Taking hydro-spatial analysis to another dimension using STEM, a 4D GIS

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Abstract

A major barrier to hydrologists wishing to make use of Geographic Information Systems for their analysis, is the lack of any real temporal functionality provided by the leading software manufacturers. Hydrology far more than other disciplines, relies heavily upon the interpretation of temporal variations in the data, such as time-series of river discharges or fluxes of sediment. Currently, time series data are mostly viewed in 2D, as graphs, showing changes in the variable(s) of interest from the head of the catchment to the mouth. While this allows some degree of visualisation of how variables are changing down the catchment, it does not provide any indication of how they might be changing spatially over time. This overview is only provided when these variables are plotted on a map (3D). Current GIS tools are able to plot 'snapshots', as individual layers, for the variable at any given time period. However, in order to build up a time series of these maps (4D), several different layers are required and this soon becomes impractical when dealing with hourly data over several months. Another problem is that the positions of features can also change over time (e.g. rivers meander, sediment bars shift) and current GIS tools can only map these as separate layers. This means that when looking at individual features over time, the user has to deal with a separate dataset for each time step, rather than a single contiguous one and this can restrict modelling capabilities. This paper describes how a new product, the Spatio-Temporal Environment Mapper (STEM), has been able to provide this 4\textsuperscript{th} dimension, as well as offering a more efficient database structure. Through a series of examples for UK catchments, the tool is applied to commonly collected hydrological data to provide novel analysis of the variables in question.
1 Introduction

Geographic Information Systems, as mapping tools have long played a role in hydrological research. For example, at the most basic level they have been used for the mapping of hydrological features such as river courses, for land cover mapping and asset management. In addition, they have often been employed for the creation of Digital Terrain Models (DTMs), to establish drainage networks (Martz and Garbrecht, [1]), and to aid with the parameterisation of rainfall / runoff and other models.

Various GIS analysis techniques have also been employed in hydrology, yet most of the functionality used, amounts to little more than sieve mapping, with the bulk of the analysis being carried out in separate models. Storck et al [2] describe one such example in their study of peak stream flow rates in Pacific Northwest, USA. They coupled their Distributed Hydrology-Soil-Vegetation Model (DHSVM) with GIS in order to generate inputs for the model and subsequently, to create maps of the model outputs. In many cases rather than being able to do the whole analysis within a GIS, there is often a degree of 'leap-frogging' between different software packages. Loague and Corwin [3], suggest that this may be due to the fact that “to date, no generalised GIS system has the data representation flexibility for space and time together with the algorithmic capability needed to construct process based models internally, consequently environmental models and GIS must be coupled.”

This presents a significant barrier to hydrological researchers wishing to exploit the full power of GIS tools, due to the fact that often the variables which are most of interest, such as discharge levels or sediment fluxes, change over both three dimensional space (x,y,z) and time (t). Moreover, the timescales over which these variables change, ranges from the highly ephemeral (e.g. soil moisture logged every few seconds during a storm), to long epochs of geological time (e.g. the formation of a gorge over tens of thousands of years). Hydrology, probably far more than other disciplines, relies heavily upon the analysis and interpretation of temporal trends within the data. Maidment [4] believed hydrological modelling within GIS was possible if time snapshots or averages were used and not time series (Clark, [5]). However, although advanced time-series analysis is well established in hydrology, the ability to analyse trends over both space and time has proved difficult. This situation has been perpetuated by the lack of any real temporal functionality provided by the leading GIS software manufacturers, despite their offering of so-called ‘hydrological analysis’ add-ons which have been largely for surface creation and watershed delineation.

2 Multidimensional GIS

There have been many GIS systems which claim to be 4 dimensional, yet it rather depends upon one’s definition of these dimensions: The first 2 dimensions are generally agreed upon, as those of traditional x, y mapping coordinates. Many GIS packages now offer facilities for displaying spatial data in a 3D environment (e.g. ESRI 3D Analyst, Erdas Virtual GIS). However, the third dimension is often
confusing because it is represented as x, y and z, (z being an attribute such as elevation). This is not true 3D because it does not include a full description of the volumetric element and is often referred to as 2.5D or pseudo 3D. Despite this, volume slices through a 2.5D datasets give a 3D result. In addition, true 3D objects such as structures and trees can be placed upon 2.5D surfaces.

True 3D data define this volumetric component explicitly and are able to describe variations in both x and y and depth, rather than having the depth component as a 'planar' surface. 

Sandison [6] suggests that by producing fly-throughs or time lapses of the 2.5D surfaces described earlier, gives a 3.5D representation. However, in order to get to the elusive fourth dimension, it is necessary to be able to query 3D data over time. Therefore, our definition of a 4D GIS, is one which is able to store, manipulate and analyse true 3D data, over time.

2.1 Spatio-temporal mapping

Time, (not space) has been the final frontier for GIS developers. Morris et al [7] suggest that this relates to the difficulties in how to represent time and how to design the database, to allow the retrieval of temporal data. The inability of GIS to handle temporal analysis is very much linked to 'dimensional dominance' (Langran, [8]) in the design of GIS databases whereby space and time have traditionally been treated as separate entities. The fact that in GIS, the emphasis has been placed upon mapping features through space and not time, has meant that time has only been dealt with implicitly. As a result, time can only be represented as a series of snapshots which is extremely cumbersome when dealing with many time intervals. Imagine the number of conventional GIS layers that would need to be loaded, to map a high resolution time series of river discharge over just one day!

The major thrust of effort in spatio-temporal mapping has come from disciplines where researchers needs must work in multi-dimensional space, for example, oceanography, exploration geology, meteorology etc. In order to better understand the processes operating within the systems of study, the need arose for a means of geo-representation in three or more dimensions. Raper [9] suggests that "when conceptual modelling is coupled with geo-representation in a multi-dimensional framework, powerful new insights can be obtained and fed back into concepts". Therefore, spatio-temporal mapping has the potential to provide a fresh perspective on many research problems. For example, the SEDimentary SIMulation model (SEDSIM) developed by Tzetlaff and Harbaugh [10] which was designed to model sediment fluxes over space and time.

Early work on spatio-temporal mapping was led by Langran ([11], [8]), who laid out many of the concepts and theoretical considerations when representing objects in space and time. Subsequently, there have been numerous spatio-temporal data models and query expressions proposed. It is beyond the scope of this paper to go into these in detail here. However, good reviews can be found in Raper [9] and Wachowicz [12].

Many of the data models proposed have not been fully implemented but rather offer the blue-prints for a spatio-temporal GIS (e.g. Jingsong and Ying,
In addition, many of these applications also rely on the Open Development Environment of existing GIS packages. For example, Wachowicz [12] used the Magik customisation language within Smallworld GIS in order to develop a system for the maintenance of public boundary records. This system allowed the addition of new records, tracking of boundary evolution, updates and archiving based upon a Spatio Temporal Data Model (STDM). Similarly, Sandison et al [14] had to use 9 different software packages, in order to develop a four dimensional GIS which was able to visualise a photochemical smog plume occurring over the course of a day in Perth, Australia. Although spatio-temporal mapping has been successfully implemented for specific applications, it is not possible for a wider audience to make use of these tools for their own specific needs. That is, unless they have a good understanding of GIS and database programming with which to 'clone' one of the data models for their own application. Clearly, this would put spatio-temporal mapping beyond the reach of most river basin managers, who may not be able to justify the investment of time and money implementing their own spatio-temporal GIS. In such circumstances, a generic, off-the-shelf GIS package which is capable of handling spatio-temporal data, would be invaluable. Therefore, it is ironic that none of the leading GIS software manufacturers offer any sort of temporal tools within their packages. Moreover, the majority of hydrological toolkits offered by manufacturers to address hydrological issues, (e.g. ESRI Hydrological Modelling Extension for ArcView) have no temporal tools either!

The remainder of this paper describes a new GIS tool, Spatio-Temporal Environment Mapper (STEM), which has been developed to provide a generic tool for the manipulation of a wide range of data types which vary through space and time. STEM is used to provide a novel analysis of various UK hydrological datasets.

3 Spatio-Temporal Environment Mapper (STEM).

STEM was born out of the Land Ocean Interaction Study (LOIS), a UK wide study on the fluxes of materials which incorporated large amounts of disparate data from river catchments, estuaries, and the coastal and marine zones. This study required a GIS capable of storing, accessing and visualising these data in the four dimensions of \( x, y, z \) and time. STEM as it exists today has evolved enormously from the LOIS version, in terms of its functionality and database efficiency and it is now being sold commercially.

3.1 STEM Software Components

The STEM GIS is divided into 3 main components, the Database Management System (DMS), the Publisher and the Data Viewer

3.1.1 STEM Database Management System

STEM employs a generic data model in order to track features as they move through 3D space and time. Associated properties or events associated with these
features are stored as attributes. For example, to store river water quality data, an individual monitoring site might be classified as a feature and the variables which describe or are observed at the site, such as its position, site name, a unique reference number, river flow, pH values and so on, would be it's attributes (Morris et al, [7]). A major feature of STEM is that all the spatial and temporal data is stored within one database whatever the data type. Each instance of a feature has an associated timestamp stored in the database and any instance or time period may be retrieved from the database. The generic database structure can handle many disparate data types, including point, line, polygon, 3D surfaces, 3D objects, non-geo-referenced images (e.g. photographs), geo-referenced images (e.g. remotely sensed images), and multi-temporal raster data (e.g. model output). The database is implemented in MS Access using Structured Query Language (SQL) expressions, in order to perform the spatio-temporal queries.

The Database Management System allows one to design, create and to edit spatio-temporal databases. Features are defined within the DMS and properties can be set for how they will appear when loaded into the Viewer. All data are loaded into a STEM database using ASCII comma separated value (CSV) files which are formatted with a special header block. Attributes are loaded with these features and data dictionaries can be set up. Different levels of security can be placed upon the database if multi-users with different privileges are required.

The generic data model adopted for STEM also offers tremendous data reduction possibilities. A recent project was able to compress 2.5GB of raw data into 250MB when loaded into the STEM database!

3.1.2 The STEM Publisher
A database publisher is also included, that allows one to distribute the database to interested parties by via CD-rom. External organisations receiving the CD-rom are able to query the database and view the data using the free viewing tool provided. However, they are unable to modify the database itself.

3.1.3 The STEM Viewer
The STEM Data Viewer is a tool for searching, retrieving and displaying spatial and temporal datasets. The Data Viewer is like an ordinary GIS in that one can display spatial information of various types and import GIS data from other packages. However, it is extraordinary, in that one can also visualise changes to spatial features and their attributes over time. This is achieved by performing spatio-temporal queries of the database using a Query Wizard.

After choosing a selection area on the map, the user may choose up to five feature types within a query. This means that is possible for the user to retrieve say, chlorophyll data for a number of features including, river monitoring stations, marine monitoring stations and so on. This allows one to investigate changes through different environments. The next stage in retrieving the data is to select the attributes that are required. Again a maximum of 5 can be chosen, which is useful for comparing the values of different attributes. e.g. salinity versus nitrates.
STEM allows the data to be aggregated into user defined time periods such as years, quarters, months, weeks, days, hours. Similarly depths are also aggregated. The data is then retrieved into a single layer within the Viewer. A consequence of the generic database structure is that one layer, can currently contain up to 700 times, 100 depths and 5 attributes. Thus, one STEM layer can represent up to 350,000 layers in a traditional GIS!

4 Hydrological applications of STEM

The following examples illustrate how a selection of commonly collected hydrological data, can be analysed within the 4D environment of STEM. Obviously, it is extremely difficult to see the full capability of the system on the printed page because the animations can only be shown as a series of individual snap-shots which were derided earlier. However, it is hope that this paper will demonstrate the effectiveness of this system for spatio-temporal analysis.

4.1 Peak River Flows and Flooding

The winter of 2000/2001 was the wettest since records began and saw flooding in the news headlines almost daily, especially at its height in November. The study of storm hydrographs in order to understand how river catchments behave under flood conditions, is not a new approach. It allows the identification of peak flows, duration and lags within the system. Typically, this information has been plotted as discharge versus time on a 2D graph for individual locations. Figure 1 shows one such graph with discharge for two sites in Humberside plotted against one another. This is useful, in that it is possible to identify peak flows and differences between the two sites. However, if one were to continue plotting sites, the graph would soon become jumbled and hard to interpret. Therefore, an holistic view, allowing river discharges to be viewed across the entire catchment or neighbouring catchments, has a significant benefit.

Figure 1: Typical Hydrograph showing two sites within the same catchment (Source: LOIS Overview CD)
Figure 2 illustrates how this 'bird's eye view' of the data can be achieved within STEM. Here the 15 minute data has been aggregated into weekly intervals over a 3 month period. However, any interval could be specified from hours to years. The flexibility of temporal aggregation means that time intervals can be tailored to the lifecycle of the process being considered. The time (or depth) dimension is accessed predominantly through a bar, which appears below the map window. This contains the time (or depth) intervals which are available to the user. By clicking on these in turn, it is possible to iterate through the time series and visualise how the attributes change. In addition to this manual option, there is also an animation tool, which automatically steps through the time series at a specified frame speed. Animation is viewed as the most instantly recognised method of representing time data (Kraak & MacEachren [15], Wachowicz & Healey [16]). STEM is very powerful for visualising changes in attributes, which are difficult to capture using conventional GIS tools. One can see that using this approach, it is possible to identify how flow levels are distributed across the catchment.

Increasingly, predictions of flow rates 'downstream' will be required and a system is currently in development which will take input flow data via telemetry in 'near real time' from river gauging stations, straight into a STEM database. It is hoped that such a system would allow the much more efficient identification of flood events higher up the system and allow early warnings to be posted when flows reached critical levels.

4.2 Water Quality

Water quality is another very topical issue in hydrology and again, the spatio-temporal variations in the parameters measured is often crucial. Pollutant plumes
vary, not only with time but also with depth. Therefore, these variables are truly 4 dimensional in nature. Figure 3 shows how not only time series of these variables can be studied, but also the depth component. In Figure 3, weekly averaged levels of nitrates, phosphorous and alkalinity values for a two year period, were loaded in a single query and are plotted side-by-side on the map as 'mini bar charts'. This is very useful in order to see how attributes change in relation to one another. The variation of phosphorous is also plotted by depth with the depth profile for a single site also shown. The temporal aspect is accessed by clicking a watch icon which toggles the time / depth bar.

Figure 3: Time series of 3 water quality variables and the variation in Phosphorous with Depth (Source LOIS Overview CD).

4.3 Morphological change of hydrological features

Another problem which is of interest, is mapping changes in the morphology of river features such as migration of meanders, sediment bar shifts, bank erosion etc. Figure 4 shows data for the position of sediment banks (derived from the low water mark) over the last 90 years on the River Humber. It was mentioned earlier that conventional GIS is inefficient in manipulating this type of dataset because each time step has to be treated as a separate layer. STEM holds the data for each year in a single layer.

Figure 4: River Humber low water mark 1909 and 1920 (Source: ABP Hull)
One can clearly see from Figure 4 how the sediment banks and river channel have changed over the first ten years. Over the entire dataset, it is possible to identify cycles in the formation and destruction of the ebb and flow tidal channels and clearly this could be applied to many other geomorphological features which are known to exhibit cyclical patterns over time, such as river meanders. Therefore, STEM is still able to handle "moveable features", and their births, existence and deaths using 'period files' which can turn the spatial features on and off. Another example of the birth, death and re-birth of a spatial feature might be a canal section, which has fallen into disrepair and is no longer navigable. This feature would be re-born if it was subsequently cleared.

### 4.4 Suspended Sediment fluxes and multi-layer animation

The final example illustrates a relatively new innovation for STEM, namely the possibility for multi-layer animation. This allows two or more time-series of spatial data to be aggregated and animated at the same time, in order to see how different variables influence one another. For example, this may be the linking of a single variable, such as model output of suspended sediment, between different measurement areas or from different models, as shown in Figure 5.

![Figures 5. Snapshots illustrating multi-layer animation and integration of suspended particulate matter across river catchments (Boorman), tidal rivers (Tappin), estuary plume (Allen) and shelf seas (Proctor & Holt) for the River Humber and North Sea. All data from LOIS Modelling CD (in preparation), copyright of NERC.](image-url)

In the animated version of this example the SPM concentration can be seen to fluctuate progressively during its downstream passage from the catchments to the sea. Given that each STEM layer can contain up to 350,000 traditional GIS layers, the animation tool when applied to multiple layers is a powerful visualisation tool, particularly when looking at integration across different environments. It does not take a huge leap of the imagination to see that if one had map layers for different variables, cause and effects could also be identified. For example, the impact of land cover changes on discharge before, after and during change episodes.
5 Conclusions

Scientists have long been formulating research problems dealing with how areas, features or variables have changed over time. Today, there is a growing archive of environmental remote sensing and GIS data available in order to pursue such investigations. In addition, the value of historical data has risen dramatically and it is increasingly being captured retrospectively, in digital format from paper maps. This offers a great deal of scope for researchers to study changes that have occurred in the past, to postulate the causes and to make predictions and projections into the future. However, as Clark [5] suggest, a major barrier to the use of GIS for these investigations, is the quality of the data. This is often better now, than it was previously due to advances in technology. The spatio-temporal analyst must be keenly aware of any variations between the datasets being compared, in order to be able to identify any real changes with confidence.

Therefore, it is vital to have good metadata documenting how data were collected, processed etc. in order to ensure that the changes which are being identified are not just spurious changes due to variations in methodology or misuse of the data. Clark [5] quotes the alarming example of how inappropriate use of Ordnance Survey elevation data by insurers led to home owners being falsely categorised as living in a high flood risk area. This is an extreme example, but in order to identify real changes within spatio-temporal datasets, it is crucial to be aware of the limitations of the data for any given time step.

Provided that this is borne in mind, STEM offers the potential for hydrologists, and others, to take a fresh look at their data. In addition, the fact that a robust spatio-temporal framework is now in place, will hopefully reduce the need for coupling between GIS and hydrological models as the software develops. It is hoped that this paper has shown how powerful 4D visualisation can be and that it may encourage others to take their analysis to another dimension.

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References


