Improvement of pre- and post-processing environments of the dynamic two-dimensional reservoir model CE-QUAL-W2 based on GIS

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Abstract An Environmental Information System (EIS) coupled with a Geographic Information System (GIS) and water quality models is developed to improve the pre- and post-data processing function of CE-QUAL-W2. Since the accuracy of the geometric data in terms of a diverse water body has a great effect on the water quality variables such as the velocity, kinetic reactions, the horizontal and vertical momentum, to prepare the bathymetry information has been considered a difficult issue for modellers who intend to use the model. For identifying Cross Section and Profile Information (CSPI), which precisely contains hydraulic features and geographical configuration of a waterway, the automated CSPI extraction program has been developed using Avenue Language of the PC Arc/view package. The program consists of three major steps: (1) getting the digital depth map of a waterway using GIS techniques; (2) creating a CSPI data set of segments in each branch using the program for CE-QUAL-W2 bathymetry input; (3) selecting the optimal set of bathymetry input by which the calculated water volume meets the observed volume of the water body. Through those approaches, it is clear that the model simulation results in terms of water quality as well as reservoir hydraulics rely upon the accuracy of bathymetry information.

Keywords Bathymetry; CE-QUAL-W2; GIS; pre-processing; reservoir; two-dimensional model

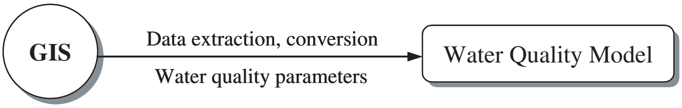
Introduction

Water quality models have been used extensively to investigate and assess virtually every type of water resource problem over the last several decades and to address water quality problems. Models have the potential to provide even greater benefits for supporting decision making on water resource management and to evaluate the best alternative for analysing complex resource problems. On the other hand, at the point of implementation of a water quality model, experts of water quality modelling often face a difficulty in preparing the geometric data on the bathymetric information because of too much time being spent and effort on file preparation. From a scientific point of view, the bathymetric file, not done by science-based procedure but from a modeller's experience and knowledge-based, could probably contain unrealistic geometric information. Since GIS as an integrated system of hardware and software has pertained closely to developments in environmental research, GIS and water quality models have developed in parallel with few interactions for the last several decades. Many researchers looking at the integration of GIS with models (Foster *et al.*, 2000; León *et al.*, 2000; Ghosh *et al.*, 2000) have increasingly recognized the mutual benefits of coupled integration between GIS and water quality models for enhancing the utility of environmental information systems (EIS). In advance of the coupling concept, Karimi *et al.* (1996) defined two categories of loose coupling (data are transferred between model and GIS) and tight coupling (either the model is embedded within the GIS or the GIS is embedded within the model). Achievement of the digital maps embodied with the real coordinate systems describing the bathymetry configuration that is a basic input file to drive water quality models was a good example of those kinds of endeavours. In the modelling approach, the accuracy of the bathymetric data can greatly affect the water quality variables such as the velocity, kinetic reactions, the horizontal and vertical momentum. Therefore, it is a critical issue to achieve high accuracy in acquiring the geometric information for water quality modelling. As far as we know, however, no extensive approach that tried to consider and solve this problem was implemented. If the modellers use these coupling methodologies, they can easily access bathymetric data to embody and these approaches enable them to get higher accuracy of the simulation results of a water quality model. The purpose of this research is to develop an advanced program for pre- and post-data processing of water quality modelling of CE-QUAL-W2 with a coupling scheme, and to evaluate the impact of bathymetric data accuracy on water quality simulation results from the application of the program developed for Daechong Dam Reservoir in Korea.

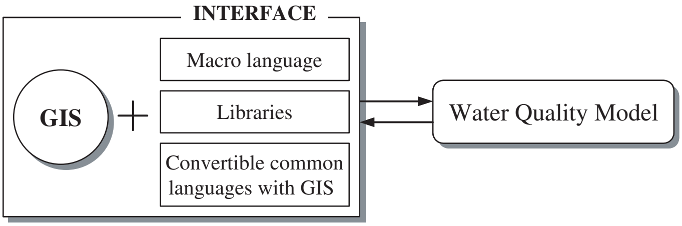
Methodology

Coupling scheme

The coupling scheme of GIS and water quality model consists of two generalized methodologies: loose and tight coupling. These definitions pertain to the application range of GIS software functions. Figure 1(a) shows a schematic sketch of loose coupling methodology. This approach aims to integrate GIS and models via data extraction using either GIS techniques or standard GIS packages (e.g., Arc/Info, Arc/View). Binary or ASCII file format, which is extracted from GIS, can be converted into the model as modeling parameters without a common user interface. The advantages of this approach are that redundant programming can be avoided and it may be the most realistic method for GIS and model users to conduct water quality modeling work. However, the data conversion between different packages could not be compatible with other formats. On the other hand, tight coupling methodology embeds certain water quality models in GIS software packages via either GIS macro or conventional languages and libraries. Figure 1(b) shows interactions between water quality model and GIS. With the recognition of the user's need to develop customized applications, more and more GIS software vendors are providing macro and script programming capabilities (such as ESRI's Avenue and AML) so that users can lump a series of individual commands in a batch mode or develop a customized user interface for specific applications. In tight coupling methodology, the GIS is frequently used as pre- and post-data processing for the water quality model and it is also employed as either the Graphical User Interface (GUI) or for data storage. This approach, however, requires a well



(a) Loose coupling



(b) Tight coupling

Figure 1 Coupling methodologies to integrate GIS functionalities and water quality model defined interface to the data structures held by the GIS. The challenge will be to develop new mechanisms for all users to access spatial data without needing to know about the particular data structures used in the GIS.

Water quality model of reservoir

CE-QUAL-W2 (Scott, 1999) which is a two dimensional dynamic model to simulate the water quality of a reservoir, is used as the target model. For spatial modelling with GIS, ESRI's Avenue and AML are used to develop the customised interface program for providing geo-spatial data to the water quality model and GUI to the user.

Implementation and data processing program

Conceptual design of a tight coupling program

The procedures can be largely classified into two categories, pre- and post-data processing. Figure 2 shows major procedures conducted to develop the customized program of pre- and post-processing of CE-QUAL-W2.

Pre-processing program

The pre-processing consists of two steps (STEP I and STEP II).

Step I. It covers four step jobs. The first is for contour data acquisition of the waterway by an image scanner. The second is for vectorizing of the scanned image to create a digital elevation map. The third is to transfer a digital elevation map into an elevation information map formatted by a lattice applying TIN function of ArcView 3D extension module. The last is to create the clipped domain of an elevation information map by which the boundary of the impounded area of the waterway is defined to be a polygon line. Therefore, all pixels of the clipped domain have the information of elevation. The coordinate transformation for this map is performed using the Arc/info package and the attribute values, which are contained in the depth range information, are added using Arc/view. The accuracy of the information of elevation assigned to each pixel is dependent on the pixel size of the lattice format and the scale of the original contour map scanned.

Step II. In this step, the establishment of GUI is done to provide end users with a more convenient environment for extracting bathymetric information of a waterway from a digital contour map. Figure 3 shows a plane view of upstream and downstream boundary conditions for branches, and examples of three typical segments (straightened, crossed, and curved section) for the water body. In the case of the straightened section, there are no difficulties to embody the geographic features and determine average cross-sectional widths for precisely contained geographical configuration. However, the cases of crossed and curved sections shown in Figure 3(b) and Figure 3(c) could contain unrealistic bathymetric data unless care is taken. In Figure 3(b), the four parallel arrow lines indicate erroneous cross section information. Those kinds of error would appear if the modeller does not subdivide the segments in detail because of dramatic varying of water volume and momentum exchanges between mainstream and branches as well as tributaries in the crossed section regions. Especially, the island encircled by the crossed section can significantly affect water quality variables such as the velocity, kinetic reactions and momentum. If the modeller ignores the island geography, it may be impossible to get an appropriate result of water quality modelling. This process, however, implies that it may be an unrealistic job for the modellers to decide the standard cross section at random because of severely diverse shapes of the plotted bathymetric configurations even in the same segment.

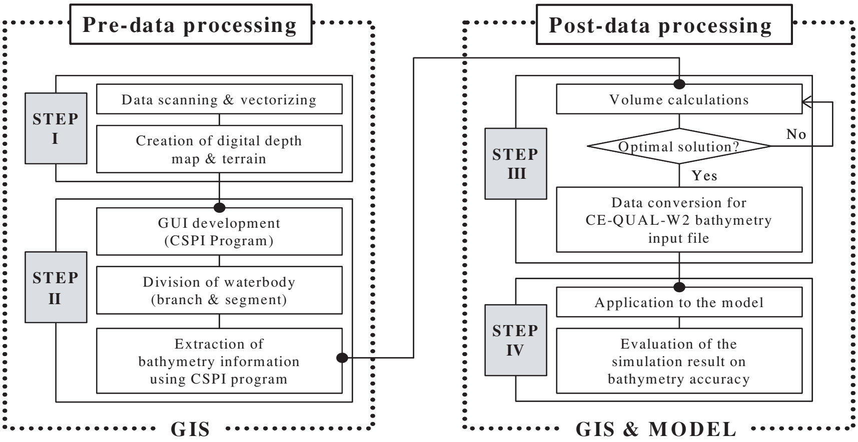


Figure 2 The schematic diagram of workflows

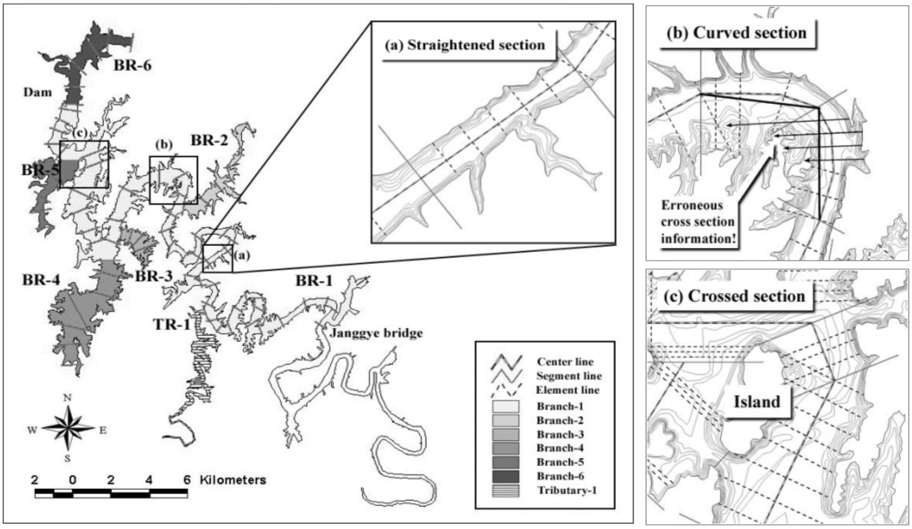


Figure 3 Up and downstream boundary conditions and considered sections for water bodies

Post-processing program

The post processing program consists of two steps (STEP III and STEP IV).

Step III. The task of step III is to select the optimal set of Cross Section and Profile Information (CSPI) that is a combination of the standard CSPI information of each segment of the water body. For instance, five standard CSPIs have to be selected if the water body considered has five identical segments. It is, however, not an easy job to get the optimal set of CSPIs because there are several alternatives of the CSPI in each segment. To achieve this task, it is the first step to choose a standard CSPI among several alternative CSPIs that represents the bathymetry of the considered segment of the water body, since the CE-QUAL-W2 model needs unique data of a standard bathymetry for a certain segment of water body modelled. As a criterion for choosing a standard bathymetry, the volume of impounded water in the segment is considered in this study. To choose the standard CSPI, the volume calculation module needs to meet the water volume observed. Water volume by arbitrary combination of cross section selected automatically is calculated using the volume calculation module of Arc/View. In addition, statistics in terms of error resulting from arbitrary combination are estimated and applied to determine the optimum bathymetry of the waterway. For automatic identifying of the CSPI that contains hydraulic and terrain features of reservoir systems, we developed the automated CSPI program using the Avenue language of the ArcView package. There are two kinds of CSPI. One is a standard CSPI that represents the shape of bathymetry of a segment. Another is an alternative CSPI representing the shape of bathymetry of an elemental cross-section. Therefore, the number of standard CSPIs is consistent with the number of the segments in the water body. On the other hand, the number of alternative CSPIs is the same as the number of reference points placed on the central line of the stream. The CSPI consists of eight stages: 1) setting two control points at up and down boundaries of each segment of water body, 2) drawing a central line linking the two control points, 3) setting several reference points along the central line by dividing with a defined length, 4) drawing a perpendicular line to the flow direction at each reference point, 5) building a definite offset line which is a part of the perpendicular line in the clipped domain of the waterway formatted by lattice, and which corresponds to the width of the water surface of the element, 6) choosing arbitrarily a definite offset line for making an alternative CSPI, 7) taking the elevation of the pixel located at an intersection of a definite offset line and a contour line and iterating the seventh stage for the number of intersections along the definite offset line, and 8) plotting CSPI for each definite offset line and repeating the seventh and eighth steps for the number of reference points in the segment concerned. On a referential coordinate system, assign a sequential number ($i = 0, 1, 2, \ldots$) to each intersection of a definite offset line and a contour line in the clipped domain of the waterway and give a coordinate name of (X_0, Y_0) corresponding to the $i = 0$ intersection, (X_1, Y_1) corresponding to the $i = 1$ intersection, and so on. Sequential numbering is assigned 0 to i from the contour line at the most left of the clipped domain of the waterway. Hence, the distance D_i, that is the distance from the starting point (X_0, Y_0) to a certain point (X_i, Y_i), can be rewritten:

$$D_i = \sqrt{(X_i - X_0)^2 + (Y_i - Y_0)^2} \tag{1}$$

The bathymetry file for CE-QUAL-W2 input data contains information specifying the segment lengths, layer heights, and average widths for each grid cell. Therefore, the CSPI of the elements has to be converted into average width information to fit CE-QUAL-W2 file formats. The calculated volume for a specific element j could be expressed as Eq. (2).

$$V_j^C = \sum_{n=0}^{(i-1)/2} [\Delta x_j \times (D_{i-n} - D_n) \times L_h] \tag{2}$$

where, V_j^C, Δx_j and L_h are the calculated volume and segment length at a specific element j as well as layer heights (2 m) respectively as shown in Figure 4.

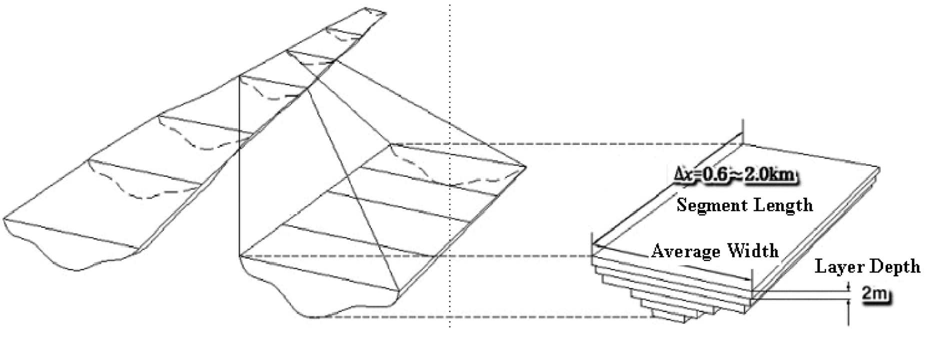


Figure 4 The conceptual sketch of volume calculation algorithms for each element

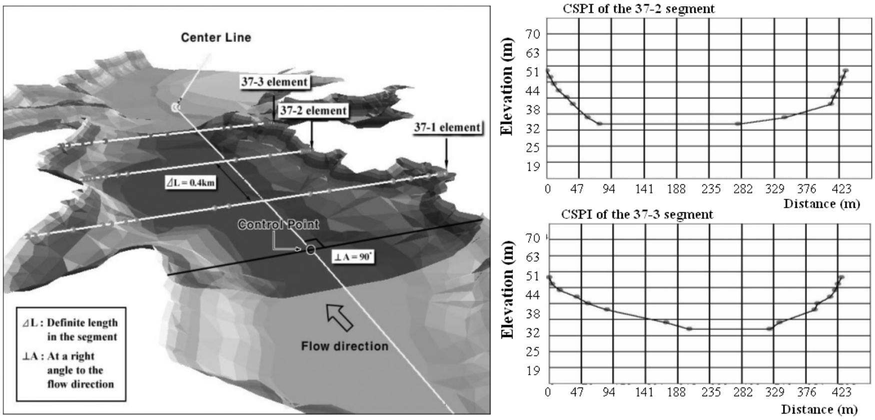


Figure 5 The example application of CSPI program at the segment No. 37

In Eq. (2), it is required that the calculation process be executed repeatedly for numerous elements. Therefore, the simple Matlab programming diversely applied to math problems is used for solving it. The GIS technique is applied to measure the area and the volume of specified zones of the TIN surface. To measure portions of a certain segment section volume correctly, the boundary polygon of a TIN is properly defined. Measuring the volumes by using the GIS technique on each segment boundary means that there can be criterion values to compare with the calculated volume for each element. The optimal set of volumes for each segment is selected to be minimized and the total volume is measured as follows:

$$V_T^m \cong Minimize \sum_{i=1}^{n} V_i^c \tag{3}$$

where V_T^m and V_i^c are the total volume measured of the entire study watershed and the calculated volume for each segment respectively.

Step IV. The linking programming is composed for coupling the pre-processing program developed with CE-QUAL-W2 model. And facilitation of it is performed to evaluate the impact of sophisticated bathymetry file accuracy on simulation results of water quality and temperature. The optimal set of volumes selected by GIS techniques is converted into average widths information format to apply CE-QUAL-W2 model as a bathymetric file. To evaluate the modelling performance, the statistics presented are the Absolute Mean Error (AME) and Root Mean Square Error (RMS) computed as follows:

$$AME = \frac{\sum_{i=1}^{N} \left| X_{i,\ observed} - X_{i,\ predicted} \right|}{N} \tag{4}$$

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} \left(X_{i,\ observed} - X_{i,\ predicted} \right)^2}{N}} \tag{5}$$

where *N* is the number of observation sites.

Results and discussion

Study watershed: Daechong Reservoir catchment

The Daechong Dam reservoir watershed, which includes Daejeon metropolitan area and Chungbuk province (126°41′~128°45′E; 35°35′~37°05′N) in Korea, is selected as a study area. This reservoir was originally constructed to supply drinking water and generate electrical energy from 1980. Since the watershed has experienced pollution caused by human activities such as deforestation, domestic sewage disposal and active land exploitation over the last decade, its water quality increasingly has deteriorated due to stratification and eutrophication.

Automatic extraction of CSPI

Pre-processing. Figure 5 shows the application result of the automated CSPI program at No. 37 segment to draw a cross section and profile a contour plot. In this station, there are three major elements that are automatically divided into defined lengths ($\Delta L = 0.4$ km) at a right angle to the flow direction. To the right of the figure, the cross sectional diagrams of elements at each location are represented with labels, elevation and distance axes respectively. Through step I and step II, the vertical and cross-sectional division of Daechong reservoir specified six branches and 80 segments including 1 tributary in consideration of the geographical characteristics. To find the optimal set of cross sectional bathymetric information within each segment, the 323 element lines are added at a right angle to the flow direction of the water body in definite lengths (0.3~0.5 km).

Post-processing. In step III and step VI an optimal volume set was produced, which involved 80 segments, in 323 elements. The optimal volume set, which is to meet the total volume measured by using the GIS, is shown in Table 1. This set is converted into average widths information format (ASCII) to apply CE-QUAL-W2 as a bathymetric file. To explore the impact of the model simulation results on each case exactly, it is essential that all input data and conditions including hydraulic and kinetic parameters are modelled in the same environment except for the bathymetric file. The model parameters are calibrated and verified with field observed data. This environmental information system can be supported not only by recognizing spatial water quality changes but also by predicting the in-out flow of pollutant sources. Figure 6 shows the three dimension visualization of water quality results especially T-N. The left picture shows the spatial concentration of T-N on 27 August and the right one describes the vertical concentration change of T-N with depth.

Table 1 The optimal set of volume calculations for the 323rd element

E_{numb}	V^{C*}	V^{m**}	E_{numb}	V^{C}	V^{m}	E_{numb}	V^{C}	V^{m}
2-1	6.61E+06		5-1	7.38E+06		76-2	5.07E+06	
2-2	4.65E+06		5-2	7.77E+06		76-3	6.25E+06	
2-3	1.49E+07	**1.6E+07**	5-3	8.26E+06	**8.0E+06**	76-4	8.94E+06	
2-4	7.35E+06		5-4	7.85E+06		76-5	8.24E+06	
2-5	1.08E+07		6-1	1.15E+07		77-1	1.58E+07	
2-6	7.20E+06		6-2	1.85E+07		72-2	1.43E+07	**1.5E+07**
2-7	5.27E+06		.....	.....		78-1	3.09E+07	
3-1	3.26E+06		.....	.....		78-2	1.52E+07	
3-2	3.96E+06		.....	.....		78-3	2.00E+07	
3-3	4.41E+06	**4.3E+06**	.....	.....		78-4	2.52E+07	**2.3E+07**
3-4	5.90E+06		73-1	4.66E+07		79-1	3.40E+07	
4-1	6.91E+06	**6.9E+06**	73-2	6.24E+07	**5.0E+07**	79-2	2.39E+07	**2.6E+07**
4-2	8.01E+06		73-3	6.26E+07		79-3	2.15E+07	
4-3	7.14E+06		73-4	3.68E+07		79-4	1.67E+07	
4-4	5.73E+06		73-5	3.65E+07		80-1	2.31E+07	
4-5	6.74E+06		73-6	3.86E+07		80-2	1.95E+07	**2.1E+07**
4-6	8.49E+06		76-1	4.25E+06	**4.5E+06**	80-3	2.03E+07	

* The calculated total volume (V^c): 1.23771E+09 (m^3); ** The measured total volume (V^m): 1.23774E+09 (m^3)

Modelling results

Modelling conditions. Two cases of bathymetric data such as case (a) and case (b) in Table 2 are considered to evaluate the impact of sophisticated bathymetric file accuracy on simulation results of water quality and temperature. The case (a) shows the optimised bathymetric file by using GIS techniques. The case (b) describes the bathymetric file produced from the modeller's experience. Temperature and four other water quality parameters such as dissolved oxygen, CBOD, nitrate-nitrogen and phosphorus are selected for identifying the internal flux of Daechong reservoir basin and calculated for concentrations of water quality constituents within each segment. In order to analyse the movement of density current after summer storm runoff and illustrate how bathymetric file accuracy affects water quality modelling, two target days, 4 August and 6 September in 2000 are selected and simulated for evaluating the model results.

Temperature. Figure 7 shows the observed and simulated vertical profiles of temperature at four different stations. On all plots, the dotted lines represent observed values, and the AME and RMS are also included for each date in order to help in interpreting the model results for each case. Results from the range of AME and RMS values presented show that the model results of the case (a) are more satisfactory than the case (b). In the Figure 7(a), the range of AME values presented is 0.42~1.36 in the case (a) and 0.56~1.33 in the case (b). The AME of 0.5°C means that the model results are, on average, within 0.5°C of the observed data. As can be seen, model predictions for all the reservoirs are within 1°C and most of them are much less.

Table 2 The comparison of two cases of bathymetric data

Data indexes	Case (a)	Case (b)
Total branches	6	5
Main stream segments	45	32
Total segments	80	64
Vertical layers	30	30
Total volume	1.238×10^9(m^3)	1.288×10^9(m^3)

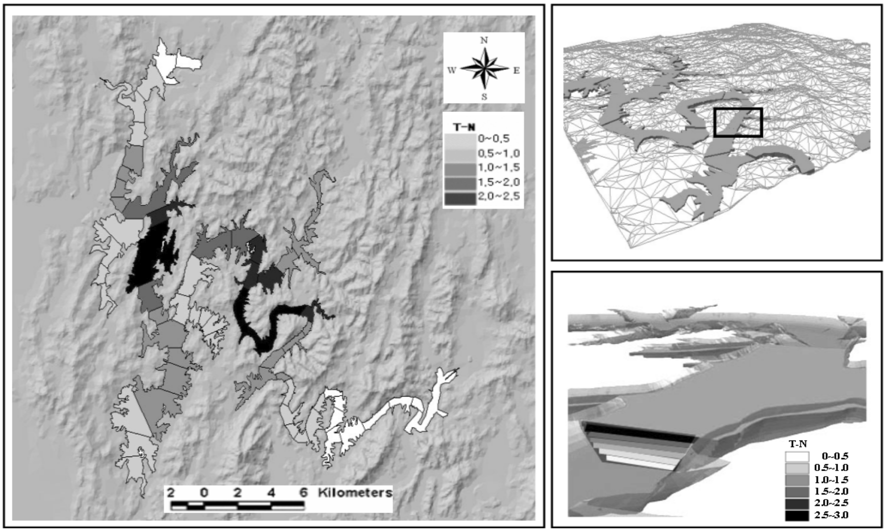
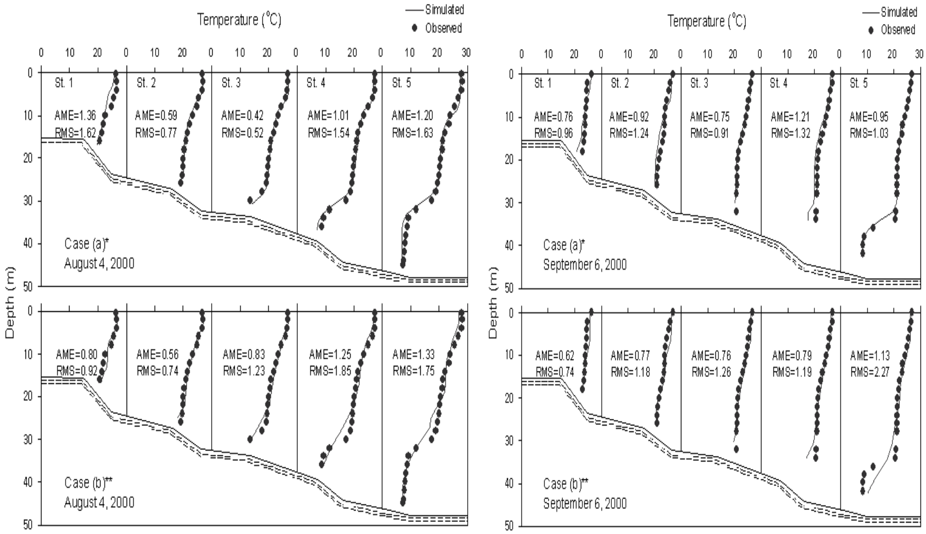


Figure 6 3D Visualization map of water quality modelling results of the predicted T-N



(a) August 4, 2000 (b) September 6, 2000

Figure 7 Comparison results of vertical profiles of temperature at each station

Water quality. Water quality simulation in terms of temperature and concentrations was conducted for Daechong reservoir basin within each segment during four months (April 28, May 25, June 26 and July 27).

From the experimental result we can conclude that heavy rainfall in June caused mixing of the reservoir and disturbed the stratification phenomenon and influenced the increase of DO concentration. The overall decreased range of DO concentration in the epilimnion and hypolimnion was 3~5 mg/l in July. The simulated COD concentration showed a relatively similar distribution over the reservoir in April. The little decrease of COD concentration in May was due to the increased water temperature. For the rainfall, the mixing contributed to the drop in the upper epilimnion of 2.4 mg/l concentration during June. The COD concentration ranged over 2.4 mg/l in June due to the mixing caused by the heavy rainfall. The nitrogen concentration of Daechung reservoir was estimated in the range of 1~2.7 mg/l, which is attributed to the inflow of nitrogen from the nearby Oakchunn tributary. The simulated PO_4-P concentration ranged from 0.004~0.036 mg/l and the average concentration was 0.025 mg/l.

Conclusion

This study proposed the tight coupling method, embedded in the CE-QUAL-W2 in GIS software via either macro language or library packages. The digital maps embodied with the real coordinate systems can describe the bathymetry configuration that is a basic input file to drive water quality models. Through these approaches, the following major results are obtained. First, the accuracy of bathymetry information may significantly affect the model simulation results. Therefore, this approach could solve more effectively the problem of selecting CSPI for CE-QUAL-W2 bathymetry file preparation by using GIS techniques rather than the modeller's experience. Furthermore, this methodology could propose the standardized bathymetry that is the best suited for Daechong reservoir's geometric information. Second, the model simulation results of predicted temperature and four other water quality parameters specified successfully the internal movement of constituents and stratification phenomenon of the Daechong reservoir, with seasonal variability. Third, the research into watershed and water quality, diverse problems and watershed environmental data management could be assisted, and the running time of model execution become shortened, by integrating GIS and water quality model (CE-QUAL-W2). Lastly, it is necessary to connect the web with modelling to maximize water quality management and reflect effectively Water Quality Management Policy and Decision Support System as an integrated system.

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