HYDROLOGIC SIMULATION TOWARDS REDUCTION OF POLLUTANT LOADS IN THE KOISE WATERSHED

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Abstract: There is a need to study both water and pollutant transport system of a watershed to reduce amount of pollutant loads, hence finding solution for watershed environmental problems. My research uses WEP (Water and Energy transfer Processes) model to simulate water and nitrogen cycle of Koise watershed. Various data such as land covers, meteorology, underground and rivers' properties of Koise watershed were processed as inputs to WEP model. As hydrograph is successfully being simulated, WEP model is confirmed to be applicable to Koise watershed. Next, inorganic nitrogen cycle is simulated and the result was compared with observed data and continuous simulation result from Artificial Neural Network (ANN) model. Analysis on the sensitivity of uncertain parameters had been conducted to achieve better simulation result.

Key words: *Hydrologic simulation, pollutant loads, WEP model, parameter sensitivity*

1 INTRODUCTION

Pollutant loads generated by human activities in watersheds have caused eutrophication in many closed water bodies such as lakes, reservoirs, and inner bay. In recent years, pollutant loads from point sources has been successfully reduced by lawful regulation. However there are still a huge amount of polluted effluents being discharged from non-point sources such as agricultural lands, livestock, poultry farms and urban areas. Therefore management and regulation of non-point sources is key issue in solving eutrophication problem. As pollutant loads from non-point sources rapidly increases during flood period, water quality analysis of monthly or even weekly sampled water does not have sufficient time resolution (Richards 1998).

Therefore, there is a need to accurately simulate both water and pollutant transport system of a watershed to find solution for watershed's eutrophication problem. Our research uses WEP (Water and Energy transfer Processes) model to simulate the hourly time series of water and nitrogen cycle in Koise watershed. Although Koise watershed is an important agricultural area and designated as a water quality control area, there were no significant water quality improvements for decades. Because of that, it is essential to improve its water quality. Time series simulation results from WEP model significantly help to better understand behavior of river outflow and pollutant loads discharge. This knowledge will greatly assist our effort in finding solution to reduce pollutant loads from non point sources in Koise watershed.

In this study, reliability of simulation results by WEP model is being tested and verified. As there are limitations in current WEP model, for pollutant loads only inorganic Nitrogen (NO_2-N, NO_3N, NH_4^+) is being considered. Simulation results of WEP model is being compared to simulation results by ANN (Artificial Neural Network) model and observed data to testify its reliability. WEP model consists of many uncertain parameters that may influence its simulation results. Therefore, analysis of uncertain parameters had been done to check its sensitivity.

2 DESCRIPTION OF KOISE WATERSHED

Koise watershed lies in the east of Japan (Fig. 1) and has an area of 222.2 km^2 and population of 69,279. It is a part of Kasumigaura watershed which is located in Ibaraki prefecture and about 64km northeast of Tokyo.

Koise watershed consists of 19.9% paddy field, 23.4% agriculture land, 39.3% forests, 9.7% urban area, 2.0% golf course, 1.7% barren land, 1.3% rivers, 0.6% highway and 2.1% others (Fig. 2). It has four seasons where temperature ranges from -6℃ to 38℃.Average precipitation per year is 1250mm, higher compared to world average of 900mm.

The main river in Koise watershed is Koise River. It discharges into Kasumigaura Lake. Land surface type is being categorized into Kanto loam, alluvium or rock foundation. Each type has different properties such as permeability coefficient, porosity and layer depth. Numerous streams and sub basins are connected to the main river. In our simulation, Koise watershed is being divided into 3 parts (Fig. 1) and 11 rivers are being modeled. Water flow direction in Koise watershed is delineated by considering difference in height (Fig. 3).

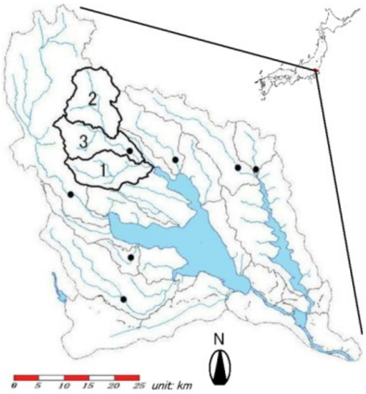

Fig. 1 Map of Koise watershed (black line) in Kasumigaura watershed (dotted line). Black dot represents observation point.

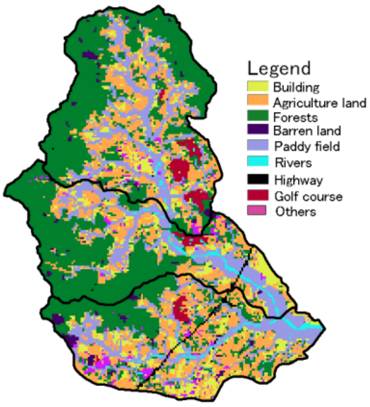

Fig. 2 Land use cover of Koise watershed. Agriculture activities cover more than 43% .

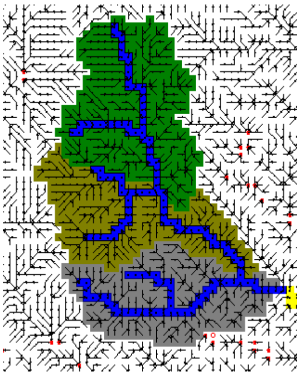

Fig. 3 Map of flow direction.

3 APPLICATION OF WEP MODEL

3.1 Hydrologic simulation

WEP model (Jia et al. 2001) is a distributed water and energy transfer model that solves physical equations of precipitation, infiltration, surface flow, underground water flow, subsurface flow, artificial water system and heat transfer process in a watershed basin mesh by mesh. The illustration of those processes is shown in Fig. 4. Unlike other hydrological models, WEP model can deal with complex land cover type. As calculation is done on every mesh, hydrological output data at any one point can be easily obtained.

Data of land covers, meteorology, underground and rivers' properties etc of Koise watershed were processed as inputs to WEP model. Information were collected from various references and related organizations. ArcGIS software was used to process these input data according to each mesh. Mesh size is 500m x 500m. Complex land cover data were reclassified into water body, vegetation land, barren land and impervious body. Changes in water flow during irrigation period are being modeled as well (Jia et al. 2005). Rate of paddy field which is irrigated by Kasumigaura Lake water for each sub basin is 0.336, 0.375 and 0.288. Else it is directly supplied by nearby river. We assume that the cross sectional face of all rivers is in trapezium shape and riverbed's roughness, thickness at 0.0035 and 1.0m respectively. The sewage treatment percentage in sub basin 1, 2, 3 is 24%, 0% and 3% where all is very low. It is assumed that all treated wastewater discharges out of Koise watershed.

3.2 Inorganic nitrogen cycle simulation

Extended version of WEP model (Iizumi et al. 2005) is capable of simulating inorganic nitrogen cycle in a watershed. The model was first developed for simulation in Ushikunuma watershed which is also in Ibaraki prefecture. The soil properties and weather condition of Koise watershed are almost the same and similarly agriculture activities are dominant in Ushikunuma watershed too. Based on that, this extended version of WEP model is considered to be applicable to Koise watershed too.

As the main purpose of this conceptual model is to simulate behavior of inorganic nitrogen in soil surface, underground water and river flow, less important behavior of organic nitrogen is being left out. Although inorganic nitrogen consists of ammonia nitrogen, nitrite nitrogen and nitrate nitrogen, the model calculates all those as inorganic nitrogen.

The model mainly considers nitrogen uptake by plant, nitrogen used in fertilizers, nitrogen concentration in rainfall, the decay of remnants and nitrogen outflow to rivers. An illustration of nitrogen cycle process is shown at Fig. 5.

Monthly average of inorganic nitrogen concentration in rainfall is obtained from Ministry of Environment. Inorganic nitrogen concentration of wastewater from untreated area, water quality of irrigation water, initial condition of underground water is being considered as constant at 5.0mgN/L, 1.0 mgN/L and 3.0 mgN/L.

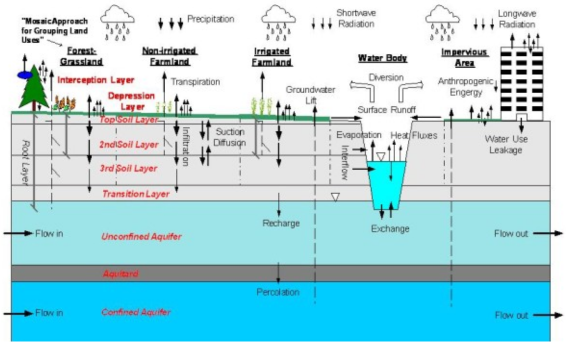

Fig. 4 Illustration of WEP model

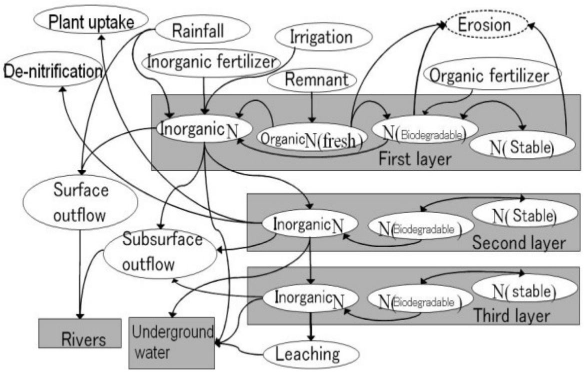

Fig. 5 Illustration of nitrogen cycle

4 SIMULATION RESULTS

4.1 Hydrologic simulation results

Hydrologic simulation had been run starting from 1st January 00:00 to 31st December 24:00 for year 2007 by WEP model. The calibrated simulation result is shown in Fig.6. Compared to observed data, there are some differences in absolute value of flow rate especially during flood period but in overall almost identical hydrograph pattern is achieved. Further analyses of hydrograph during flood period are done to check on the reliability of calibrated simulation result. Fig. 7 and 8 show two examples of enlarged flood event's hydrographs for year 2007. We compared simulated peak flow rate during flood events with observed data. High reproducibility rate of 0.975 is confirmed.

Next, for verification purpose, we used the same parameters to simulate hydrograph of year 2008. The validated simulation result is shown in Fig. 9. Hydrograph pattern is fairly well simulated but errors are still visible especially during flood event. Fig. 10 and 11 show two examples of enlarged flood event's hydrographs for year 2008. Similarly to year 2007 analysis, peak flow rate of observed and simulated results are being compared. There is a drop in correlation coefficient value but it is still high at 0.9057 (Fig. 13).Therefore it can be concluded that WEP model is applicable to Koise watershed as well. It can be derived that extended version of WEP model are applicable to Koise watershed as well.

4.2 Inorganic nitrogen cycle simulation result

The simulation results of inorganic nitrogen cycle in Koise watershed from 2007/01/01 00:00 to 2007/12/31 24:00 is shown in Fig. 12. Comparison is made with simulation result from ANN (artificial neural network) model and observed data. ANN is a model that predict water quality data by fixing the empirical correlations between data from optical sensors such as *Chl-a, D-COD* with water qualities obtained from occasional sample analysis (Yoshimi et al. 2007).

In Fig. 12, inorganic nitrogen discharges simulated by WEP model and observed inorganic nitrogen data represents the total of NO_2-N,NO_3-N and NH_4-N. Simulation results by ANN model is different as it does not consider NH_4-N.

Both results from WEP model and ANN model shows similar changing pattern of water quality data. We can judge from Fig. 12 that concentration of inorganic nitrogen decreases during irrigation period. It suggests that quality and quantity of discharged irrigation water from paddy field has big influence.

When uncertain parameters are calibrated, it is found that some parameters greatly affect the simulation result by WEP model. In order to indentify the significance of changes in each uncertain parameter, analysis on sensitivity of uncertain parameters was done. The result is discussed in following parts. 5 uncertain parameters were selected for our preliminary study.

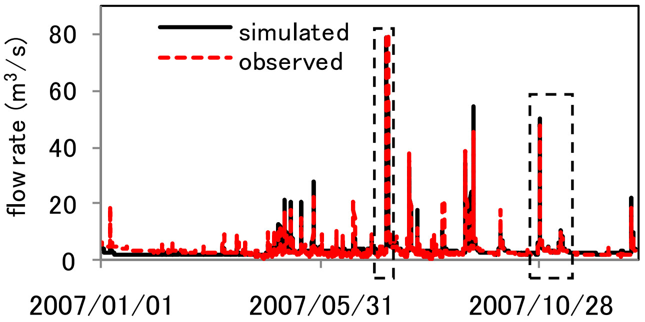

Fig. 6 Simulated hydrograph of year 2007. Enlarged image in dotted line bracket are shown in Fig. 7, 8.

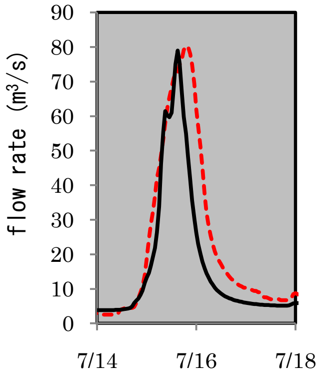

Fig. 8 Enlarged image of flood event's hydrograph ①

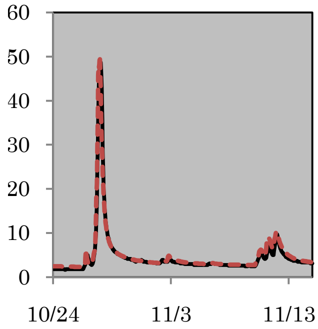

Fig. 7 Enlarged image of flood event's hydrograph ②

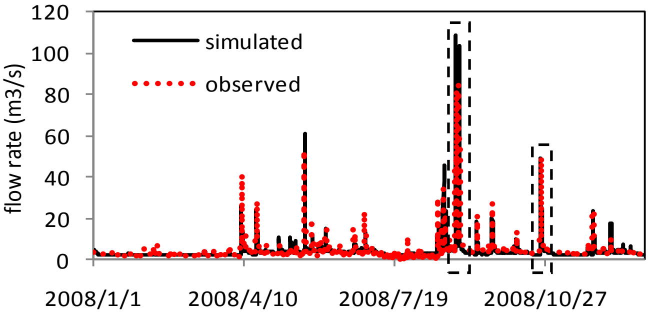

Fig. 9 Simulated hydrograph of year 2008. Enlarged image in dotted line bracket are shown in Fig. 12, 13.

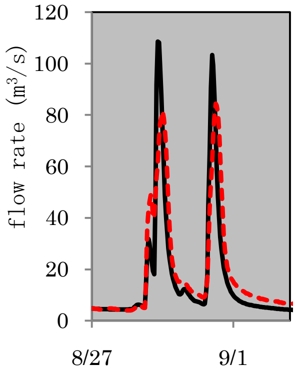

Fig. 10 Enlarged image of flood event's hydrograph ③

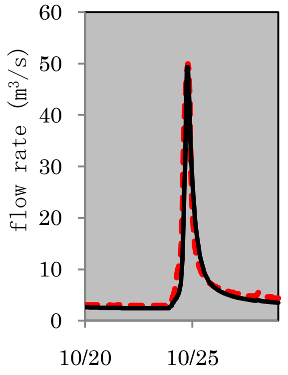

Fig. 11 Enlarged image of flood event's hydrograph ④

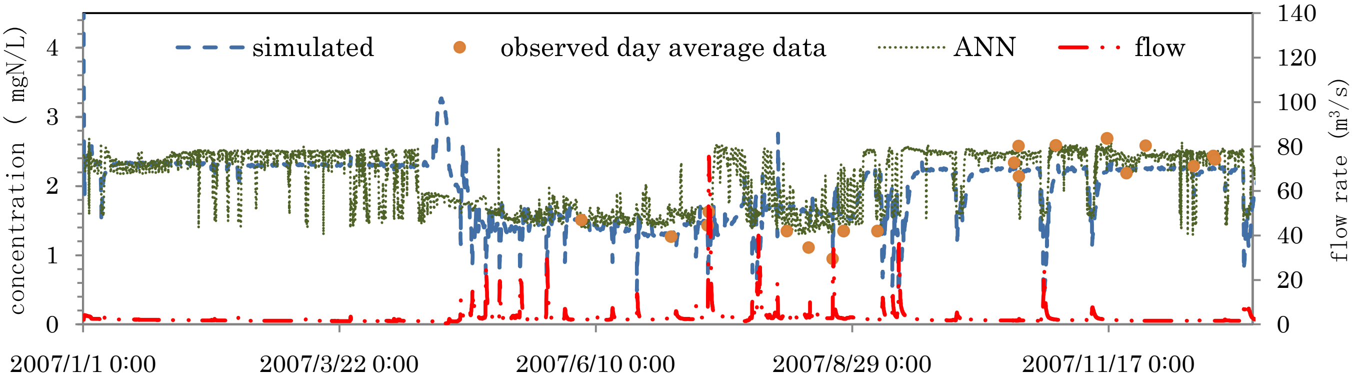

Fig. 12 Inorganic nitrogen cycle simulation result for year 2007.

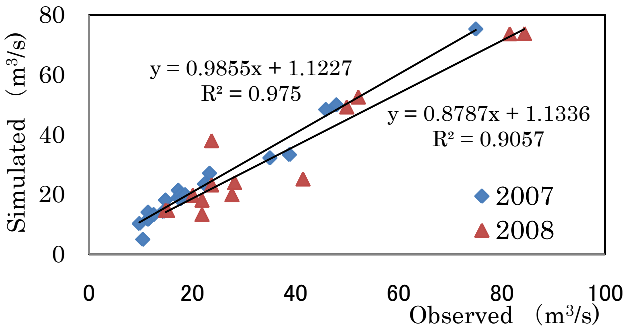

Fig. 13 Comparison of peak flow rate between observed data and simulated results during flood event.

5 ANALYSIS OF UNCERTAIN PARAMETERS

5.1 Initial underground water value

Without sufficient observation data, we assumed that inorganic nitrogen concentration in underground water to be constant at 3.0mgN/L for the whole area of Koise watershed despite the fact that nitrogen content in underground water is uncertain and has huge influences on nitrogen content that outflows into river.

In order to check this uncertain parameter's impacts, we calibrated the initial constant value in the range of 1.0 mgN/L to 5.0 mgN/L. Compare to initial setting of 3.0 mgN/L, it was a change from -66.7 % to 66.7 %. Other parameters were not altered.

5.2 Denitrification constant

Before out flowing into river, nitrate nitrogen goes through denitrification process. A constant number is being multiplied to consider the loss of nitrate nitrogen by denitrification. We assumed the constant number as 0.8.

The constant value was changed from the range of 0.2 to 1.0. A smaller constant represents higher loss of nitrate nitrogen by denitrification process.

The process is expressed by equation (1) where K is the denitrification constant, $RNO3_{GW}$ is nitrate concentration in unconfined ground water and $NO3_{GW}$ is the amount of nitrate that flows into river.

$$NO3_{GW} = K \times RNO3_{GW} \qquad (1)$$

5.3 Rainfall's inorganic nitrogen concentration

Monthly average of inorganic nitrogen concentration in rainfall is set as input data. However in reality, the inorganic nitrogen concentration differs in each rainfall event. As the aim of WEP model simulation is to accurately simulate amount of discharged pollutant loads especially during flood event, the uncertainties of concentration in rainfall is of our concern. The inorganic nitrogen concentration value in rainfall is being calibrated from -50% to 80%.

Besides nitrogen input during rainfall events, there are also increase of nitrogen content into earth surface by dry deposition. Therefore, it can be said that nitrogen input into earth surface from atmosphere is being down rated.

5.4 Inorganic nitrogen concentration of irrigated water

Current model assumes that inorganic nitrogen concentration of irrigated water is equivalent to the nitrogen concentration of Kasumigaura Lake. Uncertainty still exists in the percentage of inorganic components of the water irrigated from Kasumigaura Lake. Irrigation period is set from 15th April to 31st August.

Inorganic nitrogen is only a part of nitrogen which also consists of organic nitrogen. As concentration of inorganic nitrogen will not exceed the default constant value of nitrogen, calibration was made by decreasing the nitrogen concentration value from 1.0mgN/L till 0.2mgN/L.

5.5 Modeling nitrate transport in the surface soil

Another theory for nitrate transport in the surface soil is that nitrate from rainfall infiltrates into first layer of soil and mix with it before outflows into river. It is expressed as following equation:

$$\mathrm{C1ROF} = \alpha \mathrm{CRA} + \mathrm{C1T}(1 - \alpha) \qquad (2)$$

where CRA is concentration of inorganic nitrogen content in rainfall, C1T is concentration of nitrogen in first layer of soil, C1ROF is the total of it and α represents how well does nitrate mixes with soil's first layer. The smaller it is, the better the mixture is. The default value of α is 1 and calibration was made by decreasing the value of α till 0.2.

5.6 Results

The concentration of inorganic nitrogen outflow into Kasumigaura Lake at the end of each month for year 2007 is considered. We normalized the average of those data to determine the changes in percentage. It is then compared to percentage of changes in parameter to study the relationship between them. Same analysis method was applied to flood events as well to determine the influences during flood event.

From the comparison of change in concentration at the end of each month (Fig. 14), it is clear that parameter changes in initial underground water value and denitrification constant have big impact on the output data. Both show proportional relation with a gradient of 0.86 and 0.78. In contrast, parameter changes of inorganic nitrogen concentration in rainfall and α value in surface soil's nitrate transport system shows minimal effect.

On the other hand, from the comparison of change in concentration during flood event, it is found that parameter changes of inorganic nitrogen concentration in rainfall and α value in surface soil's nitrate transport system shows big influences. One example of such flood event is shown in Fig. 15. This implies that to correctly simulate flood event's inorganic nitrogen cycle, accurate data of inorganic nitrogen concentration in rainfall and how we define surface soil's nitrate transport system play an important role.

In both cases, change of parameter in nitrogen concentration of irrigated water which only has effect during irrigation period shows no big difference in outflow's nitrogen concentration.

5.7 Error calculation

Error evaluation for changes in each uncertain parameter is made. The error value ε is defined by the following equation:

$$\varepsilon = \sqrt{\frac{\sum(\beta-\bar{\beta})^2}{n}} \qquad (3)$$

where β is simulated inorganic nitrogen value, $\bar{\beta}$ is day average of observed data and n represents number of observed data.

It is found that 10% increase in underground's inorganic nitrogen concentration and denitrification constant; 50% decrease in irrigated water's nitrogen concentration and 50% increase in rainfall's nitrogen concentration gives the smallest error value (Fig. 16). Meanwhile, for the case of α value in surface soil's nitrate transport system, value 1 has the smallest error which means default model of nitrate transport in the surface soil is the most optimum. As we can see in Fig. 16, change in inorganic nitrogen concentration of irrigated water does not have big impact on error value. Error value varies only from 0.475 to 0.476 for the parameter change of up to -80%.

The error value from combination of all conditions mentioned above is 0.539, which is bigger than default parameter's error value of 0.528. This is because both increases of denitrification constant and inorganic nitrogen concentration in underground water give a higher value of simulation result. Double positive relation causes the simulation result to be drifted away from observed data.

By cross examining between these 5 uncertain parameters, we found that combination of 10% and 50% nitrogen concentration increase in underground water and rainfall with decrease of 20%~50% in irrigated water's nitrogen concentration gives best result of ε at 0.457.This shows an improvement of 13.56% compared to simulation result by default parameter. It is assumed as optimum parameter.

From the relation between observed data versus simulated data, it is found that optimum parameter produces better result where an improvement of 21.52% from 0.381 to 0.426 in correlation coefficient is achieved.

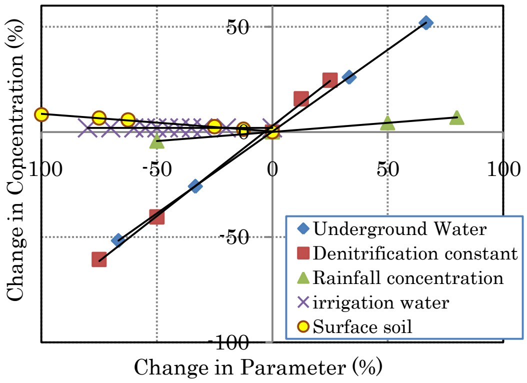

Fig. 14 Comparison of change at the end of the month.

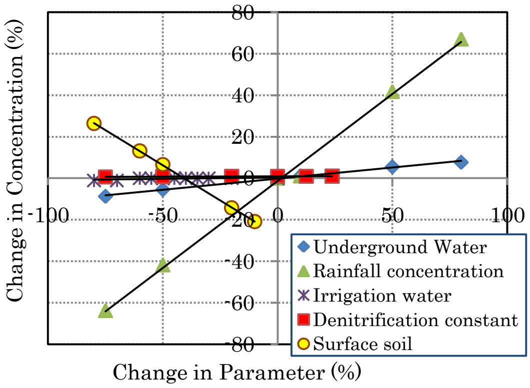

Fig. 15 Comparison of change during flood event.

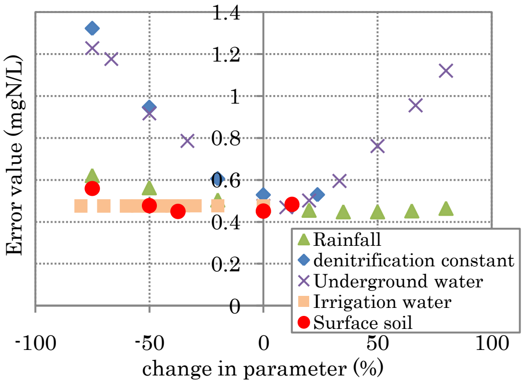

Fig. 16 Error value compare to change in parameter.

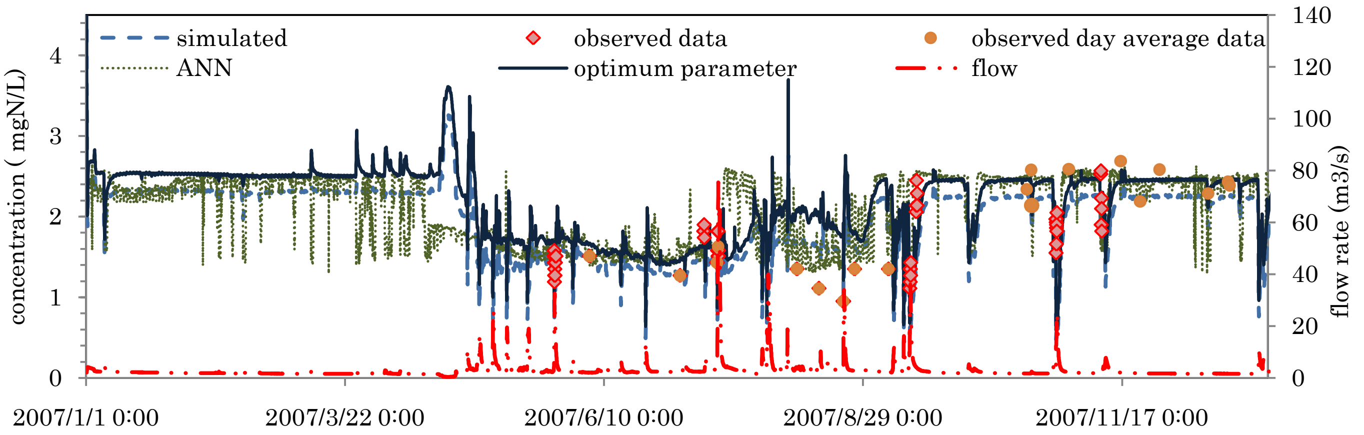

Fig. 17 Comparison of simulation result by default parameter and by optimum parameter.

6 CONCLUSION

Environment is a very complex system that consists of many unknown mechanism. In order to find solution for various environmental problems, we need better understand of unknown factors. Due to the complex nature of environment system, it is almost impossible to pursue the perfect or universal knowledge of it.

Therefore, in our aim to reduce pollutant loads in Koise watershed, we suggested the use of WEP simulation model to simulate the hydrological and inorganic nitrogen cycle process. First, calibration and verification of WEP model is done to confirm its applicability to Koise watershed. After the applicability is confirmed, we used extended version of WEP model to simulate inorganic nitrogen cycle of Koise watershed. Major conclusions of this study are as follows.

I. Comparing the pattern of whole year hydrograph and peak flow of simulation results with observed data, WEP model is found to be applicable to Koise watershed. This fact is confirmed by good result obtained through verification process.

II. Inorganic nitrogen cycle of Koise watershed could be simulated by WEP model. This is supported by the fact that its simulation results matches well with observed data and simulation results from ANN model.

III. Through analysis on sensitivity of uncertain parameters, initial underground water level is found to have big influence on simulation results. Therefore, in future studies more observation should be done to have accurate information about underground water.

IV. From the perspective of whole year, inorganic nitrogen concentration level in rainfall appears to have minimal effects but it applies great effect during rainfall event.

V. Up to 50% increase of inorganic nitrogen concentration in rainfall gives smaller error value and this can be explained by extra input from dry deposition. 1

VI. Calibration among 5 uncertain parameters as mentioned in this study, best simulation results can be achieved by increasing 50% ,10% and decreasing 20%~50% of inorganic nitrogen concentration in rainfall, underground water and irrigated water respectively. The result is shown in Fig. 17.

VII. From Fig.17, we can see that optimum parameter shows better result where it matches well with observed data and simulation results from ANN model. However, significant difference is still visible in the month of August which is also the end of irrigation period. Further studies are needed to indentify the specific reasons for this phenomenon.

ACKNOWLEDGMENT

Many input data used for WEP model are acquired from Kasumigaura River Office; Ministry of Land, Infrastructure and Transport of Japan (MLIT); Japan Meteorological Agency (JMA), Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), Ibaraki Prefectural Government, National Statistic Center (NSTAC), and report from previous related researches. We sincerely offer our appreciation to them for providing us necessary data. We are also very grateful to the staff of IDEA Consultants Inc, and all members in Ishikawa・Kinouchi・Nakamura Laboratory for their assistance in the observation data collection.

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