EnviroInfo 2002 (Wien)
Environmental Communication in the Information Society - Proceedings of the 16th Conference
 ISBN: 3-9500036-7-3

Water Quality Management of a Sub-Watershed of the River Elbe

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Abstract

Applying multi-objective decision making methods to water quality management tasks optimal compromise solutions between ecological and man-made management operations will be obtained. The DSS REHSPROX was used to compute Pareto-optimal solutions of the DO balance of the Upper Spree River as a part of the River Elbe basin. For this reason, contradictory water quality and economical goal functions describing different management policies are taken into consideration. According to multi-objective optimisation results cost functions for investments are presented.

Zusammenfassung

Die Anwendung mehrkriterieller Optimierungsverfahren gestattet eine Berechnung von Kompromißvorschlägen zur Lösung von Aufgaben des Wassergütemanagements von Flußeinzugsgebieten. Das DSS REHSPROX wurde zur Berechnung Pareto-optimaler Lösungen der Sauerstoffbilanz für die obere Spree als Teileinzugsgebiet der Elbe angewendet. Zur Ausarbeitung von Entscheidungszenarien wurden kontradiktorische Zielfunktionen verwendet. Als Ergebnis erhält man optimale Kostenverteilung für Investitionen.

1. Introduction

Rivers are polluted by various anthropogenic interactions within settlements, by agriculture, and by industries. Polluted water affect the ecosystem behaviour and various water uses, and risk human health. Therefore, water quality management (WQM) strategies on a river basin scale have to consider political, economical, environmental, social, technological, and informational objectives. Water quality monitoring of surface waters allow statements for single important state variables while the control of such systems implies situations of decision making which are characterised by

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multiple states, contradictory goal functions and different evaluation scales and appreciations. Applying multi-objective decision making methods for WQM of river basins optimal compromise solutions between ecological and man-made control operations will be obtained.

Therefore, for WQM major emphasis is laid on eutrophication and self-purification processes. Extended DO-BOD models and eutrophication models have become widespread for river basin management studies where WQM alternatives are specified either in terms of river water quality or in terms of effluent standards. Then, management decisions were made by ranking of different scenarios resulting from simulation models. In opposite of the use of water quality simulation models only some applications of decision support systems for WQM exist (Hahn and Cembrowicz 1981; Cembrowicz 1988; Ivanov et al. 1995, Gnauck 2001).

In this paper results of a DSS for WQM on a river basin scale are presented and discussed. The River Spree form a sub-watershed of the River Elbe. It contributes to the pollution of the Elbe river by dissolved inorganic load and phytoplankton biomass. For the Upper Spree River self-purification problems play an important role. The DSS REHSPROX was used to compute optimal management decisions regarding to the DO-balance. The variables DO, BOD, the amount of wastewater quantity and costs of enlargement of WWTPs are taken into consideration.

2. Multi-objective decision making

A multi-objective decision making process is given by four phases (Steuer 1986): The search phase (analysis of changes in systems structure and function), the modelling phase (modelling process, imbedding the simulation model into an optimisation procedure, formulations of goal functions), the selection phase (choosing of one alternative of action of the set of all alternatives), and the decision making phase.

Solving a decision problem three requirements have to be fulfilled (Hwang and Masud 1979, Chankong and Haimes 1983): Each solution of the decision problem is an efficient alternative (problem of validity), each efficient alternative may be a solution of the optimisation procedure (problem of non-discrimination), each solution of the decision problem is an efficient alternative (problem of identification). Ester (1987) distinguished between multiple attribute decision making (MADM) and multiple objective decision making (MODM). In the first case the alternatives can be explicitly evaluated by discrete values of the goal functions. In the latter case the evaluation of alternatives is implicitly given by functionals and can change continuously in the domain of admissible solutions. Lewandowski and Wierzbicki (1988) classified DSS by simple software tools (e.g. data bases), by expert systems and knowledge based systems and by model based DSS.

3. Experimental area and methods used

The source of the River Spree lies in hilly region in Southern Saxonia. The upper part of the river is influenced by loadings of the geological underground of the river bed and the drainage area (Gnauck 1984, Gnauck et al. 1989). To model the DO-BOD-balance a modified Streeter-Phelps type model (Streeter and Phelps 1925) was used:

$$dDO^{(i)}(t)/dt = -(K_2(TW) + Q^{(i)}/V^{(i)})\, DO^{(i)}(t) - K_1(TW)BOD^{(i)}(t)$$
$$+ Q^{(i)}/V^{(i)} DO^{(i-1)}(t-t_F) + K_2(TW)\cdot CS(TW)$$
$$+ DOE^{(i)}(t)QE^{(i)}/V^{(i)}u^{(i)}(t)$$

$$dBOD^{(i)}(t)/dt = -(K_1(TW) + Q^{(i)}/V^{(i)})BOD^{(i)}(t)$$
$$+ Q^{(i)}/V^{(i)}\, BOD^{(i-1)}(t-t_F)$$
$$+ BODE^{(i)}(t)QE^{(i)}/V^{(i)}u^{(i)}(t),$$

where t - time variable, DO - dissolved oxygen concentration (mg/l), BOD - concentration of biological oxygen demand (mg/l), K_1 - BOD decay rate constant, K_2 - reaeration rate constant for DO, Q - mean volumetric flow rate, V -mean volume of a river segment, TW - water temperature (^oC), CS - saturation concentration of DO, i - number of segment, E - input of DO or BOD, t_F - time of flow and $CS(t) = 14.65 - 0.41022\cdot TW + 0.007991\cdot TW^2 - 0.0000474\cdot TW^3$. The annual time course of TW(t) is given by $TW(t) = 13.16 + 10.23\cos((2\pi\, t-213)/365)$.

Segmentation was done in longitudinal direction by 11 segments. The global parameters describing DO-producing and DO-consuming reactions as well as pertinent hydraulic parameters (flow rate, flow velocity etc.) considered as constant for each segment. Segments are also determined by tributaries and essential waste water inputs. Inputs of organic load are located at the beginning of a segment (if any), where a segment is considered as a CSTR with complete mixing approximately. Water quality variables observed are given at the beginning and at the end of each segment. Then the output of the i-th segment will be the input of segment (i+1).

The optimisation procedure was developed by Straubel and Wittmüß (1983). The DSS works in an interactive dialogue form where no special requirements are necessary for the type of process equations and for the mathematical formulations of the goal functions. Time-dependent restrictions of the management variables in form of lower and upper bounds and other implicite formulated restrictions between state and management variables are taken into account additionally. Optimisation results presented are valid for mean flow conditions.

According to the chosen model structure the goal functions were formulated as extremal values in dependence on the ecological and socio-economical standards.

1. Efficient control of waste discharges from point sources
F(1) - mean value of dissolved oxygen (DO) ⇒ Max
F(2) - mean value of biochemical oxygen demand (BOD) ⇒ Min
F(3) - total amount of waste discharge from point sources (QE) ⇒ Max
2. Cost analysis for WWTP
F(1) - mean value of dissolved oxygen (DO) ⇒ Max
F(2) - mean value of biochemical oxygen demand (BOD) ⇒ Min
F(3) - total investment costs ⇒ Min
The results are presented in table 1 where bold values characterise the individual optima.

Table 1: Domain of decision for two WQM alternatives

Control option	**F(1) DO (mg/l)**	**F(2) BOD (mg/l)**	**F(3) QE (m^3/a), Mio EUR**
Control of wastewater input	**10,4**	32,8	$50,1*10^6$
	10,4	**32,8**	$50,1*10^6$
	9,7	56,5	**$55,1*10^6$**
Enlargement or Reconstruction of WWTP	**10,5**	40,8	44,1
	10,5	**40,8**	44,1
	8,7	100,0	**0,0**

4. Results and discussion

On the basis of DSS REHSPROX two management alternatives are considered. For the first management strategy, a maximum of waste water input will be reached for a minimum value of DO while the amount of degradable wastes is medium. In table 2 Pareto-optimal solutions are presented. Only five optimal solutions could be computed for the development of an optimal management strategy of waste water input from point sources to the river. For a low amount of purified waste water input an acceptable yearly mean concentration of DO is in accordance with a low BOD concentration. Because of small differences in DO the decision criterion should be the yearly mean BOD concentration.

A broader basis for decision making is given for the enlargement or reconstruction of WWTPs. The yearly mean DO concentration increases with increasing costs while the BOD concentration decreases. Two places marked in the list are interesting for decision making. The first one is characterised by DO=8.89, BOD=97.0 and costs=8,10 Mio. EUR. For a little higher budget (costs=8,25 Mio. EUR) a decrease of BOD concentration of about 20 mg/l and an increase of DO concentration to 9.49 mg)l will be reached. An analogous cost effect will be obtained for the second place.

Table 2: Optimal solutions for WQM

Management alternative	**DO (mg/l)**	**BOD (mg/l)**	**QE (m^3/a) Costs (Mio. EUR)**
Waste water input	9,85	52,3	54,00
	10,00	46,8	53,35
	10,14	42,1	52,37
	10,32	36,6	50,72
	10,42	32,8	50,06
Enlargement/reconstruction of WWTP	8,78	101,0	0,00
	8,78	100,7	1,00
	8,79	100,6	1,60
	8,79	100,5	2,00
	8,79	100,3	2,60
	8,80	100,3	3,00
	8,80	100,1	3,60
	8,84	98,9	4,25
	8,84	98,7	5,25
	8,85	98,5	5,85
	8,88	97,2	7,10
	8,89	97,0	8,10
	9,49	**76,6**	**8,25**
	9,50	76,3	9,25
	9,51	75,9	10,85
	9,55	74,7	12,50
	9,56	74,1	14,10
	9,60	72,8	15,75
	10,20	**52,2**	**16,50**
	10,22	51,7	18,50
	10,26	50,2	20,75
	10,31	48,5	23,60
	10,32	48,3	27,00
	10,34	47,1	39,80

Shifting the budget from 15,75 Mio. EUR to 16,50 Mio. EUR results in a diminishing BOD concentration of about 20 mg/l. In both cases the effect on DO concentration gives an increase of DO of 0.6 mg/l.

The decision making process was carried out in detail for all river segments. Mainly polluted river reaches are the segments 3, 7 and 9. Table 3 shows the Pareto-optimal results for different capacities of WWTPs for a 85%-BOD-removal.

Table 3: Proposals of scenario for WQM

Segment	**Capacity (m^3/d)**	**Capacity (%)**	**BOD (mg/l)**	**BOD (kg/d)**	**Costs (Mio. EUR)**
3	0	0	140	3013	0,00
	10750	50	82	1765	8,25
	21500	100	24	516	16,50
7	0	0	580	4009	0,00
	1037	15	561	3878	1,00
	2074	30	542	3746	2,00
	4500	65	426	2945	4,25
	4835	70	348	2405	4,50
	5875	85	329	2274	5,50
	6912	100	310	2143	6,50
9	0	0	94	2282	0,00
	1250	5	83	2015	1,00
	2500	10	78	1894	2,00
	3750	15	73	1772	3,00
	5000	20	66	1600	4,00
	7500	30	59	1491	5,60
	18750	75	45	1122	15,20
	22000	90	28	702	16,80
	23750	95	20	514	19,80
	25200	100	13	333	20,80

According to the budget available a combination of different enlargements and/or reconstructions of sewage treatment plants can be taken into consideration. Table 4 presents some scenarios for Pareto-optimal decision making.

Table 4 Results of scenario analysis for WQM

Scenario	River segment	Enlargement of WWTP (%)	Capacity (m^3/d)	Costs (Mio. EUR)	Sum (Mio. EUR)
1	3	100	21.500	16,50	16,50
2	9	90	22.000	16,80	16,80
3	3 9	100 10	21.500 2.500	16,50 1,60	18,10
4	3 9	100 75	21.500 18.750	16,50 15,20	31,70
5	3 9	100 100	21.500 25.000	16,50 20,80	37,30
6	3 7 9	50 65 95	10.750 4.500 23.750	8,25 4,25 19,80	32,30
7	3 7 9	50 100 30	10.750 6.912 7.500	8,25 6,50 5,60	20,35
8	3 7 9	50 65 30	10.750 4.500 7.500	8,25 4,25 5,60	16,10
9	3 7 9	100 100 100	21.500 6.912 25.000	16,50 6,50 20,80	43,80
10	3 7 9	100 70 15	21.500 4.835 3.750	33,00 9,00 6,00	48,00

5. Conclusions

Most of the river water quality problems are related to the interactions between the discharged matter and river organisms. The primary mechanisms for conservative non-degradable wastes are transport and dilution while degradable waste concentrations are described mathematically by considering the natural transport and decay processes. Because a complex relationship exists between the biochemical oxygen demand (BOD) of the waste discharged and the dissolved oxygen (DO) concentration at points downstream of the discharge, this relationship has become one of the main indicators governing river water quality.

1. Efficient control of waste discharges from point sources.
2. Cost-benefit analysis for reconstruction and/or enlargement of existing or new construction of WWTPs.

The use of control theory for WQM is an approach promising more theoretical understanding of complicated natural processes. The study of goal functions can be seen as a study of mechanisms underlying changes in complex systems. Such study is far from simple, because there is no direct method to observe a goal function. The next step in the development of a DSS on a river basin scale will be the usage of IS-SOP and of an eutrophication model for rivers and riverine lakes.

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