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# Flow Regulation for Water Quality (chlorophyll *a*) Improvement

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**ABSTRACT:** In this study a machine learning algorithm was applied in order to develop a predictive model for the changes in phytoplankton biomass (chlorophyll *a*) in the lower Nakdong River, South Korea. We used a “Hybrid Evolutionary Algorithm (HEA)” which generated model consists of three functions ‘IF-THEN-ELSE’ on the basis of a 15-year, weekly monitored ecological database. We used the average monthly data, 12 years for the training and development of the rule-set model, and the remaining three years of data were used to validate the model performance. Seven hydrological parameters (rainfall, discharge from four multi-purpose dams, the summed dam discharge, and river flow at the study site) were used in the modeling. The HEA selected reasonable parameters among those 7 inputs and optimized the functions for the prediction of phytoplankton biomass during training. The developed model provided accurate predictability on the changes of chlorophyll *a* (determination coefficients for training data, 0.51; testing data, 0.54). Sensitivity analyses for the model revealed negative relationship between dam discharge and changes in the chlorophyll *a* concentration. While decreased dam discharge for the testing data was applied; the model returned increased chlorophyll *a* by 17-95%, and *vice versa* (a 3-18% decrease). The results indicate the importance of water flow regulation as specific dam discharge is effective to chlorophyll a concentration in the lower Nakdong River.

**Key words:** Water quality modeling, Machine learning, Hybrid Evolutionary Algorithm, Nakdong River, Smart flow control, Sensitivity analysis

## INTRODUCTION

Flow regulation in lotic ecosystems is one of common human-induced factors, which causes large changes to the systems. It is an important issue in river basin management because of the increasing demand on the water resources for potable, industrial and agricultural purposes (Foulger and Petts, 1984; Loneragan, 1999; Gilvear, 2002; Jeong *et al.*, 2007). The seasonally heterogeneous distribution of rainfall (large amount in summer, June to August; small in winter, December to February), causes not only serious flooding disasters, but also a lack of water in dry seasons, the two most crucial problems that need to be solved in the perspective of basin management (Kim et al., 2007b). Therefore, constructing dams or weirs is a common phenomenon, resulting in a large number of impoundments under construction or operating in this region (Tharme, 2003).

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Water quality degradation through different sources as well as different monitoring methods have been widely considered in the literature (Ali et al., 2004; Nakane and Haidary, 2010; Bhatnagar and Sangwan, 2009; Taseli, 2009; Najafpour et al., 2008; Joarder et al., 2008; Rene and Saidutta, 2008; Monavari and Guieysse, 2007). The influence of flow regulation on river ecosystems has been documented in recent decades (Fox and Johnson, 1997; Wade et al., 2002; Franklin et al., 2008). Stober and Nakatani (1992) related the dynamics of ecological entities between natural and regulated river flow systems. In general, flow regulation in a river system implemented by locks and dams brings increased retention time in the reach, and the ecological structure and function in the reach resembles the characteristics found in ‘reservoir has relatively fast water flow’ (Kim, 1999; Kim et al., 2003). Flow regulation also affects the water quality in river systems, as shown in the brief summary of Jeong et al. (2007). Even though there are numerous cases in water quality problems (e.g. nutrient loading, groundwater pollution, and so on), the abnormal increase of chlorophyll a concentration due to phytoplankton over proliferation is recognized as a serious problem.

The lower Nakdong River is a good example of a 'regulated river,' whose flow is intensively controlled by multi-purpose dams. Because of seasonally variations in rainfall, the government has to control the water flow in order to satisfy water resource demands from winter to spring (December to next May). Also, the construction of an estuarine barrage in 1987 increased the of retention time in the lower part of the river, which is the water supply for approximately 4 million residents in and outside of this area. The increase of retention time was observed to cause accelerated eutrophication and serious proliferation of phytoplankton (summer cyanobacteria and winter diatom; Ha *et al.*, 2000; Ha *et al.*, 2003a). Increase of phytoplankton in the summer (mainly *Microcystis aeruginosa* in the Nakdong River) often increases water purification costs, and cyanobacterial blooms are recognized as an important environmental problem worldwide (Codd *et al.*, 1999; Codd *et al.*, 2005). Winter diatom bloom (mainly *Stephanodiscus hantzschii*) is a unique phenomenon in Korea, and the increased retention time and low water temperature are believed to be primary factors for the blooms (Kim et al., 2007b). Many studies in the Nakdong River hypothesized the possibility of water quality control by flow regulation, i.e. increased dam discharge, may dilute or flush out the largely formed population of phytoplankton in the river (Ha *et al.*, 2003b; Jeong *et al.*, 2007) but few studies have considered the quantitative impact of dam flow regulation on the changes of phytoplankton biomass. Therefore, in this study, we constructed a rule-based model for the prediction of phytoplankton biomass (chlorophyll *a*) observed in the lower Nakdong River, using Ecological Informatics (EI), and the quantitative relationship between phytoplankton and hydrological control were simulated. Further utility of the results were discussed as well.

## MATERIALS & METHODS

The Nakdong River is located in southeastern area of the Korean Peninsula (Fig. 1A, B). The river basin experiences a strong summer monsoon climate (mainly occurs in late June to late July), with several typhoon events in the remaining summer (July to early September). Annual rainfall occurs in the summer season (ca over 60%); winter to the next spring is arid

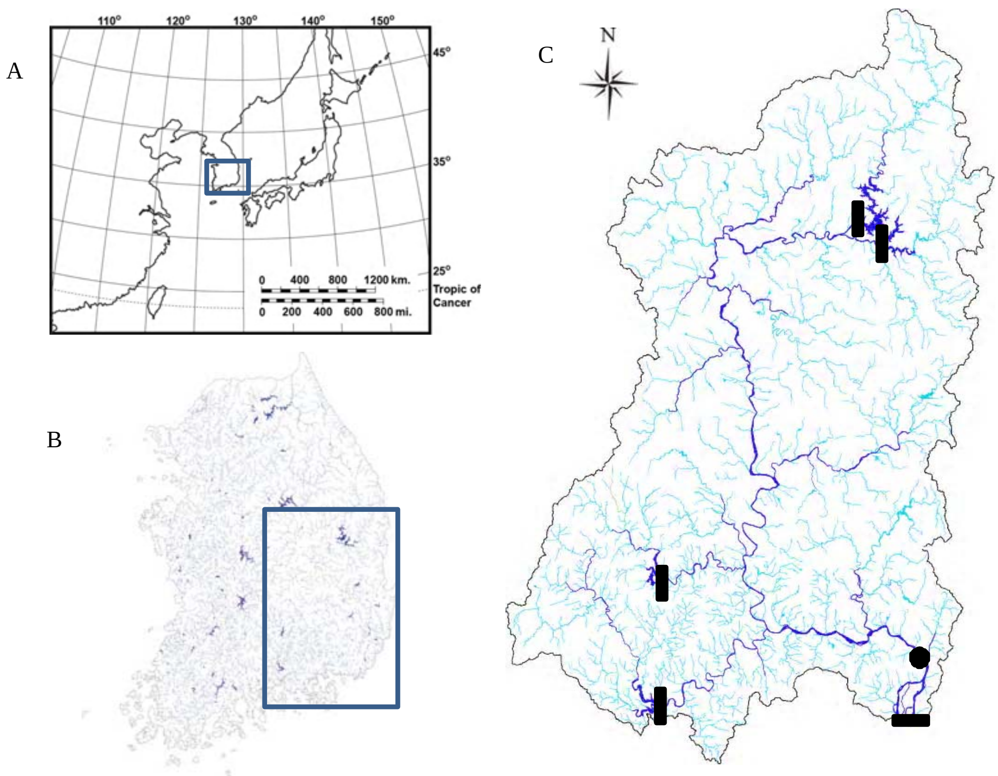


**Fig. 1. Map of the Nakdong River basin. A, Map of East Asia; B, Map of South Korea; C, Map of the river basin. I , multi-purpose dams; _, estuarine barrage; • , the study site.**

(ca less than 10%) every year (Jeong *et al.*, 2001; Park *et al.*, 2002; Jeong *et al.*, 2003a). The length of the main channel of the Nakdong River is ca 520 km, and it is the second largest river system in South Korea. About 10 million residents inside/outside of the river basin rely on this river for their water supply. There are four major multi-purpose dams in upstream area which intensively control water flow, and numerous small reservoirs are distributed in the river basin. An estuarine barrage was constructed in 1987 mainly aimed to prevent salt intrusion into the freshwater area, causing a clear separation of the freshwater zone from the brackish area. The study site is located at 27 km upstream from the estuarine barrage, where a water intake facility is installed. A series of scientific studies reported that accelerated eutrophication has occurred since the construction of estuarine barrage, resulting in serious proliferations of cyanobacteria in summer and diatoms in winter (Ha *et al.*, 1998; Ha *et al.*, 2003a; Kim *et al.*, 2007b).

In this study, we collected data a total of nine parameters comprising meteorology, hydrology and water quality. Rainfall data (mm) was provided by the Korean Meteorological Administration, and we calculated the daily average from 15 meteorological stations in the river basin. The discharge from four multi-purpose dams (Andong, Imha, Hapchon, and Namgang Dams; Figure 1C for the locations of the dams) and river flow data (all $m^3$ $sec^{-1}$) were provided by the Nakdong River Flow Control Center on a daily basis. A daily sum of the dams' discharge was produced using those data. The river flow data measured at Jindong station, the closest station to the study site, was used. Weekly monitoring of water temperature and chlorophyll *a* concentrations at the study site was used as water quality parameters. Water samples were collected at a depth of 0.5 m at the study site from April 1993 to March 2008. Water temperature was measured by a YSI DO meter (model 58), and the collected water samples were filtered through a 0.45 ›3 Advantec MFS membrane, using extraction methods described by (Wetzel and Likens, 1991) to detect chlorophyll *a*. Since the aim of this study is to provide useful information for the establishment of a hydrological management strategy, the average monthly data for all nine parameters (rainfall, four dam discharge and summed dam discharge, river flow and chlorophyll *a*) were used. Flow regulation strategy often takes monthly patterns of river characteristics into consideration. Even though phytoplankton assemblage responds quickly to the changes of environments, monthly averaged patterning would be more useful. The following modeling process used the monthly averaged data sets.

Evolutionary Computation is a biologically inspired machine learning method which mimics evolutionary processes of genetic information from generation to generation (Fogel, 1998). Hybrid Evolutionary Algorithm (HEA) is able to produce formula of a rule-based equation discovery, and it was introduced to forecast and explain algal population dynamics in lakes (Cao *et al.*, 2006). Two main attributes of the HEA are to use Genetic Programming (GP) which evolves structure of parsing trees (Banzharf *et al.*, 1998) and to use general Genetic Algorithm (GA) which is used for optimization of random parameters in the rule sets (Holland, 1975). The basic flowchart of the HEA is shown in Fig. 2. The principal procedure of the rule set evolution is similar to the framework of replication and reproduction of genes. In the initial stage, a 200-sized population of rule sets were randomly generated and this population, $P(t)$ was evolved under HEA sequential procedures by genetic operators such as crossover (vector and tree level) and mutation (tree level). This was one attribute of the HEA for structure optimization using those genetic operators in GP. Then, random parameters in each rule set of the population were optimized by means of GA, which was the other attribute of the HEA in the present study. Total number of data was 181, with 135 data used for training and 46 data for the test. Maximum tree depth was set to 5 to avoid difficult level of model's interpretability due to too high complexity. The initial population size was generated at size 200, and maximum number of generation was limited in 100 to shirk local optima of search space in given data. The length of training data was 135 cases (March 1993 to May 2004), and the test data was 46 cases (June 2004 to March 2008). Selection of the best-predicting model was based on RMSE, determination coefficients ($r^2$) between the observed and predicted values, and visual comparison. Often machine learning algorithms used in Ecological Informatics takes in account of a 'trial and error' process in model development in order to select the best model. We produced a total of 2400 rule-set models predicting chlorophyll *a* on the basis of meteorological, hydrological and water temperature variations, and the models showing the lowest RMSE for both training and testing data were filtered. Among the filtered models, we investigated the seasonal mismatch between the observed and predicted data by visual comparison as well as determination coefficients. The model that produced the closest changing patterns to the observed chlorophyll *a* was finally selected as the best-predicting model. Using the best-predicting model, several sensitivity analyses were implemented. First, we evaluated the utility condition between 'THEN' and 'ELSE' functions. This work was done by varying the data of the parameters used in 'IF' function, between mean ± standard deviation. The utility of 'THEN' or 'ELSE' function was represented by 1 (used) and 0 (not used). Sensitivity on Wide-ranged Disturbance (SWD) was applied to the model, which was used in

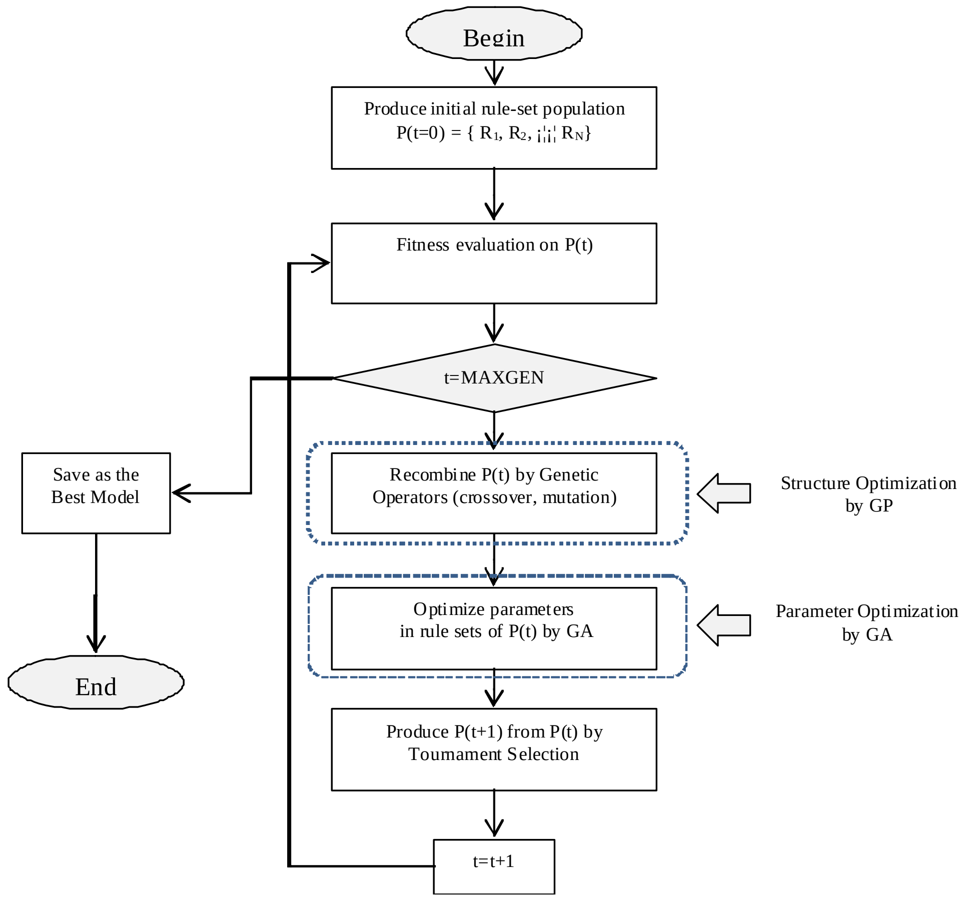


**Fig. 2. Flowchart depicting the HEA application process.**

other related potamoplankton research (Jeong *et al.*, 2003a; Kim *et al.*, 2007a). This is a common methodology to estimate output sensitivity from input variables, so that it is useful to evaluate the applicability of models. The SWD was conducted using the best predicting rule-based model. Variables in the SWD were selected from the input parameters of the best model. The figures of the SWD were displayed in two graphs of 'THEN' and 'ELSE' parts of the model, and the data were sorted by an 'IF' condition of the model and then were substituted into the sub tree sectors of the model. The range of parameter variation was determined by mean and standard deviation (i.e. ì ± ó).

Simple scenario analysis was also applied to the selected model in order to investigate the response of chlorophyll *a* to the dam discharge regulation. Both training and testing data of dam discharge parameters used in 'THEN' and 'ELSE' functions were varied by giving -20 $m^3$ $sec^{-1}$, no changes to the original data, and +20 $m^3$ $sec^{-1}$. If more than two dam discharge parameters were selected in the model functions, they were simultaneously varied (e.g. -20 $m^3$/sec of dam A with -20 $m^3$/sec of dam B). The model production under this investigation was compared with the original prediction values, to estimate the impact of dam flow regulation to the chlorophyll *a*.

## RESULTS & DISCUSSION

Fig. 3 shows the inter-annual variation of the meteorology, hydrology and water quality of the Nakdong River. Dry and wet years repeatedly occurred, and chlorophyll *a* concentration responded to the changes of rainfall and discharge. Relatively low rainfall occurred in 1994-1996 and 2001 (Fig. 3A), and relatively small amount of dam and river discharge could be observed in the first dry years (Figure 3B-G). A serious summer drought in 1994 caused no summer peaks in all discharge data, and the following years (i.e. 1995 to 1996) also had small peaks in summer. However, although year 2001 showed a similar amount of annual rainfall to 1995 or 1996, discharge peaks were larger than the previous dry years. The other years (1997-2000, 2002-early 2008) had plenty of rainfall resulting in dynamic fluctuation in discharge. Water temperature retained a general pattern, high in summer (25.6±2.4!) and low in winter (4.6±1.5!). There was no cases under the freezing point, and a relatively lower temperature was observed when

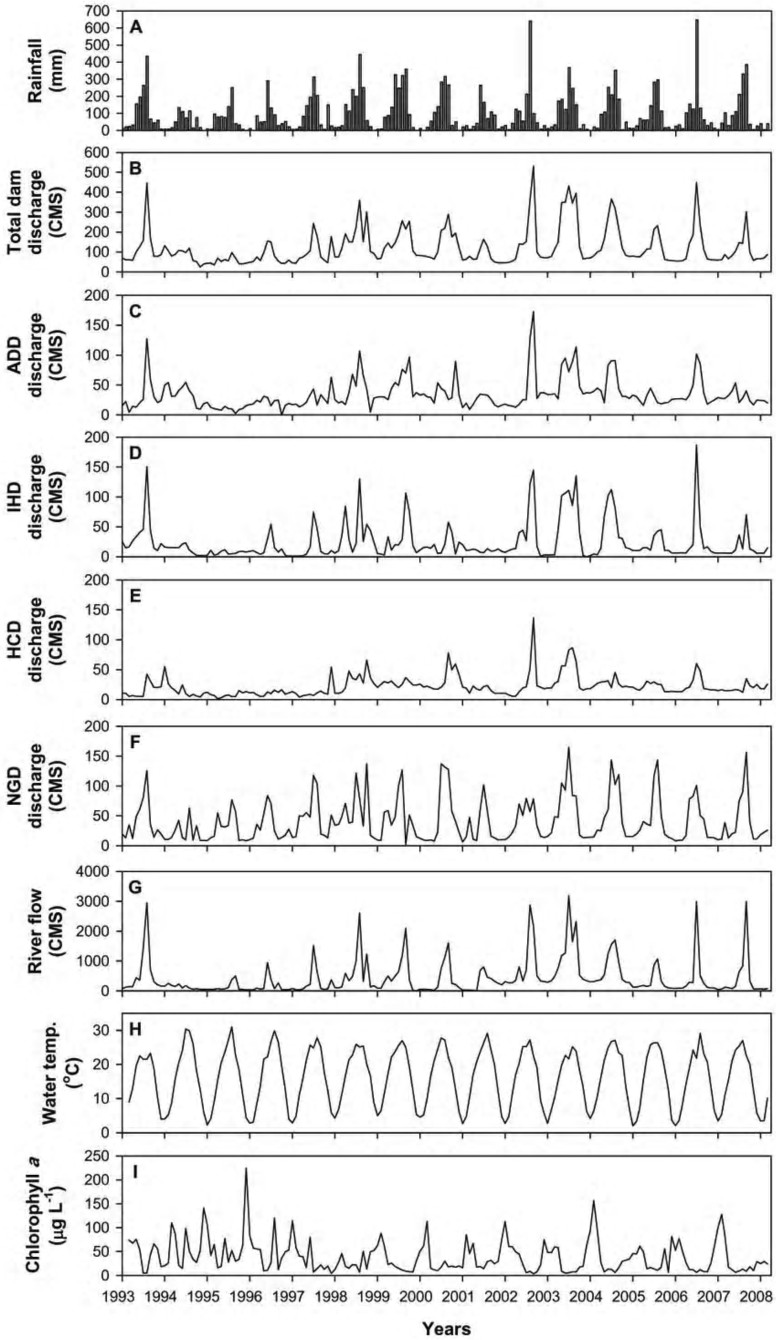


**Fig. 3. Annual changes of meteorological, hydrological and water quality parameters. A, rainfall; B, total dam discharge; C, ADD discharge; D, IHD discharge; E, HCD discharge; F, NGD discharge; G, river flow; H, water temperature; I, chlorophyll *a* concentration.**

sufficient rainfall occurred (Figure 3H). Chlorophyll *a* changes were dynamically related to the changes of hydrology (Figure 3I). In the first dry years, large peaks ranging between 100 to 200 ìg/L were observed in all seasons. However, with the start of rainy years from 1997, summer chlorophyll *a* peaks disappeared and only a winter increase with long period (ca 3 months) was observed. In 2001, even though the annual rainfall was relatively small, no summer peak of chlorophyll *a* was detected. The Hybrid Evolutionary Algorithm (HEA) produced a total of 2,400 rule-based models, and most of the models converged except one model which returned infinite values of RMSE for both training and test datasets.

The average ± standard deviation of 2,399 models' RMSE, for the training data set, was 27.2±2.4, and that for testing data set was 25.1±10.9. The minimum-maximum ranges of RMSE for both data sets were as the following: 23.2-101.2 for the training data, 18.7-357.8 for the testing data set. Among the 2400 models, we selected one rule-set model as the best-predicting model, on the basis of RMSE, determination coefficient (i.e. $r^2$), and visual comparison (Equation 1). In the rule set model, five environmental parameters out of eight were selected, and some of them were duplicated (rainfall, HCD discharge, NGD discharge, and water temperature). The 'IF' function consisted of two parameters (HCD discharge and water temperature), and data samples with high temperature and large HCD discharge would have high probability to use 'THEN' function.

Fig. 4 illustrates the condition of water temperature and HCD discharge by selectively using 'THEN' and 'ELSE' functions. When the training data was rearranged from the minimum to the maximum values of water temperature and HCD discharge, respectively, a different usage pattern of 'THEN' and 'ELSE' equations were observed (Figure 4A, B). In the case of water temperature, only the 'ELSE' equation was used when the temperature was below 5ºC, and complex usage between 'THEN' and 'ELSE' equations above 5ºC. For HCD discharge, 'THEN' equation was used when HCD discharge was less than 20 $m^3$ $sec^{-1}$. Between ca 20 and 95 $m^3$/sec of discharge, both 'THEN' and 'ELSE' tended to be used, but only 'ELSE' was used when HCD discharge exceeded 100 CMS. There was a non-linear pattern in the use of 'THEN' or 'ELSE' functions (Figure 4C). When water temperature ranges between 1~5ºC, 'ELSE' was used in chlorophyll *a* calculation. The model used the 'THEN' equation when temperature is between 5~15ºC and HCD discharge increases. A gradual decrease in the use of the 'THEN' equation was observed when the temperature exceeded 15ºC, and an increase of HCD discharge was also related with using the 'ELSE' function in this temperature range.

$$\text{If } \frac{(46.155 - \text{Water temp.} - \text{HCD discharge})}{\frac{46.155}{\text{Water temp.}^2}} > 24.963$$

$$\text{Then Chlorophyll } a = \left(\frac{-17.366}{\text{Water temp.} + \text{NGD discharge}}\right) \times \left(\frac{90.149}{\text{Raingall}} - \text{NGD discharge} + 64.087\right) \quad (1)$$

$$\text{Else Chlorophyll } a = \left(\frac{-17.366}{\text{IHD discharge} + \text{NGD discharge}}\right) \times \left(\frac{-101.674}{\text{Rainfall}} - \text{NGD discharge} - 53.589\right)$$

Fig. 5 illustrates the prediction accuracy of the best predicting rule set. The final rule-based model worked reasonably well with both training and test data sets (RMSE for training data, 24.9, test data, 20.6). Determination coefficients ($r^2$) for both data sets were higher than 0.50 ($n$=135 and 46 for training and testing data respectively; $p$<0.01). For the training data, the timing of chlorophyll *a* peaks in summer and winter were relatively well recognized, but a slight over-estimation occurred, especially in spring and autumn. Similar pattern of over-estimation was observed in the testing data set, and the end of 2007 to early of 2008 was relatively largely over-estimated, but the winter peak of 2007 was under-estimated. Sensitivity analysis revealed that most of the input parameters negatively affected the changes of chlorophyll *a* concentration in the lower Nakdong River. Between two equations, the most influential parameters for the changes of chlorophyll *a* were different; NGD discharge for the 'THEN' function, and IHD for the 'ELSE'. Two input parameters out of three were the same between 'THEN' and 'ELSE' functions (i.e. rainfall and NGD discharge), and the sensitivity of chlorophyll *a* to these two parameters were different between the equations. Rainfall did not have a strong influence on the changes of chlorophyll *a* in the 'THEN' function, but a strong negative impact could be observed in the 'ELSE' function (Fig. 6A, D). Especially, a sharp drop of chlorophyll *a* occurred when rainfall ranged between 0 to 20 mm. Chlorophyll *a* was reduced when NGD discharge increased, and their relationship was in an exponentially decaying pattern (Figure 6B, E). The impact of NGD discharge was stronger in the 'THEN' function than the 'ELSE'.

The remaining parameter was different in each of the functions. In the 'THEN' function, water temperature was used, but IHD discharge was selected instead of water temperature in the 'ELSE' (Fig. 6C, F). Both of the parameters negatively affected the chlorophyll *a* changes, similar to the other hydrological parameters. The impact of dam discharge regulation on the changes of chlorophyll *a* can be found in the Fig. 7. Inputting varied discharge values for the two dam discharge parameters (-20 $m^3$/sec to +20 $m^3$/sec; IHD and NGD discharge, respectively) resulted in the changes of predicted chlorophyll *a*. When the discharge of both dams were decreased by 20 $m^3$/sec throughout the study period, chlorophyll *a* concentration drastically increased compared with normally predicted values. In this case the changing rate of chlorophyll *a* (disturbed data vs. normal simulation) was 322%. When IHD and NGD dam discharge was decreased separately, the rates were 25% and 95%, respectively. Separate increase of dam discharge resulted in the decrease of

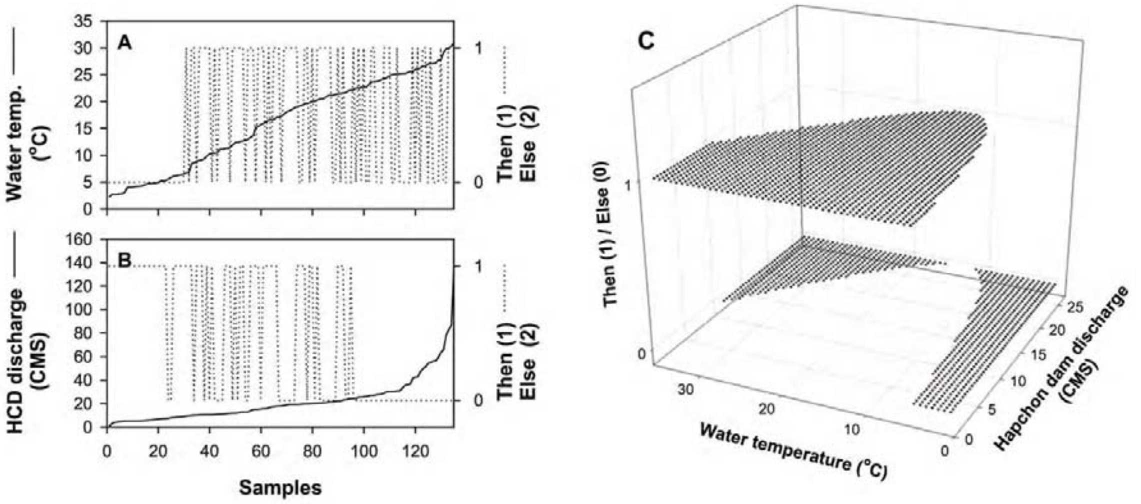


**Fig. 4. Case analysis for the utility of THEN or ELSE functions in the selected rule-set model. A, utility THEN or Else function on the basis of water temperature variation; B, on the basis of HCD discharge; C, comparison of THEN or ELSE function utility condition between water temperature and HCD discharge**

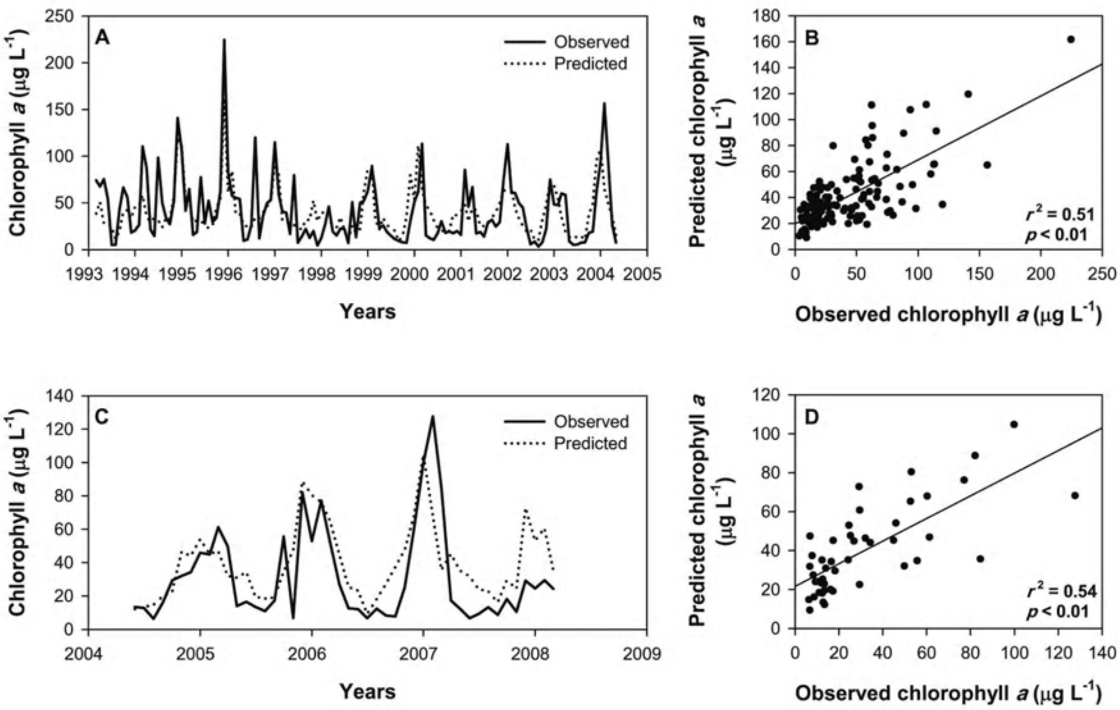


**Fig. 5. The performance results of the HEA model for the training and test data sets. A-B, comparison between the observed and predicted chlorophyll *a* for the training data set; C-D, comparison between the observed and predicted chlorophyll *a* for the test data set.**

chlorophyll *a*, by -25% from IHD and -26% from NGD. When the discharge from both dams were increased, chlorophyll *a* concentration decreased by -37%. Therefore, this result proposed the possibility of water quality improvement by regulating dam discharge. Previous research on the water quality and phytoplankton dynamics in the Nakdong River suggested that the flow regulation is responsible for the accelerated eutrophication and specific species proliferation in the river (Ha *et al.*, 2002; Park *et al.*,

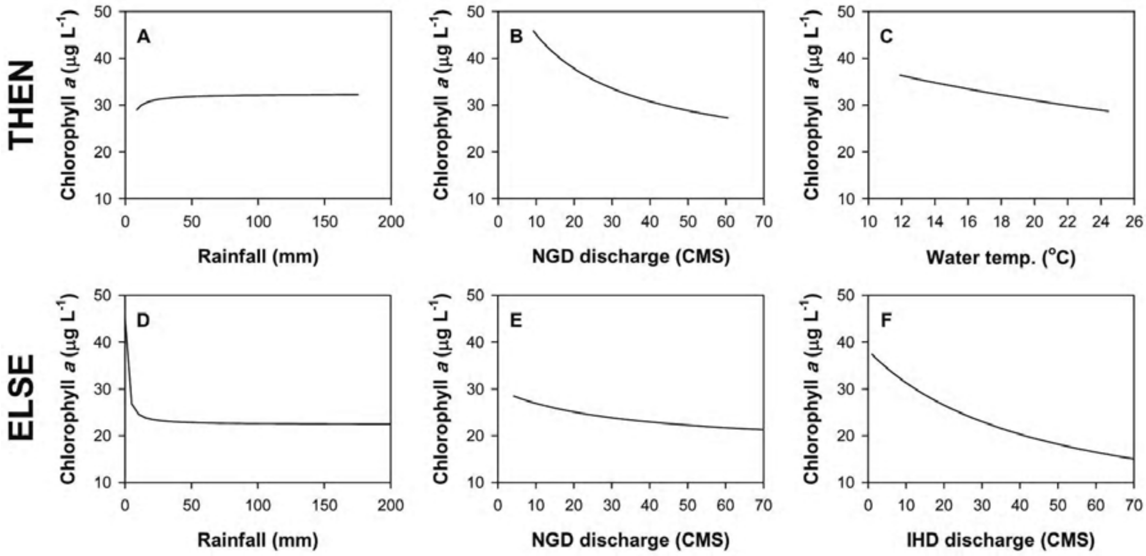


**Fig. 6. Results of sensitivity analysis for the selected model. A-C, parameters included in the THEN function; D-F, parameters included in the ELSE function. A, rainfall; B, NGD discharge; C, water temperature; D, rainfall; E, NGD discharge; F IHD discharge.**

2002; Ha *et al.*, 2003a; Jeong *et al.*, 2003b; Kim *et al.*, 2003; Jeong *et al.*, 2007). Development in the watershed and loss of numerous riparian wetlands in the recent decades has been known to result in the continuous nutrient loading into the river (Joo *et al.*, 1997). Sufficient nutrients in the water enabled phytoplankton species to easily increase (Ha et al., 1998), and they used to proliferate in the early summer just before the summer concentrated rainfall due to monsoon climate (Park et al., 2002). The start of nutrient accumulation and phyto-plankton proliferation in the lower part of the river were caused by the construction of an estuarine barrage in 1987. Flow control by multi-purpose dams was on-going before the construction of estuarine barrage, but scientific studies revealed the drastic changes in ecological structures in terms of the barrage. Since the construction of the barrage, increase in nutrients such as phosphate and nitrogen were observed (Kim, 1969; Choi and Park, 1986; Lee *et al.*, 1993), which in turn brought out assemblage changes of phytoplankton and proliferation of specific species (Cho, 1991; Kim and Lee, 1991; Moon and Choi, 1991; Cho *et al.*, 1993; Chung *et al.*, 1994; Seo and Chung, 1994; Ha *et al.*, 1998). Currently, it is difficult to remove the estuarine barrage/ therefore, a wise management strategy to eliminate the phytoplankton-causing water quality problems by adapting to the current situation is needed. Adaptive flow regulation, so called 'environmental flow,' would be a solution for this perspective. River flow in East Asia is mainly governed by the summer monsoon climate and typhoon events. Monsoon is recognized as a primary factor determining the characteristics of freshwater ecosystems (Silva and Davis, 1987; Brewin *et al.*, 2000; Kim *et al.*, 2000a; An and Park, 2002; Dudgeon, 2002; Azami *et al.*, 2004; Yoshimura *et al.*, 2005; Madhu *et al.*, 2007). Also typhoon events bring enormous quantity of rain within short period, which is also known as source for water resource in this region (Jeong et al., 2007). In consequence, reliance on summer rainfall is relatively high in East-Asian countries, and particularly in Korea it is very important how to manage and allocate water resources efficiently by constructing dams in spite of deliberation for environmentally negative effects on ecosystem. The changes of meteorology, hydrology and water quality parameters showed strong seasonality during the study period and chlorophyll *a* changes responded well to the changes in hydrological parameters. In the lower Nakdong River, previous research focused on the seasonal dynamics of phytoplankton distribution, and two bloom-forming periods were the most important phenomena for water quality point of view, such as summer cyanobacteria and winter diatom. Ha et al. (2002) revealed that the lower part of the river showed different patterns of phytoplankton succession compared with the middle part of the river. They suggested that accumulated nutrients and increased retention time would be the primary factor for the difference. Modeling results from Jeong et al. (2001) and Jeong et al. (2003a) concluded that phytoplankton would react with chemical factors such as nutrient or

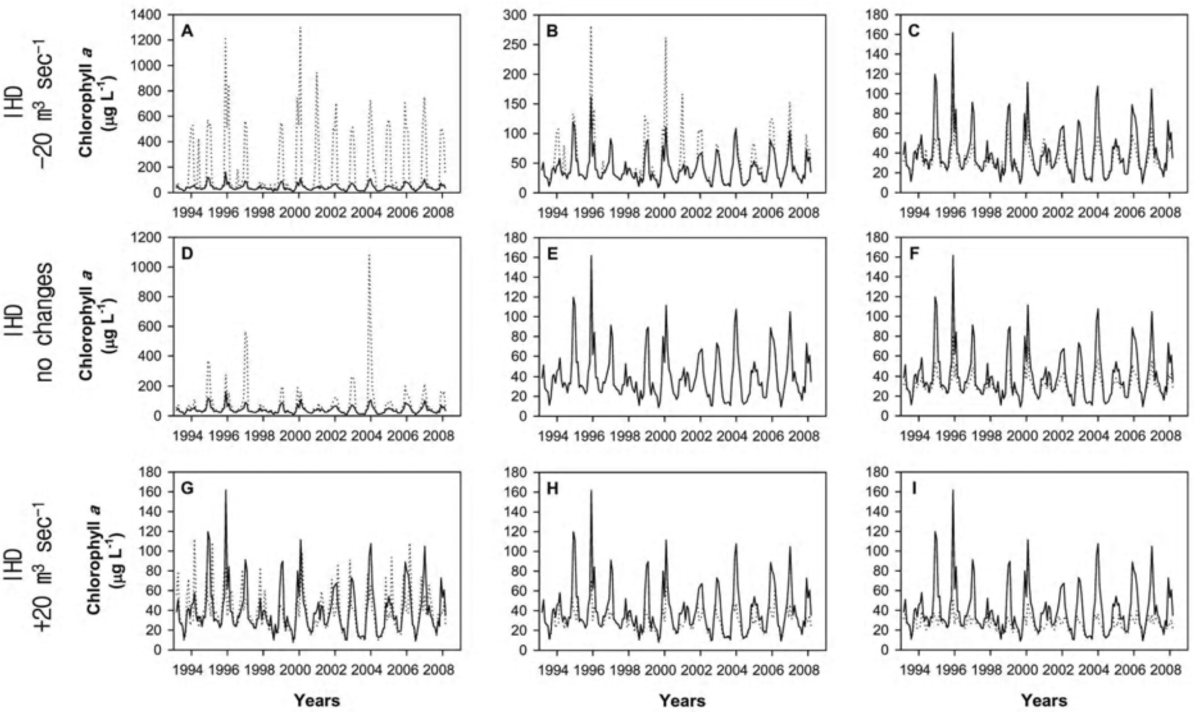


**Fig. 7. Results of the brief scenario analysis changing the input of dam discharge by ±20 $m^3$ $sec^{-1}$ in order to detect the response of chlorophyll *a*.**

pH on shorter time span (e.g. hourly or daily), but they also suggested that plankton assemblage may respond strongly to a hydrological regime when the resolution enlarged to monthly or seasonally. Jeong et al. (2007) hypothesized that the phytoplankton proliferation was linked to the monthly changes of dam flow patterns based on time-series statistics, and proposed the possibility of seasonal water quality improvement (chlorophyll *a*) by regulated flow. The results of this study can support this hypothesis. From the modeling results of this study, it is thought that determination of optimal dam discharge is very important for the changes of water quality. Even though the selected model did not take all of the dams into consideration, the influence of dam discharge control could be detected clearly from the time-series sensitivity analysis. Increase of dam discharge at two dams (i.e. IHD and NGD) resulted in a decrease of summer and winter chlorophyll *a* concentrations during the study period. This would be explained by the following relationship between hydrology and phytoplankton: 1) the increase of dam discharge affects the water velocity and water volume in the study site positively, 2) the water velocity, however, would not be significantly increased under the discharge condition (i.e. +20 $m^3$ $sec^{-1}$) compared with summer flooding period, therefore the decrease of chlorophyll *a* would not be due to flushing out effect, 3) the increase of water volume may cause a dilution effect on the density of phytoplankton represented by chlorophyll *a*. From previous studies, the discharge from the four dams, when flushing out, were detected in summer 1997 (Park et al., 2002), ranging from 100-300 $m^3$ $sec^{-1}$, but the other seasons showed ca 10-50 $m^3$ $sec^{-1}$. The results of this study showed a relatively weak impact of dam discharge on summer chlorophyll *a* but large decrease of chlorophyll *a* was found in the winter. This implied that the impact of dam discharge control would have high efficiency when implemented during dry seasons (such as the period of winter diatom proliferation period; late November to next March) (Kim *et al.*, 2007b; Kim *et al.*, 2008). Summer rainfall distribution is relatively unpredictable because climate conditions, such as monsoon or typhoon events have strong inter-annual variability (Chang and Kwon, 2007) in Korea. If a large amount of rainfall occurs in summer, enormous dam discharge raise water table in the lower part of the river, resulting in a flushing out effect. But dry summers do not show this pattern (e.g. dry summer in 1994). Therefore, it is strongly recommended to manage the quantity of impoundment during wet years, as shown in Jeong et al. (2007). Recent Korean climate research showed a positive, increasing trend of summer rainfall (Chang and Kwon, 2007), and wise and sustainable management of summer rainfall resource is required. The water retention time by the dams also affects the changes in zooplankton. They are grazers that cause a decrease in chlorophyll *a* concentrations by selective consumption of phytoplankton, resulting in the increase of water clarity (Kim, 1999; Kim *et al.*, 2000b; Kim *et al.*, 2003). Although this study only considered dam discharge as the forcing function, it was also requested to comprehend the relationship among hydrology, phytoplankton and zooplankton. If a discharge condition that can facilitate or does not inhibit spring zooplankton growth can be defined, the water quality during the dry seasons can be hydrologically and biologically controlled. If optimal discharge conditions from hydrological models are available in the future, more accurate and reliable hydro-ecological simulations would be possible.

Most river systems are regulated by dams and locks, and this phenomenon can be frequently observed in East Asia, due to the seasonally biased distribution of annual rainfall. Therefore the blockage of water flow responsible for the deterioration of water quality can be solved by prudent regulation of the water flow. Even though there were some cases showing flushing effects on the accumulated phytoplankton scum by the instant increase in dam discharge (Webster *et al.*, 2000; Maier *et al.*, 2001; Maier *et al.*, 2004), it is rare to find cases providing quantitative evidence in the perspective of total basin management. Therefore, the results of this study can provide useful information for river management in East Asia.

On the basis of this study's results, the following two water resource management strategies can be determined. First, flow regulation must be focused on controlling or improving river 'quality' on the viewpoint of watershed or rivers. Regardless of the water resource demand from the basin, the current status of the river and its basin need to be considered simultaneously. Ecosystem health, covering not only phytoplankton proliferations, but also other ecological components such as fish, benthic macro invertebrates and vegetation in the riparian zone, have to be intensively determined in the river basin, and the structure and functions of those factors need to be related to basin water resource management.

The second is 'acute therapy' for the water quality problems in the river. The model developed in this study was used to simulate the current status of phytoplankton biomass changes with relation to current hydrological patterns. This information can help producing predictive ecological models to be used in the 'acute therapy.' In other words, discharges of dams from the upstream can be implemented where rapid prescription is required for controlling water quality deterioration by flushing impact. For instance, a forecasting model based on hydrological and ecological components' relationship will be able to support early-warning systems for algal blooms (refer to Jeong *et al.*, 2008). For this purpose, data with more detailed time resolution (less than monthly time-interval) has to be available. Once this type of model can be constructed, the government can utilize the model for water environment management in a long-term strategy. The above two types of strategies, i.e. adaptive watershed management and acute therapy, can be taken into account other regulated river systems in the countries where a rainfall pattern is biased and dependence on flow regulation by dams is relatively high.

## CONCLUSION

This study focused on the simulation of a water quality parameter (phytoplankton biomass represented by chlorophyll *a* concentration), using long-term ecological monitoring data collected between March 1993 to March 2008 (16 years) from the lower Nakdong River. Hybrid Evolutionary Algorithm (HEA) known as efficient ecological informatics method was utilized and the relationship between meteorological, hydrological and water quality parameters were investigated. This paper has proposed possibility to quantify the regulation impact of dam discharge on chlorophyll *a* changes trough the developed rule-set model. In particular, it was shown that increase of HCD and NGD dam discharge by +20 $m^3$/sec respectively reduced algal biomass up to 37% in terms of total average of chlorophyll *a*. Therefore, it is strongly advised to wisely regulate water flow in preparation of water resource management strategy implementation in the regulated river systems in East Asia.

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