

# Remote Sensing—A Fast And Reliable Tool to Map the Morphodynamics of the River Systems for Environmental Management

V. Thirukumaran and Mu. Ramkumar

**Abstract** River is a dynamic morphometric agent which shapes literally earth's entire surface except the dry deserts and the ice-capped Polar Regions. The morphological variations in the river basins are under the influences of an ensemble of variables including, but not limited to, the precipitation, runoff, slope, soil, and many other processes including tectonics, sedimentation, oceanography and anthropogenic intervention. As the rivers provide sustenance to the fauna and flora including the human race, understanding the river systems is essential from the ecological and economic points of view. The river systems interact with and maintain a delicate equilibrium with the lithosphere–hydrosphere–atmosphere, which make understanding the fluvial dynamics a necessity. The ever-increasing pressures from the anthropogenic interventions, under the climate change scenarios make this task critical for sustainable management which in turn requires extensive data inputs on a spatio-temporal scale. However, the very dynamic nature of the river systems poses constraints on the data acquisition and subsequent analysis. In this paper, we attempt demonstrate the utility of remote sensing and GIS as tools for fast and reliable analysis of morphodynamics of rivers for environmental management.

**Keywords** Fluvial geomorphology • River dynamics • Remote sensing • Geohazards • Sediment load • LIDAR • Drainage • Neotectonism • Environmental management

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## 1 Introduction

When compared with other geomorphic systems, the studies on the morphological variation and evolution of the fluvial system are limited by the inaccessible nature of the terrain (either at the catchment or at the coastal swamps and tidal channel networks) and by the dynamic changes in morphological features at spatial and temporal scales. These two major inhibiting factors, along with other logistic restrictions, pose severe constraints in mapping and understanding the morphological variations of river systems that are manifested as a result of natural and anthropogenic processes. However, as the river courses and adjoining regions are the preferred locations of inland transport, agriculture, habitation, commercial, industrial and aesthetic activities, improved understanding on the fluvial geomorphic system is essential, especially in the context of accelerated rate of climate change during the recent years and also in the future scenarios. The river basins are home to a wide variety of natural fauna and flora, and also for the buried georesources such as hydrocarbon and coal. Furthermore, the river basins contain vast expanses of low lying lands and are underlain by thick pile of sediments that are under the influences of tectonic movements, recurrent flooding, wave erosion, and cyclones. Thus, understanding the river systems, particularly the morphodynamics is essential from the ecological, economical and strategic points of view.

## 2 River System and Its Dynamism

The land and water are linked in a natural system called the catchment that represents an area of land in the upstream region of a drainage basin that collects water either from the rainfall or from the snow melt or both and directs it to a stream. Recently, Thirukumaran (2012) narrated the emergence and actions of rivers from a geomorphic point of view that could be briefly stated thus: From the smallest droplet to the mightiest river, water works to shape the land, taking with it sediment and dissolved materials and delivers them to the coastal lowlands (delta) and into the sea. A river network is an integral component of any landscape that is created as water flows from higher to lower elevations. There is an inherent supply of potential energy in the river systems created by the change in elevation between the beginning and ending points of the river or within any discrete stream reach. This potential energy is expressed in a variety of ways as the river moves through and shapes the landscape, developing a complex fluvial network, with a variety of channel and valley forms and associated aquatic and riparian habitats. Excess energy is dissipated in many ways: contact with vegetation along the banks, in turbulence at steps and riffles in the river profiles, in erosion at meander bends, in irregularities, or roughness of the channel bed and banks, and in sediment, ice and debris transport. The potential energy gets rejuvenated whenever the earth's dynamics revive the elevation and landscapes. Streams are dynamic systems that

balance the water flow and the sediment transport. A river's energy must be in balance with the size and volume of the sediment carried by the river. Any aberrations in this balance, either natural, or anthropogenic in origin, results in immediate and extensive reaction from the river flow depending on the nature and intensity of the aberration. The reactions of the river system include, flooding, change of channel course, bank erosion, and channel abandonment, which serve to the detriment of downstream ecosystem as well as services provided by the river to riparian community including humans.

The dynamism of geomorphic agents is relentless in shaping the earth and the agents are the immediate respondents of the geotectonic and geodynamic processes operating on the Earth system. Being fluid, the water responds to the tectonic and other disturbances at a rate faster than other geological agents. Being entirely dependent on this fluid medium, though there are other catalytic factors such as slope and gravity, the fluvial system is inherently dynamic which requires a compatible tool, should the features and responses of the fluvial system are to be studied at their rates and spatio-temporal scales of evolution and modification.

Owing to the provision of synoptic view at spatial, temporal, spectral, and radiometric resolutions of remote sensing systems, the satellite remote sensing (RS) offers an unique tool to map the fluvial dynamics without being in direct physical contact with the ground, which obviates the logistic and inaccessibility constraints posed by the fluvial system. The geographic information systems (GIS) offer the opportunity to gain fresh insights into these earth's surficial features through the provision of analytical and data integration capabilities. These two tool-technologies can be linked together into a synergistic system that is particularly well suited to the examination of landscape conditions through the interrelationships of scale, pattern, and process. There are many automatic pattern recognition functions within the GIS environment that reduce man-hours of analysis, remove operator inconsistency and provide dynamic mapping capability. Thus, this paradigm has gained wide application and prominence in the field of mapping and understanding the fluvial morphological features.

### **3 Indicators of River Dynamics and Their Mapping and Analysis Through RS and GIS**

The river dynamics can be indicated by the frequency, duration, and magnitude of stream discharge, changes in channel morphology, and seasonal variations in sediment load, and formation and modifications in fluvial landforms. The suspension, transport and deposition of sediments are important geomorphic functions in shaping the physical landscape. The river dynamics can be categorically classified into two major types viz., related to sediment load and erosion and response of river system to tectonics or earth dynamics.

### 3.1 Sediment Load and Erosion

The sediment load of the stream is directly related to the runoff and gradient of the stream course and free supply of weathered materials. Runoff is the function of rainfall and permeability of the subsurface lithology, and gradient is the function of youngness of the terrain. Three types of analyses namely, (a) mapping of areas undergoing erosion due to channel migration over time using multirate imagery, (b) analysis of LiDAR (Light detection and ranging)-derived DEMs (Digital Elevation Models) to quantify stream bank heights to estimate soil volume loss, and (c) combined remote sensing and field observations to estimate sediment loading per eroded feature, reach, and stream, allow efficient quantification of the sediment loading mobilized by stream bank erosion at various spatial and temporal scales. It also provides information on the critical source areas that contribute a disproportionate amount of the total sediment load.

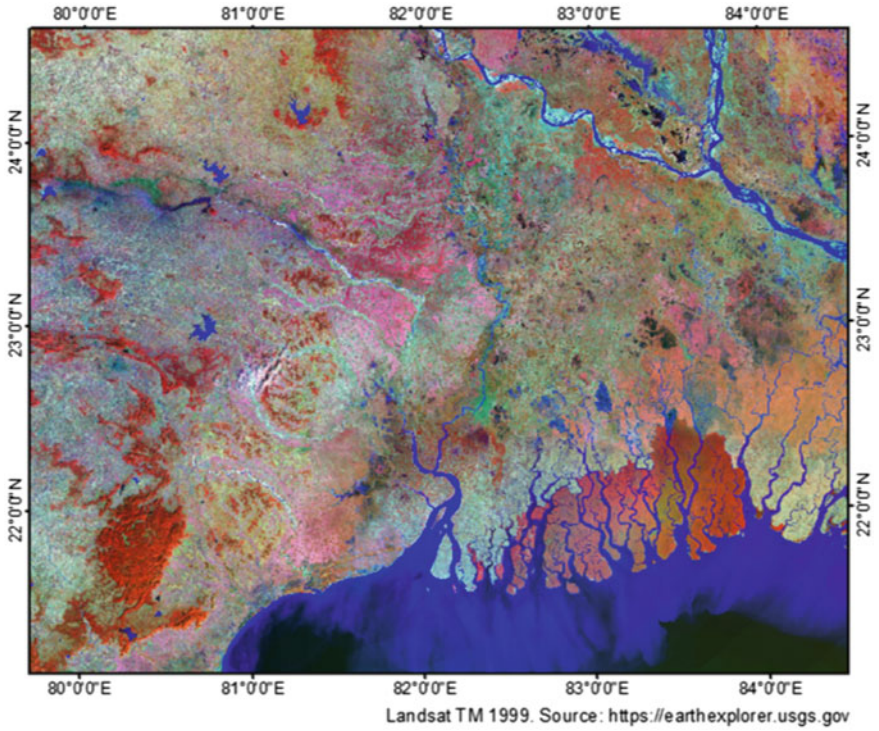
#### 3.1.1 Satellite Reflectance and Sediment Load

Remote sensing holds the potential for monitoring and estimating suspended sediments in surface water. Suspended sediments increase the radiance emergent from the surface waters in the visible and near infrared (NIR) portion of the electromagnetic spectrum. The Landsat TM and ETM+ visible and NIR bands, 1–4, are optical bands recording the electromagnetic radiation of 0.45–0.52, 0.52–0.60, 0.63–0.69 and 0.76–0.90  $\mu\text{m}$ , respectively. Cloud-free pixels in the middle of the river width, counting the information only from water surface but not from land, are generally used to estimate the suspended sediment load (Fig. 1). Wang et al. (2012) found overall increase in reflectance with the increases in the sediment concentrations (Fig. 2). To estimate the suspended sediment concentration (SSC) from the satellite images, Digital Counts (DC) are converted to at-satellite radiance and then radiance is converted to reflectance. The equation to convert satellite DCs to satellite radiance is:

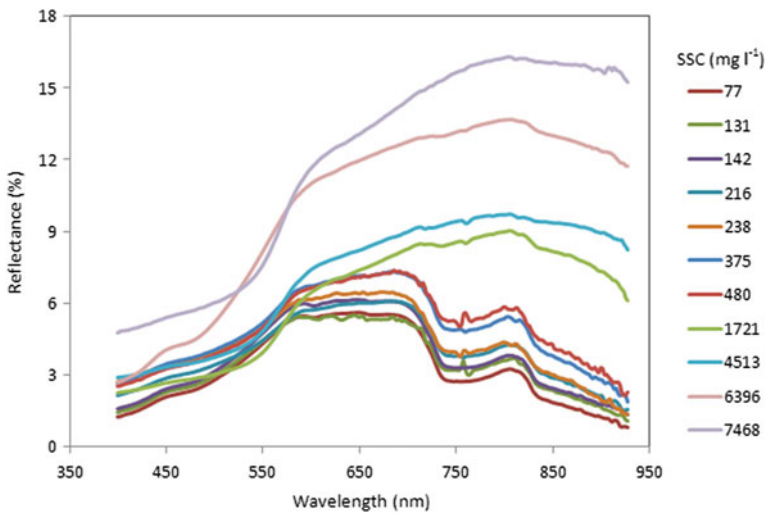
$$L = (DC + A)S$$

where  $L$  is the satellite spectral radiance for the given spectral band ( $\text{Wm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ ),  $DC$  is the digital count at a given pixel for a given spectral band,  $A$  is the offset for a given spectral band in the unit of  $DC$ , and  $S$  is the slope for a given spectral band in  $\text{Wm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}/DC$  (Chavez 1996). The offset and slope values are taken from the header file.

Atmospheric correction is applied to the satellite spectral radiance and then converted to surface reflectance. Bhatti et al. (2009) have observed sympathetic relationship between reflectance and sediment load when the suspended sediment concentration is in the range of 500–2,000  $\text{mg/l}$ . When the suspended sediments in the river is high, and 0 % reflectance or completely dark objects are not likely to exist. The improved dark-object subtraction technique (Chavez 1988, 1989) can be



**Fig. 1** Suspended sediment in Bay of Bengal showing high reflectance in RGB in landsat TM data 1,999 (Source Global landcover facility, [www.landcover.org](http://www.landcover.org))



**Fig. 2** Spectral reflectance curves versus suspended sediment concentrations (Wang et al. 2012)

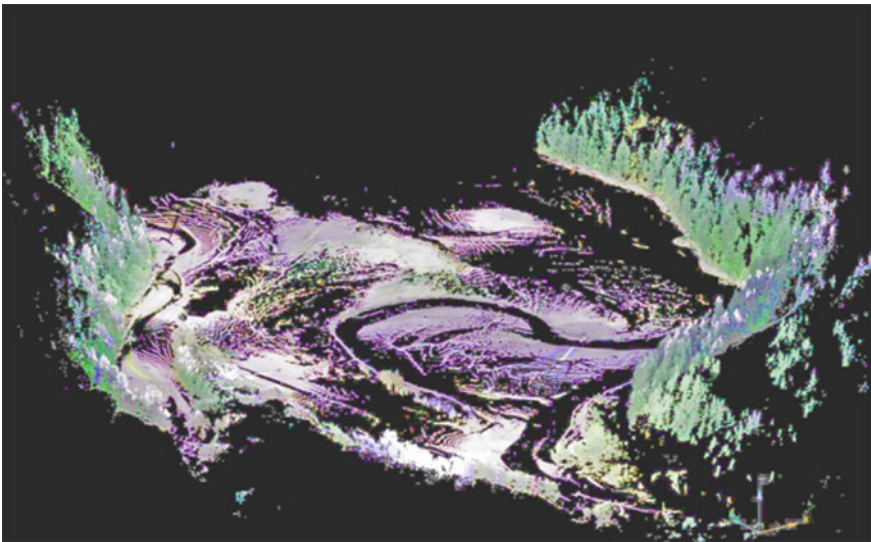
adopted to remove atmospheric path radiance or haze DC value from the images. Also, correction for atmospheric transmission coefficient due to the atmospheric absorption can be carried out based on the Cosine of solar zenith angle (COST) model of Chavez (1996). The following equation can be used to calculate reflectance from radiance data.

$$R = \frac{\pi(L_s - L_a)}{TAU_v(E_o \cos(TZ)TAU_z + E_d)}$$

where R is the spectral reflectance of the water surface,  $L_a$  is the atmospheric path radiance ( $Wm^{-2} sr^{-1} \mu m^{-1}$ ).  $TAU_v$  is the atmospheric transmittance along the path from the ground surface to the sensor,  $TAU_z$  is the atmospheric transmittance along the path from the sun to the ground surface, TZ is solar zenith angle in degree.  $E_o$  is solar spectral irradiance on a surface perpendicular to the Sun ray's outside the atmosphere ( $Wm^{-2} sr^{-1} \mu m^{-1}$ ).  $E_d$  is the downwelling spectral irradiance at the water surface due to scattered solar flux in the atmosphere ( $Wm^{-2} sr^{-1} \mu m^{-1}$ ).

### 3.1.2 Assessment of Topographic Variations Resulting from Stream Dynamics

LIDAR is a form of airborne scanning altimetry that provides high-resolution data on topography (Fig. 3). It is of great importance for mapping landforms and landform change, especially at relatively local scales. It can be used to produce Digital



**Fig. 3** Lidar image depicting topography of a delta in lake Aldwell (Source <http://www.venturariver.org>)

Elevation Models (DEMs) and is being used in a number of geomorphological applications including cliff and landslide monitoring, the study of tidal channels, assessing subsidence risk, predicting areas subject to storm surges and tsunamis and changes in beach height (Adams and Chandler 2002). Multi-temporal studies may shed light on the changes in channel pattern, sediment accumulation, etc.

### ***3.2 Drainage Anomalies as Observed from the Remotely Sensed Data***

The nineteenth—early twentieth-century geomorphologist Davis (1889, 1899) developed an elaborate scheme to describe the components of a river drainage network and related them to various stages of their physiographic development. The river system is the immediate respondent to the earth's dynamics and faithfully obeys the resultant newer landforms and structures. Miller (1937) and Chitale (1970) and a large number of workers have brought out exhaustive information on how these drainages can be used in mapping the lithology and geological structures especially from the aerial photographs.

Pope and Wilkinson (2005) studied the roles of climate and tectonics in the late Quaternary fan development on the Spartan piedmont Greece. Rejuvenated alluvial fan formation along the mountain front is an indication of slope and relief modification brought in by neotectonism. The radial drainages are the drainages that are radiating away in all directions from a central point or drainages converging from the periphery towards a central point. The former is called as centrifugal radial drainage and the latter as centripetal radial drainage. These have been interpreted to be the indicators of recent tectonic movements. However, care has to be taken to stifle through the available evidences on their origin ascribable to topographic or impact origin.

Such radial centrifugal drainages observed in many parts of the world were inferred to be due to active tectonic doming (Twidale 2004). In India too, a lot of inferences are made by many on the possible active tectonics from such radial drainages. In Saurashtra Peninsula, Sood et al. (1982) interpreted a number of such centrifugal radial drainages along with gulying and inferred the role of Post Deccan trap diapirism as the causative factor. Babu (1975) inferred the role of morpho-structures related to hydrocarbon in Krishna–Godavari delta as the causative factor for the formation of the anomalous radial cum annular drainages. Ramasamy et al. (2006a) have observed network of radial cum annular drainages in Cauvery delta and inferred them to be the reflection of recent subsurface doming.

A system of co-linear drainages is called as “parallel drainages”, whereas, the long and straight flow paths of the drainages are called as rectilinear drainages. The parallel or co-linear drainages are normally observable in the dune fields in between co-linear ridges (Miller 1937). In general, the rectilinear flow of drainages is normally attributed to the faults, whether active or dormant. In fact, most of the

lineaments and faults are interpreted by the geoscientists only from such rectilinear flow of drainages (Twidale 2004). In India, the rectilinear flow of Narmada River for over 1,000 km in Central India was inferred to be due to a major crustal dislocation (Oldham et al. 1901; Murty and Mishra 1981) along the Narmada-Son lineament. In parts of Tamil Nadu also, most of the easterly flowing near-rectilinear rivers namely the Palar, the Ponnaiyar, and the Cauvery and parts of the rivers the Vellar, and the Vagai etc. are inferred to flow along WNW–ESE transverse faults, out of which few of them are inferred to be active (Vemban et al. 1977). Chamyal et al. (2003) inferred the closely spaced parallel drainages in Saurashtra Peninsula to be indicative of tectonic uplift.

The slope and lineament controlled drainages which are sharply deflected by the lineaments are interpreted as deflected drainages. The deflected drainages are interpreted from many river systems the world (Bowler and Harford 1966; Panizza 1978; Reid 1992; Saintot et al. 1999; Kusky and El-Baz 2000; Twidale 2004 and many others). For example, Twidale (2004) had observed many such deflections in the Murray River of Australia in association with many lineaments/faults. In India too, a number of workers have utilized the drainage deflection phenomenon as a tool for detecting the land stability and neo-active tectonics. Babu (1975) has observed anomalous drainage deflections in the River Godavari, Andhra Pradesh and attributed these to various lineaments related to tectonic uplift. The rectangular flow of the Bhramaputra River, Assam valley has been explained by NE–SW, NW–SE, E–W and N–S faults (Murty and Mishra 1981). Amalkar (1988) has explained the complex drainage pattern in the Luni Basin, Rajasthan through lineaments of various orientations. Radhakrishna (1992) has observed multiple deflections in the Biligirirangan–Hogenekkal area of the Cauvery River basin and on the basis of such acute and rectangle deflections, identified a spectrum of N–S dextral and sinistral faults. Ramasamy et al. (1992) recorded that the River Cauvery has migrated during 2700–2300 B.P. towards Tiruchirappalli–Thanjavur plains.

An anabranching alluvial river is a system of multiple channels characterized by vegetated or otherwise stable alluvial islands that divide flows at bankful discharges. The islands may be developed from within-channel deposition, excised by channel avulsion from extant floodplain, or formed by prograding distributary channel accretion on splays or deltas. A specific subset of distinctive low-energy anabranching systems associated with mostly fine-grained or organic sedimentation are defined as anastomosing rivers (Smith and Smith 1980; Knighton and Nanson 1993; Makaske 2001). Van Niekerk et al. (1999) found that bedrock anabranching channels on the Sabie River in South Africa have a significantly greater potential to transport sediment than do the other channel types along that river.

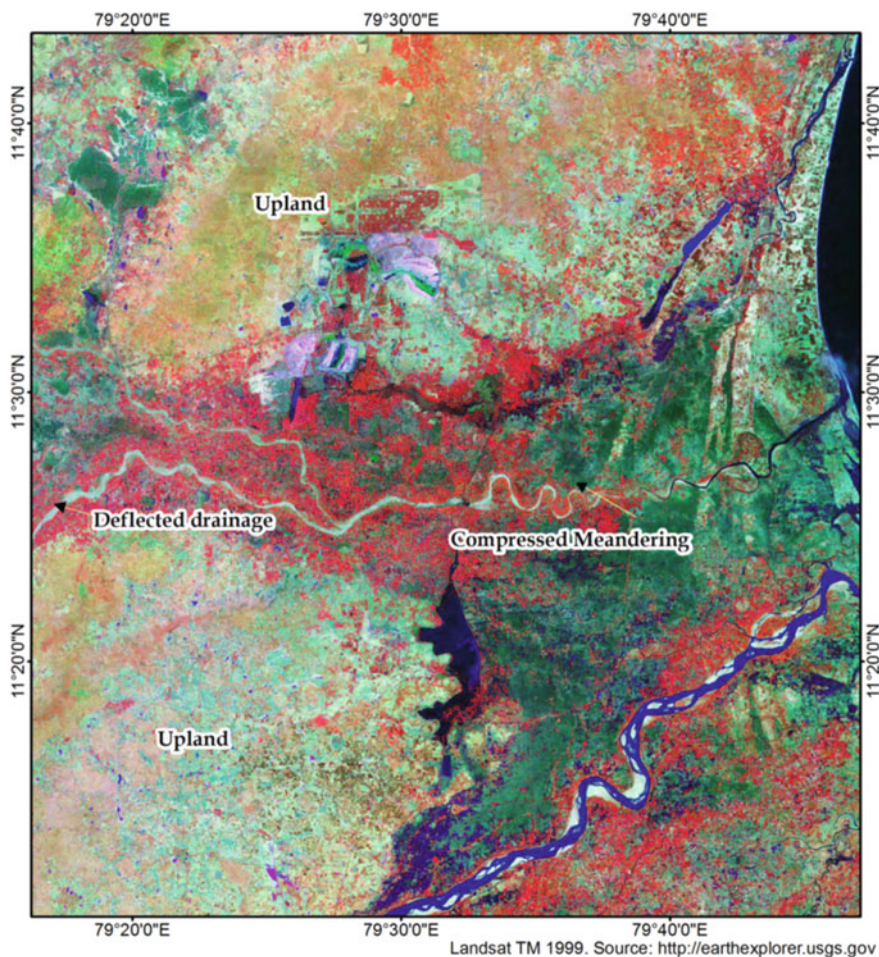
Neither of these terms now applies to the braided rivers where divided flow is strongly stage dependent around the bars that are unconsolidated, ephemeral, poorly vegetated and overtopped at less than bankful flow. The hallmark of the braided rivers is the presence of multiple active channels that divide and rejoin to form a pattern of gently curved channel segments separated by exposed bars. Braided rivers are marked equally by temporal dynamism; gradients in sediment flux associated with the complex spatial topography change in local slopes, leading the



flow to continually adjust its path as it picks its way through the network. It has been suggested that braiding was the dominant river pattern on the Earth before the first appearance of land plants in late Silurian time (Schumm 1968). The braiding of streams usually happens when the gradients drop near the confluence points. Excluding alluvial fans, if the braiding starts at much earlier stages of the stream then, it could be due to the drop in gradient which is anomalous manifestation of the land subsidence along a fault.

The drainages that flow as a single stream, branch off into two and rarely into four or five, run co-linear or curvilinear and meet after a few hundred meters or kilometers, thus ultimately giving a shape of an eye or biconvex lens are termed as “eyed drainages” because of such morphology. These eyed drainages are invariably found to be either bisected by the orthogonally/obliquely aligned lineaments or confined within two sub parallel/oblique lineaments. Such eyed drainages can be propounded that vertical cutting/incision of drainages and when it happens, it indicates tectonic emergence and the splitting up of the drainages suggests land subsidence. Significant amongst them are the observations made by Smith et al. (1997) in Okavango River, Botswana that the river on reaching a graben split up into four channels and these channels ultimately rejoin after crossing the graben. They have called this tectonically induced phenomenon as “anastomosis” (Fig. 5a).

The types of anomalous occurrences of compressed meanders in otherwise normally flowing drainage systems have been demonstrated to be indicative of active tectonics in such zones of compressions. Many workers explained the anomalous sinuosity of the river Yamuna right from its outlet from Himalayas and up to its confluence with Ganges in the Indo-Gangetic plain to be due to the active tectonics related to post collision phenomenon. On the contrary, Bakliwal and Sharma (1980) have explained the intense, acute and compressed meandering in the River Yamuna in Agra region of the Indo-Gangetic plains to active scissor fault tectonics along two sub parallel lineaments of the Great Boundary Fault System. Murthy and Sastri (1981), Barooah and Bhattacharya (1989) and many others have interpreted a large number of drainage anomalies in the form of compressed meandering in the Brahmaputra River and explained them to be due to ongoing collision of the Indian plate. The anomalous compressed meandering in otherwise 1,000 km long rectilinear Narmada River in its western end near Broach area, Western India, is demonstrated to be due to the ongoing tectonic activities by three major faults which occur in triangular pattern and caused compressed meandering within them (Ramasamy et al. 1991). Many workers observed the occurrences of compressed meanders [for example, Ramasamy et al. (1995)—in the Vellar River near Cuddalore, Tamil Nadu State (Fig. 4), Valdiya (2001)—Cauvery River in the area west of Bangalore and Jain and Sinha (2005) in the Bagmati River, Himalayan foreland basin] and interpreted them to be the result of active tectonics.



**Fig. 4** Compressed meandering and deflected drainage owing to rising upland (Vellar, Tamil Nadu, India)

### 3.3 *Paleochannels*

The occurrence of paleochannels indicates that the river has left these traces and migrated away. These Paleodrainages/Paleochannels/buried rivers show typical shapes namely, ribbon, loop, linear, curvilinear and contorted features with black tone in black and white panchromatic aerial photographs and reddish tone in the satellite colour coded FCC images. Mapping the paleochannels and interpretation of their evolutionary pattern provide reliable clues to the past geological and climatological events and processes namely, active tectonic movements, sea level changes, climatic fluctuations, flooding frequency and intensity, etc.

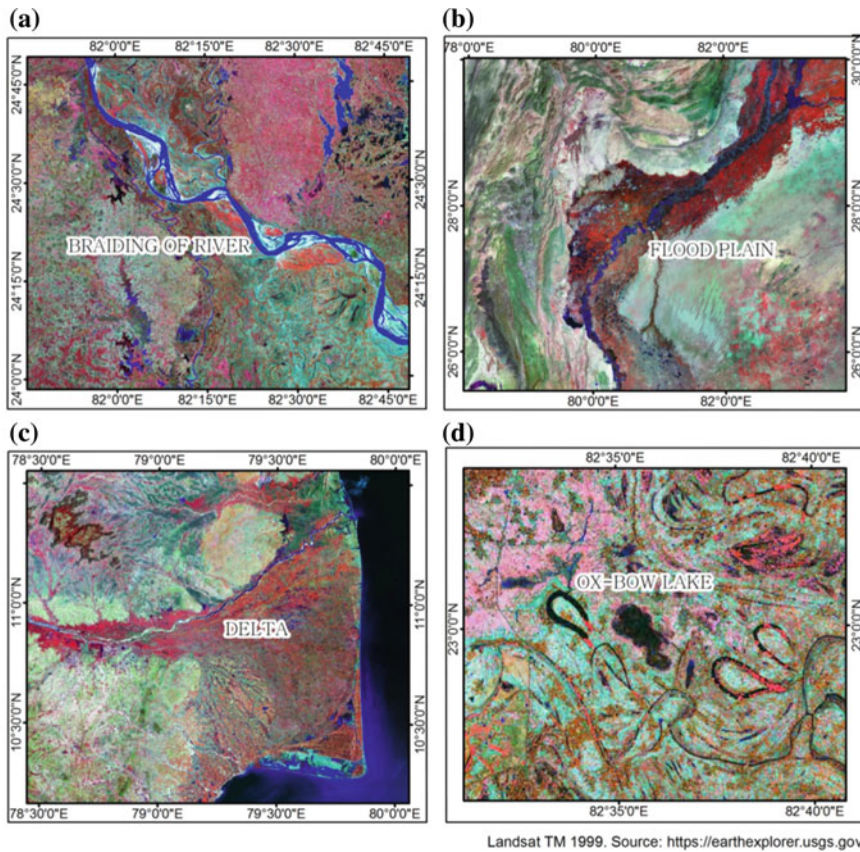
Among these, the active tectonic movements seem to play a greater role in the river migration when these rivers show preferential migrations only in one direction (Ramasamy et al. 1992). Many workers have used this as a tool to understand and map the recent tectonic movements. The phenomenal anticlockwise rotational migration of river Sarasvati and its burial in the northern part of the Great Indian Desert was attributed to the rise of Aravalli Mountains (Yashpal et al. 1980; Valdiya 1997; Gupta et al. 2004).

Ramasamy and Karthikeyan (1998) have observed the southerly migration of the Ponnaiyar River in Pondicherry due to the ongoing activism in the Holocene graben to its south. The anticlockwise rotational migration of the River Cauvery in its deltaic regime in Tamil Nadu was explained by the phenomenon of block faulting of the Mio-Pliocene Sandstone and its uplift during the last 6,000 years (Ramasamy et al. 2006b). Preferential migrations of rivers have been used as an indicators for active tectonic movements around the world viz: the Godavari delta, India (Ramkumar 2003), southerly migration of Echuca River, New South Wales (Bowler and Harford 1966; Pels 1966), the Charwell River in New Zealand (Bull and Knuepfer 1987), the Po River in Italy (Castaldini 1990), and the Murry River in Australia (Twidale 2004), etc.

### 3.4 Delta

Deltas can be either subaerial or subaqueous accumulations and may have a variety of geometries. The prevailing shape of any given delta depends on the rates of sediment supply by the rivers and the patterns and rates of sedimentation. Deltas vary immensely in both area and volume. The size of a delta depends at the lowest order on the annual sediment discharge of the river but the most extensive deltas also tend to be developed where wide, low gradient continental shelves provide a platform for prolonged sediment accumulation and morphological progradation. Hence, the largest deltas are found on passive (as opposed to active) continental margins (Wright 1985). Despite this fact, active margins are probably equally or more important than the passive margins in supplying river sediment to the sea. Milliman and Syvitski (1992) showed that the numerous small mountainous streams, particularly those of the humid tropics, are collectively the most important sources of terrestrial sediment to the sea (Fig. 5c).

Deltas contain a variety of micro-landforms or sub-environments namely, river channel—tributary and distributary (active, dormant, abandoned and paleochannel), terrace, natural levee, river bank (that can be either straight, curved or any other intermediate form; These can, be either erosional or depositional or transitional, and are termed as cut bank or inner bank of meander), crevasse splay, point bar, braided bar, channel bar, ox-bow lake (Fig. 5b, d), overbank, estuary, tidal channel, mud-flat, marsh, swamp, back water, lagoon, bay, distributary mouth bar, spit, beach-ridge-swale complex, flood plain, chenier plain, tidal flat, beach, prodelta, etc., that



**Fig. 5** a Anastomosis in Ganges: b Flood plain in Indus: c Delta of Cauvery: d Ox-bow lake along Ganges

are under the influences of a myriad varieties of processes on a spatio-temporal scale. Remote sensing plays a vital role in mapping these micro-landforms for understanding the evolutionary history and future trends.

#### 4 The Road Ahead in Monitoring Approach

Ramakrishna Nemani et al. (2009) have used a modeling framework termed as Terrestrial Observation and Prediction System (TOPS) integrating operational satellite data, microclimate mapping, and ecosystem simulation models to characterize ecosystem status and trends and patterns in landscape. The analysis of coarse or fine resolution satellite-derived normalized difference vegetation index (NDVI) measurements may indicate vegetation condition. The variation in vegetative cover

along the channel beds, river islands, sand bars and meandering loops may indicate prevailing/prevalent dynamics of a river. Analyzing MODIS (Moderate Resolution Imaging Spectroradiometer) products (vegetation indices, absorbed radiation, land surface temperature and gross primary production) in conjunction with ground-based measurements, such as runoff, lends additional utility to satellite-based monitoring of dynamic indicators, as together they provide a comprehensive view of the river dynamics. Analyses of satellite products from different seasons are corroborated by observed changes in river runoff patterns. The general overview of changes in future flooding can be created by taking the climate into consideration. This is achieved by combining climate scenarios with hydrologic models.

Laser scanning has enabled highly accurate data gathering with increased horizontal and vertical precision and better availability of detailed spatial data. For example, airborne laser scanning (ALS), ALS systems for bathymetric measurements, fixed-position terrestrial laser scanning (TLS) and mobile laser scanning (MLS), such as boat- and cart-based mapping systems (BoMMS/CartMMS), have revealed new potential in fluvial research. Aerial photography based bathymetry modeling allows us to create depth models at high spatial resolution, based on the connection between water depth and measured reflectance. Establishing protocols for monitoring the river and data from the gauging stations acquired from web-based program archives or real time data feeds as available can be of reliable method of monitoring the fluvial morphodynamics.

## 5 Conclusions

Knowing that rivers are a dynamic system and are sensitive to change, the geomorphic condition of the stream can be used as both an indicator and predictor of watershed function and health. The tradition of capturing the dynamics with a modern tool—remote sensing has been realized by the scientific community since long back. Widespread application of this tool is being encouraged by the administrators and planners owing to its fast and reliable nature. As integrating the remote sensing and GIS provide an indispensable tool for real-time impact assessment during the times of natural calamities such as flooding this is not only crucial for saving a large population from the misery of river dynamics and floods but is also important for improving the river health (Sinha and Ghosh 2012). The technology of quantifying sediments using spectral band of remote sensors has carried the science to new front in monitoring environmental issues. Hyperspectral remote sensing with high spectral resolution makes easier estimation of sediment load. To sum up, it can be stated that the river dynamics can be monitored, measured and understood better with the help of RS and GIS tool-technologies.

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