Chapter 2
Sampling Strategies in Forest Hydrology and Biogeochemistry

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2.1 Introduction

Many aspects of forest hydrology have been based on accurate but not necessarily spatially representative measurements, reflecting the measurement capabilities that were traditionally available. Two developments are bringing about fundamental changes in sampling strategies in forest hydrology and biogeochemistry: (a) technical advances in measurement capability, as is evident in embedded sensor networks and remotely sensed measurements and (b) parallel advances in cyberinfrastructure and numerical modeling that can help turn these new data into knowledge. Although these developments will potentially impact much of hydrology, they bring up particular opportunities in forest hydrology (Bales et al. 2006). New sensor technology for most biogeochemical components has lagged that for water and energy, advances in measuring forest–atmosphere exchange of carbon by eddy correlation being an exception.

The availability of accurate, low-cost, low-power sensors for temperature, snowpack, soil moisture, and other components of water and energy balances offers the potential to significantly increase the accuracy of catchment-scale hydrologic measurements by strategically sampling these fluxes and states across heterogeneous landscapes. This is especially important in seasonally snow-covered mountain catchments, where elevation, aspect, and vegetation exert a primary influence on temperature, precipitation state (snow vs. rain), snow accumulation, and energy balance. Topographic patterns are also important, influencing phenomena such as wind patterns and thus cold-air drainage and daytime heating.

Satellites can now routinely provide time series, gridded values across a catchment for snowcover, albedo and snow grain size at a 500-m resolution, but do not give snowpack water content (Rice et al. 2010). It is also well established that operational snow measurements do not provide the representative measurements of snow water equivalent (SWE) needed to blend with satellite data to produce spatial estimates of SWE (Molotch and Bales 2006). However, strategic sampling of snow depth can provide the necessary ground measurements for those interpolations (Rice and Bales 2010). Direct measurements from space of other components of the mountain water balance at similar resolution are not currently in planning;

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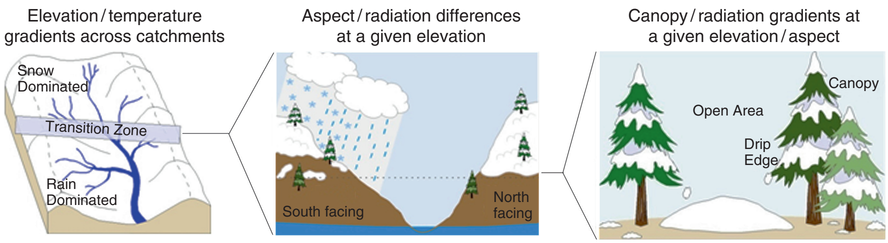

Fig. 2.1 Modeling context for measurements of multiscale heterogeneity in controlling processes, e.g., snow accumulation and melt; which would be lost in a broad regional empirical approach to modeling. Panels from *left* to *right* indicate successively smaller scales. Courtesy: Kyonqho Son

though satellites can provide vegetation information that helps constrain models of hydrologic fluxes and reservoirs. Whole-catchment vegetation characteristics at submeter resolution are being developed using LIDAR (light detection and ranging) (Andersen et al. 2005).

Improvements in cyberinfrastructure enable efficient handling and processing of the larger data streams that result from measurement approaches using dozens to hundreds of sensors, and more computationally intensive simulations. Catchment-scale hydrologic models have also improved, and can take advantage of both spatial data and statistical distributions of data as opposed to a single point value for a time step. That is, models can explicitly account for elevation differences by using either gridded elements or relatively small landscape units; and landscape units can be defined for hillslopes with different aspects, e.g., north vs. south facing, and different vegetation (Tague and Band 2004) (Fig. 2.1). Elevation differences are especially important where winter temperatures are near freezing and some catchments are rain dominated, with other nearby catchments being snow dominated.

The aim of this chapter is to describe how some of these technical advances are being used in the design of measurement systems in seasonally snow-covered, forested catchments, and specifically, how those advances have been applied to sample hydrologic variables in one catchment. The primary emphasis is on water-balance measurements using strategically placed instrument clusters for the mountain water cycle, reviewing results from one instrument cluster that was deployed in the Southern Sierra Nevada of California in 2007. This site represents a synthesis of our knowledge of sampling design. It should be stressed that at this point these systems are experimental, and that design of an instrument cluster is in itself research.

2.2 Science Questions that Build on Recent Advances in Measurement

Several recent reports highlight the need for new water information to enable better decision-making for water resources management, and for the myriad other decisions that are influenced by water (NRC 2008; Dozier et al. 2009). Explosive population growth and changing climate are combining to create supply-demand mismatches that threaten water supplies across the mountain west. As water becomes a more valuable commodity, more accurate information than is currently available will be needed to support better estimates of natural water reservoirs (e.g., snowpack, groundwater); we will need more complete understanding of water, sediment, and contaminant fluxes (e.g., evapotranspiration [ET], groundwater recharge, erosion, ion fluxes), improved hydrologic modeling (e.g., streamflow forecasting, water quality predictions), and better-informed decision making. The foundation of this new information is an improved program of representative measurements.

Effects on the water cycle are perhaps the most significant impacts of future changes in climate, and the deep uncertainty characterizing climate change require that future water measurements support decision-making under uncertainty (Dozier et al. 2009). For example, an important societal question associated with the mixed rain and snow system that characterizes western mountains is: how do we sustain flood control and ecosystem services when changes in the timing and magnitude of runoff are likely to render existing infrastructure and practices inadequate?

Partitioning rain or snow between ET and runoff is perhaps the most challenging measurement problem in hydrology, especially in mountains, where incoming solar radiation and turbulent mixing cause fine-scale heterogeneity (Dozier et al. 2009). Estimating ET throughout a watershed requires blending multiple sensors: direct measurement with flux towers, along with distributed measurements of sap flow and soil moisture, and models driven by remotely sensed data on soil moisture, surface temperature, and vegetation characteristics.

Four main science questions are driving the measurement program in the Southern Sierra Critical Zone Observatory (CZO): (a) what are the water-balance patterns across rain-dominated vs. snow-dominated forest landscapes, (b) how do snow and soil-moisture patterns control geochemical weathering and transport, (c) what are the primary feedbacks between hydrologic and biogeochemical cycles and landscape evolution, and how are they apparent across the rain-snow transition (d) what are the controlling mechanisms for vegetation, water and nutrient-cycle feedbacks? This chapter places more emphasis on the water-cycle measurements, where advances in measurement technology have been rapid over the past decade.

2.3 Sampling Design Using Embedded Sensors

A prototype water-balance instrument cluster was deployed in the Southern Sierra CZO, which is co-located with the Kings River Experimental Watersheds (KREW), a watershed-level, integrated ecosystem project for long-term research on nested headwater streams in the Southern Sierra Nevada (Fig. 2.2) (Hunsaker et al. 2011). KREW is operated by the Pacific Southwest Research Station of the U.S. Department of Agriculture, which is part of the research and development branch of the Forest Service, under a long-term (50-year) partnership with the Forest Service's Pacific Southwest Region.

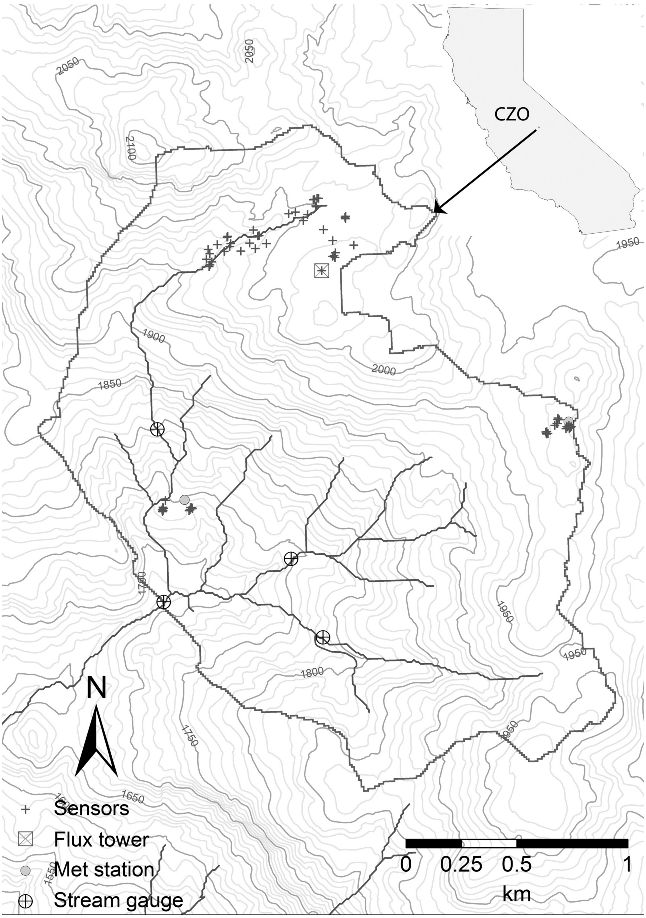

Fig. 2.2 Instrument cluster and location map

One component of the CZO involved developing and deploying a prototype instrument cluster to make comprehensive water-balance measurements across the rain-snow transition, in support of hydrologic and related research by multiple investigators. At the center of the cluster is an eddy-covariance system (flux tower) for measuring water and carbon exchange with the atmosphere. Besides providing measurements of evaporative and turbulent fluxes, the eddy covariance tower serves as the measurement and communications hub of the instrument cluster. Micrometeorological measurements and an embedded sensor network capture the spatial variability of snow depth, soil moisture, air temperature, soil temperature, relative humidity, and solar radiation around the tower.

The instrument cluster was designed to measure snow depth, snow density, soil volumetric water content (VWC), matric potential, and ET. The design of the instrument cluster was based on placing continuously recording snow-depth, VWC, and temperature sensors to sample end members across the main variables in the catchments. That is, the system was designed to capture landscape variability through stratified rather than random or gridded sampling. Based on the multiple field surveys at different locations and times of year in the Rocky Mountains and Sierra Nevada, it has been determined that five main variables affecting snow distribution are elevation, aspect, slope, canopy cover, and solar radiation (Molotch and Bales 2005; Rice and Bales 2010). Solar radiation is an integrating variable, but was not used in the design as it is redundant with the other variables. It was decided not to sample across different slopes because of shifts in sensor location and possible damage to sensors due to snow creep on steep slopes. Because spatial surveys of soil moisture were not available to guide sensor placement, VWC measurements were co-located with snow sensors. Although it is recognized that soil properties may also be a major determinant of soil-moisture patterns, in snowmelt-dominated catchments it is expected that soil wetting and drying patterns will follow the spatial patterns in snowmelt. It is also recognized that while snowmelt and soil moisture flow in three-dimensional patterns rather than just vertically, co-locating soil moisture sensors with snow sensors provided uniform placement for data analysis and modeling.

Snow density values were available from a co-located snow-depth sensors and snow pillows that measure SWE. Eddy correlation was the main method used to measure ET, supplemented with sap-flow sensors. Groundwater levels were measured at regular intervals along a transect across the main stream channel.

The catchment is southwest facing and has elevations of 1,700–2,100 m, with a mean elevation of 1,917 m (Fig. 2.3). The two meteorological stations, located at elevations of 1,750 and 1,984 m, were put in place by Forest Service scientists prior to deployment of the rest of the instrument cluster, and were located in small clearings. Only the upper meteorological station had a snow pillow. Stream gauging and geochemical sampling using automatic samplers (ISCO) was also in place prior to deployment of the instrument cluster, as were in-stream turbidity and temperature sensors.

Snow-depth and soil-moisture sensors were placed in the vicinity of the two meteorological stations and the flux tower. This was done in part to take advantage of communication links available at these sites. Sensors were then placed under the canopy, at the canopy drip edge and in the open on an east or west trending transect. All sites were located on north/northwest and south/southwest facing slopes. This sampling design was replicated at both elevations, with instruments placed around two to three trees at both north- and south-facing sites; at the higher elevation, a third pair of trees lying on flat ground was instrumented. The five subcluster sites had slopes ranging from 7 to 18°.

Ultrasonic snow sensors (Judd Communications) were mounted on a steel arm extending about 75 cm from a vertical steel pipe that was anchored to a U-channel driven into the ground. Sensors were mounted approximately 3 m above the ground, with extensions available if needed. Pits were excavated and sensors for soil temperature and VWC (Decagon Echo-TM) placed horizontally in the pit walls at depths of 10, 30, 60, and 90 cm. and the cables were routed to avoid preferential

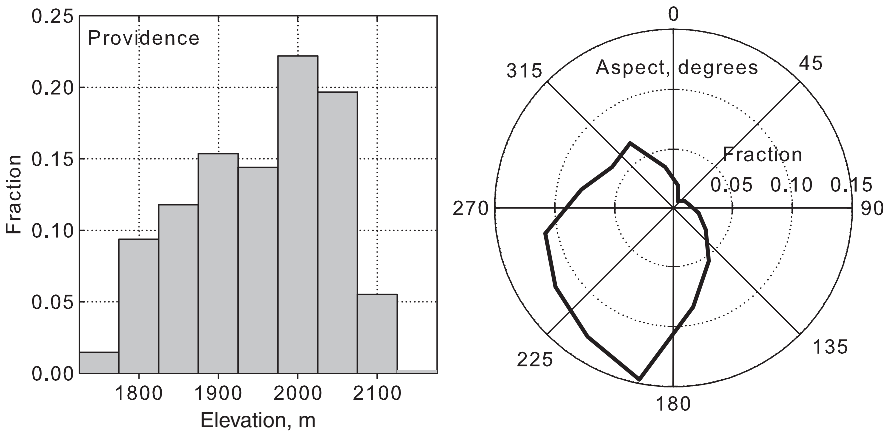

Fig. 2.3 Distribution of elevation and aspect, based on 30-m pixels, for Providence catchments (P300)

flow to sensors. Pits were backfilled and hand compacted to maintain the same horizons and density insofar as possible. Depths were measured from the ground surface, including organic layers, for the examples reported in this chapter. Later deployments measured depths from the top of the mineral soil. In total, 52 snow sensors, 214 EC-TM VWC sensors, and 113 MPS-1 matric potential sensors were deployed. At three locations, it was not possible to reach a depth of 90 cm owing to boulders or lack of soil depth. The EC-TM probes use capacitance to measure the dielectric permittivity of the surrounding medium, which is much more sensitive to the volume of water in the total volume of soil than to the other constituents of the soil. In this method, the sensor probes form a capacitor, with an electromagnetic field produced between the positive and negative plates. The charging of the capacitor is directly related to the dielectric, which depends on VWC (http://www.decagon.com).

A 60-node wireless-sensor network was deployed in 2008 with an additional set of sensors to transmit real-time data collected by the individual sensors to a base station at the eddy flux tower. Deployments of wireless-sensor networks for the purposes of environmental monitoring have been addressed previously (Mainwaring et al. 2002; Hart and Martinez 2006), though the deployment described here addresses performance in remote conditions. *Dust Networks* (2009) developed the underlying ultra low-powered network technology, the core of which relies heavily on network optimization and a randomized channel hopping protocol. These advances allow the network to self-assemble into a redundant mesh, ensuring multiple data paths between any node and the central data aggregation point. Limited acquisition and processing capabilities at each node required the construction of a separate data-manager board to interface with the external sensors. Each wireless node has a 2-year battery life, made possible by an extremely low duty cycle. For additional reliability, and increased link distance, the stock whip antennas on the network hardware were replaced with 8 dBi omni-directional antennas. Twenty-three nodes were located at snow and soil VWC sensors, while the remaining nodes were used to transfer, or “hop,” data, and extend transmission distances.

The hub of the wireless network is composed of a mobile Internet connection, and an embedded computer that actuates sensors inside the network and formats incoming readings. Communication between this computer and the wireless-sensor-network base station is conducted through an Extensible Markup Language (XML) interface over a hard-line Ethernet connection. The XML interface adds an extra layer of reliability by removing the need for low-level programming languages to control network behavior.

Extensive deployments of wireless-sensor networks have been successfully conducted for industrial and indoor monitoring purposes (Howitt et al. 2006; Jang et al. 2008). However, extreme outdoor environmental conditions, such as fluctuations in humidity, temperature, and weather patterns, can have strong effects on overall radio communications (Oestges et al. 2009; Rice and Bales 2010). As such, it becomes important to conduct an analysis of network behavior in outdoor settings to optimize parameters relevant to network performance. Two relevant measures of network performance are known as the received signal strength (RSSI), and the packet delivery ratio (PDR). The RSSI is the physical power present in a received radio signal (usually given in dB or dBm), and is used as an indicator of the quality of radio transmission between two nodes. Increasing the distance between two nodes in the network has an adverse effect on RSSI, as radio signals have to travel further and are thus more susceptible to environmental interference. Critically low RSSI values can cause links within the network to fail, leading to possible isolation of nodes. The PDR is defined as the number of successfully transmitted packets over the total number of transmitted packets, where a packet is the unit of data transmitted within a network. PDR is also a measure of link performance, where values below 100% correspond to the need to retransmit data, thus requiring network hardware to use more energy. As such, desirable RSSI and PDR characteristics are a direct function of proper spacing between network nodes.

It is important to note that our entire instrument cluster is powered by batteries charged by solar panels. Despite canopy closures in the 50–85% range, we have in most cases been able to deploy solar in small clearings and avoid the need to place panels in trees.

2.4 Performance of Sensor Networks

Both snow and soil-moisture sensors were reliable and provided consistent results over the first 2 years of deployment. Minor offsets in the snow-depth measurements from shifts in the mounting hardware were easily corrected at the end of each snow season. Laboratory and field calibration of soil-moisture sensors showed accuracy

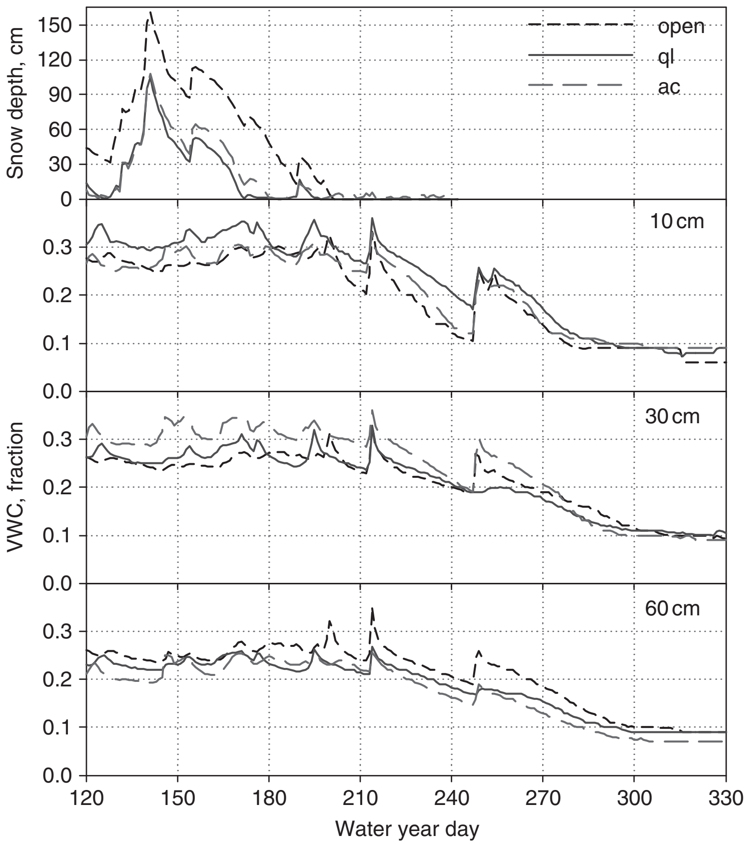

Fig. 2.4 Snow depth and volumetric water content (VWC) for sensors in the open and at the drip edge of *Quercus kelloggii* (California black oak) and *Abies concolor* (white fir), upper met south location. Water year 2009

to ±0.02 fractional VWC. Data from three of the 105 Echo-TM sensors had significant noise, which was attributed to electrical issues associated with splicing cables; however, the VWC signal was still recovered from these sensors by additional data cleaning. Typical data show wet soil while the ground is snow covered, followed by drying in the 1–2 months following depletion of the snow (Fig. 2.4). Sites in the open, i.e., not under the canopy, had on average 25–50 cm deeper snow than those at the drip edge or under tree canopies (Fig. 2.5), though differences in soil moisture were less clear. Sensors at the higher elevation also recorded more snow and later melt out than those at the lower elevation. Soil moisture also showed slightly later drying at the upper location, reflecting longer snowcover.

Across the full instrument cluster, snow-depth values showed consistent decreases during March and April for points with both shallow and deeper snow (Fig. 2.6). Soil-moisture values were slightly less variable than snow depth, and

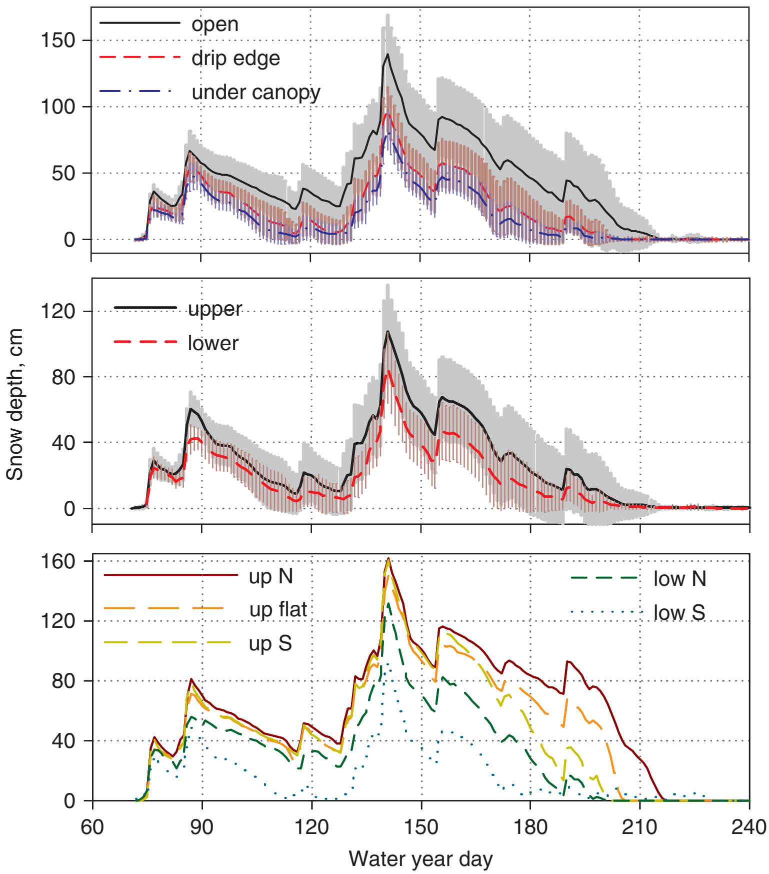

Fig. 2.5 Comparison of snow depths relative to canopy (*upper*), elevation (*middle*), and aspect (*lower*)

showed little change until after the snowpack was depleted. VWC values then decreased from April through September.

Figure 2.7 shows what is known as a *waterfall plot*, displaying network RSSI values against PDR values collected over a 4-week period. For RSSI values of above −78 dBm, PDR remains near 100%, implying that all network data is being transmitted successfully. For RSSI values below this threshold, PDR drops off significantly, requiring numerous retransmissions of the same data. Since lower RSSI values correspond to greater path distance, optimal network performance corresponds to this threshold value, where both PDR and path distance are maximized. Further analysis of RSSI vs. average link distance measures shows this threshold value to correspond to an average path distance of 100 m. Because of the variability of the forest environment, a decision was made to space nodes 50 m apart for further reliability and in anticipation of extreme storm events.

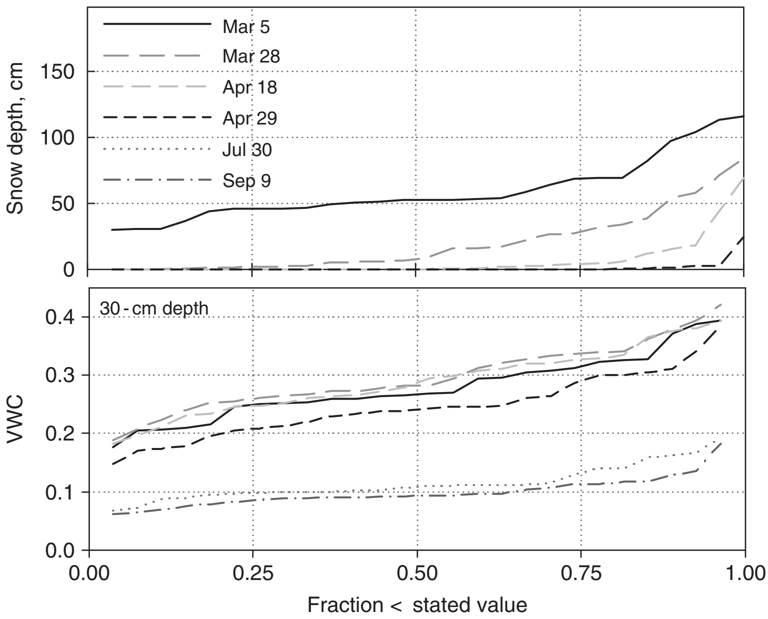

Fig. 2.6 Distribution of snow depth and soil moisture from 27 locations within water-balance instrument cluster

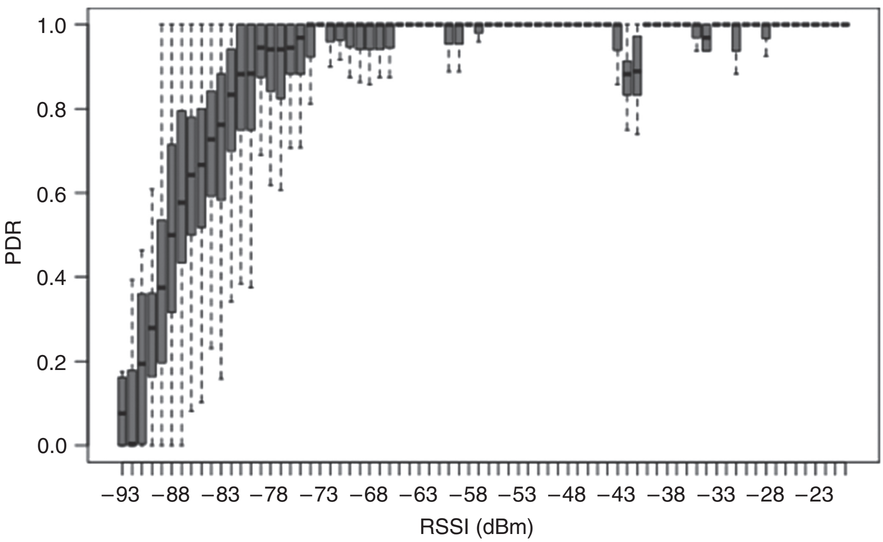

Fig. 2.7 *Waterfall plot* of average network received signal strength indicator against packet delivery ratio, of network data collected over a 4-week span. The *solid boxes* reflect the second and third quartiles around the median, while the *dashed lines* extend to the maximum and minimum measured values

Node-to-node spacing appears to be the best indicator of link performance, while terrain, vegetation, and environmental parameters give little indication as to why some links performed more reliably than others. Until WSN technology adapts to the extreme conditions of outdoor monitoring applications, future WSN deployments will require an iterative deployment process. To achieve optimal network performance (maximizing path distances and battery longevity), site-specific test deployments should be conducted to generate network data which can be used to create analytical tools such as the above *waterfall plot*. Network behavior indicates that 100% of all transmitted packets reach their destination without the need for retransmission as long as RSSI remains above −73 dBm (which corresponds to node-to-node link distance of 100 m and below).

Soil water dynamics can be monitored by either soil water content or soil water matric potential measurements. Soil water content varies between zero and the soil's porosity (at soil saturation). Accurate soil water content measurements provide a measure of soil water storage capacity. Many soil moisture measurement techniques have been developed (Robinson et al. 2008) ranging from small-scale local measurements on the order of centimeters to those that may apply to scales of kilometers (remote sensing). The accurate soil water content range as monitored with Echo-TM sensors is independent of water content, and is about 2% VWC across the complete water content range for the sandy loam soils in the CZO.

In contrast, the range of interest for soil water potential varies from zero (at soil saturation) to potential values of −1,500 kPa (corresponding to −15 bar) or lower. Soil water matric potential measurements are typically more sensitive to change as small changes in soil water content can cause large changes in soil water matric potential, especially under dry conditions. The typical measurement range for most available sensors though is much smaller. Whereas tensiometers are accurate in the relatively wet range (0–60 kPa), the measurement range for electrical-resistance blocks is typically limited to about 200 kPa. Alternatively, soil water potential can be inferred from the dielectric measurement of a porous block, such as the recently available MPS-1 sensor (Decagon Devices, Pullman, WA), however, also its measurement range is limited to about 400 kPa, and measurement accuracy varies greatly depending on calibration method. For driest conditions, heat-dissipation sensors should be considered. However, at this point they have not been incorporated into our instrument cluster. In general, accurate soil water matric potential measurements are difficult and output values are more an indication of soil water status than the exact measure of soil water matric potential.

Performance of the sensors and radios chosen for this instrument cluster was acceptable, and it is planned to use the same equipment in future deployments. The stratified sampling design that was used did show differences in snowcover, though less so for soil moisture, between the three main variables: elevation, aspect, and location relative to tree canopy. Further evaluation of the adequacy of the design, i.e., number and actual placement of sensors, to capture the variability across this particular basin is pending synoptic surveys and data from the other sensors in the instrument cluster that were deployed in 2009, and modeling to assess the spatial coverage.

2.5 Geochemical Sampling

Geochemical sampling of stream water and watershed reservoirs contributing to streamflow in the Southern Sierra CZO indicates the controls on streamflow generation, and how those controls vary with elevation and snow-rain proportion. Stream samples were collected biweekly at the stream gauge locations, thus defining three subcatchments within the larger catchment (Fig. 2.2). Samples were either grabbed by hand or collected by automated samplers that were triggered when flow exceeded a certain value, providing samples several hours apart during storm events. Soil water samples were collected from soil lysimeters (http://www.prenart.dk). Samples were analyzed for major cations and anions by ion chromatography. Three end-members contribute to streamflow. Near-surface runoff contributed more than 50% of stream flow in most catchments, though baseflow was important in two that because of topography had more soil storage of water (Liu et al. 2011). Rainstorm runoff on average contributed around 5% of streamflow. These results were developed using diagnostic tools of mixing models to identify conservative tracers and endmember mixing analysis to separate sources of streamflow.

2.6 Satellite Snowcover

Satellite snowcover data were retrieved from NASA's moderate resolution imaging spectroradiometer (MODIS) using a spectral mixing model, in which a set of endmembers (snow, soil, vegetation) in different proportions in each pixel is used to "unmix" a scene on a pixel-by-pixel basis (Dozier and Painter 2004). The algorithm uses the spectral information from MODIS to estimate subpixel snow properties: fractional snow-covered area (SCA), grain size, and albedo (Painter et al. 2009). No correction was made for trees, so the SCA values represent projected snow cover, i.e., snow that the satellite sees. The SCA threshold was set at 0.15, to prevent identification of spurious snow cover, i.e., values below 0.15 were reported as zero.

Basin snowcover for the same time period as shown above for the sensor network peaked during a storm in late February 2009, and declined to near zero by mid April (Fig. 2.8). As is apparent from the figure, part or all of 20 MODIS pixels fall within the basin. The highest snowcover values were in the higher elevations. On-site inspection showed the basin to be nearly completely snow covered on February 24. However, because of heavy forest cover, the satellite values are lower. The complete time series of cloud-free scenes shows that basin-average detectable SCA peaked at just under a fraction of 0.4 (Fig. 2.9). At that time, all 27 snow sensors had at least 60 cm of snow. It can also be seen from the figure that when satellite SCA became zero, the average snow depth from the 27 depth sensors was also near zero. However, snow was not completely absent from the pingers until about 1 month later, at the end of May. At this point, empirical corrections can be

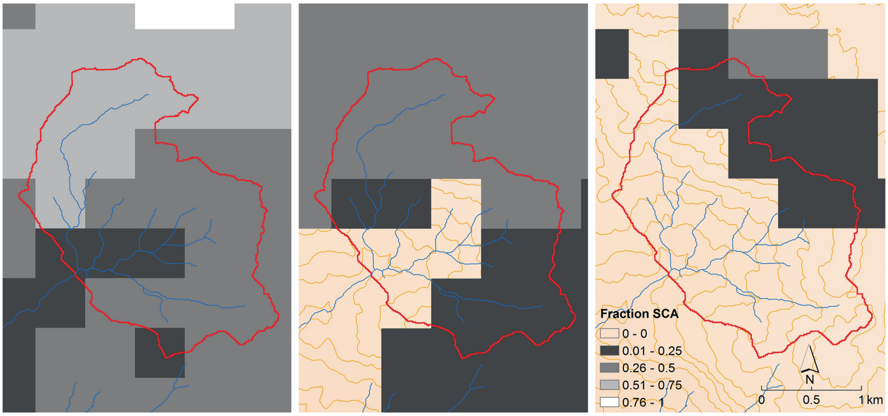

Fig. 2.8 Fractional snow-covered area (SCA) from MODIS for 3 days in 2009. SCA values are binned into four classes for ease of viewing

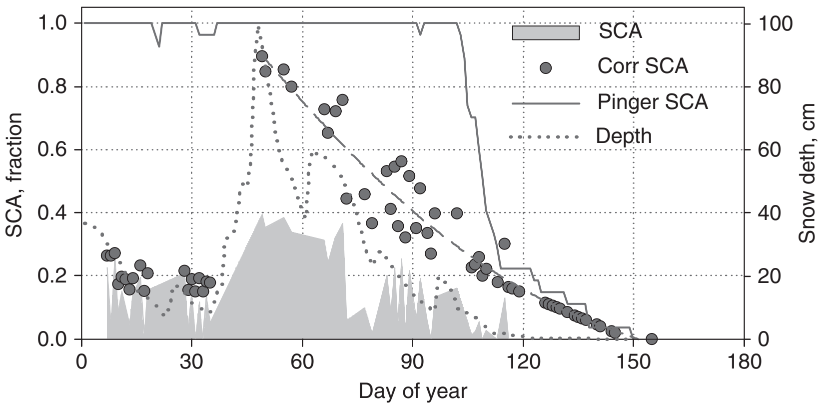

Fig. 2.9 Fractional snow-covered area (SCA) from MODIS, averaged over basin, plus SCA corrected for canopy and threshold effects and fit to corrected SCA for main period of snowmelt. Also shown is the fraction of snow sensors with measurable snow (pinger SCA) and average snow depth for the 27 sensors

made for satellite viewable gap fraction, the result of which is also shown in Fig. 2.9. Based on the field inspections, a correction of 0.5 was assumed for the day of peak snowcover, declining linearly to zero when the snow was melted out at all of the depth sensors. In this case, a detailed, gridded survey (Rice and Bales 2010) was not carried out, but a qualitative assessment was made of the SCA at maximum accumulation. More-involved corrections that make use of detailed vegetation information will be available in the future, pending completion of vegetation and snow mapping by LIDAR for calibration.

2.7 Extensions of Sampling Design

We have recently expanded our original instrument-cluster design, which initially included a single flux tower, to a transect of four towers along an elevation gradient that crosses the rain-snow transition. The transect crosses from a lower-elevation oak-forest ecosystem, where trees cease ET owing to late-summer moisture limitations, through the highly productive conifer forests with almost no shutdown during the year, to a higher-elevation forest ecosystem with subfreezing winter temperatures and cold-limited ET. Integration of sap-flow and flux-tower data is also part of the scaling strategy for water balance in the CZO catchments. The ability to substitute the lower-cost and lower-energy-use soil-moisture sensors for sap flow is also being investigated with ongoing measurements. However, good correlations between sap flow and soil moisture offer the potential to use the lower-cost, lower-power-demanding soil measurements as an index of ET (Bales et al. 2011). Further relating these to the direct eddy-correlation measurements will provide information for scaling soil moisture to regional ET. Flux towers are important components of water-balance measurements, made more valuable when they are part of a network as opposed to being stand alone. It is also expected that embedding them in an instrument cluster with an array of distributed, synergistic measurements such as described here for the CZO will overcome some of the constraints of interpreting eddy correlation data in complex terrain (Brown-Mitic et al. 2007).

It is also important to consider the role of airborne LIDAR data in determining forest and watershed characteristics for scaling and modeling of water and biogeochemical cycles. At the Southern Sierra CZO, understanding the interactions between snow distribution and vegetation, topography, and other meteorological factors has been limited by the lack of spatially distributed and high-definition data. LIDAR measurements of snow depth provide information at spatial scales that are unmatched by any other existing technology, and fill a large data gap for spatial snow depth information. A spatially distributed and high-definition LIDAR dataset from snow on/snow off flights will be combined with the time series of meteorological and snow variables obtained at the instrument clusters to further evaluate the sensor-network sampling strategy. Summer LIDAR data (snow off) characterize spatial patterns of open vs. forest cover and canopy structure that are used in coupled ecohydrologic modeling and scaling of ET and carbon flux.

Geochemical sampling using automatic sensors is generally limited to locations with line power and frequent operator attention. At the Southern Sierra CZO, the emphasis is on use of automatic samplers for collecting stream and soil water, e.g., examining the spatial and temporal patterns of nitrogen concentrations to identify "hot spots" and "hot moments," i.e., links between hydrologic and biogeochemical cycles.

Groundwater-surface water interactions in a stream/meadow complex at the southern Sierra CZO were investigated using a combination of heat and geochemical tracers (Lucas et al. 2008). A distributed temperature system (DTS) with 2-m spatial resolution and 2-min temporal resolution was deployed in the stream, enabling the capture of diurnal swings in surface water-temperatures over the course of 5 days. Point temperature sensors (Hobo Tidbits) were deployed to assess the vertical temperature profile and stratification within a number of the stream pools. Water samples were collected to determine the activity of radon-222 (3.8 day half-life) as a proxy for groundwater discharge. Temperature and pressure head data were collected from monitoring wells and piezometers. The high spatial and temporal resolution of the DTS enabled locating specific thermal anomalies in the longitudinal stream temperature profile, indicative of groundwater discharge. However, the variable and shallow depth of the stream meant that diel temperature cycles interfered with the groundwater signal. Still the DTS can be a powerful tool for sampling stream, snowpack and air temperature variations (Tyler et al. 2009).

The question of whether precipitation in forested, mountain watersheds falls as snow or rain merits further attention. Current practice relies on calibrated air-temperature relationships to determine precipitation phase, though such relationships are site specific, and highly variable. Measurements in the mountains of Idaho show a strong relationship between dew-point temperature and precipitation phase (Marks and Winstral 2007). Catchment-level measurements of humidity and temperature, supplemented by snow and precipitation along elevation transects can establish this rain-snow partitioning. Because dew point is a property of the air mass, it is less likely to be influenced by site or local conditions, and will be a more stable predictor of precipitation phase than temperature alone. Thus, a combination of regional temperature and humidity profiles, available from twice-daily soundings at a few locations, and local on-the-ground measurements along elevation transects will support estimating rain-snow partitioning of precipitation.

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