Sustainable Forest Management in Watersheds

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Outline - Forests and Watersheds

• Scaling up from stand to watershed-level process understanding
• How does the forest influence floods, low flows, timing of flows and stream channels in rain and snow regimes?
• What do forest managers need to know about forestry impacts on watershed processes to ensure they are sustainably managing watersheds?
Stand-level processes – rain
Chapter 6&7 Forrex compendium (Winkler et al., 2009)

- Canopy
  - Interception
  The fraction of rain intercepted by a forest depends on storm intensity and duration, weather conditions
  Maximum interception losses range from 3 to 30% of the storm precipitation depth depending on forest age, canopy density, and climate
  - Evapotranspiration
  measured at about 30% less in clearcut than in adjacent forest

- Throughfall (net precipitation)
  - Infiltration
  - Soil water recharge and storage
  - Groundwater storage
  - Overland flow

- Streamflow
Comparison of interception losses for different stand types

<table>
<thead>
<tr>
<th>Forest type</th>
<th>Age (yr)</th>
<th>Location</th>
<th>Elevation (m)</th>
<th>Canopy cover (%)</th>
<th>T (%)</th>
<th>S (%)</th>
<th>Imax (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western hemlock—western redcedar</td>
<td>&gt; 250</td>
<td>Prince Rupert area</td>
<td>50</td>
<td>75–80</td>
<td>73–78</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>&gt; 125</td>
<td>Carnation Creek</td>
<td>450</td>
<td>85</td>
<td>69</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Sitka spruce, western redcedar, western hemlock</td>
<td>approx. 20</td>
<td>Carnation Creek</td>
<td>5</td>
<td>75</td>
<td>77</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>Douglas-fir</td>
<td>55</td>
<td>Campbell River</td>
<td>300</td>
<td>85</td>
<td>75</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Douglas-fir # 1</td>
<td>25</td>
<td>Cowichan Lake</td>
<td>175</td>
<td>70</td>
<td>70</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Douglas-fir # 2</td>
<td>25</td>
<td>Cowichan Lake</td>
<td>175</td>
<td>40</td>
<td>85</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>&gt; 125</td>
<td>Upper Penticton Creek</td>
<td>1650</td>
<td>45</td>
<td>71</td>
<td>&lt; 0.5</td>
<td>5</td>
</tr>
<tr>
<td>Engelmann spruce–subalpine fir</td>
<td>&gt; 125</td>
<td>Upper Penticton Creek</td>
<td>1800</td>
<td>45</td>
<td>71</td>
<td>&lt; 0.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>25</td>
<td>Upper Penticton Creek</td>
<td>1750</td>
<td>40</td>
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<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>
Stand level processes - snow

- **Canopy Interception**
  - The amount of snow intercepted by forest canopies is affected by weather variables and stand characteristics.
  - Once the snow is intercepted it sublimates, evaporates or is redistributed into adjacent openings.
- Interception results in less snow on the ground beneath the canopy at the start of the melt period when the snowpack is ripe.
- Depending on the year, hillslope and canopy characteristics, clear cuts can accumulate up to 70% more snow on the ground by the start of the melt season.
Forests and the snowmelt energy balance

• Energy Balance Equation: (From Adams et al. 1998):

The rate at which a ripe snow pack melts depends upon the amount of energy available: \[ M = Rn - H - LE - G - S \]

- \( M \) is the energy for melt, **Rn is the net radiation**, \( H, LE \) and \( G \) are the sensible, latent and soil heat flux densities, respectively, and \( S \) is the change in heat storage in the pack.

• Forest canopies affect the snow melt energy balance;
  - by absorbing and reflecting incoming short-wave radiation (shading)
  - altering emissions of long-wave radiation,
  - reducing snow surface albedo with organic material.
  - Reducing wind speed, resulting in steeper temperature and humidity gradients near the surface and affecting turbulent heat transfer.
Forests stands and snowmelt

• The balance between incoming short-wave and outgoing long-wave radiation (which varies by aspect, slope gradient) determines by how much the snowpack in an opening melts sooner/faster than that in an forest (Boon, 2009).

• Seasonal ablation rates averaged over the snowmelt period (weeks) in openings are up to 2 times faster than in the forest but the differences in daily ablation rates are likely much greater (Winkler et al., 2009, Ellis et al., 2010).
Hillslope scale – rain
(Winkler et al., 2009, Chapter 7)

• Undisturbed forest soils in BC, generally have high infiltration capacities so hillslope runoff tends to be dominated by subsurface flow.

• In montane environments with shallow soils overlying bedrock or relatively impermeable glacial till, the development of a transient saturated zone triggers lateral downslope flow movement with rapid flow facilitated by root channels and other preferred pathways (macropores).
Effects of forest removal on hillslope runoff – rain (LMH 66, Chpt 9)

• Forest canopy removal reduces interception and evaporation losses increasing net precipitation at the soil surface leading to increased soil moisture content

• An increase in the amount of water that infiltrates the soil can result in higher water table levels during storms

• **Higher antecedent soil moisture** content results in increased subsurface stormflow and a smaller soil moisture deficit that must be satisfied prior to initiation of lateral flow.

• Poor logging practices that result in a lot of surface soil compaction can accelerate delivery of runoff to stream channels via overland pathways such as skid trails and roads.

Higher antecedent soil moisture causes runoff to becomes flashier and elevated compared to forested slope.
Hillslope scale - snow

• 3 recent UBC studies (Kuras et al. 2011, Smith, 2011 (PhD), and Schnorbus and Alila, 2014) have shed some light on hillslope-scale controls on runoff.

• These studies reveal that the hydrological response at the hillslope (small catchment) level is very complex and dependent in part on slope aspect, gradient, elevation, depth to impermeable layer and forest cover attributes.
  – Clearings contain upwards of 70% more snow at the start of melt season
  – Cleared areas produce runoff earlier than forested areas,
  – Steeper areas produce faster runoff response to radiation-driven melt events
  – South-aspect slopes melt off faster and earlier than other aspects.
  – Soil depth determines whether runoff will be routed to groundwater recharge
Forests effects at the watershed scale

• Asking the correct question(s) will lead you to the answers you seek....

Wise old man
What are the questions that need to be answered that will help manage a watershed sustainably?

- How can changes in hydrological processes at the stand and hillslope scale affect water quality, quantity and timing of flows at the watershed scale?
- How much logging is possible before these changes are detectable in a watershed?
- How long will these changes in hydrological processes persist following logging?
For **100 years** the forest hydrology community has been asking “How does forest harvesting affect the **magnitude** of peak flows in a watershed?”. To answer this question they applied a paired-watershed with BACI experimental design to investigate how the peak flow relation between a control watershed and treatment watershed changes from the pre-treatment to the post-treatment period.
Forests effects at the watershed scale

The question they asked led researchers to the following answer...

Forest harvesting generally increases small and moderate peak flows following logging in a watershed but larger floods are not significantly increased.
Why was this the wrong question?

1. The BACI approach for investigating changes in peak flows between control and treatment watersheds paired by year creates an **uncontrolled** experiment.
   
   - The Before-After design assumes that the treatment effect is being isolated – everything else remains constant except for the forest cover removal (treatment).
• Measuring the treatment effect on a storm by storm basis (rain) or year by year basis (snow) (i.e. Chronological pairing) to evaluate the difference in magnitude between pre- and post-harvest floods does not isolate the effects of forest cover on the magnitude of a flood.
In rain regimes, the magnitude of a flood is affected by not only the storm but also by the antecedent soil moisture condition in the watershed.

In snow regimes, the peak flows in the two adjacent basins are controlled by completely different meteorological conditions following logging – the event causing the logged watershed to peak is not the event that causes the control watershed to peak.

In both cases you end up measuring the effects of forest removal AND annual or storm by storm differences in other factors controlling flood magnitude.
Wrong question reason # 2....

2. Hydrogeomorphic processes, aquatic values and channel integrity in a watershed are intrinsically linked to the flow regime not individual peak flows (Poff et al., 1997).
What are the questions that should be asked?

1. How does harvesting affect the frequency of floods?
2. How does harvesting affect the variability of floods?
3. The timing of floods?
4. The duration of floods?
5. The magnitude and duration of low flows?
By investigating forest effect through frequency-based analysis the effects of forest removal can be isolated.

- Frequency, which is determined by considering the full post-treatment time series of floods concurrently, encapsulates the simultaneous effects of the hydrometeorological factors responsible for the flood.
How does forest removal affect flood frequency in watersheds?
What factors control changes in flood frequency in a watershed?

• Consider what we know from stand-level and hillslope-level studies (focus on snow).
  – Clearings have more snow, earlier and faster snowmelt than forests
  – Differences in melt rate and timing of melt are most pronounced on south aspect slopes
  – Steeper slopes have better conductivity of surface runoff
  – Shallow soils have less transfer to groundwater recharge.

How do these physical characteristics (slope gradient, slope aspect distribution, elevation range) in a watershed contribute to hydrological response (changes in the mean and the variability of the frequency distribution)?
Use meta-analysis approach to try to understand physical controls on watershed response
Conceptual model of watershed flood frequency response to forest removal

Effects on flood frequency distribution given increases in the mean and changes in variability

1. Decrease in variability  2. No change in variability  3. Increase in variability
Effects on flood frequency distribution given increases in the mean and changes in variability

1. Decrease in variability
   Distribution of harvesting resulting in reduced synchronization of snowmelt runoff over basin. (PDF width narrows, CDF converges).

2. No change in variability
   Distribution of harvesting causes no change in synchronization of snowmelt runoff over basin. (PDF width unchanged, CDF parallel).

3. Increase in variability
   Distribution of harvesting causes increased synchronization of snowmelt runoff over basin. (PDF widens, CDF diverges).

Possible Scenario 1:
Small alpine basin with harvesting concentrated at lower elevations causing snowmelt runoff to advance in lower harvested areas.

Possible Scenario 2:
Large basins where harvesting is distributed across elevations and aspects.

Possible Scenario 3:
Small non-alpine basins regardless of harvest distribution or larger basins with harvesting concentrated in peak flow generating region.
What are the implications of increases in flood frequency in a watershed?

• Forest removal has the effect of increasing the magnitude and frequency of floods smaller and larger than the mean.
• Floods larger than the mean flood (2 yr flood) are referred to as overbank floods

Increased occurrence of overbank floods;
  – Causes incidences of increased turbidity from fine organics and sediment
  – Causes increase rates of bank erosion and lateral channel instability
  – Causes increased rates of sediment transport leading to aggraded and degraded channel sections
  – Causes increased rates of channel avulsion on the fan resulting in damage to water intakes, public infrastructure and private land
Englishman Creek fan, Moyie BC
Englishman Creek (83km²) subject to 70% forest removal through logging and fire in early 1900’s
Forestry effects on Water quality

- Changes in frequency and magnitude of floods capable of mobilizing sediment and altering the morphology of the channel can cause on-going long-term impacts to water quality.
- Short-term impacts to water quality associated with forest development in watersheds are typically due to terrain instability including debris slides, debris flows.
Terrain instability - snow

At the hillslope scale, more water running off the hillslide;

- Drainage structures on forest roads can be overwhelmed causing intercepted water on road systems to be concentrated and diverted onto unstable slopes resulting in debris flows and debris slides.

- Studies have measured increases of 3X runoff from hillside following logging but this will depend on year. Increases could likely be upwards of an order of magnitude or more during extreme years.
- Inadequate road drainage resulted in an increase in the effective drainage area above a potentially unstable slope by 67%.
- Harvesting accounted for 55% of the effective drainage area.
At the hillslope scale, more water running off the hillslide;

- Higher pore pressure in soils (saturated soils) is a trigger of landslides in steep, coastal areas of BC.
- One study in northern California measured 400% increase in macropore flow following harvesting.

The increase in pore pressure and the loss of root cohesion following logging can cause debris slides - especially in areas with thick soils over bedrock.
Changes to flow timing

- Changes to the timing of peak flows is most evident in snowmelt regions where harvesting causes peaks to occur earlier in the freshet period compared to the forested basin.
- This has major implications for water supply in snowmelt watersheds—especially in drier regions such as Okanagan where snowmelt is the major contributor to reservoirs that serve communities throughout the summer, fall and winter months.
How long do forestry effects persist?

- Past CP based study outcomes suggest that harvesting effects on peak flows are short lived – couple of decades
- FP-based studies have revealed that harvesting effects persist for at least 50 years in snowmelt regions
- Stand level process recovery does not start until regenerating stand reaches 5 to 6 meters and likely will not reach full recovery until 80% to 90% of original stand height and density.
Hydrological recovery curve in snowmelt regions

- 1995 Interior Watershed Assessment Procedure
- Thompson-Okanagan revised 2015
- 1992 approximation for low snowpack areas
- 1992 approximation for high snowpack areas

Y-axis: Snow accumulation or ablation recovery (%)
X-axis: Average dominant/codominant tree height (m)
What about climate change?

Forest Cover vs Global Climate effects on watershed hydrology

Time scales of these effects must be considered
For sustainable forest management in watersheds

Forest managers must...

- Understand the nature of the watershed being subject to development
  - Alpine or fully forested
  - Mixed aspect or dominantly single aspect
  - Wide elevation range or gentle gradient

- Understand what is driving the frequency distribution of floods
  - Climatic conditions contributing to low, medium and large floods
  - Dominant subbasin or multiple headwater basins

- Understand how flood frequency and channel form are related in the watershed
  - Responsive, alluvial channel
  - Resilient colluvial and bedrock channel
  - Riparian function and channel stability

- Understand how to plan forest development so as to minimize any changes to flood frequency.
  - Could location of openings cause increased synchronization of melt from areas contributing to flood peaks?

- Understand how increased runoff following forest removal will affect slope stability
You and your watershed:
Relationship counselling for current and future forest managers
Tools for achieving sustainable forest management in watersheds

- The goal is to maximize harvesting opportunities while avoiding altering the hydrological regime and negatively impacting water quality, quantity or timing of flows.

- Need information
  - Terrain stability mapping
  - Landslide risk assessments (LRA)
    - For proposed roads and blocks located on or above potentially unstable or unstable terrain
  - Watershed assessments
    - Hydrogeomorphic Risk Assessment (HRA)
      Provides manager with information about the processes and an assessment of the effect of development on hazards and consequences
  - Hydrological modeling
    - DHSVM
    - SWAT
    - Cold Regions hydrological model
    - UBC watershed model

- Decision making framework
Decision making framework

Cited literature


Chapter 6 (Winkler et al., 2009)
Chapter 7 (Winkler et al., 2009)
Chapter 9 (Jordan et al., 2009)


