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Optimum Sustainable Water Management in an Urbanizing River Basin in Japan, Based on Integrated Modelling Techniques

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Abstract: In this research, a Decision Support System ("DSS") was developed, using a combination of various existing models for Integrated Water Management ("IWM"). This DSS is then applied to a small urbanized basin, the Taguri-River basin in Japan. In developing the DSS, different existing dynamic and steady state models were combined. These models include a rainfall-runoff analysis model, two river analysis models, a groundwater analysis model, and a geographical information system ("GIS"). The DSS was developed based on three basic elements: Database, model base, and tool base. A data exchange architecture was chosen and then exchange programs were written that are to act between different water analysis models in order to adequately translate the data format for each respective model. To improve the overall water condition in the basin, the DSS was used to simulate ten different measure-scenarios for the focus basin. These scenarios consider land use, ground water level, allocation of drainage system, sewerage, water quality and quantity. During the research it became evident that a combination of measures is most effective for the basin, and accordingly such combination of measures was also simulated with the DSS. Finally, this paper describes the uncertainties of the DSS and discusses its further practical applicability.

***Keywords**:* Decision Support System; Integrated Water Management; Geographical Information System; Combined Model; Data Exchange Architecture

1. INTRODUCTION

Water problems consist of many different inter-related elements: Social, ecological, and economical elements. Thus, effective water management requires a device that provides the decision maker with accurate descriptions of various water conditions, including surface water and groundwater, and considering water quality and water quantity in dry and wet weather (Water management that takes into account all the abovementioned factors is called "Integrated Water Management: IWM"). Moreover, sustainable water management requires assistance from and decision-making involving all the different groups within the focus basin: Politicians, administration officers, civil engineers, and stakeholders. In order to ensure the participation and support of these groups, it is a prerequisite to inform them about the effects of intended measures and water management in an efficient and transparent way. Therefore, a device is required to gather and display the necessary information.

A simulation model allows the user to evaluate various water conditions and their complex interaction as a whole, without generating high costs and long simulation times, and thus is useful for decision-making. Moreover, it is able to illustrate, which measure is most effective and in which way this measure influences upon different stakeholders, society, nature, and of cause the economy. Such a model that is able to simulate various water conditions in a basin and help in decision-making is the most important part of a Decision Support System ("DSS").

In this research, a DSS is developed using a combination of various existing models for IWM. It is then applied to the Taguri-River basin in Japan, a small urbanizing basin.[1]

2. THE FOCUS RIVER BASIN

The Taguri-River basin is located 30-50 km northeast of Tokyo in the Chiba prefecture in Japan (Figure 1). The basin belongs to the Inba-Numa-Lake basin. The Taguri-River basin has an area of 19 km^2. The river flows through two local communities from south to north and into the Inba-Numa-Lake. The river system consists of one main river and two small tributaries. The entire basin can be divided into four sub-basins (Figure 2). The first sub-basin (A-basin) includes the upper stream of

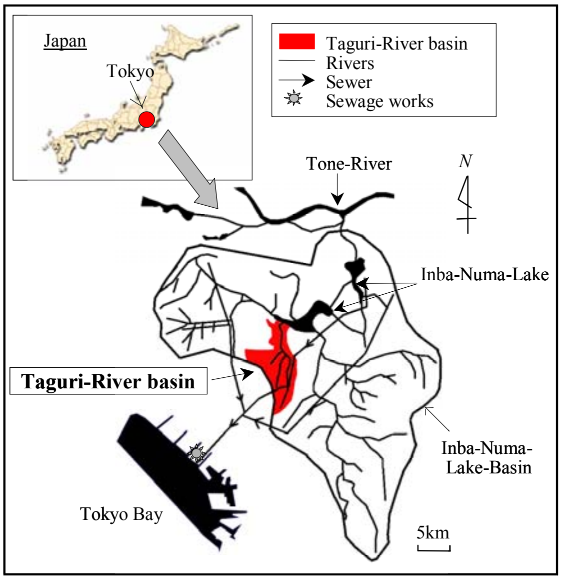

Figure 1. Location of the basin of the Inba-Numa-Lake and the Taguri-River basin

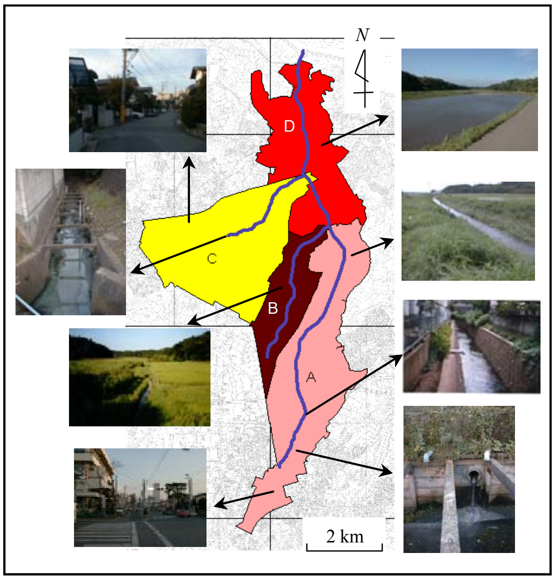

Figure 2. Location and land use of the four sub-basins of the Taguri-River basin

the main river that flows through a residential area and through rice fields. The second sub-basin (B-basin) is located west of the first sub-basin and includes a tributary, which flows through areas that contain many permeable areas (fields and forest, etc.). The third sub-basin (C-basin) is located northwest of the second basin and includes the other tributary. This river flows through a residential area that has not been fully developed yet. The fourth sub-basin (D-basin) includes the lower stream of the main river, which flows through rice fields and into the lake.

The basin was further divided into 106 smaller sub-basins that are defined according to land use and topography to analyse the basin in detail. Based on measured geological data, it is assumed that the geological system in the focus basin consists of three layers. The first layer is a permeable unconfined aquifer system that reaches from the surface to a depth of 50 m below surface. The second layer, which separates the first from the deeper aquifer, is 20 m thick silt. The third layer is a confined aquifer system reaching from a depth of 70 m to 200 m below surface. Most of the groundwater is pumped up from the third layer. The focus term of the research is five years, from 1995 through 1999. Some field investigation is done in 1997 to calibrate data between simulated and investigated data. Therefore, all results shown in the paper are the results based on the values found in 1997. The average humidity in 1997 was 66 percent, the average temperature was 14.8 ^{o}C, and total evapo-transpiration was 788.3 mm. The planned sewerage (separate-sewerage system) area was 39 percent of the basin, where 90 percent of

Table 1. Key figures for the sub basins

	Area (ha)	Population	No. of sub-basins
A	651	15,597	44
B	229	978	11
C	593	34,746	29
D	443	13,731	22
total	1,916	65,053	106

inhabitant lived. In the planned sewerage area the coverage of sewerage was 87 percent in 1997 (with 13 percent still to be constructed). Key figures for the sub-basins are shown in Table 1.

3 THE DSS FOR THE FOCUS BASIN

Bernhard Hahn et al (2000)[2] have described that a DSS consists of four components: The model base, the tool base, the database, and the user interface. In this research, the DSS is developed for technical users. Therefore there is no strong focus on user interface. Accordingly, the developing process of the DSS mainly refers to the remaining three components of a DSS.

In developing the DSS, the problems existing within the focus basin are determined through various field investigations. The major factors influencing the water circulation in the basin are wastewater from households, sewerage system, runoff from urban areas, pumping up groundwater, and resulting land subsidence.

3.1 Model Base

In order to enable a smooth combination of the different models used for analysing these major factors in the basin, each model that will be integrated into the DSS has to meet the following five requirements:

1) Each model must be capable of analysing both water quality and water quantity.
2) Import / export of files from one model to another has to be simple, thus models using ASCII-files have been chosen.
3) Input, output and temporary data files must be managed as separate files within each model.
4) Time-interval for analysis must be adjustable.
5) Handling must be user-friendly.

Considering these requirements, the following four water analysis models and a geographic information system ("GIS") have been selected:

1) SMUSI 4.0 (Schmutzfrachtsimulation: Pollution Load in Urban Drainage Systems) - rainfall-runoff analysis model (Darmstadt University)
2) CE-QUAL-RIV1 (A dynamic, one-dimensional water quality model for streams) - dynamic river analysis model (Ohio University)
3) QUAL2E (The enhanced stream water quality model) - steady state river analysis model (Texas Water Development Board and U.S. Environmental Protection Agency)
4) PMWIN (A Simulation System for Modelling Groundwater Flow and Pollution basis on MODFLOW) - groundwater analysis model (U.S. Geological Survey and Chiang et. al.)
5) Arc View 3.2 - GIS (the Environmental Systems Research Institute: ESRI)

The DSS uses many different physical, hydrologic, and hydraulic methods and equations. They include various coefficients (e.g. Manning coefficient, settle coefficients, decay rate, transmissivity, storage coefficient, hydraulics conductivity). These are defined either by means of a simple calculation or through trial and error using field investigation data.

3.2 Tool Base

The main function of the tool base is to control the interaction between the different models. The tool base had to be developed to provide for a combination of different models without changing original source codes, because most of the original source codes of the models are not available. Therefore, the data exchange architecture method is chosen. This type of integration consists of distributed systems and databases. It uses different models, with every model operating separately. Different exchange programs connecting different models transform output data into input data by using specific formats. If exchange data are given in linear or single form (e.g. water quality and water quantity), the exchange program is developed using FORTRAN. If exchange data are given in spreadsheet form (e.g. groundwater level and topography data), MS Excel is used as exchange program. In consequence, nine programs using FORTRAN und two MS Excel programs were developed as exchange programs. Figure 3 shows the basic data flow in the DSS.

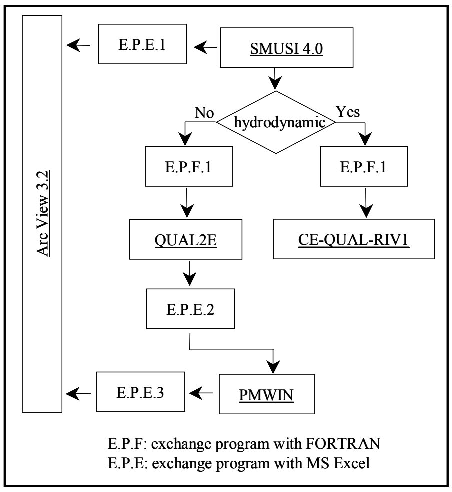

Figure 3. Data flow in the DSS model part

3.3 Database

The DSS requires user input of physical, social, geological and climatic data, which are used as independent variables in equations. Due to the necessity of parameter estimation for every model, the DSS also requires a wide range of various data measured over a long period of time. Regional information (e.g. climate, geological, and population) and site-specific information (e.g. water quality and water quantity, land use, and condition of sewerage system) are gathered through field investigations and from public offices or corporations that operate within the basin. Digital data for land use and topography, as well as precipitation data are available in 10-minute steps.

These data are prepared in different databases, such as MS Excel, ASCII files, or database for GIS.

4 OPTIMIZATION OF THE WATER MANAGEMENT

4.1 Water Conditions in Single Measure Scenarios

Optimum sustainable water management aims for overall better water conditions in the entire basin ("Optimization"). The optimum water management plan for the focus basin was developed through

Table 2. Indirect and direct evaluation of water management

	Groundwater		River				Construction				Environment
Scenario	Quality	Quantity	Quality	Quantity	Flooding	Total	Cost	Time	Decision	Running Cost	
1	0	0	2	-2	1	1	high	long	easy	low	low
2	0	2	1	0	1	4	high	long	difficult	middle	low
3	0	1	1	1	1	4	high	long	difficult	middle	low
4	0	2	2	0	0	4	high	long	difficult	high	low
5	0	1	-1	0	0	0	high	middle	difficult	high	low
6	-1	1	-1	2	0	1	high	middle	difficult	high	relative high
7	0	0	1	0	1	2	high	long	relative easy	middle	relative high
8	-1	1	1	0	-1	0	middle	middle	easy	low	high
9	-1	1	1	0	0	1	middle	middle	easy	low	high
10	0	1	1	1	2	5	low	short	difficult	low	relative high

2: better, 1: good, 0: no effect, -1: bad, -2: worse

DSS-simulation of ten scenarios using different single measures.

Scenario 1: Completing the sewerage in planned area
Scenario 2: Reusing rainwater on roofs for toilet and sprinkling
Scenario 3: Reusing rainwater on roofs for rice fields
Scenario 4: Reusing wastewater for toilet and sprinkling
Scenario 5: Reusing wastewater for rice fields
Scenario 6: Reusing wastewater for preserving mean discharge in the river
Scenario 7: Changing land use (more permeable area)
Scenario 8: Removing concrete from river bottom
Scenario 9: Constructing small riverbed
Scenario 10: Guiding runoff from non-urbanized areas into rice fields

Table 2 shows the evaluation of the different scenarios. The Table shows the direct [a] and indirect[b] evaluation of water management.

The results displayed on the left hand in the Table are evaluated using a scale of five grades (- 2, - 1, 0, 1, 2). The most effective measure (compared to the water condition without any measure) is allocated 2 positive points, the measure with the most negative effect is allocated 2 negative points. A measure that does not show any effect is allocated 0 points. The sum of points allocated to each measure is shown in the middle column of the table. Scenario 10 is allocated 5 points, scenarios 2, 3, and 4 are each allocated 4 points and scenario 5 and 8 are allocated zero points each.

The grades on the right hand in the Table are expressed in different terms (e.g. high, low, easy, and difficult). When looking exclusively at the number of points, scenario 10 appears to be the single best measure of all scenarios introduced. However, this measure is not available in reality unless an understanding can be reached with the farmers owning the fields where the measure would have to be implemented. Moreover, this measure is not effective in improving the groundwater level in the third layer. With regard to the groundwater level in this layer, scenarios 2 or 4 appear to be the most effective measures.

However, none of the single measures is satisfactorily improving the water condition in the entire basin. The aim has to be an overall improvement, taking into account the usual (dry) weather condition and long-term (yearly) water conditions.

4.2 Optimization through Combined Measures

In consequence, a combination of various measures is simulated in an additional scenario. The different measures have to be installed in different parts of the basin in order to improve water conditions. In order to optimize the water management, the measures have been combined with the aim to combine the positive effects of different measures in the most efficient way. Below is an outline of the main requirements for optimization, and the corresponding measures that were combined.

1) Water that is used in the basin has to remain in the basin.

Instead of constructing a large separate-sewerage system, all wastewater from households in planned separate-sewerage system areas is treated in several mid-sized sewage-works and is guided into the river in the upper areas of the main river in A-basin and a tributary in C-basin. The values for the treated water are below: BOD-level: 3.0 mg/l, NH_4-N-level: 3.2 mg/l, PO_4-P-level: 0.84 mg/l.

2) Groundwater consumption has to be decreased through/replaced by reuse of treated wastewater from households for toilet and sprinkling.

Rainwater on roofs and wastewater from households is reused for toilet and sprinkling.

3) Peak flow in rainy times has to be decreased in order to minimize the risk of flooding.

Permeable areas are increased by 30 percent. Rainwater from non-urbanized areas is guided into rice fields.

4) Risk of contamination of food has to be minimized.

[a] The implemented measure is evaluated depending on its effects upon water conditions.

[b] The implemented measure is not evaluated depending on its effects, but based on the construction and management necessary for the measure (cost performance, construction time, ease of decision making, and impact upon nature).

Treated wastewater from households and runoff from urbanized areas is not reused in rice fields.

5) Environmental effects have to be taken into consideration.

A small riverbed is constructed. Concrete is removed from the river bottom.

All results from this scenario (combined measure) are compared to the actual conditions in 1997. The effect of the implemented measures (increasing permeable areas and guiding rainwater into rice fields) on the water quantity and water quality at the lower point of D-basin in wet weather conditions is obvious (Figure 4). Peak flow decreases by 55 percent. The water stored in rice fields drains out continuously and slowly after rainfall. The BOD-level also decreases by about 50 percent (Figure 5). Overall water quality is significantly better than in 1997, because runoff decreases, thus also decreasing the amount of pollution source draining into the river.

While the average annual discharge in the upper area of the main river increases in this scenario (due to the reuse of wastewater) (Figure 6), the annual average discharge in the lower part of the main river in this scenario is not different from that in 1997. However, the average annual BOD-level is significantly better than it was in 1997 due to this combination of measures: Increasing coverage of sewerage and permeable area (Figure 7).

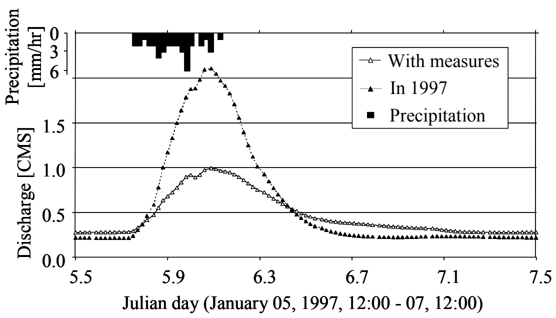

Figure 4. Discharge condition

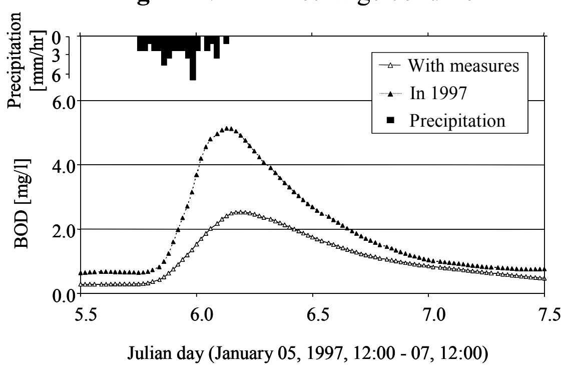

Figure 5. BOD-level condition

In this scenario, the BOD-level is lower than in 1997, which in itself is a positive effect. However, the NH_4-N and PO_4-P-levels have increased, while the total amount of discharge remains the same because of reusing wastewater for the river. The total amount of discharge and contaminants (BOD, NH_4-N, PO_4-P-level) under the combined measure, compared to the levels found in 1997, are illustrated in Figure 8.

With the combined measure, pumping up of groundwater for water supply is decreased by 30 percent (15 percent due to use of rainwater and 15 percent due to reuse of wastewater for toilet and sprinkling) and pumping up groundwater for rice fields is decreased by 25 percent through use of rainwater. Thus, a sufficient amount of water can be supplied for rice fields during the active season (from May until September). The groundwater level in the third layer is kept higher than in 1997. The maximum difference reaches about 30 cm in

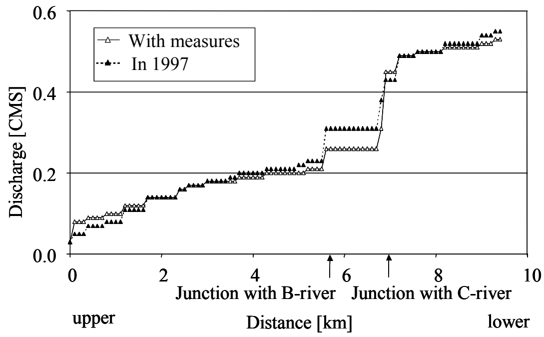

Figure 6. Annual discharge

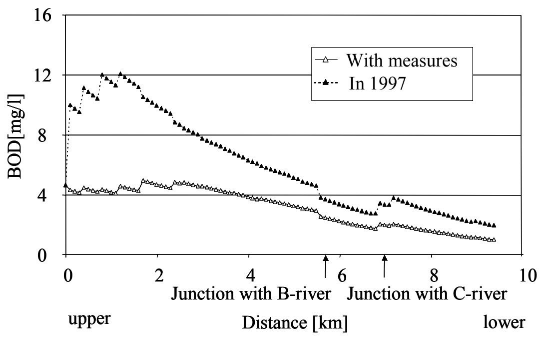

Figure 7. Annual BOD-level

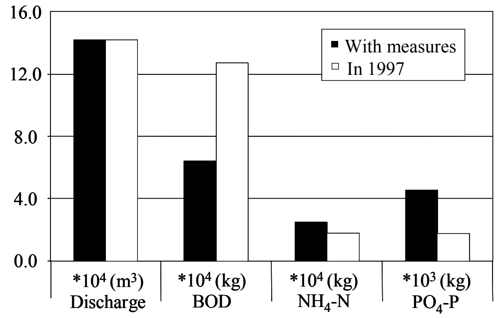

Figure 8. Total amount of discharge and contaminants

A-basin and the lower area of C-basin where much groundwater is pumped up. By removing the concrete from the river bottom and constructing a small riverbed in the upper areas of A- and C-rivers, the depth of the river can be kept at 10 cm in the upper area of A-river (3 cm in 1997) and groundwater level in the first layer can be kept up to 1 m above the level in 1997.

5 THE UNCERTAINTIES OF THE DSS

Uncertainties from a model appear in different types / forms (C.S. Melching (1995)[3]). In the DSS we can identify four types of uncertainties: Natural randomness, data, model parameters and model structure. It is important for decision makers to understand that each scenario holds the risk of a certain margin of error due to uncertainty. But it is equally important that the user understands that this does not render the DSS and its results useless. If the margin of error is kept in mind, the DSS is a useful tool for supporting the process of decision-making.

In planning water management, the main source of uncertainties from natural randomness is precipitation data. The complex randomness from precipitation influences upon the results of all scenarios, because runoff from every sub-basin is aggregated in the simulation.

Uncertainties from data may stem from outdated data. Thus, land use, topographical, and geological data (impact upon runoff condition) may give rise to uncertainties. Digital maps are not updated on an annual basis in Japan. However, if large construction (e.g. urban renewal or developing a golf area) is done, the factor of land use may differ significantly from the latest set of map data. Therefore, based on this data, land use is modified by using field investigation and aerial photographs. For similar reasons, social data (e.g. population and the coverage of the sewerage system) also give rise to uncertainties. It is very difficult to gather up-to date data annually, because the way the focus basin is divided into sub-basins does not correspond to the division into areas for which survey data from public offices are available.

A good example for uncertainty from model parameters is the parameter for load rate from non-point sources. This parameter is defined by comparing the results of other research papers (for different basins) to field investigation data gathered in one part of the focus basin. The parameter is then applied to the entire focus basin. However, in reality, such parameters change depending on land use and weather conditions. Approximate parameters can be defined by means of long-term investigation and continual survey in sub-basins with different land use and weather conditions.

There are two types of uncertainty inherent to the model structure: Mistakes in programming and inadequate model structure. This DSS has been developed using four models that have been used over a long time for various areas. Therefore, the probability of mistakes in programming in these four models can be rated as very small. Uncertainty from model structure can be limited through choice of models adequate to the focus basin and a comparison of data simulated by the model to field investigation data. Both have been taken into account in developing this DSS. Therefore, uncertainty of model structure is considered not to have a significant impact upon the results produced with it.

6 DISCUSSION

The DSS in this research is developed for an exemplary focus basin. To improve water conditions in the focus basin, various measures are simulated and subsequently combined, and thus the DSS shows different alternatives for integrated water management in the focus basin. Using a combination of various existing models, developing-cost and -time for a new model are reduced. Moreover, through using the data exchange architecture method, it holds the potential to be developed further for application in different basins and conditions. To that end, the DSS needs further enhancement by including an economic and, an ecological model. Furthermore, the implementation of functionality for automatic estimation of model parameters would be reasonable. In addition, the practical applicability of the DSS should be studied and discussed for a variety of river basins and water management problems.

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