Hydrology 2020 - Technologies

Technology - *n.* Scientific methods used in a particular field

Collins, Bank of English

Hydrology is a fundamental and diverse subject area; consequently the technologies employed within the hydrological sciences are many and varied. In this overview, hydrological technologies are summarised and the future prospects for new and more powerful technologies are reviewed. Technologies are classified as measurement (ie. providing observations of hydrological variables) and analysis technologies (ie. providing theoretical frameworks within which observations are processed to derive deeper understanding of hydrological processes).

1 MEASUREMENT TECHNOLOGIES

1.1 Introduction

The natural environment displays great variability across the entire range of spatial scales, both in terms of land surface characteristics and climatic regimes. Data to define this variability must therefore play an integral role in hydrological analyses. Traditionally, field measures of hydrological properties and fluxes have tended to be point measures. Recent advances in remote sensing and data availability are also providing new insights into a number of hydrological problems; hence, spatial data are increasingly being used in conjunction with hydrological models. The incorporation of spatial data is not however without complications.

1.2 Traditional hydrologic field measurement

In very general terms, quantitative hydrology is concerned with the estimation of one or more of the terms within the hydrological water balance, at a range of spatial and temporal scales;

$$Q = R - E - \Delta S \qquad (1)$$

where Q is surface discharge, R is rainfall, E is evapotranspiration and ΔS is the change in sub-surface storage. Whilst this equation is an inherently simple mass balance, many practical difficulties arise in the measurement, modelling and prediction of each term. In common, most hydrological measurements are point measures, or at best integrate over a variable but typically unknown area or volume.

1.2.1 Discharge

The prediction of surface discharge is critical for a whole range of applications. Catchment discharge provides surface water for abstraction, maintains many surface ecosystems, and periodically brings devastating floods. Catchment discharge is usually estimated through the installation of a gauging device such as a weir or flume. These relate the water level upstream of the device to the discharge through it. As the derivation of the basic form of this relationship is based on idealised fluid mechanics, the coefficients of the relationship for each device must be calibrated either in the laboratory or *in-situ*. Catchment surface discharge represents a catchment-integrated hydrological flux in that the response of the catchment area should drain through one point (or outlet). In practice, hydrological catchments are typically defined according to surface topography, which may or may not correspond to areas where sub-surface controls may dominate fluxes.

1.2.2 Rainfall

Rainfall might be seen as the starting point of land surface hydrology as all consequent hydrological fluxes are derived from rainfall. Measurement of rainfall has traditionally been achieved by direct sampling of precipitation volumes through the use of raingauges. Whilst a variety of designs of gauge exists, they all represent essentially point measures.

1.2.3 Evapotranspiration

The understanding of evapotranspiration is required for estimating catchment losses, vegetative growth, crop yields, the partition of rainfall into surface runoff etc. Evapotranspiration is perhaps the most difficult hydrological flux to measure. Evaporation pans have been devised to provide estimates of potential evaporation. However, they cannot represent vegetative controls on moisture loss. Additionally, the use of pans is complicated by feedbacks with the moisture content of the overlying near-surface atmosphere. If the actual evaporation rate is low, then the atmospheric demand of moisture is high thus elevating pan losses, and *vice versa*. To account for these feedbacks, empirical 'pan coefficients' are employed as corrections.

More recently, Bowen ratio and eddy correlation devices have been devised to measure actual evapotranspiration losses. Whilst these represent a significant improvement on the use of pans, they measure fluxes from an area (or fetch) of between 100 – 1000 m^3 that varies according to wind direction strength and convective stability of the atmospheric boundary layer. While they provide areally-integrated measures, it is clear that significant variability of evapotranspiration may exist within the area of the fetch. This variability may be especially important in that it will determine the available storage, which given rainfall, will determine the occurrence of saturation that is responsible for fast-flowing surface runoff.

Scintillometry…

1.2.4 Storage (sub-surface flows)

Changes in sub-surface storage and groundwater flows are typically measured through direct observation of water levels or contents. In shallow porous media this is usually achieved through installing piezometers at different locations. In deeper groundwater systems, boreholes are sunk from which the water table can be measured. Networks of boreholes provide hydraulic gradients from which groundwater velocities can be inferred. Hydraulic conductivity is estimated through slug (pulse) tests where water is removed (added) and the rate of recovery to the prior level is observed. This provides a measure of conductivity of the media surrounding the borehole.

1.3 Remote sensing

Remote sensing in hydrology is used for the identification and monitoring of relevant features such as snow-covered areas. Depending on the item of interest, processing to extract that feature requires varying levels of interpretation, classification and validation. Traditionally, hydrological science has not been the primary focus in the development of remote sensors and platforms. Consequently, our current ability to exploit remote sensing as a tool for hydrological science is sensor and platform dependent. We are restricted by the sensor's spectral resolution, and monitoring wavelengths as well as the platform's sampling frequency and spatial resolution. In general, the parameters in hydrological models for which RS are currently most commonly used are land-cover and snow-cover extent.

Typical sensors and platforms that have been successfully used to extract vital hydrologic information include, Landsat TM, MSS, NOAA, SPOT, and ERS 2 (land cover/use and vegetation); ERS-1,2, Radarsat, JERS-1, and SSM/I (soil moisture); SPOT ERS-1,2, Radarsat, Landsat TM and MSS (surface water); Nimbus 5 (spring runoff); ERS-1 and JERS-1 (temporal changes in snowmelt and soil moisture); Landsat and Topex-Poseidon, (water depth); NOAA, SPOT, Landsat, and MODIS (snow covered area); GOES, Nimbus7 (snow depth); DMSP, SSMI/I MOS-1 and MSR (snow water equivalent); ERS-1,2, and Radarsat (wet snow); NOAA and Landsat TM (surface temp); Meteor (solar radiation); AVHRR, ERS2, and GOES (surface albedo); NOAA (evapotranspiration); Meteosat, GOES, and SSMI/I (precipitation).

Nearly all the development and testing of algorithms relies on ground based measurements that are generally made at scales of less than a kilometer. Length scales are surface and time dependent. In addition, many hydrological models are not designed to use the type of spatial data provided by remote sensing and the accuracy of variables/parameters derived from remotely-sensed data may be insufficient to warrant the development of new models.

Data fusion which involves combinations of remotely sensed data and other information such as digital terrain models, etc., seem to offer the most promising approaches for the purpose of hydrological modelling.

1.3.1 Remote sensing of rainfall

Remote sensing has been used for decades to provide estimates of precipitation. The GOES precipitation index for example is one of the simplest and most widely used IR indices of precipitation in the tropics and subtropics. Most algorithms dealing in the visible, near infrared and thermal infrared wavelengths utilize information on cloud height and coldness which are both related to the amount of precipitation that is expected from the cloud. Visible and infrared methods for estimating precipitation tend to produce smoothed representations of instantaneous rainfall fields and thus, tend only to be useful over larger spatial or temporal scales. They need to be carefully calibrated for the intended region and season of use.

Alternatively, passive microwave algorithms can lead to the instantaneous estimates of precipitation. There are numerous algorithms that rely on empirically derived functions of the lower frequency passive microwave channels of such sensors as SSM/I. Microwave methods do not represent surface precipitation rates but are actually vertical integrations of rain and/or ice water content in the atmosphere. Poor temporal sampling due to deployment on polar satellites reduces the precision with which short term precipitation can be estimated.

Upcoming developments involve multi-sensor algorithms that attempt to combine the benefits of frequent infrared imagery with the more physically direct detection of precipitation by microwave methods. However, the calibration and validation of satellite based rainfall estimation algorithms are considered unresolved problems. The successful evaluation of these algorithms can only be made if there is an appropriate reference standard and the accuracy of this reference is known. As stated earlier, satellite data are integrated observations of the atmospheric column while rain gauges are point measurements with often, questionable accuracy. Sparse rain gauge networks do not provide sufficient information for realistic representations of rainfall fields and are thus of limited use for calibrating and validating satellite based algorithms for precipitation.

Improvement in the use of remotely sensed estimates of precipitation requires quantifying the sources of errors, which depending on the band region used, may be due to such things as uncertainties in absolute brightness temperature, and the deviation of rain drops from spheres that are not taken into account by the algorithms. Studies have shown that visible and infrared methods are suitable for monthly instead of daily rainfall totals. Passive microwave algorithms with SSM/I observations may or may not perform better than visible/infrared algorithms for instantaneous rain rates but performance tends to be location dependent. Visible/infrared rainfall estimation algorithms have been recommended for estimating climatic scale distributions of convective rainfall often found in tropics and subtropics during warm seasons.

Remotely sensed estimates of precipitation have been successfully used in hydrological modelling when conducting monthly water balance. They have been used operationally as input in hydrological models in the Sudan, Egypt and other places but most of the operational satellite applications for precipitation use visible or infrared wavelengths. Precipitation products are currently available through or sponsored by a variety of agencies including the NOAA, NASA, WMO and NCDC.

1.3.2 Remote sensing of discharge

Discharge is one area where direct measurement using remote sensing is difficult and primarily indirect methods are used. Delineating surface waters can be achieved by using the fact that water absorbs near and middle infrared wavelengths. Microwave sensors are also sensitive to water content and provide all weather viewing. The visible red band can be used to discern stream channel networks, while river levels can be determined using radar altimeters. The accuracy of these river elevations has been estimated at ±10 cm to ±20 cm. Satellites with onboard radar altimeters include Geosat, Seasat, ERS-1 and TOPEX/Poseidon. Few surface-based measurements are currently available for comparison but some studies have shown that for lakes directly crossed by the altimeter track, lake level errors of ±15 cm can be obtained (with ±10 cm being attributed to orbit error). Routine lake level monitoring using radar altimetry is costly and complex and thus, the accuracy achieved may not be worth the expense. Low altitude laser measurements can be used to produce topography, stream channel and gully cross sections and vegetation height, cover and distribution.

1.3.3 Remote sensing of evapotranspiration

Many tasks in hydrology require an accurate representation of how incoming radiant energy is partitioned at the land surface into sensible and latent heat. However, as noted earlier evaporative fluxes are inherently difficult to measure, especially at regional scales and beyond. Evapotranspiration remains the variable with the greatest uncertainty in hydrological water balances because of its significant spatial and temporal variability. Remote determinations of surface temperature, vegetation cover, and upper layer soil moisture are generally the components used to estimate evapotranspiration using remote sensing.

Various land surface models have been developed which describe the physical state of the land surface, the atmospheric boundary layer and the subsurface. The atmospheric forcing variables in these models include radiation, air temperature, humidity and wind speed. Realistic evapotranspiration prediction with such models requires the specification of a range of land surface parameters. However, there is considerable uncertainty associated with such predictions, particularly across regions with spatially varying vegetation, soil and terrain characteristics.

Land surface processes are controlled by a hierarchy of parameters and variables. For example, the estimation of evaporation requires information on the amount of available radiative energy, the type/nature of surface and the presence of water that can be evaporated. Remote sensing can provide insight in the spatial and temporal variability of several key parameters and variables. Remote sensing data can be used to obtain radiation, mapping land use (changes) and vegetation parameters. However, information on the aerodynamic properties of the surface and on near-surface airflow is perhaps more difficult to estimate from remote sensing.

Remotely sensed thermal imagery can be used with surface energy budget models of land surface fluxes over a range of scales. Thermal imagery from a variety of satellites sensors may be used to obtain land surface temperature observations (eg. AVHRR; LANDSAT; SPOT). It is well known that regions of high moisture content or dense vegetation with access to moisture exhibit cooler surface temperatures than dry soil or stressed vegetation. At drier sites, the surface energy balance is dominated by sensible heat exchange, whereas wetter sites are characterized by surface cooling due to evaporation. More precisely, it is the rate of change in surface temperature, which is related to soil moisture availability (surface wetness). This provides an indication of the surface resistance to evapotranspiration from the land surface.

Increased attention has been given to the use of thermal imagery obtained with geostationary meteorological satellite sensors. Such satellites include the Geostationary Operational Environmental Satellite (GOES), the European METEOSAT satellite and the Japanese Geostationary Meteorological Satellite (GMS). These sensors generate denser data streams of thermal and visible imagery than the polar-orbiting NOAA-AVHRR, but they have a coarser spatial resolution.

Significant relationships are known to exist between passive microwave observations and surface temperature. Spatial resolution of passive microwave sensor data are one to two orders of magnitude larger than operationally available infrared sensors; hence, application of passive microwave data for estimating ET may be restricted to regional and global scales. Satellite estimates of net longwave flux at the surface have been developed using sounding data and can be used with the Tiros Operational Vertical Sounder (TOVS) of the NOAA satellites, which contains infrared and microwave sensors. Statistical approaches using slowly varying surface properties such as surface albedo and soil moisture with remotely sensed data can be used to estimate net radiation.

Other techniques use narrow band reflectance data and brightness temperature from aircraft and satellite-based platforms for estimating the upwelling radiation components. In addition, numerous studies have found a significant negative correlation between *NDVI* and radiant temperature over different surfaces. However, this assumes complete canopy cover which may not be naturally occurring. Humidity profiles can be retrieved by measurements in the 183 GHz range. This has been exploited by the SSM/T2 sensor on the DMSP satellites.

1.3.4 Remote Sensing of Soil Moisture

Research in the microwave remote sensing domain has offered some promise of delivering distributed data sets of moisture data useful in model calibration and testing. However, several problems exist. The accuracy of estimated absolute soil moistures is complicated by factors such as differences in soil characteristics, surface roughness (especially vegetation type and density), and topography. A further problem is that microwave remote sensing, even in ideal conditions, can detect soil moisture fields only in the uppermost few centimetres of the soil, whereas hydrological models typically simulate variable moisture contents over deeper layers. Although continuing attempts are being made to derive relationships between surface soil moisture and the profile in deeper layers, both runoff generation and evapotranspiration are predominantly controlled by the moisture content at deeper layers. Further limitations result from the reduced sensitivity of the radar signal to soil moisture changes close to saturation and the specular nature of the signal in areas where water becomes ponded leading to decreases in the backscattering coefficient. Studies have also shown that freezing and thawing can cause problems in the estimation of soil moisture. Research using C-band from SAR images or truck-mounted scatterometers working in L and X-band is still on going.

The problems of deriving surface roughness for ***active*** microwave remote sensing are significant. It is also apparent that even if robust measurements could be achieved, the worth of surface measures, as opposed to profile (depth-integrated) measures, remains questionable.

Also, use of ***passive*** microwave for assimilation of soil moisture into landsuface-atmospheric models…

The passive microwave region, particularly around 21 cm wavelength has been reported as the most exploited band thus far for the estimation of soil moisture content. Moisture content can be measured to a depth of about 50 mm. The potential of microwave passive sensors in soil moisture measurement has been demonstrated and operational systems have been tested in the U.S.S.R. where maps with four levels of soil moisture have been obtained using a two frequency airborne sensor at 1.0 and 1.7 GHz.

Again, data combination and fusion provides the best approach for improving the use of both active and passive microwave sensors for soil moisture estimation. For example: a combination of airborne active microwave (C-band) and passive thermal infrared remote sensing has been shown to improve estimates of soil moisture to root zone depths.

1.3.5 Remote sensing of floodplain inundation

Hydrological research has sought to develop numerical models of water flow to predict the extent of flood inundation area associated with a given magnitude of flow. A key control on flow and inundation depth is the local roughness coefficient (Manning’s coefficient). However this empirical factor is subject to considerable uncertainty. To apply flood inundation models therefore requires calibration against available data. This is usually achieved using discharge data measured at occasional points along the reach of interest (where available).

In application, after calibration against point flow data, the models perform accurately in reproducing the flow volume characteristics. However, the spatial extent of flood inundation is often poorly reproduced. Recent work has demonstrated the worth of remotely sensed spatial data, particularly in correcting the model simulations of inundation extent. Using RADARSAT synthetic aperture radar data coinciding with flood events, flood inundation model may be calibrated to the measured areal extent to the flood.

Spatial data tend to contain more information than point data because of their higher dimensionality (2-D against 0-D), but this is often partially offset by the temporal nature of the point data. Discharge measurements are generally recorded as functions of time, whereas many spatial data sets (e.g. remotely sensed ones) are synoptic views, offering an observation at only one instant. In this sense we would expect conditioning against spatial and point data to provide information on two different aspects of model behaviour: spatial and temporal. Some degree of correlation between these behaviours is often assumed, for example, when predictions of inundated area from a model conditioned against point data are used. In this respect, there is a reliance on the model conditioned on one aspect of its behaviour to effectively reproduce another.

Floodplain models conditioned on discharge data alone exhibit a higher degree of prediction uncertainty when the inundated area is considered, when compared to models conditioned on the satellite sensor data itself. This emphasises an important aspect of the behaviour of these models: their complex response to their parameterisation means that models calibrated to one data set are not necessarily the best predictors of other observable features of the flood (i.e. inundation area). The incorporation of the spatial inundation data can be seen to increase the accuracy of the predictions of the model, thus providing greater confidence in its application.

Flood mapping needs real-time coverage and unfortunately, clouds are frequently present when floods occur. As a result, current research is focusing on the use of satellite-based radar to provide high resolution, all-weather coverage at the time of flooding. Active and passive microwave data have been used to monitor flooding: Merged SAR data from ERS-1 with multispectral data from Landsat and SPOT were successfully used to monitor the 14 July 1993 floods in St Louis, USA.

1.3.6 Future Sensing Platforms

New missions for covering a wide range of hydrological parameters include TRMM, AMSU, GOMS VISSR (precipitation), HYDROSTAR (soil moisture) MODIS, MIROS on the SMOS mission.

1.4 Subsurface tomography

ERT
XRT
???

2 ANALYSIS TECHNOLOGIES

2.1 Introduction

flood frequency analysis
flow duration
empirical regionalisation relationships
idf

2.2 Computers and Hydrology

Computer
- gis
- rs
- simulation modelling

2.3 Geographic Information Systems

Geographic Information Systems provide powerful platforms on which typically point hydrological measures can be collated and viewed within a spatial and multivariate framework. This enables rapid generation and analysis of derived spatial fields. For instance, point raingauges can be plotted in relation to the topographic features of a study catchment. Through the use of interpolation techniques such as thin-plate splines or other geostatistical methods, a continuous field of rainfall characteristics can be derived utilising the observed relationship between rainfall and topography.

GIS is used in hydrology in several ways including: (1) data visualization; (2) parameter estimation; and (3) modelling. Terms used to describe the types of hydrological data determined through GIS include *topographic data,* which are used to describe the topography of a region, topographically derived attributes known as *topological data* such as watershed area, flow lengths, land slope, and stream network, that are somehow derived from the topographic source data; and *thematic data* such as soil type, land cover, geological formations, and precipitation. Attributes derived from thematic data may include SCS curve numbers and other indices of runoff.

Possibly the most important spatial data within GIS frameworks have been Digital Terrain Models (DTMs). DTMs were originally built through the collation of point measures of elevation obtained through traditional manual surveying techniques. The advent of remote sensing devices, such as airborne laser altimetry (LiDAR), has meant that high resolution DTMs can be obtained for almost any study area. The ready availability of digital terrain models enables simple, routine delineation of surface catchment boundaries, drainage networks and flow paths. DTMs have been put to many other uses within hydrology including the estimation of relative moisture content based on topographic controls. Many GIS packages now included automated algorithms for typical hydrological applications.

2.4 Hydrologic modelling

The historical development of hydrological models has been primarily influenced by data availability and computer constraints. Nevertheless, there is a plethora of hydrological models due in part to the application specific nature of many of these models (example, urban hydrology versus forest hydrology). This application specific quality is primarily due to the inherent complexity of hydrological systems. In most classification systems of hydrological models, there are two branches at the most basic level: deterministic models and stochastic models. Once considered distinct branches, hydrological modelers are now realizing that successful hydrological modelling will involve aspects of both branches.

2.4.1 Deterministic Hydrological Models: Empirical, Conceptual and Physically-Based Models

The empirical model uses non-physical parameters to modify a given input to some output. Also referred to as black-box models, they tend to have few parameters making them convenient to use and easy to calibrate. However, empirical models need long meteorological and hydrological records for calibration that are not always available; and because of the non-physical nature of the parameters used in these models, it is difficult to assess whether a calibrated parameter is appropriate since it cannot be measured in the field. Conventional models in engineering hydrology for predicting runoff generation are primarily composed of black-box concepts such as baseflow separation and unit hydrograph techniques.

A quasi-physically based model, also known as a *conceptual model*, represents middle-ground between empirical models and physically-based models. They have the convenience of only having to calibrate a few parameters, yet the parameters retain some physical meaning because the model has reduced the real system to a few basic physical principals that are representative of the system.

At the other end of the spectrum is the *physically-based* model. A physically-based model is a type of model that simulates processes using equations derived from the physics governing the system and fundamental physical laws. This tends to make physically-based models naturally more attractive when compared to empirical models. The parameters have physical meaning and can theoretically be measured in the field. The models are generally very complex and involve numerous parameters. However, the use of these models and their appropriateness has recently come into question as the theoretical advantages of physically-based models remain unproven in practice and that there is a tendency for users to give rise to “uncritical believe” in their predictions.

Physically-based models are, like empirical models, simplified representations of reality and may imply a false sense of accuracy and confidence in the user.

2.4.2 Lumped vs Distributed Modelling

The most conventional and basic modelling unit in hydrology is the subbasin, which may be considered a hydrologic response unit over which all attributes are averaged. A *lumped* application assumes a homogeneous distribution of input values or basin characteristics. *Fully-distributed* models however, account for most or all the important heterogeneity that exists in the system by discretizing the system into individual units. Within these units, basin characteristics and inputs are treated in a lumped way. The distinction between lumped parameter and distributed models is not as clear as might be desired, because the subbasin may be taken to be arbitrarily large or small.

Due to their nature, black-box or empirical models often involve lumped applications. Predictions resulting from lumped applications may compromise model accuracy because the averaging process may ignore important heterogeneity in the system. An example of a lumped parameter model is the Unit Hydrograph method in which the 'lumped parameter' is the time of concentration, which is held constant for all storms.

Many physically-based models employ a fully-distributed approach which means that a great deal of data is required to run the model. Fully-distributed, physically-based models have benefited from the increase in computer technology and the invention of Geographic Information Systems (GIS). The full benefits of fully-distributed, physically-based modelling are rarely realized due to a lack of data availability. In addition, all data will have some degree of error and as the amount of data required by a model increases, the greater the effect of compounded errors.

2.5 analysis techniques

2.5.1 time series analysis
2.5.2 Artificial Neural Nets
2.5.3 Bayesian analyses
2.5.4 Uncertainty and Fuzzy concepts
others…