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SNOW HYDROLOGY IN WATERSHED ANALYSIS

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ABSTRACT

Watershed analysis refers to evolving systems of procedures for characterizing hydrologic and ecosystem processes within catchments as input to land management plans and practices. The most formalized approaches to watershed analysis were developed by the Washington Forest Practices Board and the Forest Ecosystem Management Assessment Team and its successors. Watershed analysis seeks to determine critical processes and their extent, condition of the landscape and channel, impacts of past practices, location of sensitive areas, existing problems of water regime and quality, influences on aquatic habitat, and other information about watersheds relevant to resource planning and management activities. In higher-elevation basins, information about snow cover and snowmelt processes is necessary for a thorough watershed analysis. Characterization of a basin's snow hydrology provides fundamental knowledge for understanding temporal and spatial patterns of water availability for runoff. The typical distribution of snow and related synchronization of tributary flows, alterations in snow cover from past harvesting, and potential for rain-on-snow peak flows can influence land management options.

OVERVIEW OF WATERSHED ANALYSIS

Although the general concept of watershed analysis is certainly not new, the adoption of a set of semi-formalized procedures called watershed analysis by land-management agencies is a recent event. During the early 1990s, state and federal agencies have developed approaches for evaluating the current "health" of catchments and their sensitivity to management and disturbance. These efforts formalize the idea that we should have a sound understanding of how part of the landscape functions before we alter it. Because many or most potential impacts involve water, the most appropriate landscape unit is a watershed or river basin. Many obvious similarities exist between so-called watershed analysis and environmental impact studies or assessment of cumulative watershed effects. A major difference is that watershed analysis is intended to be proactive, comprehensive, and a basis for planning future activities rather than a response to a particular project.

The philosophy behind watershed analysis has been around since at least the beginning of conservation and science-based resource management in the United States (Grant, 1994). Early assessment of water supply potential for cities such as San Francisco (Freeman, 1912) and Sacramento (Hyde et al., 1916) included detailed evaluations of watershed conditions. Comprehensive studies of river basins for water resources development, flood control, and soil conservation have been performed by irrigation districts, public utilities, county planning departments, state water agencies, as well as federal agencies such as Soil [now Natural Resources] Conservation Service, Bureau of Reclamation, Corps of Engineers, former Federal Power Commission, and Geological Survey. Watershed studies became common after Congress passed the Omnibus Flood Control Act in 1936 when land use was thought to have a dominant effect on flood generation (Leopold and Maddock, 1954; Hoyt and Langbein, 1955). Recent applications for new licenses and continuations for hydroelectric facilities have included exhaustive studies of watershed conditions.

Watershed assessments for improved land and resource management probably began in the mid-1950s as watershed management research by U.S. Forest Service Experiment Stations demonstrated effects of forest practices on water resources. An example on the Sierra National Forest in 1966 states that "Willow Creek was

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Paper presented Western Snow Conference 1995

given a watershed analysis to determine sources of sediment" (Dissmeyer, 1966). That report includes most of the elements of modern watershed analysis: identification of problems, beneficial uses, demand projections, climate, physiography, soils, runoff processes, streamflow regime, peak flows, water balance, disturbance history, sediment budget, and suggestions for erosion control and watershed restoration.

Evaluations of cumulative watershed effects (i.e., Reid, 1993) consider many aspects of watershed analysis. Procedures for analysis of cumulative watershed effects applied to national forests in California (i.e., Haskins, 1987; Kuehn and Cobourn, 1989; Carlson and Christiansen, 1993) assess sensitivity of the watershed to disturbance by examining streamflow generation processes, channel morphology, soil erodibility, and potential for mass wasting. A history of land disturbance including road construction, harvesting, site preparation, fire, grazing, and residential development is compiled. Stream channel conditions are surveyed to identify existing problems and unstable areas. Beneficial uses are described as a basis for determining appropriate water quality criteria. Although cumulative watershed effects analyses are typically prompted by a proposed project, the Eldorado National Forest has an extensive program for the entire Forest underway as a result of timber sale reconsideration. Studies on watersheds ranging in size from 1 to 80 km^2 have been completed for at least half of the Eldorado National Forest as of April 1995. Although different in goals, scope, and procedures, this program illustrates some of what a comprehensive watershed-analysis approach to a national forest might look like.

State of Washington Approach

Two detailed sets of procedures called watershed analysis have evolved in the past few years in the Pacific Northwest. The first of these to be implemented emerged from the Timber/Fish/Wildlife Agreement between state agencies, forest products industries, tribes, small landowners, and environmental groups in the state of Washington. In 1992, the state Department of Natural Resources adopted a structured process for planning forest practices specific to each watershed based on scientific study of that catchment (Washington Forest Practices Board, 1993). The state is divided into more than 600 watersheds ranging in size between 40 and 200 km^2. Watershed analysis for any of these defined watersheds can be initiated by land owners within the basin. The analysis starts off by developing knowledge of active hydrologic processes and historical and current influences on watershed condition. One of the main goals of each study is identification of areas of sensitivity within the watershed based on potential for specific impacts to public resources. These sensitive areas require special management prescriptions, which may be avoidance or restoration. By focusing timber management on lands that can support it and minimizing entry to sensitive lands, adverse impacts can hopefully be avoided for the stream system and watershed as a whole. The program emphasizes prevention of upslope impacts rather than waiting for damage to appear in aquatic habitats (Shaw, 1993). On state-owned lands, managers must demonstrate that harvesting will not adversely affect hydrologic processes and hillslope stability. The ultimate hope is that the analysis will produce a thorough description of a watershed and how it works at a scale appropriate for guiding land management (Washington Forest Practices Board, 1993).

Federal Interagency Approach

Controversy over forest management and concern about impacts to habitat for spotted owls and salmon led to a comprehensive study of environmental conditions and policy options on federal lands in the Pacific Northwest (Forest Ecosystem Management Assessment Team, 1993). Among the recommendations of this so-called FEMAT study was an aquatic conservation strategy designed to improve stream conditions for anadromous fish. A critical part of this strategy was an assessment process that became known as watershed analysis. It was originally designed to focus on riparian issues, but was quickly recognized to be of value in assessing a broad range of upland and social issues as well (Grant, 1994). Future management activities on National Forests and Bureau of Land Management holdings will be based on the environmental conditions and opportunities in each area, and watershed analysis is the tool for identifying those attributes (Reid et al., 1994). The outline of the federal watershed analysis package appeared in the FEMAT report and has been progressively improved by an interagency team (Furniss and McCammon, 1993; United States, 1994). During this same period, the Forest Service has embraced ``Ecosystem Management'' as its way of doing business for the foreseeable future. Ecosystem Management depends on understanding interactions between the physical environment, biota, and human activities. Developing such knowledge is the fundamental goal of watershed analysis and, therefore, may be the most appropriate means of providing a sound foundation for Ecosystem Management.

Watershed analysis on federal lands is more comprehensive and more flexible than the Washington approach because the range of issues and management options is much broader on the diverse federally-owned landscape. The federal watershed analysis package stops short of the management prescriptions that are an output of the Washington process. Watershed analysis on federal lands is not designed to produce a decision document and does not follow procedures akin to the National Environmental Policy Act. It is based on processes, ecosystem components, and places, but not on projects or proposals. In the federal context, watershed analysis is a tool for description and assessment of watershed processes and ecosystem conditions. From the start, it is recognized to be only a beginning and will necessarily be incomplete. Beyond compiling existing information and describing linkages between natural processes, watershed analysis should identify gaps in knowledge and the potential value of improved information (Reid et al., 1994). It is designed to be fluid and responsive to particular conditions, evolving techniques, and feedback from pilot analyses.

The basic mechanics of watershed analysis as described in the Federal Guide for Pilot Watershed Analysis (United States, 1994) are as follows. The most appropriate scale of analysis has been judged to be between 50 and 500 km^2. Less detailed analyses are also performed at the larger river-basin scale. A particular watershed receives priority and is selected for analysis on the basis of regional interests and opportunities for management. Public input is sought to identify critical issues, locate relevant information, and provide reality checks. An interdisciplinary and possibly interagency team will prepare the analysis and will stress the interactions between their specialties. The primary steps in a watershed analysis include:

1. Identify issues, describe desired conditions, and formulate key questions
2. Identify key processes, functions, and conditions
3. Stratify the watershed in similar units to expedite the analysis
4. Assemble analytic information needed to address the key questions
5. Describe past and current conditions
6. Describe condition trends and predict effects of future land management
7. Integrate, interpret, and present findings
8. Manage information, monitor, and revise

The resultant products of a watershed analysis include:

1. A description of the watershed including its natural and cultural features
2. A description of the beneficial uses and values associated with the watershed and, when supporting data allow, statements about compliance with water quality standards
3. A description of the distribution, type, and relative importance of environmental processes
4. A description of the watershed's present condition relative to its associated values and uses
5. A map of interim riparian reserves
6. A description of the mechanisms by which environmental changes have occurred and a description of the role of specific land-use activities in generating change
7. A description of likely future environmental conditions in the watershed, including a discussion of condition trends and of the potential effects of past activities
8. Interpretations and management recommendations: watershed processes and ecosystem concerns and interactions to be addressed at a project-planning-scale in different parts of the watershed, with particular applications for: a) design of riparian reserves, b) restoration, c) transportation, d) monitoring, e) cumulative effects analysis, f) general planning (United States, 1994).

These lists were already obsolete in April 1995, when the next iteration of a manual was being written. The structure of watershed analysis will continue to evolve as more people become involved and it is applied in more places. An active monitoring component is a desired part of the package to improve knowledge about physical processes, effects of forest practices, and methods of conducting watershed analysis (Schuett-Hames and Pess, 1994). The 1994 version of the interagency manual provides a variety of suggested procedures for Step 2 above, identification of key processes, functions, and conditions. Topics such as existing and potential vegetation, fire history, road condition, surface erosion, mass movements, bank erosion, sediment yield, geology, soils, streamflow characteristics, runoff generation, stream temperature, channel conditions, evapotranspiration, aquatic and terrestrial habitat, and domestic water supply are covered. The procedures discussed are intended to serve more as examples and inspiration for creative thinking rather than as a cookbook. Descriptions of these methods include generic goals, assumptions, data needs, products, and procedures at both a cursory level and a more quantitative level depending on the needs of a particular study. Analytic modules relating to snow hydrology had not been developed in time for inclusion in version 1.2 of the interagency manual. The balance of this paper discusses some potential applications for information about snow in watershed analysis.

SOME POSSIBLE USES OF SNOW HYDROLOGY IN WATERSHED ANALYSIS

Watershed analysis provides some new outlets and applications of snow studies and routine data collection. Although snow measurements have been critical to studies of forest hydrology for decades (i.e., Church, 1912; Garstka et al., 1958; Anderson, 1963), watershed analysis could integrate such information over much larger areas and in an operational or planning context.

The Washington approach considers effects of timber harvest on snow accumulation and melt to have the greatest opportunity for producing significant and long-term cumulative effects on hydrologic processes in forests. A set of procedures has been developed to assess the potential for causing such impacts. These techniques are addressed at five key questions (Washington Forest Practices Board, 1993):
1) What are the current watershed conditions influencing watershed response?
2) What is the history of floods and disturbances of hydrologic significance in the watershed?
3) What is the influence of land use on the water available for runoff?
4) What is the effect of changes in water available for runoff on flood peaks?
5) What are the effects of change in peak flows on public resources?

Climatic Characterization

A general description of an area's climate is an obvious part of any environmental document. However, information about snow is often limited in the climate section of many reports, even in regions where most precipitation falls as snow. Perhaps limited data about snow or data that are difficult to track down perpetuate the paucity of information about snow climatology. Similarly, a perceived lack of demand for such information doesn't do much to increase its collection or availability. Useful information about snow cover includes means and extremes of water equivalence at measurement sites at different times of the year, spatial extrapolations of water equivalence information, snowfall in combination with total precipitation, frequency distribution of storm magnitude by month, dates of formation and disappearance of continuous snow cover, proportion of precipitation in the form of snow for each month at different elevations, precipitation type for particular events, elevational snow lines and snow cover extent, and general rates of snow melt or snow disappearance. Some knowledge of the extremes is always valuable, so that we may have some idea of the climatic possibilities. Where records are short, as is usually the case, frequency analysis and common sense are needed to estimate the bounds of the possible. An analyst must avoid becoming trapped in the details of characterizing the role of snow in a particular basin. The obvious question of how much information is sufficient will always depend on the situation. A suggested guideline for compiling snow climatology is to provide enough information that will define the influences of snow on the landscape and compare the climate of this watershed to that of its neighbors.

Information about snowpack water equivalence at snow courses and snow sensors is available from the Natural Resources Conservation Service in most western states and from the Department of Water Resources in California. These data are becoming increasingly available in electronic form on storage media or via electronic transfer. The National Climatic Data Center continues to compile and publish snowfall and snow depth data from a limited number of its cooperative observer sites. However, many of these sites are at relatively low elevation and thereby provide information about transient snow conditions that the snow sensor networks miss entirely. Climatic data are available on CD-ROM from at least two commercial sources, but only begin in the late 1940s. Unfortunately, there are only 11 sites in the Sierra Nevada with daily snowfall and snow depth on the ground for more than 45 years. Other mountain areas are unlikely to have a much greater network density. Observations of snow and weather conditions are also recorded at many hydroelectric facilities and ski areas, but are not distributed widely. Other possible sources of snow data include irrigation districts, rural water supply districts, railroads, highway departments, and private individuals. Compilations and summaries of data and special information such as aerial photos may be available from state water-resource agencies, river forecast centers, and operators of large water projects downstream. Reports describing the climate of an area in detail (i.e., Smith and Berg, 1982; Osterhuber, 1993) can be invaluable if the watershed under study happens to be near the area of the report. Such reports often take advantage of particularly long data sets, such as the 115 years of snowfall records at Donner Summit (Osterhuber, 1993). Long periods of record are very scarce, but provide temporal context for our more recent observations. Extrapolations of such information to distant areas must be made with caution and some rational validation.

Streamflow Characteristics

Where records of streamflow are available, hydrograph analysis can inform us about many aspects of the snow hydrology of a catchment. Ideally, a few stream gages at different elevations might be present in the watershed of interest. Small catchments of 1 to 10 km^2 tend to the most informative about runoff generation because response is relatively uniform and channel routing is not a problem at that scale. However, in most basins, there is unlikely to be any stream gage or one without artificial regulation or diversions upstream. Where flow data exist, much can be learned about the typical annual cycle of hydrologic events: What is the likelihood of rainfall-runoff in different seasons? Does snow cover tend to diffuse or augment streamflow response to rainfall? What is the typical volume and range of volumes of seasonal snowmelt runoff? When does spring melt usually begin? What is different about peak flow events from different parts of the watershed? What is the duration of high snowmelt runoff? Does residual snow at high elevations sustain streamflow in summer?

Examination of the flood record from all gages in and near the watershed is essential to understanding the nature of events that may alter the landscape and channel. After dates of peak flows are identified from the streamflow record, meteorological and snowpack conditions should be tracked down to learn about the factors contributing to high flows. Are the largest flows caused by rainfall on bare earth, rainfall on a shallow snow cover, summer thunderstorms, or spring snowmelt? Regional flood histories (i.e., Waananen and Crippen, 1977; Harr, 1981; Kattelmann et al., 1991) can help one get started, but searches of meteorological records and newspapers will be necessary to define the character of past events.

Rain-on-Snow Potential

Increasing the potential for damaging peak flows during rain-on-snow events has emerged in the past few years as the most threatening hydrologic effect of timber harvesting, and both approaches to watershed analysis emphasize evaluation of rain-on-snow. The frequency and magnitude of such flows may be increasing as a result of creating openings in the forest and enhancing opportunities for snowmelt driven by turbulent exchange processes (Anderson and Hobba, 1959; Harr, 1981). Creation of large forest openings exposes the snow surface to more wind relative to the forest and can increase water input to soils by 10 to 25 percent, depending on interactions of snowpack, weather and terrain conditions (Harr, 1981; Berris and Harr, 1987).

The proportion of a watershed in the intermittent snowpack or rain-on-snow zone can determine the general nature of streamflow generation during the winter months. This zone is above the rainfall zone where occasional snowfall does not persist and below the snowpack zone where snow cover lasts a few months. During warm storms, this zone has been estimated to contribute twice as much runoff as the rainfall zone and three times as much water to streams as the snowpack zone (Anderson, 1958). At a site in the intermittent snow zone of the Sierra Nevada, snowmelt and water release to soils were observed to occur on most days of the winter and spring when snow cover is present. During warm storms, combined rainfall and snowmelt at this site exceeded

50 mm per day about 4 times each winter on the average (Kattelmann and McGurk, 1989). Runoff generated during such events can erode soils and alter channels.

The watershed analysis procedures assess the potential for rain-on-snow events and examine the flood history. Possible hydrologic changes resulting from timber harvest are evaluated by estimating the amount of water available for runoff under different scenarios of forest cover (Brunengo et al., 1992). Snow accumulation is estimated as a function of elevation and vegetation, and snowmelt is determined as a function of wind speed, air temperature, elevation, and canopy cover. The extra snowmelt produced at different levels of forest cover are added to precipitation to calculate the water available for runoff. If more water is available from the cut-over situation, then flood frequency curves are shifted to reflect more frequent occurrences of a given magnitude. This relative change in estimated streamflow at similar storm frequencies for various cover amounts is the basis for interpreting the hydrologic impacts of harvesting (Brunengo, 1990; Brunengo et al., 1992; Washington Forest Practices Board 1993).

Water Balance

Estimation of a monthly water balance for a couple of years is a worthwhile exercise to force the analyst to think about the disposition of precipitation and to illustrate how a particular watershed works. Even comparing the gross runoff efficiency (streamflow / precipitation) between wet years and dry years is informative. Development of a water balance, however crude, requires some estimates of changes in snow storage throughout the basin. Because adequate data are unlikely to be available except in research catchments (which probably won't be the subject of a watershed analysis), some serious guesswork and assumptions must be made in reconciling precipitation, snow measurements, and streamflow to produce a reasonable water balance. Sometimes a basin is of sufficient importance to regional efforts that field measurements can be justified. Streamflow is the fundamental measurement to use in estimating other quantities because it integrates water inputs from throughout the catchment and is easier to measure than the spatially diverse components. Guesses about the distribution of precipitation, snow cover, and subsurface water will be highly uncertain. The extent of snow cover tends to have a much greater influence on basin-wide snow volume than water equivalence extrapolated from a few point measurements. Unfortunately, there probably won't be any information available on snow covered area. Performing an intensive snow survey at peak accumulation is probably the best means of evaluating winter precipitation in high-elevation areas with little rainfall but is beyond the scope of most watershed analyses. Estimating a water balance from minimal information is a highly speculative and iterative process, but is still beneficial in attempting to understand how a watershed functions.

Other Considerations

Creation of openings in the forest canopy can dramatically affect snow accumulation and melt. A large amount of literature about forest influences on snow throughout western North America is now available (much of it can be found in Proceedings of the Western Snow Conference). After information about the size, shape, location, and extent of past and potential timber harvests is compiled for the watershed of interest, relevant research literature can be consulted and inferences drawn about possible local effects. General questions to be considered include: How much have harvests altered snow accumulation by eliminating interception and changing aerodynamics of the stand? How much has radiant energy input to the snowpack increased? How much has the potential for turbulent exchange (convection / condensation melt) increased? Are the layout and density of forest roads sufficient to enhance snow storage and delay melt?

What is the potential for snowmelt-induced erosion? Are shallow soils typically saturated during spring snowmelt? Are south-facing slopes subject to high snowmelt rates (20-40 mm per day)? Are channels typically dry during winter and subject to oversnow-flow induced erosion (Kattelmann, 1990)? Do snowbanks along streams prevent overbank spreading of water and, thereby increase flow depth and shear stress on the streambed (Erman et al., 1988).

Do ski areas or residential developments occupy a significant portion of the catchment? The presence of snow and snowmelt runoff may be extended later into spring on ski runs and in piles created by snow removal from roads and parking lots, frequent controlled avalanches, and roof shedding. Conversely, the presence of bare ground or pavement and structures may expose the snow to extra long-wave reradiation and thereby accelerate melt.

Is snow cover reliable enough without being excessively deep to permit oversnow logging? Are soils frozen enough to withstand compaction before snow cover begins to develop? Do soils commonly become saturated during warm winter storms? Do winter-maintained paved roads provide access to areas of possible winter logging?

SUMMARY AND CONCLUSIONS

The primary goal of watershed analysis is to develop a sound understanding of watershed conditions, processes, interactions, and trends based on available data and information. The snow hydrology of a catchment is only a small part of this understanding. Other processes and resources are much more important in assessing the state of a basin and its sensitivity to possible management activities. Nevertheless, snow hydrology is a critical piece of the picture in most mountain areas and should not be overlooked in watershed analyses.

The advent of watershed analysis as a powerful tool in guiding land management decisions and planning provides an extraordinary opportunity for resource specialists and hydrologists in particular to improve management of wildlands. Watershed analysis institutionalizes many of our long-running concerns and concepts. If fully implemented, it should provide the sound foundation for resource planning that has long been advocated but never quite accepted. If watershed analysis remains an open, adaptive, and educational process, it also has the potential to rebuild public trust in land managers and their agencies.

ACKNOWLEDGMENTS

Employees of the Humboldt Interagency Watershed Analysis Center and Weyerhaeuser Corporation were most helpful in supplying documents concerning the federal and Washington approaches to watershed analysis. Participants in a workshop on watershed analysis at the Watershed Management Council's conference in Ashland in November 1994 also provided many useful ideas. Information and material for this paper were developed during work on a compilation of hydrologic data for the Sierra Nevada under a grant from NASA's EOS program to Jeff Dozier at U.C. Santa Barbara and water-resource assessments at the river-basin scale for the Sierra Nevada Ecosystem Project funded by the USDA-Forest Service through U.C. Davis.

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