Appendix 7: Hydrologic Assessment of Spatial Harvest Plan for Forest Management Unit E8, Near Grande Cache Alberta

Hydrologic Assessment of Spatial Harvest Plan for Forest Management Unit E8, Near Grande Cache Alberta

Prepared for: Alberta Sustainable Resource Development
Forest Management Branch

By Watertight Solutions Ltd
Edmonton, Alberta

Smoky River Valley, downstream of Grande Cache

-----June 2, 2008----

Executive Summary

The Wrenss model was used to simulate the hydrologic effects of forest harvesting in FMU E8 located near the town of Grande Cache. Alberta Sustainable Resource Development designed the spatial harvest plan for the FMU and the Forestry Corp prepared input files for Wrenss simulations. A hydrologic land base was prepared for the FMU from which 35 watersheds were identified for simulation. The watersheds varied in size from 7.7-483 km^2, with an average watershed area of 96 km^2.

The spatial harvest plan was for 70 years (2008-2078). Wrenss simulations were done for 200 years and included historical (1985-2007) and planned harvesting to fully capture the effects of harvesting on water flows. The average area harvested in watersheds in the FMU was 51% with minimum and maximum values of 20% and 100%. Dominant forest species in the FMU were lodgepole pine and white and black spruce.

Simulated increases in water yield in the FMU averaged 13.3%, with minimum and maximum values of 4.4% and 25%. Increases within the FMU were greatest in the Little Smoky and Simonette watersheds with a range of 14.8-24.5%. Increases in the Muskeg and Smoky watersheds were less with values ranging from 13.6-16.7%. Volumetric increases in water yield among the watershed varied from 10-39 mm. About half of the watersheds had water yield increases (14.5-24.5%) that were significantly greater than the long term means of their representative watersheds. These increases however still fell within the range of natural variability for the region.

Water yield responses were largely determined by the amount and timing of harvesting in watersheds. Water yield increased with the extent of harvesting. Water yield increases expressed as percent and area mm were significantly correlated with percent watershed area harvested with R^2 values of 0.46 and 0.69 respectively. Maximum increases in water yield coincided with periods of heavy and/or frequent harvesting in watersheds.

Simulated increases in annual maximum daily flows in the FMU averaged from 19.7% for the 2-year events to 9.1% for the 100-year events. Peak flow increases followed a decreasing trend as recurrence intervals increased. Peak flow responses among the major drainages were variable with the lowest in the Muskeg watersheds and greatest in the Little Smoky watersheds, where annual water yield is low and topography relatively flat.

The largest increases in annual maximum daily flows were the 2 year events with values ranging from 6.8-41%. Peak flow increases for the 2-year events were significantly correlated with maximum percent ECA. The R^2 value for the regression analysis was 0.67.

An increase in the frequency of annual maximum daily flows among the watersheds varied from 6-8.7% for 2 year events to less than 1% for the 100 year events. The average shift or change in recurrence intervals from less frequent to more frequent with increased for the 2, 5, and 10 years events were 2.36 →2.0, 8.81→5.0 and 19.6 →10 years.

Maximum percent watershed ECA, a measure of hydrologic disturbance, ranged from 6.5% to 30% with an overall average of 16% for all watersheds. Hydrologic recovery for watersheds in the FMU varied from 30-119 years. The magnitude of hydrologic recovery was a function of the amount and timing of harvesting in watersheds. Sustained or frequent harvesting delayed the time for recovery of

water yields to pre-disturbance conditions. An analysis of decadal water yield increases showed an increasing trend for years 10-40 followed by a steady decrease to year 60. Water yield increases in year 60 averaged 8.1%, which was equivalent to an average recovery rate of 63% for the FMU.

In conclusion increases in water yield and peak flows were considered to fall within the range of natural variability in the Grande Cache – Grande Prairie region. Natural variability was defined as the long term water yield or annual maximum daily flow plus 0.2-1.0 of it standard deviation [e.g. ($\bar{x}$ + 0.5 std)/ $\bar{x}$]. Average variability for water yield in the region varied from 11.8- 47.2%. Simulated water yield increases for all watersheds varied from 4% -24%. Average variability for annual maximum daily flows in the region varied from 18.6% to 93.2%. Average increases in the 2 and 5-year events varied from 6.8-41.7% and 6.9-39%.

The level of watershed disturbance in terms of % ECA varied from low to moderate (6.5-30%). No definitive ECA values for acceptable levels of disturbance were found in the literature. ECA values of 15-20% were considered indicative of low disturbance or used as management objectives. In this assessment 8 watersheds had ECA values ranging from 22-30.7%. Percent harvesting in these watersheds ranged from 56-100%, which was not that different from other watersheds with lower ECA values. Changes in harvest scheduling in these watersheds probably would reduce ECA values to less than 20%.

Estimates of hydrologic recovery ranged from relatively short to long. Long times to recovery were the product of sustained or constant harvesting combined with prior historical harvesting that maintained water yield increases and delayed recovery. The levels of harvesting in some watersheds were higher than encountered in previous assessments . However, no long lasting changes to streamflow, stream channel morphology, aquatic habitats or water quality are expected to result from the proposed spatial harvest.

Table of Contents

List of Figures

List of Tables

DISCLAIMER

The assessment of hydrological impacts of harvesting presented in this report reflects the output from hydrologic simulation models and does not necessarily reflect actual impacts that may be observed. Ultimately, the reliability of estimates produced using WRENSS and other hydrological models depends on the availability of representative climatic/hydrometric data, and regional forest growth and yield data, and harvesting plans. In this context, Watertight Solutions has evaluated the hydrometric data used in this analysis and considers these data to be a reliable reflection of hydrologic conditions for the analysis. Limitations or errors due to deviation in actual forest growth rates from provincial average growth rates or limitations imposed by spatial/temporal scale of analysis are outside the author's control. In particular, the spatial distribution of harvested blocks, as well as the presence of additional disturbances (fire, insects, etc.) will also affect water yields.

Furthermore, it is re-emphasized that the WRENSS model projects average annual water yield changes over time based on un-routed flow (generated runoff), assuming average climatic/hydrologic conditions in the region and the rate of stand regeneration. Therefore, changes in annual water yield due to disturbance will vary from simulations based on the actual variability in climate and the degree of departure from average climatic conditions.

Watertight Solutions Ltd.
R.L. Rothwell RPF 150

Hydrologic Assessment of Spatial Harvest Plan for Forest Management Unit E8, Near Grande Cache Alberta

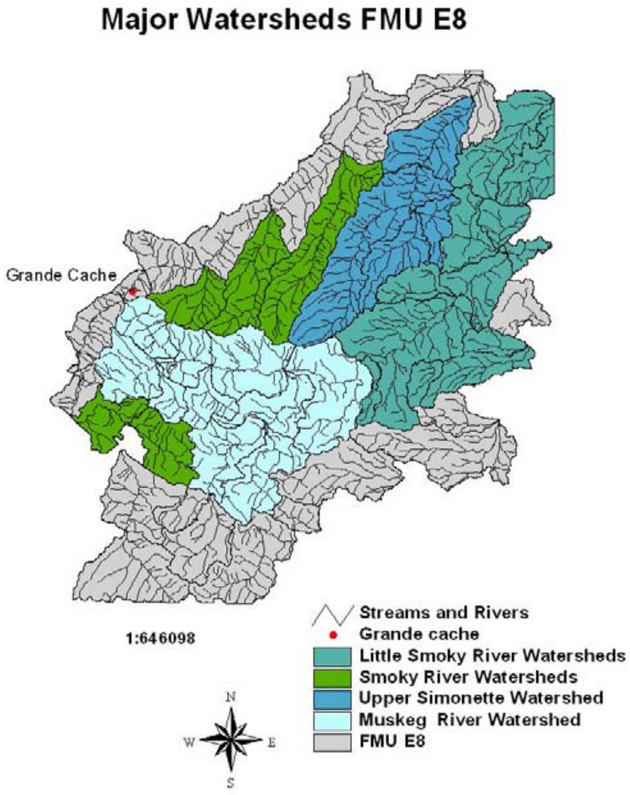
Introduction

The objective of this report was to assess the hydrologic effects of a spatial harvest plan for Forest Management Unit E8 (FMU E8). The FMU is approximately 3382 km^2 in area dominated by stands of lodgepole pine (*Pinus contorta*), white and black spruce (*Picea glauca, Picea maraiana*) and stands of aspen (*Populus tremuloides*). Major watersheds in the FMU include the Smoky, Muskeg, Simonette and Waskahigan rivers (Figure 1). FMU E8 is located near the town of Grande Cache.

Hydrologic assessment of the spatial harvest plan was done as follows:

1. Prepare a hydrologic land-base for the FMA
2. Identify 3rd order basins and consolidate them into watersheds 50-100 km^2 in size
3. Assemble hydro-meteorological data for the region
4. Run hydrologic simulations (WRENSS) of proposed harvesting
5. Analyze and report results.

Figure 2 Location of FMU E8 showing major watersheds and location relative to town of Grand Cache, Alberta



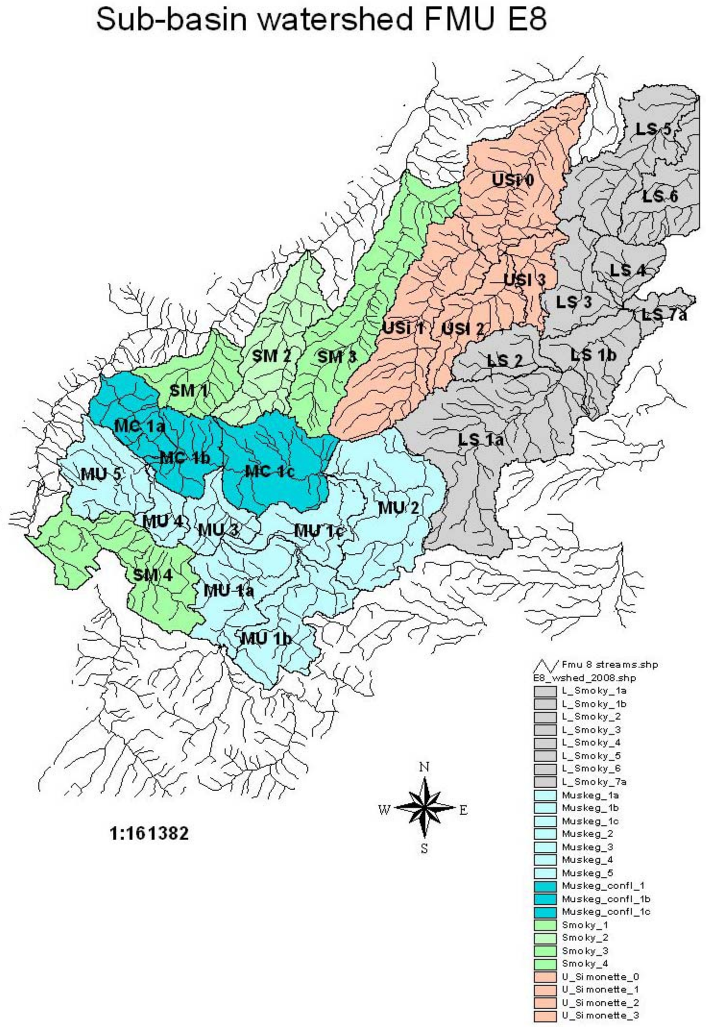
Methods

Hydrologic Land Base

A hydrologic land-base defines the number and extent of watersheds within a region. Hydrologic assessments are done on a watershed basis, which includes historical and proposed forest harvesting that can affect water flows.

The hydrologic land-base was prepared by identifying 3rd – 4th order basins in the region (Figure 2), which were consolidated into larger basins of 50-100 km^2 for simulations with the Wrenss model Attempts were made to limit watershed sizes to < 100 km^2 which is a scale commonly used in forest planning. Furthermore, the effects of forest harvesting on water flows become small or obscured on large watersheds (> 200-300 km^2) because the extent on harvesting in relative terms is less and the mix of newly harvested sites, unharvested sites and regenerated sites can moderate flow responses. A number of smaller 1st-2nd order watersheds were also included in the analysis (i.e. < 10-15 km^2). These watersheds were located in confluence zone of the Muskeg River of major drainages and represented a significant portion of the area scheduled for harvesting.

Figure 3 Hydrologic land base for planned spatial harvest in FMU E8 showing sub-basins within major drainages. Confluences (MC 1a, 1b, 1c) sub-basins in Muskeg are broken down into smaller units for simulations.

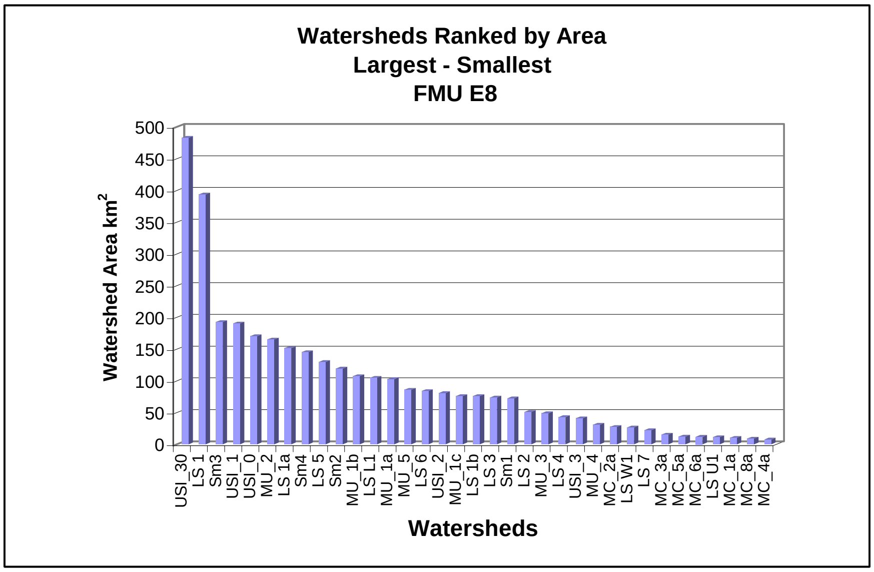


Harvest Data

The spatial harvest plan was prepared by ASRD. Input data for the Wrenss model was done by The Forestry Corp. Primary data included were: harvest block area, year of cut, harvest block aspect, species to be harvested, and species to be regenerated and site quality (Reference 1).

Harvesting was scheduled in each of the major drainages in the FMU. Thirty-five sub-watersheds were identified for assessment. Watersheds ranged in size from 7.7-483 km^2 with an average watershed area of 96 km^2 (Figure 3).

Figure 4 Watersheds in FMU E8 ranked by area: largest to smallest. Average watershed area for all watersheds 96 km^2. Average watershed area excluding two largest watersheds was 76 km^2



The spatial harvest planned for FMU E8 was 70 years, running from 2008 to 2078. Simulations were run for 200 years (1985-2185) to capture the hydrologic effects timber harvesting and hydrologic recovery of watersheds (i.e. return of flows to pre-harvest conditions). Historical harvesting (1985-2007) was also included in the simulations. This was done because the effects of harvesting on streamflow are long term, and exclusion of historical harvesting could bias simulation results. Twenty years prior to the spatial harvest plan was considered sufficient to capture any significant effects of historic harvesting.

Hydro-Meteorological Data

Streamflow and precipitation data were downloaded from the web sites of the Meteorological Service of Canada and Water Survey of Canada. Precipitation data were obtained from “2002 CDCD WEST CD” (Environment Canada 2002) for Western Canada. Streamflow data were obtained from HYDAT–CD ROM (Environment Canada 2003). Most of the precipitation and hydrometric stations for forested regions in Alberta obtained from these sources are provided in the Wrenss model as “look up tables” that allow specific stations to be input into the program.

Water yield increases in Wrenss simulations are calculated as a percent of the long term average water yield for the watershed being assessed, or a nearby “representative watershed” if flow data are not available. In an ideal situation a representative watershed should be of similar size, vegetation and climate to the watershed being assessed. These conditions are seldom satisfied as most of the available hydrometric data in Alberta are for large watersheds, whose water yields may be smaller than those of tributary sub-watersheds (≤ 100 km^2) which are normally candidates for simulation. Because of these limitations simulated changes in water yield are likely to be overestimated.

Representative watersheds selected for the FMU were the Simonette River, Waskakigan River and Muskeg River (Environment Canada 2007) (Table 1).

Table 3 Representative watersheds selected for simulations of water yield change in FMU E8

Watersheds	Area km^2	Record	*Years of Record*
Muskeg River	706	1972-2003	*31*
Simonette River	5050	1970-1998	*28*
Waskahigan River	*1040*	1968-1998	*30*

Precipitation data used in the Wrenss simulations was from the nearest station to watersheds being assessed, with 12 months of record fir a minimum of 10 years of record was used in simulation runs (Table 2).

Table 4 Meteorological stations selected for precipitation for precipitation inputs.

Watersheds	Precipitation Stations	Record	Year of Record	*Mean Precipitation mm*
Muskeg River	Grande Cache	1985-1999	14	*590*
Simonette River	Grande Cache	1985-1999	14	*590*
Waskahigan River	*Fox Creek*	1966-1998	*32*	*542*

Wrenss

Simulations were done using the Wrenss model (Water Resource Evaluation for Non-Point Silvicultural Sources) which was developed by the U.S. Forest Service and the U. S. Environmental Protection Agency (EPA 1980). Wrenss was designed to be used as an operational tool for forest planning. It is relatively simple in concept and has modest data requirements. It is not a “high end” research model designed to simulate daily flows (i.e. routed runoff).

Swanson (2000, 2005) prepared a computer version of the procedure (Wrenss) for Alberta conditions and modified it by linking climate and flow databases to the program. Outputs from Wrenss include:

- Increase in annual water yield
- Increases in maximum annual daily flows and maximum annual instantaneous flows for 2, 5, 10, 20 50 and 100 year recurrence intervals
- Equivalent Clearcut Area (ECA)
- Hydrologic Recovery

Water Yield

Estimated changes in annual water yield are based on seasonal water balance calculations of generated runoff (GRO), which is water that will eventually become runoff but has not reached the stream channel. Increases in water yield (ΔQ) are a change in evapotranspiration (ΔET) resulting from the removal of forest cover. Increases in water yield are obtained by taking the difference in ET between harvested and unharvested conditions.

Increases in water yield in Wrenss are expressed as area-millimetres (area-mm) and percentages. Area – mm is the volume of increased flow (or reduced ET) expressed as a uniform depth over a watershed. Increases in water yield are expressed as percents of the mean annual water yield (i.e. base yield in

Wrenss) for the watershed being analyzed or a nearby representative watershed, which is of similar size, forest cover and climate (i.e. precipitation).

Increases in water yield provided by Wrenss should be considered as relative changes (e.g. small, medium, and large). Few if any models are capable of providing exact, absolute changes. Furthermore, annual water yields are highly variable among watersheds and hydrologic regions. For example, annual yields in some years in boreal forest watersheds can be 0-100 mm, while in the Rocky Mountains water yields can be 400-800 mm. An increase of 40 mm in a Rocky Mountain watershed would be a small percentage compared to a similar increase in a boreal forest watershed. Percentages must be carefully interpreted.

Peak Flows

WRENSS provides estimates of increases in annual maximum daily and instantaneous flows for return periods of 2, 5, 10, 20, 50 and 100 years. Pre-harvest peak flows are estimated as a function of watershed size by regression analysis ($Q_{peak} = f$ (watershed area). The difference between mean March to September streamflow in the pre-harvest and post-harvest condition is used to estimate the change in peak flows for each recurrence interval. The difference between these two flows is added to the maximum annual daily flow estimated as a function of watershed area. In some situations the magnitude of peak flow increases are constrained (Figures xx) if they exceed the maximum daily change in evapotranspiration rate. Maximum daily evapotranspiration is assumed to represent the maximum amount of extra water added to peak flows as a result of forest harvesting. (A more detailed description of WRENSS in provided in Reference 2).

Equivalent Clearcut (ECA)

Equivalent Area Clearcut (ECA) is an index of watershed disturbance. It is a measure of the disturbed area (i.e. harvest blocks) in a watershed that is in a condition to contribute extra water to streamflow. ECA is at a maximum at the time of harvest and then decreases with the regeneration of harvest blocks. The physical model supporting ECA is that vegetation removal changes water yield in rough proportion to the leaf surface area or basal area removed from a site (Ager and Clifton 2005).

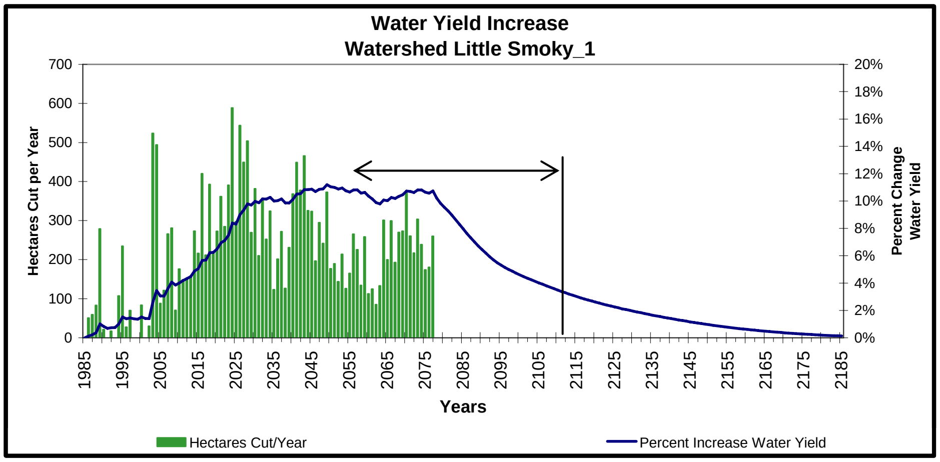
ECA is defined in this assessment as the area (hectares) harvested times a reduction factor that describes the recovery of evapotranspiration losses. ECA estimates in Wrenss are calculated in terms of basal area recovery or recovery of water yield. ECA_Q based on water yield recovery was used in this assessment. It was considered a more direct and realistic estimate of hydrologic recovery. ECA_Q is expressed in hectares of “harvested area” and as a percent of the watershed area.

Hydrologic Recovery

Hydrologic recovery is an estimate of the time required for increased water yield to disappear as trees grow on harvest blocks to full occupancy of the site or a condition similar to pre-harvest conditions. Hydrologic recovery is assumed to occur at the time of maximum leaf area (i.e. the recovery of evapotranspiration to pre-harvest levels). Stand basal area is used as a surrogate for leaf surface area in Wrenss. This provides a very conservative estimate of hydrologic recovery as the time for basal area to return to a “mature” stand level can be very long (e.g. 80-100 years).

Leaf surface area and by association hydrologic recovery is thought to occur earlier than the time to maximum basal area. Brabender (2005) reports maximum LAI (leaf area index) for lodgepole pine occurs between 25-35 years. To adjust for the conservative nature of basal area, hydrologic recovery at the stand level was assumed to occur 30 years following the end of harvesting. The time required for recovery of a watershed is different. Watershed recovery was measured from the year of maximum water yield increase to the end of harvesting plus 30 years (Figure 4). The extra 30 years allowed for recovery of blocks harvested near the end of the spatial harvest plan. For example, recovery for the last year of harvesting (2077) in watershed LS_1 occurred in 2107 (i.e. 2077+30), while for recovery for the watershed was 58 years (2107 – 2049 Figure 4).

Figure 5 The time for hydrologic recovery in watershed LS_1 was measured from the year of maximum water yield increase (2049) to the end of harvesting (2077) plus 30 years (2107). Time for recovery (arrow) in LS_1 was 58 years (2107-2049).



Statistical Assessment

The statistical significance of water yield increases was assessed by comparison to the upper 95% confidence limits of the long term average annual water yields of representative watersheds used in the simulations (Table 3). Yield increases greater than the upper 95% confidence limit were considered to be significant.

Representative watersheds used in the simulations are shown in Table 8 with statistics. The length of record for the representative watersheds varied from 28 - 31 years. Mean annual flows varied from 149.8 - 229.0 area mm. Water yield increases equal to or greater than 13.34%, 9.86%, and 14.08% were considered to be significantly different from the long term means of the Muskeg, Simonette and Waskahigan rivers respectively.

Table 5 Table Calculation of upper 95% confidence limit of water yield for representative watersheds to be used as a test for significance of water yield increases.

Watershed	Mean Annual Yield mm	Upper 95% Limit $\bar{x}+\sqrt{(s^2/n)}$	Significant %ΔQ
Muskeg River	226.4	256.209	*13.34*
Simonette River	229.0	251.588	*9.86*
Waskahigan River	*149.8*	*170.89*	*14.08*

Calculations for %ΔQ in Table xx

- Muskeg River --- 226.4 mm ± (2.042*14.794) = 30.209 Upper 95% Confidence Limit 226.4+ 30.209 = 256.209 ---%ΔQ(30.209/226.4)*100 = 13.34%
- Simonette River ---229.0 mm ± (2.052*11.008) = 22.588 Upper 95% Confidence Limit = 229 + 22.588 = 251.588 %ΔQ(22.588/229.0)*100 = 9.86%
- Waskahigan River --- 149.8 mm ± (2.042 * 10.330) = 21.09 Upper 95% Confidence Limit = 149.8 + 21.09 = 170.89 %Δ(21.09/149.8)*100 = 14.078%

Results

Water Yield

Simulated increases in annual water yield in FMU E8 ranged from a maximum of 24.5% in watershed LS 4 to a minimum of 4.4% in watershed SM 4, with an overall average increase of 13.3% for all watersheds (Figure 5 and Table 4). The average area harvested for all watersheds was 51%, with minimum and maximum values of 20% in watershed LS 5 and 100% in watershed MC 1a, which was a small third order basin (10.4 km^2). Harvesting in MC 1a occurred prior to the proposed spatial harvest (1985-2007) and affected 26% of the watershed.

Figure 6 Percent increase in annual water yield for watersheds in FMU E8.

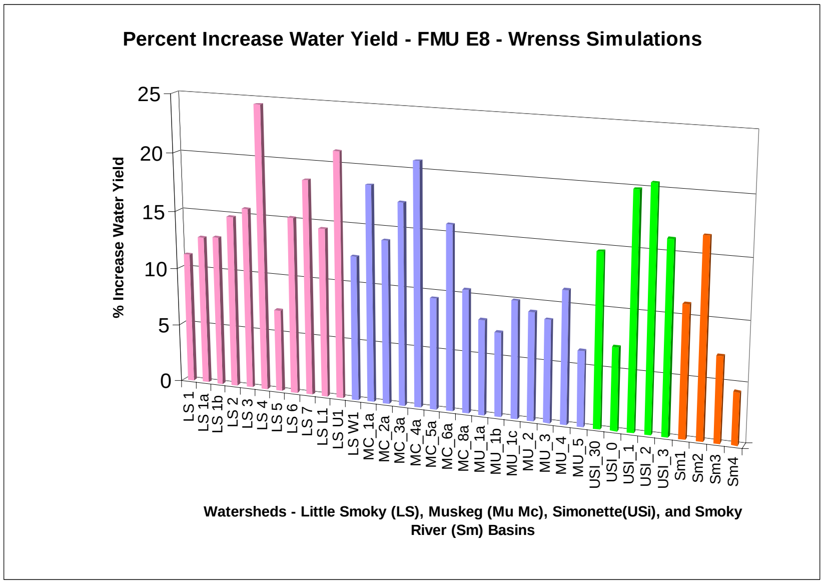
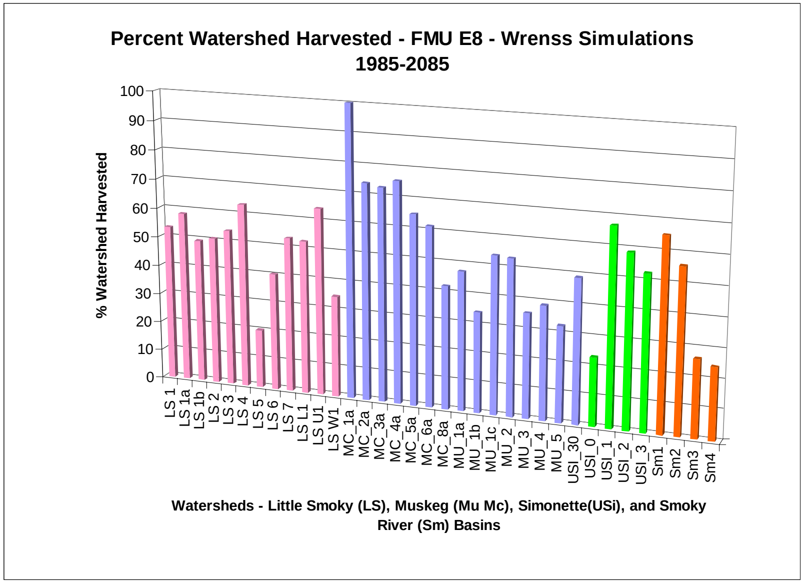


Figure 7 Percent area harvested in FMU E8 watersheds, 1985-2085.



Approximately one-half of the watersheds (17/35) had significant increases in water yield (i.e. increases > upper 95% confidence limits of representative watersheds). The greatest increases occurred in the Little Smoky and Simonette watersheds. The average increase for 7 watersheds in the Little Smoky was 17.1% with a range of 14.8-24.5%. Significant water yield increases in the Simonette averaged 17.8% in 5 watersheds with a range of 14.7-20.5%. Average increases in the Muskeg and Smoky watersheds were less with values of 13.6% and 16.7% respectively. The upper 95% confidence limits for the Little Smoky, Muskeg, Simonette and Smoky watersheds were respectively 14.08%, 13.34%, and 9.86% respectively (Table 3).

Water yield increases were significantly correlated with the percent of watershed harvested. R^2 values for the regressions were of 0.46 and 0.67 (Figures 7 and 8). Volumetric increases (area–mm) showed a higher level of correlation as they are direct estimates of extra water generated (i.e. a decrease in evapotranspiration) and are not strongly related to water yield. Percentage increases (Figure 7) were more variable because of differences in baseline flows used to calculate changes in water yield. Both regressions showed a fair amount of scatter about their curves, which was attributed to the effects of the timing and location of harvesting (i.e. concentrated or dispersed) and the amount of historical harvesting versus the proposed spatial harvest.

Water yield responses were largely determined by the amount and timing of harvesting in watersheds (Figures 9,10,11). Maximum increases in water yield usually coincided with periods of maximum harvesting, followed by a decrease in yield with regeneration of harvest blocks. Wrenss simulations were extended beyond the end of planned harvesting to fully capture the time for hydrologic recovery of watersheds.

Table 6 Maximum increases in annual water yield, watershed ECA and hydrologic recovery in years. Percent increases shown in bold were significantly greater than long term average water yield of representative watersheds used in Wrenss simulations.

Watershed Number	Area km^2	% Watershed Harvested	% Increase Yield	Increase Yield mm	% Watershed ECA	Hydrological Recovery Yrs
Little Smoky						
LS 1	394.0	53.3	11.2	16.8	11.78	58
LS 1a	151.7	58.4	12.8	19.1	13.89	58
LS 1b	76.1	49.3	12.9	19.3	13.51	80
LS 2	51.4	50.7	**14.8**	22.2	14.32	35
LS 3	74.1	53.8	**15.6**	23.4	16.11	77
LS 4	43.1	63.3	**24.5**	36.7	23.70	90
LS 5	130.0	20.1	7.1	10.6	7.20	94
LS 6	84.3	40.3	**15.2**	22.7	15.28	39
LS 7	22.6	53.2	**18.5**	27.7	19.64	58
LS L1	105.2	52.6	**14.5**	21.7	14.71	80
LS U1	11.5	64.2	**21.1**	31.7	22.09	30
LS W1	26.9	34.7	12.4	18.6	13.40	33
Muskeg						
MC_1a	10.4	100	**18.5**	41.9	28.17	93
MC_2a	27.7	74.1	**14**	31.6	20.94	117
MC_3a	15.4	73.0	**17.3**	39.2	24.08	94
MC_4a	7.7	75.6	**20.8**	47.1	30.27	118
MC_5a	12.3	65.1	9.5	21.6	15.07	119
MC_6a	12.0	61.5	**15.8**	35.8	27.25	86
MC_8a	9.3	42.1	10.5	23.9	15.74	39
MU_1a	102.9	47.5	8.1	18.4	12.57	45
MU_1b	107.8	34.3	7.2	16.2	11.36	30
MU_1c	76.3	53.9	10.0	22.7	16.76	84
MU_2	165.4	53.4	9.2	20.8	14.36	68
MU_3	49.1	35.8	8.7	19.8	13.40	30
MU_4	31.1	38.9	11.3	25.6		30
MU_5	86.1	32.7	6.4	14.6	9.26	30
Upper Simonettte						
USI_30	483.4	49.1	**14.7**	22.1	15.22	84
USI_0	170.7	23.4	7	10.6	7.55	83
USI_1	190.7	67.1	**19.9**	29.9	20.71	86
USI_2	80.9	58.9	**20.5**	30.8	20.82	85
USI_3	41.2	52.6	**16.2**	24.3	16.54	80
Smoky						
Sm1	72.6	65.4	11.1	25	18.43	86
Sm2	119.4	56	**16.7**	37.8	23.62	103
Sm3	192.9	26.6	7.2	16.3	11.96	102
Sm4	145.6	24.5	4.4	10	6.53	30

Figure 8 Regression analysis of percent increase in water yield versus percent of watershed harvested.

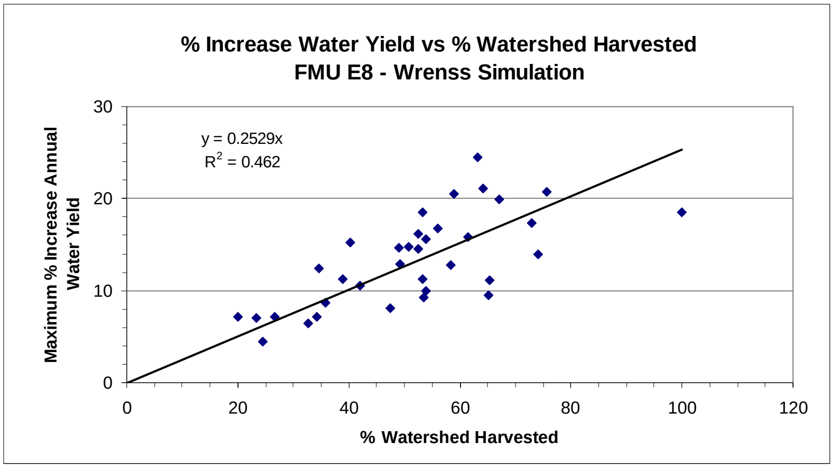


Figure 9 Regression analysis of volumetric increase in water yield (area – mm) versus percent of watershed harvested.

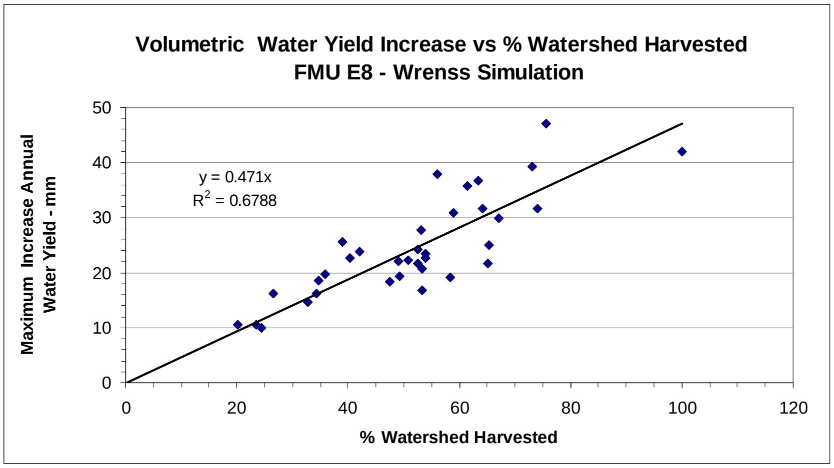


Figure 10 Water yield response and harvesting for Little Smoky_1. The rate of harvesting was relatively high and constant resulting in a maximum increase of 11.2% in 2049. Total percent of watershed area harvested was 53%. Hydrologic recovery from year of maximum increase was 58 years. Average rate of harvesting was 231 ha/yr.

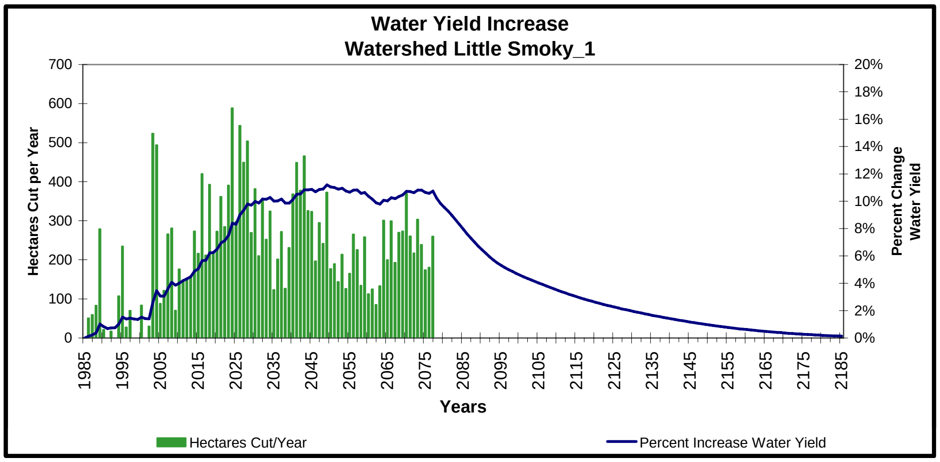


Figure 11 Water yield response and harvesting in Muskeg_1a. Harvesting was concentrated into three major periods with a maximum increase of 8.1% in 2062. Total percent of watershed area harvested 47.5%. Average rate of harvesting was 11.3 ha/year. Hydrologic recovery was 93 years.

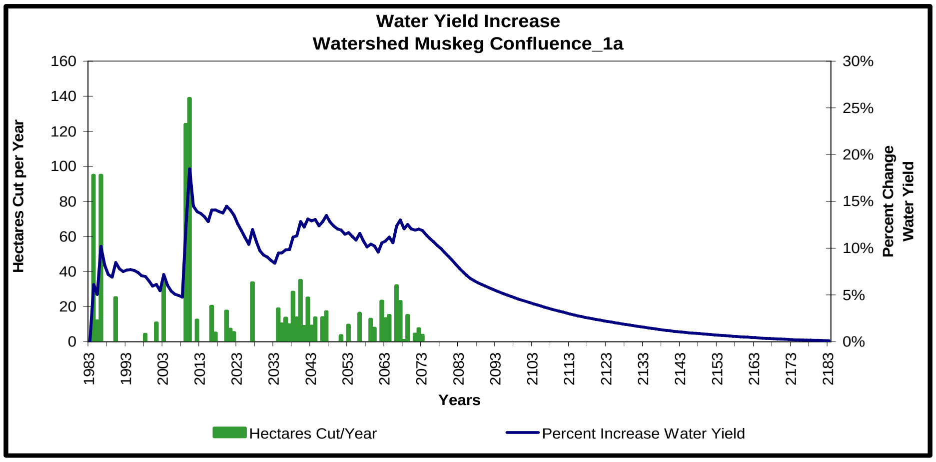
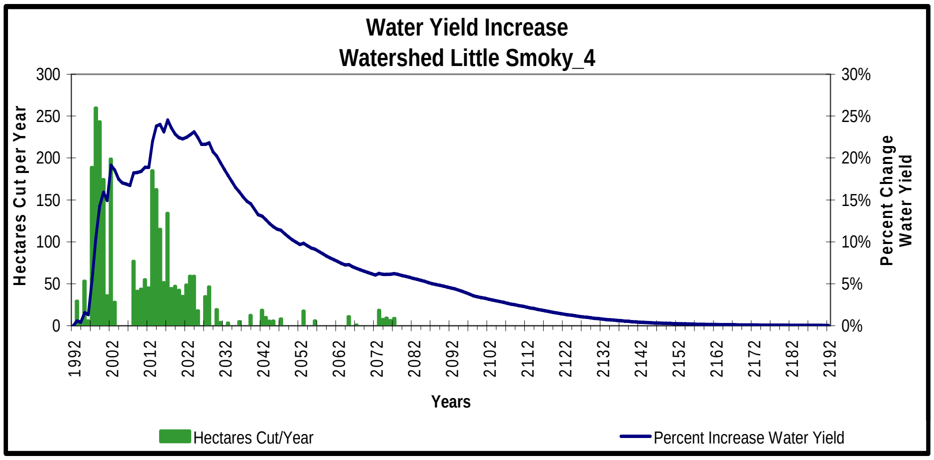


Figure 12 Water yield response and harvesting in Little Smoky 4. Harvesting was concentrated into 2 periods. Maximum increase in water yield was 24.5%. Total percent of watershed harvested was 63.3%. Average rate of harvesting was 18 ha/year. Hydrologic recovery was 90 years.



Peak Flows

Average increases in annual maximum daily flows for all watersheds ranged from 19.7% to 9.11% for the 2-yr to 100 yr events respectively (Table 5, Figure 12). Peak flows followed a decreasing trend as recurrence intervals increased. Increases were variable among the major sub-basins in the region with low to moderate responses in the Muskeg watersheds compared to the other sub-basins. Peak flow increases were greater in the Little Smoky watersheds. This was attributed to the lower streamflow in these watersheds. Increases in the 50 and 100 year events were higher than expected and should be viewed with caution as they are extrapolations well beyond the range of data available for the region (i.e. 20-30 years).

Table 7 Average increases in annual maximum daily flows by recurrence intervals for FMU E8 watersheds based on Wrenss simulations.

	2 Yr	5 Yr	10 Yr	20 Yr	50 Yr	100 Yr
All Watersheds in FMU E8						
Average	19.75	18.34	15.80	13.34	10.57	9.11
Maximum	41.70	39.00	31.50	25.90	21.10	18.60
Minimum	6.80	6.80	6.70	5.20	3.30	2.50
Smoky						
Average	23.3	23.1	21.0	18.9	16.0	14.4
Maximum	39.6	39.0	31.5	25.9	21.1	18.6
Minimum	9.5	9.5	9.6	8.6	7.0	6.2
Muskeg						
Average	18.6	15.2	11.5	8.3	5.5	4.0
Maximum	41.7	26.9	21.0	14.4	9.1	6.6
Minimum	7.0	6.8	6.7	5.2	3.3	2.5
Upper Simonette						
Average	17.8	18.0	17.0	14.8	12.0	10.6
Maximum	24.4	24.6	22.2	20.4	16.4	14.6
Minimum	7.7	7.7	7.5	6.1	4.9	4.4
Smoky						
Average	15.6	15.6	14.0	12.6	10.4	9.2
Maximum	27.0	26.8	20.5	19.6	16.6	14.6
Minimum	6.8	6.9	7.0	6.4	5.2	4.6

The largest increases in annual maximum daily flows were the 2-years events, with values ranging from 6.8-41%. Increases were greatest in the Little Smoky watersheds and smallest in the Smoky watersheds and intermediate in the Upper Simonette and Muskeg watersheds (Figure 13).

Percent increase in annual maximum daily flows was significantly correlated with maximum percent watershed ECA (Figure 14). The R^2 value for the analysis was 0.6757, which was similar to regression results of water yield increase on percent watershed harvested. This was not unexpected because of the strong co-variation between increases in water yield and peak flows, and the percent area harvested and maximum percent watershed ECA.

Figure 13 Percent increase in annual maximum daily flows for watersheds in FMU E8 based on Wrenss simulations.

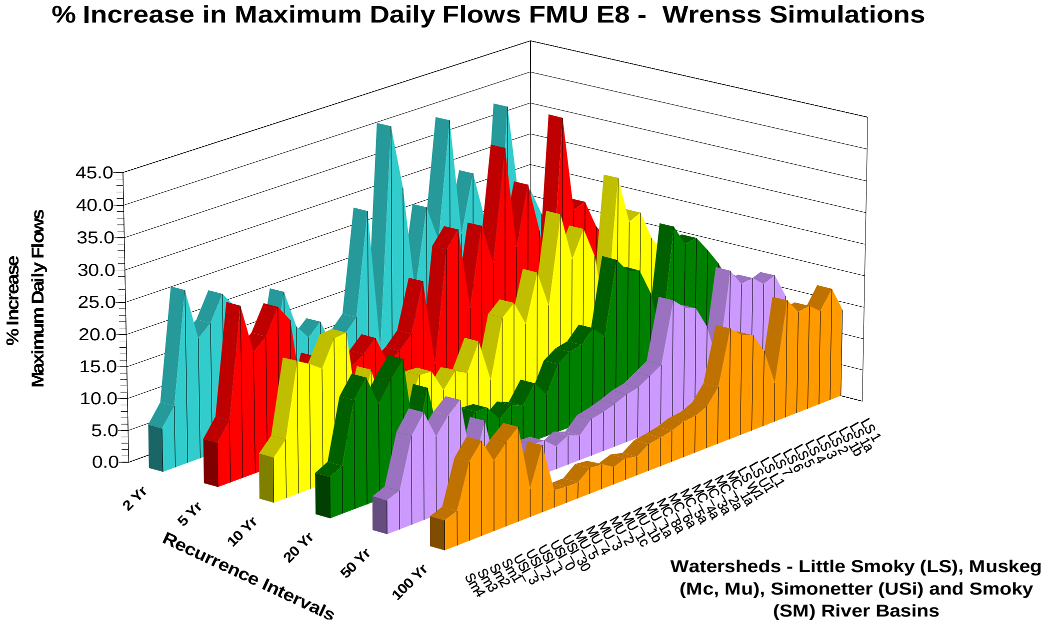


Figure 14 Average increases in annual maximum daily flows for 2, 5, 10 -year events in FMU E8 based on Wrenss simulations.

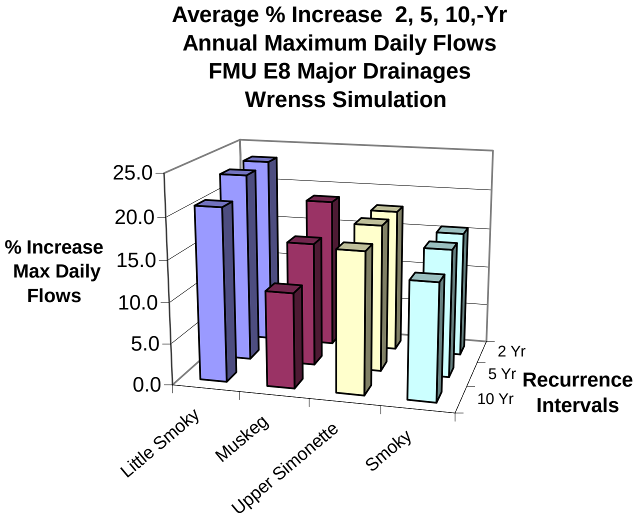
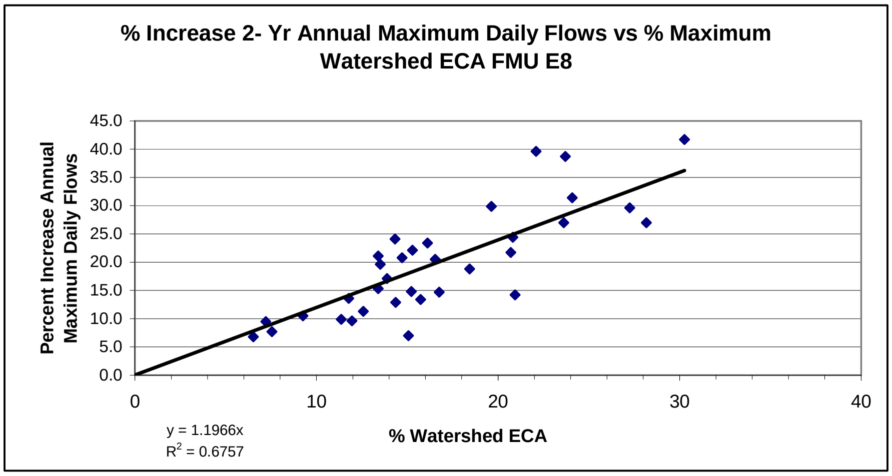


Figure 15 Regression analysis of percent increase 2-Yr annual maximum daily flows on maximum % watershed ECA.



Increases in annual maximum daily flows were also accompanied by an increase in their frequency of occurrence Table 7) (i.e. a decrease in their recurrence interval or less frequent to more frequent). For example an increase of 13.6% changed the 2-year event from 16.9 to 19.2 m^3/sec in watershed LS 1. The recurrence interval for a flow of 19.2 m^3/sec was reduced from 2.19 to 2.0 years following harvesting, which increased its frequency by ~ 4.3% (1/2 – 1/2.19 = 0.5- 0.456 = 0.043).

Average increases in the frequency of occurrence for annual maximum daily flows for all watersheds ranged from 7.39% for 2-year events to less than 1% for the 100 year events (Table 6, 7, Figure 15, 16). The largest changes in frequency were for the 2 and 5-yr events with values ranging from 6.9-41.7% and 6.9-30.2% respectively. The average shifts in recurrence intervals from less frequent to more frequent for the 2, 5 and 10 events were 2.36 →2.0, 8.81→5.0 and 19.6→10 years. The shift for the 10 year events may seem large, but its average increase in frequency was less than 5%. This changes of frequency of occurrence for all recurrence interval was low to very small.

Table 8 Average increase in frequency of annual maximum daily flows for FMU E8 watersheds based on Wrenss simulations.

	2 Yr	**5 Yr**	**10 Yr**	**20 Yr**	**50 Yr**	**100 Yr**
All Watersheds	7.39	8.26	4.74	2.47	0.91	0.41
Little Smoky	9.30	9.23	5.37	2.84	1.04	0.49
Muskeg	6.46	7.95	4.49	2.29	0.86	0.37
Upper Simonette	6.00	7.42	4.30	2.25	0.82	0.37
Smoky	6.65	7.45	4.30	2.21	0.82	0.37

Table 9 Percent increase in annual maximum daily flows and Percent increase in frequency of Maximum Daily Flows for watersheds in FMU E8 based on Wrenss simulations.

Watershed Number	% Watershed Harvested	Percent Increase Frequency Maximum Daily Flow by Recurrence Intervals						Percent Increase Frequency Maximum Daily Flow by Recurrence Intervals					
		2 Yr	5 Yr	10Yr	20 Yr	50 Yr	100 Yr	2 Yr	5 Yr	10Yr	20 Yr	50 Yr	100 Yr
Little Smoky													
LS 1	53.3	13.6	13.6	13.6	13.7	13.8	13.8	4.28	5.70	3.66	2.10	0.93	0.48
LS 1a	58.4	17.1	17.1	17.3	17.5	17.7	17.8	8.23	9.09	5.49	3.49	1.14	0.56
LS 1b	49.3	19.6	19.7	20.0	20.3	17.0	14.9	6.42	7.83	5.04	2.83	1.08	0.51
LS 2	50.7	24.1	24.3	24.7	22.8	18.6	16.4	9.09	9.48	5.74	3.00	1.15	0.53
LS 3	53.8	23.4	23.6	23.9	22.5	18.3	16.1	8.23	9.09	5.49	3.49	1.14	0.56
LS 4	63.3	38.7	39.0	31.5	25.9	21.1	18.6	15.51	12.63	6.59	3.23	1.23	0.60
LS 5	20.1	9.5	9.5	9.6	8.6	7.0	6.2	0.53	4.47	3.07	1.57	0.56	0.23
LS 6	40.3	22.1	22.2	20.3	16.6	13.5	11.9	8.39	8.42	5.01	2.41	0.92	0.42
LS 7	53.2	29.9	30.2	25.3	20.9	17.1	15.1	13.32	11.20	5.92	2.89	1.02	0.49
LS L1	52.6	20.8	20.9	21.2	21.4	17.9	15.8	7.42	8.24	5.13	2.88	1.12	0.52
LS U1	64.2	39.6	37.3	28.9	23.9	19.7	17.5	18.19	12.69	6.85	3.32	1.28	0.61
LS W1	34.7	21.1	19.6	15.1	12.4	10.2	9.0	7.15	8.17	4.33	2.02	0.70	0.32
Muskeg													
MC_1a	100	27.0	26.2	21.0	14.4	9.1	6.6	10.20	11.00	6.44	3.60	1.33	0.68
MC_2a	74.1	14.2	13.8	13.5	12.4	8.0	5.8	9.93	8.22	4.90	2.49	1.05	0.53
MC_3a	73	31.4	26.9	17.5	12.0	7.6	5.6	10.87	12.13	6.25	3.21	1.25	0.54
MC_4a	75.6	41.7	24.4	15.8	10.7	6.8	4.9	17.53	12.60	6.47	2.84	1.20	0.51
MC_5a	65.1	7.0	6.8	6.7	6.6	6.2	4.5	0.15	5.35	3.19	1.31	0.53	0.20
MC_6a	61.5	29.6	20.7	13.4	9.1	5.8	4.2	14.27	11.37	5.41	2.56	1.05	0.41
MC_8a	42.1	13.4	13.0	9.1	6.2	3.9	2.9	1.58	6.28	4.08	2.44	0.90	0.28
MU_1a	47.5	11.3	11.0	10.1	7.0	4.6	3.4	2.37	5.80	3.66	2.03	0.74	0.31
MU_1b	34.3	9.9	9.7	7.8	5.5	3.6	2.7	2.04	5.32	3.40	1.74	0.60	0.24
MU_1c	53.9	14.7	14.4	11.4	8.0	5.2	3.8	4.77	6.90	4.40	2.25	0.82	0.37
MU_2	53.4	12.9	12.5	11.5	8.1	5.3	4.0	3.90	6.21	3.92	2.18	0.79	0.35
MU_3	35.8	15.3	11.3	7.4	5.2	3.3	2.5	3.50	7.02	3.51	1.75	0.60	0.24
MU_4	38.9	21.4	11.7	7.6	5.3	3.4	2.5	7.51	7.46	3.75	1.89	0.62	0.23
MU_5	32.7	10.5	10.2	8.1	5.7	3.7	2.7	1.74	5.68	3.50	1.80	0.63	0.26
Simonette													
USI_30	49.1	14.8	14.9	15.1	14.6	11.8	10.4	4.86	6.12	3.95	2.22	0.83	0.38
USI_0	23.4	7.7	7.7	7.5	6.1	4.9	4.4	0.35	3.96	2.59	1.22	0.39	0.14
USI_1	67.1	21.7	21.9	22.2	20.4	16.4	14.6	8.02	8.47	4.89	2.80	1.06	0.50
USI_2	58.9	24.4	24.6	22.0	18.0	14.7	13.0	9.76	9.67	5.35	2.62	0.97	0.45
USI_3	52.6	20.5	20.7	18.0	14.8	12.2	10.8	6.99	8.90	4.72	2.38	0.86	0.38
Smoky													
Sm1	65.4	18.8	19.0	19.4	19.6	16.6	14.6	6.07	8.05	4.98	2.74	1.05	0.49
Sm2	56	27.0	26.8	20.5	16.8	13.7	12.1	10.91	9.90	5.08	2.50	0.93	0.42
Sm3	26.6	9.6	9.7	9.1	7.4	6.0	5.3	1.52	4.80	2.94	1.42	0.48	0.18
Sm4	24.5	6.8	6.9	7.0	6.4	5.2	4.6	8.13	7.06	4.18	2.19	0.82	0.38

Figure 16 Increases in frequency of maximum daily flows for FMU E8 watersheds based on Wrenss simulations

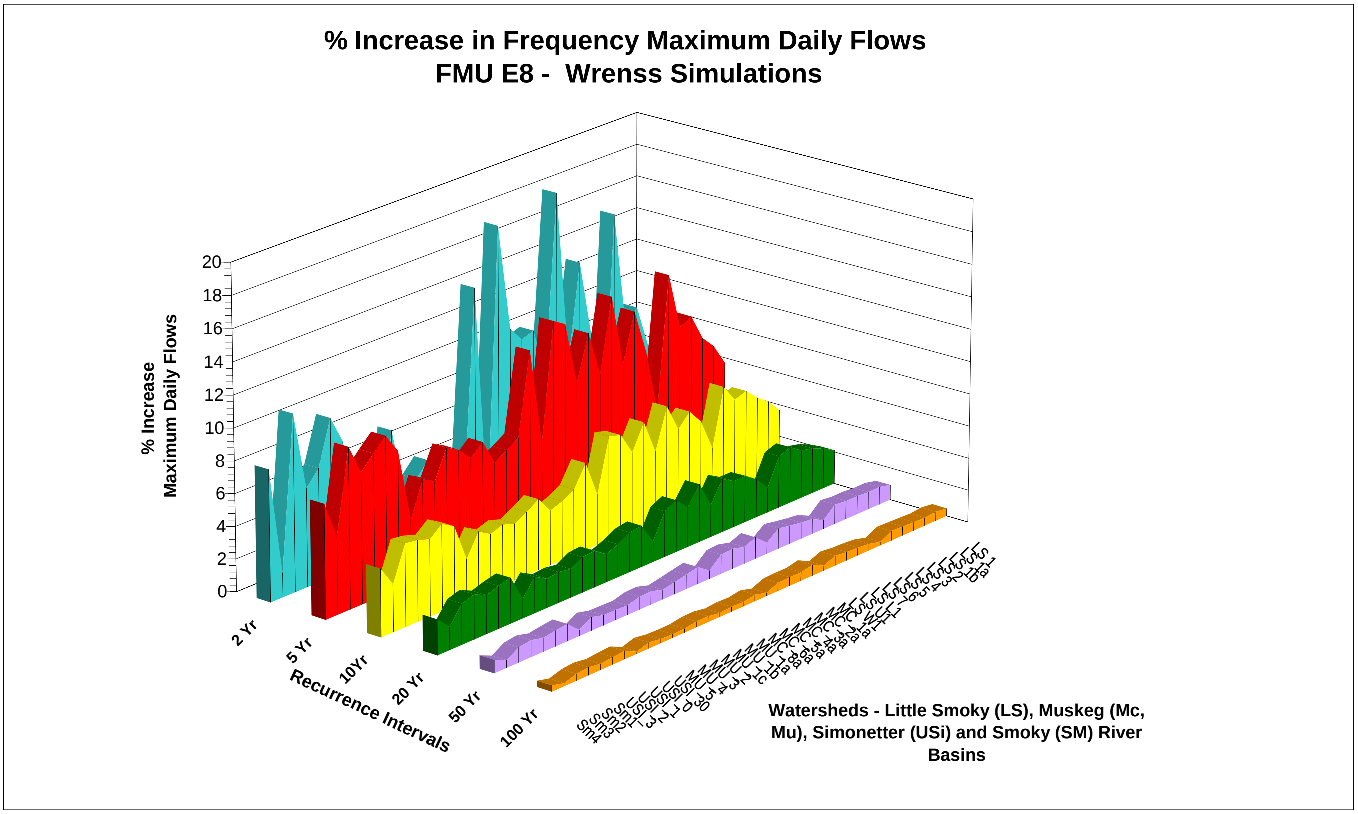
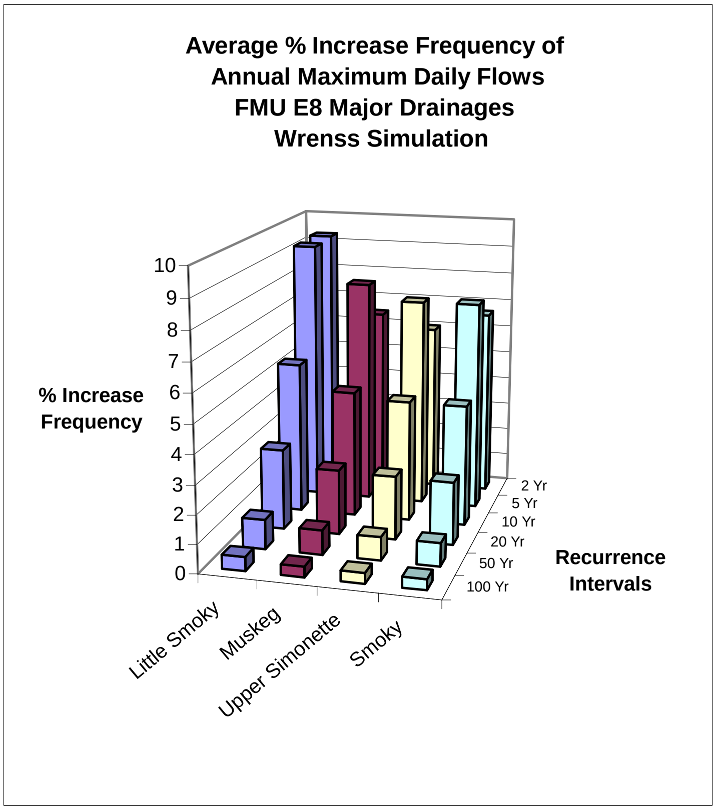


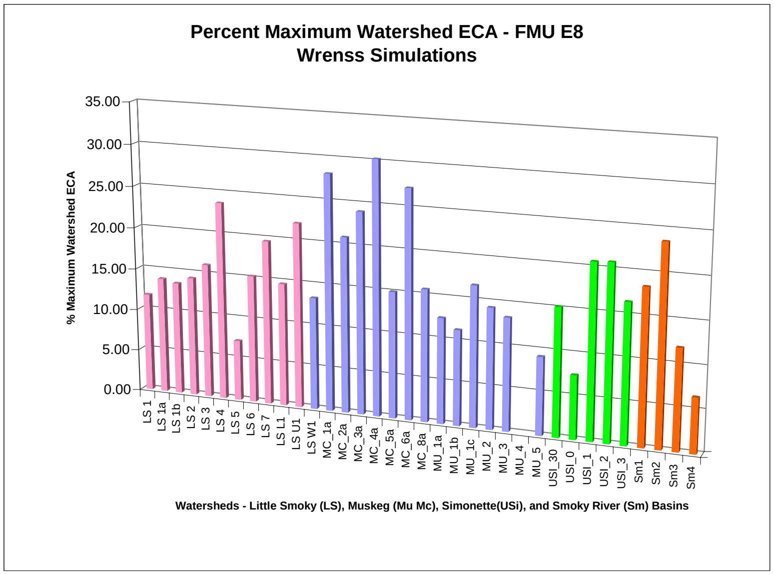
Figure 17 Aver increases in frequency of occurrence annual maximum daily flows in major watershed of FMU E8



% Watershed ECA and Hydrological Recovery

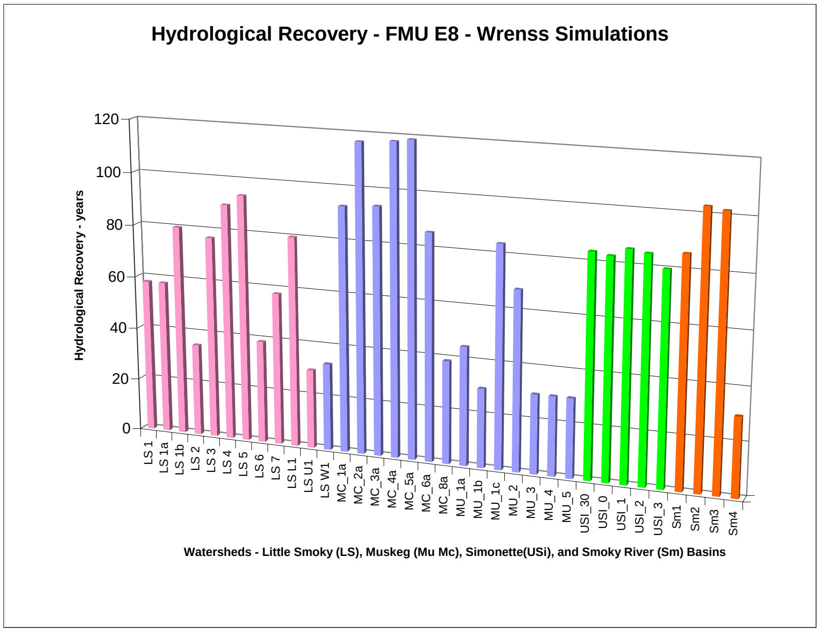
Equivalent clear cut area (ECA) is an expression of the amount of hydrologic disturbance in a watershed that incorporates the effects of past and current harvesting on water flows. Maximum percent watershed ECA ranged from 6.5 - 30%, with an overall average of 16% for all watersheds (Figure 17).

Figure 18 Maximum % Watershed ECA for FMU E8.



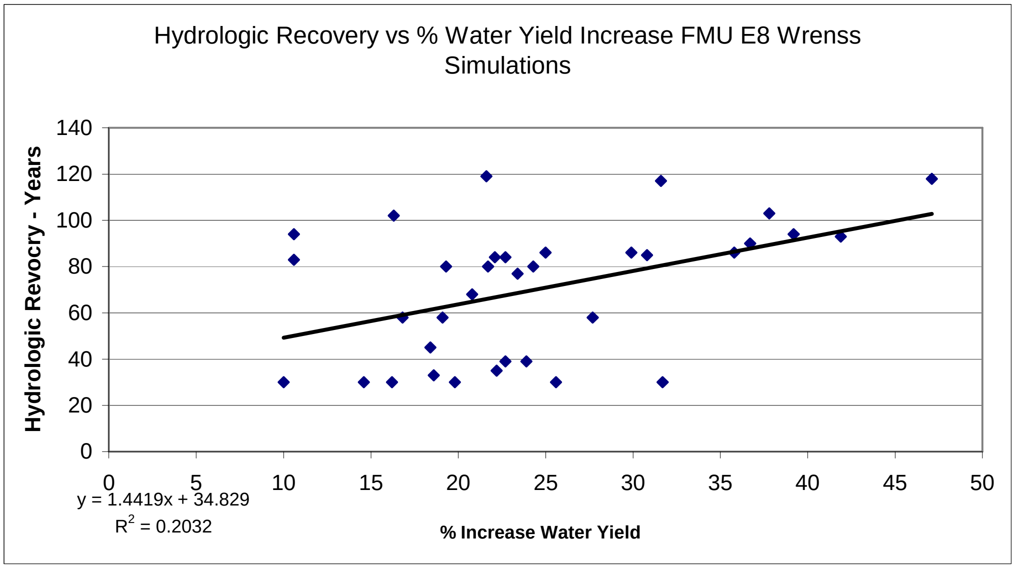
Hydrologic recovery among the watersheds ranged from 30 to 119 years with an overall average value of 70 years. Hydrologic recovery for a watershed was measured from the time of maximum water yield to the end of harvesting plus 30 years (Figure 18). Recovery in the Muskeg watersheds was longest because of historic harvesting in mid 1980s. Simulated water yield increases at the time of recovery for all watersheds (~ 2078) averaged 2.8% with maximum and minimum values of 6.6% and < 1.0%.

Figure 19 Hydrologic recovery in years for watersheds in FMU E8 based on Wrenss Simulations.



Percent water yield increases showed a weak positive trend with hydrologic recovery with considerable scatter about the regression curve (Figure 19). The scatter was attributed to the differences in timing and extent of harvesting, where repeated entries could lengthen the time for hydrologic recovery, or harvesting concentrated into a short period of time could shorten recovery.

Figure 20 Regression of hydrologic recovery on % water yield increase in FMU E8 watersheds, based on Wrenss Simulations.



Decadal water yield increases were used to assess hydrologic recovery at watershed and landscape scales (Figure 20 and Table 9). The patterns of water yield increases in 10 year increments were highly variable among watersheds in FMU E8, which was a reflection of the timing and extent of harvesting in watersheds. Patterns ranged from steady incremental increases in water yield culminating in maximum increases in the 3rd-4th decades (e.g. Little Smoky watersheds), to relatively similar increases in all decadal years (e.g. Smoky watersheds).

Average decadal responses for the major drainages (Figure 8) reduced the amount of variation between decadal years, but still showed an increasing trend in water yield for the Little Smoky and Simonette watersheds (5-12% and 11-15% respectively) compared to smaller and relatively similar increases in water yield (5-7% and 4-8%) respectively for the Muskeg and Smoky watersheds.

Average decadal water yield increases (i.e. landscape scale) for all of the FMU ranged from 5.8% in year 10 to a maximum of 9.8% in Year 40 followed by a decrease in 8.1% in Year 60 (Table 9), which was less than the maximum annual average increase of 13.3% for all watersheds. An additional number of years would be required to see decadal averages approach zero (i.e. full hydrological recovery). It should be noted that average water yield increases for the FMU in most watersheds were equal to or less than the upper 95% confidence limits of representative watersheds used to test for significance.

Table 10 Average decadal water yield increases for all watersheds in FMU E8

	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60
Average	5.8	6.9	8.7	9.8	8.8	8.1
Maximum	19.1	18.9	22.5	20.0	16.0	19.1
Minimum	0.0	0.1	0.1	1.3	2.1	3.5

Figure 21 Decadal water yield increases for individual watersheds and major drainages in FMU E8.

Decadal Water Yield Increases - Little Smoky Watersheds FMU E8 - Wrenss Simulations

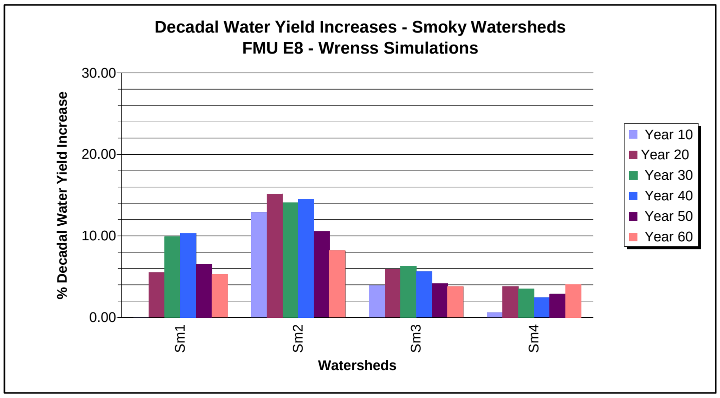
Average Decadal Water Yield Increases Little Smoky Watersheds FMU E8 - Wrenss Simulation

Decadal Water Yield Increases - Muskeg Watersheds FMU E8 - Wrenss Simulations

Average Decadal Water Yield Increases Muskeg Watersheds FMU E8 - Wrenss Simulation

Decadal Water Yield Increases - Upper Simonette Watersheds FMU E8 - Wrenss Simulations

Average Decadal Water Yield Increases Upper Simonette Watersheds FMU E8 - Wrenss Simulation


Decadal Water Yield Increases - Smoky Watersheds
FMU E8 - Wrenss Simulations
% Decadal Water Yield Increase
30.00
20.00
10.00
0.00
Sm1
Sm2
Sm3
Sm4
Watersheds
Year 10
Year 20
Year 30
Year 40
Year 50
Year 60

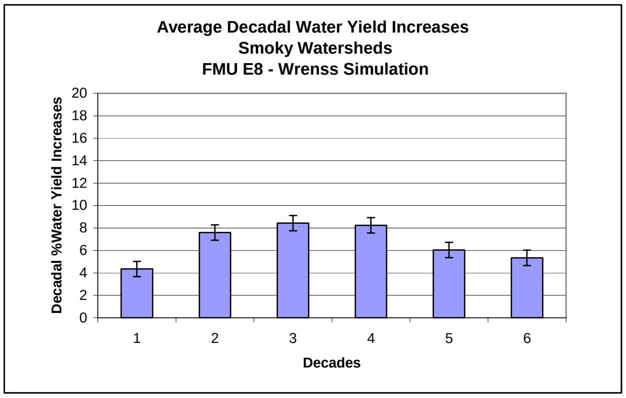

Average Decadal Water Yield Increases
Smoky Watersheds
FMU E8 - Wrenss Simulation
Decadal %Water Yield Increases
20
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
Decades

Table 11 Decadal water yield increases for watersheds in FMU E8 Maximum increases for each decade year are highlighted in yellow

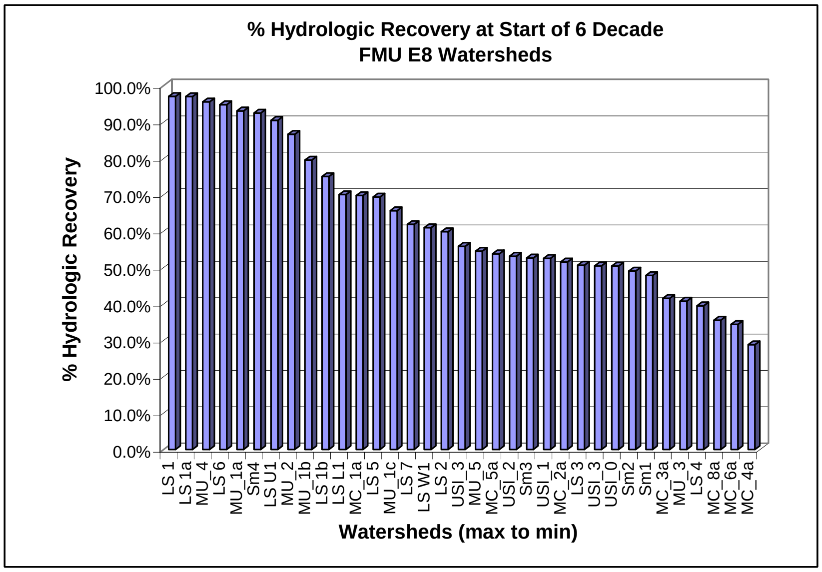
Watershed Name	Start Year	Decadal % Water Yield Increases						
		Year 0	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60
Little Smoky								
LS 1	1985	0.00	1.51	3.06	5.05	8.32	10.00	10.87
LS 1a	1985	0.00	1.55	3.76	5.30	6.45	8.99	12.42
LS 1b	1989	0.00	0.00	0.76	4.85	12.14	10.89	9.68
LS 2	1989	0.00	2.28	7.01	12.53	13.47	10.44	8.86
LS 3	1988	0.00	10.66	13.82	13.45	14.69	10.87	7.90
LS 4	1992	0.00	19.13	18.88	22.48	18.62	13.06	9.68
LS 5	1987	0.00	5.68	6.32	5.70	4.97	4.82	4.93
LS 6	1995	0.00	2.99	3.22	3.51	9.40	14.31	14.41
LS 7	2012	0.00	1.52	9.40	15.58	18.31	12.69	11.45
LS L1	1986	0.00	3.21	6.01	9.99	13.95	12.77	10.16
LS U1	2007	0.00	3.06	2.78	4.61	9.55	14.53	19.10
LS W1	2027	0.00	2.66	4.47	5.55	9.06	12.13	7.56
Averages			4.52	6.62	9.05	11.58	11.29	10.59
Muskeg								
MC_1a	1983	0.00	7.67	7.19	13.71	12.62	8.41	12.92
MC_2a	1981	0.00	10.50	12.76	10.57	10.84	7.54	7.22
MC_3a	1982	0.00	11.66	7.84	17.31	14.51	9.73	7.19
MC_4a	1986	0.00	12.08	8.92	9.85	11.82	9.74	5.99
MC_5a	1986	0.00	4.81	3.81	6.87	8.05	6.38	5.11
MC_6a	2007	0.00	10.60	10.30	6.79	4.66	6.20	5.43
MC_8a	1998	0.00	2.36	1.84	2.72	2.92	2.09	3.73
MU_1a	2007	0.00	3.08	7.59	6.87	5.00	6.55	7.54
MU_1b	2010	0.00	2.87	4.64	4.05	3.99	5.65	5.73
MU_1c	1980	0.00	0.27	0.12	6.89	7.24	7.59	6.57
MU_2	1985	0.00	2.92	2.61	3.91	6.17	7.90	7.97
MU_3	2002	0.00	1.09	2.27	3.61	2.48	2.24	3.55
MU_4	2018	0.00	4.64	5.40	3.83	3.92	6.96	10.80
MU_5	1974	0.00	0.22	0.10	0.07	1.33	4.50	3.49
Averages			5.34	5.39	6.93	6.83	6.53	6.66
Upper Simonette								
USI_30	1983	0.00	9.24	12.22	11.89	14.69	11.66	8.21
USI_0	1988	0.00	5.99	5.47	5.86	6.41	4.48	3.53
USI_1	1983	0.00	16.61	17.35	17.04	19.43	14.78	10.45
USI_2	1985	0.00	12.25	10.83	16.26	19.98	16.02	10.89
USI_3	1989	0.00	10.99	10.96	13.71	14.90	11.13	8.18
Averages			11.02	11.37	12.95	15.08	11.61	8.25
Smoky								
Sm1	1986	0.00	0.01	5.52	9.89	10.35	6.58	5.31
Sm2	1981	0.00	12.87	15.18	14.06	14.55	10.52	8.19
Sm3	1981	0.00	3.90	5.92	6.29	5.62	4.17	3.79
Sm4	2007	0.00	0.61	3.81	3.50	2.46	2.91	4.07
Averages			4.35	7.61	8.44	8.25	6.05	5.34

Percent hydrologic recovery was estimated by comparing decadal water yield increases at year 60 (Q_{60}) to the annual maximum water yield increase (Q_{max}) (Table 10). Average percent hydrologic recovery for all watersheds at the start of the 6th decade was 63% with maximum and minimum values of 97% and 29%. Hydrologic recovery in about half of the watersheds was ≥ 60% (Figure 21). To achieve complete recovery on all watersheds, decadal water yield increases > 60 years would be needed. Water yield increases in the 6th decade averaged ~ 8.1% (Table 8).

Table 12 Comparison of annual maximum increase (Q_{max}) in water yield to decadal water yield increase (Q_{60}) to estimate % hydrologic recovery.

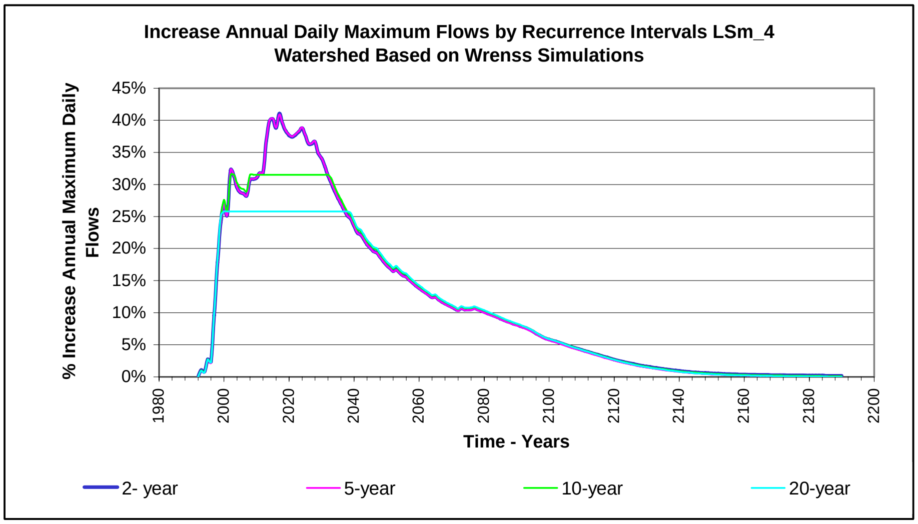
Watershed	Q_{max}	Q_{60}	Q_{max}-Q_{60}	(Q_{max}-Q_{60})/Q_{max}	% Hydrologic Recovery 1-(Q_{max}-Q_{60})/Q_{max}
LS 1	11.2	10.87	0.33	2.9%	97.1%
LS 1a	12.8	12.42	0.38	2.97%	97.0%
LS 1b	12.9	9.68	3.22	25.0%	75.0%
LS 2	14.8	8.86	5.94	40.1%	59.9%
LS 3	15.6	7.9	7.7	49.4%	50.6%
LS 4	24.5	9.68	14.82	60.5%	39.5%
LS 5	7.1	4.93	2.17	30.6%	69.4%
LS 6	15.2	14.41	0.79	5.2%	94.8%
LS 7	18.5	11.45	7.05	38.1%	61.9%
LS L1	14.5	10.16	4.34	29.9%	70.1%
LS U1	21.1	19.1	2	9.5%	90.5%
LS W1	12.4	7.56	4.84	39.0%	61.0%
MC_1a	18.5	12.92	5.58	30.2%	69.8%
MC_2a	14	7.22	6.78	48.4%	51.6%
MC_3a	17.3	7.19	10.11	58.4%	41.6%
MC_4a	20.8	5.99	14.81	71.2%	28.8%
MC_5a	9.5	5.11	4.39	46.2%	53.8%
MC_6a	15.8	5.43	10.37	65.6%	34.4%
MC_8a	10.5	3.73	6.77	64.5%	35.5%
MU_1a	8.1	7.54	0.56	6.9%	93.1%
MU_1b	7.2	5.73	1.47	20.4%	79.6%
MU_1c	10.0	6.57	3.43	34.3%	65.7%
MU_2	9.2	7.97	1.23	13.4%	86.6%
MU_3	8.7	3.55	5.15	59.2%	40.8%
MU_4	11.3	10.8	0.5	4.4%	95.6%
MU_5	6.4	3.49	2.91	45.5%	54.5%
USI_30	14.7	8.21	6.49	44.1%	55.9%
USI_0	7	3.53	3.47	49.6%	50.4%
USI_1	19.9	10.45	9.45	47.5%	52.5%
USI_2	20.5	10.89	9.61	46.9%	53.1%
USI_3	16.2	8.18	8.02	49.5%	50.5%
Sm1	11.1	5.31	5.79	52.2%	47.8%
Sm2	16.7	8.19	8.51	51.0%	49.0%
Sm3	7.2	3.79	3.41	47.4%	52.6%
Sm4	4.4	4.07	0.33	7.5%	92.5%

Figure 22 Hydrologic recovery of watersheds at the start of the 6th decade in FMU E8.



Hydrologic recovery of annual maximum daily flows paralleled that of water yield. This occurs because the same assumptions and function used for recovery of water yields in Wrenss are also applied to increases in peak flows. All watersheds showed similar patterns of recovery. The only exception was in some watersheds for recurrence intervals > 10 years where responses were constrained by the daily maximum evapotranspiration rate, which is assumed to represent the maximum amount of extra water added to peak flows as a result of forest harvesting. In these situations peak flow increases are held constant until recovery is less than the maximum daily evapotranspiration rate (Figure 22).

Figure 23 Example of increases in annual maximum daily flows for the 10 and 20 year recurrence interval events constrained by maximum daily rate of evapotranspiration.



Discussion

Water Yield

Assessing the significance of water yield responses to forest harvesting is difficult because of the variability in streamflow and precipitation at local, regional and global scales. The high variability of water yield among watersheds in the Grande Cache region and the absence of a historical flow records for small to medium sized watersheds (< 100 km^2) and an incomplete understanding of the effects of increased water yield and peak flows on aquatic systems makes it difficult to identify specific limits to manage or control the hydrologic effects of forest harvesting.

This is not a condition unique to Alberta. Bosch and Hewlett (1982) in a global review of water yield studies (i.e. pair basins studies) concluded that: reducing forest cover increases water yield, regeneration or afforestation decreases water yield and response to treatment (i.e. harvesting) is highly variable and unpredictable. Bosch and Hewlett inferred that coniferous forests, deciduous forests, grass and brush cover have a decreasing influence on water yield. A 10% reduction in vegetative cover caused ~ 40mm increase in annual water yield for coniferous forests, 25 mm for deciduous forests and 10 mm for brush or grass cover. Stednick (1996) in a more recent review confirmed Bosch and Hewlett's observations, and reports an increase of 28 mm for each 10% harvested in a watershed for U.S. studies.

Hetherington's review of Canadian studies (1987) noted that water yield increases were less than those reported elsewhere. Water yield responses in Canadian studies suggest a 15 mm response for each 10% of harvesting in watersheds. Simulated water yield responses cited in this report averaged ~ 5mm per 10% of watershed harvested. It should be noted that watersheds in paired basin studies are small (< 4-5 km^2) and often clearcut to test for maximum effect on water yield compared to larger basins scheduled for commercial harvesting.

Bosch and Hewlett (1982) also concluded that water yield responses from reductions less than 20% forest cover removal could not be measured (i.e. detected) by the paired basin approach. This is caused by a statistical limitation of the analytical technique. It does not mean that water yield changes do not occur at harvest levels less than 20% of watershed area. Stednick's update indicated thresholds for water yield changes could vary from 15-45% between the hydrologic regions (Table 11) defined in Wrenss.

Table 13 Regression statistics taken from Stednick (1996) for annual water yield increase versus percent harvest for all studies by (Wrenss) hydrologic regions. (Regression model used was y=b(x), curve forced to zero intercept. Regions with no results were those with no paired basin studies or too few to fit a regression model).

Wrenss Hydrologic Regions	Number	Sample Size (n)	Slope *(of regression curve)*	R^2	SE	p value	Threshold for Response	Water Yield with each 10% harvest
All Studies	--	95	2.46	0.17	149	0.0001	20%	28 mm
New England.Lake States	1	3	-	-	-	-	-	
Appalachain Mountains and Highlands	2	29	2.78	0.65	75	0.0001	20%	na
Eastern Coastal Plain and Piedmont	3	7	1.84	0.02	97	0.0051	45%	18 mm
Rocky Mountain Inland Intermountian	4	35	0.94	0.01	66	0.0001	15%	na
Pacific Coast	5	12	4.40	0.65	118	0.001	25%	50mm
Continental/Maritime	6	0	-	-	-	-	-	na
Central Sierra Province	7	2	-	-	-	-	-	na
Central Plains	8	7	6.15	0.31	197	0.0009	50%	na

The magnitude of simulated water yield increases (area mm) For FMU E8 watersheds fell within the range of results reported for basin studies in Alberta. Water yield increases observed in the Hinton-Edson region and at Marmot Creek basin range from 17-42 mm (Swanson et al 1986, Swanson and Hillman 1977) compared to 10-47 mm obtained with Wrenss in this assessment. The average watershed area harvested in the Alberta studies ranged from 20-54%.

The simulated water yield increases in this assessment were judged to fall within the range of "natural variability" for the Grande Cache-Grande Prairie region (Watertight Solution 2005). Natural variability was defined to be the long term average water yield ± 2 standard deviations. Once defined for a watershed, this limit was incrementally scaled downwards in multiples of its standard deviation (std increments (0.2, 0.33 0.5, 1.0) to identify water yields with recurrence intervals ≤ 5 years. This was done for 18 gauged watersheds with 10-30 years of record in the Grande Cache-Grande Prairie region. Variability of water yields by recurrence intervals was expressed as a "coefficient of variation" (*std-increment/$\bar{x}$)* (Table 12). Water yields with recurrence intervals of 5 years or less were judged to be susceptible to change from timber harvesting

Assessed by this approach simulated water yield increases for 34 out of 35 watersheds in the FMU fell within regional the limits defined by "natural variability" (*std increments*). The underlying premise is that increases to water flows within the range of "natural variability" were not expected to cause permanent change to the hydrology of a watershed, with the condition that watershed recovery occurs in a timely manner (i.e. prompt forest regeneration and stream channel/riparian protection).

Table 14 Variability (STD/$\bar{X}$) of annual water yield for the Grande Cache-Grande Prairie region (Watertight Solutions 2005).

	Variability of Water Yield			
Watersheds	**1.0 * Std/$\bar{X}$**	**0.5 * Std/$\bar{X}$**	**0.3 * Std/$\bar{X}$**	**0.2 * Std/$\bar{X}$**
Simonette River near Goodwin	35.7	17.8	11.8	8.9
Smoky River - Hells Gate	13.6	6.8	4.5	3.4
Kakwa near Grande Prairie	29.1	14.6	9.6	7.3
Wapiti River near Grande Prairie	29.9	15.0	9.9	7.5
Red Willow near Beaverlodge	55.8	27.9	18.4	14.0
Cutbank River near Grande Prairie	36.7	18.3	12.1	9.2
Muskeg River near Grande Cache	35.1	17.6	11.6	8.8
Deep Valley near Valley View	35.0	17.5	11.6	8.8
Saddle River near Woking	69.0	34.5	22.8	17.2
Pinto Creek near Grande Prairie	50.7	25.4	16.7	12.7
Grande Prairie Creek Sexsmith	72.4	36.2	23.9	18.1
Spring Creek near Valleyview	67.6	33.8	22.3	16.9
Little Berland near Grande Cache	39.0	19.5	12.9	9.8
Upper Spring Creek near Valleyview	63.8	31.9	21.0	15.9
Bridlebit near Valleyview	66.8	33.4	22.1	16.7
Rocky Creek	71.3	35.6	23.5	17.8
Wolverine Creek near Valleyview	49.1	24.6	16.3	12.3
Horse Creek near Valleyview	58.6	29.3	19.3	14.7
Regional Water Yield Variability	**47.2**	**23.6**	**15.6**	**11.8**
Average Recurrence Interval	**6.7**	**4.19**	**3.7**	**3.4**

Table 15 Variability (STD/x̄) of maximum annual daily flows for the Grande Cache-Grande Prairie region (Watertight Solutions 2005).

	Variability of Maximum Annual Daily Flows			
Watersheds	**1.0 * Std/x̄**	**0.5 * Std/x̄**	**0.3 * Std/x̄**	**0.2 * Std/x̄**
Simonette River near Goodwin	112.6	56.3	37.2	22.5
Smoky River - Hells Gate	41.2	20.6	13.6	8.2
Kakwa near Grande Prairie	93.9	47.0	31.0	18.8
Wapiti River near Grande Prairie	91.8	45.9	30.3	18.4
Red Willow near Beaverlodge	177.6	88.8	58.6	35.5
Cutbank River near Grande Prairie	94.9	47.4	31.3	19.0
Muskeg River near Grande Cache	87.3	43.7	28.8	17.5
Deep Valley near Valley View	90.8	45.4	30.0	18.2
Saddle River near Woking	159.4	79.7	52.6	31.9
Pinto Creek near Grande Prairie	105.7	52.8	34.9	21.1
Grande Prairie Creek Sexsmith	115.9	57.9	38.2	23.2
Spring Creek near Valleyview	69.8	34.9	23.0	14.0
Little Berland near Grande Cashe	68.7	34.3	22.7	13.7
Upper Spring Creek near Valleyview	69.1	34.5	22.8	13.8
Bridlebit near Valleyview	73.2	36.6	24.1	14.6
Rocky Creek	73.0	36.5	24.1	14.6
Wolverine Creek near Valleyview	91.4	45.7	30.2	18.3
Horse Creek near Valleyview	62.0	31.0	20.5	12.4
Regional Peak Flow Variability	**93.2**	**46.6**	**30.8**	**18.6**
Average Recurrence Intervals	**8.7**	**5**	**4.3**	**4.1**

Peak Flows

Simulated peak flow increases in FMU E8 were also considered to fall within the range of natural variability for the region. Analysis of maximum daily flows was similar to that done for water yields. Results indicate that the range of natural variability for annual maximum daily flows was 14-40% in the Grande Cache-Grande Prairie region (x̄+ 14-46%) (Table 13). Average recurrence intervals for values within this range varied from 4.1-5 years.

Recent literature suggests that sustained increases of ≥ 50% in bankfull[18] discharge, which is defined equivalent to the 1.5-2 year recurrence interval events, can contribute to permanent changes in stream channel morphology and aquatic habitat (Guillemette et al 2005; Verry 2004). Such changes are slow to develop and are usually expressed by widening, deepening and loss of sinuosity in stream channels along with attendant changes in aquatic habitat. The average increase in 2-year events simulated in this report for all watersheds was ~ 20%, with maximum and minimum values of 42% and 6%.

The hydrologic recovery of peak flows is determined primarily by how fast forest cover is re-established, with its attendant effects on evapotranspiration and soil water storage dynamics in a watershed. Regression analyses of water yield and peak flow responses to watershed disturbance (e.g.

---

[18] Bankfull discharge is the flow that coincides occurs when a stream channel is filled to capacity, to the top of its streambank.

area harvested, % ECA, and hydrologic recovery) suggested a significant levels of correlation between these variables. These analyses however are biased because of strong co-variation between Wrenss outputs (i.e. not statistically independent). Sets of independent variables will be needed to develop predictive models independent of Wrenss outputs.

ECA and Hydrologic Recovery

The ECA concept was initially proposed as an index to limit watershed disturbance. It was developed to assess the potential of timber harvesting to alter stream channel morphology (i.e. aquatic habitat). The underlying assumptions of the model were that changes in channel morphology and sediment discharge were a function of increased peak flows and water yield caused by the reduction of evapotranspiration (i.e. timber harvesting), and that water yield increases were proportional to the area harvested in a watershed.

ECA is widely used as an index or measure of watershed disturbance with respect to water and other resource values (e.g. roads, mining, agriculture, recreation, urbanization, wildlife and aquatic habitat). Values of 15-20% are considered to be indicative of low levels of disturbance and used as guides in management decisions. In most cases ECA values are not linked to water yield increases (or other resource responses) which makes them qualitative subjective indexes of questionable utility.

To be a useful and effective management tool ECA should be tested and validated by comparing predictions with measured values. ECA values should be linked in some way to water yield responses. Early testing of the ECA as a predictor of water yield (Belt 1980, King 1989) indicated a 38-44% underestimate. Validation of the method by monitoring is not likely because of the cost and time involved. A possible short cut would be to use research results from past paired basin studies to test and link ECA values to water yield increases if the data were readily available.

Regression analyses were used in this report to link water yield increases and % watershed ECA. Regression of maximum percent increase in water yield on maximum % watershed ECA was significant with an R^2 of 0.62 (Figure 23). The scatter of observations about the curve was attributed to differences in extent and timing of harvesting. Regression of volumetric water yield increase (mm) on ECA (Figure 24) gave a strong fit of observations to the curve with a R^2 of 0.97. The strong fit is partly caused by lack of independence between the two variables, as %ECA is based on the recovery water of yield (i.e. reduction coefficient for ECA = $[\Delta Q_n/Q_{max}]$).

The two regression analyses show a significant relationship between watershed ECA and water yield increase. ECA values corresponded to water yield increases of 15-25% (Figure 23) and 22-37% (Figure 24). These results suggest that ECA can be an effective measure of watershed disturbance and water yield responses to timber harvesting, especially if further work is done to validate the model. This could be done by monitoring, analysis of historic data (e.g. paired basin studies) or adoption of a model(s) to use as a standard for watershed assessments. The last option does not address the issue of validation but would provide a standard for assessments.

Figure 24 Regression of % increases in water yield on % watershed ECA for watersheds in FMU E8, based on Wrenss simulations.

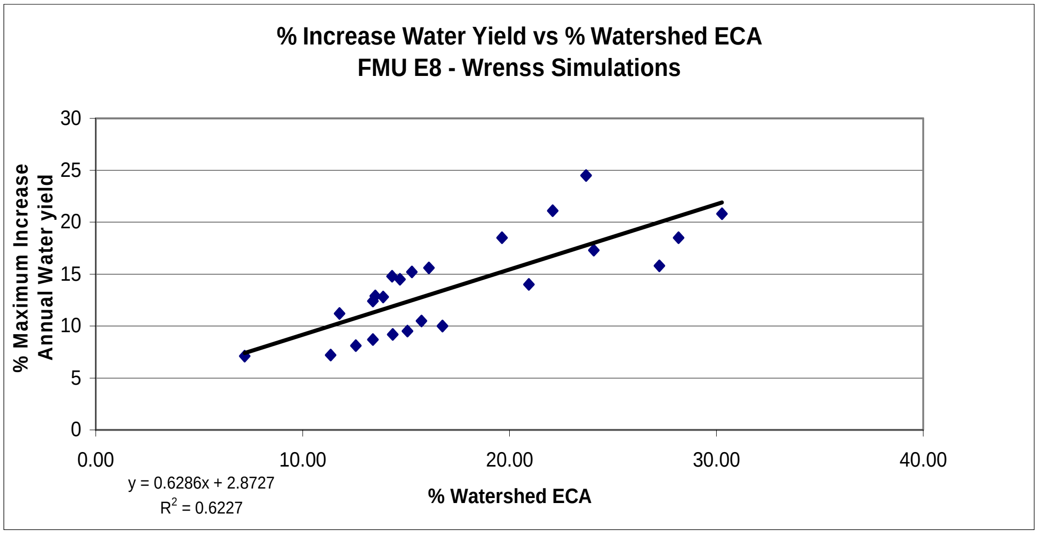
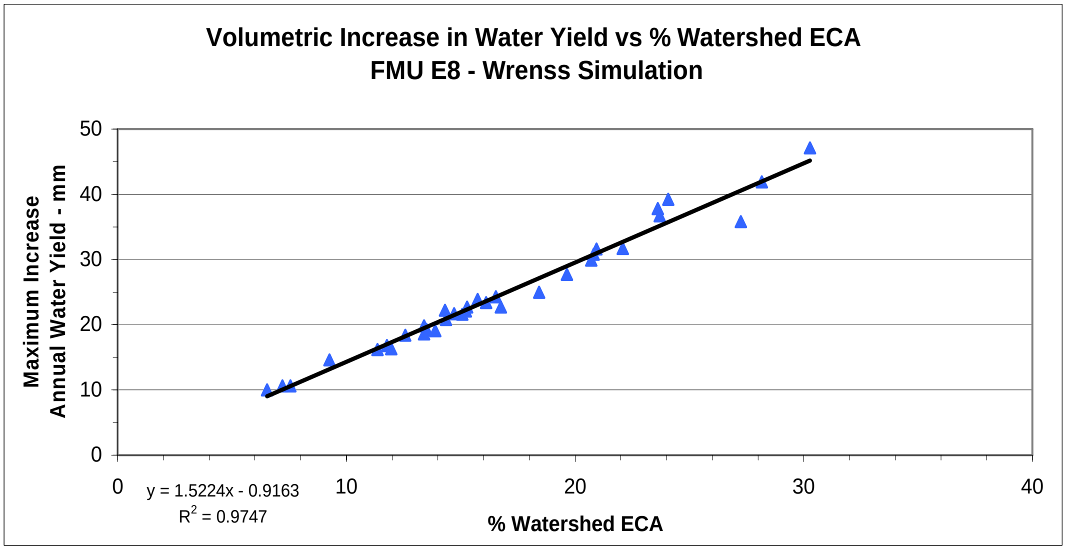


Figure 25 Regression of volumetric increases in water yield on % watershed ECA for watersheds in FMU E8, based on Wrenss simulations.



Hydrologic recovery of water yield and peak flows for watersheds in FMU E8 ranged from 30-119 years. The wide range in hydrologic recovery is largely a function of the timing and extent of harvesting in watersheds. Constant or frequent harvesting in a watershed will delay hydrologic recovery. This was most evident in the Simonette watersheds with a history of harvesting prior to the proposed spatial harvest plan. If a return to hydrologic recovery was a management objective, harvesting should be concentrated into a single watershed entry followed by a period of no harvesting. This would results in harvest blocks of similar age resulting in earlier recovery

Watershed recovery in the Wrenss model is driven by water yield increases (i.e. change in generated runoff) and the rate of evapotranspiration (i.e. recovery of basal area or leaf surface area) following harvesting. The approach taken in Wrenss has merit in that water yield increases and recovery are linked to the regeneration of forest cover (i.e. evapotranspiration). However, improvement in describing and making these linkages and others is needed to provide more reliable estimates.

For example, basal area in Wrenss is a conservative surrogate for the recovery of evapotranspiration (i.e. leaf surface area). As noted earlier maximum leaf surface area peaks earlier than basal area and is significantly correlated with annual volume increment at the stand level. Annual volume increment as a surrogate for leaf surface area is expected to provide better estimates of hydrologic recovery. (Silins 2000; Brabender 2005). Development of Alberta based estimates for evapotranspiration and upgrading growth and yield data in Wrenss would also improve its reliability.

The values for hydrologic recovery in this assessment are rough approximations of the net effects of a complex set of bio-physical watershed processes. Stednick (1996) comments that the definition of hydrologic recovery as the return of water yield to pre-disturbance as a simplistic approach that ignores streamflow generation processes and routing mechanisms in a watershed and landscape levels. Hydrologic recovery should include the return of peak flows, low flows, and hydrologic pathways of nutrient transport. Long term monitoring and research will be necessary to fully define these watershed responses and their effect on hydrologic recovery.

Summary and Conclusions

The Wrenss model was used to simulate the hydrologic effects of forest harvesting in FMU E8 located near the town of Grande Cache. Alberta Sustainable Resource Development designed the spatial harvest plan for the FMU and the Forestry Corp prepared input files for Wrenss simulations. A hydrologic land base was prepared for the FMU from which 35 watersheds were identified for simulation. The watersheds varied in size from 7.7-483 km^2, with an average watershed area of 96 km^2.

The spatial harvest plan was for 70 years (2008-2078). Wrenss simulations were done for 200 years and included historical (1985-2007) and planned harvesting to fully capture the effects of harvesting on water flows. The average area harvested in watersheds in the FMU was 51% with minimum and maximum values of 20% and 100%. Dominant forest species in the FMU were lodgepole pine and white and black spruce.

Simulated increases in water yield in the FMU averaged 13.3%, with minimum and maximum values of 4.4% and 25%. Increases within the FMU were greatest in the Little Smoky and Simonette watersheds with a range of 14.8-24.5%. Increases in the Muskeg and Smoky watersheds were less with values ranging from 13.6-16.7%. Volumetric increases in water yield among the watershed varied from 10-39 mm. About half of the watersheds had water yield increases (14.5-24.5%) that were significantly greater than the long term means of their representative watersheds. These increases however still fell within the range of natural variability for the region.

Water yield responses were largely determined by the amount and timing of harvesting in watersheds. Water yield increased with the extent of harvesting. Water yield increases expressed as percent and area mm were significantly correlated with percent watershed area harvested with R^2 values of 0.46 and 0.69 respectively. Maximum increases in water yield coincided with periods of heavy and/or frequent harvesting in watersheds.

Simulated increases in annual maximum daily flows in the FMU averaged from 19.7% for the 2-year events to 9.1% for the 100-year events. Peak flow increases followed a decreasing trend as recurrence intervals increased. Peak flow responses among the major drainages were variable with the lowest in the Muskeg watersheds and greatest in the Little Smoky watersheds, where annual water yield is low and topography relatively flat.

The largest increases in annual maximum daily flows were the 2 year events with values ranging from 6.8-41%. Peak flow increases for the 2-year events were significantly correlated with maximum percent ECA. The R^2 value for the regression analysis was 0.67.

An increase in the frequency of annual maximum daily flows among the watersheds varied from 6-8.7% for 2 year events to less than 1% for the 100 year events. The average shift or change in recurrence intervals from less frequent to more frequent with increased for the 2, 5, and 10 years events were 2.36 →2.0, 8.81→5.0 and 19.6 →10 years.

Maximum percent watershed ECA, a measure of hydrologic disturbance, ranged from 6.5% to 30% with an overall average of 16% for all watersheds. Hydrologic recovery for watersheds in the FMU varied from 30-119 years. The magnitude of hydrologic recovery was a function of the amount and timing of harvesting in watersheds. Sustained or frequent harvesting delayed the time for recovery of water yields to pre-disturbance conditions. An analysis of decadal water yield increases showed an increasing trend for years 10-40 followed by a steady decrease to year 60. Water yield increases in year 60 averaged 8.1%, which was equivalent to an average recovery rate of 63% for the FMU.

In conclusion increases in water yield and peak flows were considered to fall within the range of natural variability in the Grande Cache – Grande Prairie region. Natural variability was defined as the long term water yield or annual maximum daily flow plus 0.2-1.0 of it standard deviation [e.g. ($\bar{x}$ + 0.5 std)/ $\bar{x}$]. Average variability for water yield in the region varied from 11.8- 47.2%. Simulated water yield increases for all watersheds varied from 4% -24%. Average variability for annual maximum daily flows in the region varied from 18.6% to 93.2%. Average increases in the 2 and 5-year events varied from 6.8-41.7% and 6.9-39%.

The level of watershed disturbance in terms of % ECA varied from low to moderate (6.5-30%). No definitive ECA values for acceptable levels of disturbance were found in the literature. ECA values of 15-20% were considered indicative of low disturbance or used as management objectives. In this assessment 8 watersheds had ECA values ranging from 22-30.7%. Percent harvesting in these watersheds ranged from 56-100%, which was not that different from other watersheds with lower ECA values. Changes in harvest scheduling in these watersheds probably would reduce ECA values to less than 20%.

Estimates of hydrologic recovery ranged from relatively short to long. Long times to recovery were the product of sustained or constant harvesting combined with prior historical harvesting that maintained water yield increases and delayed recovery. The levels of harvesting in some watersheds were higher than encountered in previous assessments. However, no long lasting changes to streamflow, stream channel morphology, aquatic habitats or water quality are expected to result from the proposed spatial harvest.

Literature Cited

Ager Alan A, Clifton Caty. 2005. Software for calculating vegetation disturbance and recovery by using the equivalent clearcut area model. Gen. Tech. Rep. PNW-GTR-637. Portland Oregon, USDS USFS, NNW Forest and Range Experiment Station.

Belt, G.H. 1980. Predicting streamflow changes caused by forest practices

Bosch J. M. and Hewlett, J. d. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrology., 55: 3-23.

Bradender B. 2005. Scaling leaf area index and rainfall interception in Lodgepole pine. MSc thesis, University of Alberta.

Environment Canada 2007. Hydat CD-ROM Hydrometric Data Base. http://www.wsc.ec.gc.ca/productts/main_e.cfm?cname=products_e.cfm.

Environment Canada. 2007. CD-ROM Meteorological Data for Western Canada. http://www.wsc.ec.gc.ca/productts/main_e.cfm?cname=products_e.cfm

Environmental Protection Agency (EPA), 1980. An approach to water resources evaluation of non-point silvicultural sources. (A Procedural Handbook). EPA and Forest Service, EPA-600/80-12.

Guillemette R. A. P. Plamondon, M. Prevost, D. Levesque. 2005. Rainfall generated stormflow response to clearcutting a boreal forest: peak flow comparison fifth 50 world-wide basin studies. J. Hydrology 302(2005) pp 137-153.

Hetherington E. d. 1987. The importance of forests in the hydrological regime. In: M.D. Healy and R. R. Wallace (Editors), Canadian Bulletin Fisheries and Aquatic Sciences, Ottawa, Ont. No. 215, 533 pp.

King, J.G. 1989. Streamflow responses to road building and harvesting a comparison with the equivalent clearcut area procedure**.** Res.Paper INT-401. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 13 p.

Lieffers V,. J., Pinno B. D., Stadt K. J. 2002. Light dynamics and free-to-grown standards in aspen dominated mixedwood forest. Forestry Chronicle. Vol. 78 No. 1, 137-145.

Stednick J. D. 1996. Monitoring the effects of timer harvest on annual water yield. J. of Hydrology 176(1996) 79-95.

Silins U. 2000. ECA-Alberta Cumulative Watershed disturbance and hydrologic recovery simulator. Dept. Renewable Resources. 751 GSB, University of Alberta, Edmonton, Canada T6G2H1 (uldis.silins@ualberta.ca.

Swanson R. H. 2000. WrnsSdr Users Manual. R. H. Swanson, Forest Hydrology Consultant. #28 216 Three Sisters Drive, Canmore, Alberta.

Swanson R. H., Golding D. L., Rothwell R. L. and Bernier P. Y. 1986. Hydrologic effects of clear-cutting at Marmot Creek and Streeter watersheds, **Alberta.** Can.For. Ser., North. For. Cent., Edmonton, Alberta, Inf. Rep NOR-X-278.

Swanson R. H., Hillman G. R. 1977. Predicted increased water yield after clear-cutting verified in west-central Alberta**.** Can. Dep. Fish. Environ., Can. For. Serv., North. For. Res Cent,. Edmonton, Alberta. Inf. Rep NOR-X_198.

Swanson R. H., Hillman G. R. 1977. Predicted Increased Water Yield after Clearcutting verified in West Central Alberta. Northern Forest Research Centr, Edmonton, Alberta using the equivalent clearcut area model**.** Publ. no. 32. Moscow: University of Idaho Forest, Wildlife and Range Experiment Station; 11 p.

Verry E.S. 2004. Land fragmentation and impacts to streams and fish in the Central and Upper Midwest. In: A Century of Forest and Wildland Watershed Lessons, Eds G. G. Ice and J. D. Stednick. Society of American Foresters pp 129-155.

Watertight Solutions Ltd 2005. Variability of Precipitation and Streamflow, Grande Cache-Grande Prairie and Discussion of Guidelines for Water Yield and Peak Flow Increases. Prepare by Watertight Solutions for Weyerhaeuser Canada, Grande Prairie. FRIP Report.