REVIEWS OF PERSPECTIVES ON CONTEMPORARY APPROACHES AND TECHNIQUES IN FLUVIAL SYSTEMS EVALUATION AND MANAGEMENT

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ABSTRACT

This paper reviews fluvial geomorphology perspectives and methodologies for environmental sustainability by exploring and discussing major concepts, themes, and methodologies. To meet the multidimensional aspect of fluvial geomorphology research, multidimensional approaches are now used. Fluvial geomorphology examines river channel morphology and how it is shaped by fluid flows interacting with erodible or resistant boundaries. Understanding equilibrium conditions and thresholds is key. A systems perspective is needed - any river segment is influenced by upstream and downstream conditions as part of an integrated drainage basin system. Field surveys, mapping, remote sensing, and GIS provide important morphological data on river planform, cross-sections, longitudinal profile features, sediment characteristics, etc. Statistical analysis helps detect spatial patterns and trends. Assessing channel changes over long periods is often necessary to fully understand contemporary fluvial processes and forms. Sediment storage and release causes significant time lags. Major human impacts include land use changes affecting hydrology, sediment budgets, channel boundaries; and infrastructure interrupting continuity. Sustainable management requires addressing root causes. Watershed level processes like water balances, erosion patterns, etc. strongly influence fluvial systems - coordinating river channel and upland catchment interventions is key. Models like SWAT, MIKE-SHE, and ANSWERS simulate hydrological processes but have limitations. They require robust spatial datasets spanning geology, topography, land use, climate, etc. Overall, a multidimensional, scale-conscious, historically contextualized assessment framework is required for evaluating fluvial systems. The review highlights techniques and datasets for such integrated diagnosis.

Keywords: Fluvial processes, Watershed, Geomorphology, Channel, Environments

INTRODUCTION

Fluvial geomorphology examines river channel morphology resulting from the interaction of fluid flow and erodible channel boundary materials (Lindenschmidt & Carr, 2018). Such interactions are highly spatially and temporally variable and involve the processes of sediment entrainment, transport, and deposition. All these occur while the channel boundary maintains a coherent structure by withstanding and adjusting to a wide range of forces which establishes the hydrologic character of a drainage basin (Rumsby and Macklin, 1994). Flow quantity and timing are intrinsic to the ecological integrity of river systems as these parameters are correlated with many critical physicochemical river characteristics such as channel geomorphology, water temperature, water quality, and habitat diversity (Newson, 1992).

Spatiotemporal relationships within river systems are complex and highly heterogeneous (Lindenschmidt and Carr, 2018). Some river systems are in a steady state, maintaining the same dimensional form and location features over long periods. Other river systems exhibit a dynamic equilibrium, outwardly maintaining size and form but progressively changing location over a long time. Threshold behavior has also been observed in some rivers, whereby a small change in either a driving variable or the boundary conditions results in a rapid switch in river characteristics, from one set of dimensions and form to another (Newson, 1992). The characteristics of a river's equilibrium state therefore have extensive and significant implications which understanding requires the long-term and large-scale perspectives developed through fluvial geomorphology assessments.

According to Sear *et.al.* (2003), one of the least understood aspects of fluvial geomorphology practice is the apparent obsession with longer timescales. Why this is so remains unclear, since anyone involved in flood prevention is familiar with the value of historical documents for extending the flood record; and ecological surveyors often lament the lack of longer-term datasets. The main reason for including a longer-term perspective in geomorphological studies is simply that the processes that create the features observed in a river landscape often work slowly, or are responding to events that happened in the past. A full understanding of current river processes and forms must therefore logically extend investigation back in time.

Fluvial processes and forms, shaped by the interaction of water and sediment, are influenced by several common variables across different environments. These variables include discharge, sediment load, channel slope, and channel geometry. Understanding these variables is crucial for assessing fluvial systems and various methods, techniques, and approaches are employed for evaluation. These include field measurements such as stream gauging, sediment sampling, and geomorphic surveys, as well as remote sensing technologies like LiDAR and aerial photography. Additionally, numerical modeling, laboratory experiments, and historical data analysis contribute to comprehensive assessments of fluvial processes and forms, aiding in effective management and mitigation strategies for river systems.

EVALUATION OF RIVER AND FLUVIAL SYSTEMS

Understanding how a stream works, how it relates to other systems (natural and artificial), and how it relates to the entire watershed defines the core of knowledge necessary for designing a successful monitoring plan and interpreting the data properly.

Systems Approach

It is natural to focus on a segment or extent of a particular channel of interest when evaluating rivers. What is however forgotten is that the channel is part of a network that influences how it works (Abdulazeez, 2018). Whereas the reach-specific perspective may appear to be a logical approach, it will invariably prove to be insufficient for most purposes. Any segment of a river must be recognized as being a part of an integrated system; the characteristics and dynamics of a segment of interest will be significantly affected by circumstances prevailing in the drainage basin upstream of the reach and may also be affected by processes and events occurring downstream (Schumm, 1977). Therefore, any section of a stream should be evaluated within the context of its position in a drainage basin.

The upstream drainage basin delivers sediment and water to the channel and significant changes in the hydrology or sediment delivery from the watershed have the potential to change the equilibrium conditions in the channel. Likewise, instability originating in the downstream segments of a system has the potential to migrate upwards and destabilize a section of the channel far removed from the site of the initial disturbance (Schumm, 1977). This instability is commonly reflected by a knifepoint, which is a sharp break in the slope of the longitudinal profile of a stream. In every case, it is important to view any segment of a river within the framework of a fluvial system (Petts & Amoros, 1996).

Morphometric Analysis

Morphography, morphogenesis, morpho-chronology, morphometry, and morphodynamics are the five notions of morphometric analysis (Szypua, 2017). *Morphography* is a qualitative way of describing landforms' physical appearance. It is linked to the personal observation of forms, which allows for the specification of appearance and morpho-graphic classification (plain, hill, valley, ridge, etc.). These concepts do not describe how forms are created; rather, they describe how they are expressed externally (Szypua, 2017). *Morphogenesis* focuses on explaining the origin of the forms and determining the mechanisms of their contemporary development. Geomorphologists use different methods to determine the nature of the process in the past and the present form. *Morphochronology* aims to specify the age of the forms and the age relationships between adjacent landforms. Geomorphologists examine both absolute as well as relative age between the forms. *Morphometry* deals with establishing geometric features of landforms based on measurements. *Morphodynamics* is the study of the processes that shape and change the morphology (form and structure) of natural landscapes, including landforms such as beaches, dunes, rivers, and coastlines.

According to Sear *et al.* (2003), most geomorphological investigations require data on three categories of information: the river's morphology or form, which might entail a range of scales such as the catchment, river network, valley form, river channel size, shape, and characteristics. Materials related to morphology, such as sediment size range measurements, vegetation composition, and geology. The strength of the materials may be needed in more extensive research because it affects sediment generation and movement. Slope processes (for example, soil erosion, and land sliding), bank erosion processes, sediment deposition, and transport processes are all examples of processes connected with the fluvial system's operation. The planform, cross-section, and long profile of a river channel are all defined by data on river morphology. It also contains details on the floodplain, such as its breadth, slope, and characteristics like terraces. Data on the valley form could be useful in determining the presence or absence of connectivity between the valley sides and the channel. Morphological information is used to define the river network and drainage basin on a broader scale.

The channel type, sinuosity, position, width, and morphology are also critical morphometric components. Changes in channel planform characteristics, including depositional bar forms and materials, may be directly monitored or evaluated by examination of historic aerial photographs and maps. Changes in the hydrologic or sediment budgets (the long-term average volume of water or sediment delivered to a segment of a channel), at the watershed or reach scale (a reach of a channel is a segment of a channel), will likely cause changes in channel form and structure. Any change in channel structure will likely cause changes in the quality of stream habitats.

Stream Ordering and Classification

Stream Ordering in River Basin Development and Management explores how a river system is organized from source to mouth into a nested hierarchy of sizes. A first-order stream, for example, is a headwater stream with no tributaries. A second-order stream is generated by the confluence of two first-order streams and can receive tributaries from other first-order streams. Two streams of like order combine to form a stream of the next higher order, which can receive tributaries of any order lower than its own. In their book 'Network Analysis in Geography', Haggett and Chorley (1969) described Horton's system to show that, after all, streams have been classified, and an investigator starts at the mouth of the basin and reclassifies a portion of the streams. Strahler (1964) modified Horton's system by allowing his provisional scheme to determine the final ordering, such that fingertip channels are designated 1st; where two 1st order channels join, a 2nd order channel segment is formed; where two 2nd order channel segments join, a 3rd order segment is formed; and so on.

Streams also can be classified by describing the morphology of their channels. Examples of this approach include identifying a stream by the average size of bed material (sand-bed, gravel-bed, bedrock) or by physical setting and land use (mountain stream, meadow stream, urban channel). About this, the Rosgen Stream Classification Method is arguably the most widely used, especially in the United States. The basic tenet of the Rosgen classification approach is exactly as captured by Rosgen (1996) thus:

> Natural stream stability is achieved by allowing the river to develop a stable dimension, pattern, and profile such that, over time, channel features are maintained and the stream system neither aggrades nor degrades. For a stream to be stable, it must be able to consistently transport its sediment load, both in size and type, associated with local deposition and scour. Channel instability occurs when the scouring process leads to degradation or excessive sediment deposition resulting in aggradation.

This classification approach is divided into four hierarchical levels (Rosgen, 1996). Level I: Geomorphic characterization that integrates topography, landform, and valley morphology. At a broad scale, the dimension, pattern, and profile are used to delineate stream types. Level II: Morphological descriptions based on field-determined reference reach information. Level III: Stream “state” or condition as it relates to its stability, response potential, and function. Level IV: Validation at which measurements are made to verify process relationships.

The stream order system's utility is based on the assumption that, on average, if a big enough sample is handled, the order number is proportional to the size of the contributing watershed, channel diameters, and stream discharge at that point in the system (Strahler, 1964). Ordering also provides information on the size and strength of individual streams within networks, which is crucial for water management (Faniran, 1972). It also makes studying the amount of silt in a given area easier, as well as making better use of waterways as natural resources.

Puranik and Dhadwad's Logical Framework Analysis has been acknowledged by Gana *et al.* (2019) as a significant tool for River Basin Development and Management in Nigeria. In river basin development and management, logical framework analysis asks for the integration of physical, ecological, social, and economic components of river basins through the active participation of stakeholders for transparent and accessible analysis and decision-making processes. It also emphasizes basin-wide consideration in all river-related operations to guarantee river basin development efforts are sustainable (Puranik & Dhadwad, 2013).

Fluvial Audit

According to Pahuja & Goswami (2006), the objective of the fluvial audit is to relate sediment movement, channel stability, and morphological change at the reach scale to sediment dynamics in the surrounding fluvial system and the wider catchment. In a project-related assessment, the fluvial audit is carried out in the reaches determined by the location of the proposed interventions. Otherwise, the audit is conducted, to the extent permitted by available resources, for those reaches that are identified through the findings of the catchment baseline survey to be strategic for understanding the given river system.

The fluvial audit provides semiquantitative information on the sediment sources, pathways, and characteristics required for understanding the morphological form and state of the river system and the changes therein, resulting from the past and present adjustments of the fluvial system. By compiling and analyzing the reach-specific information within the supra-reach context. The fluvial audit develops an understanding of reach behavior that cannot be developed with an exclusive focus on the contemporary conditions in the vicinity of the reach in question. Furthermore, the audit establishes a baseline condition for the reach, from which can predict its future dynamics or its likely response to the impacts of the changes that have the potential to destabilize the system.

The fluvial audit approach uses a combination of archival information (on the history of potentially destabilizing phenomena and consequent channel change, as evidenced by photographs, maps, satellite images, and maintenance records of agencies) and field surveys to identify and inventory channel forms and features. These are then used by core geomorphologists to establish the process-form relationships and hence infer the nature of the fluvial processes at work in the study reach.

The outputs of the fluvial audit include a time chart of catchment and river changes that may have had geomorphic impacts, a description of past and contemporary sediment dynamics and channel changes in the study reach, and channel classification maps showing significant morphological features. In project-related assessments, the output of the audit forms the basis for the identification of possible solutions for sediment- and instability-related problems. In general, analysis of the fluvial audit would aid geomorphologists in assessing the likely impacts of proposed engineering interventions and in determining their acceptability from a geomorphological viewpoint.

Geomorphic Dynamics Assessment

The geomorphic dynamics assessment comprises a detailed evaluation of fluvial processes, mechanisms of morphological adjustment, and river channel dynamics. This stage involves significant fieldwork, channel planform mapping, surveys of bed topography, water surface configuration and measurement of velocity, suspended and bedload transport rates, lateral erosion rates and processes, bank stratigraphy, bank hydrology, and bank failure mechanisms. These require specialized instrumentation and are labor intensive and therefore need only be performed at one or a few key sites, which need to be carefully selected based on a thorough understanding of the fluvial system obtained from the findings of the catchment baseline survey and the fluvial audit.

The resource-intensive exercise of the geomorphic dynamics assessment is mostly undertaken in the context of project-specific assessments only, but its design, approach, and utility are all predicated on the knowledge outputs of the catchment baseline survey and the fluvial audit. The overarching context provided by the survey and the audit is therefore critical to generating a correct understanding of river processes and sustainable design of interventions. However, project-specific assessments seldom have the resources and, more specifically, the time to support the geomorphological assessments for the entire fluvial system. Therefore, the responsibility for conducting systemwide assessments is best placed with the river agencies, as part of their strategic water resource development and management program. (Pahuja & Goswami, 2006).

Sediment delivery is a critical process in geomorphology, influencing landscape evolution and environmental dynamics. It involves the transport of eroded sediment from its source areas to depositional sites, primarily driven by gravity, water, wind, and ice. The rate and efficiency of sediment delivery depend on various factors such as slope, vegetation cover, land use, and climate conditions (Trimble & Crosson, 2000). In agricultural landscapes, human activities such as deforestation, plowing, and construction can accelerate sediment delivery rates, leading to increased soil erosion and sedimentation in rivers and lakes (Montgomery, 2007). Effective management strategies, including soil conservation practices and land-use planning, are essential for mitigating sediment delivery and preserving soil resources and aquatic ecosystems (Foster & Meyer, 2012).

WATERSHED CONCEPTS AND MANAGEMENT

A *watershed* is the area that drains to a common outlet. It is the basic building block for land and water planning. A watershed is an area that supplies water by surface or subsurface flow to a given drainage system or body of water, be it a stream, river, wetland, lake, or ocean (World Bank, 2001). The characteristics of the water flow and its relationship to the watershed are a product of interactions between land and water (geology, slope, rainfall pattern, soils, and biota), their use, and management. A watershed is thus the basic unit of water supply and the basic building block for integrated planning of land and water use.

Size is not a factor in the definition and watersheds vary from a few hectares to thousands of square kilometres. Unless a watershed discharges directly into the ocean, it is physically a part of a larger watershed and may be referred to as a sub-watershed (Black, 1991). Rainfall is the main source of water in a watershed which then flows through and out of the watershed as surface or groundwater flow is incorporated into biomass, or is lost through evaporation and transpiration processes while in the watershed.

Watershed Landscape

Natural and artificial characteristics of the land cover and surface materials throughout the entire watershed constitute its landscape. Topography or slopes, rocks, sediments, hydrology, and even buildings may be monitored to assess vital signs that give information about the well-being of the watershed landscape. Changes in land cover and materials may be caused by fires, volcanism, climatic change, logging, land use, roads, and other factors. Any change will directly affect the watershed hydrology and may affect any other part of the fluvial system, such as stream form, sediment transport, water quality, flood frequency, and the quality of stream habitat.

Watersheds Degradation

Degradation of watersheds in recent decades has brought the long-term reduction of the quantity and quality of land and water resources. Degradation results from a range of natural and anthropogenic factors, including natural soil erosion, changes in farming systems, overgrazing, deforestation, and pollution. Depletion of soil productivity, sedimentation of water courses, reservoirs, and coasts, increased runoff and flash flooding, reduced infiltration to groundwater, and water quality deterioration are among the main negative impacts of watershed deterioration. The combination of environmental costs and socioeconomic impacts has led to the development of watershed management approaches.

Watershed degradation has emerged in recent decades in many different parts of the world as one of the most serious examples of natural resource degradation, with negative environmental and socioeconomic consequences, particularly in developing countries. Although watershed degradation is sometimes taken to refer to water resources only (Mazvimavi, 2002), it is best understood as the degradation of both soil and water in a watershed because of the interactions between the two.

Changes may be caused by natural and anthropogenic factors like altered farming systems, overgrazing, deforestation, construction, and the invasion of alien plants. These changes come about through pressures on the typically poor farming systems that prevail in uplands in developing countries. In Yemen, for example—the maintenance of age-old terraces for cereal production is no longer economic. In the same country, the development of commercial agriculture has led to overexploitation of groundwater in upland areas leading to the depletion of the groundwater table and drying up of streams. In other countries—Madagascar, for example—high population growth rates and poor economic opportunities in urban areas have led to widespread cultivation on steep and highly erosion-prone slopes. In Lesotho and Zimbabwe, pressure on uplands arises from inequitable land distribution and the resultant overloading of carrying capacity (Darkoh, 1987).

Managing Watersheds

Watershed management is considered by scholars and practitioners globally as the most appropriate approach to ensure the preservation, conservation, and sustainability of all land-based resources and to improve the living conditions of the people in uplands and lowlands. Moreover, watershed management technologies have proven to be effective in mitigating erosion on sloping land, stabilizing landscapes, providing clean water, and stabilizing and improving agrarian production systems on small and medium scales. The degree of success of watershed management interventions primarily depends on the will of the people and the scale of activities involved in it (Menon, undated).

Watershed management is the art and technique of managing watershed resources in such a way that maximum benefits can be derived from them without affecting ecological sustainability. Watershed management requires an integration of all scientific knowledge from many disciplines and a combination of technologies, strategies, and techniques with the development and use of available tools. Watershed management is a holistic concept, which tries to integrate several components like soil and water conservation, forestry development, agriculture, and livestock management as well as the socio-economic well-being of the people. It tries to bring about the best possible balance in the environment between natural resources on one side and human and other living beings on the other. Basin management typically refers to macro-management at the level of the entire watershed system, sometimes across country boundaries and with a focus on institutional and policy issues. Watershed management typically refers to management at the level of the micro or sub-watershed. Catchment is generally used synonymously with watersheds.

STRATEGIES AND METHODOLOGIES

Fieldwork and Landscape Reading

Fieldwork is inevitable in Geomorphology, but its design must reflect the issues to be addressed, and associated questions that are asked must help to get the desired results. Reading the landscape (Figure 1) is a constructivist framework for the analysis and interpretation of river forms and processes over various spatial and temporal scales (Fryirs & Brierley, 2013). Researchers do not simply head out into the field without carefully thinking through what they are trying to achieve and how they intend to go about it. Fieldwork is often expensive, so targeted interventions are required.

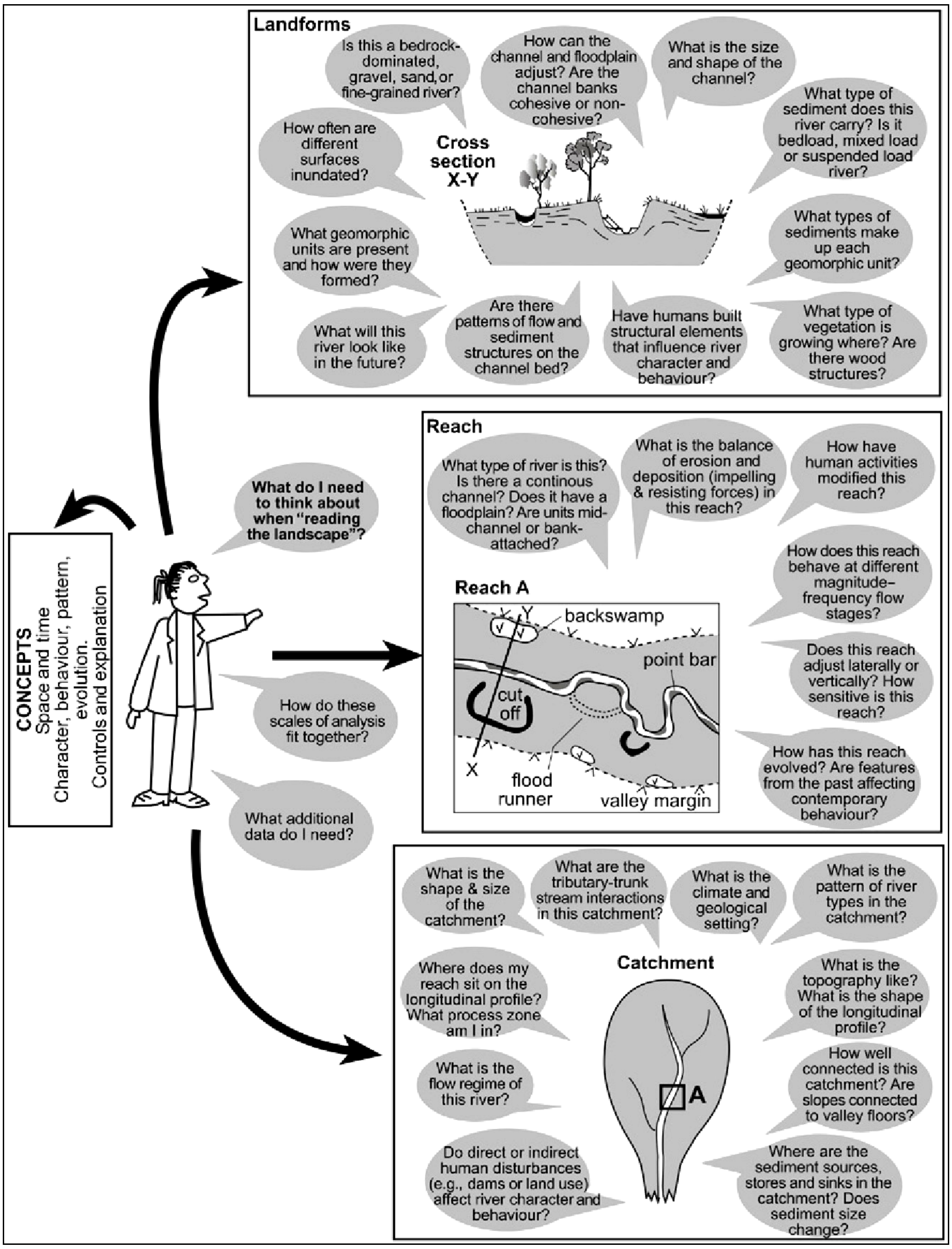

Figure 1: The right questions in fluvial geomorphology (Brierley and Fryirs, 2014)

One of the most important data sources for morphological information is the field survey. Field reconnaissance is a key tool for geomorphology. Recording the spatial arrangement (both downstream, across the valley floor, and vertically), provides the geomorphologist with a data set from which inferences can be made as to the adjustment processes and impacts of former management activity on a river system. Two methods of data collection are used; the walk-through survey, which records in mapped form the distribution of geomorphologically relevant features, and the geomorphological map. The former often simplifies the detail, but covers scales up to the river network, whilst the latter is typically used for detailed interpretation of a river and valley floor. With the advent of Global Positioning Systems, accuracy in positioning features in space has improved, increasing the value of such mapping and surveys as baseline data sources.

Cross-section surveys generally exist for those reaches of a river network that have been subject to flood modeling or for the design of land drainage or flood protection schemes, where embankment levels and bed elevations have been required. In the latter case, only long profiles may be available. In some cases, such surveys may date back to pioneer river works, but in the majority of cases, information will be more recent. The geomorphological data found in such surveys takes the form of cross-section morphology and dimensions, some estimation of bed slope, information on bank angles that might be important for bank stability analysis, and of course location of the bed elevation and channel. The opportunity to re-survey former cross-sections can provide important quantitative data on channel change in three dimensions – planform, width adjustment through bank erosion of deposition; and depth adjustment through incision into the river bed or aggradation of the bed as a result of sedimentation. The accuracy of this data depends on the ability to re-locate cross-sections and the degree of change relative to the measurement errors in the survey technique.

The main problem with the use of existing cross-section survey data for geomorphological interpretation lies in the coarse resolution of the cross-sections. In general, most cross-sections are surveyed at regular intervals and do not attempt to pick out geomorphological features such as riffle crests, height of bar surfaces, etc. Omission of these features from a long profile can lead to erroneous estimates of bed slope; a term often used in the calculation of sediment transport where water surface slopes are unavailable.

The Remote Sensing and GIS Approach

Remote sensing plays a pivotal role in fluvial system studies by providing crucial data for spatial analysis. Through satellite imagery, aerial photography, and LiDAR technology, researchers can monitor changes in river morphology, analyze vegetation patterns along riparian zones, and assess hydrological dynamics such as flow patterns and sediment transport. Remote sensing enables comprehensive spatial and temporal analysis, facilitating the identification of erosion hotspots, floodplain dynamics, and habitat alterations crucial for effective river management and conservation efforts (Lechner et al., 2018; Santos et al., 2020; Zhang et al., 2021). Moreover, advancements in machine learning techniques allow for automated feature extraction and classification, enhancing the efficiency and accuracy of fluvial system monitoring (Chen et al., 2019).

Much morphological data is derived from existing topographic surveys, aerial photography, and increasingly remote sensed data such as Multispectral imagery mounted on aircraft or satellites. In the case of existing topographic maps and air photographs, these provide the opportunity to record changes in channel morphology (for example, planform, channel width, and meander dimensions) over periods up to 200 years in some cases. Such data may be useful for establishing the presence of change in a system, or for reconstructing channel dimensions for restoration.

The GIS-based methodology has been adopted by (Blachowski, 2015) for studies of spatial concentration of rock minerals mining in the case study of the Lower Silesia region in Poland. The methodology has been used to study and interpret spatial and temporal changes in rock mineral mining distribution over 8 years (2005-2013). The proposed methodology is based on density analyses and map algebra operations for spatial modeling of regional mineral resources management in Geographical Information Systems (GIS). The objective of this work is to provide a methodology and derivative information on the spatial and temporal distribution of sand mining.

The practicality of GIS-based applications for purposes of modeling different types of spatial phenomena, environmental assessment, and optimal location analyses has been evidenced by numerous studies with a comprehensive overview provided in Malczewski (2006). An increasingly valuable source of information for geomorphology lies in the interpretation of remotely sensed data. Remotely sensed data takes the form of multi-spectral scanning (CASI) or Laser Altimetry (LiDar). The two datasets can be combined to generate 3-D thematic maps of water depths in the floodplain, vegetation classifications, detailed floodplain, and channel topography. The topographic data recorded from LiDar can be used when processed as input data to hydraulic modeling and enables a much higher resolution to be achieved than is currently possible through field surveying. Further improvements in resolution are becoming available through low-level Laser scanning of the river and floodplain through helicopter-mounted platforms (like FLIMAP).

Digital terrain analysis can be used to derive a wealth of information about the morphology and hydrodynamics of a land surface. When coupled with the spatial distribution of basic hydrologic variables, such as rainfall and runoff, digital terrain analysis is a powerful tool for estimating stream network parameters and analyzing drainage basin characteristics (Montgomery *et.al.* 1998). However, digital terrain analysis is often underutilized in tropical drainage basins due to a scarcity of appropriate data. The main principle of digital terrain analysis is that an abundance of topographic information is contained within elevation contour lines (elevation, geomorphic position, and slope) such that a continuous landscape surface can be generated from these contours. Surface water flow can be routed across this surface under the assumption that water flows downslope according to principles of least energy, i.e. water follows the path of steepest descent (Jenson and Domingue 1988). Using this simple rule, the drainage network of a landscape can be extracted.

A high-resolution Digital Elevation Model (DEM) is critical for terrain and hydrologic analysis (Table 1). Many Geographical Information Systems (GIS) packages are available that provide the necessary tools and algorithms to generate a hydrologically correct DEM from contour data. These include the ArcGIS Spatial Analyst, ArcHydro (Maidment, 2002), TauDEM (Tarboton, 2000), and GRASS open-source GIS (Neteler and Mitasova 2002). The general procedure employed by these packages involves; conversion of contour lines to Triangulated Irregular Network (TIN); conversion of TIN to DEM raster grid; fill sinks in DEM to create a hydrologically correct surface; calculation of flow direction grid; calculation of flow accumulation grid; designation of stream channel threshold from flow accumulation grid as the basis for the DEM (Seiders, 1971 and Wise, 1998).

Table 1: Selected fluvial geomorphometric indices derived from DEMs

SN	PARAMETER	FORMULA	DESCRIPTION
1	Drainage density	$D_D = L/A$ where: ***L*** is the sum of the channel lengths and ***A*** is the basin area	The sum of the channel lengths is divided by basin area. It is an important indicator of the linear scale of landform elements in a drainage basin and indicates the closeness of spacing of channels, thus providing a quantitative measure of the average length of stream channel for the whole basin.
2	Form factor	$R_f = A(lb)^2$ where: ***A*** is an area of basin, ***Lb*** is the basin length	The ratio of the basin area to the square of the basin length. Indicates the flow intensity of a basin of a defined area. The form factor value should be always less than 0.7854 (the value corresponding to a perfectly circular basin).
3	Stream Power Index	$\Omega = pgq. \tan\beta)$ where: ***pg*** is the unit weight of water, ***q*** is the discharge per unit width and ***β*** is the representative slope angle	This is the time rate of energy expenditure and has been used extensively in studies of erosion, sediment transport, and geomorphology as a measure of the erosive power of flowing water.
4	Compound Topographic index (CTI)	$CTI = \ln (Af/\tan\beta)$ where: ***Af*** is the specific catchment area draining through the point and ***β*** is the representative slope angle.	The ratio between slope and catchment area; quantification of catenary topographic convergence represented by slope angle and catchment. For the same contributing area CTI values are higher for pixels with lower slopes — this means that CTI primarily reflects accumulation processes.
5	Basin relief ratio	$Rh = H/L$ where: ***H*** is total basin relief and ***L*** is basin length	The ratio between total basin relief (difference in elevation of basin mouth and summit) and basin length, is measured as the longest dimension of the drainage basin. Indicates the overall slope of the watershed surface. It is a dimensionless number, readily correlated with other measures that do not depend on total drainage basin dimensions.
6	Relative relief	$Rp = H/P$ where ***H***is total basin relief and ***P*** is a basin perimeter	The ratio between total basin relief and drainage basin perimeter
7	Drainage basin compactness	$B_c = P/A$ where: ***P*** is drainage basin perimeter and ***A*** is the drainage basin Area	The ratio between the perimeter and area of the drainage basin. Higher values correspond to the basins of developing the long-term share erosion running in conditions of relative peace tectonic or are typical for catchment formed in low resistance rocks.
8	Drainage Basin shape ratio	$B_s = B_l/B_w$ where: ***Bl*** is max length of the drainage basin and ***Bw*** is max width of the drainage basin.	The ratio between the maximum length and maximum width of the drainage basin. Higher values correspond to more elongated basins and also indicate a relatively higher tectonic activity in the area.

Source: Szypuła (2017)

Statistical Techniques

Piégay & Vaudor (2016) defined statistics as a set of mathematical techniques used to collect, characterize, summarize, and classify numerical data, identify groups or test differences between them, detect correlations between variables, and provide predictions. Application of statistical tools in fluvial geomorphology has the advantages of reducing subjectivity, eliminating assumptions, facilitating comparison between different spatial and temporal datasets of large sizes, refining data collection, revealing exceptions or new relations, predicting performance, and improving system analysis (Piégay & Vaudor, 2016).

Table 2: Selected Statistical Applications Fluvial geomorphometric Analysis.

SN	PARAMETER	APPLICATION	EXAMPLES
1	Pearson's correlation coefficient	Describe and test the link between two variables through regressions.	Channel adjustment versus aquatic habitat characteristics
2	Spearman's correlation coefficient	Describe and test the link between two variables through regressions.	Parameters describing braiding versus control factors (exceedance flow frequency and normalized active channel width).
3	Simple and Multiple regression	Describe and test the link between two variables through regressions.	Width versus discharge, depth versus discharge, stream power versus discharge (power function). Channel bank full dimension and shape, hydraulics, bedform wavelength and amplitude, grain size, flow resistance, the standard deviation of hydraulic radius, and volume of large woody debris, versus potential control variables (drainage area, discharge, bed gradient). Grain size prediction from aerial images
4	Student's *t*-test	Describe and test differences between groups in variables through parametric tests and models.	Channel width and depth at two dates Median grain size measured by three operators Grain size measured at different sites
5	Wilcoxon signed-rank test	Describe and test differences between groups in variables through non-parametric tests and models.	Residuals of the regression "Q_2 versus catchment size" and a set of other hydro morphic indicators compared to 2 classes of reach (urban versus reference)
6	Kruskal–Wallis test	Describe and test differences between groups in variables through non-parametric tests and models.	Channel vertical changes versus the number of mining sites, number of upland active torrents, and ratio of eroding banks.
7	Chi-squared test Kolmogorov–Smirnov	Describe and test differences between groups in variables through non-parametric tests and models.	Grain size distributions (classes) Distributions of source and tributary source link lengths

Source: Piégay & Vaudor (2016)

Fluvial geomorphologists deal with complex spatial components, such as in-channel features, channel beds and reaches, valleys, watersheds, regions, and even continents, whose characteristics, occurrence, and spatial distribution change through time (Abdulazeez & Adamu, 2019). They are also concerned with processes, mainly bedload transport, suspended sediment concentrations, flow hydraulics, or vegetation dynamics, which are also variable in time. Each of them can be characterized by attributes, called 'variables', whose values can be numeric (magnitude or rank; ratios; intervals) or nominal (qualitative) (Piégay & Vaudor, 2016) (Table 2).

MODELS IN WATERSHED STUDIES

Soil and Water Assessment Tool (SWAT) Model

SWAT is a conceptual and physically-based model designed to forecast the influence of watershed management methods on hydrology, sediment, and water quality in a gauged or un-gauged watershed on a daily time step. Weather generation, hydrology, sediment, crop growth, nutrient and pesticide subroutines are among the most important model components. SWAT requires specific information about the topography, weather (precipitation, temperature), hydrography (groundwater reserves, channel routing, ponds or reservoirs, sedimentation patterns), soil properties (composition, moisture and nutrient content, temperature, erosion potential), crops, vegetation and agronomic practices (tillage, fertilization, pest control) to accurately simulate water quality and quantity.

The model mimics a watershed by splitting it into sub-basins, which are further broken into hydrologic response units (HRUs), a compartmentation unit derived by overlaying digitized soil, slope, and land use maps to detect zones of similarity. SWAT simulates soil water balance, groundwater flow, lateral flow, main and tributary channel routing, evapotranspiration, crop growth and nutrient uptake, pond and wetland balances, soil pesticide degradation, and in-stream transformation nutrients and pesticides for each HRU in each subbasin. Surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, percolation/deep seepage, consumptive use (if any), shallow aquifer contribution to streamflow for a nearby stream (base flow) and recharge by seepage from surface water bodies are all hydrologic components in SWAT. The SWAT theoretical documentation provides more thorough descriptions of the paradigm.

European Hydrological System Model *MIKE SHE*

MIKE SHE is a deterministic, physically-based, distributed model for simulating several processes in the hydrologic cycle's land phase. Finite difference representations of partial differential equations for mass, momentum, and energy conservation, as well as some empirical equations, are used to simulate hydrological processes. The MIKE SHE modeling system simulates hydrological components such as surface water movement, unsaturated subsurface water movement, evapotranspiration, overland channel flow, saturation groundwater, and surface-groundwater exchanges. The system models sediment, nutrient, and pesticide transit in the model region in terms of water quality. Water consumption and management procedures, such as irrigation systems, pumping wells, and various water control structures, are also included in the model. The many add-on modules created by the Danish Hydraulic Institute can be used to analyze a wide range of agricultural practices and environmental protection options (DHI). Depending on the scope of the investigation, model components describing different phases of the hydrologic cycle can be utilized singly or in combination. MIKE SHE represents the basin horizontally by an orthogonal grid network and employs a vertical column at each horizontal grid square to indicate the change in the vertical direction to account for spatial variations in catchment features. This is accomplished by dividing the catchment into a large number of discrete parts, or grid squares, and then solving the state variable equations for each grid into which the research area was divided. To run the model, for each cell, several parameters and variables have to be given as input.

The system has no restrictions on watershed size. Land use, soil type, and precipitation are used to split the modeling area into polygons. GIS, software like ArcView, or MIKE SHE's built-in visual pre-processor can handle most data preparation and model setup. The system includes integrated graphics and a digital post-processor for model calibration and evaluation of current conditions as well as management options. Another valuable method for studying and presenting results is model scenario animation. With state variables that indicate local averages of storage, flow depths, or hydraulic potential, the MIKE SHE Model produces predictions that are spread in space. Because of the distributed nature of the model, the amount of input data required to run the model is rather large and it is rare to find a watershed where all input data required to run the model has been measured.

Areal Non-Point Source Watershed Environment Simulation (ANSWERS)

The two key response components of ANSWERS are hydrology and upland erosion. All properties (e.g., soil properties, land use, slopes, crops, nutrients, and management strategies) are deemed homogeneous in the watershed region (less than 10,000 m). ANSWERS-2000, an extended version of ANSWERS, uses breakpoint rainfall data and simulates runoff events in 30-second time steps with a daytime step in between. Surface hydrologic processes dominate in medium-sized watersheds (5x106 to 3x107 m) where simulation is limited. The model can also simulate transformations and interactions between four nitrogen pools: stable organic nitrogen, active organic nitrogen, nitrate, and ammonium. The watershed outflow and any other user-selected site within the watershed are both presented with a surface runoff hydrograph. The ANSWERS and ANSWERS-2000 models were created to assess the effectiveness of agricultural and urban watershed best management practices in reducing sediment and nutrient transport to streams during surface runoff events. Some of the achievements and issues related to the application of these models are described in the literature. ANSWERS could be used to predict runoff at a catchment outlet and provide somewhat accurate models for various surface cover conditions; however, runoff predictions were less accurate at low rainfall intensity events than at higher intensity events. They also pointed out that complicated watersheds might be modeled without calibration; while this recommendation promotes model confidence, it is ill-advised to adopt it. One of ANSWERS' major flaws is its inability to model interflow and groundwater contributions to base flow, snowpack, and snowmelt. This shows that the model is less appropriate for areas with large base flow contributions, winter snow accumulation, and snow melt. Because ANSWERS-2000 lacks routines for channel erosion and sediment transport, the sediment and chemical components are not suitable for watersheds.

The Automated Geospatial Watershed Assessment (AGWA) Tool

Watershed, natural resource, and land use managers and scientists can utilize this multi-purpose hydrologic analysis system to conduct watershed and basin-scale research. The USDA-Agricultural Research Service, the US Environmental Protection Agency, the University of Arizona, and the University of Wyoming collaborated to develop the Automated Geospatial Watershed Assessment (AGWA) tool, which automates the parameterization and execution of the Soil Water Assessment Tool (SWAT) and KINEmatic Runoff and EROSion (KINEROS2) hydrologic models.

AGWA can undertake hydrologic modeling and watershed evaluations at many time and space scales. AGWA fully parameterizes, executes, and visualizes SWAT and KINEROS2 findings using widely available national GIS data layers. The user picks an outlet through a simple interface and AGWA uses a Digital Elevation Model (DEM) to delineate and discretize the watershed. The required model input parameters are then derived by intersecting the watershed model elements with soils and land cover data layers. After that, the chosen model is run and the results are imported into AGWA for visual presentation. Managers can utilize this information to identify possible issue areas where additional monitoring or mitigation measures can be targeted. AGWA can compare findings from many simulations to look at relative change throughout a range of input scenarios (such as climate/storm change, land cover change, current conditions, and alternate futures). Environmental decision-makers, resource managers, researchers, and user groups will benefit from the AGWA tool, which is being further developed for online decision assistance. It has also been updated to provide several new capabilities. Handling FAO soils for worldwide usage, pre- and post-fire watershed analyses and many choices for user-defined land cover modification are just a few of them.

CONCLUSION

The field of fluvial systems evaluation and management has undergone significant advancements in recent years, driven by the integration of cutting-edge technologies and interdisciplinary collaboration. Contemporary approaches have embraced the use of remote sensing, modeling techniques, and cutting-edge data analysis tools, enabling researchers and practitioners to gain unprecedented insights into the complex dynamics of river systems. These advancements have facilitated more accurate assessments of fluvial processes, sediment transport patterns, and the impacts of human activities on these delicate ecosystems.

Moving forward, it is crucial to continue fostering interdisciplinary partnerships and adopting a holistic perspective in fluvial systems management. By integrating knowledge from diverse fields such as hydrology, geomorphology, ecology, and stakeholder engagement, we can develop comprehensive strategies that balance the needs of human communities with the preservation of these invaluable natural resources. Furthermore, continuous research and innovation will be essential to address emerging challenges, such as climate change impacts and increasing urbanization pressures on river systems. Through a commitment to sustainable practices and evidence-based decision-making, we can ensure the long-term resilience and ecological integrity of our fluvial systems for generations to come.

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