Chapter 3
Bird's-Eye View of Forest Hydrology: Novel Approaches Using Remote Sensing Techniques

Gabor Z. Sass and Irena F. Creed

The science of hydrology is on the threshold of major advances, driven by new hydrologic measurements, new methods for analyzing hydrologic data, and new approaches to modeling hydrologic systems . . . scientific progress will mostly be achieved through the collision of theory and data
. . . Kirchner (2006)

3.1 Introduction

Without question, better scientific understanding of hydrological processes in forested environments will be a product of the synergistic play of theory and data. Remote sensing (RS) from satellite and airborne platforms, along with many other sources of hydrological data such as wireless sensor arrays and ground-based radar networks, is playing and will continue to play a vital role in better understanding the hydrosphere by providing the next generation of datasets to the hydrological community. RS systems are planetary macroscopes that allow the study of ecosystems from a completely new vantage point, facilitating a holistic perspective like viewing the Earth does for astronauts.

RS allows us to (1) view large geographic areas instantaneously; (2) spatially integrate over heterogeneous surfaces at a range of resolutions; (3) be totally unobtrusive; and (4) be cost effective compared to ground-based approaches. While there are challenges relating RS data recorded in radiance or backscatter to variables of interest, and RS systems have poor temporal resolution compared to ground-based measurement devices, RS and spatial analytical techniques such as digital terrain analysis and distributed hydrological modeling embedded in Geographical Information Systems (GIS) have allowed hydrologists to better understand the movement of water across a landscape.

This is a synthesis of state-of-the-art research on how RS has informed the study of hydrology, with an explicit focus on forested landscapes. Although there have been other excellent reviews published on RS and other geocomputing approaches for hydrological research, none have focused specifically on forest hydrology

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(with the notable exception of Stewart and Finch 1993). In our quest for the Holy Grail of hydrology, we evaluate the ability of RS to provide accurate estimates of various components of the hydrological cycle in forests around the globe. We focus primarily on temperate and boreal forest regions, as it is in these areas that most forestry RS research has been conducted.

The synthesis is framed around the concept of the water budget and how RS techniques can be used to estimate components of the water budget of catchments across a range of scales, from small headwater catchments to larger high-order basins and from hourly to decadal time intervals. Since there are currently no sensors or networks of sensors that can successfully estimate the water budget remotely across this range of spatial and temporal scales, data fusion and data assimilation techniques that exploit synergies of RS and GIS will also be explored. We also illustrate how these novel approaches can be used in forest operations, and outline research needs that will lead to the operational use of RS and related GIS techniques for scientific advancement of forest hydrology.

3.2 A Primer for Forest Hydrologists

RS is the observation of a phenomenon from a distance, using devices that detect electromagnetic (EM) radiation. The use of RS as a tool to understand hydrological phenomena started in the 1970s, but there have been only minor increases in the number of published forest hydrology journal articles that use or refer to RS techniques (Fig. 3.1).

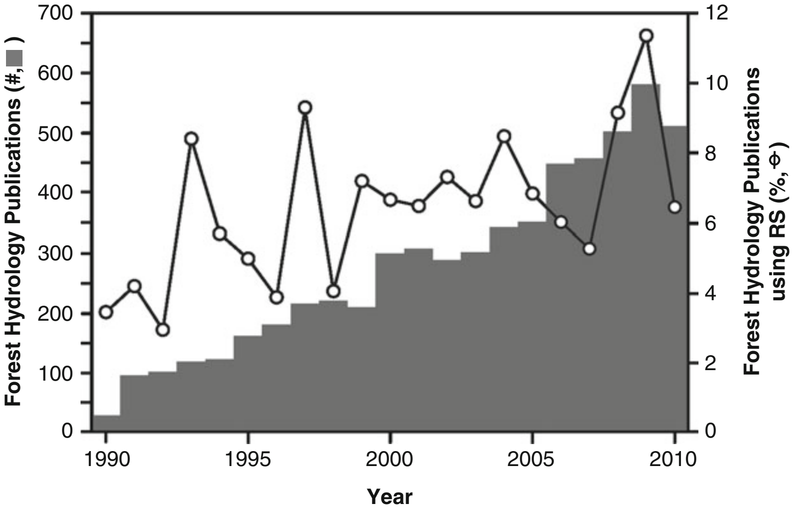

Fig. 3.1 Number of publications per year in forest hydrology (*bars*), with percentage that refer to remote sensing (RS) (*points*), as indicated by ISI Web of Science Citation Index. Search terms: (1) for forest hydrology = forest* AND hydrol*; (2) for RS = "remot* sens*" OR satellite OR airborne OR LiDAR

We hope that this synthesis will give new momentum to the consideration of RS as a worthwhile tool for the study of hydrological phenomena on forested landscapes. Before exploring the potential applications of RS to hydrology, it is important to present some basic RS terminology (Box 3.1) and general observations about the different RS systems applicable for forest hydrological investigations.

There has been a substantial increase in the number of airborne and satellite sensors that cover a large portion of the EM spectrum since 1972 when the first Landsat satellite was launched into orbit (Fig. 3.2). None of these sensors have been designed exclusively for hydrological applications; therefore, their relevance to hydrology in general and forest hydrology in particular needs to be carefully considered and evaluated. Figure 3.2 summarizes the major sensors that we believe have some potential in informing the field of forest hydrology, with detailed

Box 3.1 Terms and Terminology

Electromagnetic spectrum (*EM*): Remote sensors measure EM radiation that has been either reflected or emitted from the Earth's surface.

Optical sensors measure shorter wavelengths: visible (0.3–0.7 μm), near-infrared (0.7–1.4 μm), short-wave (1.4–3 μm), and long-wave or thermal infrared (3–15 μm).[1]

Microwave sensors measure longer wavelengths, ranging from 1 to 10 cm.

- *Frequency* is the inverse of wavelength and is the conventional unit for microwave sensors (e.g., C-band is between 4 and 8 GHz, while L-Band is between 1 and 2 GHz).[2]
- *Polarization* is the orientation of the EM radiation wave to the Earth surface (planar = horizontal; perpendicular = vertical). EM radiation waves can be transmitted or received in either horizontal or vertical orientations leading to four common polarizations (HH, VV, HV, and VH).
- *Passive* sensors record microwaves emitted by the surface (also referred to as radiometers).
- *Active* sensors transmit radiation and record the reflected or "backscattered" radiation (also referred to as scatterometers).
- Synthetic aperture radar (SAR) uses the flight path of the sensor platform to simulate an aperture much larger than the platform itself, allowing for high resolution radar imagery. Echo waves received at different positions along the flight path are distinguished to produce a series of observations that can be combined as if they had all been made simultaneously.
- Interferometric SAR (InSAR or IfSAR) uses the difference in phase (period) between transmitted microwave radiation and received backscatter response to estimate distance (elevation). Since phase is influenced by other factors, InSAR techniques use two or more SAR images of the same area and from the same position to reduce noise and ambiguity.

(continued)

Box 3.1 (continued)

Altimeter: Remote sensors that measure time between the transmission and receipt of radiation pulses. They include as follows:

- Optical altimeters – e.g., Light Detection and Ranging (LiDAR).
- Microwave altimeter – e.g., Shuttle Radar Topography Mission (SRTM).

Data fusion: The combination or integration of RS with other spatial data for analysis and/or visualization.

Data assimilation: The combination or integration of RS into a spatial model for parameterization, and/or validation.

[1]Designated by CIE (Commission internationale de l'éclairage [International Commission on Illumination]).

[2]Designated by IEEE (Institute of Electrical and Electronics Engineers).

characteristics of their wavelengths, spatial resolution, and years of operation. Building on Fig. 3.2, Table 3.1 summarizes the potential of these different parts of the EM spectrum for hydrological applications. Together, these data provide a valuable resource for forest hydrologists wishing to explore the possibilities of using RS techniques.

Optical sensors cannot penetrate vegetation or clouds. For this reason, optical sensors are ideal for monitoring open water areas (lakes and wetlands). Many of the earliest sensors (apart from some of the meteorological satellites) were optical sensors. This means, for example, that in the case of NASA's Landsat program there is a 40-year record of sub-100 m spatial resolution imagery of open water extent, a very good metric of water storage on the landscape. Optical sensors are also used to estimate snow cover and surface temperature, a useful proxy for the delineation of groundwater discharge areas and the determination of evapotranspiration (ET). In tropical regions, cloud-top reflectance and temperature are used to infer precipitation rates although only at coarse temporal resolutions.

In contrast, *microwave* sensors have the ability to penetrate vegetation and can collect data independently of cloud cover and solar illumination. This is important because of the difficulty of acquiring cloud-free imagery during optimal time periods (i.e., when there is a lot of hydrological activity!) using optical sensors. There are two types of microwave sensors: active sensors, which send and receive their own energy, and passive sensors, which detect the microwaves emitted by the Earth's surface. The microwave portion of the EM spectrum is divided into bands where the useful bands for hydrology are K, X, C, and L, ranked in increasing wavelengths. In general, K- and X-bands are useful for detecting surface temperature, snow density, and rainfall rates, whereas C- and L-bands are sensitive to soil moisture.

Although the potential for using microwave sensors for forest hydrology is promising, the technology is relatively new compared to optical sensors

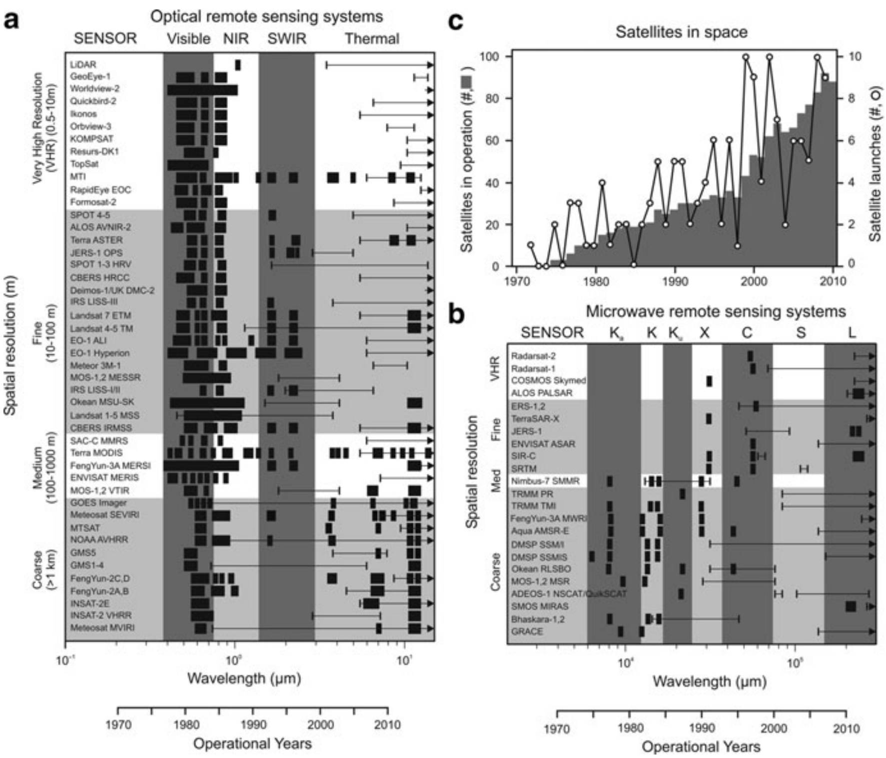

Fig. 3.2 Remote sensors useful for the study of forest hydrology. For each remote sensor, the portions of the electromagnetic spectrum detected (*black bars*) and the period of operation (line, with *arrow* indicating currently operational) are shown for (**a**) optical and (**b**) microwave sensors. The total number of satellites launched (*open circle*) and satellites operating in a given year (*bar*) are shown in (**c**)

(e.g., ERS, the first widely available and fine spatial resolution microwave sensor, was sent to orbit in 1991) and further research is needed to demonstrate their full potential. On the wish list of many hydrologists have been multipolarization and multifrequency sensors since they, much like multispectral optical data, would provide measurements sensitive to different biophysical properties of the surface including vegetation. Multipolarized sensors such as recently launched ALOS-PALSAR and RADARSAT-2 show promise in improved detection of water in forested landscapes (van der Sanden 2004).

While most optical and microwave systems measure reflectance or backscatter, *interferometric* radar (InSAR) and *altimeters* (e.g., Light Detection and Ranging [LiDAR]) measure distances. For example, a space shuttle-based InSAR system (SRTM) was used to derive 90 m spatial resolution digital elevation models (DEMs) for the entire world (van Zyl 2001), which sometimes provides the only source of hydrological data for developing nations. On the other hand, airborne LiDAR systems have been used to derive submeter spatial resolution and centimeter vertical accuracy DEMs, albeit only for smaller regions. Together, InSAR

Table 3.1 Potential application of electromagnetic spectrum to study of forest hydrology

Electromagnetic Spectrum	Water Input	Water Storage							Water Output	
	P	Pl	SC	SD	SW IA	SW SA	SW USA	GW	ET	Q
Visible (0.4-0.7 μm) Reflectance of solar irradiance used to estimate albedo for ET calculations and snow cover area. If cloudy, cloud-top reflectances can be used to infer rainfall rates.										
Near and Shortwave Infrared (NIR, SWIR) (0.7-3.0 μm) Water is a strong absorber of solar irradiance in these wavelengths, making NIR ideal for surface water and plant water mapping.										
Thermal Infrared (TIR) (3-15 μm) Emitted thermal radiation from earth's surface used to infer surface temperatures for ET calculations and to differentiate GW recharge/discharge zones. If cloudy, cloud-top temperatures can be used to infer rainfall rates.										
K-bands (K, K_a, K_u) (0.75-2.50 cm or 12-40 GHz) Emitted microwave radiation influenced by surface temperature and snow density. If precipitation is occurring, these microwave frequencies are sensitive to precipitation rates.										
X-band (2.50-3.75 cm or 8-12 GHz) Microwave radiation influenced by snow depth, soil moisture. Upwelling radiation scattering sensitive to rainfall.										
C-band (3.75-7.50 cm or 4-8 GHz) Microwave radiation that is highly sensitive to soil moisture, surface roughness and volume scattering within vegetation canopy. Useful for saturated soil estimation under low to medium density canopies, inundation even under dense canopy due to double-bounce off trunks. It is also sensitive to snow density for ripe snow packs.										
L-band (15-30 cm or 1-2 GHz) Like C-band but longer wavelengths better penetrate vegetation canopies and therefore better detect variations in soil moisture.										

P precipitation; *Pl* plant water; *SC* snow cover; *SD* snow density; *SW* surface water; *IA* inundated areas; *SA* saturated areas; *USA* unsaturated areas; *GW* groundwater; *ET* evapotranspiration; *Q* discharge systems and altimeters are critical in providing information on surface topography used in understanding water flow and wet area organization, as well as water level dynamics.

A critical component in determining the use of RS imagery is matching the sensor to the "problem," with explicit consideration of spatial and temporal scales. In practice, the selection of sensors is driven by theoretical considerations related to the way radiation interacts with the surface and the atmosphere, scale (resolution and extent) as much as data availability. Many hydrological investigations require long-term datasets; however, only a handful of sensors have a wealth of archival material (e.g., Landsat, ERS, and RADARSAT). Imagery from these sensors has been the mainstay for many long-term hydrological investigations. While it is important to look at the past, current and future monitoring of hydrological trends requires the consideration of some of the exciting new sensors available to the hydrological community. In the following sections, we detail how sensors such as those listed in Fig. 3.2 have been used to detect various components of the water balance in forested landscapes.

3.3 Water Budget

This synthesis highlights the current status and future challenges of applying RS to the study of forest hydrology. We follow a drop of water traveling through a watershed from input, storage, and finally output and assess how RS and associated GIS techniques can be used to track water fluxes and reservoirs. Comprehensive reviews that have been completed for general hydrology and each component of the water budget are listed in Table 3.2. We have used these reviews to evaluate errors in RS-based estimates so that the reader can judge if the errors are in a range that is useful to answer hydrological questions (Table 3.3). While the knowledge presented can be applied to any land cover type, we point out special considerations of using RS technologies and techniques on forested lands.

3.3.1 Water Input

RS can be used to detect rainfall rates, but only at very coarse spatial and temporal scales. Early uses of RS include visible (VIS) and infrared (IR) imagery to estimate precipitation indirectly by inferring rainfall intensity from cloud-top temperatures and reflectance (Petty and Krajewski 1996). This method is most accurate for tropical regions where the cloud-tops of convective cells are much more representative of surface precipitation rates than in more temperate regions (Tang et al. 2009). More recently, microwave sensors have been used to estimate rainfall intensity given their ability to penetrate clouds and directly interact with rain particles (Tang et al. 2009). Unfortunately, the drawback of these sensors (e.g., Advanced Microwave Scanning Radiometer-EOS) is that they capture images at

Table 3.2 Published reviews relevant to remote sensing of forest hydrology

General hydrology	Stewart and Finch (1993),[a] Hall (1996), Kasischke et al. (1997), and Tang et al. (2009)
Water inputs	Petty (1995) and Petty and Krajewski (1996)
Water storage	
Interception	Roth et al. (2007)
Snowpack	Rango (1996)
Open water, inundated, saturated, unsaturated areas	Jackson et al. (1996), Ritchie (1996), Jackson (2002), Moran et al. (2004), Wagner et al. (2007), Vereecken et al. (2008), Verstraeten et al. (2008), and Gao (2009)
Groundwater, recharge vs. discharge areas	Meijerink (1996, 2000), Becker (2006), Entekhabi and Moghaddam (2007), Jha et al. (2007), Ramillien et al. (2008), and Robinson et al. (2008)
Water outputs	
Evapotranspiration	Kustas and Norman (1996), Glenn et al. (2007), Kalma et al. (2008), Verstraeten et al. (2008), and Li et al. (2009b)
Discharge	Schultz (1996) and Smith (1997)
Hydrological modeling	Kite and Pietroniro (1996) and Singh and Woolhiser (2002)

[a] Review specifically focused on remote sensing of forest hydrology

Table 3.3 Relative error of RS-derived water budget components (based on reviews cited in this chapter)

	Units	Relative error (%)
Water inputs		
Precipitation (satellite)	mm/day	60–100
Ground-based radar	mm/day	5–50
Water storage		
Interception	mm	5–15
Snowpack (area)	km^2	1–5 (deciduous) 10–20 (evergreen)
Snowpack (SWE)	mm	30–50
Open water areas	km^2	1
Saturated areas	km^2	1–10
Soil moisture	m^3/m^3	15–30 (low biomass)
Groundwater, recharge vs. discharge areas	km^2	30–60
Water outputs		
Evapotranspiration	mm/day	15–30
Discharge	mm/s	>50

coarse spatial (4–40 km) and temporal (twice a day) resolutions, and therefore they are only useful for studies of larger watersheds and longer time periods.

In order to improve spatial and temporal resolution, microwave imagery has been combined with VIS/IR products (Hong et al. 2007). There is a new NASA mission with a mandate to achieve the estimation of precipitation on a global scale, which will use multiple VIS, IR, and microwave sensors from the same platform for simultaneous imaging (Flaming 2005). However, even this system will, at best, only offer an hourly snapshot of precipitation rates. Ground-based radar networks, operated by weather-forecasting agencies, have substantially improved our ability to qualitatively map the spatial structure of precipitation events (rainfall and snowfall intensity). Besides the difficulties in accurately estimating the rainfall rate, the coverage of ground-based radar networks in forested regions is poor. A combination of ground-based radar and rain- and snow-gauge networks with satellite-based products are likely needed to compile continuous yet spatially distributed measurements of precipitation.

3.3.2 Water Storage

3.3.2.1 Interception

Interception of precipitation by forest canopies can be estimated quite accurately using RS approaches. RS helps characterize the physical characteristics of the canopy, but this information must be fed into a hydrological model that estimates actual interception based on both canopy characteristics and antecedent conditions. A simple vegetation index using a combination of red and near-infrared (NIR) bands may be used to estimate canopy interception given the high correlation between vegetation indices and leaf area index (LAI). Typically, the normalized difference vegetation index (NDVI) is used to estimate canopy interception, modified by the inclusion of a middle IR band (Nemani et al. 1993; Hwang et al. 2009). The drawback is that NDVI becomes saturated in dense vegetation conditions when LAI becomes very high. If narrow band hyperspectral data are available, they may improve the estimates derived from NDVI because of greater penetration through the canopy (Bulcock and Jewitt 2010).

However, forests with similar LAI may have different structures, and as a result, different interception rates. Laser altimetry or LiDAR can provide a wealth of data on canopy structure including gaps, depth, bulk density, surface area, and height, thus improving estimates of interception (Roth et al. 2007). Besides the ability to estimate canopy interception, optical and LiDAR data collected to characterize vegetation canopies may also help describe other hydrological processes such as snow accumulation, snow melt, and transpiration from inside the stoma of plants. The importance of including LAI derived from RS in distributed hydro-ecological models cannot be understated and is one of the success stories in the application of RS in forest hydrology (Tague and Band 2004; Hwang et al. 2009).

3.3.2.2 Snowpack

RS of snow cover extent was one of the first hydrological applications that achieved great success. Currently, there are operational systems for snow cover mapping for the entire globe at 0.5–1 km spatial resolution and daily to 8-day composites

(Tang et al. 2009). These systems utilize VIS and NIR sensors from NOAA-AVHRR and MODIS sensors to detect snow cover. Although snow cover extent does not readily convert into snow water equivalent (SWE), which is more important from a water budget perspective, it does provide important information about the surface radiative balance since there is such a big difference between snow-covered and snow-free land areas in terms of net energy due to high reflectance of snow.

Cloud cover is the major limitation of using VIS and NIR bands. It not only prevents sensing the earth, but can also easily confuse the automated systems into classifying cloud-covered areas as snow-covered. The solution to seeing through clouds is to use passive microwave imagery, which is useful for mapping snow cover extent as well as SWE due to its ability to penetrate the snow pack. Unfortunately, current passive microwave configurations provide very coarse imagery at 25 km or poorer resolution and are only useful in flat areas with homogenous land cover such as the Prairies in North America (Tang et al. 2009).

In forested areas, the forest canopy attenuates the microwave signal and as a result the snowpack can be underestimated by as much as 50% (Rango 1996). One way to address this is to use correction factors such as the Normalized Difference Snow Index or NDVI (Klein et al. 1998; Lundberg et al. 2004). However, even modified retrieval methods need local calibration as there can be significant differences between geographic regions due to snow grain size, depth, and subpixel variability with respect to open water areas (Lemmetyinen et al. 2009).

Currently, there are no plans to launch fine spatial resolution passive microwave sensors. Therefore, RS of SWE in heterogeneous environments will remain problematic and require local calibration. The assimilation of either VIS/NIR or passive microwave imagery with snow melt models promises to be a worthwhile pursuit (Klein et al. 1998; Andreadis et al. 2008; Molotch 2009).

3.3.2.3 Surface and Near-Surface Water

Both optical and microwave RS techniques have been used to monitor areal and volumetric measures of surface and near-surface water. Surface water is water stored in lakes and wetlands as inundated land. It may be open to the sky or covered by vegetation. Near-surface water is water held in the soil as pore water (saturated if the pores are full and unsaturated if some pores have air in them). In order to estimate the volume of stored water, it is important to know the depth of water as well as the area of the particular store. In terms of areal estimation of surface water stores, optical RS of open water using short-wave IR sensors, such as Band 5 from Landsat, is one of the most accurate RS techniques, due to the strong absorption of radiation in those wavelengths (Lunetta and Balogh 1999). Unfortunately, short-wave radiation does not penetrate vegetation. One way to get around this limitation is using vegetation vigor to infer the hydrological status of the ground conditions underneath the canopy (Whitcomb et al. 2009). In deciduous forests, leaf-off imagery in combination with summer leaf-on imagery has been useful in detecting wetlands (Lunetta and Balogh 1999). In general, optical imagery is only useful in mapping open water when there is no vegetation and no clouds present.

Active microwave systems or imaging radars have distinct advantages over optical systems in monitoring the areal distribution of surface water, including (1) penetration of vegetation canopies and sensing both canopy and surface characteristics; (2) penetration of clouds; (3) more frequent data collection due to the active nature of the sensor, which operates during both day and night; and (4) imagery collection from different, programmable angles leading to different modes and very fine spatial resolution (finer than 10 m) over wide swaths (often 50–100 km) (Whitcomb et al. 2009). In general, higher frequency, shorter wavelength radars (e.g., C-band) are more sensitive to hydrological conditions under flooded short vegetation such as fens and bogs, and lower frequency, longer wavelength radars (e.g., L-band) are more sensitive to hydrological conditions under flooded, taller vegetation such as forests and swamps (Kasischke et al. 1997).

Due to the rich archived C-band datasets from ERS and RADARSAT sensors, more publications have used C-band rather than L-band to map soil water and inundated areas in forested environments. The main findings of this research may be summarized as follows: (1) microwaves in C-band are sensitive to soil saturation only in forests with sparse canopies (Sass and Creed 2008; Whitcomb et al. 2009); (2) if the forest floor is flooded, the double-bounce effect produces a strong signal that can be detected even under closed canopies (Townsend 2001); (3) polarization is important, since radiation with horizontal transmit and horizontal receive polarization mode (HH) can penetrate vegetation canopies better than can radiation with vertical transmit and vertical receive polarization mode (VV) (Lang and Kasischke 2008); and (4) time-series analysis of multiple images (e.g., principal component analysis and probability mapping) covering a wide range of hydrological conditions can reveal hydrological patterns of surface water at the landscape scale (Verhoest et al. 1998; Sass and Creed 2008; Clark et al. 2009).

While C-band imagery can detect flooding in forests and saturation under certain circumstances, its performance is inconsistent and inferior to that of L-band. L-band has a longer wavelength (23 cm as compared to 5.6 cm for C-band), allowing it to penetrate much further into the vegetation canopy and detect surface water in forested landscapes (Whitcomb et al. 2009). The next generation of sensors in both C- and L-band (RADARSAT-2 and ALOS-PALSAR) promise a much improved ability to estimate volumetric soil moisture given the multipolarized channels (van der Sanden 2004; Rosenqvist et al. 2007); however, their utility is currently being investigated (e.g., Verhoest et al. 2008).

Besides the necessary advances in sensor technology needed to improve the measurement of vadose zone soil moisture, there are other useful techniques that can be used to estimate the volume of water stored at the surface. One of these techniques uses laser altimeters (i.e., LiDAR systems) to provide bathymetric information for clear water bodies up to 70 m deep (Gao 2009). For smaller, ephemeral water features, LiDAR-derived DEMs of surface topography can be processed using (1) probabilistic approaches to delineate features (e.g., depressions) and the corresponding volumes when water is likely to pond (Creed et al. 2003; Lindsay et al. 2004), and (2) GIS approaches to compute depth to water table

(Murphy et al. 2007). Topographic information may be married with LiDAR intensity information in order to give accurate maps of inundation under forest canopies (Lang and McCarty 2009). The main limitation of airborne LiDAR approaches in mapping surface water is the expense of single, let alone repeat, coverage of large geographic areas. Satellite-based LiDAR systems should alleviate this limitation. Finally, a dynamic approach for estimating surface water volume changes is using interferometric SAR (InSAR) with C- or L-band images to capture a region from two viewing angles and compute surface heights from their combined analysis. Although only applicable for bigger hydrological systems such as large river systems in the Amazon, InSAR is being used to detect water level changes underneath the forest canopy (Alsdorf et al. 2000, 2001; Lu and Kwoun 2008).

In general, the mapping of areal distribution of surface water in forested environments is much further advanced than the mapping of volumetric measurements of near-surface water. Apart from sensor development, the cutting edge of the field is focusing on data fusion, where data from radar, optical, and topographic sources are combined using statistical approaches to downscale coarse spatial resolution imagery of surface saturation and inundation to much finer spatial resolution (Kaheil and Creed 2009), or to extract patterns not observable from single sources of information (Bwangoy et al. 2010). Further integration of data is required where water storage in watersheds can be estimated by assembling information from different sensors detailed here. This could include integrating information on inundated areas from optical sensors, inundated and saturated areas under forest canopies from microwave sensors, water depth from altimeters, and water level changes from InSAR sensors.

3.3.2.4 Groundwater

RS monitoring of groundwater resources is still in its infancy, mostly due to the inability of EM radiation used by current satellite-based sensors to penetrate the ground (Jha et al. 2007). As a result, RS studies to date have used surface information such as topographic, vegetative, geologic, surface temperature, and drainage pattern characteristics of a landscape to give clues to the presence or absence of groundwater recharge or discharge and infer groundwater storages or fluxes (Meijerink 1996; Entekhabi and Moghaddam 2007). At its simplest, images capturing these landscape features can be color coded, and an image interpreter can classify areas as belonging to a certain groundwater class; however, this method is highly dependent on expert knowledge (Meijerink 1996, 2000). More rigorous approaches take NIR and thermal imagery of carefully chosen winter or summer images to map groundwater discharge or recharge zones (Bobba et al. 1992; Batelaan et al. 1993). Similarly, soil moisture and vegetation vigor have been used to infer shallow groundwater tables (Jackson 2002).

Cross-fertilization of technologies is occurring with the introduction of airborne geophysical methods that offer RS of subsurface properties (Robinson et al. 2008). These geophysical methods use radio waves to excite the Earth's subsurface inductively and measure the resulting magnetic field (Robinson et al. 2008).

The resulting resistivity maps can be used to infer groundwater table position and general lithologic information; however, mapping can be done only in flat terrain and at approximately 100 m spatial resolution. Perhaps the most exciting recent development has been the use of microgravity sensors to infer total water storage (Ramillien et al. 2008). Unfortunately, these measurements have been made at the continental scale and are not applicable to headwater catchments. Like most other components of the water balance, groundwater storage and flux estimation are best made with the synergistic use of RS and other geospatial data in groundwater models (Batelaan and De Smedt 2007), which can model not only the flow of water but also associated nutrients and pollutants (Jha et al. 2007).

3.3.3 Water Output

3.3.3.1 Evapotranspiration

RS offers the only way to derive the spatial distribution of ET across forested catchments, albeit still at fairly coarse spatial and temporal resolutions. Although there are no current sensors that measure ET directly (Liu et al. 2003; Min and Lin 2006), satellite-derived vegetation indices, surface temperature, and surface albedo provide inputs into models that can estimate ET. The simplest approach is empirical and makes use of surface temperature and vegetation indices (e.g., NDVI) (Moran et al. 1994). Although this approach is simple with minimal inputs, it does require site-specific calibration. The expanding network of flux towers that estimate ET over a small footprint can be used in combination with this simple approach to accurately map ET over large scales (Yang et al. 2006).

More sophisticated approaches solve for the different components of the surface energy balance, where ET is often calculated as the residual (Bastiaanssen et al. 1998; Wu et al. 2006; Glenn et al. 2007; Mu et al. 2007). These require much more ground-based and satellite-based input data. In general, surface reflectance or albedo derived from visible imagery and surface temperature derived from thermal imagery are used to calculate the short-wave and long-wave portion of net radiation, respectively, and vegetation indices are used to infer stomatal conductance. Important consideration in forested environments must be given to the sunlit and shaded components of canopies, as well as the distribution of leaves (i.e., clumping) (Liu et al. 2003). Direct evaporation from wet leaf surfaces can also be a very important component of ET and requires special consideration in models (Guerschmann et al. 2009).

Operational mapping of ET at medium spatial resolution (i.e., 1 km) and medium temporal resolution (i.e., 1 day) is currently feasible, and many agencies around the world have started to publish such maps (e.g., Liu et al. 2003). However, there is a lot of heterogeneity being masked at these sampling intervals, and the current state of the science aims to improve these maps of ET. One approach is to use fine resolution maps of forest cover (5–10 m range) and interpolate ET measurements associated with each dominant cover type (Goodrich et al. 2000;

Mackay et al. 2002). A more sophisticated statistical approach uses fine resolution imagery with support vector machines to downscale coarse resolution ET maps (Kaheil et al. 2008). This is promising because in frequently cloud-covered regions only passive microwave imagery (at 40 km spatial resolution) can realistically be used to estimate surface temperature and therefore ET (Min and Lin 2006). Improving downscaling techniques is a key research need.

3.3.3.2 Discharge

The use of RS to estimate river discharge is limited to higher order catchments where rivers are wide enough to be detected by sensors (Alsdorf and Lettenmaier 2003). Discharge may be estimated by generating empirical curves relating water surface area to discharge or by using laser or radar altimeters to measure stage variation (Smith 1997). Airborne and space-based altimeters can detect centimeter changes in water levels that can be associated with discharge. Both of these techniques are limited by repeat cycles, spatial resolution in the case of the radar systems, and the fact that water level changes still need to be converted to discharge, which requires ground measurements that can be very difficult to obtain. So far RS of discharge has been most successfully applied in tropical forests where many rivers do not have confined beds and RS imagery is the only way to estimate the flow rates, even if in a crude way (Alsdorf and Lettenmaier 2003). The use of RS snapshots of inundation or stage for larger rivers can be used as input into hydrological models (Vorosmarty et al. 1996). RS also provides important input (such as land cover/land use, LAI, and surface topography) into hydrological models that simulate river discharge (Tague and Band 2004).

3.3.4 An Integrated Approach

As Kirchner (2006) stated, observations will provide direct insights into processes that are crucial to the advancement of forest hydrology. While RS offers the potential for observing hydrological pools and fluxes over a broad range of spatial and temporal scales, this potential has yet to be realized. Current limits of measurable resolutions reveal a trade-off between high temporal resolution but low spatial resolution (e.g., passive microwave) and high spatial resolution but low temporal resolution (e.g., commercial optical sensor such as IKONOS) (Fig. 3.3). Until sensors are developed that can monitor hydrological processes at the necessary time and space scales, data fusion, and data assimilation within statistical and distributed models will provide the way forward.

Distributed hydrological modeling is probably the key area where synergies between RS and GIS can advance the science the most. Distributed hydrological models are critical because they simulate processes at a range of scales from pedons to large drainage basins and they have the ability to forecast (Tague and Band 2004), a very important feature given the uncertainty related to climate change.

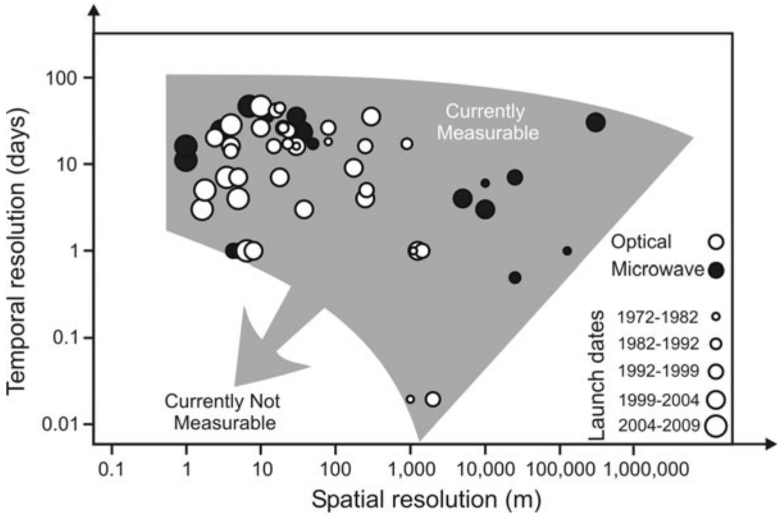

Fig. 3.3 Spatial and temporal resolution of remotely sensed data with a shaded polygon defining limits of currently measurable resolutions. The *arrow* depicts the additional resolutions needed for many forest hydrology applications

Distributed hydrological models, however, have some key shortcomings (Beven 2000), which in part may be answered by the synergistic use of RS and models. Models are plagued by equifinality, the problem of multiple parameter sets that can give the same modeling result, thereby reducing faith in a model's ability to represent real processes. RS imagery may be used as a way to reduce equifinality by providing hydrological information on state variables that can be used to eliminate some of the competing parameter sets (Puech and Gineste 2003). This may be true even if the absolute values of hydrological variables (such as soil moisture) are wrong, but the patterns provide detailed structural information. Another major limitation of hydrological models is the way they deal with water storage, especially in forested wetlands that are not easily identifiable. The power of RS can be harnessed here by mapping the surface or subsurface water reservoirs and including them as spatial objects in the model structure (Creed et al. 2002). Finally, hydrological models need spatially distributed information on initial conditions as well as periodic updates (or checks) of state variables. With the caveats described above, RS imagery may be useful estimates of state variables, including ET, soil moisture, and SWE.

3.4 From Science to Practice

Science-based forest management has been called for by many decision makers; however, implementing science in planning and operational decisions is fraught with difficulty due in part to the wide range of inferences that can be drawn from scientific findings (Szaro and Peterson 2004). If Kirchner's (2006) call for improved observation to inform theory is true for advancing the hydrological sciences, it applies equally to forest management where better observation will lead to better decisions, provided these data are properly integrated into hydrological process understanding. RS is not a panacea in the provision of data, but it definitely offers spatially explicit datasets, covering large geographies that may inform forest management for tactical and operational planning related to forest hydrology. As an example, we illustrate the use of RS in planning the placement of hydrologically relevant buffer zones.

The primary role of buffer zones around water bodies is to mitigate the adverse effects of land use activities on water, sediment, nutrient, and contaminant fluxes from impacted areas to receiving surface waters. While buffer zones are often required by regulatory agencies to minimize effects on aquatic resources in many jurisdictions, current guidelines for buffer zone width selection have often been established based on best guess, adoption from other forest regions, or political acceptability rather than scientific merit. A fixed buffer width ("one size fits all") is commonly used, but the effectiveness of this approach has been questioned in cases where water bypasses the buffer zone as concentrated flow or as subsurface flow (Buttle 2002). Due to the well-documented strengths of RS in mapping surface hydrological features, RS-derived maps can be used to assess the organization of surface flowpaths prior to the design and placement of buffer strips. These maps may be derived using either static or dynamic approaches, both reliant on RS imagery.

The static approach uses DEMs to map hydrological features. Traditionally, resource agencies derived DEMs and corresponding hydrographic maps using photogrammetry. The inability to see below the canopy meant that many small hydrological features (headwater streams and small wetlands) were inaccurately mapped or missed altogether (Murphy et al. 2007). The recent introduction of LiDAR DEMs in forestry contexts has meant unprecedented realism in the characterization of surficial hydrology compared to the same algorithms applied on existing coarser resolution, photogrammetrically derived datasets. Benefits include better representation of watershed boundaries, location of lower order streams, and more accurate identification of local depressions that form potentially wet areas (Lindsay et al. 2004; Murphy et al. 2007; Remmel et al. 2008). However, in regions with deeper and more complex soils, surface topography may not be the dominant driver of hydrological dynamics. In such cases, static approaches using DEMs may be inappropriate for the prediction of wet areas (Devito et al. 2005). In addition, static approaches do not consider climatic variability, which greatly influences the mapping of hydrological features.

In contrast to static approaches, dynamic approaches use multiple RS imagery to factor in climatic variability on surface hydrological dynamics. As a result, more hydrologically realistic buffers may be designed based on the mapped patterns. For example, Creed et al. (2008) illustrated the use of the return period of saturated and inundated areas derived from a time series of RADARSAT imagery in a boreal landscape to suggest alternatives to fixed-width buffer strip placement. Using this

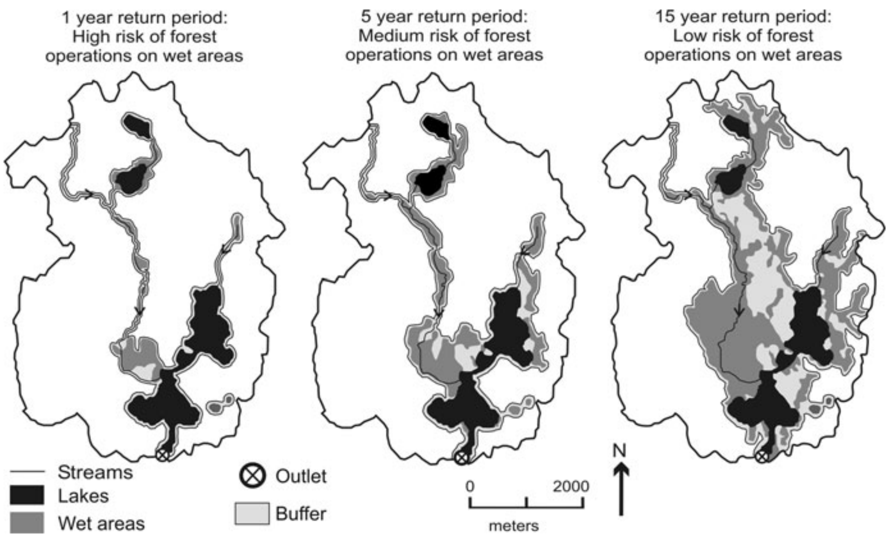

Fig. 3.4 Adaptive-width buffer design. Buffer design is based on hydrological dynamics that consider the return period of a given proportion of a catchment being saturated. If design is based on a 1-year return period, buffers protect a smaller proportion of wet areas, leading to a potentially higher risk of forest operations adversely affecting the hydrological system. If based on a higher return period, larger areas are protected by the buffers, reducing the risk of possible impacts of forest operations on the hydrological system (figure modified from Creed et al. 2008)

probabilistic approach, the amount of area to be retained in buffers is based on the risk tolerance of the forest manager or policy maker. Buffer boundaries may then be prescribed based on the return period of observing a certain proportion of the catchment wetting up, which is in turn related to the magnitude of nutrient and sediment transfer (Fig. 3.4). This exercise is akin to designing bridges and roads to withstand floods of a certain magnitude. However, it is difficult to determine how these return periods are changing in response to climate change and what values society place on maintaining a certain level of water quality.

The incorporation of static or dynamic RS-based hydrological approaches in tactical or operational forestry planning is slowly gaining momentum. While forestry companies have started to use wet area maps in the placement of roads and culverts in an operational sense, the incorporation of RS-derived hydrological information is not routine (Murphy et al. 2008). Unfamiliarity with the strengths and weaknesses of RS technology, high costs of data acquisition, especially for fine resolution datasets such as LiDAR DEMs, and lack of in-house expertise are important obstacles in using RS for tactical and operational forest management planning. This highlights the need for more effective communication of scientific findings to decision makers in policy and management, training of planners and operators in the use of RS techniques, and cooperation between the private sector and government to make RS datasets available at reasonable prices.

3.5 Toward an Operational Bird's-Eye View

There is an urgent need to improve the accuracy and reliability of RS in order to measure fluxes and storages in the hydrological cycle at a range of scales. This will be achieved through innovations in technology, data management, and analytical techniques. More widespread adoption will also result through education and greater sharing of resources. The following recommendations have been echoed by many of the recent review papers in the field of forest hydrology.

3.5.1 *Technical Innovation*

We need sensors that are designed with the specific purpose of sensing hydrological phenomena. While some of the recently launched and proposed sensors speak to this need (e.g., RADARSAT-2 and SMAP), so far the hydrological community has had to work with products that are not optimized for hydrological purposes. The development of optimal sensors will greatly benefit from the collaboration of ecosystem scientists with design engineers. Key breakthroughs are required in microwave, microgravity, and airborne geophysical sensors. Microwave sensors, especially radar imagers, with multiple polarizations and frequencies are needed in order to better penetrate vegetation canopies to detect soil moisture and to detect SWE. Finer spatial resolution microgravity sensors along the lines of the GRACE sensor, which measures total water content, and airborne geophysical systems, which measure electrical resistivity, will tremendously increase our ability to better characterize the subsurface, still the blackest of the black-boxes for hydrologists. Although airborne geophysical systems are much more expensive (for achieving global coverage) than satellite systems, the slowly changing nature of groundwater systems might make it reasonable to fly such missions.

The synergistic use of satellite RS and airborne geophysical systems would enable powerful imaging of subsurface water systems, since one is strong spatially and the other is strong vertically (Vereecken et al. 2008). Real-time monitoring of the entire hydrological cycle will most likely only occur if the disparate technologies detailed in this chapter are fully integrated into a system, where the strengths of RS, geophysical sensors, distributed wireless sensors on the ground, ground-based radars, and hydrological models are fully exploited and complemented with each other in a GIS setting and broadcast on the internet (e.g., Li et al. 2009a).

3.5.2 *Data Archives and Access*

There are terabytes of data being processed every day by many sensors; however, much of them are being discarded because there is no mandate or resources to archive all imagery. We need a coordinated public and private effort to archive imagery acquired by million-dollar sensors. In some instances, imagery has been stored but is locked up in vaults, sometimes in analog format. The opening of the USGS Landsat archives is a boon to scientists, especially ones looking at long-term hydrological trends. Governments around the world need to be encouraged to release their archived RS databases at minimal or no cost (at least to researchers). These programs should be integrated with other long-term monitoring of forest hydrological systems (e.g., monitoring of lake area). It is important that the data made available are in common data formats that can seamlessly interface within GIS.

3.5.3 Data Analytical Techniques

Cross-fertilization of statistical techniques from other fields (such as support vector machines, neural networks, and random forests) has opened up large opportunities for research in applying these methods to hydrological applications. They have already led to breakthroughs in data downscaling (Kaheil et al. 2008). The integration of RS in hydrological models will continue to be a critical research area for years to come. At the minimum, RS products will provide important inputs for parameterization or corroboration such as maps of LAI, land use/land cover, or surface topography. Somewhat more sophisticated is the use of time-series RS imagery as an input, in fashion similar to precipitation. Another novel approach is the identification and input of remotely sensed spatial objects such as wetlands that can inform water redistribution in models. The integration of hydrological models in networks with multiple sensors both on the ground (i.e., wireless sensors, Doppler-radar, and eddy-covariance flux towers) and in the sky can advance the science the most (Chen and Coops 2009). Further integration with spatial decision support systems within GIS will be especially important for managers and other decision makers such as planners.

3.5.4 Interdisciplinary Training

The adoption of RS/GIS techniques by forest hydrologists has been slow. We need transparent and thorough knowledge transfer from product developers and RS scientists to forest hydrologists. Uncertainty, error, and caveats of the latest imaging products need to be well documented; otherwise their use will not be universal. The users of RS imagery will need to learn how to manage and process the raw data, turn it into information, and then transform it into knowledge. The best way for this learning to occur is through the use of Web 2.0 technologies where information flows both ways and "end-users" become "engaged-users" of RS techniques.

3.6 Conclusions

RS of hydrological fluxes and reservoirs at scales relevant to most forest hydrologists is not yet a reality. RS techniques are best suited to observing hydrological storages that cover large areas and change slowly. There are currently operational systems at the global scale that provide daily or weekly updates on the distribution of snow cover, soil moisture, and ET. However, RS of the water budget in headwater catchments on an hourly basis, the main focus for many forest hydrologists, remains problematic. This is related partly to the fact that RS platforms do not continuously observe the same area and therefore do not have the ability to measure continuously key fluxes such as discharge or precipitation. Also, many sensors collect information at spatial scales too coarse for observing hydrological fluxes and storages in low-order catchments. Data fusion and data assimilation of RS imagery within GIS provide ways to improve our ability to monitor low-order catchments. However, the long-term solution is the development of sensors that are being explicitly designed for hydrological applications. This will only occur if hydrologists become more vocal lobbyists in the political arena.

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