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EFFECTS OF FOREST HARVESTING ON BASIN-WIDE WATER YIELD IN RELATION OF % OF WATERSHED CUT:

A REVIEW OF LITERATURE

By

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INTRODUCTION

The use of watersheds as geographical boundaries for forest management purposes has been popular for many years. For example, two experimental watersheds were established in Czechoslovakia in 1867, for the purpose of investigating the importance of forests in moderating surface runoff. To settle debate over the importance of forests with regards to floods, and peak flow volumes, paired watersheds were used in Switzerland, in 1902. As concern about dwindling timber supply and soil erosion grew, National Forests were created in the United States, and the Wagon Wheel Gap project started in 1909 (Swank and Johnson 1994). This was the first of many subsequent efforts made to quantify stream flow before and after harvesting. When the worst flood on record occurred in the Mississippi delta in 1927, pressure on the government to investigate the impacts of forest management on water resources increased. This initiated a boom in watershed research across the United States and elsewhere, of which the Coweeta Hydrologic Laboratory, the Hubbard Brook Experimental Forest, the Jonkershoek Research Station in South Africa, and the Nashwaak Experimental Watershed in New Brunswick, Canada, are notable examples. As a result of much of this work, it was found that post-harvest streamflow tends to be larger than pre-harvest streamflow. Clarke, (1994) therefore examined the role of mathematical models in finding optimal harvesting scenarios for the enhancement of streamflow. As well, Anderson was interested in learning how to increase snow capture and hence water yield through varying forest management practices (Anderson 1956; 1960; 1962; 1963; 1967; Anderson and Gleason 1960; Anderson and Hobba 1959).

Regardless of the focus of forest watershed research, related projects are used to effectively characterize the various hydrological properties of the watersheds, as they differ by region, geological substrate, topography, climate, forest cover, and responses to various surface (forest) treatments. As such, most watershed projects are very site specific, and lack a process that permits extrapolation of results to other watersheds (Clayton and Kennedy 1985). While the impacts of specific watershed management on water yield and quality tend to be well documented, watershed-specific treatments have not been oriented towards testing refined hypotheses. Thus, portable concepts about process are lacking somewhat.

Many literature reviews of watershed studies are readily available (Bosch and Hewlett 1982; Hewlett et al. 1970; Hibbert 1967; Hornbeck et al. 1993; MacGregor 1994; Bell et al. 1974). Some in fact concentrate on issues of water yield and water quality in relation to portion or percentage of the watershed cut, which is the topic of this review. There are fewer examples, where the importance of the spatial arrangement of the cuts, their size, and their positional relationship within the watershed are addressed.

Today's realities present forest management with a new challenge that was not encountered in many parts of Canada in preceding decades, namely the increasing fragmentation of the forested land into a patchwork (mosaic) of cut, and uncut, planted and not planted regenerating forest stands. There have also been increasing pressures from the public to limit opening sizes, and to preserve old-growth forest, wildlife habitat, rare forest types, and forest streams as much as possible. This now provides another impetus regarding the refining of forest hydrology at a scale that can take into account small cut sized in relation to topography, and position within a watershed. The objectives for this chapter are to

1. to review current literature regarding the effects of forest harvesting on discharge;
2. in doing so, examine the effects of cutting (complete, partial, thinning) on the watershed wide water input/output balance for the purpose of modelling;
3. also examine a number of processes that affect the input/output balance, especially evapotranspiration and snow capture.

LITERATURE REVIEW

Hibbert (1967) reviewed 39 catchment experiments and came to three main conclusions:

1. Reduction of forest cover increases water yield
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable and, for the most part, unpredictable.

With the addition of 55 new experiments, Bosch and Hewlett (1982) supported the first two conclusions made by Hibbert, but refined the third conclusion, by stating that there are observable differences in response to harvesting, by vegetation classes. Through regression analysis, coniferous and eucalyptus forests were found to increase annual water yield by roughly 40mm for every 10% reduction in cover (Figure 3.1). This number was roughly 25mm for hardwoods, and roughly 10mm for shrub land. Bosch and Hewlett admitted that the confidence levels that are associated with these numbers are low, however Evans and Patric (1983) cited similar numbers.

The variability of response within these forest types and associated watersheds was extensive, with 100% removal of hardwood inducing both a 31 mm increase (Ursic

1970), and a 414 mm increase (Swank and Miner 1968) in streamflow in the first year following harvest. A 100% removal of softwood overstory induced a 226 mm (Rogerson 1979) and an 840 mm increase in streamflow (Pace and Fogel 1968).

In another review, Sahin and Hall (1996) used a fuzzy linear regression technique to analyze the results of 145 experimental catchments, and found that a 10% reduction of overstory in coniferous watersheds tends to increase annual streamflow rates by 20 to 25mm. For deciduous forest watersheds, the numbers amount to 17 to 19 mm increases in annual streamflow.

The review by MacGregor (1994) summarizes some of the same projects, generates the same conclusions and generalizations, but does not address the issue of cut size, or the contribution of cut size to streamflow. Maximum increases in mean annual streamflow for the first year following harvesting, however, were found to be 4.5 mm for every percent removal of the cover.

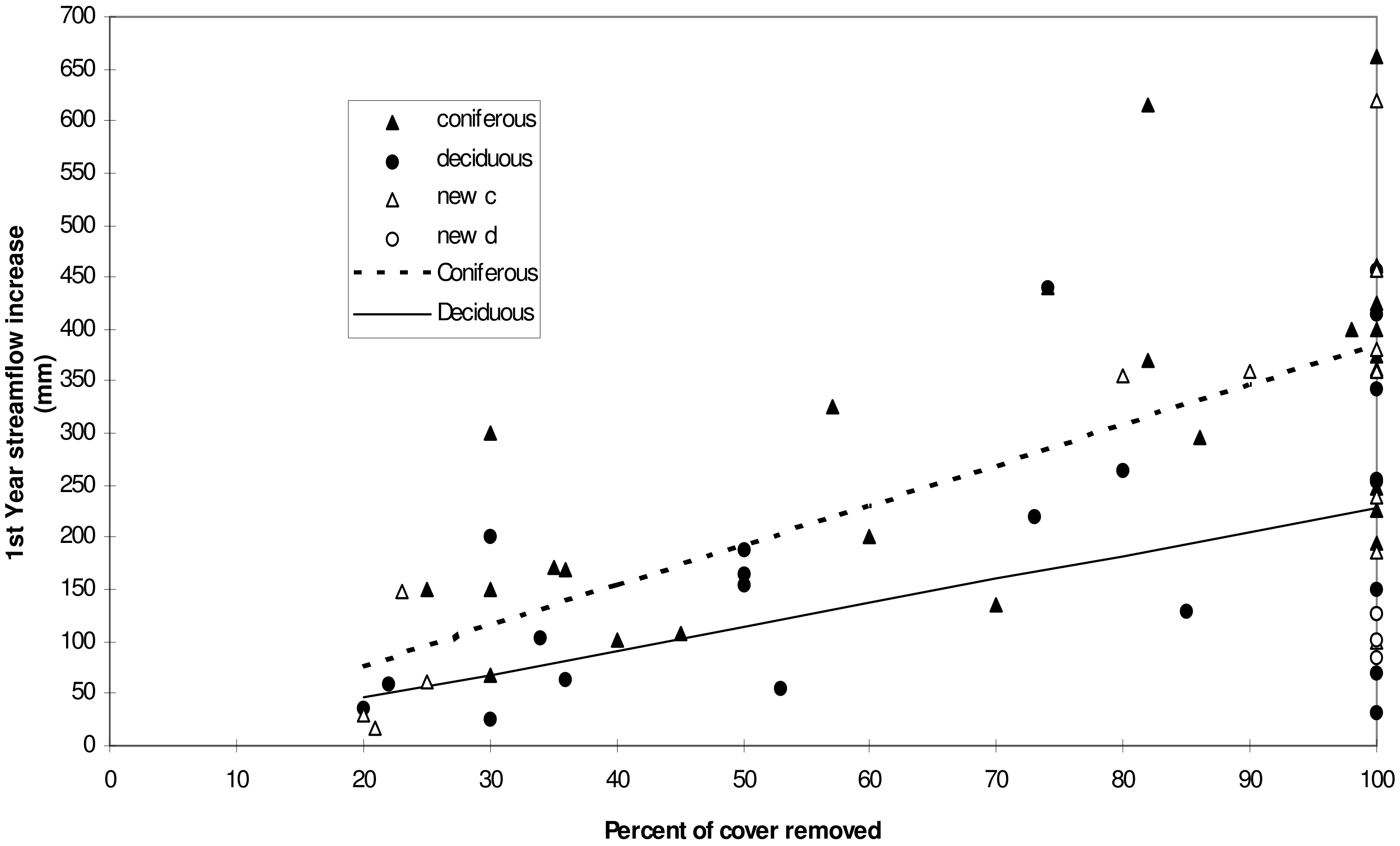

Figure 3.1 First year streamflow increases (mm) following different degrees of harvesting with regression lines from Bosch and Hewlett (1982) and new data points (open symbols).

Bosch and Hewlett (1982) reported that any reduction in forest cover of less than 20% was not detectable by measuring streamflow. Schroder (1996), who reviewed many of the same watersheds, organized them by climatic regions, and found that as little as 15% removal of vegetation in mountainous regions can result in an increase in streamflow. In contrast, a 50% removal was required to yield demonstrable changes in streamflow in the central plains of the USA. Here are further citations:

1. A 21% removal of softwood cover in the Marmot creek watershed induced a 17mm increase in annual streamflow (Swanson et al. 1986).
2. Deforesting 50% of two mountainous watersheds in West Virginia resulted in a yearly increase of 282 and 300mm in total streamflow (Patric and Reinhart 1971).
3. Megahan et al. (1995) reported the results of a paired catchment study in Idaho, where 23% of one watershed was clearcut with heli-logging and burned; there was no significant increase in streamflow.
4. When roughly the same portion of a larger lodgepole pine watershed was harvested, it resulted in a 147mm increase in annual water yield (Burton 1997).
5. After clearcutting and mechanical site preparation of a 28.6 ha watershed in the central Appalachians, Koehenderfer and Helvey (1989) reported a 99mm, 71mm, and 31mm increase in streamflow for the first three years after harvest.
6. Croft and Monninger (1953) reported a 102mm increase in water available for streamflow after removing dominant aspen and leaving the understory, and another 100+ mm after the removal of the understory.

7. Johnston (1970) used a neutron meter to measure soil moisture in the upper 9 feet of the soil profile in an aspen stand, and found clearcutting to increase soil moisture by about 152 mm per year.
8. Converting an oak forest to grassland resulted in a mean annual increase in streamflow over six years of 114mm (Lewis 1968).
9. In the Carnation Creek study, one watershed was clearcut on 90% of its area, with a resultant 360mm increase; another watershed was evenly cut over 7 years on 40% of its area with no significant increase (Hetherington 1982).
10. When 80% of the Jamieson Creek watershed in the foothills of the Rocky Mountains, British Columbia, was harvested, the resultant increase in streamflow was 356mm.
11. Fahey (1994) reported a 60-80% increase in water yield following clearcutting for hardwood watersheds in New Zealand, with recovery in 6-8 years; a 30 to 50% decrease in streamflow would be expected after converting grasslands to plantations.
12. Reforesting grassland with conifers in central New York reduced November to April peak flows by 40%, while reducing the overall annual runoff by 26% (Ayer 1968).
13. Clearing 50% of a watershed in Japan with 50m wide contour strips resulted in a 21 to 35% increase in summer streamflows.
14. Insect infestation and fire also can have similar effects on the hydrological cycle (Hillman 1971). For example, Love (1955) reported that after insects killed 30% of the forested area of the White River Basin in Colorado, annual water level increased by 22%.
15. Beaty (1994) reported a 60% increase in streamflow following a fire which burned all of a watershed in western Ontario.

16. In the Nashwaak Experimental Watershed Study, 100% clearcutting produced a post harvest increase of less than 10% over twelve post harvest years (Jewett et al. 1996).

An explanation of the variation of streamflow responses to clearcutting within vegetation classes has been attempted using differences in the mean annual precipitation (MAP). Regardless of the vegetation class, high precipitation areas usually induce rapid regrowth, and thus rapid return of streamflow to its original state, with the opposite applying to low MAP areas. First post-harvest year effects, however, are usually pronounced in high rainfall areas. For example, Rothacher (1970) reported an increase in water yield of 457mm after clearcutting a 237 acre watershed in a high precipitation region of the Oregon Cascades.

In “Opportunities to increase water yield in the southwest by vegetation management”, Hibbert (1981) refers to the Rich and Thompsons (1974) method for estimating post-treatment streamflow increases as a function of pre-treatment streamflow (Figure 3.2).

Evapotranspiration

Evapotranspiration, defined as evaporation from all water, soil, snow, ice, vegetation and other surfaces, plus transpiration (Chow 1964), is generally recognized as the most pronounced direct way by which watershed hydrology is changed (Biswell 1968; Croft and Hoover 1951; Goodell 1965; McGinnies et al. 1963; Rich 1952; Sinclair 1960; Woods 1966; Zor 1912; DeByle et al. 1969; Rosenzweig 1969). Grelle et al. (1997),

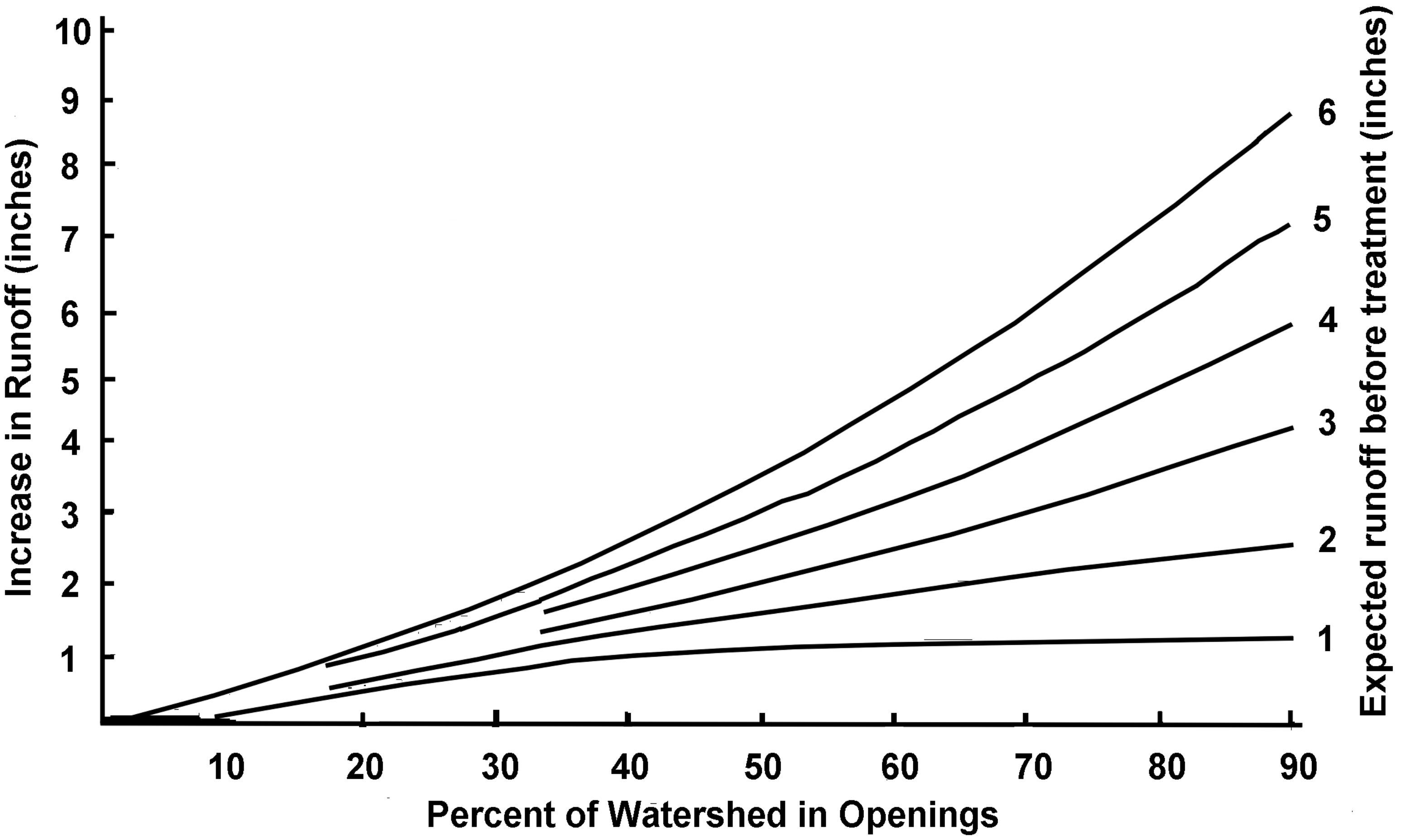

Figure 3.2 Expected increase in runoff (streamflow) as it relates to pre-treatment runoff verses the percentage of the watershed in openings.

therefore, evaluated the three major components of the evapotranspiration budget for a boreal forest:

1. evaporation from the forest floor (56mm),
2. interception evaporation (74mm), and
3. transpiration (243mm).

Baier (1967) estimated that evapotranspiration is responsible for returning 70% of annual precipitation to the atmosphere, and suggested that evapotranspiration is determined primarily by soil moisture availability, meteorological factors, and plant physiological characteristics. Through modeling, Federer and Lash (1978) estimated that a four week change in the timing of leaf development would cause a 10 to 60mm change in simulated streamflow, and that a 20% variation in daily transpiration would result in 120mm variation in simulated streamflow. Johnston (1969) compared water usage by different vegetation types at different ages. Aspen sprouts, for example, used 114 mm less water than mature aspen, and oak sprouts used 30mm less than mature oak.

Transpiration from understory vegetation is usually not differentiated from overstory vegetation. However Roberts and Rosier (1994) estimated that transpiration from understory vegetation in a beach and ash stand at a chalk site in southern Britain contributed to 45% of the annual water loss from the watershed. Johnson and Kovner (1956) reported an average increase in annual streamflow of about 51mm for six years after removing the laurel and rhododendron understory from a hardwood stand in the southern Appalachian mountains. Croft and Monninger (1953) reported a 100+ mm increase in water available for streamflow after removing the understory vegetation from a clearcut aspen stand.

Actual evapotranspiration (AET) is often less than potential evapotranspiration (PET), as soil water levels are often limiting for much of the year. The relationship between evapotranspiration and soil water, however, is still not well understood. There is some evidence that evapotranspiration rates are independent of soil moisture until the water levels drop below the permanent wilting point (PWP) (Veihmer 1956; Van Bevel 1960; Lowry 1959). Other studies have shown that AET typically remains at 90% of PET until about 65% of the total available water has left the soil, after which AET decreases steadily (Pierce 1958; Gardner 1960; Shaw 1968). The third predominant hypothesis is that of a linear relationship between AET and soil moisture, with AET decreasing with decreasing soil moisture until the PWP is reached (Thornthwaite and Mather 1955).

Calculating evapotranspiration from climatic data is complicated and has been approached in many different ways (Stricker 1982). Mihan (1986) cites seven methods for calculating evapotranspiration, all of which vary considerably in their data requirements and have had numerous modifications made since their initial conception. Yin and Brook (1992) compared some of the temperature-based PET calculations in a swamp watershed where they state that AET should be equal to PET due to the lack of a water deficiency at any time of the year. When AET was estimated with a steady state water balance model, it was found to be most highly correlated with the PET estimate calculated by the Thornthwaite equation (r^2=0.817), followed by the Blaney-Criddle equation (r^2=0.781), followed by the method used by Holdridge (r^2=768). Another study took the Penman equation as correct, and compared this equation with others by means of regression analysis to provide a means for correcting the other equations (Mohan 1991).

Further support for the Penman equation can be found in a report by Essery and Wilcock (1990) where PET estimates from the Penman equation are compared with the evaporative looses from irrigated grass lysimeters, from open water tanks based on rainfall data, from streamflow data and from groundwater data. Using 12 years of data showed the Penman equation to be the most accurate. Other comparisons of calculations and estimations are also available (Stricker 1982). Abbaspour (1991) compared eight different methods of estimating daily evapotranspiration, and compared them to measurements of AET from the Peace River region of British Columbia, Canada.

Some alternative methods for quantifying evapotranspiration also exist. For example, Claassen and Halm (1996) estimated evapotranspiration in a mountainous watershed from chloride ion concentrations in stream baseflow. DeByle et al. (1969) consider measured soil moisture depletion plus summer precipitation to be an estimate of actual evapotranspiration, and showed how AET varied from 130mm for grasslands, to 613mm for an aspen stand. Walker and Brunel (1990) examined evapotranspiration through daily variations of isotopic compositions in foliage.

Attempts have been made by researchers to quantify the spatial variations of evapotranspiration across a watershed (Famiglietti and Wood 1993; Flerchinger et al. 1996; Sabur 1991). For example, Dunn and Mackay (1995) illustrated how land-use changes may have significant effects on the hydrology of lowland areas, but not upland areas. Moelders and Raabe (1995) discussed that simply increasing the temporal resolution of hydro-meteorological modeling is insufficient for adequate hydrological assessments at the catchment scale, because meteorological conditions, are also affected spatially, especially by topography and related flow accumulation patterns. Ambroise and Najjar (1982) found that evapotranspiration on a mountainous watershed could be calculated accurately by using the Brochet and Gerbier formula, which is derived from the Penman equation.

Fog

Most research does not account for the potential effects fog has on the water budget in watersheds. Fog can not only add water to a watershed through fog drip from foliage, but it can also essentially halt evapotranspiration processes. Yin et al. (1994) estimated fog water input to be as high as 106mm for a coastal watershed in Nova Scotia, and Ingraham and Matthews (1995) noted a similar importance of fog water inputs for the coastal watersheds in California.

Snow Capture

Snow capture in a forested watershed is governed by a number of factors, the major ones being meteorological conditions (wind, snow density and quantity), and type and condition of the vegetation. Schmidt and Gluns (1991) examined three conifer species: pine (*Pinus contorta* var. *latifolia* Engelm.), fir (*Abies lasiocarpa* (Hook.) Nutt.) and spruce (*Picea engelmannii* Parry), to characterize any differences in snow catch efficiency by foliage type. These authors found that spruce branches intercepted 43% of the total snow water equivalent; pine 38% and fir 37%. Satterlund and Haupt (1967) showed snow fall capture to follow a sigmoidal curve given by

$$S= S_O/[1+e^{-k(P-Po)}]$$

where S_O is the interception storage capacity, P is the total storm precipitation in inches, and Po is the amount of snow accumulated at the time of most rapid accumulation.

For Douglas fir and western white pine, roughly 5% of intercepted snow is lost through evaporation, while the rest falls to the ground in liquid or solid form (Satterlund and Haupt 1970). Guttenberger (1994) measured evaporation of intercepted snow, and found that this makes up 60% of the evapotranspiration budget for a spruce stand. Lundberg and Halldin (1994) found that a snow-evaporative loss of 3.3 mm/day maximum from 6 m spruce trees in Sweden. These authors also concluded that one needs to measure relative humidity, aerodynamic resistance, wind speed, and total intercepted snow mass accurately to model snow the rate evaporation from intercepted snow in an accurate manner.

The difference in snow capture between harvested and non harvested watersheds is a primary cause of increased spring peak flow levels. Even in unharvested watersheds, spring peak flow has been calculated to contribute up to 68% of the total year's flow for a watershed in Utah (Glasser 1969), and 80% for a watershed in southern British Columbia (Shiau 1975). In a study in Lodgepole pine in Wyoming (Berndt 1965) with three opening sizes (5, 10, and 20 acres) located on four aspects (N, S, E, W), snowpack was always greater (405mm average) in the openings than in the undisturbed stand, with no significant differences between opening size. Aspect had a small impact on snowpack, with the eastern aspect having the most snow, followed by the southern, western, and northern aspects, with about 100mm of snow water equivalent between the lowest and highest snowpack accumulations. Snow in the uncut areas, however, persisted for 10 days longer than in the openings.

In a study of snow catch in circular openings of nine opening sizes varying from 0.25 to 6 tree heights in diameter in Alberta (Golding and Swanson 1978), 2H and 3H opening sizes accumulated the most snow, followed by 1H and 0.75H openings. Ablation rates were smallest in the 0.75H and 1H diameter openings, and steadily increased up to the largest opening sizes.

Evaporation from snowpack is counteracted by increased capture of snow in openings (Meng et al. 1995). Stegman (1996) states that geographic location, latitude, orientation to prevailing wind, and aspect are the primary factors effecting snowpack evaporation, but that a 5H by 1H sized opening maximized water yield, and minimized evaporation. In a Lodgepole pine study in Wyoming (Gary 1974), an opening 1H in width, and 5H in length perpendicular to the prevailing wind did not induce a watershed-wide increase in snowpack. However, within the clearing itself, snowpack was greater at peak times than in adjacent stands, with the upwind adjacent forest capturing slightly more snow than the downwind one.

When two Colorado watersheds of the same size (40 ha) had 40% of their areas harvested, one by 12 1.2 Ha circular cuts, and one by a single continuous clearcut, each induced significant increases in streamflow comparable to each other (Troendle and King 1987). This was probably due to the large sizes of the circular cuts (roughly 125m in diameter). Troendle and King (1985) also noted a 9% increase in snow water equivalent over the watershed when 50% of the area was harvested by strip cutting. Due to the apparent increase in snowmelt rate, peak stream flows increased by 20%, and were advanced by seven days over the average of the previous years.

In a study in Lodgepole pine by Wilm and Dunford (1948), twenty 5-acre plots were arranged in a randomized pattern, with sixteen harvested with selective cutting. Snow disappeared at roughly the same time, however accumulations (262mm in unharvested areas versus 343mm in harvested areas) and associated melt rates were greater in harvested blocks. Similar results have been noted for ponderosa pine (Berndt and Swank 1970), red pine (Hansen 1969), black spruce (Bay 1958), and mixed conifers (Anderson 1967).

The presence of slash has been noted to affect snowmelt. Anderson and Gleason (1960) measured snow depth on May 4., 1959, and found the average water equivalent to be 107mm in areas where slash had been burned; areas containing slash contained an average water equivalent of 23mm. Obviously, this difference is due to radiation capture of exposed slash, which helps to warm and melt the snow that is in immediate contact with the exposed slash.

It is important to note that clearcutting is only one way to modify the snow catch efficiency of watersheds. Snowpack after thinning a stand of lodgepole pine increased 30% over pre-thinned values (Gary and Watkins 1985). Hansen (1969) reported on a study where portions of a red pine stand were thinned to 30, 60, 90, 120, and 150 square feet per acre. The snowpack after snow events increased roughly 2% for every 10 square foot decrease in basal area within the 180 to 60 square foot range. Lesch (1997) reported on two separate thinnings of radiata pine in Australia. Here, removing roughly 1/3, and 2/3 of the stems resulted in 19 and 99mm increased annual streamflow. Afforesting of grasslands in Malawi with pine induced significant changes in minimum low flows, but not in maximum peak flows (Mwendera 1994).

Roughly two thirds of the 20% increase in annual streamflow from an herbicided grassland watershed in Wyoming came from increased snowmelt (Sturges 1994).

Models

Mathematical models are often used simulate the hydrological behavior of forested watersheds before and after harvesting, and in relation to other factors such as climate change, acid precipitation, expected water yield, flood forecasting, etc. MacGregor (1994) provides citations and abstracts for 17 different hydrological models, some designed for year-round predictions of streamflow (Bernath et al. 1982; Bernier and Hewlett 1982; Croley 1982; Dickinson 1982; Leaf and Alexander 1975; Tsykin et al. 1982), with others predicting other components of watershed hydrology as well. Arp and Yin (1992,1993) cited 22 models that deal with the flow of water and/or the flow of energy (heat) through forest soils and forest watersheds. These authors then proceeded to formulated a new series of forest hydrological models that emphasize:

1. integration of heat and water flow based on mass and energy balances;
2. ready yet reliable application to forest watersheds for which only limited data for model initialization is available;

3. portability of model calibrations from one watershed to another, across climatic regions, across forest cover types, and for specific forest disturbance regimes (e.g., harvesting);
4. emphasis on year-round model verification by testing model output with information about water and heat flow observations (throughfall, forest floor and soil percolates, stream flow, heat flux), soil moisture, water table, snowpack depth or snow water equivalents, for specific watersheds;
5. adopting new high-level modeling platforms such as STELLA and ModelMaker to facilitate the use of models not only by modelers but also by field practitioners;
6. availability of dynamic linkages to other modeling tools, e.g., spreadsheets, mapping programs, to expand model use within, e.g., the Windows modeling environment;
7. expansion of the hydrological modeling process to include the spatial distribution of forest cover, topography and soils within the watershed context, in order to obtain day-by-day updates on changes in soil moisture distributions, by model simulated soil moisture regimes.

Models have been applied to predict spatial variations in soil moisture, and thus soil properties for different situations (Keys and Arp 1996a; 1996b; Meng and Arp 1997; Meng et al. 1997; 1996). They have also been used as essential subcomponents of larger projects (Oja et al. 1995; Yin et al. 1994; Yanni et al. 1994).

Still, much work needs to be done. For example, many models do not account for, or incorrectly account for water losses due to deep seepage through permeable bedrock, or excessively deep soils. Miller et al. (1988) noted no significant differences between preand post-harvest water yields for both clearcut and selection harvesting of watersheds with permeable bedrock in Arkansas. Wallach (1997) noted errors in surface runoff predictions because of inappropriate formulations for infiltration and subsurface lateral flow. Most importantly, work has only begun to predict hydrological behavior of individual watersheds based on the basic physiography of the watersheds, such as size, orientation, soil and bedrock substrate, vegetation type, extent of disturbance to the vegetation type.

CONCLUSIONS

According to the literature, we find that the reduction of vegetated cover reduces transpirational losses and interception losses, increases soil moisture, and the amount of soil water available for streamflow. Opening the forest canopy can either reduce or increase snow catch efficiency, depending on gap size, though snow in openings typically melts sooner than under a canopy. Opening sizes with dimensions of two to three tree heights generally produce the greatest snow accumulation. Also, elongated cuts oriented parallel to the prevailing wind capture more snow than those oriented perpendicular. Thinning stands also increases snowpack depth beneath the remaining canopy.

Due to the greater decrease in leaf area and other vegetative surfaces, the reduction in transpiration and interception is greater with softwood species than with hardwood species. Since hardwoods typically occupy richer sites, regrowth following cutting is usually more rapid, and hydrological impacts are more short-lived on hardwood sites.

The spatial arrangement of cuts can be important, especially in northern latitudes with areas of moderate to strong relief, where the solar radiation balance can be strongly affected by the sunlight angle of incidence. As well, removal of vegetation from wet areas of a watershed can affect the groundwater table more than removing it from areas where water is often growth limiting.

Forest hydrology models are starting to show promise as management tools. Caution should be used to ensure that models are not applied without understanding model input requirements, and modeling results in general. The aim is to predict the hydrological repercussions of harvesting scenarios, in advance of implementation, such that the repercussions do not conflict with other management objectives, especially those pertaining to sustainability.

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