Journal of the Indian Society of Remote Sensing (January 2021) 49(1):151–160
https://doi.org/10.1007/s12524-020-01280-8

REVIEW ARTICLE

Role of IRS-1C in Developing Remote Sensing Applications for Water Management in India

K. Abdul Hakeem[1] · P. V. Raju[1] · E. Siva Sankar[1] · Saindranath Jonna[1]

Received: 12 October 2020 / Accepted: 29 November 2020 / Published online: 1 January 2021

Abstract

Efficient water management is essential for water and food security leading to socio-economic development. In order to build resilience and achieve water security, planning and management of water resources projects needs to be based on realistic assessment of related aspects. This requires comprehensive, reliable and easily accessible information on demand, availability and utilisation of water resources. Observational capabilities from ground monitoring systems and supplementary/complementary data from satellite remote sensing provide unique opportunities for data integration and value addition supporting water management decisions. While LANDSAT-1 initiated various remote sensing based activities with respect to management of hydrology and water resources across the globe, the launch of Indian remote sensing satellite, IRS-1A in 1988, along with its follow-up satellites, provided fillip to these activities mainly in India. The launch of IRS-1C in December 1995, with unique combination of sensors, has greatly improved extensive utilisation of satellite remote sensing for various facets of water management. This article presents a review of various applications carried out using IRS-1C data while highlighting the capabilities and advantage of IRS-1C sensors achieving significant improvement in mapping water bodies, inventory and monitoring of irrigated crops, irrigation system performance evaluation, assessment of reservoir sedimentation, mapping and monitoring of snow cover, snowmelt runoff forecasting, watershed developmental planning and management, etc.

Keywords IRS-1C · Water management · Remote sensing · Irrigation · Reservoir sedimentation · Snow hydrology · Hydropower

Introduction

Water, as an abundantly available natural resource, is potentially beneficial for agricultural, industrial, domestic, environmental and recreational activities. Water is inextricably linked to the development of all nations but unsustainable development and use of water resources are making it a scarce commodity. By 2030, global demand for water is expected to increase by 50%. Meanwhile, agriculture, which currently consumes around 70% of global water usage, is expected to experience a 70% increase in demand by 2050 (UNU-INWEH 2019). A recent research found that two-thirds of the Global population (4.0 billion people) live under conditions of severe water scarcity at least 1 month of the year (Mekonnen & Hoekstra 2016) and nearly half of those people live in India and China.

India is the second most populous country in the world. As per 2011 census, the total population of the country was 1,210,854,977, with more than 30% of them living in urban areas (Census of India Website 2013). The population of India is expected to increase to 151.8 crores by 2036, at the rate of 1.0 percent annually (National Commission on Population 2019). As the population grows, the demand for water increases and pressure on finite water resources intensifies. Climate change, which is also closely tied to population growth, will also lead to greater pressure on the availability of water resources. The estimated per capita average water availability is expected to decrease from 1434.13 m^3 in 2025 to 1219.02 m^3 in 2050 (Central Water Commission 2019). India has been ranked 40 among 180 countries based on baseline water stress index (3.58 out of

✉ K. Abdul Hakeem
abdulhakeem_k@nrsc.gov.in

[1] National Remote Sensing Centre, Indian Space Research Organisation, Hyderabad, India

5) that measures total annual water withdrawals expressed as a percentage of the total annual available blue water (Gassert et al 2013). India is ranked #13 on Aqueduct's list of "extremely highly" water stressed countries through Aqueduct^{TM} water risk framework, in which 13 water risk indicators including quantity, quality, and reputational risks are considered into a composite overall water risk score (Hofste et al 2019). Management of water resources in India has been a challenge whose magnitude has risen manifolds over the past 50 years due to a variety of reasons, notably the rising demands and growing environmental degradation (Jain 2019). Broadly, most of the challenges in Water Management in India can be categorized in the following groups: (a) water availability, variability and increasing withdrawals, (b) environment and quality, (c) water infrastructure construction, (d) water sharing disputes, (e) water governance and institutions and (f) challenges induced due to climate and anthropogenic changes. In order to address these challenges, comprehensive, reliable and easily accessible information on water resources demand, availability and utilisation is very essential. Towards this, remote sensing technology proved to be a viable source of information due to its unique advantage of synoptic and repetitive coverage. Due to their capability to image the spatial variations in the hydrometeorological variables and frequent temporal resolution sufficient to represent the dynamics of the hydrologic processes, remote sensing techniques have significantly changed the water resources assessment and management methodologies (Bastiaanssen 1998, Schmugge et al. 2002, Nagesh Kumar & Reshmidevi 2013, Xie & Wang 2018). Recent researches demonstrate the use of rapid advancements in technologies (Unmanned Aerial Vehicles in combination with Global Navigation Satellite Systems) to accurately, safely and efficiently establish river flow observation through remote and non-intrusive observation methods (Samboko et al 2020).

IRS-1C and its advantages

IRS-1C was the fourth Indian Remote Sensing Satellite built and designed by Indian Space Research Organisation (ISRO). It was considered to be the most advanced Satellite among contemporary satellites in the world, mainly by virtue of its capability to provide high resolution data and more frequent coverage from a combination of unique sensors (Kalyanaraman et al 1995; Kasturirangan et al 1996). It was for the first time that an Indian Remote Sensing satellite was designed as a global mission and the availability of data all over the world was ensured by establishing a network of ground stations. Launched on 28th December, 1995, IRS-1C offered the then remote sensing community, a unique combination of payloads consisting of three cameras: one operating in the panchromatic and the other two in the multispectral mode. The panchromatic camera (PAN) had a spatial resolution of 5.8 m, which was the highest offered during that time by any civilian remote sensing satellite orbiting the earth. The PAN camera operated in spectral range of 0.5–0.75 µm with a swath of 70 km, had across track stereo viewing capability with a revisit frequency of 5 days. The Linear Imaging Self Scanner (LISS-III) had four multispectral bands with spatial resolution of 23.5 m in visible and Near Infra-Red (NIR) bands and 70 m in Short-Wave Infra-Red (SWIR) band. The swath of LISS-III in visible and NIR bands was 141 km, while SWIR band had a swath of 148 km. The third unique sensor on-board IRS-1C was Wide Field Sensor (WiFS) with spatial resolution of 188 m and swath of 810 km, offering repeated coverage for any part of the globe once in every five days. WiFS had only two spectral bands, namely, Red and NIR. The satellite also had on-board data recording facilities to provide global coverage (Chandrasekhar et al. 1996).

The availability of multiple sensors on the same platform covering different regions of electromagnetic spectrum provided plethora of opportunities to use satellite data for natural resources monitoring and societal applications including the most dynamic water resources. Krishnamurthy and Rao (2017) detailed the historical development of remote sensing applications to natural resources, disaster management support and governance. While PAN camera with stereo viewing capability provided better digital elevation model for hydrologic modelling applications (Rao et al 1996, Gopala krishna et al. 1998, Bahuguna and Kulkarni 2005), LISS-III camera with visible, NIR and SWIR bands were of immense help to improve the separability of various types of crops (Raju et al 2007), study crop canopy water stress, snow cover, surface water logging (Dwivedi and Srinivas 1998), etc. The high repetivity of WiFS sensor with wide swath was expected to help in monitoring of natural resources and disaster events like flood, drought and forest fire. The availability of data with 5-day repetivity also expected to enable generation of spectral growth profiles of crops at different growth stages (Kasturirangan et al 1996). Subsequent launch of IRS-1D on 29th September, 1997 with similar payload configuration, improved the repetivity of coverage and resulted in higher probability of getting cloud-free images. Initial evaluation of IRS-1C satellite data has highlighted the exciting potential for improved Water Management through its repetitive coverage of dynamic changes and the capability to generate locale-specific details (Thiruvengadachari et al 1996).

Remote Sensing Applications for Water Management—Role of IRS-1C

Water Resources Management (WRM) for sustainable development throws many challenges in areas with sparse in-situ monitoring networks. The exponential growth of satellite based information over the past decade provides unprecedented opportunities to support and improve WRM. Satellite remote sensing is increasingly being used as a complementary source of information to in-situ monitoring networks and, in many cases, it is the only feasible source (Sheffield et al. 2018). Satellite remote sensing has been recognised in India as a useful tool, even before 1980s, for quick information gathering in many fields of resources management. One of the earliest studies in India applying satellite technologies to WRM was done way back in 1981 itself by Thiruvengadachari to distinguish areas irrigated by surface water and groundwater using LANDSAT imagery and was a good showcase of technological advancement. Subsequently, many significant works have been carried out in Hydrology and Water Resources Management related problems using the remote sensing data from LANDSAT satellites, airborne remote sensing and Indian experimental remote sensing satellites BHASKARA I & II. In particular, Bhavsar (1984) had found that these data are useful in surface water resources and flood-plain mapping, monitoring of sediment and water pollution, water management in command areas and ground water targeting. While the launch of LANDSAT-1 in 1972 initiated various remote sensing activities across the Globe, in India, Ramamoorthi et al. (1991) found that IRS-1A launched in March 1988 provided great fillip to Remote Sensing applications in Hydrology and Water Resources. Saindranath Jonna in his review (1999) stated that satellite remote sensing has been successfully used in the areas of water resources assessment, ground water targeting, flood management, irrigation water management, reservoir capacity surveys, assessment & monitoring of environmental impacts of water resources projects and water quality mapping and monitoring, with the launch of IRS-1C and 1D satellites during 1990s.

Multi-spectral and multi-spatial resolution data available from IRS-1C/1D platforms provided much-needed fillip to applications development in water resources. Synergistic availability of medium resolution multi-spectral data and high resolution panchromatic data led to various newer/ enhanced applications, integrating terrain and land cover for water resources related applications. Some of them are micro watershed level planning and development, impact evaluation of developmental activities (irrigation, watershed, etc.) at smaller spatial units (distributary/minor canal level, micro-watershed scale) and snow cover monitoring of Himalayan river basins (Krishnamurthy and Rao 2017). One of the significant developments is in hydrological process modelling: scaling up from lumped to distributed, thus enabling improved representation of parameter variability leading to more accurate hydrological fluxes estimation. The details on use of IRS-1C/1D satellite data for various domains of WRM are discussed in the following sections.

Irrigation Water Management

India invested significant proportion of State/Central outlays towards development of irrigation infrastructure. These investments helped the economic and social development of the country, and irrigation infrastructure development has progressively increased crop production thereby supporting national food security. However, these Indian irrigation systems, developed through huge investments of State/Central plans are typically characterised by low water use efficiency with high water demand for growing water intensive crops.

During early 80′s and 90′s, various programmes at National and State level have been initiated to improve the performance of existing irrigation systems. The objectives of these programmes are to provide reliable, predictable and equitable water supply to the entire command area. Some of these programmes are Command Area Development (CAD) programme, National Water Management Project (NWMP) and Water Resources Consolidation Project (WRCP). Through structural and management improvement measures, these programs aimed at improving irrigation service leading to higher irrigation utilisation and agricultural productivity. These programs also envisaged an effective monitoring and evaluation at various levels to provide information required for taking up improvement measures. Before taking up improvement measures of any system, it is necessary to know how well or poorly the system is performing, both at gross command level and at distributary/minor level. In most of the existing irrigation schemes, there is a serious lack of reliable and adequate information on system performance at micro level. Lenton (1986) commented that one of the extraordinary characteristics of irrigation projects is that a large number of projects generated revenue in far excess of the largest business corporate. The various phases of irrigation system interventions include baseline inventory, performance assessment, diagnostic analysis, and monitoring impact of interventions. The conventional approaches/ methodologies do not provide opportunities to study the whole to part (command level to individual canal) in identifying the problematic/low performing canal units. Satellite remote sensing data have unique advantage of synoptic coverage of entire command, yet providing spatial variability at dis-aggregated level (irrigation unit level) providing irrigation command inventory and performance assessment. IRS-1C with multi spectral and multi resolution observation capability has been applied through various studies supporting irrigation command management.

Jonna et al (1995) demonstrated the potential of IRS-1C through simulated WiFS data for concurrent monitoring of command area. Performance evaluation of 13 irrigation projects was conducted using multi-year satellite data to assess the impact of CAD programme in terms of cropping pattern, crop condition, crop productivity, identification and delineation of waterlogged and saline areas at disaggregated level (NRSA 2005). IRS-1C/1D LISS-III data of 1997–98 was conjunctively used to map the changes in crop/irrigation performance during pre and post CAD implementation. The impact of modernisation under National Water Management Project (NWMP) in Bhadra irrigation project was evaluated using time-series WiFS data by Sakthivadivel et al (1999). Twenty overpass dates during rice growth cycle proved valuable to evaluate the water distribution between the distributary commands during the rabi season (January to May). Raju et al (2007) assessed the changes in crop extent and irrigation utilisation in Upper Krishna Complex, Nagarjuna Sagar Project and Krishna Delta command during low and normal/good rainfall years using WiFS data. The high temporal coverage of WiFS helped in capturing the agricultural crop lands both in kharif and rabi seasons, thus providing annual irrigation utilisation. Spatial distribution of degraded areas in the catchment and potential cultivation areas in command areas were demarcated, in addition to the growth in the crop area during the past 30 years in Bhogawati River basin in India (Nagarajan and Suresh 2002). Multi-year satellite data of SPOT, LANDSAT TM and IRS-1C LISS-III were used to map the temporal changes in land use and performance assessment.

Environmental impact analysis of Dudhganga Dam was carried out using multi-year satellite data (Nagarajan 2000). The surface-cover status of the catchment, reservoir and dam site before-during-after the completion of water resources project was assessed. Impact of changes in cropping system on the exploitation of water resources in two districts, namely Ludhiana in central Punjab and Muktsar in South-Western Punjab was conducted using IRS-1D LISS-III and Radarsat data sets (Sood et al 2009). The study brought out the need of crop diversification for sustaining ground water table in these districts. Suresh Babu et al (2007) carried out benchmarking of Nagarjuna Sagar Left Canal Command (NSLC) using multi-year satellite data of 1990–91 and 1998–99 in terms of water utilisation index at canal level. IRS-1C with 5.8 m PAN camera provided the highest spatial resolution in conjunction with multi-spectral observations of 23.5 m LISS-III. This capability of IRS-1C led to development of newer approaches in extending the satellite data applications to finer spatial units. Murthy and Raju (1998) used PAN data for precise demarcation of water course (terminal irrigation channel) command which was used for subsequent analysis with LISS-III data. The study successfully demonstrated the methodology for accurate registration cadastral/chak maps with medium resolution satellite through complimentary use of high resolution panchromatic data from IRS-1C. This in turn enhanced capabilities of remote sensing technology for micro level inventory in irrigation systems.

Waterlogging and subsequent salinisation/alkalinisation are the major land degradation problems in irrigated commands in the arid and semi-arid regions. IRS-1C data with multi-spectral observation extending into SWIR region provided the capability to map surface water logged and salt affected lands in command areas. Dwivedi and Srinivas (1998) evaluated the potential of IRS-1C LISS-III data with that of IRS-1B LISS-II data for mapping salt affected soils and waterlogged areas in the Indo-Gangetic alluvial plains of northern India. Chatterjee et al (2003) used pre- and post-monsoon period IRS-1C LISS-III data during 1998–99 to delineate surface water logged areas in parts of Bihar. Verma et al (2008) assessed the impact of poor quality ground water on soils in terms of secondary salinisation and availability of soil nutrients in Faridkot district of Punjab in northern India.

Reservoir Sedimentation

Reservoir sedimentation is the gradual accumulation of the incoming sediment load from a river. This accumulation is a serious problem in many parts of the world and has severe consequences for water management, flood control, and production of energy. The worldwide loss in reservoir storage capacity is reported to be between 0.5% and 1.0% per annum (White 2000). The periodical assessment of sedimentation in a reservoir is required to determine the useful life of a reservoir. The conventional method of reservoir capacity survey is laborious, time consuming and costly in comparison to the capacity survey based on remote sensing techniques. The water-spread area of the reservoir reduces with the sedimentation at a given level and this natural process is utilised in estimation of reservoir capacity (Mani & Chakravorty 2007). With the launch of Indian Remote Sensing satellites in the 1980s and imagery becoming easily available, the extensive use of remote sensing technique for reservoir sedimentation survey began. The primary output from the analysis of remote sensing data is the surface area of the reservoir at different time periods which is used for capacity estimation using trapezoidal or prismoidal formula. The accuracy of the water spread area estimated depends on how correctly the water pixels are delineated, especially the land–water boundary pixels. The availability of LISS-III sensor onboard IRS-1C with better repetivity and resolution along with SWIR band reduced uncertainties leading to improved accuracies. This enlarged the scope of utilisation of remote sensing techniques for reservoir sedimentation survey and increased the frequency of survey over conventional methods.

Appreciating the gravity of sedimentation problems and urgent need to tackle them, Government of India constituted a Working Group for National Action Plan for Reservoir Sedimentation Assessment using Satellite Remote Sensing. The Working Group recommended and selected 124 reservoirs for sedimentation survey using satellite Remote sensing technique during Tenth Five-Year Plan (2002–07). This was executed by Central Water Commission (CWC), National Institute of Hydrology (NIH) and Central Water and Power Research Station (CWPRS) with the support of ISRO. A study of 23 reservoirs was undertaken to assess the sedimentation rate using the Remote Sensing method and results were documented in a series of reports (Jain et al. 2008a). Comparison of these results provided by the Remote Sensing method with those obtained using the hydrographic survey method showed that the results of the two techniques were generally within ± 4% (Jain & Jain 2009). There were many other studies carried out using IRS-1C LISS-III data including sedimentation assessment of Linganmakki, Hirakud and Bargi reservoirs (Durbude & Purandara 2005; Rathore et al 2006; Goel et al 2002). Satellite data of IRS-1C PAN were also used to estimate water spread area of Singoor reservoir for comparing the results obtained from LISS-III sensors (Shanmuga Priyaa et al 2018). Even though designed for a life period of 3 years (eoPortal Directory Website 2000), both IRS-1C and IRS-1D outlived the expectations and continued to provide images for more than 10 years. Such long-term data ensured continuity of information and also enabled analysis of sedimentation process over time in Hirakud reservoir (Raju & Abdul Hakeem 2007).

Snow Hydrology

The Himalaya Mountains located in northern part of India holds one of the largest resources of fresh water in the form of snow and ice. A significant portion of the low flow contribution of Himalayan Rivers during the lean season (April-May-June) is from snow and glaciers melt. The runoff supplies communities with water for drinking, irrigation, hydropower and industry, and is also vital for maintaining river and riparian habitat (Abdul Hakeem & Siva Sankar 2010). Melt water from the Himalayan region is important for generation of hydropower and sustainability of Himalayan bio-diversity and environment. Monitoring of the Himalayan snow and glaciers is important in view of its hydrological significance and also the associated natural hazards like avalanches, bursting of high altitude lakes and consequent flooding downstream, mass wasting and debris flow, etc. leading to several disasters in the region (SAC 2016). Remote sensing was used to generate snow-covered area as critical input in snowmelt runoff studies using Advanced Very High Resolution Radiometer (AVHRR) imageries of NOAA (Ramamoorthi 1983). However, the limitation of AVHRR for estimating snow cover areal extent in medium sized Himalayan basins such as Sutlej was overcome with the launch of WiFS onboard IRS-1C due to its improved spatial resolution and wide swath (Thiruvengadachari et al 1996). In addition to this, LISS-III with high spatial resolution and additional band in SWIR helped in snow cover mapping in very small basins (up to 100 km^2) and discriminating snow from cloud. Long-term data of 33 images from IRS-1C/1D LISS-III sensor for the period 2001–2008 were used to monitor Gangotri glacier in the Ganga basin (Negi et al 2012). The study observed an overall decreasing trend in the areal extent of seasonal snow cover area. Many other studies have also shown the potential of IRS-1C for snow cover mapping (Jain & Chaudhry 2003; Jain et al 2008b).

The Himalaya contains about 5000 glaciers of varying extents, covering an area of approximately 38,000 km^2 (Kaul, 1999). The glaciers of the Himalaya contribute to varying degree for the overall river runoff in South Asia. The highest contribution is from the Indus River which originates in the north-west Himalaya (Immerzeel et al, 2010). Precise information about the extent and distribution of glaciers is needed for many research applications like water resource management, mitigation of glacial hazards and estimation of the past and the future contributions of glaciers to sea-level change (Rastner et al 2014). Mapping of glaciers for inventory, monitoring and various other purposes have been carried out using remote sensing techniques. Studies were carried out for mapping glaciers in different basins of Himalayas like Chenab (Shukla, A et al. 2009a), Tista (Bahuguna et al 2001, Basnett et al. 2013) and Bhaga (SAC 2016) using IRS-1C LISS-III data. Few studies used stereo capability of IRS-1C PAN sensor for monitoring the changes in glacier dimensions/retreat in Basapa valley (Bahuguna et al 2004; Bahuguna & Kulkarni 2005) as well as Gangotri glacier (Bahuguna et al 2007).

Watershed Management

Integrated watershed development aims at optimal and sustainable management of natural resources leading to ecological balance (Singh 1990, NRSA 1995). RS& GIS technology is an efficient tool for generation of systematic geo-database comprising various thematic maps (such as land use/land cover, slope, rock types, landforms) required for watershed developmental planning, management and monitoring. The synergistic availability of 23.5 m multi-spectral data (LISS-III) and 5.8 m panchromatic data provided newer opportunities in extending remote sensing applications to smaller spatial units and led to newer studies such as watershed characterisation, resources mapping, integrated planning and management. Various studies reported the application potential of LISS-III and PAN data in watershed management. Prioritisation watersheds through morphometric analysis of drainage (Biswas et al 1999), morphometric and land use analysis (Suresh et al 2004; Javed et al 2009), delineation and watershed parameterisation (Pandey et al. 2006), erosion in river island (Mani et al. 2003), site suitability for water conservation & harvesting structures at micro-watersheds (Saptarshi and Raghavendra 2009; Singh et al 2009; Varade et al 2013), characterisation and management of micro-watershed (Shukla et al. 2009b), watershed prioritization and reservoir sedimentation (Katiyar et al 2006), impact assessment of watershed development programme (Shanwad et al 2008).

The temporal multi-spectral data in combination with toposheets helped to make an inventory of soil resources, diagnose degradation status and assess the potential of the soils (Saxena et al. 2000). Chowdary et al (2004) modelled non-point source pollution from watershed. Solanke et al (2005) used IRS-IC PAN merged LISS-III data to prepare maps of watershed characteristics in terms of land capability, land irrigability, cotton suitability and action plan for taking appropriate soil conservation and management measures for optimum utilization of the resources. Arun et al (2005) used LISS-III data and Digital Elevation Model (DEM) to derive Agricultural Hydrologic Response Units for estimating their resources condition and capability.

Summary

With the launch of IRS-1C and 1D satellites during 1990s, potential use of Satellite Remote Sensing increased exponentially expanding into the areas of water resources assessment, ground water targeting, flood management, irrigation water management, reservoir capacity surveys, assessment and monitoring of environmental impacts of water resources projects and water quality mapping and monitoring. Synergistic availability of medium resolution multi-spectral data and high resolution panchromatic data led to various newer/enhanced applications integrating terrain and land cover for water resources related applications. IRS-1C and 1D outlived the expectations to provide images beyond 10 years that ensured continued availability of information.

IRS-1C/1D LISS-III data were found useful in capturing the changes in crop/irrigation performance during pre & post CAD implementation. The impact of modernisation under National Water Management Project (NWMP) in irrigation projects could be evaluated using time-series WiFS data. The high temporal coverage of WiFS helped in capturing the agricultural crop lands both in kharif and rabi seasons, thus providing annual irrigation utilisation. IRS-1C enhanced the capabilities of remote sensing technology for micro level inventory in irrigation systems. IRS-1C data with multi-spectral observation extending into SWIR region provided the capability to map surface water logged and salt affected lands in command areas.

The accuracy of estimation of reservoir surface area needed to arrive at reservoir capacity depends on how correctly the water pixels are delineated, especially the land–water boundary pixels. The availability of LISS-III sensor with better repetivity and resolution along with SWIR band enabled to overcome these issues. This enlarged the scope of utilisation of remote sensing techniques for reservoir sedimentation survey and increased the frequency of survey over conventional methods. IRS-1C and IRS-1D continued to provide images for more than 10 years which enabled analysis of sedimentation process over long time periods.

Due to improved spatial resolution and wide swath of IRS-1C WiFS, the limitation of AVHRR in estimating snow cover areal extent of medium sized Himalayan basins was overcome. In addition to this, LISS-III with high spatial resolution and additional band in SWIR helped in snow cover mapping of very small basins (up to 100 km^2) and in discriminating snow from cloud. The stereo capability of IRS-1C PAN was found to be useful for monitoring the changes in glacier dimensions/retreat.

The synergistic availability of 23.5 m multi-spectral data from LISS-III and 5.8 m high resolution PAN data apart from higher temporal resolution WiFS data provided newer opportunities in extending Remote Sensing applications more periodically to smaller spatial units and this led to newer studies such as watershed characterisation, resources mapping, integrated planning and management. Various studies reported the application potential of LISS-III in watershed management including prioritisation of watersheds. IRS-IC PAN merged LISS-III data were used to prepare maps of watershed characteristics in terms of land capability, land irrigability, crop suitability and action plan for taking appropriate soil conservation and management measures for optimum utilisation of the resources. LISS-III data and DEM were used to derive agricultural hydrologic response units in estimating condition and capability the resources.

While IRS-1C was the only mission with multi-resolution imaging capability in a single platform at the time of its launch, the sensors specifications were not fully meeting the information requirements of water management. Some of the gaps in application potential of IRS-1C data were: irrigation infrastructure mapping, flood inundation modelling through medium/fine resolution, minor irrigation studies, village & field scale irrigated agriculture applications, snow cover mapping, etc. The non-availability of SWIR band in WiFS sensor restricted its usability in snow-cloud discrimination, crop water stress studies, etc. However, these application requirements were systematically addressed through enhanced sensor data from subsequent Indian satellite missions like Resourcesat & Cartosat series with many newer features—the advanced imaging sensors, the more precise attitude and orbit determination systems, the satellite positioning system on-board, the mass storage devices and many other features (Seshadri et al. 2005).

Conclusions

IRS-1C/1D were considered to be the most advanced Satellites among all contemporary satellites in the world, mainly by virtue of their capability to provide high-resolution data and more frequent coverage from a combination of unique sensors (Senthil Kumar et al 2020). The PAN camera with stereo viewing capability provided digital elevation model for hydrologic modelling applications. The LISS-III camera with visible, NIR and SWIR bands were of immense help to improve the separability of various types of surface features like crops, useful in estimation of cropped area, water stress, snow cover, surface water logging, etc. The high repetivity of WiFS sensor with wide swath was found useful in monitoring natural resources and disaster events like flood, drought and forest fire. IRS-1C provided much needed fillip to the potential of remote sensing for improved water management through its unique capability to capture local & regional scale details with high spatial and spectral resolution.

Acknowledgements The authors would like to thank the editors of the special issue on IRS-1C for extending invitation to submit this review article. The authors place on record sincere gratitude to all the present and past senior colleagues of Water Resources Group (WRG) in National Remote Sensing Agency (NRSA) / Centre (NRSC) for their support and contribution during execution of various activities referred in this article. Authors also appreciate and acknowledge Group Directors of WRG, Deputy Directors and Directors of NRSA/NRSC for their encouragement and technical guidance during all these years. The authors express their sincere appreciation for the insightful comments provided by anonymous reviewers which improved this manuscript.

References

eoPortal Directory Website (2000). Satellite Missions: Missions Database: IRS-1C/1D (Indian Remote Sensing Satellites-1C/1D). Directory of Satellite Missions: Observation of the Earth and its Environment. https://directory.eoportal.org/web/eoportal/satellite-missions/i/irs-1c-1d. Accessed 25 September 2020.

Abdul Hakeem, K. & Siva Sankar, E. (2010). Remote sensing inputs for snowmelt runoff modelling and glacial lakes mapping. In *Conference: International Symposium on Benefiting from Earth Observation: Bridging the Data Gap for Adaptation to Climate Change in the Hindu Kush-Himalayan Region*, Kathmandu, Nepal

Arun, P. S., Jana, R., & Nathawat, M. S. (2005). A Rulebase physiographic characterization of a drought prone watershed applying remote sensing and GIS. *Journal of the Indian Society of Remote Sensing, 33*(2), 189–201. https://doi.org/10.1007/BF02990035.

Bahuguna, I. M., & Kulkarni, A. V. (2005). Application of digital elevation model and orthoimages derived from IRS-1C PAN stereo data in monitoring variations in glacial dimensions. *Journal of the Indian Society of Remote Sensing, 33*(1), 107–112. https://doi.org/10.1007/BF02989998.

Bahuguna, I. M., Kulkarni, A. V., Arrawatia, M. L. & Shresta, D. G. (2001). Glacier atlas of Tista basin (Sikkim Himalaya). Report. Ahmedabad: Space Application Centre, SAC/RESA/MWRG-GLI/SN/16/2001

Bahuguna, I. M., Kulkarni, A. V., & Nayak, S. (2004). Technical Note: DEM from IRS-1C PAN stereo coverages over Himalayan glaciated region—accuracy and its utility. *International Journal of Remote Sensing, 25*(19), 4029–4041. https://doi.org/10.1080/01431160310001652376.

Bahuguna, I. M., Kulkarni, A. V., Nayak, S., Rathore, B. P., Negi, H. S., & Mathur, P. (2007). Himalayan glacier retreat using IRS-1C PAN stereo data. *International Journal of Remote Sensing, 28*(2), 437–442. https://doi.org/10.1080/01431160500486674.

Basnett, S., Kulkarni, A., & Bolch, T. (2013). The influence of debris cover and glacial lakes on the recession of glaciers in Sikkim Himalaya India. *Journal of Glaciology, 59*(218), 1035–1046. https://doi.org/10.3189/2013JoG12J184.

Bastiaanssen, W. G. M. (1998). Remote Sensing in Water Resources Management: The State of the Art. Report. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Bhavsar, P. D. (1984). Review of remote sensing applications in hydrology and water resources management in India. *Advances in Space Research, 4*(11), 193–200.

Biswas, S., Sudhakar, S., & Desai, V. R. (1999). Prioritisation of subwatersheds based on morphometric analysis of drainage basin: a remote sensing and GIS approach. *Journal of the Indian Society of Remote Sensing, 27*(3), 155–166. https://doi.org/10.1007/BF02991569.

Census of India Website (2013).Tabulations Plan of Census Year - 2011. New Delhi: Office of the Registrar General & Census Commissioner. https://censusindia.gov.in/DigitalLibrary/TablesSeries2001.aspx Accessed 18 September 2020.

Central Water Commission (2019).Water and Related Statistics. Report. New Delhi: Information System Organisation, Water Planning & Project Wing, Central Water Commission.

Chandrasekhar, M. G., Jayaraman, V., & Rao, M. (1996). Indian remote sensing satellites: Planned missions and future applications. *Acta Astronautica, 38*(4–8), 647–658. https://doi.org/10.1016/0094-5765(96)00022-7.

Chatterjee, C., Kumar, R., & Mani, P. (2003). Delineation of surface waterlogged areas in parts of Bihar using IRS-1C LISS-III data.

Journal of the Indian Society of Remote Sensing, 31(1), 57–65. https://doi.org/10.1007/BF03030752.

Chowdary, V. M., Yatindranath, Kar, S., & Adiga, S. (2004). Modelling of non-point source pollution in a watershed using remote sensing and GIS. *Journal of the Indian Society of Remote Sensing, 32*(1), 59–73. https://doi.org/10.1007/BF03030848.

Durbude, D. G., & Purandara, B. K. (2005). Assessment of sedimentation in the Linganmakki Reservoir using remote sensing. *Journal of the Indian Society of Remote Sensing, 33*(4), 503–509. https://doi.org/10.1007/BF02990735.

Dwivedi, R. S., & Sreenivas, K. (1998). Delineation of salt-affected soils and waterlogged areas in the Indo-Gangetic plains using IRS-1C LISS-III data. *International Journal of Remote Sensing, 19*(14), 2739–2751. https://doi.org/10.1080/014311698214488.

Gassert, F., Reig, P., Luo, T. & Maddocks, A. (2013). Aqueduct country and river basin rankings: a weighted aggregation of spatially distinct hydrological indicators. Working paper. Washington, DC: World Resources Institute. https://www.wri.org/publication/aqueduct-country-and-river-basin-rankings. Accessed 7 September 2020.

Goel, M. K., Jain, S. K., & Agarwal, P. K. (2002). Assessment of sediment deposition rate in Bargi Reservoir using digital image processing. *Hydrological Sciences Journal, 47*(sup1), S81–S92. https://doi.org/10.1080/02626660209493024.

Gopala Krishna, B., Iyer, K.V., Goswamy, A., Alurkar, M., Rana, Y.P., Srivastava, P.K. & Majumdar, K.L., (1998). Approach for generation of Digital Elevation Models (DEM) and orthoimages from IRS-1C stereo data. *International Archives of Photogrammetry and Remote Sensing*, ISPRS Archives - Volume XXXII Part 1, pp. 164-171.

Hofste, R., Kuzma, S., Walker, S., Sutanudjaja, E.H., et al (2019). Aqueduct 3.0: Updated Decision-Relevant Global Water Risk Indicators. Technical Note. Washington, DC: World Resources Institute. Available online at: https://www.wri.org/publication/aqueduct-30

Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the asian water towers. *Science, 328*(5984), 1382–1385. https://doi.org/10.1126/science.1183188.

Jain, S. K. (2019). Water resources management in India - challenges and the way forward. *Current Science, 117*(4), 569–576. https://doi.org/10.18520/cs/v117/i4/569-576.

Jain, S. K., & Chaudhry, A. (2003). Snow and forest cover assessment of Uttaranchal state using IRS-1C WiFS data. *Journal of the Indian Society of Remote Sensing, 31,* 91–99. https://doi.org/10.1007/BF03030776.

Jain, S. K., Goel, M. K., Rathore, D. S., Rao, Y. R. S., Durbude, D., Nayak, T. R., Purendra, B. K., Galkate, R., Jaiswal, R. & Jeyakanthan, V. S. (2008a). Assessment of sedimentation rate of reservoirs using remote sensing techniques. Report Number CS/AR-1/2007–2008, National Institute of Hydrology, Roorkee, India.

Jain, S. K., Goswami, A., & Saraf, A. K. (2008). Accuracy assessment of MODIS, NOAA and IRS data in snow cover mapping under Himalayan conditions. *International Journal of Remote Sensing, 29*(20), 5863–5878. https://doi.org/10.1080/01431160801908129.

Jain, S. K. & Jain, S. K. (2009). Assessment of reservoir sedimentation using remote sensing. *Sediment Problems and Sediment Management in Asian River Basins*, IAHS Publication No. 349. pp.163-170

Javed, A., Khanday, M. Y., & Ahmed, R. (2009). Prioritization of sub-watersheds based on morphometric and land use analysis using remote sensing and GIS techniques. *Journal of the Indian Society of Remote Sensing, 37,* 261–274. https://doi.org/10.1007/s12524-009-0016-8.

Jonna S. (1999). Remote sensing applications to water resources: Retrospective and prospective. In *National Symposium on "Remote Sensing Applications for Natural Resources: Retrospective and Perspective"* (pp. 19–21), Bangalore, Jan, 1999

Jonna, S., Abdul Hakeem, K., Murthy, C. S., Raju, P. V., & Chari, S. T. (1995). Evaluation of simulated IRS-1C WiFS data for concurrent monitoring of command areas at disaggregated level. *Journal of the Indian Society of Remote Sensing, 23*(1), 185–194. https://doi.org/10.1007/BF03024499.

Kalyanaraman, S., Rajangam, R. K., & Rattan, R. (1995). Indian remote sensing spacecraft - 1C/1D. *International Journal of Remote Sensing, 16*(5), 791–799. https://doi.org/10.1080/01431169508954443.

Kasturirangan, K., Aravamudan, R., Deekshatulu, B., Joseph, G., & Chandrasekhar, M. (1996). Indian remote sensing satellite (IRS)-1C - The beginning of a new era. *Current Science, 70*(7), 495–500.

Katiyar, R., Garg, P. K., & Jain, S. K. (2006). Watershed Prioritization and reservoir sedimentation using remote sensing data. *Geocarto International, 21*(3), 55–60. https://doi.org/10.1080/10106040608542393.

Kaul, M. K. (1999). *Inventory of the Himalayan glaciers: a contribution to the international hydrological programme*. Kolkata: Geological Survey of India, GSI Special Publication 34.

Krishnamurthy, Y. V. N., & Rao, P. V. N. (2017). Indian Satellite Remote Sensing: Focus on Selected Applications and Societal Needs. *Proceedings of the National Academy of Sciences, India - Section A: Physical Sciences, 87,* 487–502. https://doi.org/10.1007/s40010-017-0430-1.

Lenton, R. L. (1986). On the development and use of improved methodologies for irrigation management. Chapter 2. In K. C. Nobe & R. K. Sampath (Eds.), *Irrigation management in developing countries: current issues and approaches* (pp. 47–66). Boulder: Westview Press.

Mani, P., & Chakravorty, B. (2007). Remote sensing based sedimentation study of Maithon reservoir. *Journal of the Indian Society of Remote Sensing, 35*(1), 117–120. https://doi.org/10.1007/BF02991840.

Mani, P., Kumar, R., & Chatterjee, C. (2003). Erosion study of a part of Majuli River-Island using remote sensing data. *Journal of the Indian Society of Remote Sensing, 31*(1), 12–18. https://doi.org/10.1007/BF03030747.

Mekonnen, M. M. & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science Advances*, https://doi.org/10.1126/sciadv.1500323

Murthy, C.S. & Raju, P. V. (1998). Performance evaluation of water courses: A study in Bhakra canal command area, Haryana state, India using remote sensing data. Project Report. Hyderabad: National Remote Sensing Agency, June 1998, p. 66.

Nagarajan, R. (2000). Environmental impact analysis of Dudhganga Dam in India—a multi-temporal remote sensing approach. *International Journal of Remote Sensing, 21*(3), 483–497. https://doi.org/10.1080/014311600210704.

Nagarajan, R., & Suresh, M. (2002). Performance assessment of water resource project using remote sensing and a Geographical Information System—a case study. *International Journal of Remote Sensing, 23*(20), 4475–4485. https://doi.org/10.1080/01431160110104719.

Nagesh Kumar, D., & Reshmidevi, T. V. (2013). Remote sensing applications in water resources. *Journal of the Indian Institute of Science, 93*(2), 163–187.

National Commission on Population (2019). Population Projections for India and States 2011–2036. Report of the Technical Group on Population Projections. New Delhi: Ministry of Health& Family Welfare.

Negi, H. S., Thakur, N. K., Ganju, A. & Snehmani. (2012). Monitoring of Gangotri glacier using remote sensing and ground observations. *Journal of Earth System Science*, 121, 855–866. DOI: https://doi.org/10.1007/s12040-012-0199-1

NRSA. (1995). Integrated Mission for Sustainable Development (IMSD) Technical Guidelines. Project Report. Hyderabad: National Remote Sensing Agency, Dept. of Space, Govt. of India.

NRSA. (2005). Satellite Remote Sensing Based Evaluation Study of Irrigation Projects Covered Under CAD Programme. Project Report. Hyderabad: National Remote Sensing Agency, March 2005, p. 94. NRSA-RS&GISAA-PR-696-CONCUSIONS-R02.

Pandey, V. K., Panda, S. N., Raghuwanshi, N. S., & Sudhakar, S. (2006). Delineation and parameterization of Banikdih watershed using remote sensing and AVSWAT model. *Journal of the Indian Society of Remote Sensing, 34*(2), 143–152. https://doi.org/10.1007/BF02991819.

Raju, P.V. & Abdul Hakeem, K. (2007). Satellite Data Based Updation of Elevation-Area Capacity Curves and Sedimentation Assessment of Hirakud Reservoir, Orissa State for the Year 2005-06. Project Report. Hyderabad: National Remote Sensing Agency, p. 49. NRSA/RS&GIS-AA/WRD/HRK-SED/PR/R1/ Dec '07.

Raju, P.V., Abdul Hakeem, K. & Saindranath Jonna (2007). Assessment of Agricultural Crop Lands in Parts of Krishna River Basin using IRS WiFS Data. Project Report. Hyderabad: National Remote Sensing Agency, February 2007, p. 120. NRSA/RS&GIS-AA/WRD/ISWR/PR/R1/Feb '07.

Ramamoorthi, A. S. (1983). Snow-melt run-off studies using remote sensing data. *Proceedings of the Indian Academy of Sciences Section C: Engineering Sciences, 6,* 279–286. https://doi.org/10.1007/BF02842888.

Ramamoorthi, A., Thiruvengadachari, S., & Kulkarni, A. V. (1991). IRS-1A applications in Hydrology and Water Resources. *Current Science, 61*(3 & 4), 180–188.

Rao, M. T. C., Venugopalarao, K., Ravikumar, A., Rao, D. P., & Deekshatulu, B. L. (1996). Digital terrain model (DTM) from Indian remote sensing (IRS) satellite data from the overlap area of two adjacent paths using digital photogrammetric techniques. *Photogrammetric Engineering and Remote Sensing, 62*(6), 727–731.

Rastner, P., Bolch, T., Notarnicola, C., & Paul, F. (2014). A Comparison of Pixel-And Object-Based Glacier Classification with Optical Satellite Images. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 7*(3), 853–862. https://doi.org/10.1109/JSTARS.2013.2274668.

Rathore, D. S., Choudhary, A., & Agarwal, P. K. (2006). Assessment of sedimentation in Hirakud reservoir using digital remote sensing technique. *Journal of the Indian Society of Remote Sensing, 34,* 377–383. https://doi.org/10.1007/BF02990922.

SAC. (2016). Monitoring Snow and Glaciers of Himalayan Region, Space Applications Centre, ISRO, Ahmedabad, India, 413 pages, ISBN: 978-93-82760-24-5

Sakthivadivel, R., Thiruvengadachari, S. & Amarasinghe, U. A. (1999). Modernization using the structured system design of the Bhadra Reservoir Project, India: an intervention analysis. Colombo, Sri Lanka: International Water Management Institute (IWMI) v, 24p. (IWMI Research Report 033). https://doi.org/10.3910/2009.040

Samboko, H. T., Abas, I., Luxemburg, W. M. J., Savenije, H. H. G., Makurira, H., Banda, K., & Winsemius, H. C. (2020). Evaluation and improvement of remote sensing-based methods for river flow management. *Physics and Chemistry of the Earth, Parts A/B/C, 117,* 102839. https://doi.org/10.1016/j.pce.2020.102839.

Saptarshi, P. G., & Raghavendra, R. K. (2009). GIS-based evaluation of micro-watersheds to ascertain site suitability for water conservation structures. *Journal of the Indian Society of Remote Sensing, 37,* 693–704. https://doi.org/10.1007/s12524-009-0057-z.

Saxena, R. K., Verma, K. S., Chary, G. R., Srivastava, R., & Barthwal, A. K. (2000). IRS-1C data application in watershed characterization and management. *International Journal of Remote Sensing, 21*(17), 3197–3208. https://doi.org/10.1080/014311600750019822.

Schmugge, T. J., Kustas, W. P., Ritchie, J. C., Jackson, T. J., & Rango, A. (2002). Remote sensing in hydrology. *Advances in Water Resources, 25*(8–12), 1367–1385. https://doi.org/10.1016/S0309-1708(02)00065-9.

Senthil Kumar, A., Aparna, N., & Nayak, S. R. (2020). Remembering IRS-1C Mission: The "Game Changer" of Indian Earth Observation Program. *Journal of the Indian Society of Remote Sensing*. https://doi.org/10.1007/s12524-020-01183-8.

Seshadri, K. S. V., Rao, M., Jayaraman, V., Thyagarajan, K., & Sridhara Murthi, K. R. (2005). Resourcesat-1: A global multi-observation mission for resources monitoring. *Acta Astronautica, 57*(2–8), 534–539. https://doi.org/10.1016/j.actaastro.2005.03.050.

Shanmuga Priyaa, S., Jeyakanthan, V. S., Heltin Genitha, C., & Sanjeevi, S. (2018). Estimation of water-spread area of singoor reservoir, southern India by super resolution mapping of multispectral satellite images. *Journal of the Indian Society of Remote Sensing, 46*(1), 121–130. https://doi.org/10.1007/s12524-017-0666-x.

Shanwad, U. K., Patil, V. C., Gowda, H. H., & Dasog, G. S. (2008). Application of remote sensing technology for Impact Assessment of Watershed Development Programme. *Journal of the Indian Society of Remote Sensing, 36,* 375–386. https://doi.org/10.1007/s12524-008-0037-8.

Sheffield, J., Wood, E. F., Pan, M., Beck, H., Coccia, G., Serrat-Capdevila, A., & Verbist, K. (2018). Satellite remote sensing for water resources management: Potential for supporting sustainable development in data-poor regions. *Water Resources Research, 54,* 9724–9758. https://doi.org/10.1029/2017WR022437.

Shukla, A., Gupta, R., & Arora, M. (2009). Estimation of debris cover and its temporal variation using optical satellite sensor data: A case study in Chenab basin Himalaya. *Journal of Glaciology, 55*(191), 444–452. https://doi.org/10.3189/002214309788816632.

Shukla, E. A., Prasad, J., Nagaraju, M. S. S., Srivastava, R., & Kauraw, D. L. (2009). Use of remote sensing in characterization and management of Dhamni micro-watershed of Chandrapur district of Maharashtra. *Journal of the Indian Society of Remote Sensing, 37,* 129–137. https://doi.org/10.1007/s12524-009-0004-z.

Singh, G., Venkataramanan, C., Sastry, G., & Joshi, B. P. (1990). *Manual of soil and water conservation practices* (p. 385). New Delhi: Oxford & IBH Publishing Company.

Singh, J. P., Singh, D., & Litoria, P. K. (2009). Selection of suitable sites for water harvesting structures in Soankhad watershed, Punjab using remote sensing and geographical information system (RS&GIS) approach—A case study. *Journal of the Indian Society of Remote Sensing, 37,* 21–35. https://doi.org/10.1007/s12524-009-0009-7.

Solanke, P. C., Srivastava, R., Prasad, J., Nagaraju, M. S. S., Saxena, R. K., & Barthwal, K. (2005). Application of remote sensing and GIS in watershed characterization and management. *Journal of the Indian Society of Remote Sensing, 33*(2), 239–244. https://doi.org/10.1007/BF02990041.

Sood, A., Choudhury, B. U., Ray, S. S., Jalota, S. K., Sharma, P. K., & Panigrahy, S. (2009). Impact of cropping pattern changes on the exploitation of water resources: A remote sensing and GIS approach. *Journal of the Indian Society of Remote Sensing, 37,* 483–491. https://doi.org/10.1007/s12524-009-0033-7.

Suresh Babu, A. V., Venkateshwar Rao, V., & Muralikrishna, I. V. (2007). Satellite remote sensing derived spatial water utilisation index (WUI) for benchmarking of irrigation systems. *Journal of the Indian Society of Remote Sensing, 35*(1), 81–91. https://doi.org/10.1007/BF02991836.

Suresh, M., Sudhakar, S., Tiwari, K. N., & Chowdary, V. M. (2004). Prioritization of watersheds using morphometric parameters and assessment of surface water potential using remote sensing. *Journal of the Indian Society of Remote Sensing, 32*(3), 249–259. https://doi.org/10.1007/BF03030885.

Thiruvengadachari, S. (1981). Satellite sensing of irrigation pattern in semiarid areas: An Indian study. *Photogrammetric Engineering and Remote Sensing, 47*(10), 1493–1499.

Thiruvengadachari, S., Jonna, S., Hakeem, K. A., Raju, P. V., Bhanumurthy, V., Rao, G. S., et al. (1996). Improved water management: The IRS-1C contribution. *Current Science, 70*(7), 589–599.

UNU-INWEH (2019).Water-Related Sustainable Development Goals, *Accelerating Success for Water-related Sustainable Development Goals*. Hamilton, Canada: United Nations University Institute for Water, Environment and Health. https://inweh.unu.edu/projects/water-related-sustainable-development-goals/ Accessed 17 September 2020.

Varade, A. M., Khare, Y. D., Mondal, N. C., Muley, S., Wankawar, P., & Raut, P. (2013). Identification of water conservation sites in a watershed (WRJ-2) of Nagpur District, Maharashtra using geographical information system (GIS) technique. *Journal of the Indian Society of Remote Sensing, 41*(3), 619–630. https://doi.org/10.1007/s12524-012-0232-5.

Verma, V. K., Setia, R. K., Sharma, P. K., & Singh, H. (2008). Geoinformatics as a tool for the assessment of the impact of ground water quality for irrigation on soil health. *Journal of the Indian Society of Remote Sensing, 36*(1), 273–281. https://doi.org/10.1007/s12524-008-0028-9.

White, W. R. (2000). Contributing paper: Flushing of sediments from reservoirs. *Prepared for thematic review IV5: operation, monitoring and decommissioning of dams.* Cape Town: World Commission on Dams.

Xie, H. & Wang, X (Eds.) (2018). Applications of Remote Sensing/GIS in Water Resources and Flooding Risk Managements. *Special Issue published in Water*. https://doi.org/10.3390/books978-3-03842-981-4

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.