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10 Geospatial Technology Applications in Forest Hydrology

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10.1 Introduction

Two separate disciplines, hydrology and forestry, together constitute 'forest hydrology'. It is obvious that forestry and forest hydrology disciplines are spatial entities. Forestry is the science that seeks to understand the nature of forests through their life cycle and interactions with the surrounding environment. Forest hydrology includes forest soil water, streams and other small waterbodies encompassed by forest cover, and the hydrological cycle itself within a forested land cover. 'Forest' and (forest) 'Water' are two standardized land cover mapping classifications of the National Land Cover Database (NLCD) used by environmental planners in the USA (USGS LCI, 2015), CORINE (Co-ORdinated INformation on the Environment) data sets (EEA, 2006) established and used by the European Community, and other countries' national land cover mapping systems for developing an environmental management decision support system (DSS).

In Europe in general, and in France as an example, forest management (private and public) started earlier than in the USA. Since the 14th century, regulations and laws have been enacted in France to manage forests as a strategic resource (Morin, 2010) for timber production, for energy to sustain proto-industry's (steel production) needs and as a financial resource to raise funds for any purpose, including funding wars. Since the 18th century, forest management has been conducted in the USA as an ecosystem management approach while still including timber and fibre production as an important goal (Richmond, 2007).

Systemic forest management in the Indian subcontinent started late under the British colonial rule with establishment of the Imperial Forest Department in India in 1864 (Ramakrishnan *et al.*, 2012). An estimated 200+ million people in India depend on forests for their livelihoods in the form of fodder, fuelwood, increased agricultural growth through forest humus production and transportation to agricultural land with runoff and soil moisture conservation, and ecosystem services. In the Korean peninsula, however, unlike most of the Asian countries, forests are managed by private and public participation as done in the USA and Europe (Lee and Lee, 2005). Private and public participation in forest and forest hydrology management has its advantages (Lee and Lee, 2005). Therefore, due to its spatial discipline and recent proven management strategies, all together, forestry, and especially forest hydrology, could be managed well

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worldwide with the involvement of the respective governments and the availability of a sound DSS based on a geospatial technology (GT) application such as remote sensing (RS), geographic information systems (GIS), global navigation satellite systems (GNSS) and information technology (IT).

Forest hydrology can be managed by GT with the sound management decision support of water, soil, wildlife and environmental resources within the forest land cover. It is humanly impossible to deal with or analyse features of larger areas (like forests or their smaller fragments) for accurate management decision making, because site-specific forest management decision support (SSFMDS) based on scouting only would take years. Management of forests to support silviculture involves large-scale spatial and tabular (attribute) data (gigabytes or even terabytes) and numerous SSFMDS parameters including soil, climatologic, hydrological and crop growth attributes. This inherent data volume and intricacy related to SSFMDS, and especially forest hydrology phenomena, can be effectively and efficiently monitored using GT as conducted and well documented for site-specific crop management (von Gadow and Bredenkamp, 1992; Panda *et al.*, 2010). In fact, GT, especially GIS, has become a fundamental part of forestry management in many commercial forestry enterprises (Austin and Meyers, 1996). Currently, applications of advanced RS technologies such as ultra-high (<1 m) spatial resolution ortho- or satellite images, hyperspectral images and radio detection and ranging (RADAR) data have been extremely useful in the effective management of forest hydrology. Unmanned aerial vehicles (UAV) and unmanned aircraft systems (UAS) are making forest hydrology management more efficient through the acquisition of centimetre-scale spatial resolution images with user-specified bandwidths – thus helping in SSFMDS by mapping soil moisture, plant stomatal conductance, canopy temperature and leaf area index (LAI) to measure forest evapotranspiration (ET) and by monitoring forest fires (Grenzdörffer *et al.*, 2008).

GT, through raster imagery acquisition and mapping, has the ability to depict accurate pixel-based analysis of larger areas using several parameters such as land use/land cover (LULC), soil, elevation/topography, hydrology, transportation, population density and adjacency, and climate/weather, which directly or indirectly impact environmental management and especially forest hydrology management. RS technology helps in surveying the entire earth with unprecedented regularity; thus, major global forest cover change can be discovered or monitored efficiently to provide insight into forest hydrology management. Shuttle Radar Topography Mission (SRTM) satellites obtain global elevation data from which earth topographic changes can be monitored proficiently, suggesting changes to forest hydrology. In the current decade, with the introduction of LiDAR and UAV/UAS technology, earth elevation including tree heights in forests is being monitored with centimetre accuracy for forest biomass estimation and ET assessment (Zarco-Tejada *et al.*, 2014; Khosravipour *et al.*, 2015). Currently, weather satellites monitor global atmospheric conditions hourly, including water vapour in the atmosphere on a spatial basis (Panda *et al.*, 2015). RS imagery provides information on drought, vegetation vigour, flood damage, forest fires, deforestation and other natural disasters that are directly or indirectly influenced by forest hydrology (Panda *et al.*, 2015). D'urso and Minacapilli (2006) used a semi-empirical approach for forest surface soil water content estimation using radar data. Potential RS systems, such as colour infrared (CIR) aerial photography, most other multispectral scanners (MSS) (Landsat, QuickBird) and hyperspectral systems (AVIRIS, HyMap, CASI), bathymetric LiDAR, MISR, Hyperion, TOPEX/Poseidon, MERIS, AVHRR and CERES, are being used by scientists to remotely estimate the hydrological flux on the earth's surface, including forest land cover (Panda *et al.*, 2015).

GIS provides the tools to accurately map this information globally and locally, including development of automated geospatial models for precise and proficient forest hydrology management decision support (FHMDS). In recent times, most widely used global positioning system (GPS) technology (a part of GNSS) accurately tracks the position of environmental disasters such as forest fires, mudslides and other phenomena related to forest hydrology. IT helps improve the DSS development and popularize these fascinating but sometimes challenging-to-comprehend tools (Panda *et al.*, 2004b).

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10.2 Geospatial Technology Application in Forest Hydrological Processes Management

The most important aspect of forest management is that forest cover provides a cleaner and more dependable supply of water compared with all other land covers on earth (Richmond, 2007). The basic forest hydrological concept explains that the first element of the hydrological process, interception of raindrops by the plant canopy or the forest canopy, occurs in abundance – about 25 to 30% of total precipitation (Zinke, 1967; see Chapters 1 and 3, this volume) – and with higher infiltration and lower runoff than any other land cover type except wetlands due to supportive forest soil texture and structure (Zinke, 1967).

People have been observing the link between forests and water for thousands of years (Amatya *et al*., 2015). Before hydrology was recognized as a specialty or subfield of forestry, engineering, geography and other disciplines, the study of forests, water and climate was referred to as 'forest influences'. This is still a useful term and a meaningful concept (Barten, 2006). Globally, the forest flourishes when precipitation (P) is much greater than potential evapotranspiration (PET), the growing season is long, the climate is moderate and the frequency of natural disturbance is low (Barten, 2006).

Forest hydrology also influences natural disturbances, such as droughts in forests creating consequential wildfires, severe precipitation after prolonged drought and wildfire increasing chances of landslides, and unpredictable hydrological cycles in forest areas creating pest/disease infestation (see Chapter 1, this volume). The following subsections exemplify the importance of GT use in FHMDS.

10.2.1 Forest cover mapping and change analysis

The forest cover supports climate stabilization, biodiversity preservation, soil enrichment for agricultural lands, erosion control, clean water supply and its cycle regulation, bioenergy production, and fodder and timber supply for human and animal sustenance. Forest plant litters decompose and recycle nutrients through the shedding of leaves and seeds with the support of forest hydrological cycles, thus enriching the soil (Osman, 2013). These enriched soils from higher-elevation forest cover move to more flat topographic agricultural land and help in higher crop production (Osman, 2013). The tree roots and soil binding in the forest reduce excessive soil erosion (Kittredge, 1948). Forest cover regulates the water cycle by absorbing and redistributing rainwater equally to every species living within its range (Perry *et al*., 2008). Moreover, riparian forest has proved its potential to clean surface water and reduce nitrate accumulation in soils and river flows (Lowrance, 1992; Pinay *et al*., 1993). Additionally, mapping the forest plant canopy can help to quantify the first element of the hydrological cycle: interception and subsequent evaporation. Therefore, efficient mapping and analysing of the forest cover with GT supports better management DSS.

The Food and Agriculture Organization of the United Nations (FAO) monitors global forest cover with 250-m resolution MODIS data. The National Oceanic and Atmospheric Administration (NOAA) uses 1-km resolution AVHRR satellite imagery to constantly monitor the global vegetation change over time. Figure 10.1 represents the global forest cover density by climatic domain in 2010 as developed by FAO with MODIS data. Lepers *et al*. (2005) have used remotely sensed imagery to construct a temporal change analysis of global forest land cover between 1981 and 2000 (Fig. 10.2). The map and their study (Lepers *et al*., 2005) provide quick insight into forest loss and its worldwide impact on forest hydrology, global climate, biodiversity and others. Areas in the map (Fig. 10.2) are defined as hotspots when deforestation rates exceed threshold values, as estimated from available deforestation data or from expert opinion.

The NLCD classifies three prominent forest land covers excluding forested wetland. Medium-resolution (30 m) Landsat (five MSS, seven ETM+) images are used to classify the land cover of the USA on a temporal basis (based on the satellites' fly-over cycle). The Anderson land cover classification scheme includes deciduous forest (#41), evergreen forest (#42) and mixed forest (#43) as forest categories. The National Aeronautics and Space Administration (NASA) GAP project develops US land cover maps at regular intervals,

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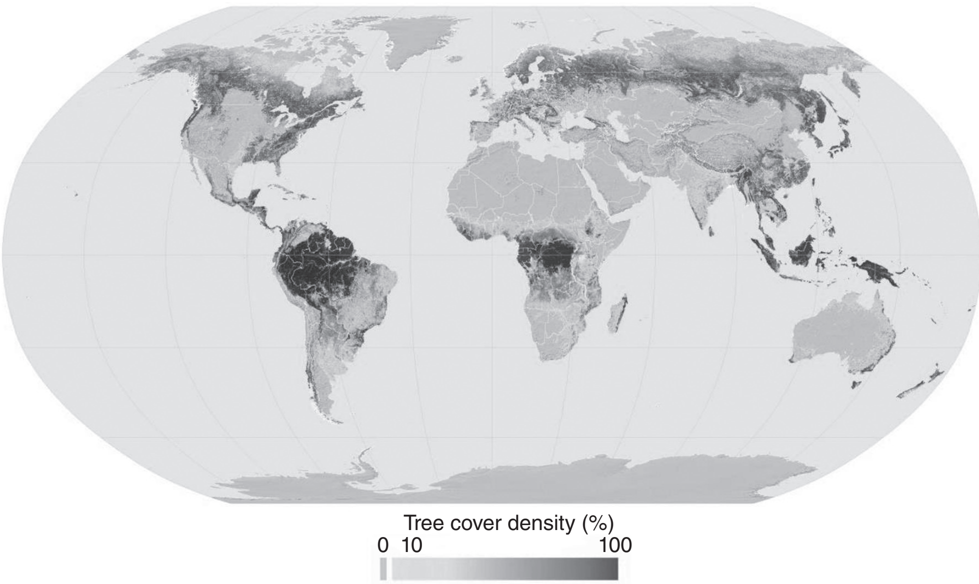

Fig. 10.1. Year 2010 world forest cover map by climatic domain developed by the FAO (Food and Agriculture Organization of the United Nations) using 250-m resolution MODIS (Moderate Resolution Imaging Spectroradiometer) satellite imagery. (From FAO, http://www.fao.org/forestry/fra/80298/en/; published with permission from FAO.)

i.e. 1974, 1985, 1992, 2001, 2005 (few states) and 2011. These NLCD data help in studying the US land cover change, especially forest cover change.

The conversion of natural land cover into human-dominated land-use types such as forest harvesting, deforestation, urbanization and agricultural intensification continues to be a change of global proportion with many environmentally unfriendly consequences for local climate, energy, hydrology and water balance, biogeochemistry and biodiversity (Potter *et al.*, 2007). Deforestation allows soil erosion, and nutrient-rich soils are lost into rivers, lakes and oceans (Panda *et al.*, 2004a). According to Sundquist (2007), the global tropical deforestation rate is about 8% of the current tropical forest inventory per decade. In the Indian subcontinent, Asia and Africa, shifting cultivation (e.g. slash-and-burn agriculture) is a prime example of mismanaging forest resources (forest soils and water) (Panda *et al.*, 2004a).

The global inventory of tropical land under shifting cultivation (including fallow) was 3 million km^2 by the 1980s (Sundquist, 2007; Fig. 10.2). Shifting cultivation in high-elevation forest lands adds to forest degradation by reducing the fertility level of the soil, which is accelerated by soil erosion due to land mass exposure. In the areas under shifting cultivation, nutrient losses occur through leaching, runoff and erosion, making the land uncultivable after two or three cropping seasons (Szott *et al.*, 1999; Panda *et al.*, 2005). Due to the changing dynamics of forest hydrology as a result of deforestation, it is almost impossible for the regeneration of the forest in the area under shifting cultivation (Szott *et al.*, 1999; Sundquist, 2007).

Potter *et al.* (2007) assessed land cover change detection in the majority of California, USA, using the MODIS 250-m resolution time series of enhanced vegetation index (EVI) data. The authors reported that areas affected by forest management and encroachment of residential development into natural vegetation zones should be prime locations for applications of land cover change detection. Goward *et al.* (2008) reported that a number of research projects within the North American Carbon Program (NACP) are combining RS and forest inventory data to map the extent and rate of forest disturbance in the conterminous USA. Given that disturbance processes vary in their extent, duration and

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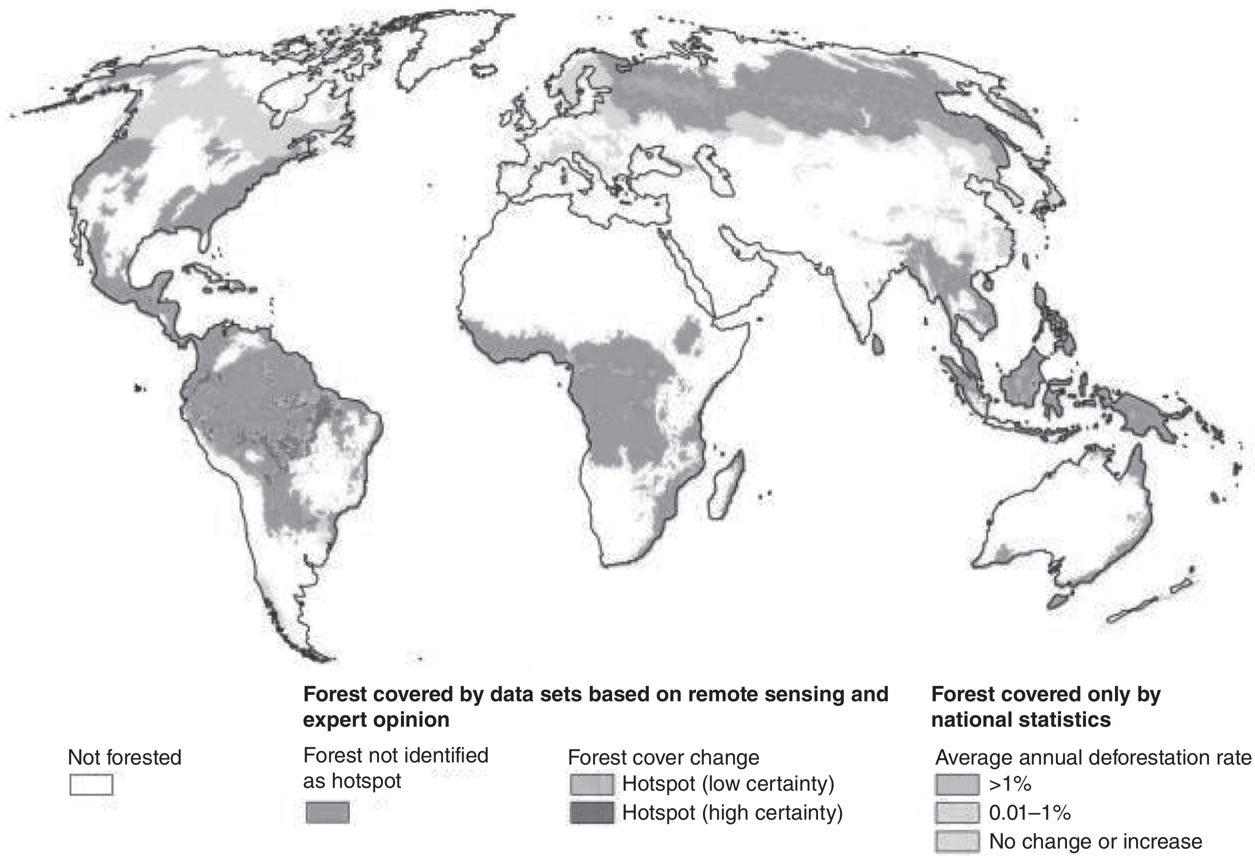

Fig. 10.2. Forest cover change between years 1981 and 2010 using remote sensing data and expert opinion. (From Lepers *et al*., 2005, published with permission from the source.)

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intensity, the authors suggested a multipronged approach with different satellite technologies targeted towards different space and time scales. For example, NOAA's AVHRR and NASA's MODIS are being used to map transient phenomenon occurring at the coarsest spatial scales, including insect outbreaks, drought stress and storm damage, and for estimating fire emissions and global mapping of active fires and burned areas.

Since 1994, the CORINE land cover data have provided land cover levels in Europe at a 25-ha minimum surface unit, and 5-ha change detection between each data version, according to four forest classes (EEA, 2006). The European programme used SPOT, MSS, TM, ETM+ and IRS P6 data for the 1994, 2000 and 2006 data sets. The 2012 update was released in September 2015 with significant improvement and reliability according to the RS data used (i.e. SPOT 4 and IRS P6 data) for a spatial coverage of 39 European countries. Plate 7 shows the forest and other natural cover changes in Europe between 2000 and 2006 as developed by the European Environmental Agency (EEA).

Kim *et al.* (2015, 2016) studied the land cover change in North Korea from 2001 to 2014. They found consistent decreases in normalized difference vegetation index (NDVI) values for 14 years, but interestingly observed a 4% increase in forest land covers that include evergreen needle-leaf forest, evergreen broadleaf forest, deciduous needle-leaf forest, deciduous broadleaf forest, mixed forest, closed shrublands, open shrublands and woody savannahs (Plate 8). Even though further study is required, this is a positive development by forest managers in North Korea. At a global scale, two aspects of climate change, namely temperature and precipitation, affect the photosynthesis of forest ecosystems. High-elevation tropical forests of five continents have been experiencing higher 'browning' (i.e. forests are losing foliage) and less photosynthetic activities (Krishnaswamy *et al.*, 2014).

Because the mangrove forests are declining in many parts of the world and even more rapidly than inland tropical forests, it is essential to determine the rate of change in cover and the causes behind it. Giri *et al.* (2007) used RS data along with geospatial mapping to understand the forest and its hydrodynamics through a multitemporal analysis of Landsat satellite data from the 1970s, the 1990s and the 2000s in the mangrove forests of the Sundarbans of Bangladesh. They found that the mangrove forest and its intertidal zone hydrology processes are changing constantly due to erosion, aggradation, deforestation and mangrove rehabilitation programmes.

10.2.2 Forest soil water/moisture estimation and forested wetlands analysis

The soils horizon of forests consists of a prominent typical litter layer (O), a larger organic, nutrient-rich, mixed topsoil layer (A) and a mineral-rich layer (B and C). In general, forest soils naturally consist of high organic matter with high porosity and permeability, allowing high infiltration and low runoff (Pritchett, 1979; Osman, 2013). Soils in forested wetlands, found mostly in coastal and lower-elevation flat areas, in general are saturated in nature with abundant availability of soil water. Upland forests also hold high amounts of soil moisture (Jipp *et al.*, 1998). Therefore, forest soils are the nexus for many ecological processes, such as energy exchange, water storage and movement, nutrient cycling, plant growth, and carbon cycling at the base of the food web (Johnson *et al.*, 2000). Hence, forest soil and forest soil water are different from soil water in other land covers. According to the FAO soil map development process, forest soil is considered different from soils within other land cover types. For example, a lesser Himalayan overland flow study under forested versus degraded land cover showed that although Hortonian overland flow generation is dominant in both systems, hydrological characteristics vary in terms of runoff coefficient and soil physical properties. GTs, including ground-penetrating radar (GPR), can help study the soil water phenomena of the forest in a non-intrusive and efficient manner. For soil map development in the areas where no maps are available/developed, forest land cover (using RS data) can be used as the area of a specific type of soil (Panda *et al.*, 2004a). Figure 10.3 shows a GT-based procedure to create soil maps using forest hydrology information and FAO-suggested processes.

Understanding the dynamics of soil moisture and its measurements and modelling is critical for broad environmental areas such as agricultural and silvicultural crop management, water

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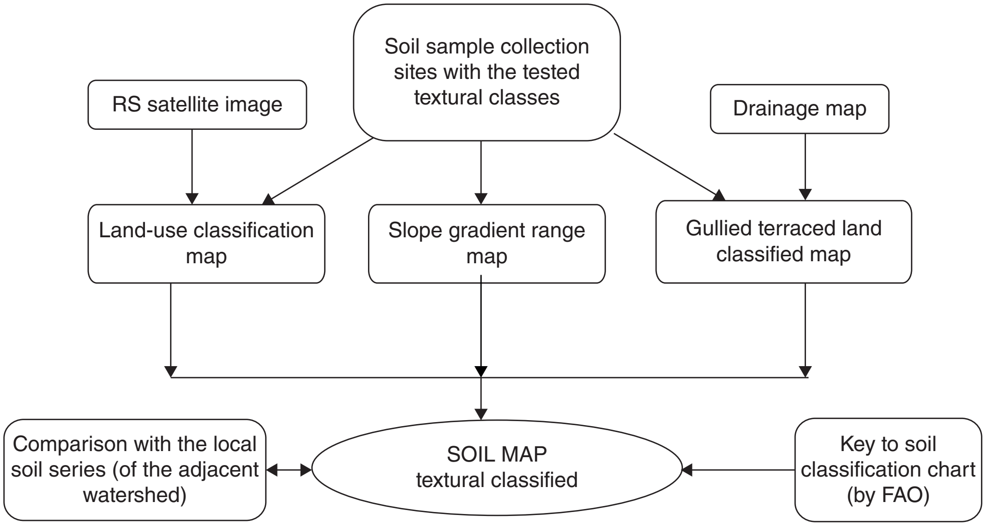

Fig. 10.3. Forested watershed soil map development procedure using geospatial technology (RS, remote sensing) and the soil classification key of the FAO (Food and Agriculture Organization of the United Nations). (From Panda *et al*., 2004a.)

cycle and climate dynamics, flooding and forest fires, including hydrological processes. Although many methods are available to measure soil moisture, *in situ* measurement of the spatial distribution of soil moisture on a watershed/landscape scale is not typically possible. International efforts have been underway for decades to reliably measure soil moisture with an acceptable spatial resolution using a satellite-based RS technique.

Active microwave RS observations of backscattering, such as C-band vertically polarized synthetic aperture radar (SAR) observations from the second European Remote Sensing (ERS-2) satellite, have the potential to measure moisture content in a near-surface layer of soil (Walker *et al*., 2004). However, SAR backscattering observations are highly dependent on topography, soil texture, surface roughness and soil moisture, meaning that soil moisture inversion from single-frequency and polarization SAR observations is difficult. The authors reported some improvements in measurements of near-surface soil moisture with the ERS-2 satellite over Landsat. Microwave RS-based soil moisture estimates are limited to bare soil or low to moderate amounts of vegetation cover. Passive microwave sensors have the advantage of collecting soil moisture remote data in areas with high vegetation cover like forest land cover, but with a trade-off in the spectral resolution range. While the most useful frequency range for soil moisture sensing is 1 to 5 GHz, passive microwave RS is in a range of 10 to 20 km (Njoku and Entekhabi, 1996). Njoku and Entekhabi (1996) outlined the basic principles of the passive microwave technique for soil moisture sensing and how to optimally assimilate passive microwave data into hydrological models. Schmugge *et al*. (2002) remotely estimated forest surface soil moisture from passive microwave data.

Nolan and Fatland (2003) reported that recent advancements in making soil moisture models may act as the Rosetta stone that allows for the InSAR (Interferometric Synthetic Aperture Radar) measurement of soil moisture using existing satellites. Lu *et al*. (2005) demonstrated the feasibility of measuring changes in water level beneath tree cover more accurately using C-band InSAR images from ERS-1 and ERS-2 satellites than the L-band for swamp forests in Louisiana, USA. This capability to measure water level changes in wetlands, and consequently in water storage capacity, using RS may provide a required input for hydrological models and flood hazard assessments. Panda *et al*. (2015) in their recent study used Band 5 (near-infrared) and Band 7 (mid-infrared) to estimate plant moisture (stomatal conductance) and soil moisture in the

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forest cover with mature and young pine, switchgrass and pine understorey with more than 70% accuracy.

10.2.3 Forest vegetation and biomass mapping

Forest vegetation has an apparent influence on microclimate (air temperature, humidity and wind speed) under the canopy compared with open area land covers. It is the 'active' surface for the absorption of solar energy and carbon dioxide and the release of oxygen and water vapour through evapotranspiration, and has a localized effect. In the context of global warming and a climate change scenario, understanding the forest microclimate with respect to forest vegetation or forest biomass is a necessity. High-resolution orthoimagery along with an advanced image processing approach is successful in forest vegetation speciation. Plate 9 depicts the advantage of an object-based image analysis (OBIA)-image segmentation approach in forest tree speciation in the Elachee Nature Center in Georgia, USA with the use of very high resolution (30 cm) orthoimagery and LiDAR data (to determine tree height) along with Visual Basic for Application (VBA) coding in ArcObjects platform.

In Europe in general, and in France specifically, forest mapping and species identification were developed using RS data such as aerial infrared photography in the 1970s (Touzet and Lecordix, 2010) and more recently (since the 1990s) SPOT imagery at 10- to 20-m resolution (i.e. panchromatic and visible and near-infrared (VNIR) bands). The Soil and Water Assessment Tool (SWAT) model ArcGIS add-in is being used to conduct ecohydrological modelling. Bärlund *et al.* (2007) assessed SWAT model performance in the evaluation of hydrology management actions for implementation of the Water Framework Directive in a Finnish forested catchment. The study suggests that GT is an efficient tool to differentiate individual trees in the forest, determine the forest biomass, and subsequently define the loss of water from the forest land via evapotranspiration. Panda *et al.* (2015) developed a procedure to assess the water loss through evapotranspiration in plots with pine only, pine plus understories, pine and switchgrass intercropping, and switchgrass only using 30 cm LiDAR, 15 cm orthoimagery and expert knowledge of the field. Riegel (2012) used LiDAR data to develop a forest biomass quantification model which provided insight into overall forest health and helped in forest ET modelling.

Forest net primary production (NPP) is a field of RS research that includes hyperspectral data from airborne or satellite platforms like AVIRIS or Hyperion (Ollinger and Smith, 2005). 'Primary production' is the accumulation of organic material produced by a plant (biomass). 'Net primary production' is the remaining biomass after subtracting energy used (respiration) for plant growth and development. In the coming years, the HYPXIM project (Michel *et al.*, 2011) aims at providing researchers, including forest RS topics, with hyperspectral satellite data, including VNIR and shortwave infrared sensors, at a high resolution (8 to 15 m). This project will be of great interest for forest research that needs the spatial resolution of airborne data with the global coverage facility of a satellite mission.

10.2.4 Forest evapotranspiration estimation

Different plant species compete for water at different amounts in a forest due to the dense and complex composition of the vegetation. However, the temporal water uptake or evapotranspiration (ET) rate and amount for each species of forest vegetation are poorly understood in a watershed/landscape. The forest ET rate depends upon many factors such as forest soils, vegetation, and climatic conditions such as air and canopy temperature, solar radiation, vapour pressure, wind velocity, and the nature and type of the evaporating surface in the forest range (Viessman and Lewis, 2002). Plant evaporation occurs mostly from the above canopy interception and understorey/litter evaporation. Transpiration encompasses the withdrawal and transport of water from the soil/aquifer system from plant roots and stems, and eventually from plant leaves into the atmosphere (Senay *et al.*, 2013). According to Viessman and Lewis (2002), available heat energy (radiation and air temperature), capacity to transport vapour away from the evaporative surface by wind and humidity, and soil water-content availability are the guiding factors for ET. LAI, canopy temperature (T_c), canopy (G_c) or stomatal

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conductance (g_s), wind velocity, and soil moisture or volumetric water content are the most important parameters of ET estimation (Panda *et al*., 2014; see also Chapter 3, this volume, for more details on forest ET processes and controlling factors).

In recent years, RS-based GT has been increasingly used for development and application of ET models for determining and assessing the ET rates compared with field measured data for agricultural and irrigated crop ecosystems (Cammalleri *et al*., 2014). These novel approaches have been tested recently for individual forest species (see Chapter 3, this volume; Panda *et al*., 2014, 2016). These ET-related parameters (albedo, conductance, canopy temperature, soil moisture, LAI) are estimated with RS imagery data (Narasimhan *et al*., 2003; Mu *et al*., 2007; Chen *et al*., 2014; Panda *et al*., 2016). Thus, forest hydrologists could make decisions on forest vegetation species to grow or not grow. The RS-based spectral information is particularly useful in applications dealing with mapping and modelling biophysical properties of ecosystems such as water quality, plant vigour and soil nutrients (i.e. Landsat individual bands cater to very specific earth observation applications) (Panda *et al*., 2016). As shown in Fig. 10.4, Landsat individual bands or a combination of bands through ratio development can estimate the ecohydrological parameters. Panda *et al*. (2016) have used free Landsat 7 and Landsat 8 images to develop ET and ET parameter models for homogeneous pine forest in coastal North Carolina, USA. Table 10.1 provides a geospatial-based input and ET/ET parameters output correlation chart. *Remote Sensing and Hydrology 2000* (Owe *et al*., 2001) includes many individual research articles describing the use of RS in ET and ET parameter estimation along with other hydrological processes.

10.2.5 Forest hydrology attributed geohazards analysis

Different geohazards are directly or indirectly related to forests and forest hydrology. Geohazards such as wildfires, landslides, drought and flooding are very harmful for humans and the biodiversity directly associated with forest cover. All of these hazards can be monitored, managed and even pre-warned with the use of GT. The following presents a few applications analysing the susceptibility or vulnerability of such geohazards related to forest hydrology.

Forest fires

Forest fire management is a very big issue today. A persistent La Niña effect in the last four years (from 2011 to 2015) created severe drought conditions in the US west coast states (Lenihan and Bachelet, 2015). The drought in California and other west coast forests led to increased wildfires in 2015. Forest fires or wildfires are regulated by many environmental features of forests, including soil water content, forest topography, forest infrastructure, forest cover microclimate and especially forest species. A combined understanding of these spatial features would help manage wildfires better. Dudley *et al*. (2015) developed a geospatial model for determining locations of forest fire susceptibility in Sumter National Forest in South Carolina, USA. The authors used slope, aspect, slope rate of spread, slope suppression difficulty, NDVI, road buffer, fuel biomass density, urban fuel load and lightning strike frequency rasters to develop a comprehensive and fully automated geospatial model that predicts wildfire-vulnerable locations on a scale of low to high. Plate 10 provides the wildfire vulnerability map of Sumter National Forest (see also Chapter 13, this volume, for more about hydrology of forests after wildfire/prescribed fire).

RS applications for studying watershed-scale fires, their remote measurement techniques, their effects on biogeochemistry and the atmosphere, and their ecohydrological effects have been studied extensively by Riggan *et al*. (2004, 2009). Riggan's group also led development of the FireMapper thermal-imaging radiometer and its application to measurement and monitoring of large wildland fires and forest drought stress and mortality in mixed conifer forest (Riggan *et al*., 2003). A study on tracking the MODIS NDVI time series to estimate fuel accumulation was conducted by Uyeda *et al*. (2015).

Forest fires significantly affect the hydrological cycle and thus rainfall–runoff modelling (Eisenbies *et al*., 2007; Folton *et al*., 2015). Recently, Chen *et al*. (2013) analysed satellite observations of terrestrial water storage from

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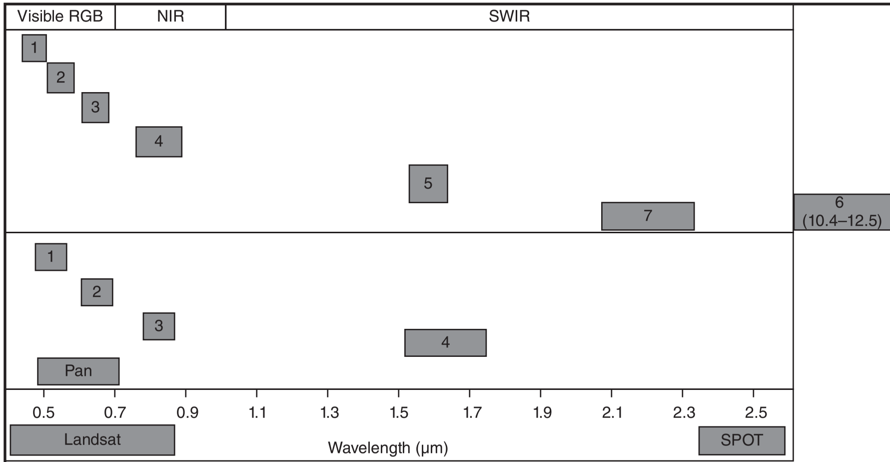

Landsat 7 ETM+ band (µm)	Applications	SPOT 4 band (µm)
Band 1 – Blue IR (0.45–0.52)	Coastal water mapping, soil/vegetation differentiation, deciduous/coniferous differentiation	
Band 2 – Green (0.52–0.60)	Green reflectance from healthy vegetation, iron content in rocks and soil	Band 1 (0.50–0.59) (Green)
Band 3 – Red (0.63–0.69)	Chlorophyll absorption for plant differentiation	Band 2 (0.61–0.68) (Red)
Band 4 – NIR (0.76–0.90)	Biomass survey, waterbody delineation	Band 3 (0.79–0.89) NIR
Band 5 – MIR (1.55–1.75)	Plant moisture content, cloud/snow differentiation	Band 4 (1.58–1.75) MIR
Band 6 – TIR (10.4– 2.5)	Thermal mapping, soil moisture	
Band 7 – MIR (2.08–2.35)	Soil analysis	

Landsat 8 OLI and TIRS bands (µm)	Applications
Band 1 – Coastal aerosol (0.43–0.45)	Coastal and aerosol studies
Band 2 – Blue (0.45–0.51)	Bathymetric mapping, distinguishing soil from vegetation and deciduous from coniferous vegetation
Band 3 – Green (0.53–0.59)	Emphasizes peak vegetation, which is useful for assessing plant vigour
Band 4 – Red (0.64–0.67)	Discriminates vegetation slopes
Band 5 – NIR (0.88–0.85)	Emphasizes biomass content and shorelines
Band 6 – SWIR 1 (1.57–1.65)	Discriminates moisture content of soil and vegetation; penetrates thin clouds
Band 7 – SWIR 2 (2.11–2.29)	Improved moisture content of soil and vegetation and thin cloud penetration
Band 8 – Panchromatic (0.50–0.68)	15 m resolution, sharper image definition
Band 9 – Cirrus (1.36–1.38)	Improved detection of cirrus cloud contamination
Band 10 – TIRS 1 (10.60–11.19)	100 m resolution, thermal mapping and estimated soil moisture
Band 11 – TIRS 2 (11.5–12.51)	100 m resolution, improved thermal mapping and estimated soil moisture

Fig. 10.4. General comparison of Landsat and SPOT spectral bands for earth observation application (R, red; G, green; B, blue; NIR, near-infrared; SWIR, shortwave infrared; MIR, mid-infrared; TIR, thermal infrared; ETM+, Enhanced Thematic Mapper Plus; OLI, Operational Land Imager; TIRS, Thermal Infrared Sensor).

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Table 10.1. Input–output correlation relationship for model development.

Models (with 2006–2012 data)	Input parameters (remote sensing Landsat 7 ETM+ based)	Output parameters (field data)
ET	Plot SAVI means Plot NDVI means Plot VVI means Individual Band 5, 6 and 7 DN value averages	Plot averages of calculated ET values from FLUX instrument (average of 12.00–14.00 hours) (in W/m^2)
Soil moisture	Band 7 means	Plot averages of 30 cm depth soil moisture value (in %)
Canopy temperature	Band 6 means	Plot averages of 12.00–14.00 hours (in °C)
Canopy conductance	Band 5 means	Plot averages of 12.00–14.00 hours (in m/s)

ET, evapotranspiration; SAVI, soil-adjusted vegetation index; NDVI, normalized difference vegetation index; VVI, vegetation vigour index; DN, digital number.

the Gravity Recovery and Climate Experiment (GRACE) mission, along with satellite observations of fire activity from the MODIS mission for the Amazon region. Based on the contrasting analysis of data for high- and low-fire years from 2002 to 2011, the authors suggested that, at least qualitatively, water storage as measured by GRACE can provide information to help predict the severity of a fire season in the region several months in advance.

Landslides

Landslides are attributed to drought and large wildfires. Large wildfires after a persistent drought decrease the forest plant density, and hence the plant root and soil-binding power diminishes. Forest soils are looser due to drought conditions and, hence, are more vulnerable to erosion. Therefore, with immediately succeeding precipitation, a large mass of soil from the steep slope forest area slides down, creating life- and resource-threatening landslides. The geology of the forest area plays a greater role in landslides. Nolan *et al*. (2011), in their award-winning presentation in the 2011 Georgia Urban and Regional Information Systems Association (GA-URISA) conference, showed the advantage of GT to determine the susceptibility of landslides in the Coosawhatchee watershed in the Chattahoochee National Forest of north Georgia, USA. They used geospatial data such as soil texture, soil drainage, maximum water capacity, bulk density, lithology, basement depth, slope, storm surge and LULC.

Floods

Forest hydrology plays a bigger role in determining flooding susceptibility due to the distinct topography, soil composition and hydrological parameters in forest cover compared with other spatial locations. Forest cover is a low-contributing land cover towards flooding due to its soil composition (Booth *et al*., 2002; van Dijk and Keenan, 2007). However, as discussed earlier, deforestation or forest degradation generally would change the soil dynamics and lead to higher runoff from the forest cover. In general, steeper topography is part of forest land cover and flooding vulnerability increases in those spatial locations. Several methods have been used to model the flood potential sites throughout the world, but GT usage is preferred, because all flooding parameters are considered to be spatial in nature. Choi and Liang (2010) in South Korea used the DEM (digital elevation model) hydrological soil group in their models to study the mostly mountainous watershed for flood vulnerability analysis. Ramsey *et al*. (2013) reported that SAR inundation mapping could provide an improved representation of coastal flooding, including flooding in the mangrove areas.

10.2.6 Forest stream water quality management

Stream water quality is the consequence of forest hydrology management. The riparian forest cover along streams is the transition or ecotone between terrestrial and aquatic ecosystems.

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It supports a host of essential functions (Naiman and Décamps, 1997), like filtering runoff nutrients, providing shade that influences water temperature and dissolved oxygen concentration in waterbodies, putting leaf litter into the water as a carbon source for microbes and invertebrates at the base of the food web, supporting the stream banks structurally, supporting channels with large woody debris, diversifying stream habitats, and providing essential cover for flood flows and sediment transport. RS technology is efficiently being used to delineate the riparian forest cover, or the lack of it, along streams. The Watershed Habitat Evaluation and Biotic Integrity Protocol (WHEBIP) developed by Dr Reuben Goforth (Carlsen, 2004) and a similar protocol developed with the USDA Forest Service use stream riparian forest cover and stream channel attributes as major parameters to determine stream health. The lead author has developed an online estimation tool (https://web.ung.edu/gis/water/calculator.aspx) for calculating stream faecal coliform load from non-point and point sources, including forest land cover.

Zhang and Barten (2008) developed the Watershed Forest Management Information System (WFMIS) to help protect water resources from watershed/forest degradation. The WFMIS was developed as an extension of ArcGIS with three sub-modules to address non-point source pollution mitigation, road system management and silvicultural operations (Zhang and Barten, 2008). Panda *et al*. (2004b) developed a GIS-based watershed management DSS for determining water quality and quantity variability due to annual land cover changes. The study area, the 12-digit HUC (Hydrologic Unit Code) Beaver Lake watershed, was a forested watershed with more than 61% forest cover. This DSS is very important for FHMDS in water quality monitoring of forested streams (Panda *et al*., 2004b). Zhang and Barten (2008) have also developed a standalone interface in VBA. A user can input the forest cover loss area in acres and the software will predict the water quality change (total P, total N, PO_4^{3-}, NO_3^- and total suspended solid) in kg/ha/year. The GT-based forest biomass studies discussed earlier would help quantify the water quality dynamics of forest streams. Forest trails, nutrient-rich forest soils and unique forest hydrological cycles are the causes of different forest stream water quality dynamics (Lowrance *et al*., 1997). The Water Erosion Prediction Project (WEPP) is a process-based model that allows continuous simulation in small watersheds and hillslope profiles to estimate soil erosion and subsequent water quality dynamics in forests (Flanagan *et al*., 1995). Geospatial interface for WEPP (GeoWEPP) has the potential to predict soil- and water erosion-based forest stream water quality monitoring and management using PRISM climate data, burn severity data, distributed WEPP land-use data, distributed WEPP soil parameters and DEM. The model would accurately and efficiently predict the forest soil erosion rate to support forest managers.

10.3 Modelling Forest Hydrological Processes with Geospatial Technology Support

Distributed models like MIKE Système Hydrologique Européen (SHE), SWAT, TOPMODEL (topographic model) and others are widely used to simulate ecohydrological processes in a large watershed-scale landscape, which generally contains the forest land use (Amatya *et al*., 2011). Such distributed models use parameters directly related to the physical characteristics of the catchment (watershed), namely topography, soil, LULC and geology; and spatial variability in physical characteristics and meteorological conditions (Pietroniro and Leconte, 2000). Therefore, these models provide the possibility of deriving their inputs from remotely sensed data (Gupta *et al*., 2008). The RS technique is useful in deriving high-resolution information in spatial and temporal domains about the hydrological parameters and thus provides a new means for calibration and validation of distributed hydrological models (Fortin *et al*., 2001).

A decade in hydrological research on ungauged basins (Hrachowitz *et al*., 2013) has demonstrated the interest of using RS in collecting data to predict water flows including topographical (i.e. DEM) and land cover layers for spatially distributed hydrological models (Doten *et al*., 2006; Khan *et al*., 2011). In France, impacts of the Mediterranean forest basin have been studied (Cosandey, 1993; Cosandey *et al*., 2005) using IFN (National Forest Inventory, France) forest land cover data derived from aerial photography

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mapping. Using an existing hydrological model that includes lateral groundwater flow, Sutanudjaja *et al*. (2014) showed that remotely sensed soil moisture data can be valuable for accurately predicting groundwater dynamics at a local level and could be scaled up to provide more accurate information about groundwater variability, availability and reserves across the globe.

Troch *et al*. (2007) investigated the potential use of GRACE data to detect the monthly changes in terrestrial water storage in the Colorado River basin using *in situ* data from 2003 to 2006 and comparing those data against the basin-scale water balance (BSWB)-based models. The authors found that the GRACE results agree with the BSWB model that winter 2005 was generally wet, but the GRACE results disagree with the exact timing of this event. With respect to BSWB, GRACE underestimates the severity of the subsequent dry period. Scanlon *et al*. (2012) reported that general correspondence between GRACE and groundwater level data found in the California Central Valley validates the methodology and increases confidence in the use of GRACE satellites to monitor groundwater storage changes. Van Griensven *et al*. (2012) evaluated LAI and ET simulated by the SWAT model with corresponding values obtained using remotely sensed data. The authors' evaluation showed that values for ET tend to be slightly underestimated, while those for LAI were visibly overpredicted. At the same time, the satellite images clearly followed the land-use pattern of the basin and showed uniform values for the different types of vegetation. This suggests that the SWAT model's forest species input parameter development process needs updating to provide correct results in forest ET estimation.

10.4 New Technology in Forest Hydrology Management

Higgins *et al*. (2014) used a satellite-based interferometry technique to map the subsidence of the Ganges–Brahmaputra river delta covering 10,000 km^2 area over 4 years. The authors found that the delta is subsiding at a rate of about 10 mm/year around Dhaka, Bangladesh's capital, and at about 18 mm/year outside the city, and indicated that satellite interferometry can be a useful method in accurately gauging the subsidence in deltas. Such techniques may be useful in large deltas with mangrove forests in Asia and Africa. Groundwater is the last component of the hydrological cycle to realize the benefits of RS (Becker, 2006). The author explored the potential for RS of groundwater in the context of active and planned satellite-based sensors. Again, these methods may well be applicable for large groundwater-dominated forested landscapes around the world.

Ongoing efforts under the planned NASA/Center National d'Etudes Spatiales (CNES) Surface Water and Ocean Topography (SWOT) satellite mission, including the planned new algorithm using AirSWOT (an airborne platform approximating SWOT's capabilities), will provide an enhanced tool to accurately characterize river discharge from space by providing concurrent observations of water surface elevation, surface slope and inundated area for wide rivers (Pavelsky, 2012). Efforts are also underway to develop and expand space techniques to measure changes in terrestrial waters (Alsdorf *et al*., 2003; Cazenave *et al*., 2004). Such techniques will be useful for large forest landscapes like the Amazon River basin and streams/rivers draining long-term USDA Forest Service experimental forests and ranges in the conterminous USA.

10.5 Conclusions

This chapter provides a detailed discussion on the GT applications in forest hydrological processes management that includes: (i) forest cover mapping and change analysis; (ii) forest soil water/moisture estimation and forested wetlands analysis; (iii) forest vegetation and biomass mapping; (iv) forest ET estimation; (v) forest hydrology attributed geohazard analysis, such as forest fires, landslides and flooding; and (vi) forest stream water quality management. The chapter also provides insight on modelling forest hydrological processes with GT support. The last section of the chapter discusses new technology applications in forest hydrology management and provides suggestions on future studies.

As discussed in the chapter, GTs including RS, GIS, GNSS and IT have tremendous potential for better decision support in forest management and especially forest hydrology management. More and more hydrology models/software, such

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as GeoWEPP (http://geowepp.geog.buffalo.edu/versions/arcgis-10-x/), the Automated Geospatial Watershed Assessment (AGWA) tool (http://www.epa.gov/esd/land-sci/agwa/) and the USDA Forest Service database tools, Natural Resource Manager (NRM) (http://www.fs.fed.us/nrm/index.shtml), are being developed for forest hydrology management that use GT. As mentioned in the chapter, comprehensive complete automated geospatial models are being developed in ArcGIS ModelBuilder platform that can use any type of RS and GIS data to analyse forest hydrological behaviour. Most importantly, GPS technology is getting better and more efficient with the introduction of more satellites into space by Europe, Russia, India and China. The GNSS – the advanced version of GPS – is being used as a major tool in fighting forest fires, landslides and other forest-related geohazards in all parts of the world. Image spatial and spectral resolutions are getting better, in part due to the participation of private entrepreneurs in real-time image data collection, and also with the introduction of large-scale hyperspectral imaging.

The future of forest hydrology management lies in the hands of every stakeholder, but reliance on trained forest managers may not be enough to keep the global forest cover in good shape and health. Therefore, everyone has a responsibility towards global forest upkeep, as it was found that the forest cover flourishes when private and public entities collaborate. Erratic weather conditions due to global warming and climate change, and the consequential El Niño and La Niña effects, are creating severe disruption in forest management. Therefore, freely available MODIS and Landsat 8 data and the subsequently generated NDVI and EVI, along with open-source (free) GIS software like Map Window (http://www.mapwindow.org/), QGIS (http://www.qgis.org/en/site/) and GRASS (https://grass.osgeo.org/), would help develop FHMDS to save forest land cover from degradation. Above all, it is expected that with the advent of UAVs and UASs, which will be in the hands of many stakeholders in the near future, forest management could be easier. GT is getting easier, and the working procedures are becoming available in the public domain for the layman's use. Stakeholders should take advantage of these advanced technologies to take prudent steps towards FHMDS.

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