# GIST, A GEOGRAPHIC INFORMATION SYSTEM TOOLKIT FOR WATER RESOURCE AND ENGINEERING APPLICATIONS

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## Abstract

Problems increasingly facing engineers and planners concerned with using varied types and sources of spatial information are being overcome by the development of GIST, a Geographic Information System Toolkit, capable of incorporating all forms of conventional survey and remote sensing data which may be integrated, stored, manipulated, analysed, transformed and displayed according to user-defined specifications. Reference is made to current applications of the GIST development for ongoing groundwater and highway engineering projects in Asia, the Middle East, and Africa.

## 1. Introduction

The engineering profession is increasingly making use of the power of modern computers and associated developments in geographic information systems (GIS) to overcome the many varied problems of integrating and utilising large volumes of data from different sources. Current database systems are designed to accept large volumes of spatial data, derived from a variety of sources, and to efficiently store, retrieve, manipulate, analyse and display these according to user-defined specifications. To date, the most common sources of information have been in vector form on topographic and thematic maps or engineering plans, from which relevant parameters can be digitised into computer database files. Significant potential however, now exists to make use of information available from remote sensing systems, and especially earth observation satellite data in developing countries, where the lack of up-dated mapping and information on the physical properties of the terrain and socio-economic activities supported can provide major obstacles for engineering infrastructure development.

Previously, poor resolution has been a major factor in the full potential of satellite remote sensing data not being realised, in addition to the inability to integrate this raster form of information with that available from traditional vector map sources. As the spatial resolution of remote sensing, and significantly satellite imagery, continues to improve, a clear need has been established to develop an integrated system capable of efficiently handling all forms of spatially referenced information, but especially allowing the simultaneous interrogation, combination and up-date of data held, or originally captured, in either raster or vector formats. This paper reviews the approach which Scott Wilson Kirkpatrick & Partners in association with Wimpey Laboratories Ltd have undertaken through a joint research programme to overcome these problems by developing a computer-based Geographic Information System Toolkit (GIST), capable of integrating and handling all forms of conventional and new remote sensing data, which is now being used for the planning, management and control of the various engineering and development projects being undertaken by the two firms.

## 2. GIS in Civil Engineering

Engineers and planners increasingly face the problem of the integration and selective use of information derived from spatial data acquired in different formats from a wide variety of sources. Lack of quickly available information in the correct form can prove a major limitation to efficient engineering practice and management. This is increasingly evident in current interests on maintenance of infrastructure and asset management, where considerable data are continually required to locate, inventory, evaluate, up-date and monitor roads, water mains, buildings, pipelines, reservoirs, utilities etc, so that priorities may be defined, cost controls and financial management improved, and best use of available resources ensured.

The potential value of establishing systems of engineering data storage has been recognized for a long time (Brink et al, 1966, Aitchison and Grant, 1968). In recent years, for example, an interest has been growing in developing countries on the compilation of regional or national inventories of road building materials, as their location and proving accounts for a substantial proportion of total costs and times spent on most engineering projects (Beaumont 1979). Specific studies have also drawn attention to the value of engineering data storage systems in preventing wasteful repetition of survey effort, and in facilitating the transfer of information from one area to another (Lawrance 1977). As the concept of data storage has become familiar to engineers involved with regional planning, and faced with the task of evaluating increasing volumes of information acquired from different sources, corresponding interest has grown in the use of recent computer-based geographic information system (GIS) developments for engineering planning purposes.

The planning and implementation of highway maintenance, for example, is becoming increasingly important in developing countries where the simultaneous requirements to keep up standards of existing infrastructure and continue new developments pose severe strains on the availability and allocation of scarce financial and technical resources. One approach to overcoming these problems is to increase efficiency through improved practice in planning and methods of management which, in turn, are initially dependent on acquisition of reliable information. Satellite imagery can play a significant role in providing relevant data for highway maintenance both for purposes of inventory (e.g. roads, drainage structures, sources of construction material) and the identification of physical and socio-economic features which will influence the road network, and possibly the measures required to keep it in good repair. This has recently been demonstrated on road studies undertaken for the Ministry of Public Works and Town Planning in the Republic of Niger (Beaumont 1985a).

Much interest is currently being shown in engineering GIS development, and already operational applications of database systems have been identified in such areas as regional and urban planning; transportation and traffic planning; land and resource management; land use planning; interaction of highway location, environmental effects and engineering actions before, during and after construction; detailed cost evaluation and environmental impact assessment studies concerned with site selection based on engineering feasibility, social, economic and ecological considerations; and regional or national inspection of dam programmes. The potential for incorporating remote sensing data into such systems has also been identified as in Saudi Arabia, satellite imagery is now being used for national housing, urban land use and road maintenance database projects. Integration of spatial information acquired from satellite imagery into geographic information management systems is also becoming recognised in many parts of the world for regional engineering planning studies concerned with the environment (Beaumont 1985b), irrigation (Johnson, Vining and Loveland 1980, 1981), pollution, rural development, water resources management, hazard warning and safety, and various aspects concerning project management.

## 3. GIST Applications Driven Design Philosophy

It is the experience of both Scott Wilson Kirkpatrick & Partners and Wimpey Laboratories Limited, that the key to successful implementation of software projects in engineering is to insist that development be driven by the requirements of a given application which provides the only practical way of creating a product which satisfies the requirements of the user. Experience has also shown that in order for the project to have a lifetime long enough to justify development costs, it is necessary to predict future advances in the computing field, and to incorporate these ideas into the design, so that full advantage may be taken of the realisation of any significant developments. Such software engineering considerations were thus fundamental to the development.

The applications initially addressed concerned geology and hydrogeology, together with road maintenance and rehabilitation. Traditionally such fields of investigation have not tended to fully exploit the potential benefits of satellite imagery. Consequently, it was felt that there would be distinct advantages in developing a GIS which could exploit the full potential of these data sources. In order for this to be realised, a requirement was identified whereby the user could interpret features on the image directly from the screen monitor, using a cursor and digitising tablet, which immediately would be automatically entered into the GIS for future display and analysis.

The components of GIST were initially chosen to be a GEMS image processing system and an ORACLE relational database management system interfaced with a computer aided design and digital mapping facility. In the course of the development programme these facilities were integrated using software written by the development team to produce a functioning Geographical Information System. Design commenced with detailed applications reports being prepared by a specialist in each field. The reports consisted of two distinct parts; the first detailing the way in which remotely sensed and especially earth observation data is currently used in that application, and the second providing suggestions of how a GIS might improve or indeeed revolutionise this work.

### 3.1 Analysis of Applications Reports

Analysis of the applications reports (and many subsequent reports) gave rise to the following requirements:

The developed system would have to:

a) accept input from a variety of data sources available in or transferable to a digital format.

b) have the ability to work with both raster and vector data types simultaneously,

c) have the ability to transform vector and other related data between different map projections in real time,

d) have unique storage of information,

e) be able to communicate with other software packages for specialist analysis,

f) be able to present high quality output.

Each of these requirements which have been developed into the system may now be briefly considered in more detail.

#### 3.1.1 Data Input Sources

Typical data sources which may be incorporated in the developed system include satellite imagery, digitised aerial photographs and video recordings, thermal infra-red imagery, digital maps, manually digitised and other non-spatial data, such as geological borehole records and time series information from meteorological or gauging stations and the like. Additionally data in the UK National Transfer Format can be input to GIST.

#### 3.1.2 Rasters and Vectors

GIST has the capability of displaying and zooming both raster and vector data simultaneously either in plan view or, if a digital terrain model is available, in true perspective. In many situations perspective views are useful as an aid to visualisation, and for such tasks as checking whether an interpretation of drainage is correct.

#### 3.1.3 Co-ordinate Transformations

In view of the number of potential information sources and the desire to maintain accuracy, all spatial data is stored in its original map projection. This requires the facility to transform the data into any common and desired projection for display or output. Moreover it has distinct benefits for use of the system in large countries where changing the scale of the display requires there to be a change of projection. (For example, many countries use a Universal Transverse Mercator projection for large scale mapping, but this projection is unsuitable for displaying areas wider than approximately 6 degrees of longitude.) The technique chosen for data transformation is one which is more usually found in finite element analysis work. Each transformation is decomposed into a set of quadratic Lagrangian iso-parametric shape functions which approximate the transformation over a rectangular area. The areas are formed into a linear quadtree so that the accuracy of the transformation can be increased to a value appropriate to either the display device or the pen plotter. The conversions are made in real time.

#### 3.1.4 Information Storage

The philosophy behind the database storage development has been to separate the graphical representation of a feature from the details of the characteristics of the feature stored in the relational database. This enables a single line to be both a geological fault in its own right and also to be part of say the boundary of a geological unit. The geographical representation of the line is stored only once, but with multiple attributes, ie. all information is stored uniquely. This has the advantage that should the fault be moved within the course of final image interpretation and mapping, only the single graphical representation need be modified.

#### 3.1.5 Communication with other Packages

GIST is able to communicate with other software packages for specialist analysis. This is not just a transfer of data via disk files but an integration of these packages within GIST. Examples are: 'DEVONET' a highway maintenance/management system (developed by Devon County Council, UK) and interface with 'MOSS' an engineering highway design 3D analysis package (marketed by Moss Systems Ltd, Horsham, UK).

#### 3.1.6 Output of Data

Data within GIST, or the results of analysis of that data, can be output in the form of reports, tables, graphs or maps. In particular, maps can contain a wide range of line types and stipples (ornamentation of areas). Near cartographic quality is achieved bearing in mind the inherent limitations of pen plotters.

### 3.2 Software Engineering Considerations

The software design has been implemented in modular form so that each module could be written in the standard machine independent language most appropriate to its function. Modular design also allows software which is machine dependent to be isolated within a limited number of modules, making it possible to "port" the software onto different machines.

In the near future, computers with a parallel architecture will be available at an economic price. Such computers are likely to be capable of performing many tasks simultaneously, thereby significantly increasing their speed and performance. GIST has been structured so that it can take advantage of this development. Work is currently being undertaken on the transfer of the system to a personal computer with an 'add-on' INMOS transputer board to provide a powerful, low cost workstation based on hardware which is maintainable in the Third World.

Control of the software has been amalgamated into a single module to permit the introduction of artificial intelligence at a later date. Artificial intelligence techniques have the potential to simplify the user interface of the software thereby enabling the applications specialist to manipulate the sytem without extensive computing knowledge.

### 3.3 The Final Design

GIST is an acronym for Geographic Information System Toolkit, a name reflecting the underlying approach which has been to supply the user with a set of tools to solve their particular problem. Such an approach moreover is further assisted by the system talking to each specialist in their own "language".

The majority of the software which has been developed is independent of any particular application, so that although the system has been designed to solve specific problems, a comprehensive GIS has none-the-less been produced. This means that the effort required to incorporate additional applications should be minimal and likely to decrease with each new application.

## 4. Water Resource Engineering Applications

The production of hydrogeological maps and resource assessments in arid and semi-arid terrains may now be economically and satisfactorily based upon remotely sensed imagery. To integrate the collection, compilation and analysis of the vast range of data types used in such assessments, GIST applications for water resources have been developed to enable the hydrogeologist to both maximise his use of the imagery and encourage efficient data entry.

In describing the hydrogeology of a study area, it is essential to establish a framework in which groundwater resources can be related to the physiographic characteristics of the region. For instance, a geological framework may provide a good basis for the description of uniform sedimentary aquifers, and a geomorphological framework for alluvial and saprolitic aquifers. Satellite imagery provides data ideally suited to regional studies whose mapping base will not exceed 1:50,000 scale. However, these data are collected in raster form, or pixels. The work of an interpreter will be executed in vector form utilising points, lines and polygons. GIST allows this electronic superimposition of vector data on the raster imagery, effectively offering the geologist or hydrogeologist a set of electronic 'pens' with which to compile conventional interpretations. Not only is the laborious task of overlay and registration dispensed with, but having made this superimposition, the abstracted vector data can provide the spatial framework with which the relational database is able to be integrated.

This database is directly interrogable, and is able to answer requests relating to individual or selected sub-sets of classes at both spatial and non-spatial levels. For example, it is possible to ask for all boreholes with specified aquifer thickness located on a particular outcrop to be displayed in space, together with rainfall isohyets for the region. Alternatively the operator may simply wish for a listing of all boreholes in the region with depths greater than 100m.

Brief reference to three case studies illustrates the possible range of GIST applications for water resource assessments.

Wadi Ma'awil, Northern Oman

Wadi Ma'awil enters the Batinah coastal plain immediately south of the coastal town of Barka. Its hard rock catchment comprises 418 sq km of incised, early Cretaceous limestones and emplaced ophiolite. The annual discharge of the catchment is estimated at 21.1 $Mm^3$/yr. Floods generated in the hard rock catchment pass on to an extensive alluvial fan of approximately 300 sq km. Significant transmission losses occur near the apex of the fan and very few flows reach the coast. In an attempt to develop groundwater resources on the distal margin of the fan endowed with suitable soil resources, satellite imagery of the catchment was obtained with a view to developing structural models to explain the geology underlying the fan, and the configuration of the fan aquifers, as well as providing a mapped database for existing borehole information that was to develop into a groundwater monitoring network.

GIST provided the tools for quick interactive image processing to carry out detailed structural mapping at 1:100,000 scale from the satellite imagery which produced a wide range of spectral values, from the dark ultra-basics of the ophiolite to the much lighter subtle contrasts in spectral signatures of the superficial materials on the alluvial plain. The photogeological interpretation was achieved with an easy to use digitising tablet which acts as an electronic 'pen-plot' that allows the interpreter to electronically superimpose his vector line information upon the raster image.

A hydrogeological interpretation then followed detailing the aquifer geometries by combining known borehole information with the structurally defined limits of a downthrown Tertiary block underlying the fan. Subsequent drilling proved the structural model and provided more information for the borehole database, allowing detailed cross-sections to be displayed and aquifer piezometry to be plotted. This in turn permitted the development of a distributed surface and groundwater model of the catchment to be developed, with calibration and validation performed using two separate data sets from the monitored time series information collected on surface and groundwater movements using digital data loggers capable of uploading their records directly into the GIST database.

Zhob Valley, Baluchistan

GIST has been used to evaluate the water resources of a Miocene conglomerate aquifer set in a complex thrust zone of northwest Pakistan, and to recommend a programme of aquifer management for a 60 borehole well field constructed to provide perennial irrigation for a 2,500 hectare agricultural development.

Satellite imagery at 1:200,000 scale was used to provide a basis for field mapping and compilation of hydrogeological data for the upper catchment (1,500 sq km) of the Zhob river basin. The mapping subsequently developed used GIST not only to interpret the satellite data but also to integrate the detailed information collected in the field and entered into the project database. On establishing the strutural complexity of the region, it became possible to interpret the hydrogeological setting of the well field. Using the spatially coordinated relational database, it was possible to correlate specific capacity data from the boreholes with the reinterpreted geology, and account for considerable variations in aquifer transmissivity.

As evident in Oman, the wealth of borehole data and monitoring information for the well field enabled the succesful development of a spatially distributed groundwater model within GIST which was able to form the basis of a groundwater management strategy for the aquifer.

Ethiopia, Wolo Province

As part of a major borehole rehabilitation project throughout Wolo Province, GIST has been used to collect, analyse and present some 250 borehole records. The locations of each borehole were electronically compiled onto a regional hydrogeological interpretation derived from Landsat 4/5 satellite data using GIST. Refined geological interpretations were then carried out with Thematic Mapper and SPOT satellite data in areas where coinciding resource demands and low yielding boreholes indicated potential constraints to further development. Detailed examination of the groundwater resources of these localities using GIST was backed up with field observations and subsequently led to the development of groundwater exploitation options which were presented to the water planning authorities.

In addition, a database of borehole pump maintenance records has been developed through the GIST facilities to allow engineers to effectively plan the development of maintenance teams. Moreover this information has also been combined with the regional hydrogeological interpretation to identify hydrogeological factors controlling borehole pump reliability.

## 5. Geotechnical and Highway Engineering Applications

As the planning of a highway project progresses from the stages of reconnaissance and feasibility survey through to design and construction, the need for accurate geotechnical appreciation of the terrain increases. Although the alignment chosen may be influenced to some degree by political and social factors, the final design is only achieved after a detailed examination has been made of the landforms, drainage, soils and materials to be found within the route corridor. On this basis, the selected alignment may deviate from the shortest distance route in order to reduce construction and vehicle operating costs. Construction costs in the main are minimized by reducing earthworks, bridge and drainage structures; by selecting the strongest soil foundations and locating conveniently sited sources of durable road building materials; and by avoiding, where possible, ground hazards such as swamps, shifting sands, landslides and areas prone to erosion. As the optimum alignment will depend on achieving an appropriate balance between all the many opposing factors influencing final location on the ground, this may now be most effectively accomplished by incorporation and analysis of all the relevant data for the route, and area upon which it will have an impact within a GIST facility. Thereby, the effects of significant changes in geotechnical, engineering or economic road location factors can quickly be evaluated against each other. Similarly, a more efficient means is provided to analyse environmental impact and establish a basis for maintenance and the monitoring of physical and socio-economic change attributable to the newly developed road.

Incorporation of remote sensing satellite data into a GIS offers unique advantages for highway planning in that information on all the factors which influence route selection, such as those mentioned above, may be initially acquired at the regional level through an interpretation of single and multidate imagery. Limitations in the ground resolution of multispectral scanner imagery usually determine that the acquisition of useful information is restricted to the reconnaissance and feasibility stages of highway planning. However, even at the detailed design and construction phases, information may be derived on specific features such as the extent of black clay soils or the location of lines of drainage and geological faults. The opportunity of quickly being able to examine features relevant to detailed design in their regional setting is also often of considerable advantage, as for example in the evaluation of the catchment area of a line of drainage which the alignment must cross that is not totally covered in the route corridor aerial or ground survey.

In Eastern Nepal, an engineering route selection and feasibility study, involving geotechnical investigations and leading to detailed design, has been undertaken for a 180 km road alignment required to traverse severe Himalayan mountain terrain for the provision of access to the site of a new hydro-electric power station on the River Arun. On this project, the GIST facility was used to develop a 3-dimensional perspective for a portion of the route by geometrically matching, and specially folding by contour smoothing, Landsat TM satellite colour composite data over a digital terrain model. The 3-dimensional view of the terrain additionally combined a perspective display of the interpreted map overlay vector data which, with the remote sensing satellite imagery, accurately forms the integrated surface of the terrain model. A major advantage of using GIST was that the interpretation was entirely undertaken by use of a cursor on the image processing screen, whilst all of the resulting map overlay vector data and attribute information associated with it, as for example field observations, measurements, borehole logs etc, were simultaneously stored within the database for subsequent use and correlation by the road and geotechnical engineers.

In using the relational database to incorporate other information, acquired from both the interpretation of satellite imagery and different survey sources, on such features as land use, agriculture, settlements, erosion, hydrology, etc relevant for route selection, the consulting engineers assigned to the project were thereby greatly assisted in selecting the most feasible corridor location, in view of their requirements to assess all the pertaining factors in a limited schedule of time, for the final road alignment. Incorporation of the digital terrain model information, digitised from existing map sources, also enabled slope and height data to be classified and correlated with other parameters interpreted from the imagery such as vegetation, watershed characteristics, drainage and landslide features. Interpretation of the satellite imagery could also be refined, and accuracy improved, especially with respect to checking headwater drainage channels not traversing watersheds, and the definition of geomorphological terrain units. Many other features characteristic of the GIST facilities, for simultaneously handling and processing information in both raster and vector formats, are similarly anticipated to obtain maximum benefit and encourage further engineering use of satellite remote sensing data on such projects.

On the most recent projects, this has already become evident as SPOT satellite imagery is currently being deployed in conjunction with GIST facilities on a new economic feasibility study of a proposed road alignment between Molo and Litein in West Kenya, which must traverse poorly mapped,ecologically sensitive areas, where there are significant requirements to evaluate the land use and natural rsources of the region in relation to the physical and socio-economic environmental impact of the likely route corridor development.

## 6. Conclusions

The applications driven design philosophy which has guided the development of GIST has enabled the system to fulfil the immediate requirements of current projects, whilst also facilitating a general toolkit for the integration of all forms of spatially referenced data and associated information for future engineering projects.

A flexible, modular approach to the design of the software and carefully defined interfaces with specialist hardware make full use of existing facilities and will also allow the system to exploit the potential of current and future developments in computer technology.

Projects which have already made use of GIST in water resources, geotechnical, and highway engineering clearly indicate the advantages of integrating together spatially referenced information from a number of different sources to carry out design and analysis, whilst the general solutions adopted for the storage, integration and transformation of different types of data make the system ideal for a much wider range of applications.

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