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Utilizing Aspects of Geographical Information System (GIS) to Support Water Quality Modeling in Lake Environment

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Abstract: Predictive modeling of water quality is increasingly becoming a crucial aspect of water resources management as water quality models not only provide an explanation for the transport and transformations of key water quality components but also provide a platform for useful scenario evaluation and testing. Likewise, the use of Geographical Information System (GIS) to support or aid predictive modeling further underlines the versatility and usefulness of GIS as a tool. In this study, a water quality model has been established to simulate parametric concentrations in a natural lake system. The utilization of GIS in the modeling process is described and the benefits highlighted. Among other practical applications, GIS significantly aided model input generation and output display. Output spatial visualization facilitated by GIS, enabled a clearer presentation of spatial variation and progression of water quality components within the lake. This is significant for water resources management purposes as it makes analysis on a spatial and temporal scale easier and also enhances the geographical linkage between pollution sources and areas of impact.

Key words: Geographical information system, water quality, modeling, water simulation, lake management, Malaysia

INTRODUCTION

The application of mathematical modeling techniques for dealing with water quality issues has proven to be an effective and powerful tool in water resources monitoring and management. Mathematical modeling facilitates the abstraction of a highly complex real world. There are various categories of models such as stochastic models which incorporate uncertainty and random measurement errors in input parameters as well as models that use expected inputs and yield predictions that are also expected values known as deterministic models. On the basis of space dependence, models can be classified as lumped parameter models if they are zero dimensional in space or distributed in which the model varies in one or more spatial dimensions. A vast number of models have evolved over time, ranging from simple empirical, input-output models to very sophisticated ones based on neural networks and Geographical Information Systems (GIS). Due to the impossibility of detailing all the attributes and complexities of the natural world, efficient modeling requires the discernment and identification of both anthropological and natural phenomena that are relevant to the water quality problems under consideration. Mathematical models serve as predictive tools and enable the forecasting of outcomes from alterations and changes whether man-made or natural on water quality. It has been recognized that due to the complex nature of some water quality problems, mathematical models provide the only real means for predicting the source of impacts and possible management alternatives to correct such problems. Various types of water quality models have been developed and applied for different situations, water quality management purposes and different types of water bodies including streams, lakes and estuaries (Lung, 1993; Pelletier *et al*., 2006; Zhang *et al*., 2008).

The need for more precise model development and refinement has led to the application, linkage and connection of GIS with water quality and models. This is mainly because GIS is an effective tool for spatial analysis interpretation and has become a very popular display method for achieving scientific and engineering objectives. GIS offers representations of spatially

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referenced data through vector data models and raster data models. Within the vector structure, geographic features and objects are represented by points, lines and polygons with specific coordinates in continuous map space. Raster structures divide space into a two-dimensional grid of cells similar to a spreadsheet where each cell contains a representative value of the attribute being mapped (Garbrecht *et al*., 2001; Toriman *et al*., 2006, 2009). GIS is now commonly used for various environmental processes including watershed delineation, surface water representation, non-point source pollutant loading calculation and assessment as well as ground and surface water modeling predictions. The levels in which GIS is applied to modeling can be broadly represented as ad how integration, partial integration and complete integration. In the 1st level, the GIS data structure and environmental model are developed independently. The data is extracted from GIS, the model runs separately and the output analyzed at the user's discretion. The 2nd level results in GIS playing more of an integrated role in the modeling. GIS supplies the data and then accepts the modeling results for processing and presentation. The

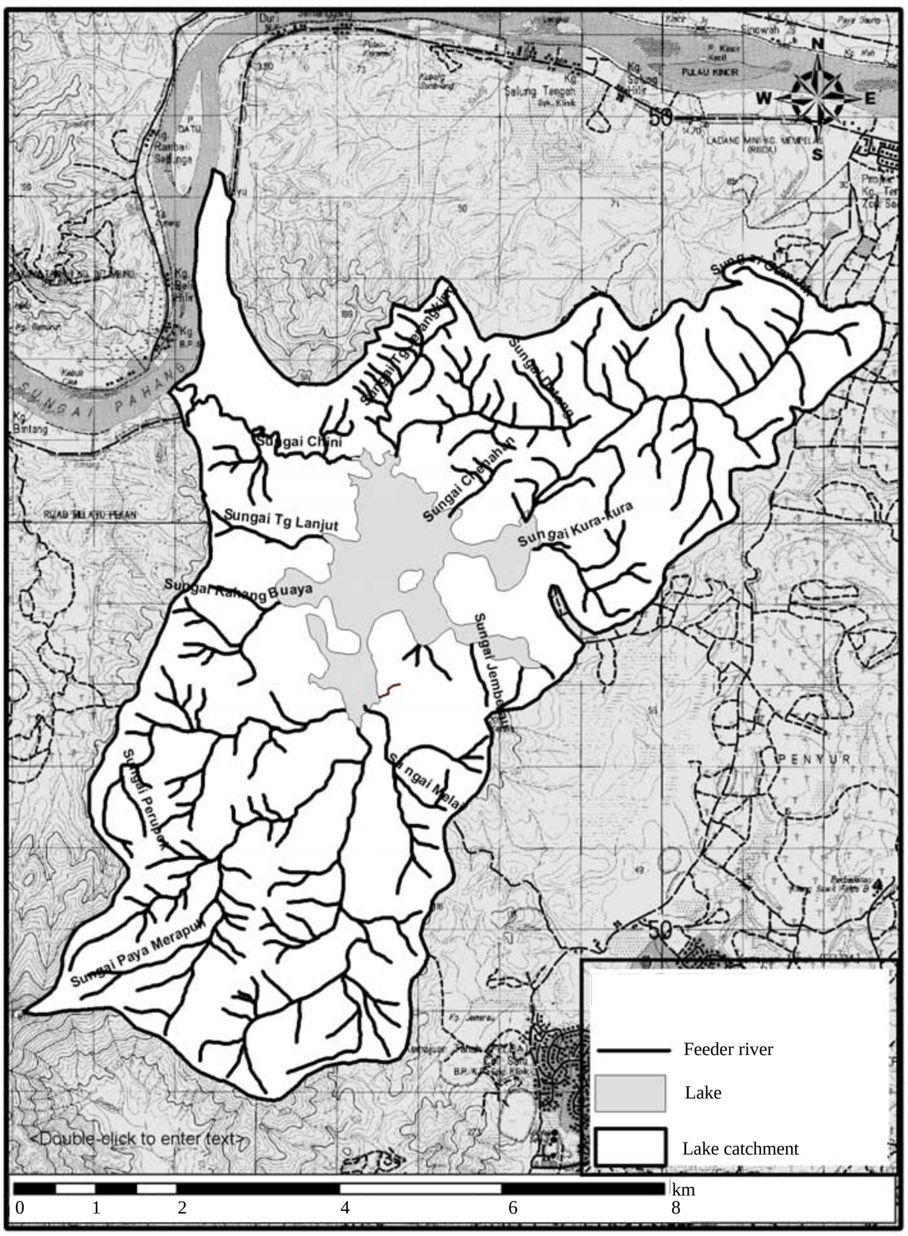

Fig. 1: Study site with associated rivers within the lake watershed

3rd level consists of complete model development within the GIS software. The user has a single operating environment where the data stored in the GIS is structured to meet the demands of the model and vice versa (Tim and Jolly, 1994).

In this study, a water quality model was developed and applied in a shallow natural lake system using the WASP 7 models which is a dynamic compartment-modeling program for aquatic systems including both the water column and the underlying bonds. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are simulated in the model (Wool *et al*., 2001). The water quality model is expected to identify and quantify how physical, biological and chemical processes and their interactions control the spatial distributions of water quality components within the lake. The use of GIS at various stages of the modeling process such as input data acquisition and verification as well as output display in spatial form is emphasized and highlighted in this research. Furthermore, the research concentrates on the outcome of the simulation process based on two important water quality and eutrophication related variables, namely Dissolved Oxygen (DO) and phytoplankton biomass represented by chlorophyll a.

Study area: The study site under focus is Tasik Chini which is located in Pahang state, Malaysia (Fig. 1). Tasik Chini is the 2nd largest natural lake in Malaysia and consists of 12 sub-lakes which are fed by the tributaries surrounding the water catchment areas of the Chini forest before flowing into the Pahang river via the Chini river. Tasik Chini is surrounded by variously vegetated low hills and undulating lands which constitute the watershed of the region. There are three hill areas surrounding the lake namely; Bt. Ketaya (209 m) located at the Southeast; Bt. Tebakang (210 m) at the North and Bt. Chini (641 m) at the Southeast. The volume of water in Chini lake was estimated to be between 4×106 and 7×106 m^3 while the mean inflow discharge was between 0.46 and 3.53 m^3 sec^{-1}.

The climate of Tasik Chini is typical of the equatorial climate of Peninsular Malaysia which is characterized by moderate average annual rainfall, temperature and humidity. In an effort to enhance the tourism features of the lake, a barrage was built on Chini river in 1995, so as to facilitate water retention within the lake. The construction of the barrage has had a critical effect on the hydrological system state of the lake and is believed to have caused ecological and water quality changes within the lake. There are about 500 settlers around the fringes of the lake and its watershed which also houses tourist resorts and facilities (Idris and Abas, 2005). The continued development of tourism facilities and conversion of forest areas to agricultural farms and logging sites have been identified as sources of adverse impacts to the lake through increased run-off and pollution potential.

MATERIALS AND METHODS

Modeling tool: The model utilized for this study was WASP 7 through its module EUTRO designed for dissolved oxygen and eutrophication modeling. The WASP model provides a generalized framework for modeling contaminant fate and transport in surface waters and is based on the finite-segment approach. It is a versatile program, capable of being applied in a time variable or steady state mode and in one, two or three dimensions.

WASP is designed to permit easy substitution of user written routines into the program structure and is regularly used to address water quality issues that include dissolved oxygen dynamics, biochemical oxygen demand, eutrophication and toxic chemical movement. The time varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model (Ambrose *et al*., 1993; Chapman, 1996). The model is primarily based on the processes of advection, dispersion and chemical reactions. As such mass balance equations for dissolved constituents in the water body account for all the material entering and leaving through direct and diffuse loadings; advective and dispersive transport and physical, chemical and biological transformations. The model requires a range of data input to perform mass balance computations. Input supplied to the model in combination with the general WASP mass balance equations and the specific chemical kinetics equations are numerically integrated by WASP as the simulation proceeds in time. The model can be used in conjunction with watershed models that can supply pollution load data as well as hydrodynamic models that simulate complex hydrodynamics and supply hydraulic data.

Dissolved oxygen: The determination of DO concentrations is a fundamental part of water quality assessment since, oxygen is involved in or influences all chemical or biological processes within water bodies. The measurement of DO can be used to indicate the degree of pollution by organic matter, the destruction of organic substances and the level of self purification of water (Gasim *et al*., 2011). Dissolved Oxygen (DO) levels in natural waters are controlled by the physical, chemical and biochemical activities in the water body. This can be summarized as its sources and sinks which refer to the addition and removal of DO in a water body. DO is added through re-aeration, photosynthesis as well as water entering through tributaries. Removal of DO from the water body occurs through Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Sediment Oxygen Demand (SOD) and respiration by plants and other organisms living in the water. Dissolved oxygen measurement is probably the most commonly used indicator of lake, river and stream health because the resultant effect of pollution is the lowering of dissolved oxygen levels caused by the decomposition of organic wastes. This occurs as dissolved oxygen is used up in the decomposition process. DO levels <5 mg L^{-1} will likely cause stress to aquatic fauna and DO levels below the standard are usually attributed to increased biological activity resulting from nutrient enrichment. The usual consequence of this is increased biological activity and excessive algal growth. DO is depleted due to the Biochemical Oxygen Demand (BOD) of the decomposition process. The processes related to oxygen depletion, production and kinetics within a water body are generally modeled using 1st order reactions incorporating co-efficients while taking into consideration the effects of advection and dispersion on the concentration of important water quality parameters. According to Juahir *et al.* (2010) and Cox (2003), the flux of DO in a stream or river can be represented by:

$$\frac{dM}{dt} = M_i - M_o + (P - R) + C_R - BOD - COD - SOD - C_D \pm \Delta S$$

Where:

- t = Time
- M_i = Mass flux of DO entering the water body
- M_o = Mass flux leaving
- P = DO added through photosynthesis
- R = DO utilized by respiration
- C_R = Aeration and reaeration (represented by the reaeration coefficient)
- BOD = Biochemical Oxygen Demand
- COD = Chemical Oxygen Demand
- SOD = Sediment Oxygen Demand
- C_D = Degassing of oxygen due to temperature
- ΔS = Changes in the water body due to transport from external sources

Chlorophyll a: The distribution and concentration of phytoplankton is of major water quality and ecological concern. Water quality assessment usually encompasses the occurrences of excess concentrations of phytoplankton and associated nuisance conditions in surface waters, resulting from point and non-point inputs of important plant nutrients. Chlorophyll a is a green pigment found in plants which absorbs sunlight and converts it to sugar during photosynthesis. Chlorophyll a concentrations are an indicator of phytoplankton abundance and biomass in water bodies and a commonly used indicator of water quality. It is also an effective measure of trophic status. Other reasons which make chlorophyll a the widely used surrogate for phytoplankton biomass include its relatively simple measurement and integration of all cell types. Also, it can be easily related to the optical characteristics of water. High levels often indicate poor water quality and low levels often suggest good conditions. It is natural for chlorophyll a levels to fluctuate over time. Expectedly, Chlorophyll a concentrations are usually higher after rainfall and increased run-off events which usually facilitate higher rates of nutrient transfer into the water. Elevated concentrations of chlorophyll a can reflect an increase in nutrient loads and possibilities of eutrophication. Water quality models that account for phytoplankton concentrations usually consider the growth rate of phytoplankton to be a function of factors such as solar radiation, water temperature, nutrient availability and euphotic depth.

Model setup and application of GIS: Lake Chini was divided into eight segments based on a review of bathymetric data and depth measurements obtained during fieldwork as well as the spatial occurrence of sampling locations and measured data within the lake (Fig. 2). In the WASP model, each segment is assumed to have uniform modeling parameters such as depth, cross sectional area as well as dispersion coefficients and is the spatial component in which the WASP model solves its equations. The use of GIS made it possible to access a wide range of spatial analytical functions that were useful for data preparation utilized for the modeling. For example, the application of GIS played a key role in determining lake geometric and hydrological data used as model input. This process started with digitizing and geo-referencing each of the eight segments using ESRI's ArcGIS 9.3, so as to retrieve information used for augmenting and verifying field measurements of segment characteristics such as lengths, interfacial areas and volumes. GIS also facilitated the identification and assessment of active rivers and tributaries which contributed flows to the lake system. The water quality model was then calibrated for the relevant parameters and run in a 30 days simulation. The goals of the calibration exercise included; to determine the parameters that best represent the spatial gradients of the lake and also to predict the dissolved oxygen and

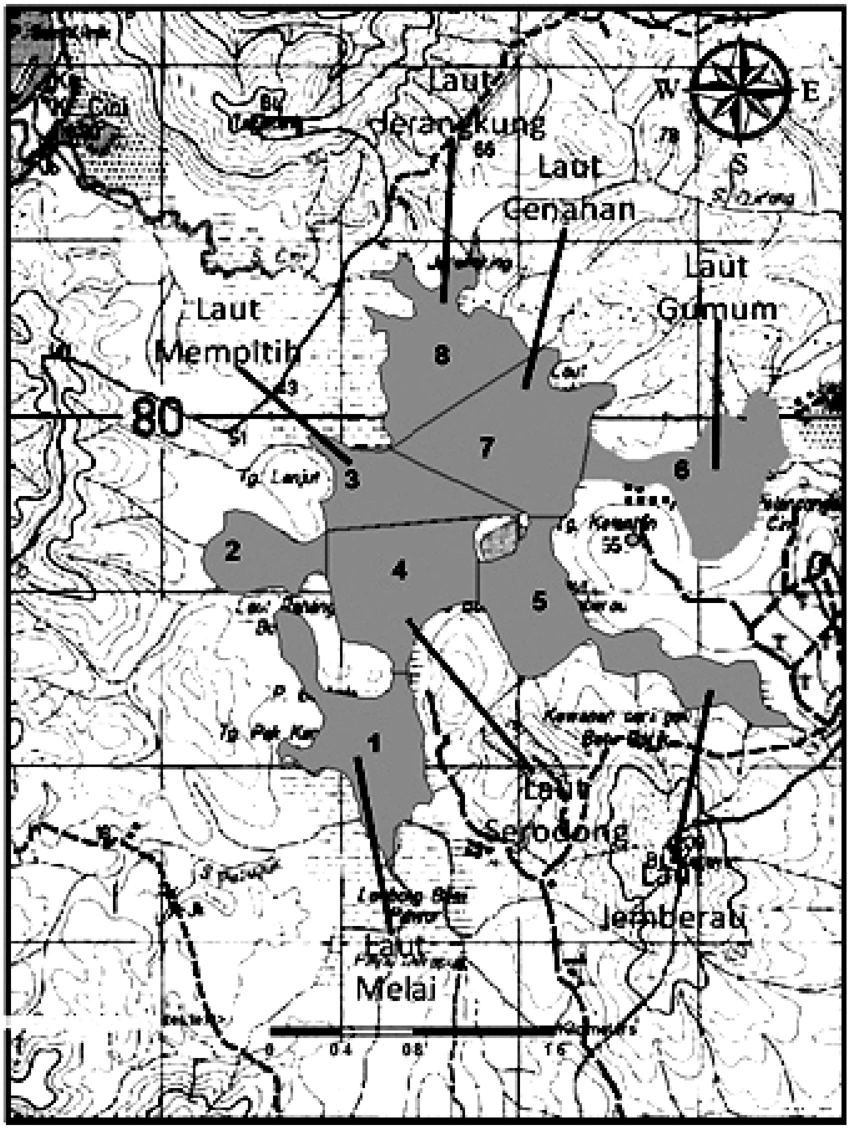

Fig. 2: Water quality model segmentation

chlorophyll a concentrations in both time and space. The attainment of these goals was later made clearer by utilizing GIS dependent display capabilities. The calibration exercise yielded a reasonably acceptable goodness of fit between model results and measured data from the lake.

Furthermore, another major way in which GIS was utilized in this modeling effort pertained to the output display for the model runs conducted. The WASP model allows for spatial display and animation through its graphical post processor which has the ability to display GIS shape files such as the model network as well as other coverage as layers (Toriman *et al*., 2010). This spatial analysis grid of WASP enables the display of results for a given variable at a given time and gives the user the ability to control the display of variables and time. However, the prerequisite for enabling and using this feature lies in the development of the relevant GIS coverage and shape files. In line with this, the model network and coverage related database for Tasik Chini was developed using ArcGIS and later superimposed and combined with other GIS coverage such as the topographical map of the lake watershed and feeder rivers. These coverages as shape files were then loaded into the model for the post processor to display. In summary, GIS essentially provided a platform for which additional data was generated as inputs to the model with the output dependent on the use of GIS for display and spatial analysis.

The reliance on GIS is expected to continue for future applications and advancement of Tasik Chini's water quality model for future studies such as the development and assessment of Non Point Source (NPS) loads going into lake. This can be done by using a grid of land use-based Estimated Mean Concentrations (EMCs) multiplied by spatially distributed runoff volumes to obtain an annual areal loading over the lake watershed. GIS will also function in the assessment of relationships between the lake segments, existing and future inflows and also the identification of potential discharge or loading sources along lake fringes and the entire watershed. Furthermore, GIS can provide an interphase to implement changes in land use or engineering practices while studying the effects of these factors on the water quality of the lake.

RESULTS AND DISCUSSION

A 7,14 and 21 days water quality forecast was made from simulations based on model inputs and conditions from the calibration process of the water quality model. The results of the forecast from the simulations for DO and chlorophyll a are shown in Fig. 3 and 4, respectively. The image form of the results was made possible by producing a geo-registered thematic layer of the model network as a conversion from the numerical form or an alternative to a graphical illustration. By using the spatial display, the distribution of the variation of dissolved oxygen and chlorophyll a within the lake is clearly shown geographically. This allows for easier and more effective spatial queries regarding the concentration profiles of the water quality variables for risk assessment and management decision making in comparison with using tabular or graphical forms of the modeling result. For example, it is easy to infer from the simulation that there exists a similarity in DO concentrations for the Gumum area of the lake which corresponds to segment 6 and the areas closest to the point at which water drains out from the lake (segments 7 and 8) in the 21 days DO forecast. These areas had DO concentrations within the range of 5.11-5.17 mg L^{-1} for that forecast period. Also, the spatial display provides a basis for a dynamic display of the results in animated form which helps to visualize the progression of the simulation and the simulated water quality variables for time dependent modeling such as the present effort.

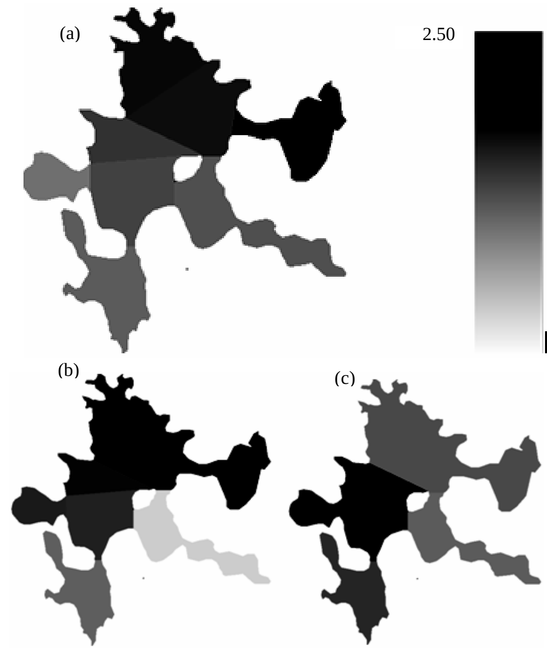

Fig. 3: Model simulation of chlorophyll a concentrations (µg L^{-1}) at various time periods; a) 7 days forecast; b) 14 days forecast and c) 21 days forecast

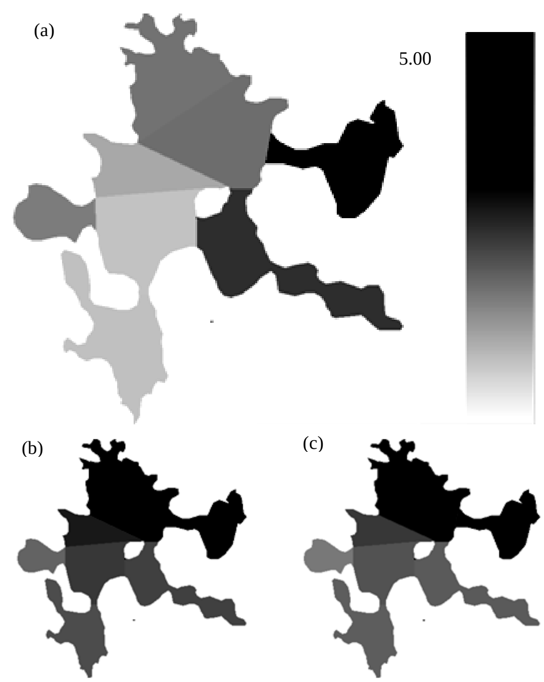

Fig. 4: Model simulation of dissolved oxygen concentrations (mg L^{-1}) at various time periods; a) 7 days forecast; b) 14 days forecast and c) 21 days forecast

CONCLUSION

In this study, a water quality model was established for a natural lake system and an attempt was made to highlight the usefulness of GIS in the modeling exercise. It is deducible that GIS can play a significant role in aiding the usually labour and cost intensive data gathering processes necessary for water quality modeling input purposes. Also, the significance of GIS in providing a platform for visual display and spatial analysis in water quality modeling has been re-emphasized. It is easily seen that the display of water quality simulation provides spatially-referenced information that can be of immense benefit to managers and decision-makers as the imagery facilitated by GIS helps to recognize the geographic variation of key water quality parameters. However, it is pertinent to note that limitations such as disparities in spatial scales, data incompatibility or differences in data structure between GIS and a predictive model might be encountered while using or applying GIS in water resources modeling. Nevertheless, GIS remains a helpful tool in the predictive modeling environment, especially for solving water pollution problems and assisting managers in prioritizing remediation action.

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