Indian Journal of Science and Technology, *Vol 10(17), DOI: 10.17485/ijst/2017/v10i17/111541, May 2017*
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Applications of Remote Sensing, Hydrology and Geophysics for Flood Analysis

Mohd Talha Anees[1*], K. Abdullah[1], M. N. M. Nawawi[1], Nik Norulaini Nik Ab Rahman[2], Abd. Rahni Mt. Piah[3], M. I. Syakir[4], A. K. Mohd. Omar[4] and Kaizar Hossain[5]

[1]School of Physics, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia; talhaanees_alg@yahoo.in, khirudd@usm.my, mnawawi@usm.my
[2]School of Distance Education, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia; norulain@usm.my
[3]School of Mathematics, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia; arahni@usm.my
[4]School of Industrial Technology, Universiti Sains Malaysia, 11800, Minden, Penang, Malaysia; misyakir@usm.my, pultexsb@yahoo.com
[5]Detartment of Environmental Science, PACE Institute of Technology and Sciences, Ongole – 523272, Andhra Pradesh, India; kaizar.kaizar@gmail.com

Abstract

Objective: To propose an integrated approach for flood analyses in order to understand the causes and effects of flooding, and to achieve better measurements in flood risk predictions and mitigation. **Method:** The role of remote sensing, hydrology and geophysical methods in determining and selection of input and model parameters in hydrological modeling for flood analyses were discussed. **Findings:** Remote sensing and GIS are found to be important in any preliminary flood analysis while hydrological parameters such as precipitation, infiltration, evapotranspiration and runoff and their factors such as meteorological characteristics, land use land cover changes, types of vegetation and soil properties play a crucial role for accurate hydrological modelling. In hydrogeological investigation, geophysical methods such as Transient Electromagnetic and Resistivity methods are found best for the determination of subsurface hydrological factors such as hydraulic conductivity, porosity and permeability. **Improvement:** It is found that the combination of these methods can furnish precise flood analyses through modeling techniques.

Keywords: Flooding, Geographic Information System, Geophysical Methods, Hydrology, Remote Sensing

1. Introduction

Natural hazards are inescapable events that result from a combination of natural, geological and anthropogenic disturbances. According to United Nation's report[1], since 1995, floods accounted for 47 percent of all weather-related disasters, affecting 2.3 billion people, killing 1.57 lacs and damages about US$19.3 billion and US$0.83 billion for Asia and Africa respectively[2]. Flooding is one of the main natural hazards and occurs frequently all over the world[3] especially in Asia and Africa than other countries. Flooding causes such devastation as a result of increased settlement along levees, unexpected high rainfall[4], deforestation[5], river channel changes[6], and sediment deposition[7,8].

The complex processes of river and floodplain have been assessed through numerical modeling by several researchers which can provide spatial and temporal changes over large areas and simplification of a complex reality[9,10]. However, the modeling techniques also have some uncertainties which effect accuracy and efficiency of numerical models[11,12] mentioned some uncertainties in hydrological modelling which include uncertainties in input and model parameters. Meteorological and hydrological components such as precipitation, temperature, wind characteristics, relative humidity,

** Author for correspondence*

evapotranspiration, infiltration and runoff are one of the basic inputs and model parameters for any hydrological modelling but their poor spatial distribution can affect the model accuracy. For instance, precipitation has uncertainty in its spatial distribution in complex topography because of uplifting air masses by the wind. [13,14]considered precipitation's spacial discontinuity and used different occurrence/non-occurrence estimation approach to improve the spatial distribution of precipitation. The spatial distribution of input and model parameters affects the accuracy of river such as selection of their spacing[15] and channel shape[16].

In this review, input and model parameters are studied with the role of remote sensing, hydrological and geophysical methods, and evaluate their effectiveness. We discuss the flooding parameters, and their related methods which were used in previous flood analysis studies. The aim is to identify the combination of flooding parameters and integrated methods that would lead to improvements in modeling techniques for flood risk assessment and monitoring.

2. The Role of Remote Sensing in Flood Analysis

Any flood-related study requires some initial considerations, namely, the areas to be analyzed, the parameters to be measured during field data collection, the procedure and the actual collection of field data. Remote sensing and GIS play an important role in the initial stages of flood analysis. They are reportedly used over other techniques because of their broad reach in data-sparse environments. Satellite remote sensing provides useful geospatial data and is increasingly being used to expand useful sources of information for a wide array of applications[17,18] while GIS can deliver a synoptic view of large areas which is very useful in analyzing drainage morphometry and spatial-temporal mapping. Remote sensing and GIS are also useful for input data preparation either in data availability or in data-sparse environments[19–21]. Therefore, remote sensing and GIS are both crucial techniques in the initial stages of flood analysis.

Flooding is primarily the result of heavy and continuous rainfall exceeding the absorption capacity of the soil and the flow capacity of river channel and streams. In order to achieve accurate flow magnitudes and water levels, flood models need to use parameters that accurately describe the channel and flood plain geometries[22]. Airborne LIDAR (Light Imaging, Detection, And Ranging) bathymetry (ALB) technology (up to 2.5 m resolution topographical data) has recently been developed, with significant advancements during the past two decades. The recent advancements have allowed for unlimited data collection and better measurements that have greater depth penetration, are free from shadows or surface disturbance error, and are not affected by sun angle and glint on the water surface[23]. Typically, LIDAR based Digital Elevation Model (DEM)is divided into topographic LIDAR and bathymetry LIDAR. Topographic LIDAR uses infra-red laser which is not able to penetrate into water while bathymetry LIDAR uses infra-red to detect water surface and green laser to identify under water floor[24] which is helpful in accurate measurement of river cross-section.

Space-borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) is a freely available data (30 m resolution) source and it can be processed through GIS by converting it into raster and grid formats. However, ASTER GDEM data has vertical errors that are enhanced by the GIS conversion. Therefore, this method is useful to measure the river cross-sections, but only up to water surface level, Figure 1 shows the detailed floodplain information from surveying, when high resolution aerial images are not available[22] but in water depth data must be required if ASTER GDEM is taken into account for bathymetry measurements. Although, LIDAR based DEM are useful in accurate bathymetry measurement because of higher resolution and greater penetration ability in water, the ASTER GDEM can be used for floodplain modeling (which is a basic input in hydrological modeling) to reduce the cost and processing time.

In river modeling, cross-section shape selection is the most important task in data sparse region. Some common shapes such as the trapezoid and rectangular (horizontal bottom), semicircle, parabolic, catenary and semi-cubic parabolic, egg and circular sections (Curved bottom) are generally used in different situations such as the hydraulic, economical, hydrogeological and seepage situations[15]. Curved channel, especially parabolic shape has advantages such as slope stability and lacking of sharp edges[25,26] mentioned that the best hydraulic section is those which are having the least wetted perimeter for a given cross-sectional area has the maximum hydraulic radius. As far as channel cross-section spacing is concern, [27] presented several guidelines for the choice of cross-section and distance between them on the basis of river geometry and flows. [15]investigate the guidelines and their results confirmed the validity of these rules on the optimal spacing between cross sections. They also mentioned different equations for cross-section spacing based on different situations.

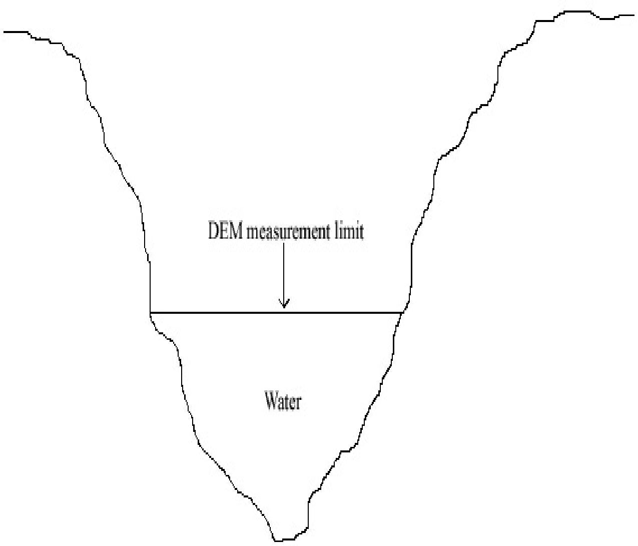

Figure 1. A cross-section showing the limit of DEM measurement.

Many studies have investigated the spatial-temporal changes of the earth surface, which could be used in place of field work data[28–31]. Landsat data, which is freely available in 30 m resolution with 15 m panchromatic (Landsat 7 & 8), has been used to study the spatial-temporal changes in land use/land cover. This data is useful because Landsat sensors records blue, green, and red light along with the near-infrared, mid-infrared, and thermal-infrared light. Landsat data has been used to monitor water quality, glacier recession, sea ice movement, invasive species encroachment, coral reef health, land use change, deforestation rates and population growth. Landsat is also helpful in assessing the damage from natural disasters such as fires, floods, and tsunamis, and subsequently help in planning disaster relief and flood control programs (NASA).

The SPOT program, which consists of a series of optical remote sensing satellites, has been widely used for applications in the areas of agriculture, environmental protection and land use/land cover. SPOT's HRV (High Resolution Visible) and HRVIR (High Resolution Visible IR) instruments provide higher resolution. SPOT-5 is generally used high resolution data because it has advantages over its predecessors. SPOT-5 can cover vast areas in a single pass at high resolution (5 m to 2.5 m), which is a cost-effective imaging solutions (EESA). It has also been used in urban and rural planning[32,33] and natural disaster management[34,35]. Both the Landsat and SPOT instruments are important for providing a long-term series of earth observation data.

3. The Role of Hydrology in Flood Analysis

In hydrological modeling, along with the model inputs, model parameters selection is an important task for researchers. Therefore, in this section, basic flooding parameters and their importance in flooding will be discuss to know the behavior, effect and the controlling factors of these parameters.

3.1 Precipitation

Precipitation is one of the most important variables in hydrological modeling and its dynamic behavior and spacial distribution due to climate changes is a major factor of concern in recent studies. The changes in climatic extremes, especially precipitation extremes, may affect the occurrence, duration, and intensity of floods and droughts[36,37]. The impacts of precipitation, flood and climate change on hydrology have been widely investigated in many watershed studies around the globe[38]. These studies have analyzed the effects of rise in temperature and decrease in rainfall[39,40], seasonal shifting of precipitation and increase in temperature[41,42] and increase in extreme precipitation in different seasons: in winter[43,44], in autumn, winter and spring[45,46] while decrease in summer[44,46,47] studied the trend between extreme precipitation and hydrological floods in Europe, using observations and future climate projections, to estimate impacts of climate change on flood risk. They found potential increase in extreme precipitation in the future, by the climate model projections, and positive and negative changes in the peak flows and flood frequency, by the hydrological projections. Therefore, seasonal shifting of precipitation, extreme precipitation, orographic effect and behavior of meteorological parameters such as wind characteristics, temperature and relative humidity are very important to understand the behavior of precipitation in any region to get accurate results in hydrological modeling.

3.2 Infiltration

Precipitated water first encounters intercepting surfaces, such as foliage and man-made structures, then infiltration starts when surface water interacts with soil or bed rock. It first restores the soil moisture deficiency and then percolates downward by the force of gravity and reaches the water table[48]. During this process soil properties and bed rock properties play an important role in the movement of water. [49]explained in detail the control of soil properties on the spatial-temporal variability of infiltration and soil moisture processes. On the other hand, [50]explained the influence of land use on soil moisture. [51]studied the effects of seasonal variability on soil conditions and subsequently its effect on infiltration. They found that during the winter, low suction field in the soil reduced infiltration and enhanced evaporation, while during the summer, high water-driving gradients in the shallow soils reduced evaporation and increased rainfall infiltration. [52]determined the seasonal infiltration rate in natural and cultivated sandy soil with water repellency due to the soil properties and lime content. They found similar result of greater infiltration in dry condition than wet condition. They also found that calcite is effective in alleviating the water repellency in the tested soils.

Decomposing plant material on the forest floor also plays a crucial role in hydrological processes[53]. Litter (fresh leaves) and duff (fermented humus) are the two layers on the forest floor[54]. Infiltration is also influenced by different slopes, as discussed by[55] in pine and rain forests. Therefore, it can be concluded that land use and land cover change and soil properties are the major factors which affect the rate of infiltration.

3.3 Evapotranspiration

Evaporation loss occurs from free water surfaces (e.g., lake or soil surfaces) and transpiration loss from vegetation. The rate of both are mostly affected by air and water temperature, relative humidity, wind velocity and exposed surface area, and is least affected by barometric pressure and salinity of the water[48]. The evaporative process is primarily driven by radiative and aerodynamic components[56]. The former is related to the energy available to evaporate water, which depends on solar radiation, land surface albedo, air and surface temperatures and vapor pressure. While the latter is related to the capacity of the air to store water, which depends on air temperature, humidity and wind speed[57]. The rate also affected by tall and short vegetation because of their higher aerodynamic conductance in tall vegetation and vice versa[58,59]. As far as soil evaporation is concern, it is dominant in areas with a shallow groundwater table, hot and dry climate, and bare surfaces exposed to sunlight and wind. Soil evaporation can have worsened if the area is composed of a uniform fine-grained soil and has sparse vegetation[60]. The rate of soil evaporation is controlled by atmospheric conditions, if the surface has moisture while the rate of water movement to the surface through the soil profile and the water table in non-moisture surface[61]. Therefore, it can be concluded that meteorological components, soil properties and types of vegetation are the leading factors controlling evapotranspiration. However, it can be hypothesizing that, in case of flash flood simulation, high intensity with long duration of precipitation, evapotranspiration is not an effective parameter in hydrological modeling because radiative and aerodynamic components are negligible during that period.

3.4 Runoff

Surface runoff generation is mainly affected by climatic factors, topography, soil type, land use/land cover, vegetation, existing moisture condition, and infiltration. Climatic factors include types of precipitation, intensity, duration and distribution of precipitation, and intensity and direction of prevailing wind[62–64]. Rainfall spatial variability can control peak runoff discharge at the catchment scale, which depends on the combined influences of rainfall, slope and size of the catchment, and runoff generation processes[65,62,66]. Topography is another important parameter that affects overland flow dynamics. It was found in previous studies that soil saturation is more observed near streams, due to lateral subsurface flows from upslope or groundwater table rise[67,68]. Therefore, it can be concluded that the characteristics of precipitation and topography have a major role in surface water flow while other factors, as mentioned above, are dependent on the characteristics of precipitation and topography.

4. The Role of Geophysical Methods in Flood Analysis

Subsurface investigations are very important in identifying the hydrogeological lcharacteristics such as hydraulic conductivity, porosity, permeability and ground water table that can affect flooding parameters as discussed in previous section. To investigate these, an integrated branch of geophysics, called hydro-geophysics, has evolved in recent years to explore the potential that geophysical methods hold for improving the quantification of subsurface properties and processes relevant for hydrological investigations[69]. Some geophysical methods such as seismic, electrical resistivity, gravity and magnetic methods are generally used to extract subsurface heterogeneity information[70,71]. Seismic and resistivity methods are widely used in hydrogeological investigations[72]. Because of the advantages and disadvantages inherent in individual geophysical methods, data from different geophysical methods should be combined to increase the accuracy of the data[73,74]. So in the following section, these two methods, which are useful in identifying accurate hydrological flood affecting parameters, will be discussed.

4.1 Seismic Method

A simple subsurface requires measurements from a few monitoring wells, in order to describe the groundwater level over a large area. However, a complex subsurface needs closely spaced monitoring wells, which is expansive or almost impossible[75]. To measure the shallow groundwater level, [75] applied integrated electromagnetic and seismic surveys in an arid environment. They found that common mid-point seismic reflection and refraction methods integrated with shallow piezometer control, provided detailed subsurface information and measured the ground water level with an error less than 5 m.[76] applied high-resolution seismic reflection methods to know the pre-conditions for landslides. They found that a profile with a highly permeable sandy-silty layer, which can infiltrate surface water through it, situated between quick clay layers and then bedrock is a pre-condition for landslides. They showed how high-resolution reflection techniques can be used to determine such detailed structures.

4.2 Electrical Resistivity Methods

Electrical resistivity methods such as electrical resistivity (ER), induced polarization (IP), electromagnetic induction (EMI), ground penetrating radar (GPR), and time-domain reflectometry (TDR), are generally used in engineering and hydro-geophysical high resolution investigations of the subsurface structure and electrical properties[77,69]. Theoretical and empirical discussion is beyond the scope of this paper, instead the use of these methods in estimating hydrogeological subsurface condition will be discussed.

Subsurface heterogeneity, which exhibits electrical properties of the subsurface material, affects the potential difference. ER tomography alone or in combination with other geophysical methods is widely used in hydrogeological investigations, such as porosity and hydraulic conductivity[78,79], groundwater studies[80,81] and subsurface fissure mapping[82,83,79] used Vertical Electrical Sounding (VES) with a Schlumberger array to determine the porosity and hydraulic conductivity of an aquifer and then correlated the results with Kozeny–Archie equations for porosity, Ohm's–Darcy's laws for hydraulic conductivity and pumping test results. They found that bulk resistivity changes can be imaged as the moisture content varies and that saturated hydraulic conductivity ranges from 3 to 9 cm/day.

Subsurface fissures and cracks can affect the hydraulic conductivity of the soil. [82]used a 3D inversion method of ERT to locate subsurface fissure networks. They found that the method can predict individual fissures and their depth in the subsurface, and that the Schlumberger method is better for fissure network mapping. Furthermore,[84,85] introduced new inversion algorithms to improve their results.

Time-lapse ERT is an emerging technique to monitor dynamic processes occurring in the shallow subsurface[80,85,86]. [80] used time-lapse ERT to improve the mapping of dense non-aqueous phase liquids by using horizontal boreholes instead of vertical ones. They found that a high resolution image could be achieved by a S2HB ERT configuration in horizontal boreholes. [86]applied this technique in leachate injection monitoring with a new methodology called MICS (multiple inversions and clustering strategy), which improved some of the limitations encountered by previous studies. [87]used time lapse ERT in watershed characterization.

In Induced Polarization (IP), both resistivity and conductivity of the soil are measured using multi-electrode arrangements in either the time-domain or the frequency-domain. IP is widely used in exploration of ore bodies and groundwater (USEPA). It is not widely used in hydro-geophysical investigations. Some hydro-geophysical studies used IP with other geophysical methods to get better results[88–90]. [91] discussed the use of multiple arrays with other conventional arrays to improve the image resolution of geoelectrical and IP surveys.

Ground Penetrating Radar (GPR), a high resolution geophysical technique used to measure subsurface heterogeneity by passing ElectroMagnetic (EM) waves through the subsurface. This technique is used by many researchers either alone or in combination with other geophysical techniques as per the suitability of the investigation. [92]used GPR with a Complex Refraction Index Model (CRIM), which is helpful in direct measurement of water table depth, to detect the macro-porosity in unsaturated lime stone. [93]applied the same technique to detect porosity in an aquifer and found that between two acquisition modes of GPR, common offset and common midpoint; common offset has several advantages over common midpoint. A study by [94]used ERI and GPR to detect cavities and solution features, which affect the groundwater flow direction, 4 - 9 m below the water table. [95] used GPR with a data analysis algorithm called AutoRegressive Moving Average (ARMA) to detect the varying values of compactness and moisture contents in sandy loam. They found that GPR is an effective method in this application, with the advantage of speedy and efficient measurement collection. In another study, [96]used GPR with Frequency Domain Reflectometry (FDR) and a different data analysis algorithm, to estimate the spatial-temporal changes in surface soil moisture content along a hill slope. [97]also used GPR to measure the spatial variation of the moisture content in the active layer. They were able to improve the vegetation cover information and estimate the depth of the cryoturbated soil water content.

Geophysical methods are able to detect surface water and groundwater interactions. [98]used joint analysis of EM and GPR to find fractures in the presence of dissolution-enhanced features and found that the combination of methods improved the results, compared to previous studies. In the same study, [98]used GPR and EMI to understand the complex surface water and groundwater interactions and found that these methods are effective in exploring the bedrock river system and detecting fracture zones. Other researchers, such as[99], used ERT and GPR to detect the geological information, such as fracture and stratification orientations.

The time-domain electromagnetic method that uses inductive loop sources is known as the Transient Electromagnetic (TEM) method[100]. Due to its simple and economical use, TEM is used by many hydro geologists for groundwater exploration[101]. [100]used TEM surveys to analyze the quaternary sediment deposits in an aquifer, over a 55 m deep. [102] used TEM in shallow-depth studies to investigate the advantages and disadvantages of electrical induction methods, and found that it has good sensitivity to heterogeneity at depth, but reduces the useful signal at an early stage. [103]estimated the maximum depth of penetration of transient electromagnetic soundings by using 10 x 10 m to 400 x 400 m loop sizes. They found that the maximum depth of penetration was deeper than the deepest interface estimated from the inversion of the data.

Based on the above assessment of all the geophysical methods used in hydrogeological investigations, TEM is considered the best method in achieving accurate measurements, in terms of deeper penetration and economy. Resistivity methods would be the next best method after TEM. However, the use of these methods depends on the topographical conditions. For example, it is more difficult to use resistivity methods than TEM in areas where the topography is dynamic (has high slope).

5. Conclusion

Integrated methods of remote sensing and GIS, hydrology and geophysical methods were investigated for the measurement and identification of input and model parameters and their factors in hydrological modeling to simulate accurate flood analysis. In this study, it found that remote sensing and GIS are important tools for the initial study of flood analysis and can facilitate the future planning. Remote sensing and GIS also helps to detect accurate spatio-temporal changes with high resolution data and parameters estimation and have greater use in data sparse environments. Bathymetry and topographic LIDAR based DEMs are best to measure river-cross sections and floodplain data which are the basic input in grid based river and floodplain modeling techniques. Hydrological parameters such as precipitation, infiltration evapotranspiration and runoff with their effecting factors were discussed in this review and found that intensity and duration of precipitation, land use land cover changes, soil properties, types of vegetation and meteorological parameters should be used as input in hydrological modelling and these also used in model parameter identification. Furthermore, geophysical methods were investigated for the identification of best method for subsurface hydrogeological parameter measurement. Resistivity and TEM were found to be the best methods for subsurface hydrogeological investigations, due to their greater depth penetration, ease in use and their ability to detect changes in saturated regions. These methods can provide data for a small area. Finally, all the above information can be used as inputs for model parameter selection in modeling techniques which can provide accurate causes and effects of flooding.

6. Acknowledgement

We gratefully acknowledge the School of Physics and School of Industrial Technology of University Sains Malaysia for providing the required research facilities for this work. We are also thankful to the reviewers of this paper for reviewing the paper and providing their valuable suggestions. We would also like to acknowledge University Sains Malaysia for providing the financial support through grant 203/PJJAUH/6764002 to carry out this work.

7. References

1. The human cost of weather related disasters [Internet]. [cited 2016 Feb 09]. Available from: Crossref.
2. Nkwunonwo UC, Malcolm W, Brian B. Flooding and flood risk reduction in Nigeria: Cardinal gaps. Journal of Geography and Natural Disasters. 2015; 5(1):136.
3. International strategy for disaster reduction. Global assessment report on disaster risk reduction: Risk and poverty in a changing climate Invest today for a safer tomorrow; 2009.
4. Sidek LM, Nor MM, Rakhecha PR, Basri H, Jayothisa W, Muda RS, Ahmad MN, Razad AA. Probable Maximum Precipitation (PMP) over mountainous region of Cameron Highlands-Batang Padang Catchment of Malaysia. IOP Conference Series: Earth and Environmental Science. IOP Publishing. 2013; 16(1):1–4. Crossref
5. Ismail MH, Othman CKACK, Malek IAA, Abdullah SA. Land use trends analysis using SPOT 5 images and its effect on the landscape of Cameron Highlands, Malaysia. Designing Low Carbon Societies in Landscapes. Springer; 2014. p. 223–38.
6. Kamarudin MKA, Toriman ME, Rosli MH, Juahir H, Aziz NAA, Azid A, Zainuddin SFM., Sulaiman WNA. Analysis of meander evolution studies on effect from land use and climate change at the upstream reach of the Pahang River, Malaysia. Mitigation and Adaptation Strategies for Global Change. 2015; 20(8):1319–34. Crossref
7. Ghani AHA, Lihan T, Rahim SA, Musthapha MA, Idris WMR, Rahman ZA. Prediction of sedimentation using integration of RS, RUSLE model and GIS in Cameron Highlands, Pahang, Malaysia. In the 2013 UKM FST Postgraduate Colloquium: Proceedings of the Universiti Kebangsaan Malaysia, Faculty of Science and Technology 2013 Postgraduate Colloquium, AIP Publishing. 2013; 1571(1):543–8. Crossref
8. Teh SH. Soil erosion modeling using RUSLE and GIS on Cameron highlands, Malaysia for hydropower development. University of Iceland; 2011.
9. Dimitriadis P, Tegos A, Oikonomou A, Pagana V, Koukouvinos A, Mamassis N, Koutsoyiannis D, Efstratiadis A. Comparative evaluation of 1D and quasi-2D hydraulic models based on benchmark and real-world applications for uncertainty assessment in flood mapping. Journal of Hydrology. 2016; 534:478–92. Crossref
10. Bladé E, Gómez-Valentín M, Dolz J, Aragón-Hernández JL, Corestein G, Sánchez-Juny M. Integration of 1D and 2D finite volume schemes for computations of water flow in natural channels. Advances in Water Resources. 2012; 42:17–29. Crossref
11. Chen AS, Evans B, Djordjević S, Savić DA. A coarse-grid approach to representing building blockage effects in 2D urban flood modelling. Journal of Hydrology. 2012; 426:1–16. Crossref
12. Engeland K, Steinsland I, Johansen SS, Petersen-Øverleir A, Kolberg S. Effects of uncertainties in hydrological modelling. A case study of a mountainous catchment in Southern Norway. Journal of Hydrology. 2016; 536:147–60. Crossref
13. Hwang Y, Clark M, Rajagopalan B, Leavesley G. Spatial interpolation schemes of daily precipitation for hydrologic modeling. Stochastic environmental research and risk assessment. 2012; 26(2):295–320. Crossref
14. Castro LM, Gironás J, Fernández B. Spatial estimation of daily precipitation in regions with complex relief and scarce data using terrain orientation. Journal of Hydrology. 2014; 517:481–92. Crossref
15. Castellarin A, Di Baldassarre G, Bates PD, Brath A. Optimal cross-sectional spacing in Preissmann scheme 1D hydrodynamic models. Journal of Hydraulic Engineering. 2009; 135(2):96–105. Crossref
16. Han YC. Horizontal bottomed semi-cubic parabolic channel and best hydraulic section. Flow Measurement and Instrumentation. 2015; 45:56–61. Crossref
17. Bhaskaran S, Paramananda S, Ramnarayan M. Per-pixel and object-oriented classification methods for mapping urban features using Ikonos satellite data. Applied Geography. 2010; 30(4):650–65. Crossref
18. Mahmoud A, Elbialy S, Pradhan B, Buchroithner M. Field-

based landcover classification using TerraSAR-X texture analysis. Advances in Space Research. 2011; 48(5):799–805. Crossref
19. Asante KO, Arlan GA, Pervez S, Rowland J. A linear geospatial streamflow modeling system for data sparse environments. International Journal of River Basin Management. 2008; 6(3):233–41. Crossref
20. Artan G, Gadain H, Smith JL, Asante K, Bandaragoda CJ, Verdin JP. Adequacy of satellite derived rainfall data for stream flow modeling. Natural Hazards. 2007; 43(2):167–85. Crossref
21. Hughes D. Comparison of satellite rainfall data with observations from gauging station networks. Journal of Hydrology. 2006; 327(3):399–410. Crossref
22. Gichamo T, Popescu I., Jonoski A, Solomatine D. River cross-section extraction from the ASTER global DEM for flood modeling. Environmental Modelling and Software. 2012; 31:37–46. Crossref
23. Hilldale RC, Raff D. Assessing the ability of airborne LiDAR to map river bathymetry. Earth Surface Processes and Landforms. 2008; 33(5):773–83. Crossref
24. Quadros ND, Collier PA, Fraser CS. Integration of bathymetric and topographic LiDAR: A preliminary investigation. Remote Sensor and Spatial Information Science. 2008; 37:1299–304.
25. Easa SM. Improved channel cross section with two-segment parabolic sides and horizontal bottom. Journal of Irrigation and Drainage Engineering. 2009; 135(3):357–65. Crossref
26. Vatankhah AR. Semi-regular polygon as the best hydraulic section in practice (generalized solutions). Flow Measurement and Instrumentation. 2014; 38:67–71. Crossref
27. Samuels PG. Cross-section location in one-dimensional models. In 2nd International Conference on River Flood Hydraulics; 1990. p. 339–50.
28. Hutchinson J, Jacquin A, Hutchinson S, Verbesselt J. Monitoring vegetation change and dynamics on US Army training lands using satellite image time series analysis. Journal of Environmental Management. 2015; 150:355–66. Crossref
29. Scullion JJ, Vogt KA, Sienkiewicz A, Gmur SJ, Trujillo C. Assessing the influence of land-cover change and conflicting land-use authorizations on ecosystem conversion on the forest frontier of Madre de Dios, Peru. Biological Conservation. 2014; 171:247–58. Crossref
30. Al-Bakri JT, Duqqah M, Brewer T. Application of remote sensing and GIS for modeling and assessment of land use/cover change in Amman/Jordan. Journal of Geographic Information System. 2013; 5(5):509. Crossref
31. Eisakhani M, Malakahmad A. Water quality assessment of Bertam River and its tributaries in Cameron Highlands, Malaysia. World Applied Sciences Journal. 2009; 7(6):769–76.
32. Jebur MN, Mohd Shafri HZ, Pradhan B, Tehrany MS. Per-pixel and object-oriented classification methods for mapping urban land cover extraction using SPOT 5 imagery. Geocarto International. 2014; 29(7):792–806. Crossref
33. Duro DC, Franklin SE, Dubé MG. A comparison of pixel-based and object-based image analysis with selected machine learning algorithms for the classification of agricultural landscapes using SPOT-5 HRG imagery. Remote Sensing of Environment. 2012; 118:259–72. Crossref
34. Gallo F, Lavé J. Evolution of a large landslide in the High Himalaya of central Nepal during the last half-century. Geomorphology. 2014; 223:20–32. Crossref
35. Hirschboeck K, Ely L, Maddox R. Hydroclimatology of meteorologic floods. Inland Flood Hazards: Human, Riparian and Aquatic Communities; 2000. p. 39–72. Crossref
36. Zin MHM, Ahmad B. Assessment of forest encroachment using remote sensing technique. Case Study: Mentigi Forest Reserve, Cameron Highlands. Jurnal Teknologi. 2015; 73(5):33–7.
37. Mirza MMQ, Warrick R, Ericksen N. The implications of climate change on floods of the Ganges, Brahmaputra and Meghna rivers in Bangladesh. Climatic Change. 2003; 57(3):287–318. Crossref
38. Santos R, Fernandes LS, Moura J, Pereira M, Pacheco F. The impact of climate change, human interference, scale and modeling uncertainties on the estimation of aquifer properties and river flow components. Journal of Hydrology. 2014; 519:1297–314. Crossref
39. Narisma GT, Foley JA, Licker R., Ramankutty N. Abrupt changes in rainfall during the twentieth century. Geophysical Research Letters. 2007; 34(6):710. Crossref
40. Taylor CM, Lambin EF, Stephenne N, Harding RJ, Essery RL. The influence of land use change on climate in the Sahel. Journal of Climate. 2002; 15(24):3615–29. Crossref
41. Boyer C, Chaumont D, Chartier I, Roy AG. Impact of climate change on the hydrology of St. Lawrence tributaries. Journal of Hydrology. 2010; 384(1):65–83. Crossref
42. Steele-Dunne S, Lynch P, McGrath R., Semmler T, Wang S, Hanafin J, Nolan P. The impacts of climate change on hydrology in Ireland. Journal of Hydrology. 2008; 356(1):28–45. Crossref
43. Kyselý J, Beranová R. Climate-change effects on extreme precipitation in central Europe: uncertainties of scenarios based on regional climate models. Theoretical and Applied Climatology. 2009; 95(3–4):361–74. Crossref
44. Zolina O. Changes in intense precipitation in Europe. Changes in Flood Risk in Europe, IAHS Special Publication. 2012; 10:97–120. Crossref
45. Osborn TJ, Hulme M, Jones PD, Basnett TA. Observed trends in the daily intensity of United Kingdom precipitation. International Journal of Climatology. 2000; 20(4):347–64. Crossref
46. Jones MR, Fowler HJ, Kilsby CG, Blenkinsop S. An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. International Journal of Climatology. 2013; 33(5):1178–194. Crossref
47. Madsen H, Lawrence D, Lang M, Martinkova M, Kjeldsen T. Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. Journal of Hydrology. 2014; 519:3634–50. Crossref
48. Raghunath HM. Hydrology: Principles, analysis and de-

sign. New Age International; 2006.
49. De Lannoy GJ, Verhoest NE, Houser PR, Gish TJ, Van Meirvenne M. Spatial and temporal characteristics of soil moisture in an intensively monitored agricultural field (OPE 3). Journal of Hydrology. 2006; 331(3):719–30. Crossref
50. Zucco G, Brocca L, Moramarco T, Morbidelli R. Influence of land use on soil moisture spatial–temporal variability and monitoring. Journal of Hydrology. 2014; 516:193–9. Crossref
51. Rianna G, Pagano L, Urciuoli G. Investigation of soil–atmosphere interaction in pyroclastic soils. Journal of Hydrology. 2014; 510:480–92. Crossref
52. Orfánus T, Dlapa P, Fodor N, Rajkai K, Sándor R, Nováková K. How severe and subcritical water repellency determines the seasonal infiltration in natural and cultivated sandy soils. Soil and Tillage Research. 2014; 135:49–59. Crossref
53. Keith D, Johnson E, Valeo C. A hillslope forest floor (duff) water budget and the transition to local control. Hydrological Processes. 2010; 24(19):2738–51. Crossref
54. Keith D, Johnson E, Valeo C. Moisture cycles of the forest floor organic layer (F and H layers) during drying. Water Resources Research. 2010; 46(7):7529. Crossref
55. Neris J, Tejedor M, Rodríguez M, Fuentes J, Jiménez C.Effect of forest floor characteristics on water repellency, infiltration, runoff and soil loss in Andisols of Tenerife (Canary Islands, Spain). Catena. 2013; 108:50–7. Crossref
56. McVicar TR, Roderick ML, Donohue RJ, Van Niel TG. Less bluster ahead? Ecohydrological implications of global trends of terrestrial near-surface wind speeds. Ecohydrology. 2012; 5(4):381–8. Crossref
57. Azorin-Molina C, Vicente-Serrano SM, Sanchez-Lorenzo A, McVicar TR, Morán-Tejeda E, Revuelto J, El Kenawy A, Martín-Hernández N, Tomas-Burguera M. Atmospheric evaporative demand observations, estimates and driving factors in Spain (1961–2011). Journal of Hydrology. 2015; 523:262–77. Crossref
58. Muzylo A, Llorens P, Valente F, Keizer JJ, Domingo F, Gash JHC. A review of rainfall interception modelling. Journal of hydrology. 2009; 370(1):191–206. Crossref
59. Ringgaard R, Herbst M, Friborg T. Partitioning forest evapotranspiration: Interception evaporation and the impact of canopy structure, local and regional advection. Journal of Hydrology. 2014; 517:677–90. Crossref
60. Stormont JC, Coonrod J. Water depletions from soil evaporation. Identifying technologies to improve regional water stewardship: North-Middle Rio Grande Corridor; 2004. p. 21–2.
61. Brutsaert W. Daily evaporation from drying soil: Universal parameterization with similarity. Water Resources Research. 2014; 50(4):3206–15. Crossref
62. Sarkar R, Dutta S, Dubey AK. An insight into the runoff generation processes in wet sub-tropics: Field evidences from a vegetated hillslope plot. 2015; 128:31–43.
63. Wei W, Jia F, Yang L, Chen L, Zhang H, Yu Y. Effects of surficial condition and rainfall intensity on runoff in a loess hilly area, China. Journal of Hydrology. 2014; 513:115–26. Crossref
64. Shi ZH, Fang NF, Wu FZ, Wang L, Yue BJ, Wu GL. Soil erosion processes and sediment sorting associated with transport mechanisms on steep slopes. Journal of Hydrology. 2012; 454:123–30. Crossref
65. Emmanuel I, Andrieu H, Leblois E, Janey N, Payrastre O. Influence of rainfall spatial variability on rainfall–runoff modelling: Benefit of a simulation approach? Journal of Hydrology. 2015; 531:337–48. Crossref
66. Ferreira CSS, Walsh RPD, Steenhuis TS, Shakesby RA, Nunes JPN, Coelho COA, Ferreira AJD. Spatiotemporal variability of hydrologic soil properties and the implications for overland flow and land management in a peri-urban Mediterranean catchment. Journal of Hydrology. 2015; 525:249–63. Crossref
67. Segond ML, Wheater HS, Onof C. The significance of spatial rainfall representation for flood runoff estimation: A numerical evaluation based on the Lee catchment, UK. Journal of Hydrology. 2007; 347(1):116–31. Crossref
68. Aryal SK, O'Loughlin EM, Mein RG. A similarity approach to determine response times to steady-state saturation in landscapes. Advances in Water Resources. 2005; 28(2):99–115. Crossref
69. Rubin Y, Hubbard SS. Hydrogeophysics, 50. Springer Science & Business Media; 2006.
70. Seth A, Kwasi MP, Antwi GD. Application of electrical resistivity method in groundwater exploration in the fractured crystalline basement aquifers in Buma in the East Gonja District of Northern Ghana. International Journal of Scientific Research and Education. 2014; 2(05).
71. Stummer P, Maurer H, Green AG. Experimental design: Electrical resistivity data sets that provide optimum subsurface information. Geophysics. 2004; 69(1):120–39. Crossref
72. Šumanovac F, Weisser M. Evaluation of resistivity and seismic methods for hydrogeological mapping in Karst terrains. Journal of Applied Geophysics. 2001; 47(1):13–28. Crossref
73. Solberg IL, Hansen L, Rønning JS, Haugen ED, Dalsegg E, Tønnesen JF. Combined geophysical and geotechnical approach to ground investigations and hazard zonation of a quick clay area, mid Norway. Bulletin of Engineering Geology and the Environment. 2012; 71(1):119–33. Crossref
74. Konstantaki L, Carpentier S, Garofalo F, Bergamo P, Socco L. Determining hydrological and soil mechanical parameters from multichannel surface-wave analysis across the Alpine Fault at Inchbonnie, New Zealand. Near Surface Geophysics.2013, 11(4):435-448. Crossref
75. Parks EM, McBride JH, Nelson ST, Tingey DG, Mayo AL, Guthrie WS, Hoopes JC. Comparing electromagnetic and seismic geophysical methods: Estimating the depth to water in geologically simple and complex arid environments. Engineering Geology. 2011; 117(1):62–77. Crossref
76. Malehmir A, Saleem MU, Bastani M. High-resolution reflection seismic investigations of quick-clay and associated formations at a landslide scar in southwest Sweden. Journal of Applied Geophysics. 2013; 92:84–102. Crossref
77. Kearey P, Brooks M, Hill I. An introduction to geophysical

exploration. John Wiley & Sons; 2013.
78. Farzamian M, Santos FAM, Khalil MA. Application of EM38 and ERT methods in estimation of saturated hydraulic conductivity in unsaturated soil. Journal of Applied Geophysics. 2015; 112:175–89. Crossref
79. Niwas S, Celik M. Equation estimation of porosity and hydraulic conductivity of Ruhrtal aquifer in Germany using near surface geophysics. Journal of Applied Geophysics. 2012; 84:77–85. Crossref
80. Power C, Gerhard JI, Tsourlos P, Soupios P, Simyrdanis K, Karaoulis M. Improved time-lapse electrical resistivity tomography monitoring of dense non-aqueous phase liquids with surface-to-horizontal borehole arrays. Journal of Applied Geophysics. 2015; 112:1–13. Crossref
81. Mouhri A, Flipo N, Réjiba F, De Fouquet C, Bodet L, Kurtulus B, Tallec G, Durand V, Jost A, Ansart P, Goblet P. Designing a multi-scale sampling system of stream–aquifer interfaces in a sedimentary basin. Journal of Hydrology. 2013; 504:194–206. Crossref
82. Jones G, Zielinski M, Sentenac P. Mapping desiccation fissures using 3-D electrical resistivity tomography. Journal of Applied Geophysics. 2012; 84:39–51. Crossref
83. Sentenac P, Zielinski M. Clay fine fissuring monitoring using miniature geo-electrical resistivity arrays. Environmental Earth Sciences. 2009; 59(1):205–14. Crossref
84. Kim JH, Tsourlos P, Yi MJ, Karmis P. Inversion of ERT data with a priori information using variable weighting factors. Journal of Applied Geophysics. 2014; 105:1–9. Crossref
85. Karaoulis M, Revil A, Werkema DD, Minsley BJ, Woodruff WF, Kemna A. Time-lapse three-dimensional inversion of complex conductivity data using an active time constrained (ATC) approach. Geophysical Journal International. 2011; 187(1):237–51. Crossref
86. Audebert M, Clément R, Touze-Foltz N, Günther T, Moreau S, Duquennoi C. Time-lapse ERT interpretation methodology for leachate injection monitoring based on multiple inversions and a clustering strategy (MICS). Journal of Applied Geophysics. 2014; 111:320–33. Crossref
87. Miller CR, Routh PS, Brosten TR, McNamara JP. Application of time-lapse ERT imaging to watershed characterization. Geophysics. 2008; 73(3):G7–17. Crossref
88. Doetsch J, Ingeman-Nielsen T, Christiansen AV, Fiandaca G, Auken E, Elberling B. Direct current (DC) resistivity and induced polarization (IP) monitoring of active layer dynamics at high temporal resolution. Cold Regions Science and Technology. 2015; 119:16–28. Crossref
89. Antonov EY, Kozhevnikov N, Korsakov M. Software for inversion of TEM data affected by fast-decaying induced polarization. Russian Geology and Geophysics. 2014; 55(8):1019–27. Crossref
90. Loke M, Chambers J, Ogilvy R. Inversion of 2D spectral induced polarization imaging data. Geophysical Prospecting. 2006; 54(3):287–301. Crossref
91. Aizebeokhai AP, Oyeyemi KD. Application of geoelectrical resistivity imaging and VLF-EM for subsurface characterization in a sedimentary terrain, Southwestern Nigeria. Arabian Journal of Geosciences. 2014; 8(6):4083–99. Crossref
92. Mount GJ, Comas X, Wright WJ, McClellan MD. Delineation of macroporous zones in the unsaturated portion of the Miami Limestone using ground penetrating radar, Miami Dade County, Florida. Journal of Hydrology. 2015; 527:872–83. Crossref
93. Mount GJ, Comas X. Estimating porosity and solid dielectric permittivity in the Miami Limestone using high-frequency ground penetrating radar (GPR) measurements at the laboratory scale. Water Resources Research. 2014; 50(10):7590–605. Crossref
94. Yeboah-Forson A, Comas X, Whitman D. Integration of electrical resistivity imaging and ground penetrating radar to investigate solution features in the Biscayne Aquifer. Journal of Hydrology. 2014; 515:129–38. Crossref
95. Cui F, Wu ZY, Wang L, Wu YB. Application of the ground penetrating radar ARMA power spectrum estimation method to detect moisture content and compactness values in sandy loam. Journal of Applied Geophysics. 2015; 120:26–35. Crossref
96. Tran AP, Bogaert P, Wiaux F, Vanclooster M, Lambot S. High-resolution space–time quantification of soil moisture along a hillslope using joint analysis of ground penetrating radar and frequency domain reflectometry data. Journal of Hydrology. 2015; 523:252–61. Crossref
97. Gacitúa G, Tamstorf MP, Kristiansen SM, Uribe JA. Estimations of moisture content in the active layer in an Arctic ecosystem by using ground-penetrating radar profiling. Journal of Applied Geophysics. 2012; 79:100–6. Crossref
98. Steelman C, Kennedy C, Parker B. Geophysical conceptualization of a fractured sedimentary bedrock riverbed using ground-penetrating radar and induced electrical conductivity. Journal of Hydrology. 2015; 521:433–46. Crossref
99. Carrière SD, Chalikakis K, Sénéchal G, Danquigny C, Emblanch C. Combining electrical resistivity tomography and ground penetrating radar to study geological structuring of karst unsaturated zone. Journal of Applied Geophysics. 2013; 94:31–41. Crossref
100. Simard PT, Chesnaux R, Rouleau A, Daigneault R, Cousineau PA, Roy DW, Lambert M, Poirier B, Poignant-Molina L. Imaging quaternary glacial deposits and basement topography using the transient electromagnetic method for modeling aquifer environments. Journal of Applied Geophysics. 2015; 119:36–50. Crossref
101. Fitterman DV, Stewart MT. Transient electromagnetic sounding for groundwater. Geophysics. 1986; 51(4):995–1005. Crossref
102. Plotnikov A. Evaluation of limitations of the transient electromagnetic method in shallow-depth studies: Numerical experiment. Russian Geology and Geophysics. 2014; 55(7):907–14. Crossref
103. Flores C, Romo JM, Vega M. On the estimation of the maximum depth of investigation of transient electromagnetic soundings: The case of the Vizcaino transect, Mexico. Geofísica Internacional. 2013; 52(2):159–72. Crossref