Three 'S' Technologies for Watershed Management

Moe Myint

Objectives

- To discuss three 'S' technology in the context of watershed management and to highlight the information generated by these technologies

What are three 'S' technologies?

The 3S technology— global positioning system (GPS), geographic information system (GIS) and remote sensing (RS)—is a multi-disciplinary science of geo-informatics to measure, record, process, analyse, represent and visualise geospatial data. 3D application, data acquisition for digital elevation models (DEM), data processing and analyses, and 3D-image output are emphasised in geo-informatics. 3S technology with 3D applications add a new dimension to research and applications in watershed management.

What is the global positioning system (GPS)?

The global positioning system (GPS) is a world-wide radio-navigation system formed from a constellation of 24 satellites and their ground stations in Hawaii, Ascension Island, Diego Garcia, Kwajalein and Colorado Springs. GPS satellites are called NAVSTAR. The altitude of the satellites is 10,900 nautical miles. The orbital period is 12 hours. The orbital plane is 55 degrees to other equatorial plane. The GPS provides three dimensional positioning, velocity and time information. The first and most obvious application of GPS is the simple determination of a basic position or location. GPS is the first positioning system to determine highly precise location data for any point on the earth in any weather.

How does GPS work?

The position is calculated from distance measurements (ranges) to at least four satellites to determine the exact position of the antenna of the GPS receiver. It is called triangulation. The distance to the satellite is determined by measuring how long a radio signal takes to reach the receiver from the satellite. In order to make the measurement, both the satellite and the receiver are generating the same pseudo-random codes at exactly the same time. By comparing how late the satellite's pseudo-random code appears compared to the receiver's code, determines how long the signal took to reach the receiver. This time is then multiplied by the speed of light to determine the distance. Therefore, accurate perfect timing is the key to measuring distance to satellites. Receiver clocks do not have to be too accurate because an extra satellite range measurement can remove errors.

There are a wide variety of possible errors. For example, as the GPS signal passes through the ionosphere and troposphere, it slows down and creates an atmosphere-induced error. One way to counteract this error is to compare the relative speeds of two different signals. The dual frequency measurement is sophisticated and is only possible with advanced receivers. When the signal reaches the ground, it may bounce off various obstructions before it reaches the receiver. This is called multipath error. Good receivers use sophisticated signal rejection techniques to minimise multipath error. Atomic clocks are very precise but they are not perfect. Miniscule discrepancies can occur in travel time measurements, so slight position errors can appear. The configuration of satellites in space can magnify these errors. This is called geometric dilution of precision (GDOP). There are more satellites available than the receiver needs to fix the position, the receivers pick a few and ignore others. If the receiver picks satellites close together in space, the intersection circles that define the position will close at very shallow angles. This increases the error margins around a position and GDOP is high. If the receiver picks satellites that are widely separated, the circles intersect at almost right angles and minimise the error regions: GDOP is low. Good receivers can select satellites that will give the lowest GDOP. Alternatively GDOP is also referred to as PDOP (positional dilution of precision). The position should be measured when the PDOP value is less than 6.

The accuracy range of position is from 100m to better than one cm depending on the design of the GPS and method of measurement. Use of a single GPS is called autonomous GPS. The positional accuracy of an autonomous GPS is 100 m and the speed accuracy of autonomous GPS is about 3 mph. Mapping applications use GPS receivers with sub-metre accuracy. In order to obtain better than a 100-m accuracy, differential GPS (DGPS) must be used. Differential GPS can eliminate almost all the errors. It can provide a position accuracy of about 10 m to 1 cm and speed accuracy of better than 0.1 mph. DGPS corrections are available for both real time and post-processing. DGPS requires the cooperation of two receivers. One receiver is a stationary or reference station and another receiver is moving around to mesa positions—the rover receiver. If two receivers are within a few hundred kilometres, the signal that reaches both of them will have travelled through virtually the same slice of atmosphere, and so will have virtually the same error. The reference station is placed at a point that has been accurately surveyed. The reference station calculates the timing using its known position instead of calculating the position using timing. So it calculates backwards. Since the reference station knows where the satellites are supposed to be in space, and it knows exactly its location, the theoretical distance between itself and each satellite can be calculated. Dividing the theoretical distance by the speed of light determines the time. The reference station compares the theoretical time and the time actually taken. Any difference is the error or delay in the satellite signal. The reference station uses all visible satellites and computes their instantaneous errors. It encodes this information into a standard format and transmits it to the roving receivers through a radio link. The roving receivers receive the complete list of errors and apply corrections for the particular satellites they are using. In the early days of GPS, reference stations were established privately. Now there are enough public agencies and commercial firms transmitting corrections. One service provider for DGPS is Omnistar. The home page is http://www.omnistar.com/

Deriving high-accuracy data in real time uses real-time kinematics' (RTK) techniques, while post-processing techniques require phase data to be collected. Radio links are required for real-time DGPS. A number of different types of radio transmitters are used. The main types are radio navigation beacons, commercial FM transmitters, and geostationary satellites. Many GPS receivers are designed to accept corrections, and some are even equipped with built-in radio receivers. FM stations can be used to transmit correction data cost-effectively, especially in the HKH region. Some DGPS applications do not need radio links because they do not need immediate precise positioning. Rover receivers record all measured positions and the exact time each measurement is made. Then the data can be corrected at a reference receiver. This is called post-processing DGPS. Internet can also be a good source of corrected data because some academic institutions are experimenting with the Internet as a way of distributing corrections.

Post-processing DGPS will be an excellent tools for positioning and mapping in the watershed areas. GPS can pinpoint the position of a gauging station, a meteorological station, a drain, a trail or a particular patch of forest or sample plots in a watershed. Moreover the position of soil samples, elevations points, endangered animals, sources of pollution and villages can be recorded for inclusion in a spatial database of a GIS. Moreover ground control points in a watershed can be precisely measured by DGPS and used for rectification of digital image data in remote sensing.

What is a geographic information system (GIS)?

A geographic information system (GIS) is a computer-based geospatial database tool on which location information (where) and attribute information (what) of spatial objects such as houses, rivers, and forests can be recorded and stored. This information can be represented as points, lines and polygons. In a watershed, gauging and meteorological stations, pollution sources and villages are the point features, trails and drainage are line features, and land use and watershed boundaries are the polygon features. GIS generate new information based on the spatial relationship of individual objects for particular spatial decision support and problem-solving. For example, by examining the spatial relationship and connectivity of pollution sources, drainage and villages, GIS can derive new information on 'villages that stand a high risk of toxic pollution'. GIS can visualise and present results cartographically. The capability carry out to spatial analyses distinguish GIS from other information systems and make it valuable to a wide range of applications such as urban planning, telecommunication network monitoring, transportation planning, environmental planning, watershed classification and natural resources' applications, etc.

Components of a GIS

Hardware is the computer on which a GIS operates. The digitiser, scanner, printer, and plotter are also hardware components. GIS software runs on a wide range of hardware types — stand-alone or network computers in client server environments.

Software allows a GIS to input, correct, store, analyse and display geographic information. Major components of GIS software are

- inputting, cleaning and manipulation of location and attribute information,
- database management system,
- spatial query, spatial analyses, database query, spatial modelling and visualisation of geographic data,
- graphical user interface for easy access by users, and
- application programming language to customise applications.

Data are the most important component of a GIS. A database of spatial data and attributes can be created in-house or by sharing or by purchase from a commercial data provider. Creating the data is time consuming. By sharing existing data from different agencies and organizations, the capability of a GIS can be increased by reducing the time and effort spent in creating duplicate data. Data quality and data standard are important, and data requirement analyses should be performed in the watershed. The data in the GIS, especially location data, contain explicit geographic references such as latitude and longitude or national grid co-ordinates. The attribute data contain nominal variables that are described by name (such as park, pine forest) , ordinal variables such as lists of discrete classes with an inherent order (classes of stream: first order, second order and so forth), interval variables that have a natural sequence within addition (such as temperature 10-20 °C , 20-30 °C), ratio variables that have the same characteristics as the interval variables but in addition have a natural zero or starting point, and implicit references such as an address range, postal code and census tract name. The attribute information is stored in the attribute table of a particular spatial object. GPS technology provide the basic location information of x,y co-ordinates to GIS. However, by using the data dictionary facility of a GPS data collector, attribute information can be recorded. Location and attribute information can be downloaded from GPS to GIS by using the utility software of the GPS.

GIS users range from technical specialists, who design and maintain the system and manage the data; application specialists from different disciplines, who apply GIS to a particular field; and policy-makers who use the GIS as a support tool for decision-making. GIS integrate not only different data layers but also professional knowledge from different disciplines in order to solve a particular spatial planning problem. GIS are of limited value without the knowledge of people who develop plans for the real world. In a watershed, the knowledge of the hydrologist, agriculturist, agronomist, soil scientist, ecologist, forester, economist, GIS specialist and land-use planner is essential for sustainable management and planning.

GIS Models

Geographic information systems are based on two fundamentally different types of spatial data models—the vector model and the raster model. In the vector model, the position of points, lines and polygons are precisely specified. Location of a point feature, such as a gauging station, is described by a single x,y geographic co-ordinate and its attributes are described by its identifier number and name or label and other attribute information defined by the user. The location of a line feature, such as drainage, is described by a series of x,y geographic co-ordinate pairs, and its attributes are described by its identifier number and name or label and other related attribute information defined by the user. The location of a polygon feature, such as a lake, is described by the close loop of x,y geographic co-ordinates and its attributes are described by its identifier number, name or label and other related attribute information defined by the user. Vector data are efficient at recording and describing discrete features, but less useful for describing continuously varying features such as soil types, temperature and rainfall.

The raster model represents point, line and polygon spatial features as a collection of grid cells. Each cell is assumed to be a homogeneous unit. Each grid cell is only assigned one value. In a soil pH map, each cell is assigned the pH value of that particular location. In a soil texture map, each cell is assigned the soil texture value of that particular location. The raster model is efficient at recording and describing continuously varying features such as temperature, soil and rainfall and transition zones.

Modern GIS, so-called hybrid GIS, are able to handle both models.

How can GIS be used for a watershed management?

In a watershed, line features and their attributers; such as trails, drainage, and contour lines; point features and their attributes; such as rainfall stations, gauging stations, water origins, villages, pollution sources and ground water wells; and polygon features and their attributes such as land use/land cover, watershed boundary, catchment boundary can be recorded in a vector GIS.

A digital elevation model (DEM) of a watershed can be generated with a triangular irregular network (TIN) model in a vector GIS by using a network of irregularly spaced, randomly selected elevation points. More sample elevation points are selected in the areas of rough terrain and fewer in smooth terrain. Alternatively, in a raster GIS a DEM can be generated based on digitised elevation points by using interpolation algorithms. Using stereo aerial photographs and stereo space images, automated DEM can be generated by stereo-image matching algorithms. This will be discussed in more detail in the section on remote sensing. Topographic features such as slope, aspect, drainage network and elevation contours can be generated in vector or raster GIS based on the digital elevation model. A rainfall map or temperature map can be generated by using thiessen polygons and by interpolation based on the location and temperature and rainfall data of meteorological stations.

What can GIS do?

GIS performs the five tasks: input, manipulation, management, query and analyses and visualisation.

The location and attribute data of a paper map can be input to a GIS by scanning or digitising. Tabular data can be imported from a database management system or spreadsheet or directly input to the DBMS. Many types of geographic data already exist in GIS-compatible formats. These data can be obtained by data sharing or from data suppliers. Departments of Agriculture, Forest, Geology, Mining, Meteorology, Statistics and Hydrology are useful sources of data for the watershed.

The data may have to be transformed from one geographic co-ordinate system to another (for example, the latitude-longitude geographic co-ordinate system to the UTM [Universal Transverse Mercator] co-ordinate system). The data format may have to be manipulated to be compatible to a particular GIS (for example, the MapInfo MIF file format to the ArcView Shape File format). Data may have to be merged to obtain complete coverage of a watershed or it may have to be clipped out for an area within a watershed. Data may have to be cleaned and the dangle errors (overshoots and undershoots of arcs) and attributes of spatial objects corrected. Changes have to be updated. GIS technology offers tools for manipulation, transformation, map joining, clipping, reclassification, updating and cleaning of spatial and non-spatial attributes.

A database management system (DBMS), especially a relational DBMS (RDBMS), is best for storing, organizing and managing data. In the relational database design, data are stored as a collection of tables. Common fields in different tables are linked to one another. Therefore, to normalise the database, tables can be split into smaller tables based on common fields.

GIS provide simple point-and-click spatial query and attribute query systems. In a simple point-and-click spatial query, click on a spatial object (point or line or polygon) and the GIS provides attribute information. In a simple point-and-click attribute query, click a particular record in an attribute table or enter a query (such as land use=forest and elevation >500 m) and the GIS highlights spatial objects (such as all the forest above 500 m). GIS also provide sophisticated tools for analysis to look for suitability, patterns, trends and to model 'what if' scenarios. Proximity or buffer analyses are a useful tool for answering spatial queries such as 'derive forest types and areas within 200m of first order drainage'. Overlay analyses are another powerful tool used to integrate data layers of spatial objects according to criteria derived from the integration of knowledge from application specialists. The overlay or spatial join can integrate data on soils, slope, vegetation and elevation in order to derive 'an area suitable for reforestation with soil types of sandy loam or loam, slope <30°, eastern aspect, deforested and elevation <500 m'. Land-use dynamics and change maps can be derived by simply overlaying time series' land-use maps.

The end results of GIS operations are maps, graphs and tables. Maps are efficient at storing, communicating and presenting geographic information. GIS and automated cartography will provide new and exciting tools such as integrated image output with DEM , birds eye views, and image animation.

What is remote sensing (RS)?

Remote sensing is defined as the use of electromagnetic radiation reflected, emitted or backscattered from an object, area, or phenomenon in order to acquire, identify, measure and analyse the characteristics (spectral, spatial, temporal) of the object, area and phenomenon without direct contact. It is recognised as an essential data source, especially when there is no map available or existing maps are out of date. It provides multi-spectral, multi-resolution, multi-temporal and multi-sensor imagery of the latest conditions of an area.

Passive remote sensing makes use of sensors that detect the reflected (visible, near infrared) or emitted (thermal infrared) electro-magnetic radiation from object, area and phenomenon. Active remote sensing makes use of sensors that detect the backscatter energy from an object, area or phenomenon through artificially generated energy sources such as synthetic aperture radar (SAR).

The electro-magnetic radiation characteristics used in remote sensing are listed in Box 1.

In general, resolution is defined as the ability of an entire remote-sensing system, including lens, antenna, display, exposure, processing and other factors, to render a sharply defined image. Resolution of a remote-sensing system is of different types. Spectral resolution is the number of spectral bands of the remote-sensing satellite. More spectral channels means higher spectral resolution. For example, Landsat TM has seven spectral bands and the SPOT multispectral mode has three spectral bands, so the Landsat TM has a higher spectral reso-

Box 1

EMR	*Wavelength*	*Remote Sensing*
Visible	0.4 - 0.7 ?m	Visible and Infrared Remote Sensing (VIR)
Near infrared	0.7 - 1.3 ?m	Visible and Infrared Remote Sensing (VIR)
Short wave infrared	1.3 - 3.0 ?m	Visible and Infrared Remote Sensing (VIR)
Intermediate infrared	3.0 - 8.0 ?m	Visible and Infrared Remote Sensing (VIR)
Thermal infrared	8.0-14.0 ?m	Visible and Infrared Remote Sensing (VIR)
Microwave	1 mm - 1 m	Microwave Remote Sensing

Characteristics of microwave and VIR

	<u>VIR</u>	<u>Microwave (active)</u>
General		
Detection	Reflected sunlight	Radar backscatter emission
Interaction	Chemical	Geometric/dielectric
Resolution	2 - 1,000 m	9-100 m
Swath width	36 - 2,700 km	45 - 510 km
Geometry	Vertical looking	Side looking
Interaction with earth surface		
Penetration		
Soil	None	Yes (variable)
Vegetation	None	Yes (variable)
Water	Yes (variable)	None
Information	Surface	Volume
Interaction with atmosphere		
Independence		
Cloud cover	No	Yes
Haze	No	Yes
Rainfall	No	Yes
Sunlight	No	Yes
	Yes (Thermal Infrared)	
Data presentation capability		
Stereo	Yes	Yes
Interferometry	No	Yes
Multispectral	Yes	Yes* (VV, HH, VH, HV Polarisation)
Multitemporal	Yes	Yes
Available since	70's	90's
Difficulties between VIR and microwave		
Interpretation	Relatively Intuitive	Relatively not intuitive
Illumination	Variable	Constant
Distortion	Limited	Topographic layover Foreshortening and shadow
Noise	limited	Highly speckled

lution than SPOT. Radiometric resolution is determined by the number of discrete levels into which signals may be divided. For example, the NOAA AVHRR sensor has 10 bit (2^{10} = 1024) and Landsat TM has 8 bit (2^{8} = 254) digital levels. Therefore, the NOAA AVHRR has higher radiometric resolution than the Landsat TM. Spatial resolution describes the representation of each pixel size to the ground distance. For example, spatial resolution of the SPOT Multispectral sensor is 20 m and that of Landsat TM is 30 m. Therefore the SPOT Multispectral sensor has higher spatial resolution than the Landsat TM. Spatial resolutions related to accuracy for map production are provided in Box 2.

Temporal resolution is the revisit capability of a remote-sensing satellite to the same location. the Landsat TM revisits every 16 days and SPOT revisits every 20 days. Therefore the Landsat TM has higher temporal resolution.

Some visible and infrared sensor system characteristics of earth resource satellites used in natural resource studies are illustrated in Table 1. The SAR instrument characteristics for Radarsat, ERS-1, ERS-2 and JERS-1 are illustrated in Table 2.

Land cover/land-use mapping is an important application of remote sensing. Land cover corresponds to the physical condition of the ground surface, such as forests, grasslands ,etc, while land use reflects human activities such as industrial zones, residential zones and agricultural fields, etc. Land cover/land-use change mapping is another application for updating land cover maps and the management of natural resources. Change vector analyses of remote-sensing data can be applied at the watershed level for multispectral monitoring of land cover and condition. Remote-sensing data can be use for forest-type mapping and biodiversity inventory. Coarse resolution data, such as NOAA AVHRR, can be used to monitor land cover. Temperature can be derived by using the thermal infrared channel of Landsat TM or MOS-1 (Marine Observation Satellite) VTIR (Visible and Thermal Infrared Radiometer). Water-quality monitoring is a typical application, especially in offshore areas. The visible bands are useful for monitoring clear water and suspended turbid water near offshore areas.

Digital elevation models (DEM) can be generated from a stereo pair of satellite images. The height accuracy Dh depends on the base:height ratio and the accuracy of parallax, which can be approximated by ground resolution, DG.

$$\Delta h = H/B\ ?G$$

Satellite	Satellite height (H)	Orbital interval (B)	Spatial resolution (DG)
Landsat MSS	705,000 m	145,000 m	80 m
Landsat TM	705,000 m	145,000 m	30 m
SPOT Pan	830,000 m	840,000 m	10 m

Δh of Landsat MSS is approximately 400 m.
Δh of Landsat TM is approximately 145 m.
Δh of SPOT Pan is approximately 10 m.

Level 1A SPOT stereo pair with base:height approximate to 1 is suitable for DEM generation of a watershed. Based on the DEM, drainage network and watershed, slope and aspect can be extracted. In addition to the SPOT satellite, the IRS1-C, IRS1-D, JERS and Radarsat satellites have the capability of acquiring the stereo-image data.

Box 2

Scale	Pixel Size Spatial Resolution	Height Accuracy	Contour interval	Position Accuracy	Application
1:250,000	25.0 m	33 m	100 m	33.3 m	Natural Resources
1:100,000	10.0m	17 m	50 m	50 m	RegionalPlanning
1:50,000	5.0 m	7 m, 13 m	20 m, 40 m	25 m	Base topo map
1:25,000	2.5 m	3 m, 7 m	10 m, 20 m	12.5 m	Base topo map
1:10,000	1.0 m	3 m	10 m	5.0 m	City map

Remarks:
1. Height accuracy is one third of the contour interval
2. Pixel size is taken as 0.1 mm on maps
3. Position accuracy is taken as 0.5 mm on maps

Conclusions

3S technologies of GPS, GIS and remote sensing can be integrated to create a powerful complementary tool for real-time mapping, data collection, feature extraction, data modelling, data analyses and data visualisation for watershed, environmental and natural resource management. The ability of GPS technology to define the geographical features to a high degree of positional accuracy has greatly enhanced the value of data for GIS application. Moreover, high-resolution remote-sensing data, such as Quick Bird from Earth Watch, Orb View-1 from Orbital Sciences and CRSS from Space Imaging, 1-m spatial resolution data with stereo-image matching technology, 1:25,000 scale topographic maps with 10-m contour intervals, can be produced. These high-resolution remote-sensing data will enhance the value of data for GIS application. At the same time, visualisation and spatial analyses functions of GIS and three-dimensional information processing technology such as image orientation, image matching, and automated cartography are much improved. In recognising 3S technologies as powerful tools, conventional systems will have to be modified or replaced by these new technologies in order to use geo-informatics effectively in watershed and natural resource management.

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