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Boise, ID

2007

Journal of Service Climatology

Volume 1, Number 4, Pages 1-12

A Refereed Journal of the American Association of State Climatologists

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Editor's note: This is an invited review paper on the state of service climatology.

Abstract: To understand how variations in climate, land use, and land cover will impact water, ecosystem, and natural resources in snow-dominated regions, we must have access to long-term hydrologic and climatic databases. Data from watersheds that include significant human activities, such as grazing, farming, irrigation and urbanization, are critical for determining the signature of human induced changes on hydrologic processes and the water cycle. One of the primary components of effective watershed research is a sustained, long-term monitoring and measurement program. Such an effort was undertaken when the Reynolds Creek Experimental Watershed (RCEW) was added to the USDA Agricultural Research Service watershed program in 1960. The RCEW, a 239 km^2 drainage in the Owyhee Mountains near Boise, Idaho, has been continuously monitored since the early 1960's and continues to the present. The vision for RCEW as an outdoor hydrologic laboratory in which watershed research would be supported by sustained, long-term monitoring of basic hydro-climatic parameters was described in 1965 in the first volume of *Water Resources Research*. Research at the RCEW continues to be supported by monitoring at 9 weirs, 21 primary and 4 secondary meteorological measurement stations, 24 precipitation stations, 8 snow courses, 5 snow study sites, 14 soil temperature profiles, 4 soil moisture profiles and 3 sub-surface hill-slope hydrology sites. These support a wide range of experimental investigations including snow hydrology and physics, cold season hydrology, water quality, model development and testing, water and carbon flux experiments, ecosystem processes studies, grazing effects, and mountain climate research. Active watershed manipulation allows research on fire ecology and hydrology, vegetation-climate interaction, watershed restoration, grazing and wildlife management, and invasive plants. All data are ingested into a computer database, and available to the public via both web-based and on-line ftp access.

1. Introduction

Flooding and associated damage, droughts and water shortages, and compromised water quality are major concerns currently facing populations worldwide. Understanding these issues requires that the hydrologic research community has access to high quality long-term data sets. Hydrologic data acquisition, processing, analysis and archiving, however, is often arduous and always expensive.

The National Research Council [1998] recognized the special need for research and monitoring that is long-term and integrated across scales and time frames, and further emphasized the research value of watersheds of 'intermediate' size (tens to a few thousand km^2) which encompass complex landscapes with slopes and flood plains supporting a variety of processes, including temporary storage of water, sediment, and associated chemical species, with the recommendation that "Particular emphasis should go to maintaining sites with exceptionally long-term records." During the past decade, initiatives by the U.S. National Science Foundation (NSF) [CUAHSI, 2004, 2007], the American Geophysical Union (AGU) [Blöschl, 2006], the American Meteorological Society (AMS) [Loescher *et al.*, 2007] and the International Association of Hydrological Sciences (IAHS) [Sivapalan, 2002] have brought attention to the value of long-term hydrologic data and focus on the importance of sustaining and improving the facilities within experimental watersheds where these data are collected.

The Reynolds Creek Experimental Watershed (RCEW), described by Robins *et al.* [1965] in the first volume of *Water Resources Research*, has been just such a vital field laboratory for hydrologic research for the past 44 years. In 2001 a series of papers was published describing the historical context, instrument layout and telemetering system, and the geographic characteristics of the Reynolds Creek Experimental Watershed (RCEW) [Marks, 2001; Slaughter *et al.*, 2001; Seyfried *et al.*, 2001a]. The basic data from the 1961-1996 period of operation was also presented by Hanson [2001], Marks *et al.* [2001a], Hanson *et al.* [2001], Seyfried *et al.* [2001b,c&d] and Pierson *et al.* [2001]. In this paper we describe the changes in research focus, instrumentation, and technology that have occurred over the twelve years since 1996 as the RCEW has been transformed into an outdoor hydro-climatic laboratory for the 21st century.

2. A Developing Measurement Strategy at RCEW

The northwest Hydrology Research Watershed was authorized by Congress in 1959 to address five essential issues: water supply, seasonal snow, soil freezing, water quality, and rangeland hydrology. Development began in 1960 in the semiarid rangelands of the interior Pacific Northwest. The 239 km^2 Reynolds Creek Experimental Watershed (**Figure 1**) is located in the Owyhee Mountains of southwestern Idaho, approximately 80 km southwest of Boise, ID, USA. Headquarters for the RCEW are located in Boise, Idaho, at the USDA Agricultural Research Service (ARS) Northwest Watershed Research Center (NWRC). A detailed description of the topographic, geologic, vegetation, land use, and anthropomorphic features of the RCEW can be found in Seyfried *et al.* [2001a].

Because there is wide diversity in local climate, geology, soils and vegetation across the RCEW catchment, it was recognized that long-term, whole-catchment and sub-catchment field measurements would be necessary to characterize the landscape and its hydrologic regime, and to support process research, model development, and validation. The field instrumentation, therefore, was designed to

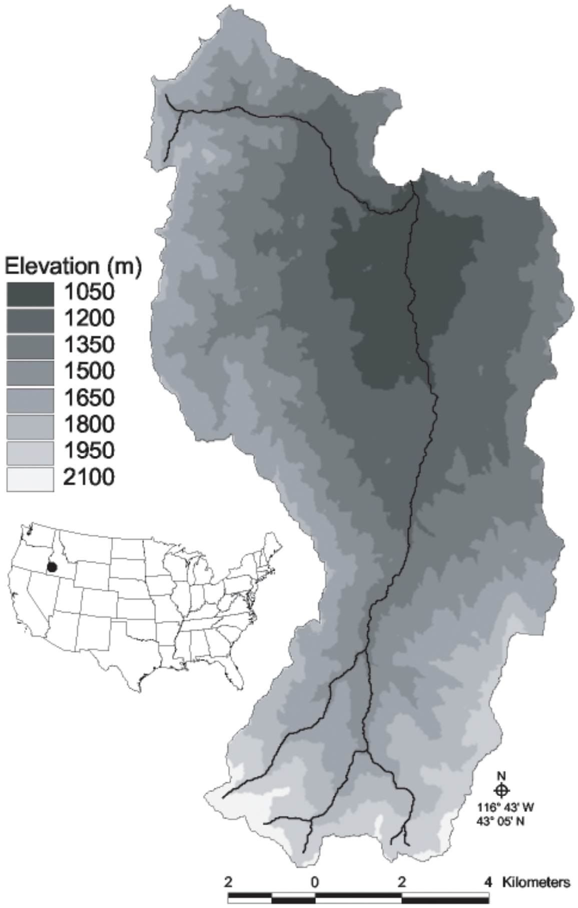

Figure 1: Topographic map, based on 30m DEM, showing the topographic structure of RCEW, and its location within southwestern Idaho in the U.S.

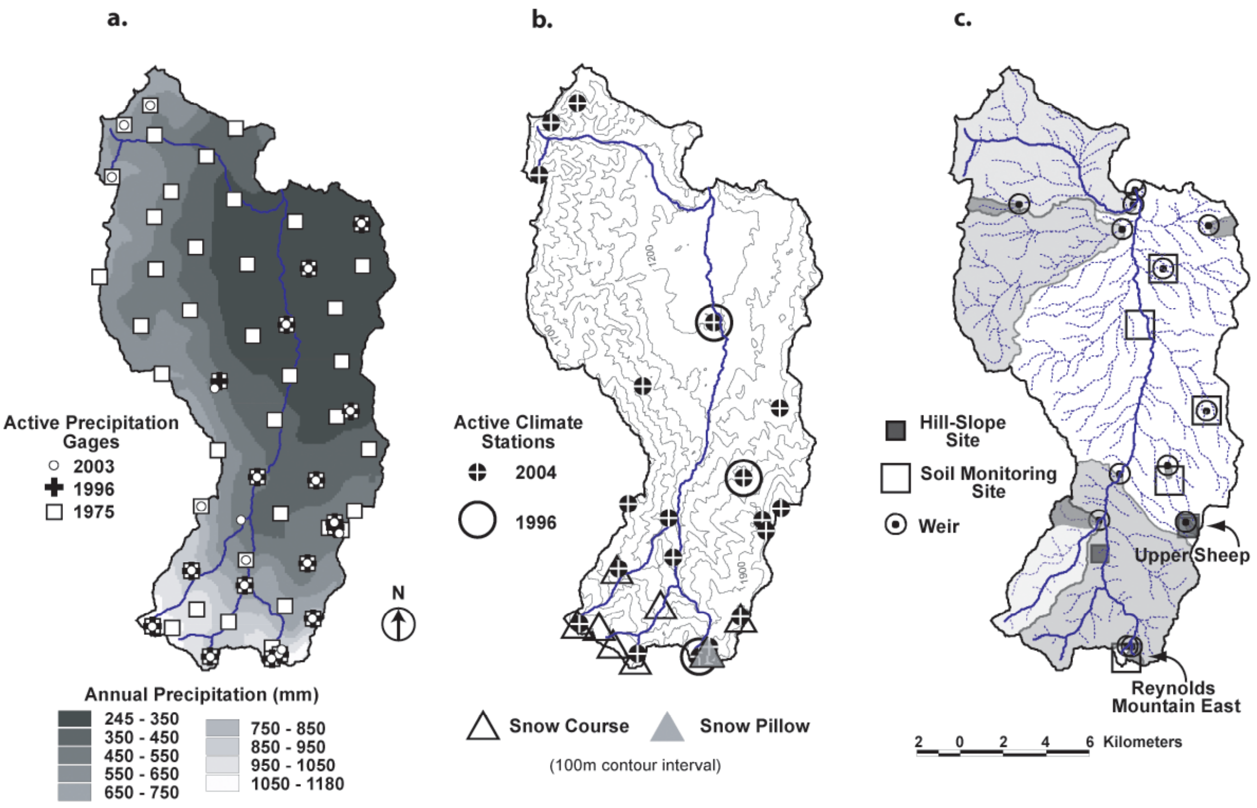

Figure 2: Maps of measurement site locations and sub-watershed boundaries within the Reynolds Creek Experimental Watershed showing: (a) active and discontinued precipitation gauges, over long-term average precipitation; (b) active and 1996 meteorological measurement sites, snow pillow, and snow course locations; (c) weir locations, the stream channel network, and the sub-watershed boundaries.

encompass the spatial complexity of topography, climate and vegetation of a mountainous rangeland watershed. The measurement program was planned for long time series to encompass temporal variability in climate, weather and hydrologic regime. Instrumentation within the RCEW initially focused on a suite of nested, gauged catchments [Pierson *et al.*, 2001] and an extensive grid of precipitation measurement sites [Hanson, 2001] (**Figure 2, c&a**).

Very large gradients in climate, precipitation, and hydrology occur over the RCEW. Annual water yield varies over the watershed from a few mm in small sub-drainages in lower portions of RCEW to over 583 mm in the higher elevations at the southwestern edge of RCEW. Average annual water yield measured at the outlet is 75 mm or 0.564 $m^3 s^{-1}$. The largest streamflow recorded at the outlet occurred on December 23, 1964, during a rain-on-snow and frozen soil event that peaked at just over 107 $m^3 s^{-1}$. Mean annual precipitation varies from about 250 mm at the northern lower elevations, to over 1100 mm in the higher regions at the southern and southwestern watershed boundaries where more than 75% of annual precipitation occurs as snowfall. Because gage-measurement of snowfall is problematic in windy, mountainous catchments such as RCEW, a manual snow measurement program has been in operation in the upper basin since 1961 and a snow pillow program in the Reynolds Mtn. East catchment since 1982 [Marks *et al.*, 2001a] (**Figure 2, b&c**).

Until 1996 meteorological data collection was limited to three primary monitoring sites established to represent low elevation, mid elevation, and upper elevation conditions within the RCEW (**Figure 2b**). Daily climate data, including pan evaporation, were manually recorded beginning in 1961. Automated data collection on strip charts began around 1968, and fully digital data recording around 1980 and have been collected contiuously since [Hanson *et al.*, 2001]. Soil micro-climate measurement sites were established at five locations across a range of elevations and precipitation regimes (**Figure 2c**). Neutron probe measurement of soil moisture was initiated in 1976 [Seyfried *et al.*, 2001c], and soil temperature monitoring was undertaken as part of the standard climate monitoring in the early 1980's [Seyfried *et al.*, 2001b]. Two sets of paired lysimeters operated for 16 years (1976-1991). These provided detailed data on soil moisture dynamics, evaporation, and evapotranspiration at the mid- and high-elevation sites [Seyfried *et al.*, 2001d].

During the past decade, an effort has been undertaken to improve our understanding of how hydrologic processes are distributed over a landscape and to support the development and testing of process-based hydrologic modeling. As a result, it has been necessary to investigate the linkages between topography, landscape characteristics and vegetation, and patterns of precipitation, weather, and snow deposition. This has fundamentally changed the measurement and monitoring strategy within RCEW. Rather than establish measurement sites to monitor general conditions, we are locating sites to measure gradients over the watershed, and to establish catchment-scale ranges of highly variable parameters such as precipitation and wind.

a. Monitoring Patterns of Weather and Precipitation

To address how weather and precipitation are distributed over the landscape, we have begun to sample specific hydro-climatic niches. The application of distributed hydrologic models is limited by the availability of quality forcing data to show how weather and precipitation vary in both time and space over an area, particularly in mountainous regions [Marks *et al.*, 1999]. A number of methods have been used to simulate these distributions from sparse station data [eg. Garen *et al.*, 1994; Susong *et al.*, 1999], or to estimate lapse rates from distant data stations [eg. Running *et al.*, 1987; Dodson and Marks, 1997; Hanson *et al.*, 1999; Daly *et al.*, 1994, 2002]. However, hardly any data exist to verify or determine parameter uncertainty, particularly at catchment to small basin scales (1-1000 km^2). This is much larger than the observed scale of variability of snowmelt and hydrological processes in complex terrain, and has important implications for modeling in mountain catchments [Wilcox *et al.*, 1991a&b; Seyfried and Wilcox. 1995]. The scale of variation of snow deposition and melt energy in mountain catchments is on the order of 10-100 m [Gelfan *et al.*, 2004; Pomeroy *et al.*, 2004; Essery *et al.*, 2004], and it is critical that we design our monitoring systems to characterize this scale of variation.

In mountainous regions, large differences in precipitation and wind can occur over distances as small as a few hundred meters. In a snow-dominated catchment, these differences can affect the timing of spring runoff [Marks *et al.*, 2001b] or the hydrologic response to a particular storm or event [Marks *et al.*, 2001c]. Winstral *et al.* [2002] showed that it was possible to efficiently model the wind field and subsequent wind redistribution of snow from digital elevation model (DEM)-derived topographic structure. The availability of data that allowed us to differentiate between regions of wind exposure and shelter was central to the development of this approach.

b. A Perennial Headwater Catchment: Reynolds Mountain, East

The fortuitous placement of precipitation and meteorological measurement sites on an exposed ridge and in a protected aspen grove in a small perennial headwater catchment in RCEW (Reynolds Mtn. East, RME) (**Figure 2c, 3a**) provided data to support the application and testing of the method developed by Winstral *et al.* [2002], giving us a reliable estimate of the expected range of wind and precipitation across RME. Subsequent work showed that both topographic structure and vegetation interact

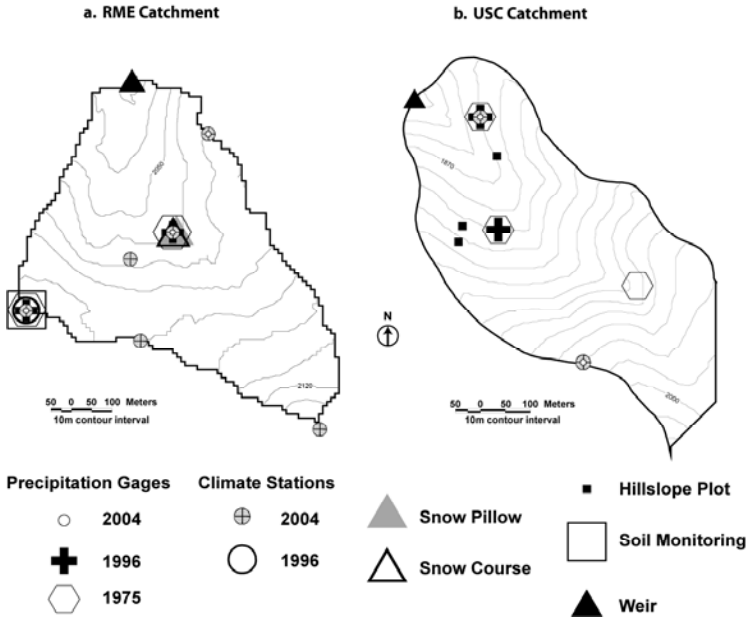

Figure 3: Detail of instrumentation and measurement sites within (a) RME and (b) USC.

with wind to affect the distribution of snow, the development of large drifts, the distribution of melt energy, and the delivery of water to the soil and stream [Marks and Winstral, 2001; Marks *et al.*, 2002]. Detailed snow sampling has been done several times in each year since 2001, providing data on snow depth and SWE at a 30m grid over the RME catchment for validation of spatial simulation modeling, and for refining snow sampling strategies as we scale up to larger basins.

To further refine our understanding of the effect of wind and vegetation on snow deposition and melt energy, seven additional hydrometeorological measurement sites have been located within the RME catchment. These provide data on two very exposed sites, a fir and a sage canopy, a 15 m tower through the aspen canopy, and eddy covariance systems below the aspen, and on the exposed ridge (**Figure 3a**). These data will allow us to verify and improve hydrologic models, develop more effective transfer schemes for distributing hydro-meteorological parameters across complex landscapes, and allow us to more directly compare the processes and conditions within RME to other sites.

Much of what was learned in the RME catchment has been extended to all of the RCEW and to other mountain locations. Meteorological monitoring has been extended to become part of the basic precipitation measurement network (**Figure 2, a&b**), expanding from the 3 climate stations that existed within RCEW in 1996, to an elaborate network of 24 meteorological measurement sites. Methods developed in RME to model snow redistribution and drifting have been successfully applied over other watersheds [Winstral *et al*., 2008]. In addition to wind and precipitation, temperature and humidity are critical to determining the phase of the precipitation (rain or snow) and the magnitude of available melt energy [Essery and Pomeroy, 2004; Marks *et al.*, 1999, 2001b&c, 2002; Marks and Winstral, 2001]. Efforts to characterize the canopy effects and shading on the snow surface energy balance have been undertaken [Hardy *et al*., 2004; Link *et al*., 2004; Sicart *et al*., 2004]. Initial efforts to measure and model the distribution of soil temperature and moisture over the catchment as a function of snow deposition and melt have also been initiated [Grant *et al*., 2004; Seyfried *et al*., 2008].

Many of the meteorological measurement sites also monitor snow depth, soil temperature and moisture, and a few now monitor heat flux between the snow and the soil (see **Table 1**). The modeling strategy developed within the

Table 1: Summary of RCEW telemetered data collection system. The period of record indicates the initial and current, or final year of data collection. Some sites may have started later or ended earlier, and gaps in the record may occur. The 2004 sampling interval may not reflect that of the entire period of record. The sampling interval may not be the same as the data recording interval in the database.

Parameter:	Measured Value:	# of Stations			Years of Record:	Sampling Interval:
		1975	1996	2007		
Precipitation	shielded precipitation	53	17	24	1962-2008	Breakpoint (bp)[1],
	unshielded precipitation	53	17	24	1962-2008	15 min
Snow	snow course SWE	8	8	8	1961-2008	bi-weekly
	snow pillow SWE	1	1	1	1961-2008	15 min
	snow depth			20	1994-2008	15 min
Daily Climate	T_{max} and T_{min}	3	3	1	1964-2008	Daily
(evap- summer only)	pan evaporation	3	3	1	1974-2008	summer
Climate	air temperature	3	3	25	1981-2008	15 min avg
	humidity	3	3	22	1981-2008	
	solar radiation	3	3	19	1981-2008	
	thermal radiation			3	1995-2008	
	wind speed & direction	3	3	22	1981-2008	
	barometric pressure	3	3	4	1981-2008	
	heat flux			6	2002-2008	
	surface & canopy temp			3	2003-2008	
Eddy Correlation	H, L_vE, H_2O, C-flux			5	2002-2008	10 Hz, 30 min avg
Soil Lysimeter	lysimeter water content	4	0	0	1976-1991	hourly
Neutron Probe	soil water (various depths)	18	14	35[3]	1970-2008	bi-weekly
Soil Moisture	% water (various depths)			10	2000-2008	hourly
Soil Temperature	soil temp (various depths)	5	5	14	1981-2008	hourly
Discharge & Sediment	stream discharge	13	8	9	1963-2008	bp[2], 15 min
	suspended sediment	3	3	7	1965-2008	event-based

1) Nominal value, 0.25mm of precipitation or 15 min sample;
2) Nominal value, 0.5mm of stage in 5 min or 15 min stage sample for small weirs, fixed 15 min stage sample for large weir
3) Only 14 of the 35 NP measurement sites are long-term and considered “permanent”

RME catchment was coupled to a below ground hydrology and routing model and extended to a much larger basin [Garen and Marks, 2005], indicating the value of detailed instrumentation and data collection for development and testing of operational hydrologic models [Etchevers *et al*., 2004]. Work is currently underway on integrating the snowcover energy balance modeling with below-ground soil moisture and temperature modeling [Grant *et al*., 2004; Seyfried *et al*., 2008].

c. An Ephemeral Headwater Catchment: Upper Sheep Creek

In Upper Sheep Creek (USC), an ephemeral headwater catchment in RCEW (**Figure 2b, 3b**), a combination of meteorological and sub-surface soil monitoring, with manual field surveys were used to characterize snow distributions, soil moisture, ground water, and water balance [Flerchinger *et al.*, 1992, 1993, 1994; Deng *et al.*, 1994] culminating in the use of the SHAW model [Flerchinger and Saxton, 1989] to simulate a 10-year land cover partitioned water balance for USC [Flerchinger *et al.*, 1998; Flerchinger and Cooley, 2000].

To extend the USC analysis to 2 decades, the catchment was re-instrumented in 2004 so that it could be directly compared to RME, and to accommodate plans to use the USC catchment for a detailed evaluation of the hydrologic effects of fire [Flerchinger and Clark, 2003]. Three additional hydrometeorological measurement sites have been located on an exposed ridge, below an aspen grove, and on a tower through the aspen (**Figure 3b**). A 23-year modeling data set has been developed and used to extend the analysis of Flerchinger and Cooley [2000] over a longer time period and a wider range of conditions [Chauvin *et al*., 2008]. Eddy covariance has been installed above the aspen, and over Wyoming big mountain sage. The additional hydrometeorological data were collected for 3 years prior to the controlled burn, conducted in September 2007. The augmented data collection will be continued for at least a decade following the controlled burn to evaluate the hydrological implications of fire during vegetation recovery.

d. Eddy Covariance

Technological advances have allowed us to improve instrumentation, expand the number of parameters adapted for continuous measurement, and to significantly increase the data rates and sampling frequency at our measurement sites. Eddy covariance (EC) instrumentation, once limited in application to carefully established field laboratories, is now much more robust. Currently EC systems are operated continuously at five remote sites within RCEW (**Figure 2b, 3a,b)**), including measurements over low and high sage, and above and below aspen groves. Though this effort has just begun, we are beginning to use EC measurements of sensible and latent heat flux over snow [Marks *et al.*, 2008], and of heat, mass, and momentum transferred between the snow and the atmosphere through a vegetation canopy to validate and improve our models [Reba *et al.*, 2008]. All of the EC systems measure carbon flux, but these data have not yet been analyzed.

e. Hill-slope Hydrology

Extensive work has been conducted at RCEW over the last decade to improve instrumentation and methodologies for measuring and monitoring soil temperature and moisture, with a focus on conditions at, or around the triple point of water (0°C) [Chandler *et al*., 2004; Seyfried, 1993; Seyfried and Murdock, 1996, 1997, 2001, 2002, 2004]. A result of these efforts has been a more complete understanding of spatial variability of soil microclimate [McNamara *et al*., 2005; Seyfried, 1991, 1995; Seyfried *et al*., 2005], which has had a significant impact on modeling [Seyfried, 1998; Seyfried and Wilcox, 1995; Wilcox *et al.*, 1991a&b].

This effort has led to the development of a suite of instrument systems designed to continuously monitor detailed profiles of soil microclimate. By developing improved calibration techniques appropriate to the cold conditions found in snow-dominated systems, measurement uncertainty and reliability have been improved. At present, four hill-slope hydrology sites have been established (**Figure 2c, 3b**) where measurements of near-surface heat flux and temperature and moisture profiles from the surface to as deep as 2m will be collected. Data from these sites are being used to provide forcing data for models, and to verify and improve simulations of heat and moisture exchange between snow and soil, soil and vegetation, and vegetation and the atmosphere.

3. Data Acquisition and Telemetry

The research methodology for gathering data has gone through a vast change since the establishment of RCEW. Data recording has evolved from spring driven chart recorders, which were reduced and digitized by hand, to the design and construction of custom data loggers and telemetry systems, to the current use of standard commercial data loggers, instrumentation, and telemetry. This significantly reduced the time and cost of maintaining the database for RCEW through 1996, and is currently allowing the acquisition of more detailed and higher time frequency data from a more diverse selection of sites than in the past.

Replacement of custom, hand-made sensors, data recorders and telemetry systems from the 1980's allowed us to take advantage of the technological advances in electronics and instrumentation during the 1990's. In the last decade we have begun to investigate the use of new measurement technologies that integrate state-of-the-art instrument design, high-speed computers and data recording and telemetry. Measurements that could previously be made only manually or through the use of very specialized facilities are now integrated into the RCEW data acquisition and telemetry system. **Table 1** is a list of most of the measured parameters that are part of the RCEW system.

Since the 1996 publication of the RCEW data [Marks, 2001], the amount of telemetered data has more than doubled. The RCEW instrumentation network now consists of over 50 telemetered data acquisition systems located throughout the Reynolds Creek Experimental Watershed. Data are telemetered to the USDA-ARS Northwest Watershed Research Center in Boise, Idaho, approximately 80 km from RCEW, by a combination of telephone lines and a land based VHF radio system. The data are automatically uploaded to the central computer database once each day, where they are automatically processed, quality-checked, and graphed. Fifteen minute averages are collected for most meteorological parameters, 15 minute or hourly measurements for soil microclimate parameters, and breakpoint or 15 minute totals for precipitation. Selected sites, such as the canopy towers in RME and USC, collect 5 minute samples or averages.

4. Data Availability

The historical RCEW data through 1996 are currently available from the anonymous ftp site *ftp.nwrc.ars.usda.gov* in the directory "reynoldscreek" maintained by the USDA Agricultural Research Service, Northwest Watershed Research Center in Boise, Idaho, USA. We are moving toward an agreement with the NSF CUAHSI Hydrologic Information System (HIS) [Horsburgh, 2008; Maidment, 2008] to host the complete dataset from 1960 to 2008. Data collected since 1996 are also available upon request by contacting the author, Dr. Danny Marks at ars.danny@gmail.com.

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