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Arc River: Geo-Referenced Representation of River Hydrodymnamics

ARC RIVER: GEO-REFERENCED REPRESENTATION OF RIVER HYDRODYNAMICS

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ABSTRACT

Given the massive volume of data produced by the contemporary instruments, extensive research in the hydroscience community is currently focused on the design and development of information systems for storing, assembling, processing, and querying available data for the myriad of needs of scientists, engineers, and practitioners. Illustrative in this regard are Arc Hydro (Maidment, 2002) and Arc Marine (Wright et al., 2007) data models. The former data model has been increasingly used in recent years in the hydrological community due to its flexible and extensible design that allows users to customize the model for accommodating additional research and monitoring needs. Arc Marine aims to provide accurate spatial representations integrated in 3D space and time, providing a means for conducting complex spatial analyses of marine and coastal data by capturing the behavior of real-world objects.

The present paper describes initial efforts for developing a multi-dimensional geospatial and temporal data model for representation of river geometry and flow characteristics. The model, labeled Arc River, is a customized data repository building on, and enhancing the Arc Hydro data model capabilities. Currently, the Arc Hydro model handles representations of one and two-dimensional river-related information, such as hydro networks and river morphology. Arc River assimilates three-dimensional measurements acquired for characterization of the river hydrodynamic and morphological features. Ancillary tools for organizing and categorizing various types of multidimensional hydrodynamic datasets varying space and time on the top of any available relational database management system (RDBMS) were also developed to facilitate tracking of various river processes. The paper exemplifies Arc River versatility using Acoustic Doppler Current Profilers (ADCP) measurements collected in Kissimmee and Mississippi rivers.

Keywords: Arc River, ADCP, data model, GIS

1. INTRODUCTION

The traditional approach for describing river hydrology is based on one-dimensional river network representations. The main quantity associated with this representation is the streamflow discharge, usually measured by a gaging station. Additional insights and more details on the various river processes are usually obtained from local measurements complemented by results of numerical simulations that usually are based on 1-D and 2-D approaches. Although these simulations are widely used in many engineering and scientific investigations, their results are often times just crude approximations of the complex 3-D processes occurring as a result of multiple interactions within the continuously changing river boundaries. Therefore, considerable efforts have been directed in the last decades toward understanding the river behaviour in more details such as to be able to address emerging societal problems such as erosion and pollutant transport, floods, riverine ecohabitat restoration. The efforts included 3-D approaches, but the production of these data and derived information is still prohibitive irrespective of their origin, i.e., measurements or numerical simulations. The 3-D numerical simulations are expensive because with the increase of the solution dimension, the computational efforts (code development, computational resources, and running time) and the amount of field data required for calibration, validation, and running the models increase exponentially. Similarly, the acquisition of detailed three-dimensional hydrodynamics datasets for observation-driven analysis is in many cases prohibitive as most of the available measurement techniques require a great deal of effort and time to acquire the needed data.

The advent and subsequent fast-paced implementation of new riverine measurement instruments in the last decade promise to radically change river research by providing a wealth of data with considerable less effort. Most notably, is the increase use of the Doppler acoustic technology introduced in the riverine environment in early 1980's. Instruments, such as the Acoustic Doppler Current Profiler (ADCP), have revolutionized the efficiency, accuracy, and the amount of three-dimensional hydrodynamic data obtainable over river cross sections and even river reaches. The amount of data produced by these instruments is unprecedented, requesting adequate approaches for storing and extracting the useful information from the raw measurements. Among the emerging solutions for data handling are geographic information system (GIS)-based data models and the ancillary tools. The most recent advances in GIS technologies and data model enable to synthesize data and support multi-disciplinary analyses. GIS technologies allow to geo-reference measurements, conduct data mining and powerful (layered) visualizations, and take advantage of the GIS-based modeling tools. The use of specialized data models in conjunction with the new instruments and the GIS technology have the potential to produce a paradigm shift in understanding and management of the water-related processes by enabling new capabilities to assemble in a one place information regarding various aspects of the watershed processes, easily query and analyze the multilayered information, observe and share the data.

Currently, there is a sustained effort for data model development in several water-related domains. Among them are Arc Hydro (Maidment, 2002), Arc Hydro Groundwater (Strassberg, 2005), Arc Marine (Wright, 2007) developed for watershed, ground water and ocean areas respectively. These models are gaining popularity in the respective communities for both incorporating simulated data as well as observed multi-dimensional datasets. Notably in this last respect are Arc Marine and Arc Hydro Groundwater models that were designed to accommodate three-dimensional dynamic datasets and developed tools to track features and processes in time and space. One of their distinct features is their GIS connection (or geodatabase). This connection enables to efficiently integrate diverse multidimensional hydrodynamic features and make full use of a variety of GIS functionalities for advanced data analyses. A GIS-based data model connects the data to objects in the real world and has embedded building validation rules, and capabilities to link objects to information tables for synthesized analysis. Another essential feature of the above data models is that they are build using the RDBMS structure, a feature that distinguishes them from the traditional file-based data storage through their capabilities to efficiently store the information in hierarchical tables connected through internal and external relationships, quickly search, retrieve, and distribute the data.

Collectively, these new conceptual frameworks and technologies have prepared the ground for a new type of information management system for the aquatic research: the digital observatory. The observatories are comprehensive cyberinfrastructure platforms capable to handle unprecedented volume of multidimensional geologic, morphologic and hydrodynamic data acquired over large portions of the environment for facilitating observations, analysis and interfacing of the real data with numerical simulations. As Wright (2007) pointed out: "data models lie at the heart of GIS, determining the ways in which real-world phenomena may best be represented in digital format".

Despite that the river is central to any hydraulic and hydrologic study, as of to date there are no such multi-dimensional data models for the riverine environment. The most advanced data models for rivers, such as Arc Hydro, handles observational data for describing 1-D features of the river network or 2-D morphologic information. Motivated by the recent availability of multidimensional hydrodynamic data collected with the new instruments (e.g., ADCP), advances in GIS technologies, and nation-wide effort toward building hydrologic information system, the pioneering research reported by this paper attempts to build a customized integrated system for riverine environment. The model aims at representing complex multidimensional river hydrodynamic features and behavior in a GIS framework, and enhancing considerably our current capabilities of analyzing, sharing, publishing, feeding numerical simulations, and nevertheless distributing the spatial datasets within the water-related communities via the Internet.

2. MULTIDIMENSIONAL RIVER DATA ACQUIRED BY ADCPs

It is assumed herein that the reader is familiar with the principle, configuration and the results provided by ADCPs. For more information on all of these aspects there is a vast supporting literature (e.g., Simpson and Oltmna, 1993; RDI, 1996; Sontek, 2000).

2.1. One dimensional characterization of the stream

The ADCP individual pulses (pings) provide 3-D instantaneous velocities along verticals in the water column and depth measurement at the ping location. When operated from moving boats the data is voluminous, though rapidly and efficiently acquired in comparison with the conventional point measurement instruments. For example, the operational settings used for acquiring velocity data in the 60-m wide Kissimmee River produced about 800 pings (verticals) and 8000 bins in each transect (see Figure 1). Average cross-sectional velocities and depth can be estimated obtain bulk stream flow parameters such as mean flow velocity, Froude number, aspect ratios. Discharges can be obtained using customized algorithms developed for ADCP measurements conducted from moving boats (Christensen & Herrick, 1982) or conventional algorithms, such as the velocity area method (Boiten, 2000) for fixed measurements across the stream section.

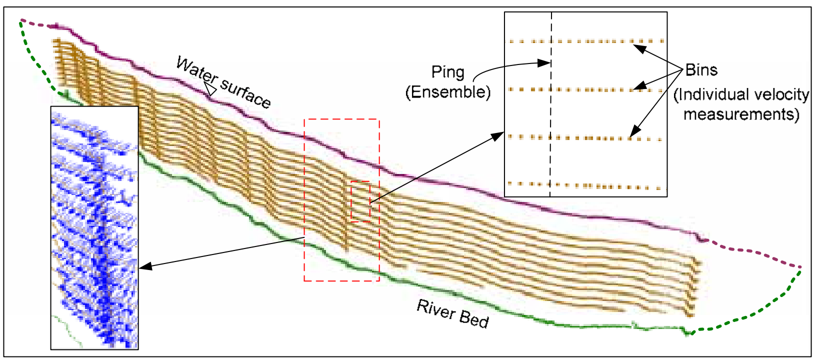
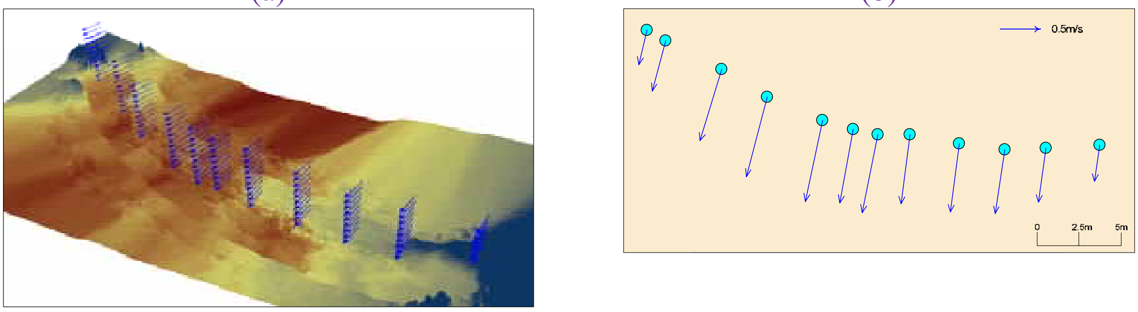


Figure 1. Instantaneous velocities acquired by ADCP operated from moving boat across the stream cross section

2.2. Two- and three-dimensional characterization of the stream cross-section

ADCP operations at fixed point can provide accurate description of mean flow and turbulence. Because of the voluminous data collected by ADCP in each bin which increase with depth, ADCP time series in each bin can provide vertical profiles of mean velocity and turbulence under uniform flow condition (Nystrom et al., 2002; Kim et al., 2005). Time-averaged velocity profiles obtained from time series of ADCP velocity collected at fixed points in the Kissimmee River are illustrated in Figure 2. Time series of mean velocities in each bin can be averaged to produce a profile of mean velocity along a water column (Figure 2a). Profiles in Figure 2.a show total velocity vectors computed by using all three (x,y,z) velocity components. Average mean velocity in all bins at a fixed point can be averaged to produce depth-averaged velocity for each point as shown in Figure 2b, which characterizes the stream through a vector field in horizontal plane. Finally, the velocity measurements in each bin can be used to produce a velocity distribution across the stream cross-section as shown in Figure 2c, which characterizes the stream through a vector field in vertical plane.

(a) (b)



(c)

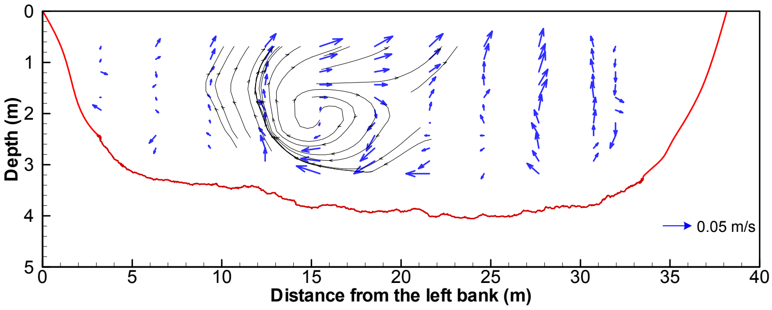


Figure 2. Mean flow characteristics from fixed point ADCP measurements: (a) mean vertical velocity distributions; (b) depth-averaged profile; (c) velocity distribution mapping in the stream cross section

2.3. Two- and three-dimensional characterization of river reaches

In principle, all the above discussed quantities and representations can be readily extended for the hydrodynamic analysis at reach scale. Samples of hydrodynamic information mapping at reach scale are provided in Figure 3.a, b. One can easily image the strong potential that such information can support a wide variety of complex hydraulic and hydraulic-related problems, such as the quantification of the availability of river habitat preferred zones across a range of scales (Shields, 2003). The principle of operation, the various configurations and modes of operation currently available for ADCPs allow collecting the raw data needed for such complex and large-scale analysis.

(a) (b)

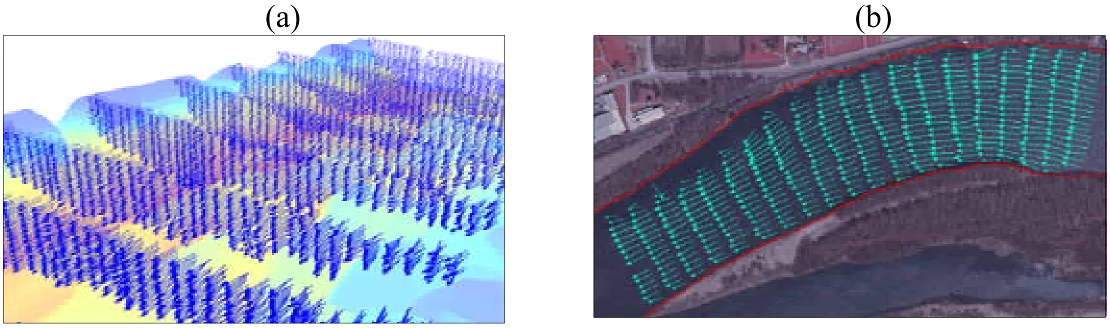


Figure 3. River morphology and mean hydrodynamic characteristics in Pool 16 in Mississippi River; a) spatially interpolated river morphology based on individual beam ADCP data; b) spatially averaged ADCP transect measurements within the reach

3. ARC RIVER DESIGN

3.1. Connectivity with existing data models

In order to take advantage of the Arc Hydro geospatial and temporal capabilities to represent water systems, Arc River architecture was closely connected to this already well-established data model. The current version of Arc Hydro model can only describe channel features through one- and two-dimensional representations (Maidment, 2002). Figure 4 illustrates the connectivity between Arc River and Arc Hydro. In the context of ADCP measurements, Arc Hydro's HydroEdge feature is associated to an ADCP transect or fixed-point measurement (depending on the procedure used to acquire the data). These measurements are then used to generate Arc Hydro's HydroNetwork which topologically connects stream lines and points to provide the one-dimensional river network description.

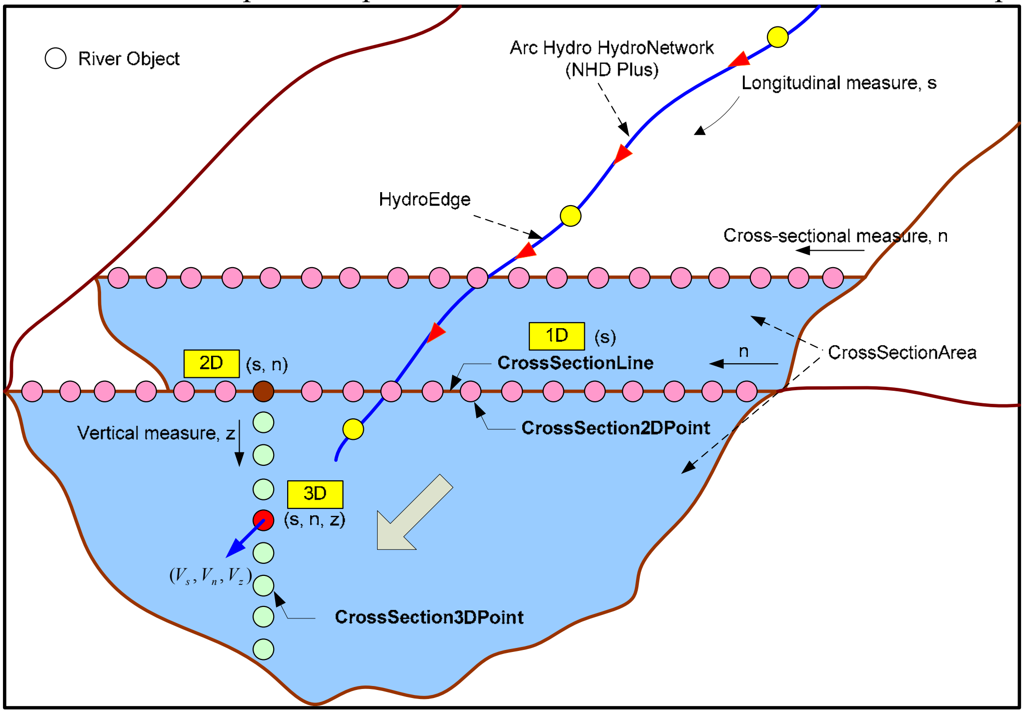


Figure 4. Connectivity between multidimensional river objects and river network along the cross-section

The river network consists of a set of connected line segments (HydroEdge), represented in the Figure 4 as blue lines between yellow points. Thus, connectivity rule between river objects and network is that if a river object (e.g., point) is closer to a HydroEdge than any other HydroEdge in the river network, then the object becomes connected to the HydroEdge. The closest HydroEdge to an object is searched by minimum distance among distances of the perpendicular line between a river object and nearby line segments of the river network.

In addition to the connectivity between a certain river object and the river network, river objects themselves are related each other based on their dimensions. For instance from illustrated in the Figure 4, a CrossSectionLine, named after a polyline connecting point measurements across a cross-section, is classified as one-dimensional object because of containing various cross-section averaged one-dimensional information such as discharge. The CrossSectionLine object contains multiple two-dimensional points (by one to many relationship), which are called as CrossSection2DPoint. So by exchanging key identifier between them, CrossSection2DPoints are connected a CrossSectionLine. Similarly, many three-dimensional objects, such as CrossSection3DPoint along the vertical direction of the cross-section can be related to a two-dimensional object, CrossSection2DPoint.

Once a river object is connected to the river network, a new address following flow-driven coordinate is simultaneously assigned according to its dimension and the linear location of the connected river network. The flow-oriented coordinate system is the best suited than a conventional Cartesian coordinate system for representation of the processes. This coordinate system identifies an object in the river through a distance along the streamwise or centerline distance (s-coordinate), spanwise or perpendicular distance from the centerline (n-coordinate), and vertical distance from the water surface (z-coordinate), respectively (Merwade, 2005).

3.2. Vector and Raster type of Gridded data

In contrast with the in-situ measured data, the direct numerical simulation results are provided in a grid (mesh) format. Consequently, for comparing datasets from simulation and observations (or interpolated values) in the same flow domain the quasi-randomly located measurements provided by ADCPs need to be associated to the grid used in the numerical simulation. To accommodate this request, the RiverGrid feature dataset in the Arc River was created. It supports gridded information within the GIS environment, similarly with the approach adopted in previous studies (Strassberg, 2005; Wright, 2007). RiverGrid feature dataset is classified in two- or three-dimensional space as point (GridPoint), area (GridArea), and volume (GridVolume), as illustrated in Figure 5.

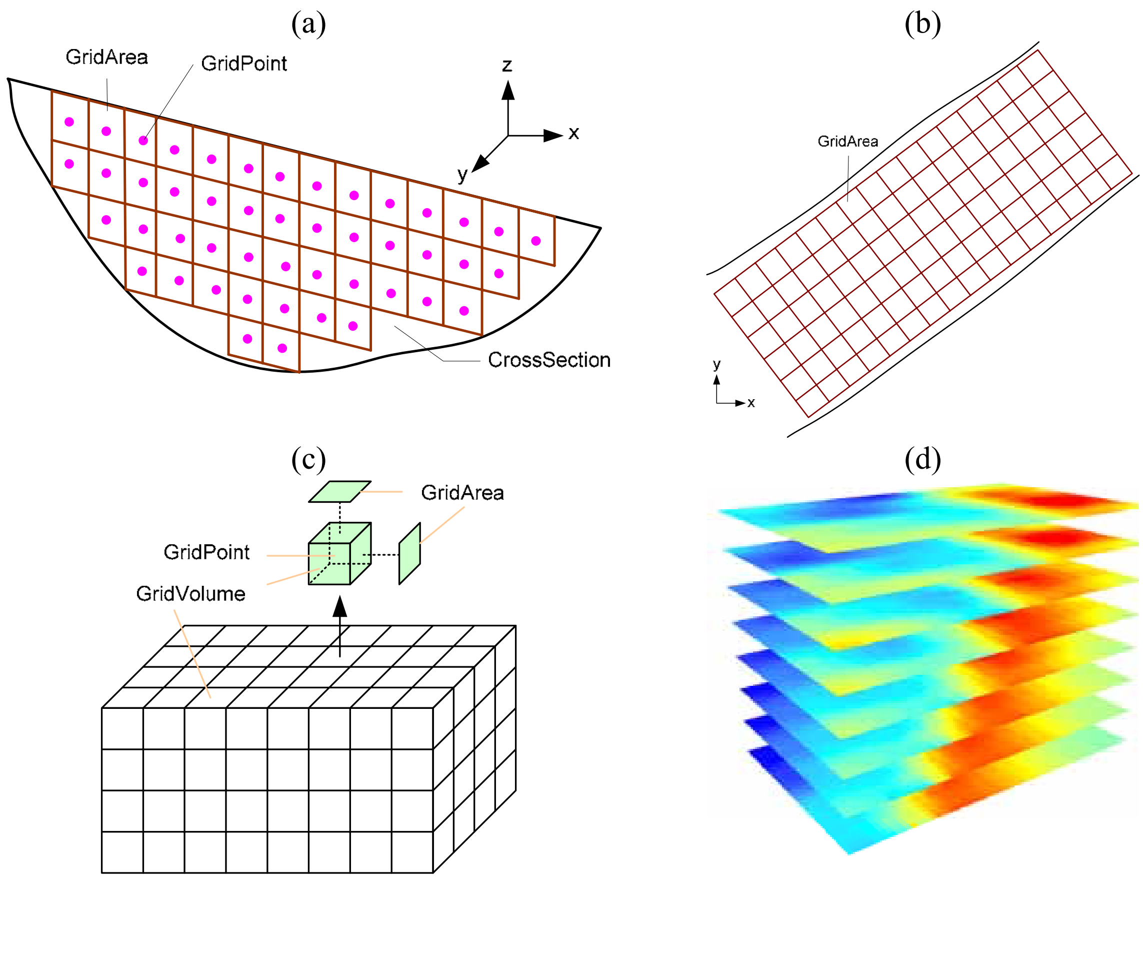


Figure 5. Gridded features and raster in the Arc River; a) GridPoint and GridArea in the vertical space; b) GridArea in the horizontal space; c) GridVolume in the three-dimensional space; d) a stack of raster dataset describing spatial variation over time

GridArea indicates a finite element face (polygon), which can be regular or irregular mesh (cell). GridPoint represents points for either the center or the nodes of the GridArea and GridVolume of the finite element faces. GridVolume represent volumetric cells (cunes). As seen in Figure 5(a) and (b), GridPoint and GridArea can be located in both two- and three-dimensional space. Figure 5(a) is especially applicable when the scatter data along the cross-section (e.g., ADCP transect measurement) are interpolated for the given grid cells of that cross-section. Three-dimensional GridVolume illustrated in Figure 5(c) represents cell-based volumes which are able to accommodate the results of the three-dimensional numerical simulation into GIS. Figure 5(d) shows a stack of raster type of gridded information which enables to represent variation of spatial distribution over time.

3.3. Objects moving in space and time

The traditional measurement approach is the Eulerian framework, whereby observations in a point, line, surface or a volume are recorded by fixed instrument. Most of the current data models use the Eulerian approach for their representation. The real processes, however, are occurring within volumes that are changing their shape over time and can be also subjected to a travel in space. The alternative view of the same process where the evolution of the process is tracked in space, rather than time is labelled as Lagrangian framework. Such an example is the cloud movement and the associated transformation of their water vapour state in time. From the data model perspective, the feature object moves in the three-dimensional space over time, where the shape (e.g., volume) of the object changes. In addition, the feature object can have single or multiple events at a given time to address dynamic change of quantities that the object contains. The river process selected for illustration purposes in this paper is the evolution of a pollutant plume in space and time (see Figure 6). The cloud propagation is estimated using the analytical formulation for dispersion and convection in conjunction with ADCP velocity profiles collected in the Mississippi River. Figure 6 visually displays the pollutant movement downstream associated with the continuous dilution in time.

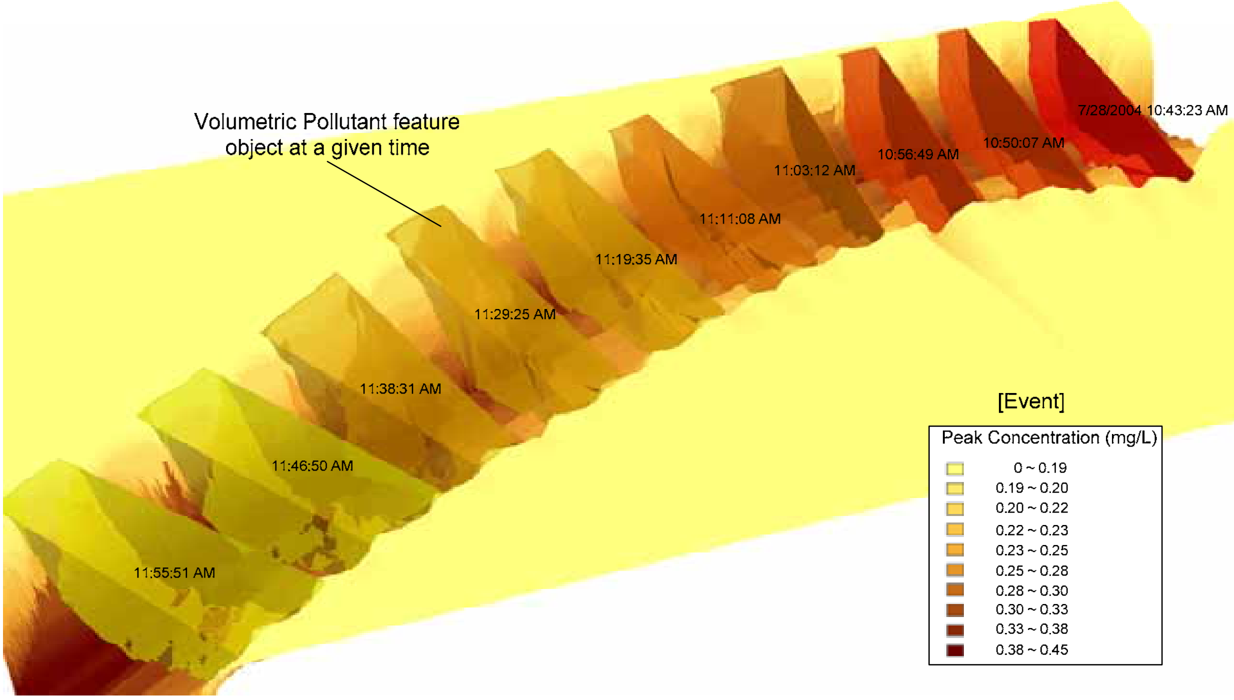


Figure 6. Moving river object varying its position, shape, and event value over time

The representation illustrated above is a known challenge for the GIS-based data models. The successful solution of the problem is based on the Feature Series concept developed previously by other researchers (Goodall, 2005; Arctur, 2004). The RiverFeatureSeries dataset in the Arc River model was designed based on the idea that the dynamically varying features are captured for each particular time index. By doing so, any feature moving in time as well as changing its shape in time can be represented. Each feature in Feature Series stores its shape and geographical location and it is relationally linked to time series table which stores events and their scalar and vectorial values.

3.4. Event-based ancillary information

Arc River is designed to store events and their related values separately from the river object by using a unique identifier in the river object that relates the river object with comprehensive information about the specific event. Elements of such an approach were used in previously developed hydrologic data models such as Arc Hydro (Maidment, 2002) and the Observations Data Model (ODM, Tarboton 2007). For example, Arc Hydro data model integrates the spatial monitoring locations and their time series data within the GIS database. On the other hand, the Observations Data Model documents extensively observations with metadata entailing comprehensive information including both hydrologic observations and ancillary explanations (i.e., data characteristics and observation method). Arc River fusions in its architecture elements from both Arc Hydro and ODM structures. Specifically, an event in Arc River is defined as an occurrence (variable) at a river object, and each event has two types of value such as vector and scalar. In particular, vector value has multiple components of vectorial value (e.g., three-dimensional velocity vector) rather than storing single scalar value, which enables description of directional features of river objects. In addition, Arc River supports other ancillary information such as variable, method, instrument, and group. Method table provides information about how a value was obtained, for example, spatially interpolated or depth averaging. Variable (event) table classifies the name of value (event), and instrument table records the name of instrument used in the data observation. Figure 7 illustrates the connectivity between river objects, events, and values with river objects.

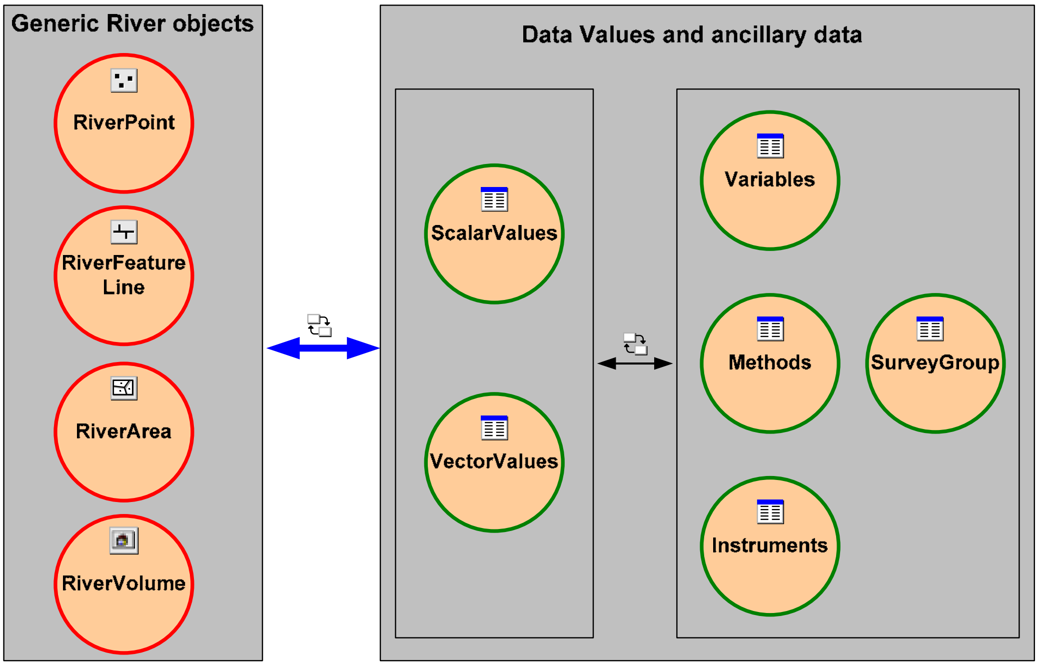


Figure 7. Connectivity between generic river objects and ancillary information.

4. IMPLEMENTATION OF ARC RIVER

The Arc River data model is instantiated inside the ESRI geodatabase, as illustrated in Figure 8.a. The river objects are grouped into three categories: RiverHydroFeatures, GridGrid River, RiverFeatureSeries, and ancillary tables. They individually represent multidimensional observed, gridded, and moving objects. After completing the instantiation of the Arc River into the geodatabase, the actual population of various multidimensional river feature object classes and their ancillary information in the Arc River geodatabase is made. The manual implementation is very tedious or sometimes nearly impossible due to complexity of the relational data model and the amount of raw data, hence a tool for automatic loading of the data is needed. For this purpose, the data loading tool labeled ‘ArcRiver toolset was developed on the top of the GIS platform (ArcGIS) using ArcObject programming library (Zeiler, 2001). The tools are customized to deal with the multidimensional hydrodynamic and geomorphologic information that can be created using ADCP measurements (see Figure 8(b)). The input raw data is post-processed by AdcpXP (Kim, 2005; Kim, 2007) in the ASCII format (e.g., CSV file) to efficiently generate various dimensional datasets. Each toolset has its own graphical user interface for facilitating the loading of the ADCP data (see Figure 8(c)).

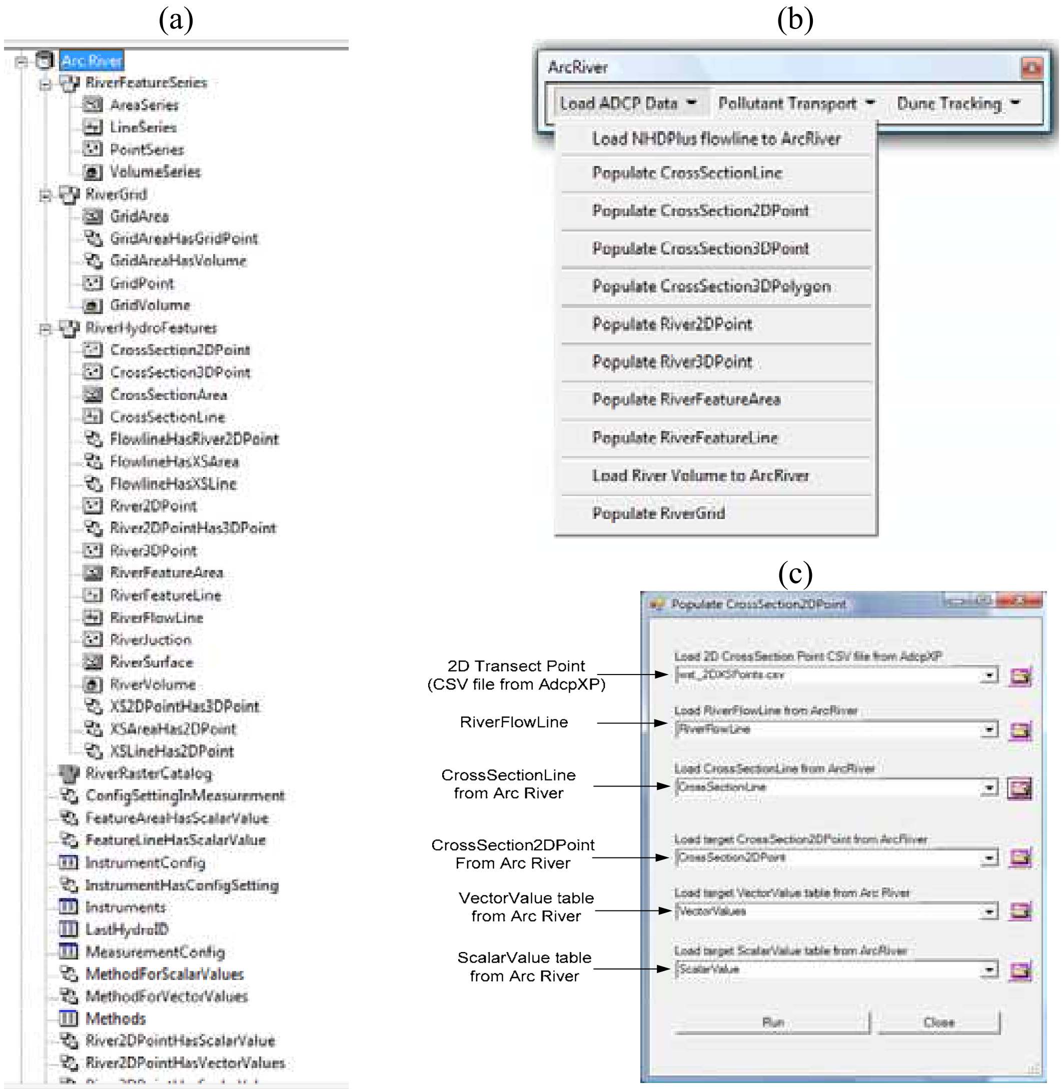


Figure 8. Instantiation and implementation of Arc River data model; a) Arc River data model instantiated inside ESRI geodatabase; b) ArcRiver toolsets for populating Arc River geodabase; c) an example of the interface of ArcRiver toolsets

5. CONCLUSION

Arc River data model enables for the first time a comprehensive geospatial and temporal representation of river morphologic and hydrodynamic characteristics. Arc River framework can be implemented as a stand-alone data model or on top of another data model. The distinct model features are the three-dimensional indexing of spatial features to capture both stationary and moving object over time, the three-dimensional visualization of vector fields and changes of the river morphology, capabilities to represent velocity-derived quantities at the river-reach scale (e.g., dispersion coefficients, shear stresses, and turbulence characteristics). Arc River is currently tailored for ingesting ADCP measurements, but it can be easily expanded to accommodate other scalar and vector quantities from different types of measurements. The development of the Arc River data model represents a typical incremental effort towards establishing the cyberinfrastructure-based information systems for watershed-scale eco-hydrologic observatories.

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