Hydrologic Recovery of the Peak Flow Regime in Two Snow Dominated Meso-Scale Watersheds in the Southern Interior of British Columbia:
An Investigation Using a Conceptual Hydrologic Model

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ABSTRACT

Hydrologic recovery is defined as the process by which the hydrologic characteristics of a watershed that has been subject to harvesting are restored to near pre-harvest condition by forest regeneration. Although the relation between the level of clearcut and hydrology at the watershed scale is not well understood threshold rate of cuts continue to be used to constrain forest management in British Columbia (BC). Until this relation is understood in a quantitative manner we may be unduly restricting forest development at great cost to the industry. The urgency to understand how clearcut affects hydrology has increased with recent pine beetle epidemics and wildfires that are creating disturbances in large watersheds equivalent to 100% ECA. In this project, we use the University of British Columbia Watershed Model (UBCWM) at two interior snow dominated watersheds to quantify the effects of total clearcut of an entire watershed and investigate the nature of the relationship between these effects and hydrologic recovery over time. The main focus of the project is the effects of clearcut on the water yield and peak flow regime.
1. Introduction

Equivalent Cut Area or ECA is a metric that quantifies the level of harvesting in a watershed with consideration to the regeneration of historically harvested blocks and the resulting hydrologic recovery. Hydrologic recovery is defined as the process by which the hydrologic characteristics of a watershed that has been subject to harvesting are restored to near pre-harvest condition by forest regeneration. ECA thresholds are used to restrict logging in BC. However, the relationships between ECA and hydrologic effects are not well understood [Thomas, 1990]. In BC, research work on the relationship between ECA and hydrology has been conducted at the stand level [Winkler, 2001]. At this small spatial scale, hydrologic recovery had been quantitatively linked to stand height and canopy density and is also found to be highly dependent on elevation, species, precipitation regimes, site index and relative maturity (i.e. second growth vs. old growth) [Winkler et al. 2004 and 2005]. How such knowledge translates to the watershed scale remains an elusive question.

Hydrologic modelling can be used to synergistically supplement experimental results at the stand level (Ziemer et al. 1991). A hydrologic model acts as a control to filter out the effects of climatic spatial and temporal variability, allows the same watershed to act as its own control, and is useful for integrating stand-level information into a physically or conceptually reasonable description of basin response to forest disturbances. In recent years, and with the advances in computing power and Geographic Information System (GIS) and Global Positioning System (GPS) technologies, the use of models to quantify the effects of forest management on hydrology has intensified, particularly at heavily instrumented, small experimental watersheds (Alila and Beckers 2001). A numerical modelling approach uses a period of extensively monitored hydro-climate data to develop and calibrate watershed model applications and uses them subsequently in a long-term simulation exercise to generate time series of watershed hydrologic response for alternative forest disturbance scenarios.

There are two types of hydrologic models. First, there is the fully distributed, quasi-physically based model such as the DHSVM of Wigmosta et al. (2002). For example, DHSVM has recently been extensively used in forestry applications in BC (Beckers and Alila 2004, Schnorbus and Alila 2004, Thyer et al. 2004, Whitaker et al. 2002) and the United States (Bowling et al. 2000, Leung and Wigmosta 1999, Waichler et al. 2005). However, this type of model, with heavy input data requirements, can only be applied with a reasonable level of success at heavily instrumented (and therefore small) watersheds, and is not useful for routine operational purposes at larger ungauged watersheds. The second category of models is lumped, conceptually simpler and less parameterized. As such, these models are more suitable for applications at larger watersheds with much less available data. Examples of such models used in Europe and North America are: HBV (Bergstrom 1992, Lindström et al. 1997) and UBCWM (Quick 1995). For example, the UBCWM has been applied extensively for forecasting inflows to hydropower generation reservoirs in large basins (e.g. Druce 2001). The model was also applied to simulate hydrological response to climate change in 30 to 200 km² watersheds in BC (Merritt et al. 2006) and in a 10 000 km² watershed in the Himalayan Mountains (Singh and Kumar 1997). Micovic and Quick (1999) applied the model to a series of watersheds from 70 to 1150 km² in BC to estimate a set of average parameters for the purpose of predicting streamflows at ungauged watersheds. Being applicable to large-scale watersheds with much less input data, the UBCWM has long been accepted by government and industry as an operational decision support tool.
The application of the UBCWM to meso-scale watersheds for the purpose of quantifying the effect of salvage logging on streamflows requires careful investigation into, and evaluation of, the model parameters, particularly those related to the forest cover characteristics and the way they affect the energy and water balance.

The objective of this study is to test, calibration and validate the UBCWM at two meso-scale watersheds (10s and 100s of square km) and use it subsequently to investigate the extent of hydrologic recovery in time after clearcut logging.

2. Description of Watersheds and Input Data

In this study, two watersheds, the Bellevue Creek and Whiteman Creek located in the center and north of the Okanagan Basin, are selected to perform the simulation of forest regeneration effects on streamflows after 100% salvage logging. The Okanagan Basin is located in the Thompson Plateau in the southern interior of BC, lying east of the crest of the Coast and Cascade mountain ranges and west of the Columbia Mountains. The mean annual temperature at the lower elevations of the Okanagan Basin is 6 ºC, with a winter mean of -3.5 ºC and a summer time mean of 25 ºC. Unconsolidated deposits of glacial drift covers much of the area with numerous bedrock outcrops. The vegetation includes bunchgrass, ponderosa pine, interior Douglas-fir, montane spruce, Engelmann spruce and subalpine fir (Scherer and Pike, 2003). The areas of these two watersheds are 73 and 112 km$^2$, respectively, and the Bellevue Creek watershed is of north aspect and the Whiteman Creek watershed has an aspect of south. Both watersheds have similar areas of forest cover and crown closure. Figure 1 shows the locations of these two watersheds, and Table 1 shows some of their physiographic parameters.

<table>
<thead>
<tr>
<th>Hydro Station</th>
<th>Watershed</th>
<th>Area (km$^2$)</th>
<th>Ave El (m)</th>
<th>Domi. Aspect</th>
<th>Ave. SLP (%)</th>
<th>Forest Cover (%)*</th>
<th>Crown Closure (%)**</th>
<th>EFA ***</th>
<th>Mean Q (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08NM035</td>
<td>Bellevue Ck (Oka.)</td>
<td>73</td>
<td>1500</td>
<td>North</td>
<td>26</td>
<td>85</td>
<td>56</td>
<td>0.48</td>
<td>0.51</td>
</tr>
<tr>
<td>08NM174</td>
<td>Whiteman Ck (Oka.)</td>
<td>112</td>
<td>1400</td>
<td>South</td>
<td>32</td>
<td>89</td>
<td>56</td>
<td>0.50</td>
<td>0.63</td>
</tr>
</tbody>
</table>

* From BTM 1:250,000 land use map, Ministry of Sustainable Resources Management
** From 1:50,000 forest cover map, Ministry of Forest;
*** EFA (Equivalent Forest Area) = Forest Cover (column 7) x Crown Closure (column 8)
3. UBC Watershed Model (UBCWM) and Model Calibration

The UBCWM was originally developed by Quick and Pipes (1977) in the University of British Columbia. Over the years, the model has been further improved and tested and now incorporates many user-friendly features as described by Quick (1995). The model calculates daily or hourly watershed outflows using daily precipitation and maximum and minimum daily temperature as inputs. The model was designed for the prediction of streamflows in mountainous watersheds where runoff is a combination of snowmelt, glacier melt and rainfall.

Since the hydro-meteorological behavior of the mountainous watershed is a function of elevation, the model employs the area-elevation band concept to account for the orographic gradients of precipitation and temperature, which are assumed to behave similarly for each storm. The UBCWM also provides information on area of snow cover, snowpack water equivalent, energy available for snowmelt, evapotranspiration and interception losses, soil moisture, groundwater storage and surface and subsurface components of runoff for each elevation band as well as averages over the whole watershed. The physical description of a watershed is given for each elevation band separately in the form of different variables such as band area, forested fraction,
forest density or crown closure, glaciated fraction, band orientation or aspect, and fraction of impermeable area. A schematic diagram for the UBCWM structure is shown in Figure 2.

The UBCWM is made up of three major sub-models. The meteorological sub-model distributes the point values of precipitation and temperatures to all elevation bands of the watershed. The variation of temperature with elevation controls whether precipitation falls as rain or snow and also controls the melting of the snowpacks and glaciers. The soil moisture sub-model controls the non-linear behavior of the watershed and sub-divides the water input (rain and melt) into four components of runoff: fast (surface), medium (interflow), slow (upper groundwater) and very slow (deep groundwater). The routing sub-model allows the delivery of runoff to the outlet of the watershed and is based on linear reservoir theory that guarantees conservation of mass and water balance. More details about the internal workings of the UBCWM can be found in Quick (1995).

Figure 2. Structure of UBC Watershed Model (Quick, 1995)

The UBCWM uses the full energy balance approach to calculate the snowmelt. The physical basis of the full energy equation provides a better control of estimation of snowmelt for forested and open conditions, for clear or cloudy weather, for various slopes and aspects of mountainous watersheds, and for changes in elevations. Because detailed meteorological input data required for driving the full energy balance equations are usually not available, especially for high mountain regions, the UBCWM drives the full energy balance equations with just daily minimum and maximum air temperature. In this process, different sources of energy creating the
melt are estimated by a set of highly non-linear functions of temperature (Quick 1995). Through comparisons to measurements, it has been shown that the temperature-only-driven full energy balance method is not only reliable, but also provides much better results than the degree-day method (Pipes and Quick 1987, Walter et al. 2005).

During the calibration, the performance of the model with any set of parameter input values is evaluated visually and statistically. The visual criterion involves plotting the simulated hydrograph and comparing it with the measured one. The statistical criterion involves the use of the Nash and Sutcliffe (1970) coefficients of model efficiency ($C_e$) and determination ($C_d$). The model efficiency describes how well the volume and timing of the simulated hydrograph compares to the observed one and is calculated as:

$$C_e = 1 - \frac{\sum_{i=1}^{n} (Q_{obs}^i - Q_{sim}^i)^2}{\sum_{i=1}^{n} (Q_{obs}^i - \bar{Q}_{obs})^2}$$  \hspace{1cm} (1)

where,

$$\bar{Q}_{obs} = \frac{\sum_{i=1}^{n} Q_{obs}^i}{n},$$  \hspace{1cm} (2)

in which $n$ is the number of time-steps, $Q_{obs}^i$ is the observed discharge at time step $i$, and $Q_{sim}^i$ is the simulated discharge at time step $i$. The coefficient of determination, $C_d$, measures how well the shape of the simulated hydrograph reflects the observed hydrograph and depends solely on the timing of changes in the hydrograph and is given by (Nash and Sutcliffe, 1970):

$$C_d = 1 - \frac{\sum_{i=1}^{n} (Q_{obs}^i - (a \cdot Q_{sim}^i + b))^2}{\sum_{i=1}^{n} (Q_{obs}^i - \bar{Q}_{obs})^2}$$  \hspace{1cm} (3)

where,

$$a = \frac{\sum_{i=1}^{n} (Q_{obs}^i \cdot Q_{sim}^i) - \frac{1}{n} \sum_{i=1}^{n} Q_{obs}^i \sum_{i=1}^{n} Q_{sim}^i}{\sum_{i=1}^{n} (Q_{sim}^i)^2 - \frac{1}{n} (\sum_{i=1}^{n} Q_{sim}^i)^2}, \hspace{1cm} \text{and} \hspace{1cm} b = \frac{1}{n} \left( \sum_{i=1}^{n} Q_{obs}^i \right) - a \frac{1}{n} \left( \sum_{i=1}^{n} Q_{sim}^i \right)$$  \hspace{1cm} (4)

The closer the values of $C_e$ and $C_d$ are to 1, the more successful the model calibration is. The calibration results are shown in Table 2.
Table 2. Calibration results in the two watersheds

<table>
<thead>
<tr>
<th>Ind.</th>
<th>WATER-</th>
<th>CALIBRATION</th>
<th>VALIDATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SHED</td>
<td>PERIOD</td>
<td>C_e</td>
</tr>
<tr>
<td>1</td>
<td>08NM035</td>
<td>1979-1982</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td>08NM174</td>
<td>1972-1976</td>
<td>0.82</td>
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</tbody>
</table>

### 4. Forest Regeneration Scenarios

The UBC Watershed Model is a conceptual and lumped model and therefore only one crown closure is required for each elevation band, and a uniform crown closure is used for the whole watershed in this simulation of forest regeneration effects. Table 3 shows 15 scenarios of crown closures, which are the averages of the values that are estimated by two methods: regression analysis using the GIS inventory data from the Ministry of Forests (MoF) and TIPSY. TIPSY is a growth and yield program developed by MoF that provides electronic access to the managed stand yield tables generated by TASS (Tree and Stand Simulator) and SYLVER (Silvicultural treatments on Yield, Lumber Value, and Economic Return). TIPSY retrieves and interpolates yield tables from its database, customizes the information and displays summaries and graphics for a specific site, species and management regime. Yield tables are available for various even-aged coniferous species of commercial importance growing on the coast and in the interior of British Columbia. In this study, two methods of TIPSY (natural and planted) were used for the regeneration simulation. Both watersheds use the same regeneration scenarios given in Table 3.

Table 3. Forest regeneration scenarios

<table>
<thead>
<tr>
<th>Year of Regeneration</th>
<th>Crown Closure (%)</th>
<th>By Regression</th>
<th>By TIPSY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Natural</td>
<td>Planted</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>26</td>
<td>52</td>
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<td>30</td>
<td>37</td>
<td>52</td>
<td>77</td>
</tr>
<tr>
<td>40</td>
<td>42</td>
<td>68</td>
<td>82</td>
</tr>
<tr>
<td>50</td>
<td>46</td>
<td>74</td>
<td>84</td>
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</tbody>
</table>

### 5. Results

The long term simulation for each watershed uses the observed climate data downloaded from Environment Canada, and Table 4 shows the periods of data of the two climate stations utilized in this study.
Table 4. Years of climate data series available from Environment Canada

<table>
<thead>
<tr>
<th>Index</th>
<th>Hydro Station</th>
<th>Watershed</th>
<th>Climate Station</th>
<th>Period From</th>
<th>Period To</th>
<th>Years of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>08NM035</td>
<td>Bellevue Creek</td>
<td>1123750</td>
<td>1961</td>
<td>1993</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>08NM174</td>
<td>Whiteman Creek</td>
<td>1125700</td>
<td>1926</td>
<td>2001</td>
<td>76</td>
</tr>
</tbody>
</table>

The simulation results for the two watersheds are shown in Table 5 and Table 6, each of which contains all of the 15 scenarios. The flow duration curves and charts of frequency analysis are shown in Figure 3 to Figure 32, each for a scenario in one of the two watersheds.

From Tables 5, one can see that the differences in peakflow between regeneration scenarios and the control scenarios (current forest conditions), when the crown closure is estimated by the regression method, are statistically significant at the 95% confidence level for all return periods for the regeneration period of 10 years. However, these same differences are statistically significant only for the return periods ranging from 2 to 50 years and from 2 to 20 years for the regeneration periods of 20 and 30 years, respectively. The same differences are not statistically significant for the regeneration periods of 40 and 50 years because the regenerated crown closures are close to that of the control scenario. The differences in season 2 water yield are statistically significant for the regeneration periods from 10 to 30 years, while are not statistically significant for the regeneration periods of 40 and 50 years for the same reason as for the peakflows.

Table 5. Simulation results for Bellevue Creek

<table>
<thead>
<tr>
<th>Scen.</th>
<th>CC (%)</th>
<th>ΔQ_{1,02}</th>
<th>ΔQ_{2}</th>
<th>ΔQ_{10}</th>
<th>ΔQ_{20}</th>
<th>ΔQ_{50}</th>
<th>ΔQ_{Av}</th>
<th>ΔWY (%)</th>
<th>ΔTp (d)</th>
<th>ΔSea2</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>m^3/s</td>
<td>%</td>
<td>m^3/s</td>
<td>%</td>
<td>m^3/s</td>
<td>%</td>
<td>m^3/s</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>RG10</td>
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<td>1.5</td>
<td>73</td>
<td>2.5</td>
<td>50</td>
<td>3.1</td>
<td>44</td>
<td>3.3</td>
<td>42</td>
<td>3.5</td>
</tr>
<tr>
<td>RG20</td>
<td>30</td>
<td>1.0</td>
<td>49</td>
<td>1.7</td>
<td>33</td>
<td>2.1</td>
<td>29</td>
<td>2.2</td>
<td>28</td>
<td>2.3</td>
</tr>
<tr>
<td>RG30</td>
<td>37</td>
<td>0.7</td>
<td>32</td>
<td>1.1</td>
<td>22</td>
<td>1.4</td>
<td>20</td>
<td>1.5</td>
<td>19</td>
<td>1.5</td>
</tr>
<tr>
<td>RG40</td>
<td>42</td>
<td>0.4</td>
<td>21</td>
<td>0.7</td>
<td>15</td>
<td>0.9</td>
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<td>12</td>
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<td>2.6</td>
<td>34</td>
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<td>0</td>
<td>-0.1</td>
<td>-1</td>
<td>-0.1</td>
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<tr>
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<td>-0.8</td>
<td>-36</td>
<td>-1.0</td>
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9
<table>
<thead>
<tr>
<th>Scen.</th>
<th>CC (%</th>
<th>$\Delta Q_{1.02}$</th>
<th>$\Delta Q_{2}$</th>
<th>$\Delta Q_{10}$</th>
<th>$\Delta Q_{20}$</th>
<th>$\Delta Q_{50}$</th>
<th>$\Delta Q_{Av}$</th>
<th>$\Delta WY$ (%)</th>
<th>$\Delta Tp$ (d)</th>
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<td>20</td>
<td>1.2</td>
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<td>-18</td>
<td>-1.8</td>
<td>-18</td>
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</tbody>
</table>

Note 1: -- Statistically significant at the 95% confidence level ($\alpha =0.05$).

Note 2: Column 1 is the Scenarios code: RG means regression, TN means TYPSE natural, TP means TIPSY planted, and the numbers (10 to 50) are the years of forest regeneration; column 2 is crown closure (CC); columns 3 to 7 are changes in peakflow either in cubic meter per second or in percent for return periods 1.02, 2, 10, 20 and 50 years, respectively; column 8 is the average of columns 3 to 7; column 9 is the change in water yield for season 2 (April to July); and the last column is the timing advance in peakflow averaged over the full simulated record.

For those scenarios with the crown closure estimated by TIPSY for natural regeneration, differences in peakflow and water yield for the regeneration periods of 10 and 20 years are statistically significant at the 95% confidence level. However, differences in peakflow and water yield were not statistically significant at the 95% confidence level the regeneration periods of 30 years, and were reversely statistically significant for the regeneration periods of 40 and 50 years. The term “reversely” means that the peakflow or season 2 water yield of the control scenario is larger than the regeneration ones. The effects of those scenarios with the crown closure estimated by TIPSY for planted regeneration are similar but the reverse effect shifts 10 years earlier because the planted forest has a much healthier canopy or larger crown closure than the naturally growing forest.
The results for Whiteman Creek watershed are similar to those for Bellevue Creek watershed. However, the differences in peakflow and water yield between the control and regeneration for Whiteman Creek are smaller than those for Bellevue Creek on the whole because of the overall effects of their difference in watershed physiographic characteristics, which are mainly aspect, area, and basin mean slope (see Table 1). Bellevue Creek watershed is north-facing while Whiteman Creek watershed is south-facing, and the area of Bellevue is 39 km$^2$ or 35% smaller than that of Whiteman. These two factors are mainly responsible for the differences in simulation results for the two watersheds.

6. Conclusions and Management Implications

According to the simulation results by applying the UBCWM in two watersheds of different physiographic characteristics in the Okanagan Basin, it can be concluded that: 1) within the first ten years of forest regeneration, regardless of the method of regeneration, the differences in peakflow and water yield between the regenerated forest and the control forest are statistically significant at the 95% confidence level; 2) after 30 years of regeneration by the method of regression, the differences in peakflow and water yield are statistically insignificant at the 95% confidence level because most of the forest canopy has recovered to its original or control conditions; 3) the forest regeneration by the method of TIPSY, either natural or planted regeneration, has reverse effects namely the regenerated peakflow and water yield are smaller than the control peakflow and water yield due to the healthier regenerated canopy and larger crown closure compared to the control; and 4) watershed physiographic characteristics, such as aspect and watershed area, affect the magnitude of forest regeneration effects and the differences in peakflow and water yield between the regeneration and control are larger in a watershed of north aspect and larger area than those in a watershed of south aspect and smaller area.
Figure 3. Results for Bellevue Creek: regression (10 years)

Figure 4. Results for Bellevue Creek: regression (20 years)

Figure 5. Results for Bellevue Creek: regression (30 years)
(a) Flow duration curve  
(b) Frequency analysis  
Figure 6. Results for Bellevue Creek: regression (40 years)

(a) Flow duration curve  
(b) Frequency analysis  
Figure 7. Results for Bellevue Creek: regression (50 years)

(a) Flow duration curve  
(b) Frequency analysis  
Figure 8. Results for Bellevue Creek: TYPSY natural (10 years)
(a) Flow duration curve

(b) Frequency analysis

Figure 9. Results for Bellevue Creek: TYPSY natural (20 years)

(a) Flow duration curve

(b) Frequency analysis

Figure 10. Results for Bellevue Creek: TYPSY natural (30 years)

(a) Flow duration curve

(b) Frequency analysis

Figure 11. Results for Bellevue Creek: TYPSY natural (40 years)
(a) Flow duration curve   (b) Frequency analysis
Figure 12. Results for Bellevue Creek: TYPSY natural (50 years)

(a) Flow duration curve   (b) Frequency analysis
Figure 13. Results for Bellevue Creek: TYPSY planted (10 years)

(a) Flow duration curve   (b) Frequency analysis
Figure 14. Results for Bellevue Creek: TYPSY planted (20 years)
Figure 15. Results for Bellevue Creek: TYPSY planted (30 years)

(a) Flow duration curve

(b) Frequency analysis

Figure 16. Results for Bellevue Creek: TYPSY planted (40 years)

(a) Flow duration curve

(b) Frequency analysis

Figure 17. Results for Bellevue Creek: TYPSY planted (50 years)
(a) Flow duration curve
(b) Frequency analysis
Figure 18. Results for Whiteman Creek: regression (10 years)

(a) Flow duration curve
(b) Frequency analysis
Figure 19. Results for Whiteman Creek: regression (20 years)

(a) Flow duration curve
(b) Frequency analysis
Figure 20. Results for Whiteman Creek: regression (30 years)
Figure 21. Results for Whiteman Creek: regression (40 years)

Figure 22. Results for Whiteman Creek: regression (50 years)

Figure 23. Results for Whiteman Creek: TYPSY natural (10 years)
Figure 24. Results for Whiteman Creek: TYPSY natural (20 years)

Figure 25. Results for Whiteman Creek: TYPSY natural (30 years)

Figure 26. Results for Whiteman Creek: TYPSY natural (40 years)
Figure 27. Results for Whiteman Creek: TYPSY natural (50 years)

Figure 28. Results for Whiteman Creek: TYPSY planted (10 years)

Figure 29. Results for Whiteman Creek: TYPSY planted (20 years)
Figure 30. Results for Whiteman Creek: TYPSY planted (30 years)

Figure 31. Results for Whiteman Creek: TYPSY planted (40 years)

Figure 32. Results for Whiteman Creek: TYPSY planted (50 years)
7. References


Thomas, R. 1990. "Problems in determining the return of a watershed to pre-treatment conditions: Techniques applied to a study at Casper Creek, Water Resources Research, 26(9), 2079-2087.


