Development and application of a Watershed Information System (WIS) for water quality analyses

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Abstract This paper describes the development, implementation and evaluation of a watershed information system (WIS) to assist in the planning of programmes for water quality control in river basins incorporating both point and nonpoint pollutant sources. The system simulates rainfall–runoff processes and the transport of water quality constituents and sediment. WIS includes two nonpoint source models, a network design component, a flow and sediment routing component and a water quality component. Simple models of rainfall–runoff and water quality were selected for WIS. The models in the system are integrated through their inputs and outputs. Friendly Graphical User Interfaces (GUI) facilitate the interaction with user-models. WIS was applied in a watershed in Delaware County, New York. The results showed that the system is a suitable computational tool to identify source areas of pollution in river basins and indicate where more complex modelling and analysis might be recommended.

Key words water quality; information system; nonpoint source models; sediment

INTRODUCTION

A watershed information system is defined as a computer tool designed to represent the elements comprising a watershed and their interactions. The need for reliable watershed information systems has increased as a response to an accelerated implementation of water quality programmes. Since the simulations from watershed information systems will support watershed management decisions, confidence in them is extremely important for the implementation of any water quality programme. Developing or selecting appropriate watershed information systems is therefore essential for the credibility and scientific veracity of management and policy decisions.

Although the literature illustrates an increasing use of models as the basis for implementation of water quality programmes (Loucks *et al.*, 1995; Bouraoui & Dillaha, 2000; Dai & Labadie, 2001), their application remains restricted to experts or to a small group of professionals directly involved with the model development itself. Decision makers and stakeholders are often excluded during the simulation modelling exercise, jeopardizing their acceptance and support of recommendations suggested as a result of the model application. Most of the time, the complexity of models, their large number of parameters and poor interfaces are obstacles for the effective application of models and appropriate interpretation of their results.

In a recent modelling review, Thomann (1998) concluded that the interpretation of model output and model quality control will assume a progressive importance in coming years due to the economic and political consequences of making a wrong environmental policy decision, adding to the fact that environmental decision-making processes have grown in complexity. Developing computational tools capable of overcoming these obstacles has been a challenge and a goal yet to be accomplished. These tools should be able to integrate different types of models and still be easy to apply.

The present paper contributes to efforts to develop watershed information systems by integrating different simulation models to help define and implement water quality programmes. Its motivation stems from the need for simple and reliable watershed information systems that could facilitate the participation of stakeholders and decision makers in the implementation of water quality programmes, thereby improving their chances of success.

FRAMEWORK OF WIS

Some innovative methods of software engineering have been applied to the development of watershed information systems. Object-oriented methods are moving to the mainstream of these efforts and are providing a promising philosophy of systems development. In the last few years, several research papers have discussed the use of object-oriented approaches to the development of watershed information systems (Wilson & Droste, 2000). The application of object-oriented analysis and design methods permits software modularity and re-use. Delphi 6.0 was chosen for the development of the watershed information system discussed in the present paper.

The mathematical models included in WIS are organized in components integrated through graphical user interfaces (GUIs) that provide the connection among the models and permit interaction between models and users and model inputs and output data. Figure 1 depicts the major components of the system: a nonpoint source (NPS) component at sub-basin scale; a watershed representation component that defines a network of nodes and links; a nonpoint source component at watershed scale that sums up outputs from the NPS component at sub-basin scale; a routing component for flows along the main channel of the watershed, a sediment transport component; and finally, a stream water quality component.

WIS Interfaces

There are eight major interfaces built into the system interconnecting the inputs and outputs of each component cited in Fig. 1. Some features are common to all interfaces, such as the use of editing fields to input parameters values, the automatic simulation and presentation of new results in response to changes in parameters values, the presentation of results in time series plots with the possibility to export the graphical results to tabular results in text files. The initial interface is responsible for the interaction between all the available models through their interfaces. It has three main pull-down menus. They are: *Runoff*, *Network* and *Simulation*. The *Runoff* menu

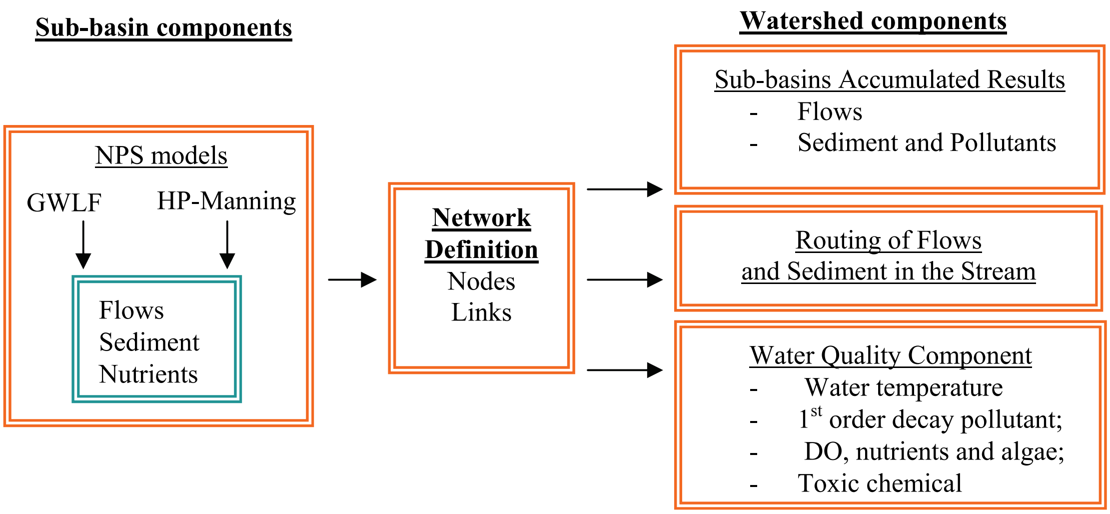

Fig. 1 The interaction of components in WIS during a simulation exercise.

presents the two alternative models for the simulation of rainfall-runoff and runoff of pollutant loads from the land to the outlets of sub-basins. The *Network* menu launches the interface to read input files of nodes and links of the network representing the main channel of the watershed. In the *Simulation* menu, the user can select any of the following sub-menus: *NPS Inputs*, *Routing* and *Quality*. Figure 2 illustrates the initial menu of WIS and the interface for the NPS component with a focus on the GWLF model.

Mathematical models in WIS

The models in the system are integrated through their inputs and outputs. Beginning with the simulation of flows and pollutant loads from land at sub-basin scales, non-point source models generate inputs for the routing of flows and pollutant loads (including sediment) along the main channel of the watershed. Likewise, outputs from the routing component are inputs for the in-stream water quality component. Details and the mathematical formulation of all models included in WIS are available in Alves (2005).

NPS models: flows, sediment and nutrient loads from the land The simulation of flows and the pollutant loads from the land surfaces to the main channel is performed using either one of the two NPS models. The first model, named HP-Manning, is based on a parameterized set of equations describing the hydrological processes in the catchment. The hydrological processes are computed daily and modelled for each sub-basin as a hydrological unit. A daily water balance is maintained. The accumulation of pollutant on the land is represented by a build-up function and its transport from the land to the main channel of the watershed is described by a wash-off function.

The second NPS model is a revised version of the Generalized Watershed Load Function (GWLF) model (Haith *et al*., 1996). This model includes some modifications suggested by Schneiderman *et al*. (2002). It simulates daily streamflow, sediment and

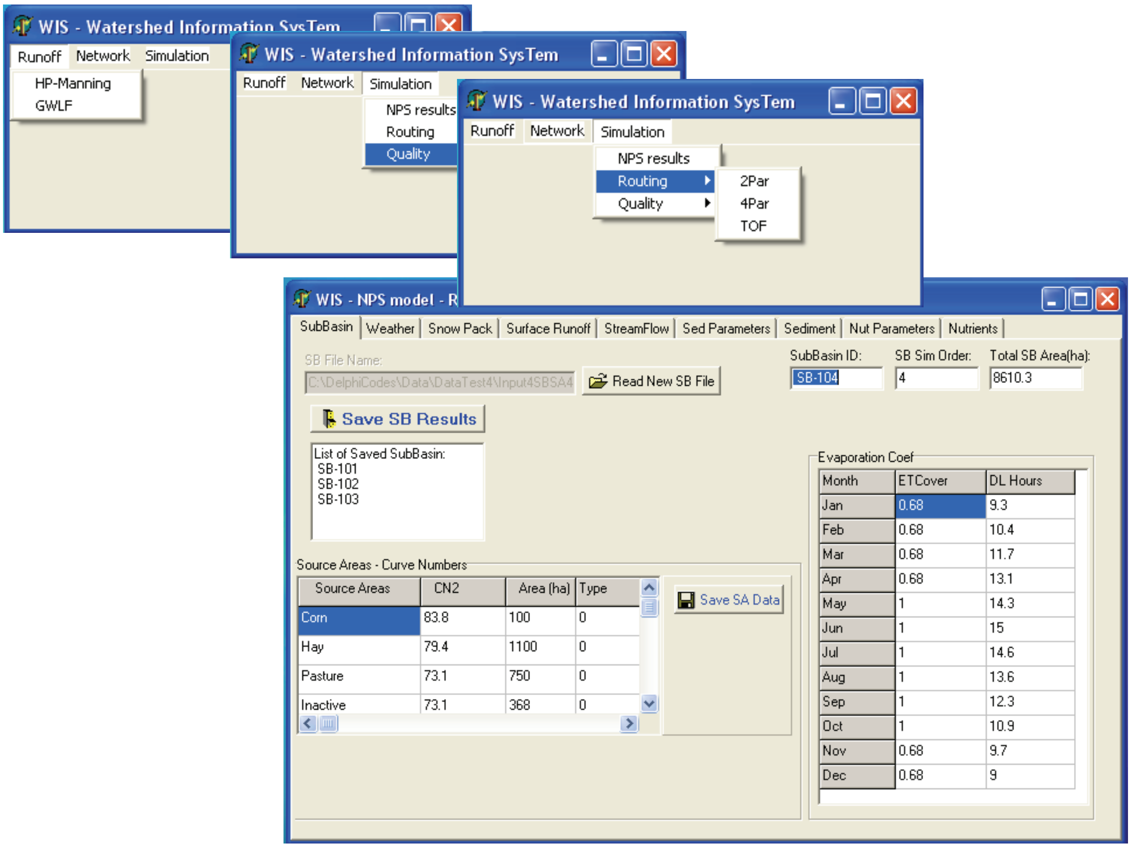

Fig. 2 Examples of interfaces of the Watershed Information System (WIS).

nutrient (nitrogen and phosphorus) loads. The rainfall–runoff model follows the US Soil Conservation Service (US SCS) Curve Number (CN) approach.

Both NPS models included in WIS, HP-Manning and GWLF, are defined as conceptually-based lumped and continuous-time models. The models are applied in a semi-distributed manner by disaggregating the basin into linked sub-basins. The daily changes in flows and pollutant loads are simulated at sub-basin scales. In the revised version of the GWLF, equations of the models are applied for each source area with uniform characteristics according to land use and soil type. In the HP-Manning, each sub-basin is assumed to be homogeneous with respect to slope, land use and soil type. In this case, these average characteristics represent a weighted average from all source areas in the sub-basin.

The routing component: flows and sediment transport The flow routing models available in this component operate on a daily time step and accept inputs from the continuous-time NPS models. WIS incorporates three simple flow routing algorithms based in two or four parameters or use inputs for the time of flow in the elements (nodes and links) of the network.

The sediment routing model simulates the transport of sediment in the stream and in the riverbed. It considers the total sediment load in one-dimensional streams. The total mass of sediment in the stream or river is divided into discrete size classes according to the size of the particles being transported. The classes considered in this sediment transport component are: gravel, sand, silt and clay. The erosion, transport and deposition of each size class of sediment depend in part on the hydrological and hydraulic parameters that are computed in the flow routing simulation model. The model divides the main channel of the watershed into relatively homogeneous channel reaches.

The water quality models The water quality simulation component has the role of describing, in a simplified but realistic scheme, the fate and transport of substance in a water body. Modelling of the evolution of transient pollution loadings along fluvial ecosystems is founded on the advection–dispersion transformation equation. The present water quality simulation model considers that the major transport mechanisms are significant only along the main direction of the flow (the longitudinal direction). Instantaneous complete cross-sectional mixing is assumed. Advection is the mechanism that represents the transport of mass along the system (no dispersion is taken into account). Transformation of mass (sinks or sources due to physical, chemical or biological reactions) is represented by different equations. There are models for the simulation of water temperature, first-order decay constituents, dissolved oxygen, nutrients, algae and toxic chemicals (including the interactions between water and sediment phases).

Temperature model Temperature models are based on a heat balance in the water body, which is predicted by evaluating the sources and sinks of heat. The main sources of heat in a water body are short-wave solar radiation, long-wave atmospheric radiation, conduction of heat from the atmosphere to the water and direct heat inputs. The main sinks of heat are long-wave radiation emitted by the water, evaporation and conduction from the water to the atmosphere.

The first decay model The first-order reaction equations are probably the simplest and most used models in water quality. They can represent decay of substances such as Total Coliform, Dichloro-Diphenyl-Trichloroethane, (DDT) and Polychlorinated Biphenyls (PCB), growth and death of microorganisms and consumption of biochemical oxygen demand (BOD). A constituent can be modelled as a first-order-decay process if the constituent has no interaction with other substances, and the rate of reaction is only proportional to its own concentration multiplied by a constant coefficient.

Dissolved oxygen and nutrient model The model for dissolved oxygen (DO) in the stream is related to the decomposition of waste in water. The DO modelling includes the following constituents: dissolved oxygen, carbonaceous biochemical demand, nitrogenous biochemical demand, organic nitrogen, ammonium, nitrate nitrogen, phosphate and a number of algae elements.

Toxic chemicals model In order to model toxic chemicals, adsorption and desorption processes in both water and sediment phases, as well as first-order decay processes, should be taken into account at the same time. The estimation of the suspended sediment concentration, re-suspension from the bottom, and settling are required inputs for the simulation. The adsorption/desorption model assumes that the equilibrium is reached instantaneously between the dissolved and adsorbed concentration.

APPLICATION OF WIS

The application presented here has the purpose of testing the NPS component of WIS and evaluating its performance in terms of simulation results and adequacy of the interfaces designs. The case study was applied to the Townbrook watershed located in Delaware County, New York State, USA. This watershed has been object of many modelling exercises as part of the efforts to reduce the high concentration of phosphorus in the Cannonsville reservoir which is part of the water supply system of New York City. It is believed that the high concentration of phosphorus results mostly from nonpoint source loadings (Cerucci, 2002; Benaman, 2003).

The Townbrook watershed has an approximate area of 3707 ha. The largest land covers are agricultural areas and forests. The urban area in the Townbrook watershed is minimal and there are no point source loads from wastewater treatment plants. The Townbrook watershed was divided into 14 sub-basins according to its topography. Within each sub-basin, source areas were defined according to the land use and soil type information.

The daily weather data inputs for WIS simulation exercise are average temperature (°C) and precipitation depths (mm). The Townbrook watershed does not have a climate station inside its boundaries. The closest climate stations were Stamford and Delhi. Both stations provide precipitation data, but only Delhi has temperature data. The WIS nonpoint source component can read a separate weather input data file for each sub-basin within the watershed. In the Townbrook watershed, all the sub-basins receive precipitation data from the Stamford climate station and temperature inputs from the Delhi station. Inputs for parameter values in each sub-basin were defined in separate input files. The values for the parameters used in this application were derived from a literature review and suggestions in Schneiderman *et al*. (2000) and Cerucci (2002).

Model performance statistics

The results for this WIS application were compared to measured data for monthly streamflow, dissolved phosphorus and nitrogen, particulate phosphorus, total phosphorus and sediment. Measured data were available for the period from October 1998 to September 2000. Three statistics were calculated for the evaluation of model performance: the percent difference, D, the Nash-Sutcliff coefficient of simulation efficiency, SE_{NS}, and the coefficient of determination, R^2.

Results of the simulation for the GWLF model in the nonpoint source component of WIS

The analyses in the present section refer to the evaluation of performance for the GWLF model using the values of parameters presented in Table 1. The evaluation was based on statistics of monthly simulation results. Table 2 provides the statistics for streamflow, sediment, dissolved phosphorus, particulate phosphorus and dissolved nitrogen.

Results for streamflow were slightly overestimated in most of the 24 months of simulation. Part of these errors may be related to deviations in the precipitation and

Table 1 GWLF parameters for the WIS application in 14 sub-basins of the Townbrook watershed (continues overleaf).

Symbol	Unit	Description	Value	Categories
		Hydrological parameters		
CN		Curve number	70	Forest deciduous
			70	Forest coniferous
			71	Grass-shrub and grass
			83	Corn
			77.2	Alfalfa
			92	Water
ETCV		Evapotranspiration vegetative cover coefficient	0.68	November to April
			1	May to October
Season		Growing season months	May to Oct	
DLHours		Daylight hours per month	9.3–10.4–11.7–13.1	Jan–Feb–Mar–Apr
			14.3–15–14.6–13.6	May–Jun–Jul–Aug
			12.3–10.9–9.70–9	Sep–Oct–Nov–Dec
Km	cm/ºC	Temperature melt factor	0.48	
SWCap	cm	Soil water capacity	10.9	
IniUnsSto	cm	Initial unsaturated storage	10	
IniSatSto	cm	Initial Saturated storage	0	
GWRecCoef	1/d	Groundwater recession coefficient	0.1	
GWSeepCoef	1/d	Groundwater seepage coefficient	0	
UnsLeakCoef	-	Unsaturated leakage coefficient	0.06	
IniSD	cm	Initial snow depth	0	
SDR	-	Sediment delivery ratio	0.065	
GWDisNit	mg/L	Groundwater dissolved nitrogen	0.34	
GWDisPho	mg/L	Groundwater dissolved phosphorus	0.013	
		Dissolved nutrient parameters		
DisNitConc	mg/L	Dissolved nitrogen concentration in runoff	0.19	Forest dec. and con.
			2.6	Grass-shrub
			2.9	Grass
			2.9	Corn
			2.8	Alfalfa
DisPhoConc	mg/L	Dissolved phosphorus concentration in runoff	0.006	Forest dec. and con.
			0.15	Grass-shrub/alfalfa
			0.25	Grass
			0.26	Corn
DisNSnowM	mg/L	Dissolved nutrient concentration from manured	1.9	P-corn
		areas (in snowmelt events)	20.716	N-corn
GWDisNit	mg/L	Groundwater dissolved nitrogen	0.292	
GWDisPho	mg/L	Groundwater dissolved phosphorus	0.013	
AnnGWFlow	cm/year	Mean annual groundwater flow	60.1	
		Sediment		
SDR		Sediment delivery ratio	0.065	
TCPower		Transport capacity power	1.67	
EnrRatio		Enrichment ratio	2.91	
AnnEros	kg×10^3/year	Average long-term annual erosion	402.77	Forest deciduous
			730.1	Forest coniferous
			1075.93	Grass-shrub
			735.03	Grass

Symbol	Unit	Description	Value	Categories
Continued from overleaf		Sediment		
			2868.37	Corn
			7.96	Alfalfa
AnnTC		Long term annual avg for the streamflow TC	28.1	
		Solid nutrient parameters		
SoilConcNit	mg/kg	Nitrogen concentration in soil	650	
SoilConcPho	mg/kg	Phosphorus concentration in soil	1500	

Table 2 Statistics of the GWLF model performance in the period October 1998–September 2000.

		Model performance for monthly results:			
Statistics	Streamflow	Sediment yield	Particulate P	Dissolved P	Dissolved N
Mean measured data[a]	56.87	194.02	235.15	85.79	1346.11
Mean simulated results[a]	60.72	56.04	118.79	78.83	1345.13
D	6.76	–71.12	–49.48	–8.11	–0.07
R^2	0.84	0.18	0.16	0.58	0.77
SE_{NS}	0.82	–0.01	0.09	0.53	0.73

[a] Units: streamflow (mm); sediment (ton); particulate P, dissolved P and N (kg).

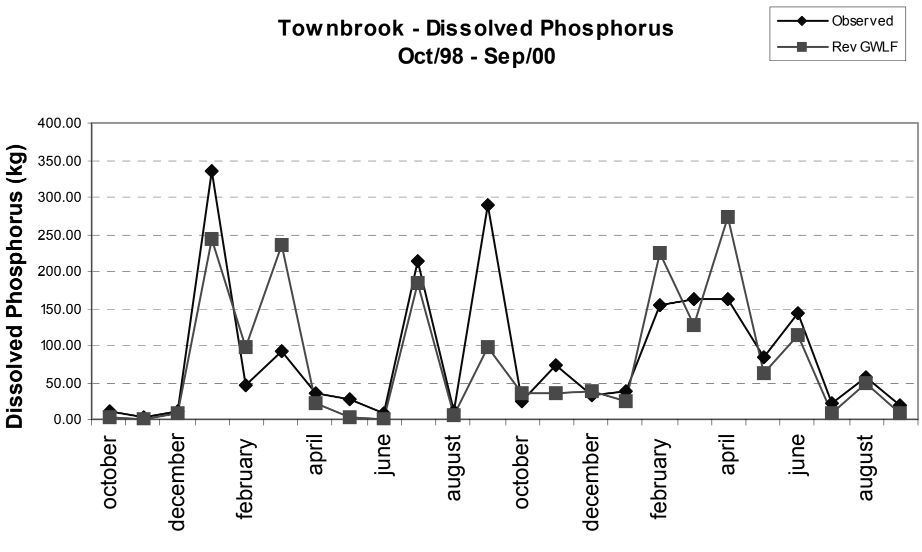

Fig. 3 Measured data and GWLF simulated results for dissolved phosphorus.

temperature input data considering that the Stanford weather station is located outside the Townbrook watershed. The measures of model performance presented good results. The coefficient of determination R^2 and SE_{NS} were both greater than 0.80 suggesting that the model depicts the trends in the measured data with very good approximation. The sediment results show that the seasonality of sediment yield is well represented but the model did not capture the large peaks of sediment during the summer of 1999. The model does not depict the large effects of summer rainfall on unprotected soil (unprotected meaning not covered by snow accumulation).

The model performance statistics for simulated results of dissolved loads for nutrients indicate a good representation of measured data by the model. Figure 3 shows the measured data and simulated results for dissolved phosphorus. The graph illustrates that the model performs well in describing the seasonality of dissolved nutrient loads. The values of the simulation model efficiency SENS also indicate that the use of the model to represent the dissolved loads of nutrient gives much better predictions than simply using the average of observed data.

Despite the poor representation of sediment load peaks, the general results for this simulation exercise are considered good. The seasonality of flows, sediment and nutrient loads is preserved. It is possible that improvements in the definition of parameters values for the present simulation exercise may improve the performance of the model.

Semi-distributed results of the sediment and dissolved nitrogen at the watershed scale

In this section, the results from the NPS component are investigated in each sub-basin. The system sums up the results of the GWLF model beginning from the most upstream node until the outlet of the watershed. Sediment and dissolved phosphorus loads were selected to illustrate the application of this component. This analysis can help to identify problem areas or sub-basins that are generating the higher loads of pollutants. The cumulated sediment yield, from the sub-basin TB14SB-01 up to sub-basin TB14SB-06, accounts for 7.60% of the total sediment generated in the watershed. If sub-basin TB14SB-07 is included in the cumulated results, the percentage of sediment increases to 53.95% and the area adds up to 35.95% of the total watershed. The large area of this sub-basin and well distributed land uses contributes to this result. The largest accumulation of sediment yield is observed from sub-basins TB14SB-09 to sub-basin TB14SB-11. There is an increase of sediment yield from 45.86% to 85.34% of the total sediment yield in the entire watershed.

Nutrient loads can also be evaluated based on the analysis of accumulated loads from each sub-basin. The first six sub-basins, TB14SB-01 to TB14SB-06, generate on average only 14.48% of the watershed total monthly loads of dissolved phosphorus. Most of the entire watershed loads of dissolved phosphorus seems to be generated in the lower or most downstream sub-basins. The sub-basins TB14SB10 to TB14SB-14 represent 27% of the total area of the Townbrook watershed. However they contribute some 38.82% of the total dissolved phosphorus loads in the basin.

CONCLUSIONS

Two NPS models, a network definition component, three flow routing algorithms, a sediment transport model and a stream water quality model comprised the WIS presented herein. A case study was developed in order to evaluate the performance of the GWLF model in the NPS component and the design of the interfaces and this resulted in good measures of model performance for monthly streamflow and dissolved nutrients (nitrogen and phosphorus). The features in WIS interfaces facilitated the definition of parameter values and the visualization of outputs. The automatic update and presentation of simulation results in response to parameter changes is a great help for the visual investigation of model sensitivity.

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