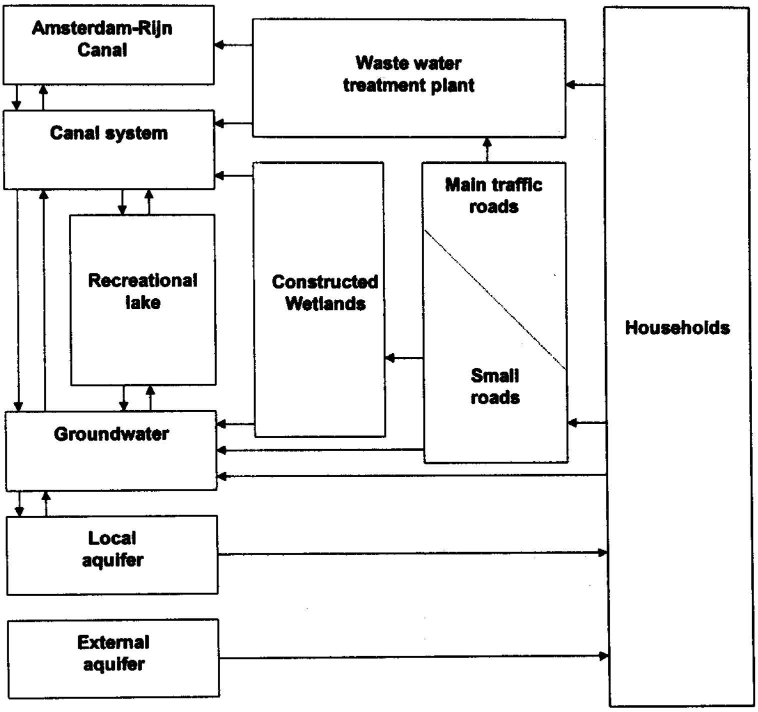

Figure 1. Model outline: scheme of the major components, affecting the urban water and phosphorus cycle.

The model includes mass balances for water and phosphorus for all major components in the urban water cycle, such as waste water production, runoff from impervious areas, transport and treatment, surface water and groundwater. A sub model for water use and waste water production by households is included as well (see Figure 2). This allows for the evaluation of the impacts of the use of rain water and reuse of grey water in households. Four different sewer systems have been evaluated with the model: the combined sewer system, the improved combined sewer system, the separated sewer system and the improved separated sewer system.

The water cycle is driven by rain, evaporation, water demands and water transport in the sewer system and surface waters. The exchange of water between the groundwater and both surface water systems is modelled in a simple way. It is assumed that equilibrium levels are reached at the end of each time step of one month. Since the availability of water of good quality is limited during dry years, the meteorological data of the typically dry year 1976 have been used. The water demand in households was derived from the number of inhabitants and the average water use in The Netherlands (Achtienribbe, 1996).

The quality of the domestic waste water flows was estimated from Butler *et al.* (1995). As for runoff quality, data from Mikkelsen *et al.* (1994) and NWRW (1989) were used. A distinction has been made between relatively clean areas (roofs etc.) and intensively used areas such as main roads. An estimate of phosphorus retention in the impervious pavement was obtained from Urbonas (1994). The removal efficiency for constructed wetlands was estimated at 50% according to De Ridder (1996). The phosphorus concentration in the lake and in the channel system was calculated using a Vollenweider type of model, relating the summer average P level to the loading, residence time and hydraulic load of the system. An empirical equation formulated for Dutch lake systems was used (Lijklema *et al.*, 1989).

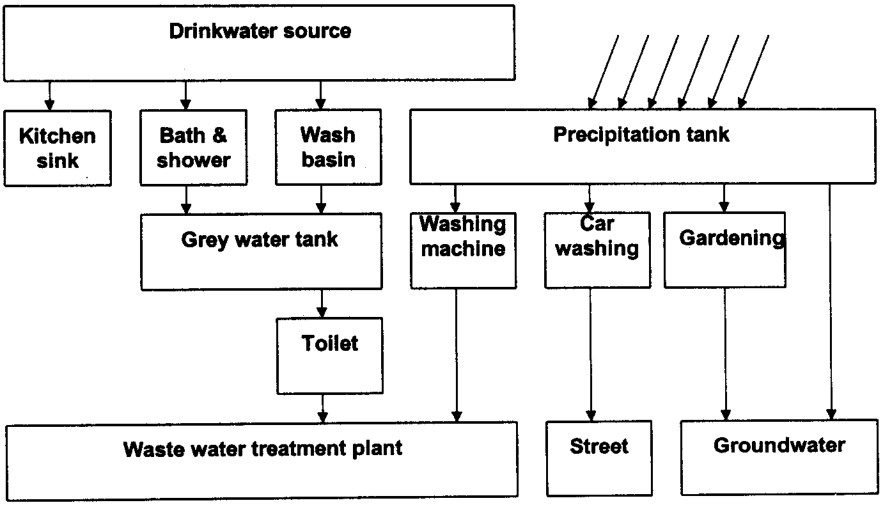

Figure 2. Sub model: a household with a tank for the collection of precipitation and a tank for the reuse of grey water.

Sensitivity analysis

A sensitivity analysis has been carried out with the model, showing the sensitivity of the model for the control variables. For this senstivity analysis a standardized regression model was used, with normalised data and standard deviations as input. The meta model has been made with linear regression, based on runs with randomly varying control variables. With the standard regression coefficients (SRC) the control variables can be ranked, revealing those measures that have the biggest impact on the sustainability rate (Janssen *et al.*, 1990).

Cost functions

Simple linear cost functions were coupled to the model, describing the relation between the control variables and the investment cost and maintenance cost. These cost functions are based on rough estimates and indicate about the cost related to the management options for sewer system, surface water system, the waste water treatment plant etc. A detailed calculation of the cost is rather difficult and depends on many specific factors and local circumstances that are often not known at an early stage of town planning.

RESULTS AND DISCUSSION

Sensitivity analysis

The results of the sensitivity analysis are shown in Table 1. The control variables have been ranked by the SRC: a high SRC stands for great influence of the control variable on the goal variables and subsequently on the sustainability rate. In the analysis, large scale management options turned out to be contributing most in achieving a sustianable urban water cycle, such as the management options separated sewer system and the use of a local aquifer for the production of drinking water.

Additional measures, such as the disconnection of local roads from the (separated) sewer system and the treatment of urban run off in helophytefilters turned out to have little impact if any. These measures are affect relatively unimportant water flows. However, in existing towns where management options are fewer, these small scale measures might still prove to be very useful to achieve a more sustainable water system.

Table 1. Sensitivity analysis: the sensitivity of the sustainability rate for the control variables

	control variable	SRC
C12	sewer system	0.539
C11	drink water source	0.450
C14	effluent P concentration	-0.314
C2	surface area canal system	0.275
C13	Dephosphating installation canal system	0.210
C8	grey water tanks households	0.171
C7	rain water tanks households	0.136
C4	depth canal system	0.109
C5	local roads: disconnection from sewer	-0.067
C3	depth recreational lake	0.059
C6	surface area helofyts	0.052
C1	surface area recreational lake	0.042
C9	Permeable pavement local roads	0.021
C10	Permeable pavement main roads	-0.001

Scenario studies

The following four scenarios have been evaluated with the model:

Scenario 1:	All control variables at their minimum values: no specific measures are applied;
Scenario 2:	All control variables at their maximum values: all available measures and management options are fully applied;
Scenario 3:	The seven control variables for which the sustainability rate is most sensitive are at their maximum value;
Scenario 4:	Out of a set of 10,000 alternatives generated by randomly varying control variables, the alternative with the highest rate of sustainabliliy is selected.

For each scenario the values of the goal variables are calculated, as well as the sustainability rate, the investment cost and the maintenance cost. The results of the simulations are presented in Table 2.

The phosphorus concentration in the hydrologically isolated lake is always below 0.05 mg P/l, whereas the phosphorus concentration of the canal system is above the desired level during a dry year. The import of water is varying between the scenarios. The town is clearly not self supporting with water. An increasing use of locally recharged groundwater source leads to an increasing import of surface water from outside of town.

A striking contrast was found between scenario 1 and the other three scenarios. These scenarios can be characterized by a high sustainability rate and few differences between the goal variables. The investment cost of the most sustainable systems are about two times as high as the investment cost of a 'traditional' water system. The most expensive investments are the improved separated sewer system and a large scale surface water system. The maintenance cost seem to decrease with an increasing sustainability rate. In a more sustainable water system the water demand is lower and consequently the cost related to the production, transport and treatment of water are lower as well.

Table 2. The simulation results for 4 different scenarios. For explanation of the scenarios: see the text

	Control variable	Units	scen. 1	scen. 2	scen. 3	Scen. 4
C1	Surface area recreational lake	Ha	50	150	50	68
C2	surface area canal system	Ha	50	150	150	140
C3	depth recreational lake	M	1.50	3.50	1.50	2.60
C4	depth canal system	M	1.50	3.50	1.50	2.50
C5	local roads disconnected from sewer	-	0	1	0	0.25
C6	surface area helophytes	Ha	0	15	0	14
C7	rain water tanks in houses	-	0	1	1	0.73
C8	grey water tanks in houses	-	0	1	1	0.67
C9	permeable pavement on local roads	-	0	0.5	0	0.45
C10	permeable pavement on main roads	-	0	0.5	0	0.44
C11	drinking water source: deep / local aquifer	-	0	1	1	0.75
C12	(improved) sewer system: combined / separated	-	1	4	4	4
C13	Dephosphating installation canal system	G P/y	0	$5\ 10^5$	$5 \cdot 10^5$	$4.7 \cdot 10^5$
C14	effluent P concentration wwtp	Mg P/l	1.00	0.10	0.10	0.14
	goal variable	Units	scen. 1	scen. 2	scen. 3	Scen. 4
G1	Import of water	10^6 m^3/y	3.48	1.54	1.53	2.12
G2	Export of phosphorus	10^6 g P/y	6.98	0.41	0.44	0.62
G3	P concentration recreational lake	Mg P/l	0.055	0.004	0.008	0.005
G4	P concentration canal system	Mg P/l	0.403	0.060	0.084	0.065
G5	P accumulation lake sediments	G P/m^2,y	0.104	0.019	0.022	0.023
G6	P accumulation canal sediments	G P/m^2,y	1.551	0.269	0.224	0.238
G7	P accumulation soil	G P/m^2,y	0.031	-0.031	-0.039	-0.029
	Sustainability rate	Units	scen. 1	scen. 2	scen. 3	Scen. 4
	0: least,1: most sustainable water cycle	-	0.12	0.95	0.93	0.92
	Cost	Units	scen. 1	scen. 2	scen. 3	Scen. 4
	Investment cost	10^6 Dfl	390	878	769	735
	Variable cost	10^6 Dfl/y	12	9	9	10

A brief cost-sustainability analysis

About 1,000 scenarios were generated with the model by randomly varying the control variables. For each scenario the sustainability rate and cost were calculated. Figure 3 shows the scattered plot of the investment cost versus the sustainability rate. A slightly positive correlation can be found between the investment cost and the sustainability rate. Clearly, for a certain amount of money one can develop both a sustainable and a non-sustainable water system. On the other hand, a more or less sustainable water system can be achieved either for low cost or for high cost. The scatterplot can be explained as follows:

- the small scale additional measures, which have little impact on the sustainability rate, is still costing money;
- some measures are as effective as others, but have a different cost.

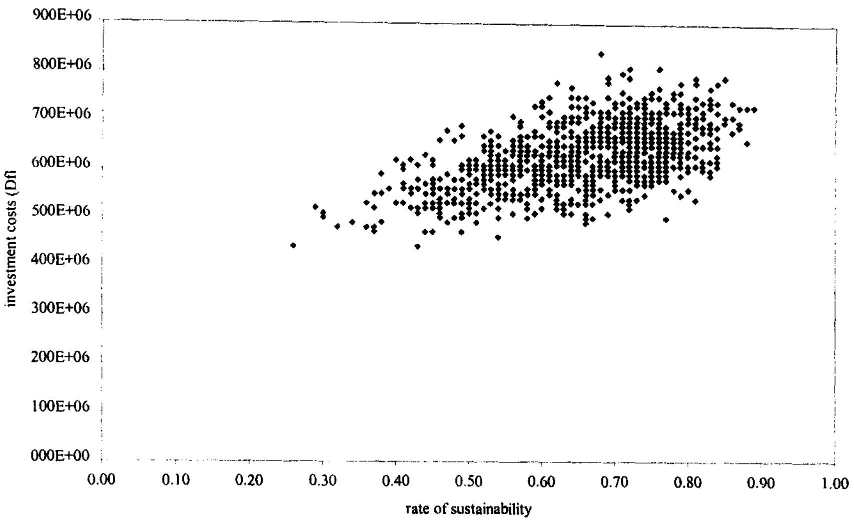

Figure 3. The investment cost of the urban water cycle versus the sustainability rate.

CONCLUSIONS

The case study about the Leidsche Rijn method showed that an improved separated sewer system and the use of locally discharged ground water contribute most to a more sustainable urban water cycle. A slightly positive correlation was found between the investment cost and the sustainability rate. The presented method is the subject of ongoing development: in the near future non-linear cost functions will be coupled to the model. The relatively simple method for a cost-sustainability analysis of urban water management will be applied for other new building sites too, in an early stage of town planning, together with a sensitivity analysis of the weighing factors.

REFERENCES

Achttienribbe, G. E. (1996). Het waterverbruik thuis onder de loep, VEWIN-NIPO onderzoek 1995. *H2O*, **29**(10), 278-279. (Domestic wateruse in The Netherlands, 1995)

Butler, D., Friedler, E. and Gatt, K. (1995). Characterising the quantity and quality of domestic wateruse inflows. *Wat. Sci. Tech.* **31**(7), 13-24.

House, M. A., Ellis, J. B., Herricks, E. E., Hitved-Jacobsen, T., Seager, J., Lijklema, L., Aalderink, R. H. and Clifford, I. T. (1993). Urban drainage impacts on receiving water. *Wat. Sci. Tech.* **27**(12), 117-158.

Janssen, P. H. M., Slob, W. and Rotmans, J. (1990). *Gevoeligheidsanalyse en Onzekerheidsanalyse: een Inventarisatie van Ideeën, Methoden en Technieken.* Rijksinstituut voor volksgezondheid en milieu, Bilthoven. (Sensitivity analysis and uncertainty analysis: a review of ideas, methods and techniques.)

Larsen, T. A. and Gujer, W. (1997). The concept of sustainable urban water management. *Wat. Sci. Tech.*, **35**(9), 3-10.

Lijklema, L., Jansen, J. H. and Roijackers, R. M. M. (1989). Eutrophication in the Netherlands. *Water Sci. Tech.*, **21**(12), 1899-1902.

Lijklema, L., Tyson, J. M. and Lesouef, A. (1993). Interactions between sewers, treatment plants and receiving waters in urban areas: A summary of the INTERURBA '92 Workshop conclusions. *Wat. Sci. Tech.* **27**(12) 1-29.

Mikkelsen, P. S., Weyer, G., Berry, C., Wladen, Y., Colandini, V., Poulsen, S., Grotehusmann, D. and Rohlfing, R. (1994). Pollution from urban stormwater infiltration. *Wat. Sci. Tech.*, **29**(2), 293-302.

Nationale werkgroep riolering en waterkwaliteit NWRW (1989). *Eindrapportage en evaluatie van het onderzoek 1982-1989.* Ministerie van Volkshuisvesting, ruimtelijke ordening en milieu, Den Haag. (National research group on sewer systems and water quality: final report 1982-1989.)

Ridder, R. P. de (1996). *Integratie van oppervlaktewaterzuivering, natuur en andere functies in moerassen.* LBL-mededeling 206, Dienst Landinrichting en Beheer Landbouwgronden, Utrecht. (Integration of surface water treatment, nature and other functions in wetlands)

Schilling, W., Bauwens, W., Borchard, D., Krebs, P., Rauch, W. and Vanrolleghem, P. (1997). Receiving water objectives. Scientific arguments versus urban wastewater management practice. Proc. 27th IAHR Congress, San Francisco, USA. 510-515.

Urbonas, B. (1994). Assessment of storm water BMPs and their technology. *Wat. Sci. Tech.* **29**(1-2), 347-353.