Hydrologic Effects of Proposed 20-Year Harvest (2006-2025) Manning Diversified Forest Products

Report Prepared for:
Manning Diversified Forests Products
Manning, Alberta

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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.

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Executive Summary

Hydrologic assessment of a proposed 20-year harvesting plan for Manning Diversified Forest Products (MDFP) forest management area (FMA) that includes strategies to manage for caribou habitat and minimize mountain pine beetle infestations was conducted with WRENSS to assess potential increases in annual water yield and annual maximum daily flows. A sample of 14 watersheds fully contained with the boundaries of the FMA was selected for analysis. The watersheds were 2nd the 4th order basins ranging in size from 18-724 km^2 in size. Percent area harvested in the watersheds varied from 3.3% to 45.5%. Harvesting occurred in tributaries to the Notikewin River and the Chinghaga River.

Long term average flows for the Notikewin and Chinchaga rivers were used as representative watersheds in the WRENSS simulations as a base to express percent changes in water yield and annual maximum daily flows. Annual and monthly precipitation data from Manning were used for input in the WRENSS. Simulations were run for a period of 150 years on an annual time step, starting in 2006.

The significance of changes in annual water yield and annual maximum daily flows was assessed based on the upper 95% confidence interval for mean annual flow of the two representative watersheds, and an analysis of 'natural variability" of flows in the Manning region using established hydrometric stations operated by Water Survey of Canada. Simulated increases in annual water yield, represented by the upper 95% confidence interval, less than 18% and 15% were considered acceptable respectively for basins tributary to the Notikewin and Chinchaga rivers. Water yield and peak flow increases, based on natural variability, less than 23% and 26% were respectively considered acceptable for annual water yield and annual maximum daily flows.

Increases in annual water yield ranged from 21% to 55% in small to medium sized (< 100 km^2) watersheds, where harvesting varied from 30% to 45% of watershed area. Simulated increases in larger watersheds (166 -724 km^2) were smaller ranging from 9.9% to 21%. Harvesting in these basins varied from 3% to 17.3% of watershed area.

The large increases in the small to medium size watersheds were attributed to the high levels of harvesting in a relatively short period of time. Harvest levels >30-40% of watershed area in small basins can be expected to generate large responses in water yield and peak flows. The increases in most of the small-medium watersheds exceeded levels considered "acceptable" based on long term average flow for the representative watersheds and natural flow variability for the region.

Simulated increases in the larger watershed were judged "acceptable". The increases in the larger watersheds were less because they are averaged over a larger area that contains a mix of uncut stands, older stands at some stage of hydrologic recovery and freshly cut stands that moderates the effects of harvesting.

Changes in peak flows followed a pattern similar to water yield. Increases were greatest in the small-medium watersheds with heavy levels of harvest and less in the larger watersheds. The largest increases in maximum daily flows occurred in the 2-yr to 5-yr recurrence interval events. Increases in the 2-yr events ranged from 41% to 111%, with the maximum event occurring on the smallest watershed where harvesting affected 45.5% of the basin. Increases for the 5-yr events were smaller ranging from 28.5% to 44.7%. Simulated increases for the 10-yr to 100 yr events were ranged from 6% - 20% and considered "acceptable". Peak flow increases in most of the small watersheds were sustained for periods of 30-15 years, which may have the potential to affect stream morphology and aquatic habitats of the longer term.

Hydrologic recovery of water yields and peak flows to pre-disturbance levels was of long duration, with values ranging from 53 to 107 years. The long periods for hydrologic recovery were a function of the large increases in water yield. Watersheds with the greatest increases in water yield and peak flow took the longest for recovery. Maximum percent equivalent clear area for the watersheds (i.e. a measure of disturbance) varied from values of 2.6% - 10.1% for the large watersheds and 9.5%-30.7% for the small watersheds.

The high increases in these simulations were attributed to the extent and pattern of harvesting in the small to medium sized watersheds. These changes can be managed by a reduction and rescheduling of harvesting. However, this may not be acceptable to MDFP as the proposed harvest schedule incorporates strategies to address a range of different resource issues such as caribou habitat management, biodiversity and mountain pine beetle infestations that require trade off in values and objectives. From a hydrological perspective the potential effects of widespread mountain pine beetle infestations are significant. Changes in water yield similar to those in these simulations or greater could occur if the stands were attacked and destroyed by mountain pine beetles (Love 1955; Troendle and Nankervis 2000; Uunill et al, 2006).

Hydrologic Effects of Proposed 20-Year Harvest (2006-2025) Manning Diversified Forest Products

Introduction

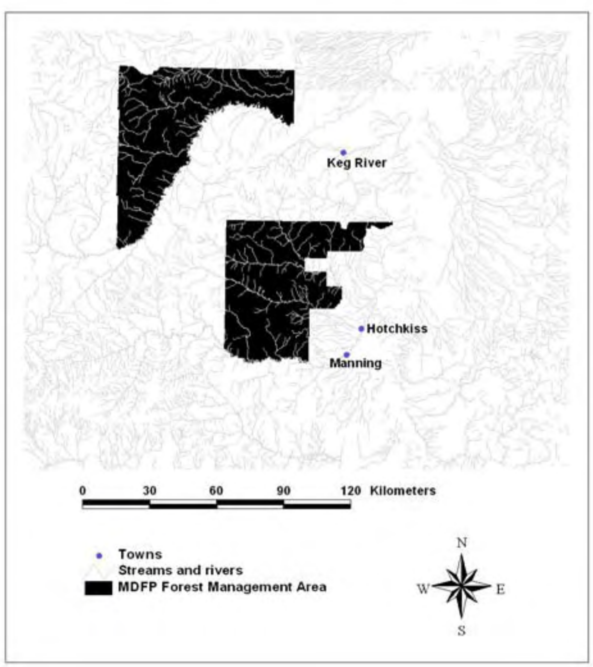
The objective of this report was to assess the hydrologic effects of a proposed 20-year harvest plan for Manning Diversified Forest Products (MDFP) forest management area. The assessment addresses the effects of forest harvesting on water yield, peak flows, the time of hydrologic recovery and equivalent clear-cut area (ECA).

MDFP's forest management area (FMA) is located northwest of Manning Alberta as two separate blocks, with one located in the Chinchaga River watershed and the other in Notekewin River watershed (Figure 1). Proposed harvesting is planned for 2006-2026, with the majority of harvesting occurring in the Notekewin Rivers watersheds. Forest cover in these watersheds includes pure to mixed stands of aspen (*Populus tremuloides*), white spruce (*Picea glauca*) and lodgepole pine (*Pinus contorta*) and poorly drained wetlands with black spruce (*Picea mariana*).

Hydrologic assessments were done for a sample of watersheds in the FMA ranging in size from small to medium (20- 80 km^2) to large watersheds (100-700 km^2). Steps followed were as follows:

1. Prepare a hydrologic land base for the Forest
2. Assemble and prepare harvest data for analysis
3. Assemble hydro-meteorological data
4. Run hydrologic simulations (WRENSS) of proposed harvesting
5. Analyze and report results

Figure 1 Location of Manning Diversified Forest Products forest management area.



Methods

Hydrologic Land Base

A hydrologic land base defines the number and extent of watersheds within the FMA. Hydrologic assessments are ideally done on a watershed basis, which includes all of the historical and proposed forest harvesting (i.e. disturbances) that can affect water flows. Assessments done on total watershed area includes the total, cumulative effects of all disturbances on water flows.

The hydrologic land base for MDFP's forest management area was developed by modifying a spatial coverage of watersheds provided by MDFP to include portions of watersheds that extended beyond the boundaries of the FMA. The hydrologic land base (Figure 2) showed that significant portions of most major watersheds were outside of the FMA. Hydrologic assessments for these watersheds would be compromised without information for land use activities outside of FMA boundaries. Water yield and peak flow responses to harvesting could be underestimated without information from outside areas.

To avoid the above problem, a sample of watersheds ranging in size from small to large, with a majority of their area within FMA boundaries were selected for analysis (Figure 3). (Is it possible, somewhere in the summary or elsewhere, to indicate that, for those watersheds not modeled, a relative indication of impacts could be derived by examining the % area harvested (if this was available for the watershed) and watershed size and comparing it to those watersheds that were assessed?) Most of the watersheds were 3^{rd} and 4^{th} order basins. A range of different sizes was selected to provide balance between watershed size and stream order. For a given stream order watershed size can be highly variable, especially in northern boreal forests characterized by gentle topography and low stream densities compared to foothill conditions. Furthermore, small to medium sized watersheds were included because the hydrologic effects of harvesting on them can be greater than on large watersheds. The reason for this is that a greater proportion of small watersheds can be harvested, spatially and/or temporally, than on large watersheds.

Harvest Data

Harvest data and scheduling used in these assessments was prepared 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 (Appendix 1).

Most of the proposed harvesting was located in the Notikewin River block of the forest management area. Ten watersheds in this block were selected for analysis. Percent of area harvested in the watersheds selected for assessment ranged from 11.6% to 45.5% (Table 1).

Four watersheds were selected in the Chinchaga River block, which only accounts for 20% or 4895 hectares scheduled for harvesting. Percent of area harvested in watersheds selected for assessment ranged from 3.30% to 31.3% (Table 1).

Figure 2 Hydrologic land base for Manning Diversified Forest Products forest management area.

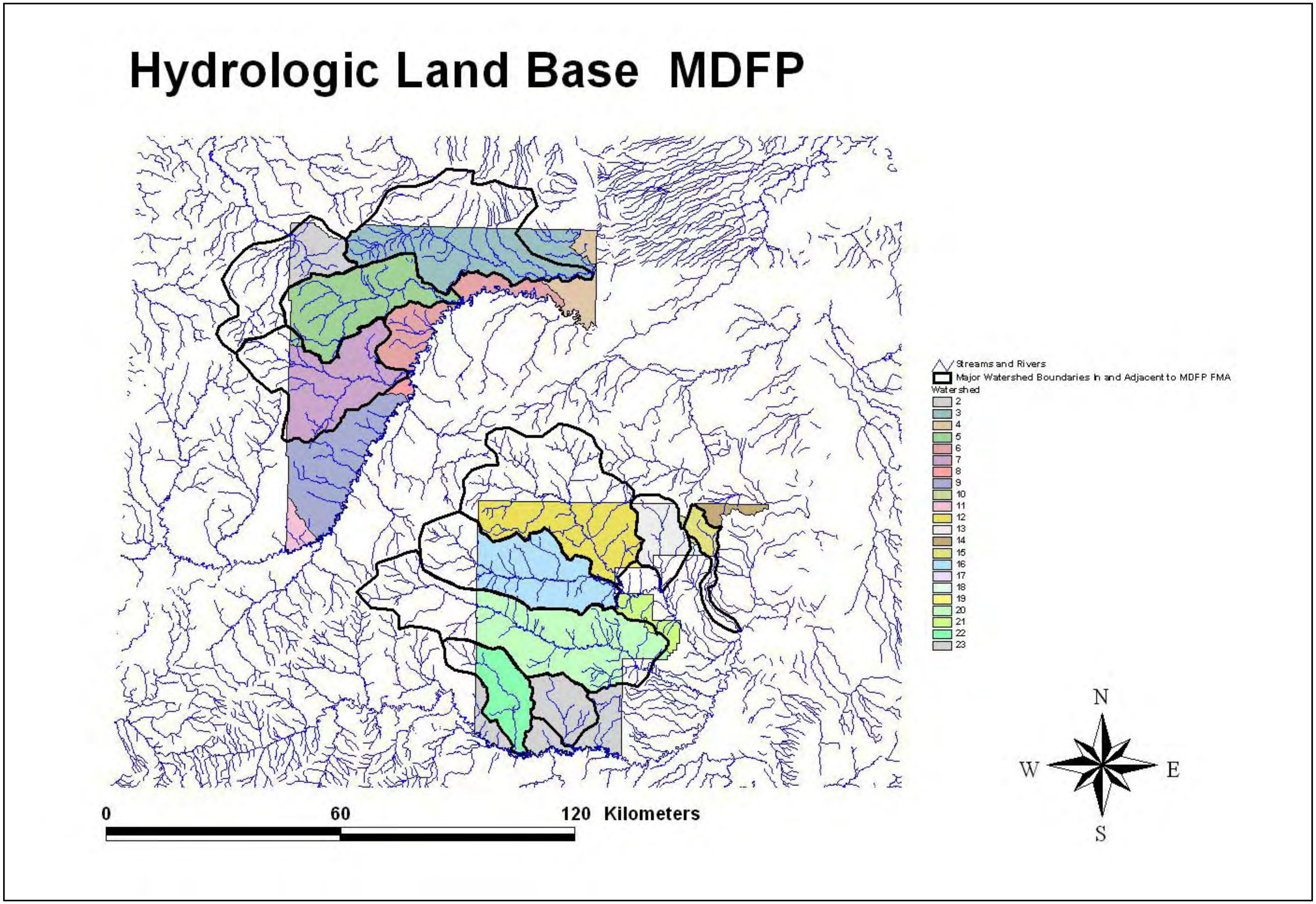
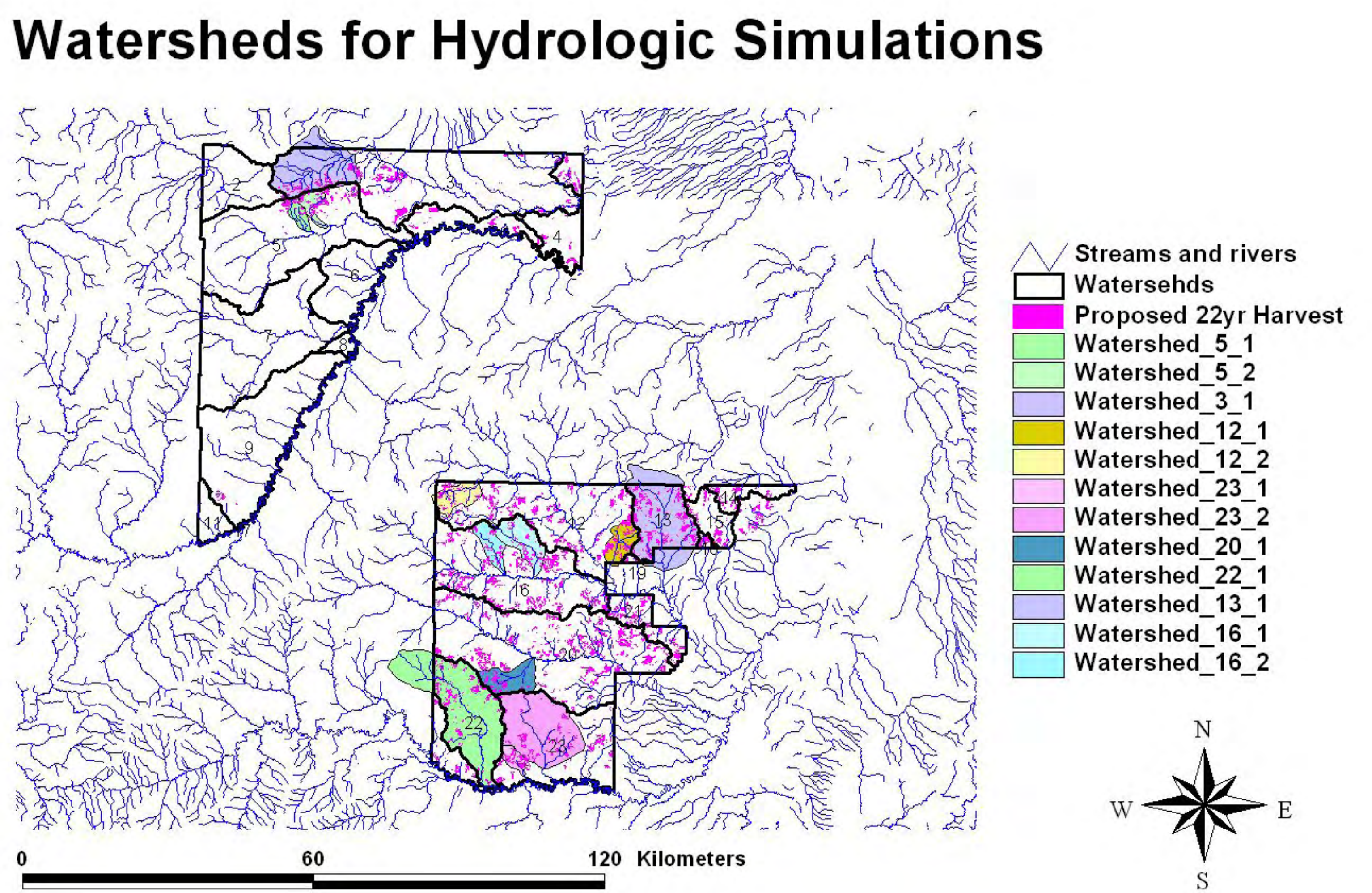


Figure 3 Watersheds selected for hydrologic assessment.



Hydro-Meteorological Data

Streamflow and precipitation data were downloaded from 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) which contains flow data for all of Canada. Most of the precipitation and hydrometric stations for forested regions in Alberta obtained from these sources are provided in WRENSS as "look up tables" that allow specific stations to be input into the program.

Table 1 Harvest levels and stream orders in watersheds scheduled for harvesting.

Watershed Name	Area km^2	Basin Order	Hectares Harvested	% Watershed Harvested
Chinchaga River Watersheds				
3_1	166.4	3rd	1357	9.3
5_1	19.82	2nd	195	15.1
5_2	27.58	3rd	721	31.3
5	573.0	4th	2622	3.3
Notikewin River Watersheds				
12_1	43.64	2nd	1121	17.6
12_2	43.38	3rd	554	19.5
13_1	231.28	3rd	3408	11.6
16_1	65.04	3rd	912	29.8
16_2	36.53	3rd	520	28.2
20_1	59.24	3rd	902	26.9
22_1	302.26	3rd	2307	11.7
23_1	18.31	2nd	567	45.5
23_2	198.2	4th	1419	15.8
16	724	4th	7805	17.3

Streamflow data for the Chinchaga and Notikewin rivers were used in hydrologic simulations (Table 2).These were two hydrometric stations in the region with long term data. Both watersheds are very large compared to those selected for hydrologic assessment. Streamflow data from watersheds of similar size to those assessed would be the ideal choice for simulations if available.

The average annual water yield for the Chinchaga and Notikewin rivers should be considered as "regional averages" because of their large watershed areas. Water yields from small watersheds in general are greater than those from large watersheds. The significance of this is that percent water yield increases from these simulations could be "overestimates". The average water yields for the Chinchaga and Notikewin rivers are used as base flows to calculate percent increases in water yield.

Table 2 Hydrometric stations used in WRENSS simulations

Watershed	Area km^2	Years of Record	Annual Water Yield mm		
			Avg	Max	Min
Chinchaga River	10,400	1970-1997	91.6	249.0	30.1
Notikewin River	4,680	1961-1998	95.7	227.1	34.0

Annual and monthly precipitation records are required for WRENSS. The closest weather stations to MDFP's forest management area with 12-months of precipitation were Manning and Keg River (Table 3). Closer stations (Chinchaga and Notikewin Lookouts) were only for 6 months (May-October).

Table 3 Annual precipitation at Manning, Chinchaga Lookout and Keg Lookout

Station	Years Record	Annual	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sept	Oct	Nov	Dec
Manning Elev. 491	1985 2003	465.9	32.3	22.5	19.7	20.1	37.3	72.3	83.8	43.4	38.3	24.6	45.6	26.1
Keg River Elev 407 m	1935 1980	412	22.7	20.4	21.7	18.1	39.7	58.8	63.5	58.5	40.8	22.6	27.5	26
Chinchaga Lookout Elev 762 m	1958 2003	m	m	m	m	11.2	44.5	79.3	89.2	59	35.6	20.5	m	m
Keg River Lookout Elev.	1935 1980	m	m	m	m	16.6	49.7	90.9	102	69.3	58.9	31.4	m	m
Notikewin Lookout Elev 762	1957-2003	m	m	m	m	19.1	50	83.5	100.7	66	40.8	21.4	m	m

Hydrologic Simulations

WRENSS

Simulations were done using WRENSS (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
- Hydrologic recovery
- Equivalent clear-cut area
- Increases in maximum annual daily flows and maximum annual instantaneous flows for 2, 5, 10, 20 50 and 100 year recurrence intervals

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 between harvested and unharvested conditions.

Increases in water yield in WRENSS are expressed as area-millimeters (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 (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 should be considered as relative changes (e.g. small, medium, and large). Few if any models are capable of providing exact, absolute outputs. 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.

Hydrologic recovery is an estimate of the time required for increased water yield to disappear with the growth or regeneration. Hydrologic recovery is estimated as a function of increasing basal area (or leaf area index) with regrowth of trees on harvest blocks. Recovery occurs when increased water yield approaches or equals pre-harvest levels. Hydrologic recovery for annual/seasonal flows and peak flows in this assessment was defined as the time required for the maximum increase in annual flow to decrease to levels equal to or less than 1%.

Equivalent Area Clearcut (ECA) is an index of hydrologic recovery. 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 as the area (hectares) harvested times a reduction factor that describes the recovery of evapotranspiration losses. ECA estimates in WRENSS are provided in terms of basal area recovery and recovery of water yield. ECA_Q based on water yield recovery was used in this assessment. It is 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.

WRENSS also estimates increases in maximum daily and instantaneous flows due to harvesting for return periods of 2, 5, 10, 20, 50 and 100-year events. WRENSS uses watershed area to estimate peak flows ($Q_{peak\text{-}area}$) for all return periods in the unharvested condition. The difference between the mean March to September streamflow in the unharvested and harvested condition is used to estimate the change in peak flow ($Q_{peak\ mean\ flow}$) caused by harvesting for each return period. The difference in $Q_{peak\ mean\ flow}$ between the harvested and unharvested conditions is added to $Q_{peak\text{-}area}$ to obtain the maximum flow for a given return period. (A more detailed description of WRENSS in provided in Appendix 1).

Simulations

Hydrologic simulations were done for 150 years (2006-2156-2087) for each watershed with a 1 year time step. Percent increases in water yield were determined using Chinghaga River and Notikewin River as representative watersheds (i.e. base yield). The hydrologic region used was the New England/Boreal. Peak flows equations were for the Grande Prairie region. Specific data requirements for WRENSS simulations are shown in Appendix 2. Defaults used in the WRENSS simulations are shown in Table 4 Watersheds selected for simulations and the extent of harvesting and basin order are described in Table 1

Table 4 Default options for WRENSS runs.

Option	Condition
Apply gauge snow catch corrections for wind	Yes
Allow sublimation loss from harvest blocks	Yes
Allow snow scouring in harvest blocks	Yes
Auto calibrate on watershed yield	Yes
Time step	1 year
Estimated water equivalent, mm of snow per day	5 mm
Precipitation lapse rate, mm per m of elevation	0.0
Number of year after first harvest to simulate	150
Number of days that the bulk of annual runoff occurs	214
Multiplier for estimating peak daily from average daily ET	2.10

Statistical Assessments

Increases in water yield and peak flows were assessed in two ways. The first was to compare increased water yields to those of nearby representative watersheds. The second was to compare water yield increases based on the "natural variability" of seasonal water yield and peak flows in the Grande Prairie-Grande Cache region.

Representative Watersheds

In this approach simulated increased water yields were compared to the long term mean annual/seasonal flows of nearby representative watersheds with 10 years or more of flow record. If a simulated increase in water yield exceeded the upper 95% confidence limit for the mean annual flow of its representative watershed it was considered to be a significant increase in water yield.

Statistically the ideal situation for evaluating water yield increases would be to have long term streamflow record for the watershed being assessed. This seldom occurs, other than on experimental watersheds. The approach adopted in WRENSS is based on the assumption that nearby watersheds of similar size, forest cover, topography and climatic regimens represent a reasonable benchmark upon which managers can evaluate potential changes in water yield.

The Chinchaga River and Notikewin River were used as representative watersheds in the WRENSS simulations. Confidence limits for mean water yield were calculated as: $0 \pm (t)\ (s_0)$ where $0 =$ mean water yield, t = t value and s_0 = standard error of the mean = $\sqrt{(s^2/n)}$. Confidence limits for each watershed were:

Chinchaga River ---- 91.6 mm ± (2.120 * 7.8360) = 16.612 mm ---- (16.61/91.6)*100 = 18.10%
Upper 95% confidence limit = 91.6 + 16.612 = 107.61 mm

Notikewin River ---- 95.7 mm ± (2.045 * 6.36) = 13.57 mm ----(13.57/95.7)*100 = 15.10%
Upper 95% confidence limit = 95.7 + 13.57 = 109.27 mm

Simulated water yield increases greater than 18% and 15% were considered significant for comparisons made with Chinchaga River and Notikewin River respectively. Significant increases in water yield were assumed to contribute to higher seasonal flows in affected watersheds.

Natural Variability

The second approach used the concept of "natural variability of water flows" (Watertight Solutions 2005) as an alternative to existing informal guidelines. Setting limits on increases in water yield caused by forest harvesting is difficult because changes in water yield are affected by climatic variation, silvicultural methods, extent of harvesting and the temporal and spatial distribution of harvesting.

In the absence of definitive information that identifies thresholds to minimize possible "negative" effects of increases in water yield and peak flows following forest harvesting, the idea of "natural variability of water flows" (Watertight Solutions 2005) was used. Natural variability" for a watershed was defined as the long-term mean water yield ± 2 standard deviations. "Acceptable" increases in water yield and peak flows were identified by systematically scaling "natural variability downwards (2x std dev, 1x std dev, 0.5x std….0.15x std dev) to focus on hydrologic events characterized by recurrence intervals of 2-5 years, which were considered susceptible to change by forest harvesting.

Tables 5 and 6 show the results of these analyses. "Acceptable" water yield increases for the Manning region based on available flow records range from ≤ 10% to 23%. "Acceptable increases in peak flows are larger because of their higher variability, ranging from ≤ 12% to 26%. Increases defined by this approach were relatively small amounting to an extra 5-12 mm for water yield and 0.6-2.04 m^3/sec for peak flows.

Table 5 Water yield increases based on "natural variability" for the Manning region. A = Water Yield. B = Recurrence intervals for water yield increases in A. Shaded portions of the table identify increases considered acceptable.

A

Watershed Name	Area km^2	Mean Annual Water Yield mm	% Increases in Water Yield based on "natural variability" (2 Std Dev/0)*100						
			2 Std Dev	1 Std Dev	0.5 Std Dev	0.33 Std Dev	0.25 Std Dev	0.20 Std Dev	0.15 Std Dev
Boyer River	94	30.0	177.59	88.79	44.40	29.30	22.20	17.76	13.32
Buchanan Creek	232	32.4	209.80	104.90	52.45	34.62	26.22	20.98	15.73
Chinchaga River	10400	89.4	102.26	51.13	25.57	16.87	12.78	10.23	7.67
Keg River	667	97.3	109.23	54.61	27.31	18.02	13.65	10.92	8.19
Montagneuse River	230	44.8	151.33	75.66	37.83	24.97	18.92	15.13	11.35
Notikewin River	4680	91.6	95.05	47.52	23.76	15.68	11.88	9.50	7.13
Whitemud River	2010	69.2	124.84	62.42	31.21	20.60	15.61	12.48	9.36
Regional Averages		**64.9**	**138.58**	**69.29**	**34.65**	**22.87**	**17.32**	**13.86**	**10.39**

B

Watershed Name	Area km^2	Mean Annual Water Yield mm	Recurrence Intervals (years) for % Increases in Water Yield based on natural variability						
			2 Std Dev	1 Std Dev	0.5 Std Dev	0.33 Std Dev	0.25 Std Dev	0.20 Std Dev	0.15 Std Dev
Boyer River	94	30.0	14.01	5.98	3.91	3.38	3.16	3.03	2.90
Buchanan Creek	232	32.4	13.36	5.81	3.83	3.32	3.11	2.98	2.86
Chinchaga River	10400	89.4	15.10	6.25	4.02	3.46	3.22	3.08	2.95
Keg River	667	97.3	15.56	6.34	4.04	3.47	3.23	3.09	2.95
Montagneuse River	230	44.8	14.22	6.04	3.94	3.40	3.18	3.05	2.92
Notikewin River	4680	91.6	15.62	6.38	4.08	3.50	3.26	3.12	2.98
Whitemud River	2010	69.2	14.61	6.14	3.98	3.43	3.20	3.07	2.94
Regional Averages		**64.9**	**14.64**	**6.13**	**3.97**	**3.43**	**3.19**	**3.06**	**2.93**

Table 6 Increases in annual maximum daily flows based on "natural variability" for the Manning region. A = Water Yield. B = Recurrence intervals for water yield increases in A. Shaded portions of the table identify increases considered acceptable.

A

Watershed Name	Area km^2	Mean Max Annual Peak Flow m^3/sec	% Increases in Annual Max Daily Flow based on "natural variability" (2 Std Dev/0)*100						
			2 Std Dev	1 Std Dev	0.5 Std Dev	0.33 Std Dev	0.25 Std Dev	0.20 Std Dev	0.15 Std Dev
Boyer River	94	3.9	199.39	99.70	49.85	32.90	24.92	19.94	14.95
Buchanan Creek	232	8.1	229.80	114.90	57.45	37.92	28.72	22.98	17.23
Chinchaga River	10400	336.4	108.90	54.45	27.23	17.97	13.61	10.89	8.17
Keg River	667	35.7	159.85	79.92	39.96	26.37	19.98	15.98	11.99
Montagneuse River	230	6.9	189.17	94.58	47.29	31.21	23.65	18.92	14.19
Notikewin River	4680	195.6	118.96	59.48	29.74	19.63	14.87	11.90	8.92
Whitemud River	2010	50.1	112.54	56.27	28.14	18.57	14.07	11.25	8.44
Regional Averages		**91.0**	**159.80**	**79.90**	**39.95**	**26.37**	**19.98**	**15.98**	**11.99**

B

Watershed Name	Area km^2	Mean Max Annual Peak Flow m^3/sec	Recurrence Intervals (years) for % Increases in Max Daily Annual Flows based on natural variability						
			2 Std Dev	1 Std Dev	0.5 Std Dev	0.33 Std Dev	0.25 Std Dev	0.20 Std Dev	0.15 Std Dev
Boyer River	94	3.9	13.97	5.97	3.91	3.38	3.16	3.03	2.90
Buchanan Creek	232	8.1	13.55	5.99	3.98	3.47	3.25	3.12	2.99
Chinchaga River	10400	336.4	14.82	6.19	4.00	3.45	3.21	3.08	2.94
Keg River	667	35.7	11.12	4.59	2.95	2.53	2.36	2.26	2.16
Montagneuse River	230	6.9	14.05	6.01	3.93	3.40	3.17	3.04	2.92
Notikewin River	4680	195.6	15.45	6.34	4.07	3.50	3.26	3.11	2.98
Whitemud River	2010	50.1	14.90	6.20	4.00	3.45	3.21	3.07	2.94
Regional Averages		**91.0**	**13.98**	**5.90**	**3.83**	**3.31**	**3.09**	**2.96**	**2.83**

Results

Water Yield

The largest increases in maximum annual water yield ranged from 21% to 55% in the small to medium sized watersheds (18-59 km^2). Harvest levels in all but two of these drainages varied from 30% to 45% of watershed area. Increases of these magnitudes were judged as significant or "unacceptable" (Table 7). Lower levels of harvesting in watersheds 5_1 and 12_1 (15.1% and 17.6%) resulted in water yield increases of 21% and 14.5% which were considered "acceptable". Water yield increases on the larger 3rd-4th order watersheds (166 – 720 km^2) were also "acceptable" ranging from 9.9% to 21%.

Water yield increases judged "acceptable" were those within the range of natural variability for annual water yield ($\leq$ 10% - 23%) for the Manning region (Table 5) or close the to the upper 95% confidence limit for mean flows of the representative watersheds. These two approaches were adopted as they are familiar statistical parameters that use real data to describe the variability of regional flows, which can be expected to vary between climatic zones in the province. Furthermore, the limits identified by these approaches target flow events with 2-5 year recurrence intervals that are considered susceptible to change by forest harvesting. Flow events of these magnitudes are close to or slightly elevated above the long term means for a watershed.

Water yield responses and simulation inputs and outputs for individual watersheds are shown in Appendices 3 and 4.

Table 7 Water yield increases as percents and area mm. Yield increases shown in red exceed the upper 95% confidence interval for average water yield of watersheds used for base yield.

Watershed Name	Area km^2	Basin Order	% Watershed Harvested	Yield Increase mm	% Increase Yield
Chinchaga Watersheds					
5_1	19.9	2nd	15.1	19.3	21.0
5_2	22.2	3rd	31.3	46.9	**51.2**
3_1	166.4	3rd	9.3	9.1	9.9
5	571.6	4th	3.3	4.1	4.5
Notikewin Watersheds					
23-1	18.4	2nd	45.5	53.1	**55.5**
16-2	36.5	3rd	28.2	25.8	**27.0**
12_2	42.4	3rd	19.5	28.2	**29.5**
12_1	43.6	2nd	17.6	13.9	14.5
20-1	59.2	3rd	26.9	26.1	**27.3**
16_1	65	3rd	29.8	34.5	**36.0**
23-2	197.5	4th	15.8	14.8	15.5
13_1	231.4	3rd	11.6	10.6	11.1
22-1	301.6	3rd	11.7	9.5	10.0
16	720	4th	17.3	15.1	15.8

Peak Flows

Simulated increases in peak flows followed a decreasing trend as recurrence intervals increased (Figure 4). Increases for the 2-year events varied from 14% to 63%, with the exception of watershed 23_1 which showed an increase of 111.5% (Table 8). Increases for the 100-year events varied from 2% to 13%. The pattern of peak flow responses to harvesting was similar to those for water yield. Percent increases in 2-year events in the large watersheds ranged from 4.8%-21.7%, while those in the small watersheds were 22.5% to 111.5%. The largest increase was in the smallest watershed 23_1 (18.4 km^2), where 45.5% of the area was harvested.

Figure 4 Increase annual maximum daily flows for NDFP watersheds

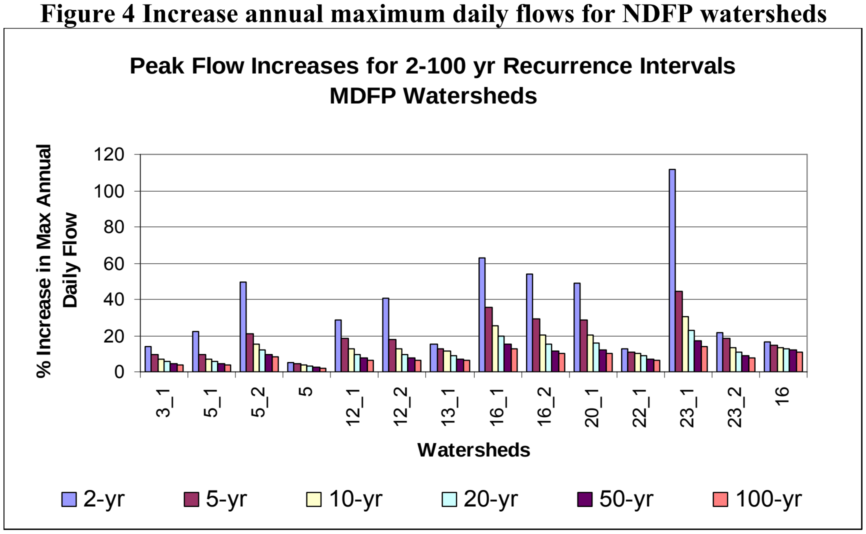


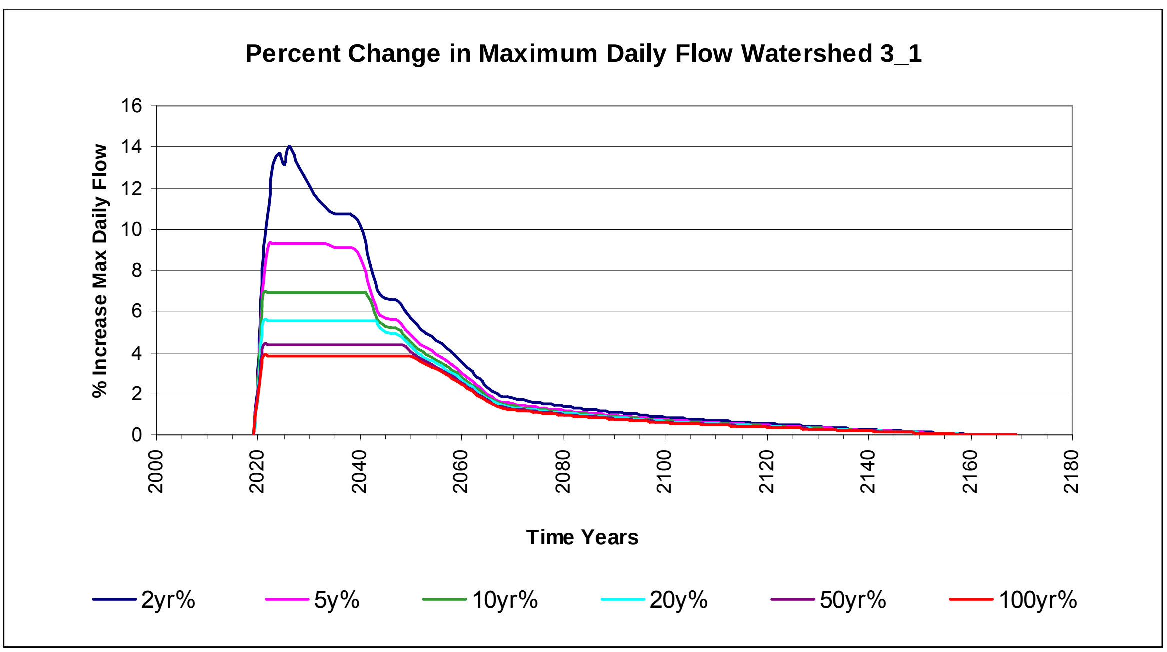
Table 8 Simulated increases in annual maximum daily flows for Chinchaga River and Notikewin River watersheds. Simulated increases in red font exceeded levels considered acceptable.

Watershed Name	Area km^2	% Watershed Harvested	% Increase in Annual Maximum Daily Flows by Recurrence Intervals _ years						Maximum % Watershed ECA
			2 yr	5 yr	10 yr	20 yr	50 yr	100 yr	
Chinchaga Watersheds									
3_1	166.4	9.3	14.0	9.3	6.9	5.5	4.4	3.8	7.2
5_1	19.9	15.1	22.5	9.5	6.9	5.6	4.4	3.9	12.2
5_2	22.2	31.3	**49.4**	21.0	15.3	12.2	9.8	8.5	26.4
5	571.6	3.3	4.8	4.2	3.5	2.9	2.4	2.1	2.6
Notikewin Watersheds									
12_1	43.6	17.6	28.3	18.3	12.8	9.8	7.5	6.4	9.5
12_2	42.4	19.5	**40.9**	17.9	12.5	9.6	7.4	6.2	17.5
13_1	231.4	11.6	15.1	12.8	11.2	9.1	7.3	6.4	7.1
16_1	65	29.8	**63.1**	**35.4**	25.2	19.7	15.2	13.0	21.3
16-2	36.5	28.2	**54.0**	**29.0**	20.1	15.4	11.7	9.9	18.1
20-1	59.2	26.9	**49.1**	**28.5**	20.3	15.7	12.2	10.4	16.4
22-1	301.6	11.7	12.8	10.9	10.2	8.6	7.0	6.2	6.0
23-1	18.4	45.5	**111.5**	**44.7**	30.2	22.6	16.9	14.1	30.7
23-2	197.5	15.8	21.7	18.2	13.6	11.0	8.8	7.7	9.9
16	720	17.3	16.7	14.4	13.6	12.9	11.9	10.6	10.1

Increases in annual maximum daily flows were judged "acceptable" (Table 6) for the 10-year-100-year events for all watersheds (≤ 26%). Six watersheds exceeded acceptable levels for the 2-year events and 4 of these six exceeded acceptable levels for 5-year events. These watersheds were small to medium in size and harvesting in the watersheds averaged 30% with maximum and minimum values of 45.5% and 19.5%.

These peak flow changes are estimates of the contribution of forest harvesting to peak flows, which cannot exceed the maximum daily evapotranspiration (ET) rate calculated by WRENSS. When this occurs (i.e. $Q_{peak} > ET_{daily\ max}$)) peak flows are constrained by an area-weighted reduction in maximum daily ET for a watershed. In other words, the extra water generated by harvesting that contributes to increased peak flows becomes constant for a given period of time until evapotranspiration rates have recovered where a reduction in flows can occur. Figure 5 illustrates how this constrains the magnitude of changes in peak flows. Peak flow changes on most of the small to medium size watersheds remained elevated (i.e. constrained) for periods of 5-30 years depending on the extent of harvesting (watershed output Appendix 4).

Figure 5 Percent increases in maximum daily flows for watershed 3_1 for 2-yr to 100-yr recurrence intervals. Peak flow changes for the 5-yr to 100-yr intervals are constant (i.e. constrained) for 17-29 years, until evapotranspiration rates recover allowing a reduction in flows.



ECA and Hydrologic Recovery

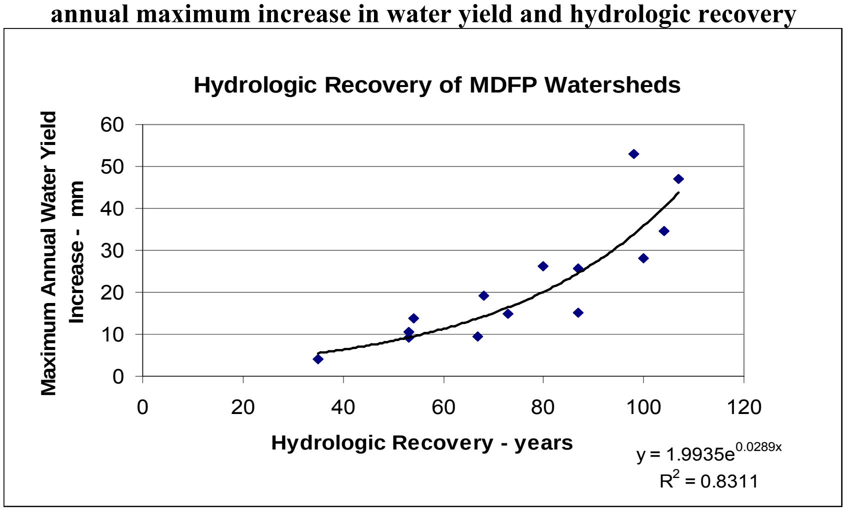
Maximum watershed ECA% for all the basins ranged from a minimum of 2.1% to a maximum of 30.7%. Average %ECA for the small to medium watersheds was 19% compared to 8% for the large watersheds (Table 9). The maximum %ECA was in the smallest watershed (23-1/18.4 km^2), where the 45.5% of the area was harvested.

Table 9 ECA and hydrologic recovery for MDFP Watersheds

Watershed Name	Maximum Watershed ECA		Year of Max ΔQ~ 1%	Year of Max ΔQ	Hydrologic Recovery Years	Max ΔQ mm
	ECA ha	ECA % Watershed Area				
Chinchaga Watersheds						
3_1	1193.8	7.2	2079	2026	53	9.1
5_1	243.6	12.2	2091	2023	68	19.3
5_2	586.6	26.4	2130	2023	107	46.9
5	1469.0	2.6	2061	2023	35	4.1
Notikewin Watersheds						
12_1	415.4	9.5	2080	2026	54	13.9
12_2	742.5	17.5	2126	2026	100	28.2
13_1	1640.0	7.1	2079	2026	53	10.6
16_1	1385.4	21.3	2127	2023	104	34.5
16-2	660.9	18.1	2110	2023	87	25.8
20-1	969.5	16.4	2107	2027	80	26.1
22-1	1813.9	6.0	2093	2026	67	9.5
23-1	565.3	30.7	2115	2017	98	53.1
23-2	1956.0	9.9	2093	2020	73	14.8
16	7288.0	10.1	2110	2023	87	15.1

Hydrologic recovery amongst the watersheds varied from 35 years to 107 years. The time to hydrologic recovery is largely a function of the magnitude of water yield increases and the timing or frequency of harvesting in a watershed (Figure 6). The larger the increase in water yield the longer for recovery to pre-harvest conditions.

Figure 6 Regression analysis showing relationship between annual maximum increase in water yield and hydrologic recovery



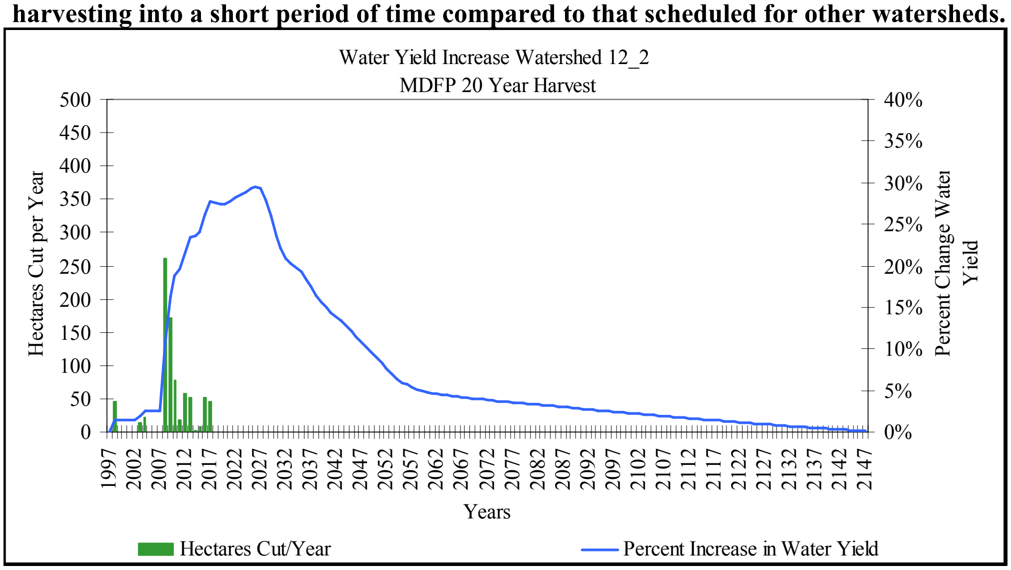
Discussion

Water Yield Increases

Increases in water yield are determined primarily by the extent and frequency of harvesting and watershed size. Harvesting that exceeds 30% - 40% or more of a watershed can be expected to increase water yield above "acceptable levels". This was the case for the small to medium sized watersheds in these simulations where harvesting averaged 30% with maximum and minimum values of 19.5% and 45.5%. Concentrating harvesting temporally can also contribute to high increases in water yield as occurred for watershed 12_2 (Figure 7).

Higher responses in water yield in smaller watersheds (< 100 km^2) are more likely as the opportunity to harvest a larger proportion of a watershed is greater than that in large watersheds. For example harvesting 721 ha in watershed 5_2 (2758 ha in size) generated a yield increase of 51.2% compared to harvesting 7805 ha in watershed 16 (72,400 ha) with an increase of 17.3%. Percent increases in flow in large watersheds will be moderated by a mix of areas that are unharvested and in various stages of hydrologic recovery.

Figure 7 High water yield increases in watershed 12_2 were attributed to the concentration of harvesting into a short period of time compared to that scheduled for other watersheds.



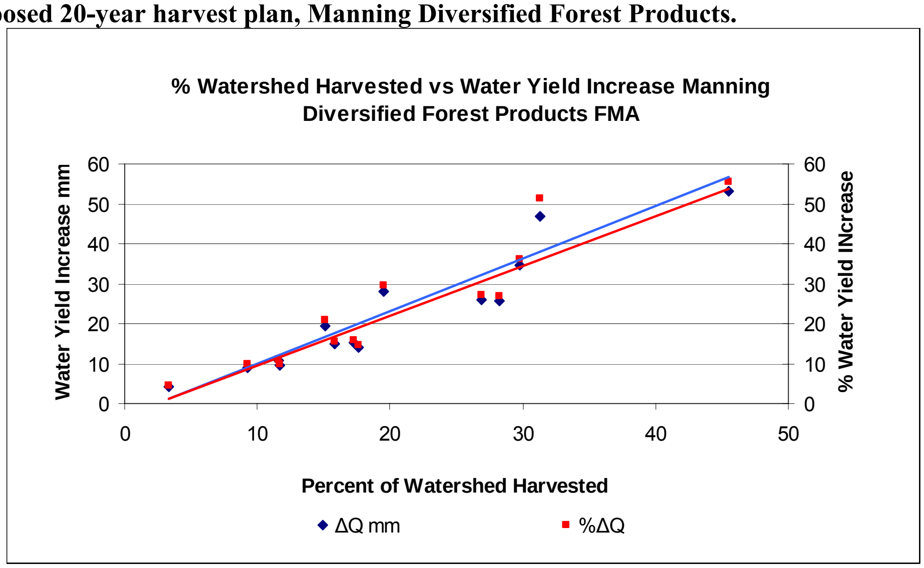
It should be noted that flow responses in WRENSS simulations can be affected the magnitude of mean annual water yield of representative watersheds which is used as a base to calculate percent change in water yield. Ideally representative watersheds should be of similar size, topography vegetation and climate. The Chinchaga and Notikewin rivers used as representative watersheds in these simulations are many times bigger in area than the watersheds assessed. Water yields from smaller watershed are often greater than those of larger watersheds because the volume of flow is expressed on an areal basis. The significance of this is that the water yield increases from these simulations could be "over estimates". When interpreting these results it is best to consider the changes in flow in relative terms (low, med, high or acceptable unacceptable) and not as absolute numerical changes.

The magnitude of these water yield increases could have been reduced by a small amount if MDFP's policy for retention of "green" structure in cut blocks had been incorporated into the input data for the simulations. The policy requires retention of 6% of cut block areas as live individual trees, small patches and large patches, with a minimum of 3% merchantable trees. Reductions probably would be higher for harvesting in small watersheds than large watersheds.

Another point to consider is that watersheds or regions characterized by low annual flows will usually produce higher percent increases in flow than those with high annual flow. For example, watershed 16_2 had a volumetric water yield increase of 28 mm (watershed 16_2), which expressed as a percentage of the average flow for the Notikewin River was 27%. The same volumetric increase expressed as a percent of the average flow for Crownest River in southern Alberta, with an annual flow of 380 mm would be 7%. Differences in base water yield between regions or watersheds within a region can have pronounced effect on the magnitude of simulated water yield increases.

The high increases in these simulations are attributed to the extent and pattern of harvesting in the small to medium sized watersheds (Figure 8). Based on past simulations harvest levels that exceed 30%-40% of watershed area can be expected to generate large increases in water yield and peak flows. Large increases in water yield can be reduced to some degree if harvesting is scheduled for multiple entries with intervening periods of no logging to allow for hydrologic recovery of the watershed. One drawback to this strategy is that water flows remain elevated for some period of time. Single harvests of lower intensity will recover more quickly. The pattern of increases in Figure 8 can be considered indicative of the potential for large to small changes in water flows in other watersheds of MDFP's forest management area, assuming similar levels of harvesting.

Figure 8 Water yield increases in mm and as a percent versus percent of watershed area harvested for hydrologic simulations of proposed 20-year harvest plan, Manning Diversified Forest Products.



Changes in water flows can be managed by a reduction and rescheduling of harvesting. However, this may not be acceptable to MDFP as the proposed harvest schedule incorporates strategies to address a range of different resource issues such as caribou habitat management, biodiversity and mountain pine beetle infestations that require trade off in values and objectives. From a hydrological perspective the potential effects of widespread mountain pine beetle infestations are significant. Changes in water yield similar to those in these simulations or greater could occur if the stands were attacked and destroyed by mountain pine beetles (Love 1955; Troendle and Nankervis 2000; Uunill et al, 2006).

Peak Flows

The pattern of increases for peak flows was similar to that of water yield, with larger increases occurring in the small to medium size watersheds and lesser responses in the large watersheds. The primary focus for assessment was on 2-3 year events which were assumed to be most susceptible from land use change. Increases in maximum daily flows for these watersheds for the 2-year events varied from 41% to 111% and 28% - 44.7% for the 5-years events. Increases for recurrence interval events > 10 years for all watersheds (small to large) fell within acceptable levels.

The duration of peak flow changes in the small to medium size watersheds were 5-30 years, while those in the large watersheds were smaller in magnitude and of shorter duration. These sustained changes are most likely to result in a significant increase in the magnitude of the 2-5 year events, which could contribute to long term changes in stream channel morphology and aquatic habits. The higher frequency of these events over 20-30 years could cause widening and deepening and a loss of sinuosity of stream channels.

ECA and Hydrologic Recovery

Hydrologic recovery indicated by the simulations was long varying from 35 to 107 years, with the greatest time for recovery in the watersheds with the highest levels of harvesting and water yield responses. Hydrologic recovery probably occurs earlier than that indicated by the conservative definition used in this assessment (time for $\Delta Q \sim 1\%$). An %ECA estimate based on the recovery of leaf area index or volume increment (Silins 2000, Brabender 2004) would provide a shorter and most likely a more realistic estimate of hydrologic recovery.

Summary and Conclusions

Hydrologic assessment of a proposed 20-year harvesting plan for Manning Diversified Forest Products (MDFP) forest management area (FMA) that includes strategies to manage for caribou habitat and minimize mountain pine beetle infestations was conducted with WRENSS to assess potential increases in annual water yield and annual maximum daily flows. A sample of 14 watersheds fully contained with the boundaries of the FMA was selected for analysis. The watersheds were 2nd the 4th order basins ranging in size from 18-724 km^2 in size. Percent area harvested in the watersheds varied from 3.3% to 45.5%. Harvesting occurred in tributaries to the Notikewin River and the Chinghaga River.

Long term average flows for the Notikewin and Chinchaga rivers were used as representative watersheds in the WRENSS simulations as a base to express percent changes in water yield and annual maximum daily flows. Annual and monthly precipitation data from Manning were used for input in the Wrens. Simulations were run for a period of 150 years on an annual time step, starting in 2006.

The significance of changes in annual water yield and annual maximum daily flows was assessed based on the upper 95% confidence interval for mean annual flow of the two representative watersheds, and an analysis of 'natural variability" of flows in the Manning region using established hydrometric stations operated by Water Survey of Canada. Simulated increases in annual water yield, represented by the upper 95% confidence interval, less than 18% and 15% were considered acceptable respectively for basins tributary to the Notikewin and Chinchaga rivers. Water yield and peak flow increases, based on natural variability, less than 23% and 26% were respectively considered acceptable for annual water yield and annual maximum daily flows.

Increases in annual water yield ranged from 21% to 55% in small to medium sized (< 100 km^2) watersheds, where harvesting varied from 30% to 45% of watershed area. Simulated increases in larger watersheds (166 -724 km^2) were smaller ranging from 9.9% to 21%. Harvesting in these basins varied from 3% to 17.3% of watershed area.

The large increases in the small to medium size watersheds were attributed to the high levels of harvesting in a relatively short period of time. Harvest levels >30-40% of watershed area in small basins can be expected to generate large responses in water yield and peak flows. The increases in most of the small-medium watersheds exceeded levels considered "acceptable" based on long term average flow for the representative watersheds and natural flow variability for the region.

Simulated increases in the larger watershed were judged "acceptable". The increases in the larger watersheds were less because they are averaged over a larger area that contains a mix of uncut stands, older stands at some stage of hydrologic recovery and freshly cut stands that moderates the effects of harvesting.

Changes in peak flows followed a pattern similar to water yield. Increases were greatest in the small-medium watersheds with heavy levels of harvest and less in the larger watersheds. The largest increases in maximum daily flows occurred in the 2-yr to 5-yr recurrence interval events. Increases in the 2-yr events ranged from 41% to 111%, with the maximum event occurring on the smallest watershed where harvesting affected 45.5% of the basin. Increases for the 5-yr events were smaller ranging from 28.5% to 44.7%. Simulated increases for the 10-yr to 100 yr events were ranged from 6% - 20% and considered "acceptable". Peak flow increases in most of the small watersheds were sustained for periods of 30-15 years, which may have the potential to affect stream morphology and aquatic habitats of the longer term.

Hydrologic recovery of water yields and peak flows to pre-disturbance levels was of long duration, with values ranging from 53 to 107 years. The long periods for hydrologic recovery were a function of the large increases in water yield. Watersheds with the greatest increases in water yield and peak flow took the longest for recovery. Maximum percent equivalent clear area for the watersheds (i.e. a measure of disturbance) varied from values of 2.6% - 10.1% for the large watersheds and 9.5%-30.7% for the small watersheds.

The high increases in these simulations were attributed to the extent and pattern of harvesting in the small to medium sized watersheds. These changes can be managed by a reduction and rescheduling of harvesting. However, this may not be acceptable to MDFP as the proposed harvest schedule incorporates strategies to address a range of different resource issues such as caribou habitat management, biodiversity and mountain pine beetle infestations that require trade off in values and objectives. From a hydrological perspective the potential effects of widespread mountain pine beetle infestations are significant. Changes in water yield similar to those in these simulations or greater could occur if the stands were attacked and destroyed by mountain pine beetles (Love 1955; Troendle and Nankervis 2000; Uunill et al, 2006).

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Appendix 1 WRENSS

WRENSS

WRENSS (Water Resource Evaluation for Non-Point Silvicultural Sources) 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 (1997) prepared a computer version of the procedure (WRENSS) for Alberta conditions and modified it by linking climate and flow databases to the program. WRENSS uses long-term monthly precipitation, annual flow data from representative watersheds, GIS-generated harvest data, watershed characteristics, and growth functions to estimate changes in annual water yield. Swanson also included methods for estimating changes in peak flows for 2, 10, 20, 50 and 100 year recurrence intervals. Estimates of watershed disturbance in terms of equivalent clear-cut area (ECA) (Ager A. A. and C. Clifton. 2005) based on recovery of basal area or water yield increases are included in WRENSS. Version 3.0 of WrnsEcaAb (Swanson 2000) was used in this assessment.

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 GRO before and after harvesting.

Eq.1 $GRO = Input - Losses = P - ET \pm \Delta S$

P = precipitation

ET = evapotranspiration losses

ΔS = change in watershed storage.

Eq.2 $\Delta Q \sim \Delta ET = (P_{after\ harvest} - GRO_{after}) - (P_{before\ harvest} - GRO_{before})$, where precipitation before and after harvest is assumed to be the same.

GRO is strongly affected by watershed storage and in the short term may not equal actual flow (Q_A). Over the long-term however $GRO = Q_A$ as average annual change in watershed storage approaches zero ($\Delta S \sim 0$). Long term precipitation and streamflow data are essential for the application of WRENSS.

Increases in water yield in WRENSS are expressed as area-millimeters (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 (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).

Percent increases should be considered as relative changes (e.g. small, medium, and large). Few if any models are capable of providing exact, absolute outputs. 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.

Water responses provided by WRENSS are cumulative in that they can show both water yield increases and the rate of hydrologic recovery, which is the time for evapotranspiration and water flows to return to pre-harvest levels. Hydrologic recovery in WRENSS is estimated in two ways. The first is the traditional approach based on the recovery of basal area to pre-harvest conditions with the establishment of forest regeneration. Recovery occurs when current basal area equals maximum basal area for a given site. The second is based on the recovery of simulated water yield increases to pre-harvest or undisturbed conditions ($\Delta Q \sim 0$). Hydrologic recovery based on water yield was defined as the time required for the maximum increases in annual flow (or peak flows) to decrease to levels equal to or less than 1%. The time required for hydrologic recovery is a function of the amount and frequency of harvesting in a watershed, and the occurrence and rate of growth of forest regeneration.

Equivalent Area Clearcut (ECA) is an index of hydrologic recovery. 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 establishment and growth of regeneration. 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 as the area harvested times a reduction factor that describes the recovery of evapotranspiration losses. ECA estimates in WRENSS are provided in terms of basal area recovery (Eq.3) and recovery of water yield (Eq.4). ECA is expressed in hectares of harvested area and as a percent of the harvested area. %ECA in this assessment was reported as a percent of watershed area, which is hydrologically more informative.

Eq.3 $$ECA_{BA} = \frac{BA_{current}}{Max\ BA} \times Harvest\ Area$$

Max BA = maximum basal area possible for a given site
$BA_{current}$= basal area for year –n of a specified time series

Eq.4 $$ECA_{Q} = \frac{\Delta Yield_{current}}{\Delta Yield_{\max Q}} \times Harvested\quad Area$$

$\Delta Yield_{maxQ}$ = maximum water yield increases in a given time series
$\Delta Yield_{current}$ = water yield increase for year- n in a given time series

It should be noted that hydrologic recovery based on ECA_{Q} includes both recovery of basal area and the effects of snow redistribution in harvest blocks (i.e. snow scour/sublimation). Hydrologic recovery based on maximum water yield increase can be shorter by half the number of years obtained with basal area. ECA_Q is considered a more direct and realistic estimate of hydrologic recovery, and was used in this report.

WRENSS also estimates increases in maximum daily and instantaneous flows due to harvesting for return periods of 2, 5, 10, 20, 50 and 100-year events. WRENSS uses watershed area to estimate peak flows ($Q_{peak\text{-}area}$) for all return periods in the unharvested condition. The difference between the mean March to September streamflow in the unharvested and harvested condition is used to estimate the change in peak flow ($Q_{peak\ mean\ flow}$) caused by harvesting for each return period. The difference in $Q_{peak\ mean\ flow}$ between the harvested and unharvested conditions is added to $Q_{peak\text{-}area}$ to obtain the maximum flow for a given return period.

In WRENSS the maximum change in peak flow attributable to the effects of forest harvesting is constrained by the maximum reduction in daily evapotranspiration rate (i.e. the volume of extra water made available by harvesting), estimated by WRENSS for a completely undisturbed watershed.
In some situations (e.g. high precipitation) the change in peak flow can exceed the daily maximum evapotranspiration rate. When this occurs it is area weighted with respect to the amount of disturbance in the watershed. For example, if the maximum evapotranspiration was 5.0 mm/day and 47% of the watershed was undisturbed, it would be reduced to 2.65 mm/day (e.g. 5.0 mm/day*(1-0.47) = 2.65 mm/day or 4.13 m^3/sec). The adjusted value would then be added to the estimated peak flow (i.e. $Q_{peak\text{-}area}$).

This constraint is built into the WRENSS program. The assumption inherent in this constraint is that the increase in peak flow generated by harvesting "alone" is controlled by the maximum reduction in daily potential evapotranspiration. Under these conditions the increase in maximum daily flows attributable to harvesting can be similar for a range of return periods, and persist for sustained periods until evapotranspiration recovers with regrowth of harvested areas. When this occurs, a plot of peak flow increases will appear to be flat or truncated.

WRENSS simulations can be based on average, maximum or minimum precipitation conditions. For average conditions, estimated changes in flow are what can be expected in an "average" year. WRENSS cannot provide an estimate of the effects of climatic variation on water yield and peak flows. Simulations for maximum or minimum conditions can provide an estimate of the effects of climatic extremes. In years of high precipitation flow changes would be larger and in years of low precipitation smaller. Precipitation inputs are constant for the length of a simulation and conditions being simulated.

WRENSS does not estimate flow for ungauged basins and does not produce routed stream flow (i.e. it does not indicate how much water will flow on a given day). It also does not carry over surpluses or deficits from one year to the next. The reliability of results from WRENSS can only be as good as the precipitation and flow data used. If precipitation data is representative, accurate and of sufficient duration, then WRENSS will provide an estimate of average annual water yield that is generally within 10% of measured water yield (Swanson 2000). However, it is important to remember that most precipitation data is usually under estimated.

Appendix 2 Data requirements for WRENSS Simulations

To run a WRENSS simulation two files are required. The first is a "control" file containing information describing a watershed and the streamflow data and precipitation data to be used in the simulation (Table 1). The second is a unit file containing information for each harvest clock to be harvested in the watershed (Table 2)

Table 1 – Watershed data for WRENSS simulations (Control File)

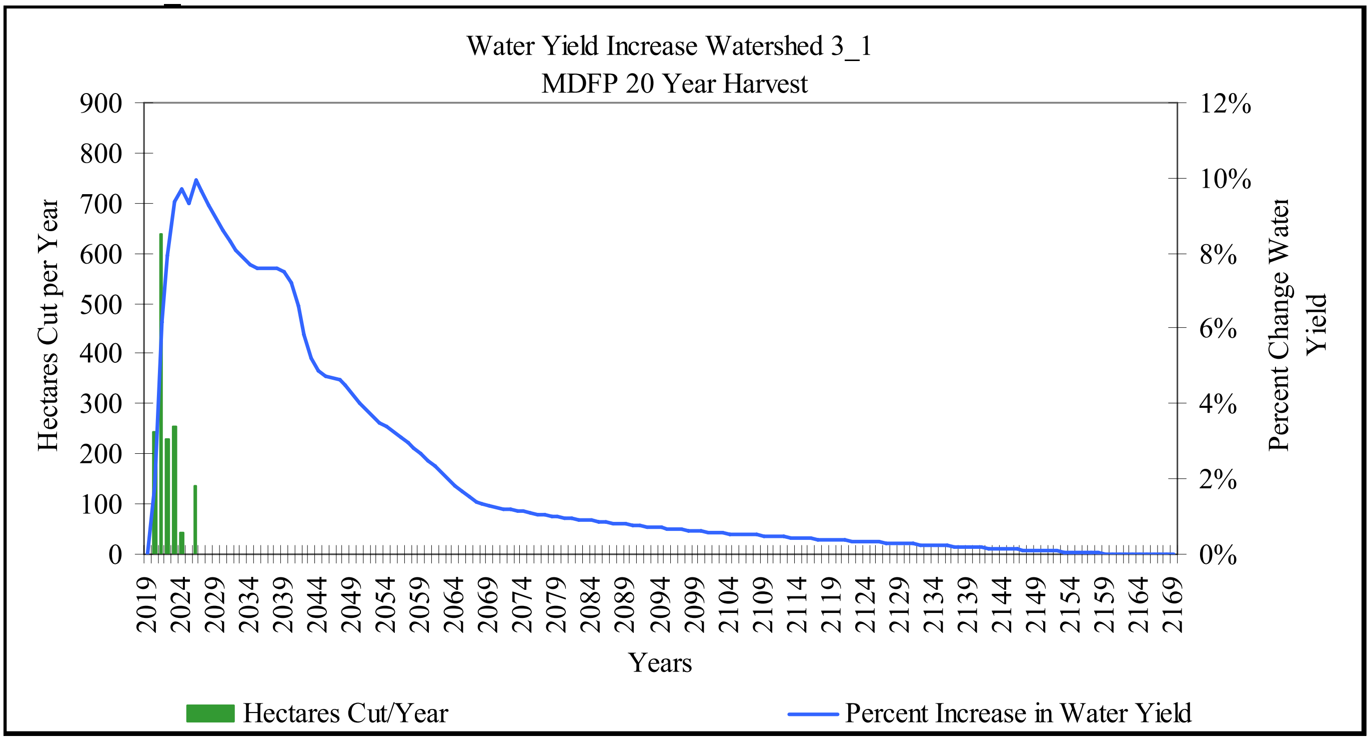
Field name	Type	Size	Dec	Description
SCENARIO	C	100		Joint identifier to link this table with the harvested blocks in tbl_Units. This name must be the same as the one used for all of the harvested blocks in any given scenario, usually a watershed.
AREA_ CUT	N	20	5	Total area of the scenario or watershed in km^2.
WS_STATION	C	100		The name or identifier of a stream gauging station in the Foothills Model Forest Area. Can be supplied at run time.
WS_YIELD	N	20	5	Supplied by link to WS_STATION at run time.
WS_STAT	C	6		Unless specified as Max or Min, defaults to Avg at run time.
WS_PERIOD	C	9		Supplied by link to WS_STATION at run time.
WS_REGION	C	100		The name of the type of analysis used in peak flow determinations, Instantaneous Max or Daily Max. Can be supplied at run time.
REGION	C	5		WRENSS regions CM or RM only. Can be supplied at run time.
WX_SOURCE	C	100		The name or identifier of a weather station in the Foothills Model Forest Area. Can be supplied at run time.
WX_STAT	C	6		Unless specified as Max or Min, defaults to Avg at run time.
WX_PERIOD	C	9		Supplied by link to WX_STATION at run time.
ANNUAL_PPT	N	20	5	Supplied by link to WX_STATION at run time.
BASE_YEAR	N	6	0	Default of 1-year prior to earliest year in the BLK_YRCUT field in tbl_Units is supplied by WrnsSdr at run time. Any year earlier than the first year cut can be supplied by the user.
START_YEAR	N	6	0	Default of 1-year prior to earliest year in the BLK_YRCUT field in tbl_Units is supplied by WrnsSdr at run time. Any year earlier than the first year cut can be supplied by the user.
END_YEAR	N	6	0	Default of 100-years after the START_YEAR is supplied by WrnsSdr at run time. This default of 100 years can be changed in the WrnsSdr Global Options form. Any year later than the first year cut can be supplied by the user.
RECORDNO	N	10	0	The user should not enter any information into this field. It is used internally within WrnsSdr.

Table 2 – Harvest data for WRENSS simulations (Unit file)

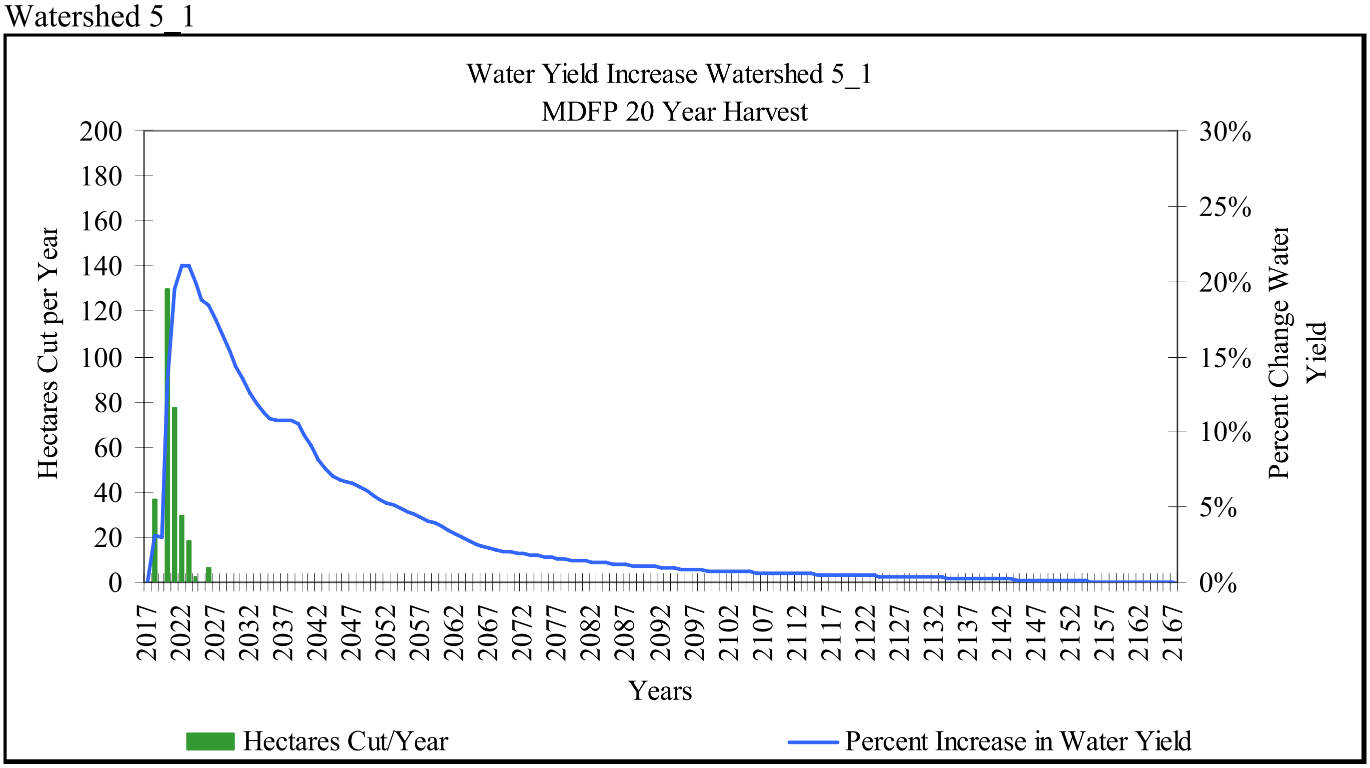
SCENARIO	Title of scenario being tested.
AREA CUT	Area of harvested unit in hectares
NUMBLOCKS	Number of blocks comprising the harvested unit. This field and the BLKSIZE field allow the grouping of several blocks of similar size, species, aspect and year of harvest into one area. The Total area of all of these similar blocks goes into AREACUT field, and either the number of blocks comprising that area go into this field or the average size of the individual block goes into the BLKSIZE field.
BLKSIZE	The size of individual blocks in hectares
BLK YRCUT	The year the block or group of blocks was cut in yyyy format.
BLK ELEV	The average elevation of the block or group of blocks in meters. Used in WRNSSDR-MF to adjust precipitation data from a different elevation to that the cut blocks being analyzed.
BLK ASPECT	The average aspect of the block as N, S, or EW. Aspect is used in conjunction with precipitation to estimate potential evapotranspiration. Maximum potential ET on south aspects and minimum on north aspects.
BLK REGEN	The species that the block is to be regenerated on a block. Lodgepole Pine, White Spruce or Deciduous are the only appropriate choices.
BUF SPECIES	The species of the surround stand, again LPP or WS or Deciduous are the only appropriate choices. Used to estimate species harvested on existing cut blocks.
BUF BA	The basal of the surrounding stand in m^2/ha. Used to estimate basal on existing cut blocks.
LUT BASEBA	The anticipated basal area of regeneration on the site at maturity, or the number of years in the rotation. Represents maximum basal area in ratio to adjust ET upwards or downwards.
LUT BAYEAR	The anticipated number of years to reach the basal area at maturity or the number of years in the rotation.
IN BAFUNCT	The name of the basal area growth function for regeneration in the unit. This is assigned during operation of WRNSSDR-MF.
BUF HT	The height of the surrounding stand in meters. Used to estimate redistribution effects of snow movement in cut blocks and surrounding stands.
LUT BASETH	The anticipated height of the regeneration on the site at maturity or at the end of the rotation.
LUT THYEAR	The anticipated number of years to reach the height of maturity, of the number of years in the rotation.
IN THFUNCT	The name of the height growth function for regeneration in the unit. This is assigned during operation of WRNSSDR-MF.
IN RECORD	Block ID. This may be changed to a 15 character wide field if necessary to identify your blocks. This is not used in WRNSSDR-MF runs.

Appendix 3 – WRENSS Water Yield Responses

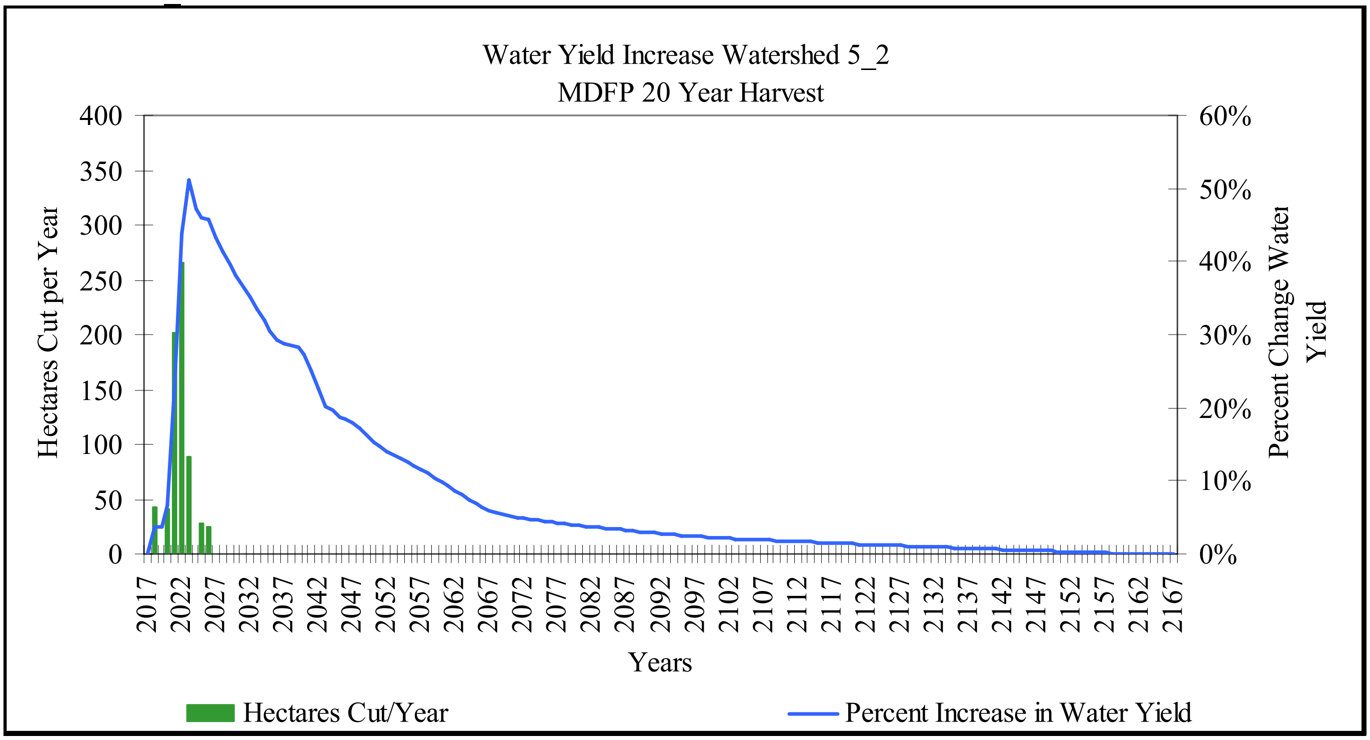
Watershed 3_1



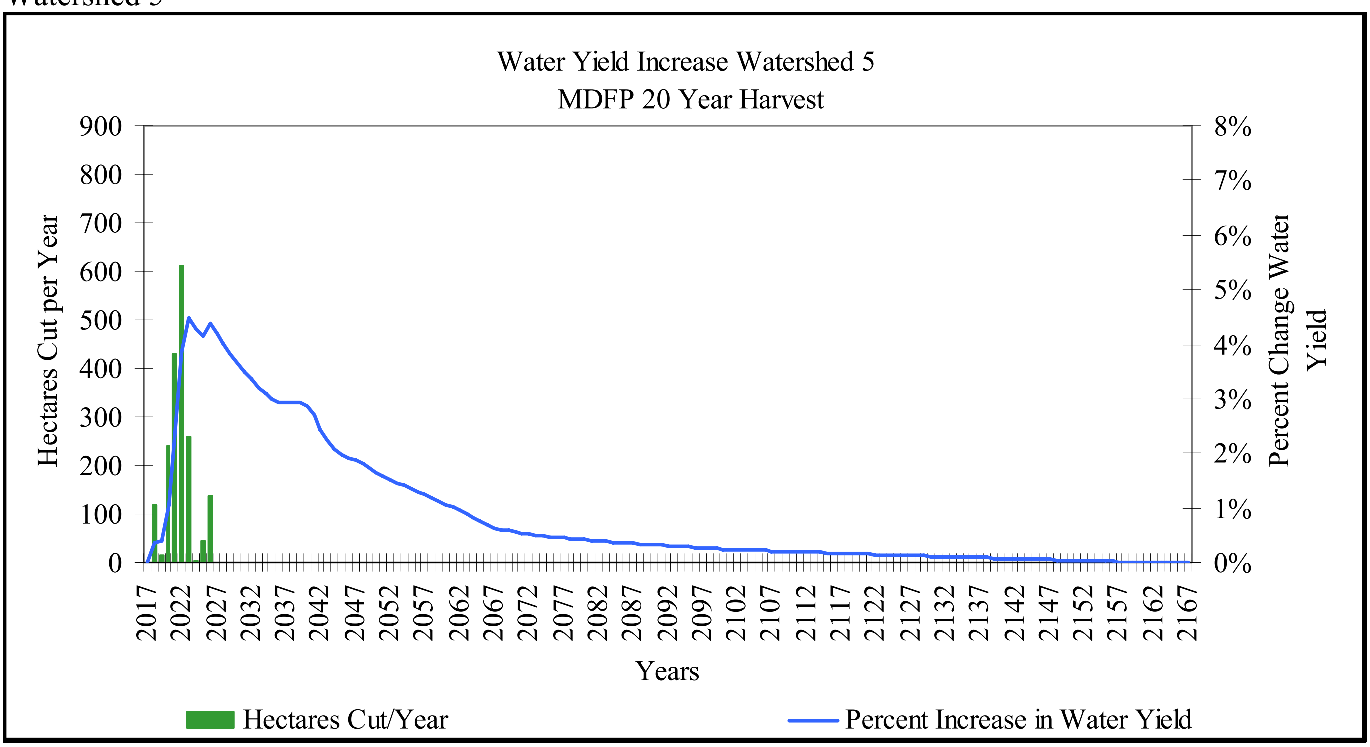
Watershed 5_1



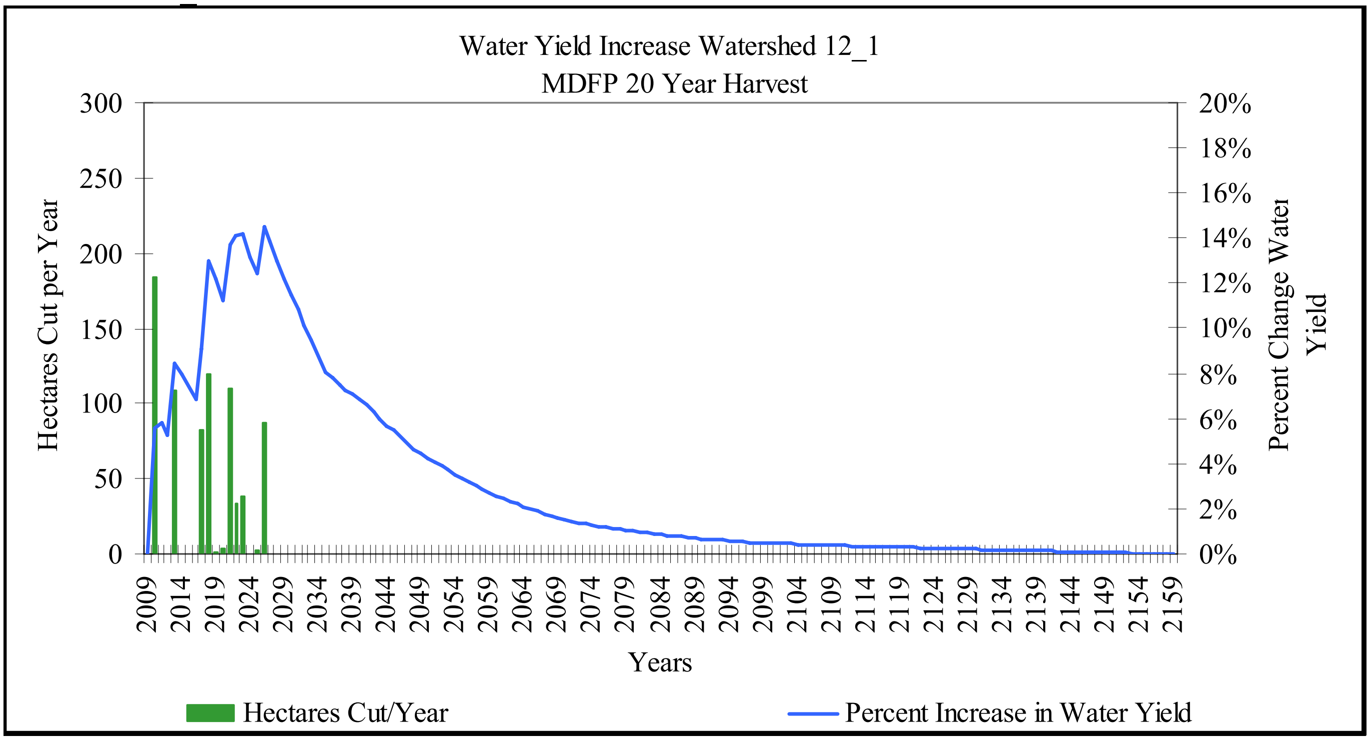
Watershed 5_2



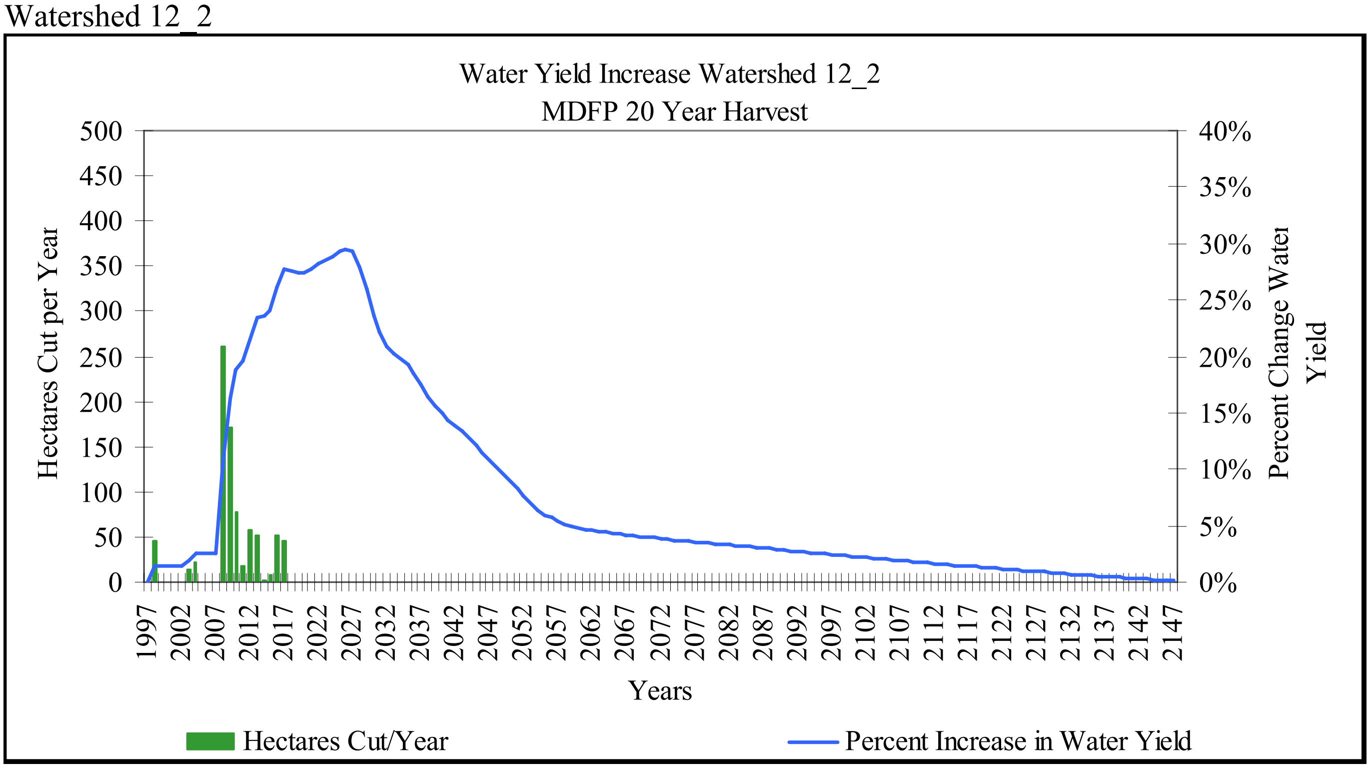
Watershed 5



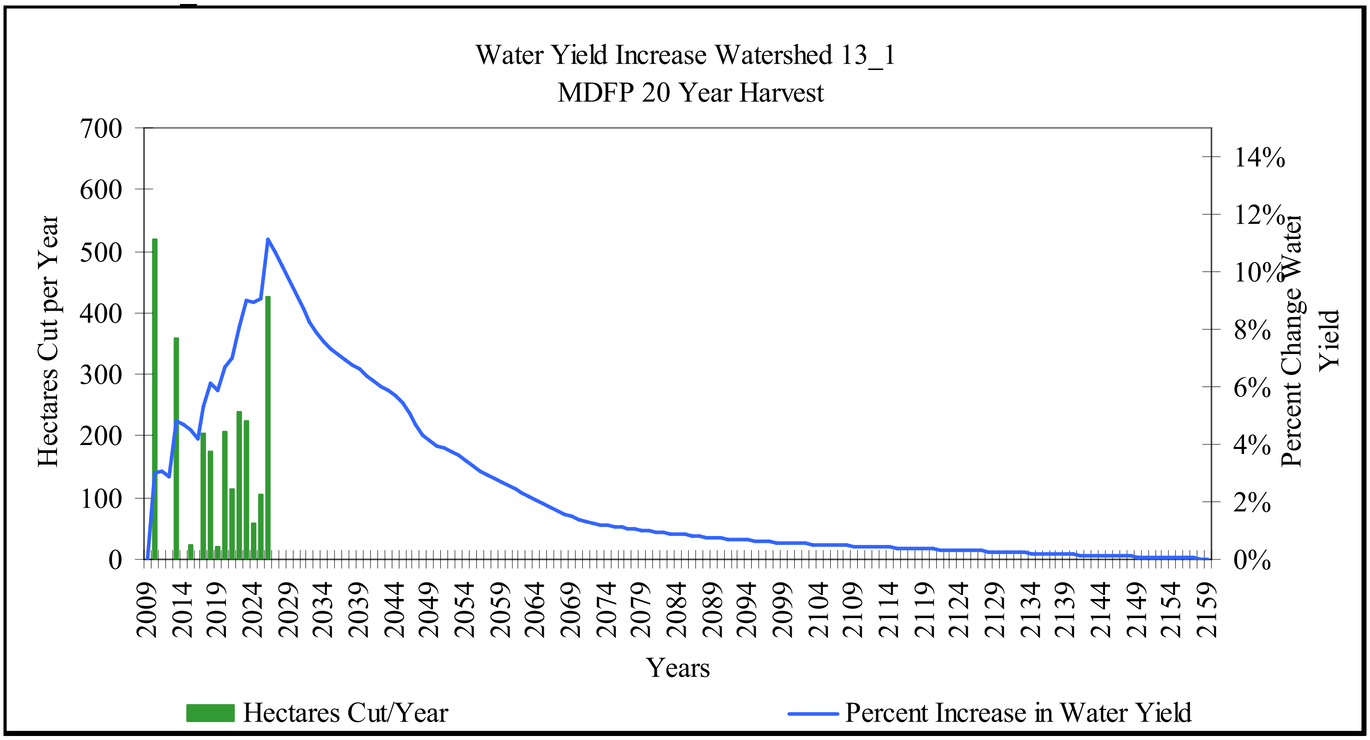
Watershed 12_1



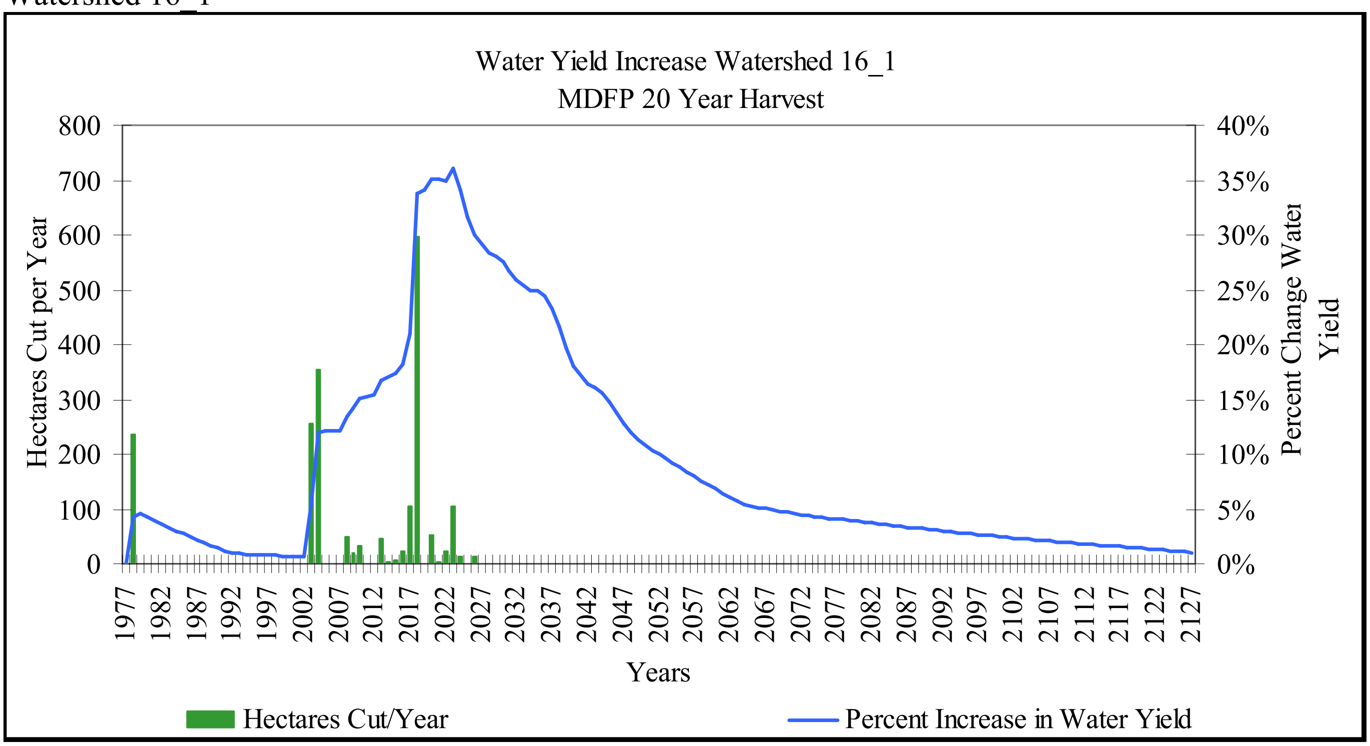
Watershed 12_2



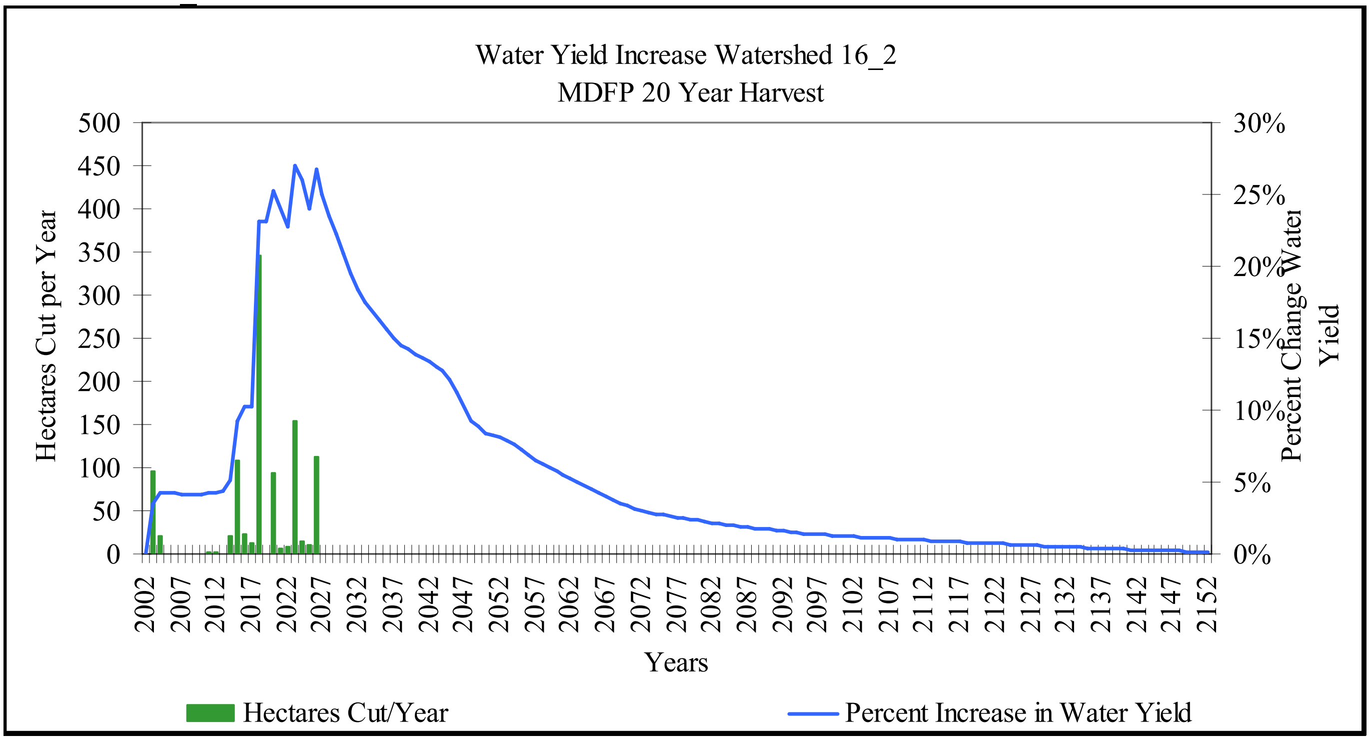
Watershed 13_1



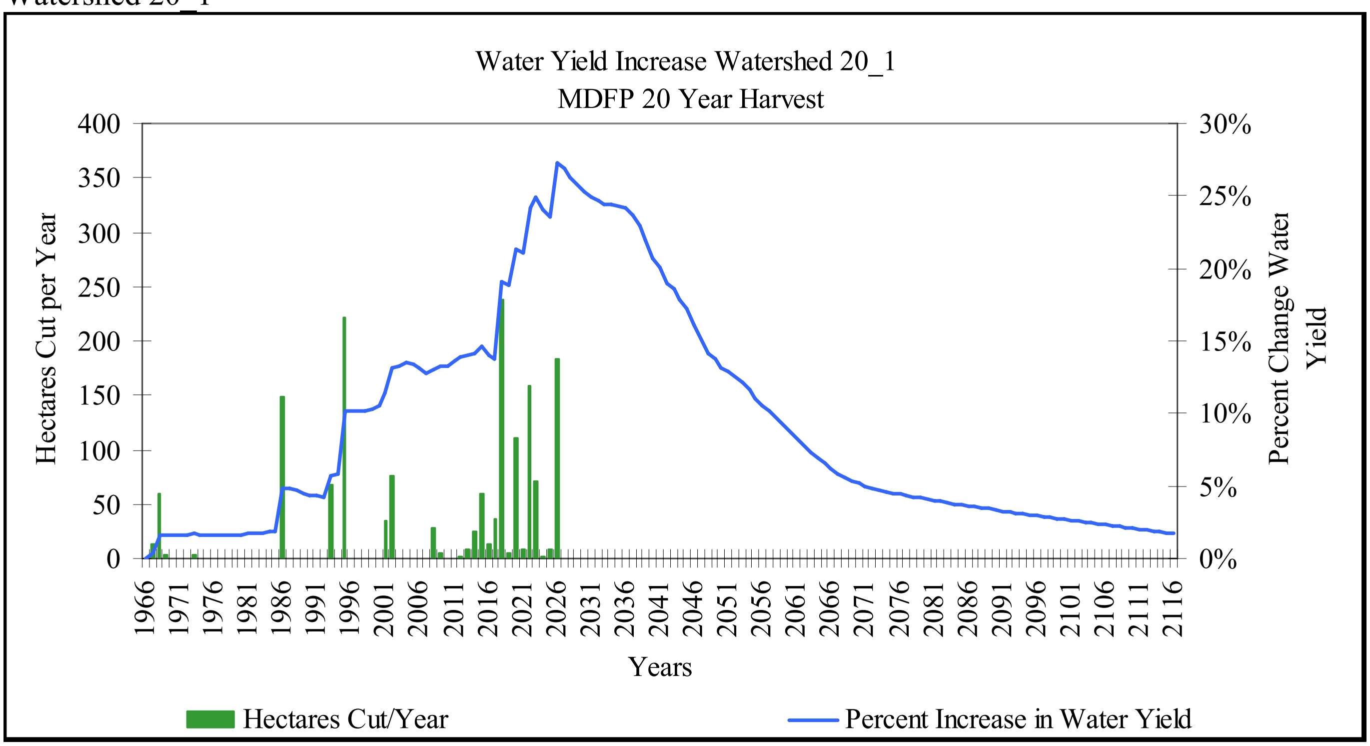
Watershed 16_1



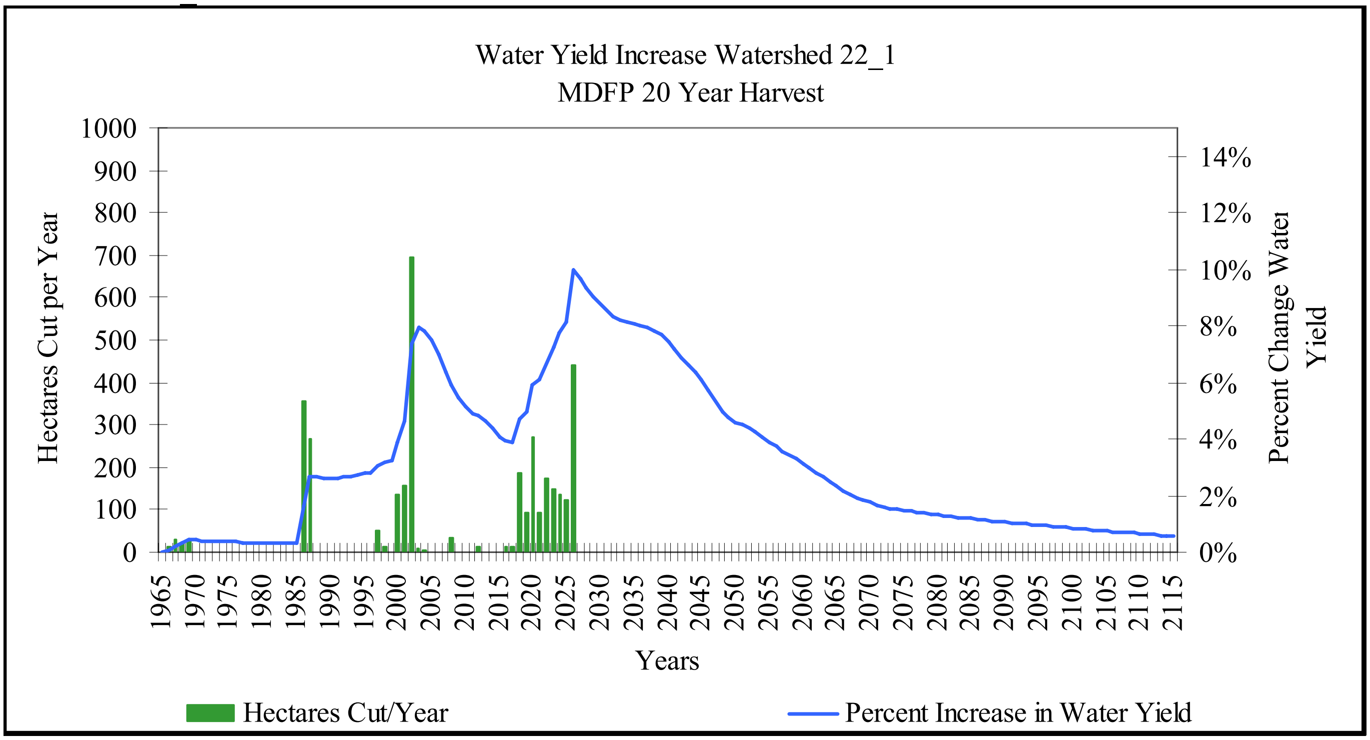
Watershed 16_2



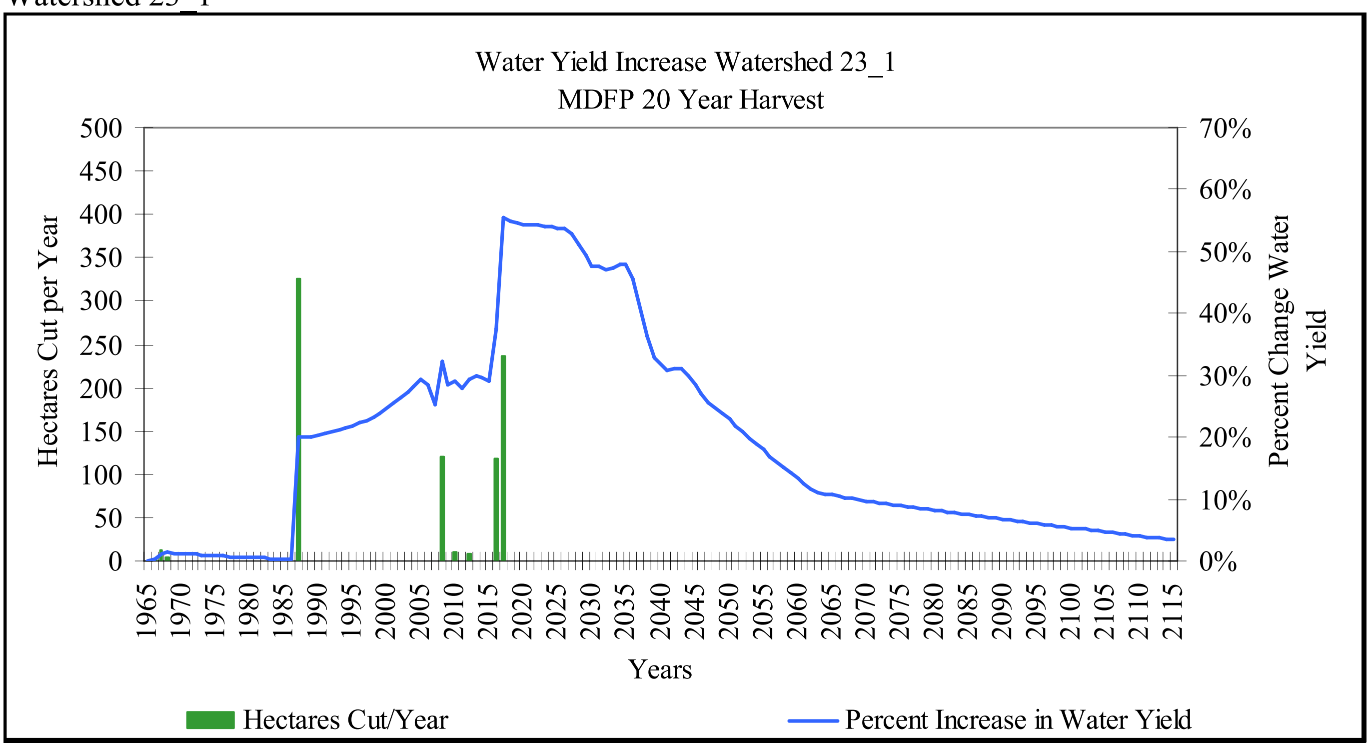
Watershed 20_1



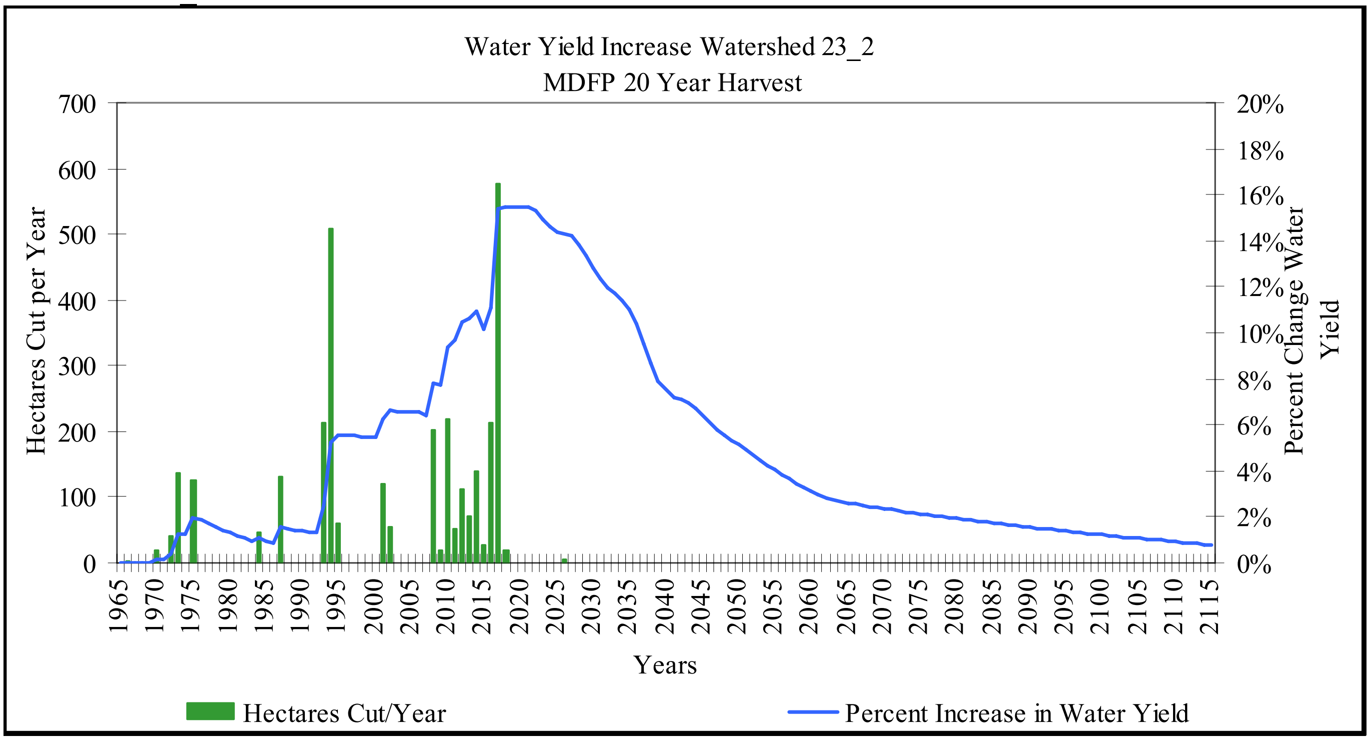
Watershed 22_1



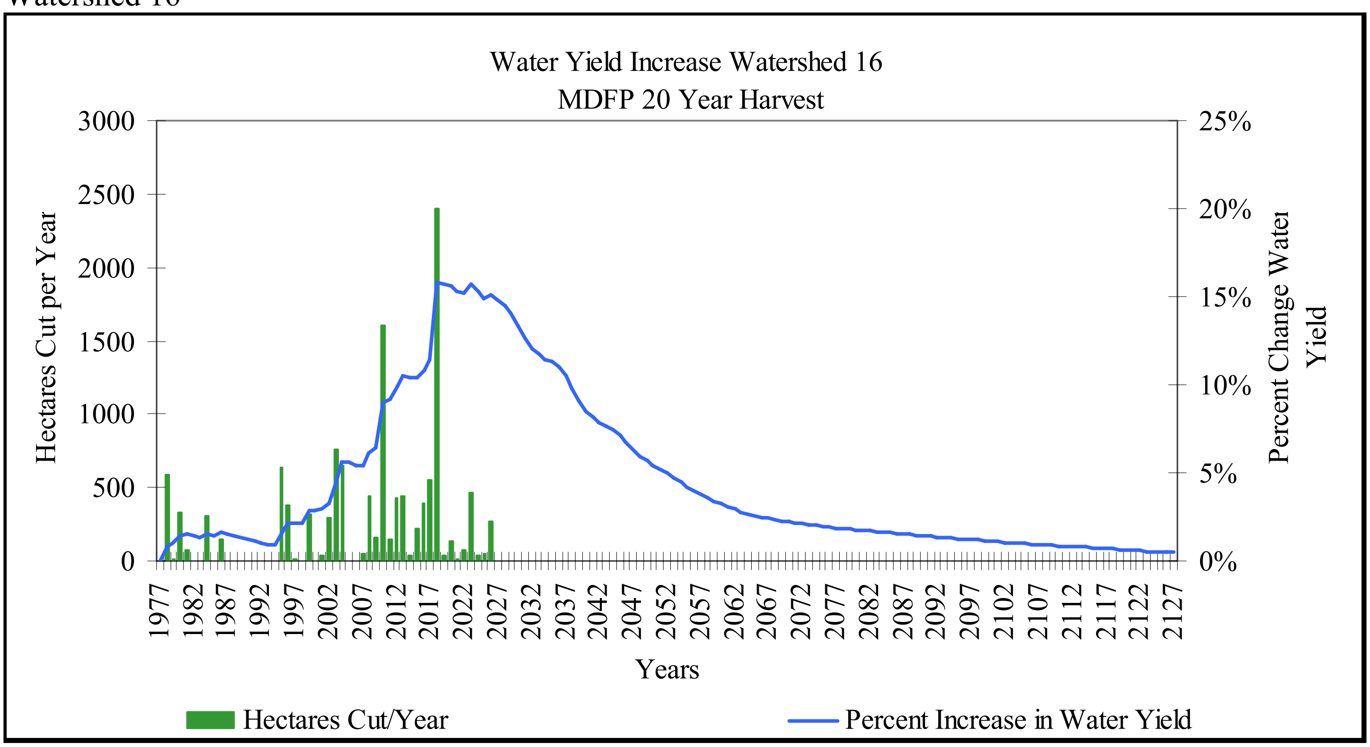
Watershed 23_1



Watershed 23_2

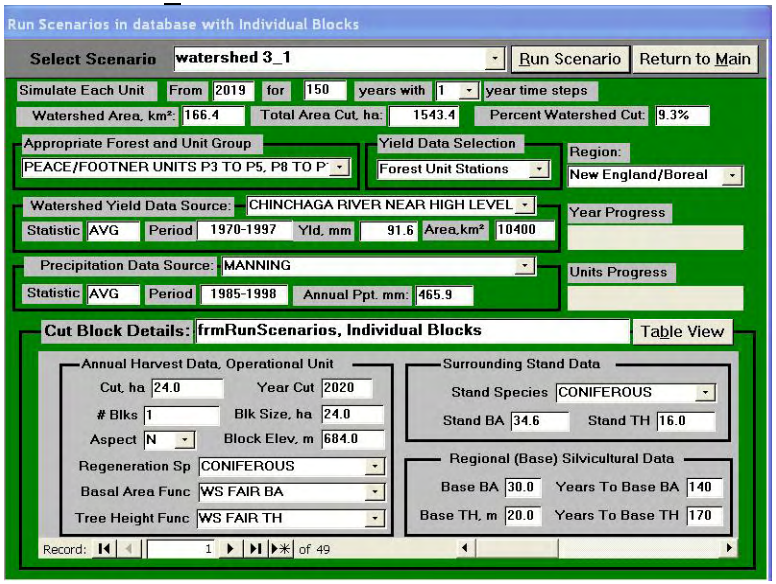


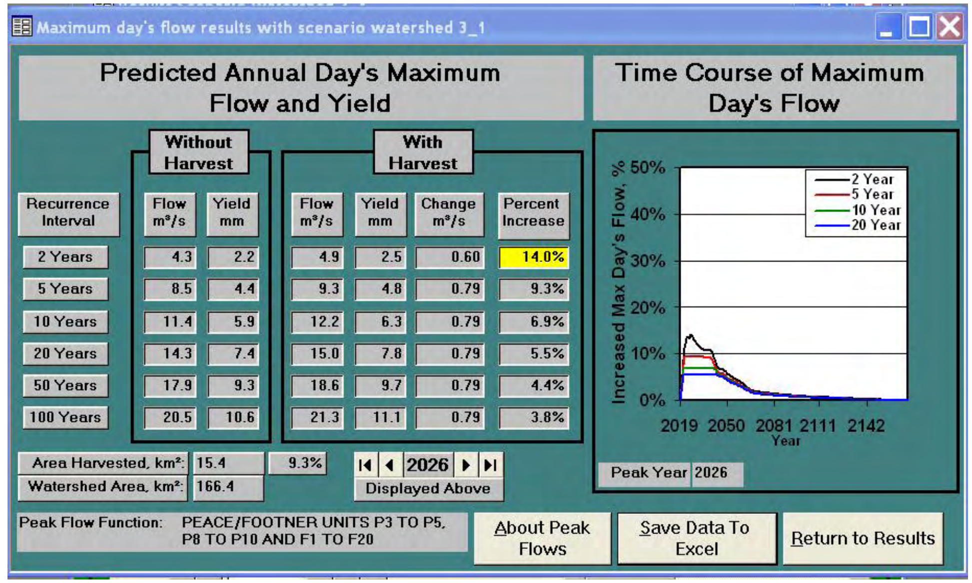
Watershed 16

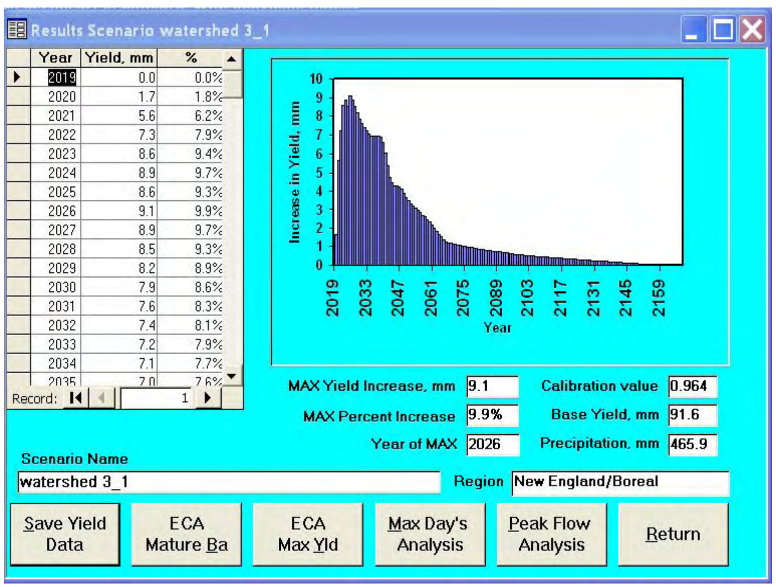


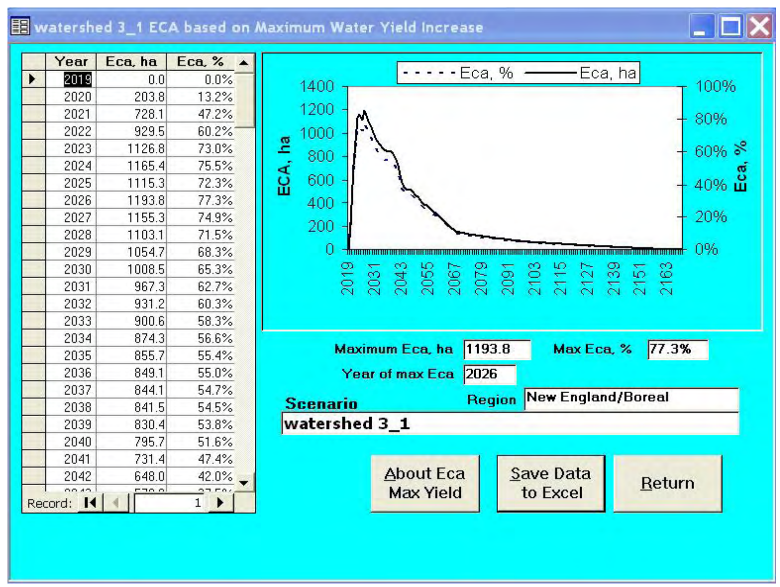
Appendix 4 WRENSS Inputs and Outputs

Watershed 3_1

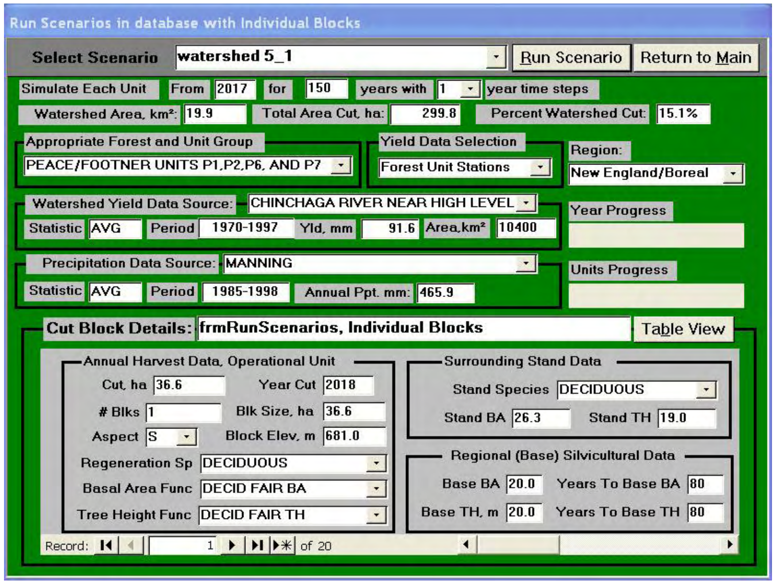


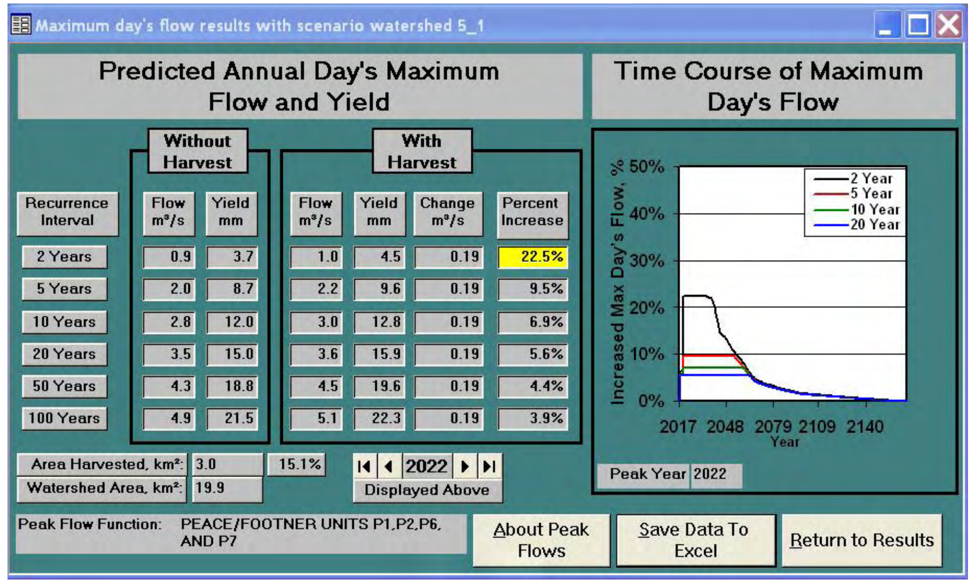


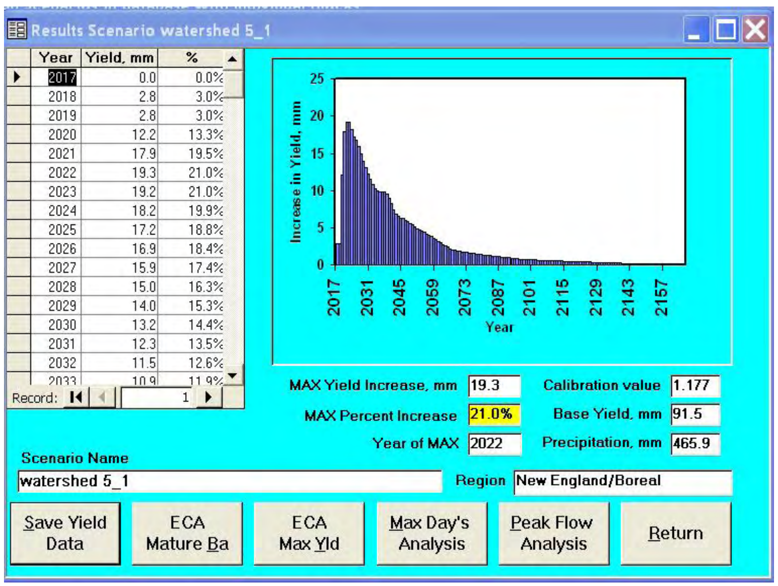


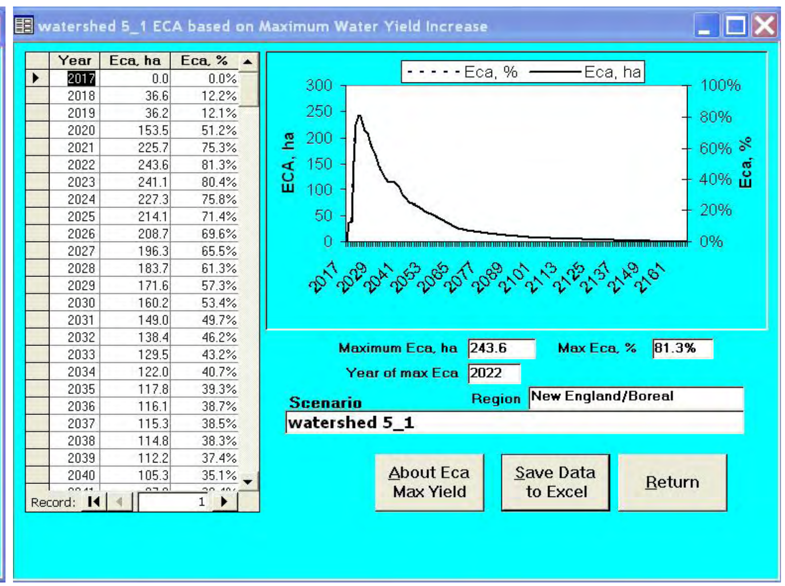


Watershed 5_1

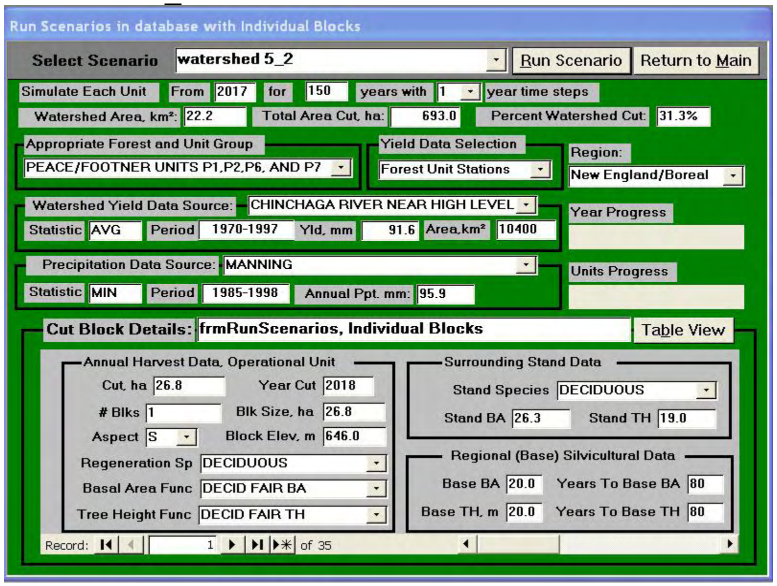


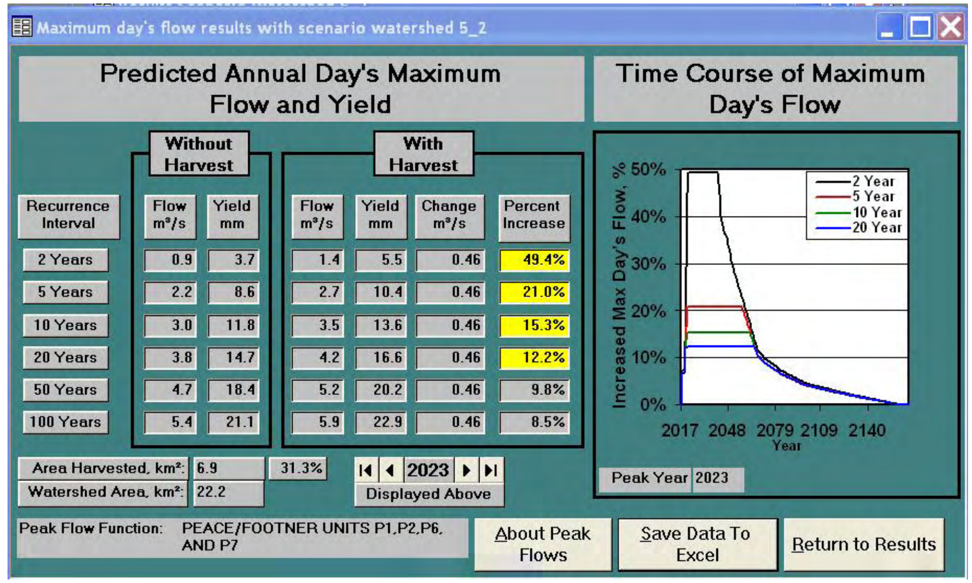


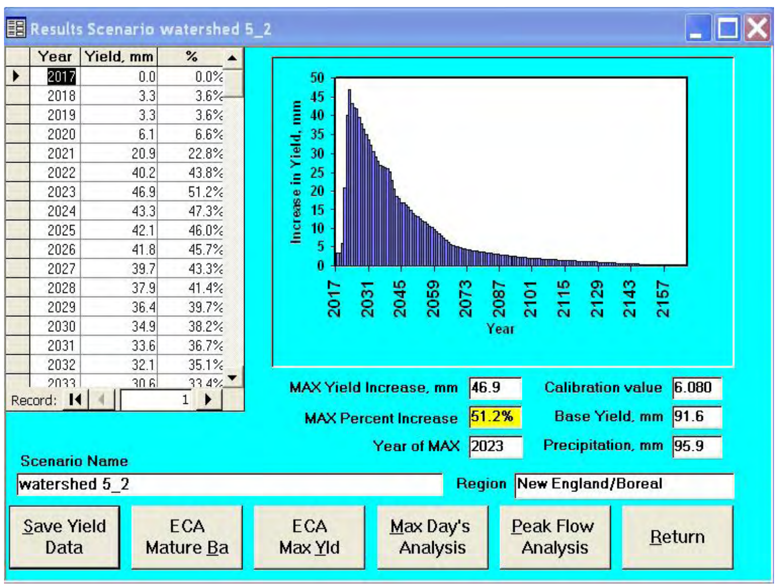


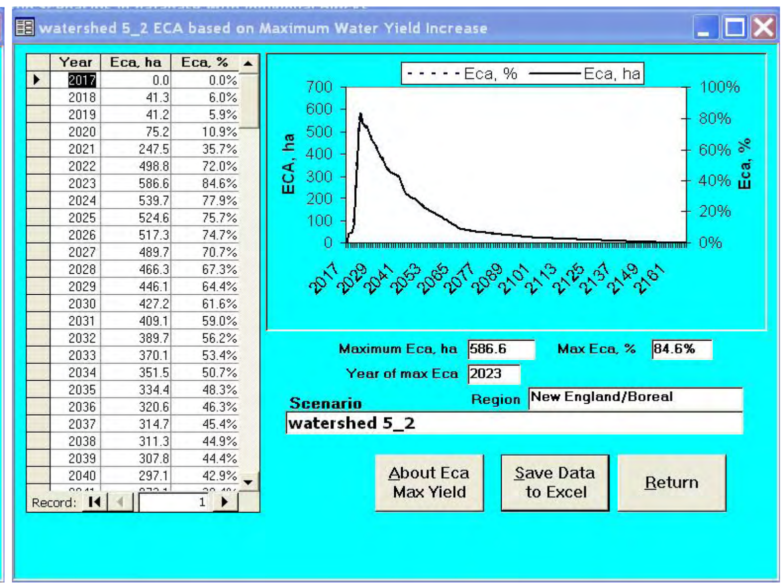


Watershed 5_2

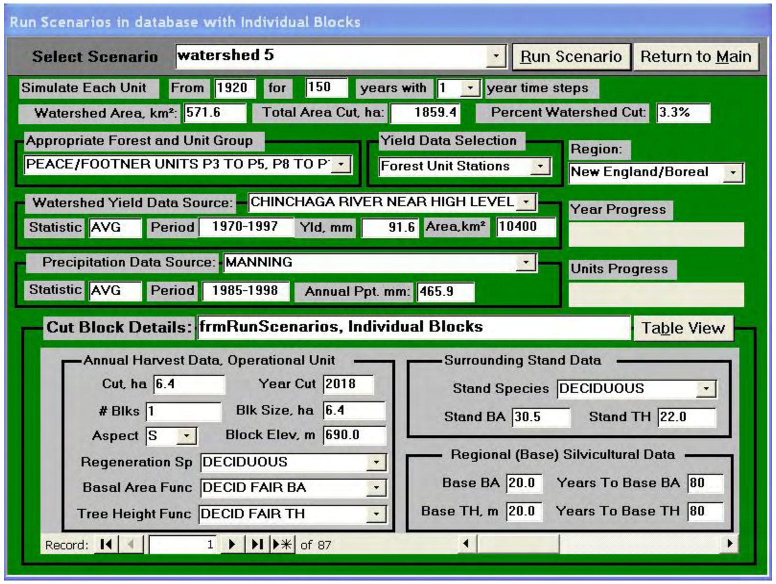


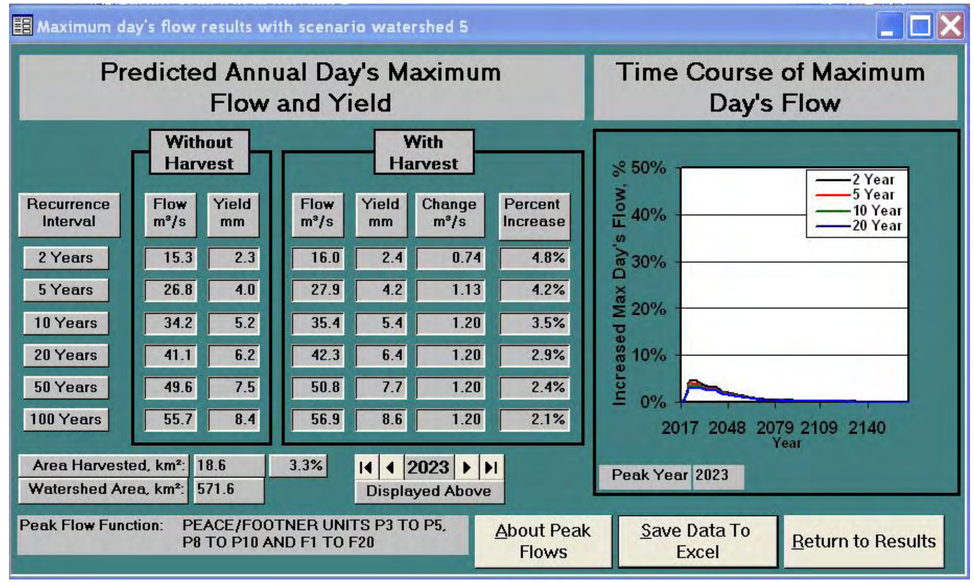


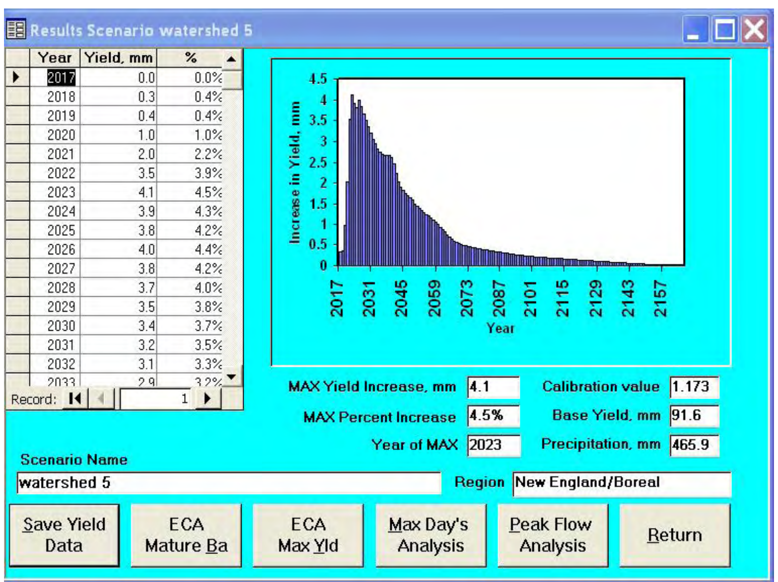


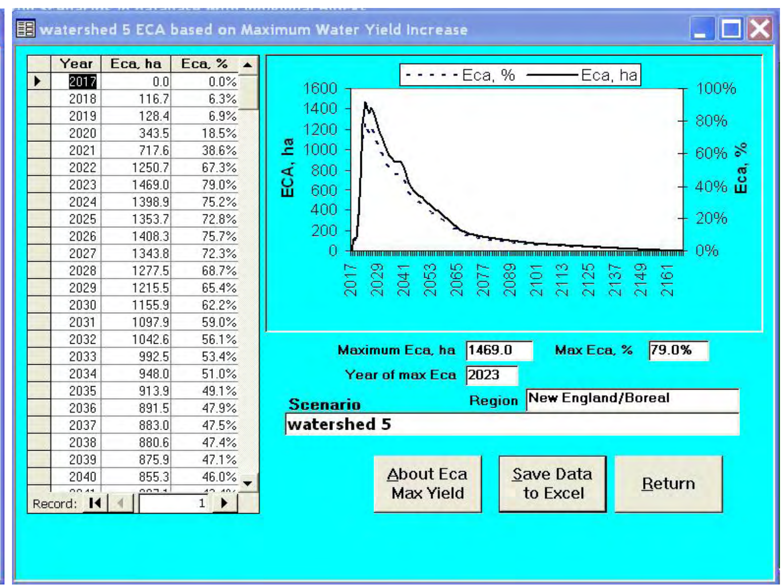


Watershed 5

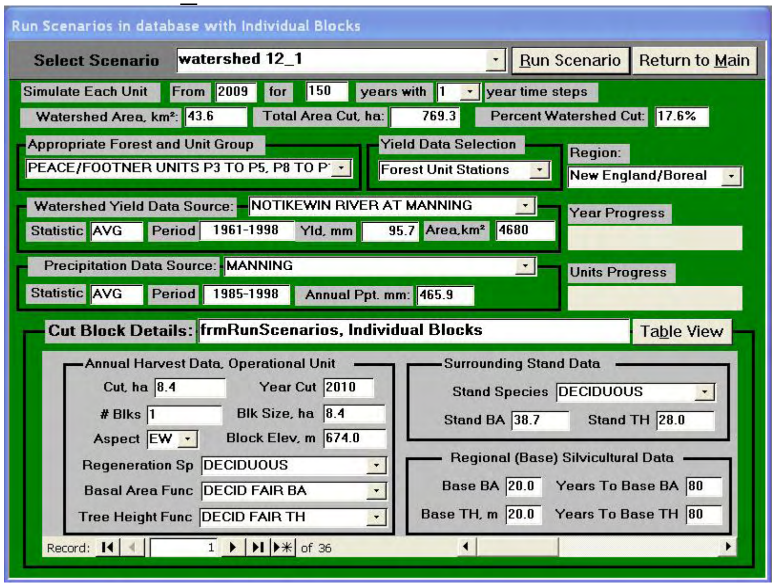

Run Scenarios in database with Individual Blocks
Select Scenario
watershed 5
Run Scenario
Return to Main
Simulate Each Unit From 1920 for 150 years with 1 year time steps
Watershed Area, km²: 571.6
Total Area Cut, ha: 1859.4
Percent Watershed Cut: 3.3%
Appropriate Forest and Unit Group
PEACE/FOOTNER UNITS P3 TO P5, P8 TO P
Yield Data Selection
Forest Unit Stations
Region:
New England/Boreal
Watershed Yield Data Source: CHINCHAGA RIVER NEAR HIGH LEVEL
Statistic AVG Period 1970-1997 Yld, mm 91.6 Area,km² 10400
Year Progress
Precipitation Data Source: MANNING
Statistic AVG Period 1985-1998 Annual Ppt, mm: 465.9
Units Progress
Cut Block Details: frmRunScenarios, Individual Blocks
Table View
Annual Harvest Data, Operational Unit
Cut, ha 6.4 Year Cut 2018
Blks 1 Blk Size, ha 6.4
Aspect S Block Elev, m 690.0
Regeneration Sp DECIDUOUS
Basal Area Func DECID FAIR BA
Tree Height Func DECID FAIR TH
Surrounding Stand Data
Stand Species DECIDUOUS
Stand BA 30.5 Stand TH 22.0
Regional (Base) Silvicultural Data
Base BA 20.0 Years To Base BA 80
Base TH, m 20.0 Years To Base TH 80
Record: 1 of 87

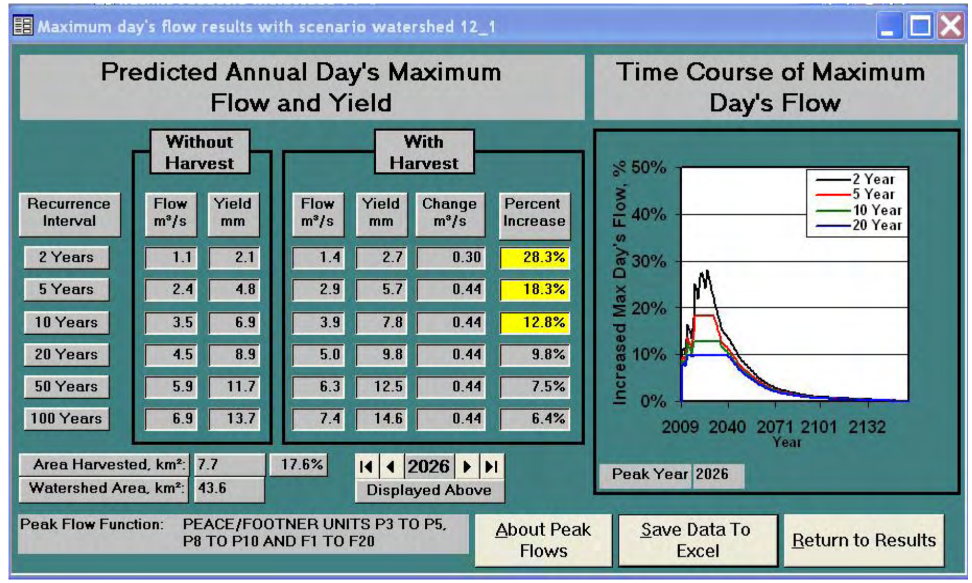

Maximum day's flow results with scenario watershed 5
Predicted Annual Day's Maximum Flow and Yield
Time Course of Maximum Day's Flow
Without Harvest
With Harvest
Recurrence Interval | Flow m³/s | Yield mm | Flow m³/s | Yield mm | Change m³/s | Percent Increase
2 Years | 15.3 | 2.3 | 16.0 | 2.4 | 0.74 | 4.8%
5 Years | 26.8 | 4.0 | 27.9 | 4.2 | 1.13 | 4.2%
10 Years | 34.2 | 5.2 | 35.4 | 5.4 | 1.20 | 3.5%
20 Years | 41.1 | 6.2 | 42.3 | 6.4 | 1.20 | 2.9%
50 Years | 49.6 | 7.5 | 50.8 | 7.7 | 1.20 | 2.4%
100 Years | 55.7 | 8.4 | 56.9 | 8.6 | 1.20 | 2.1%
Area Harvested, km²: 18.6 3.3%
Watershed Area, km²: 571.6
2023
Displayed Above
Increased Max Day's Flow, %
50%
40%
30%
20%
10%
0%
2 Year
5 Year
10 Year
20 Year
2017 2048 2079 2109 2140
Year
Peak Year 2023
Peak Flow Function: PEACE/FOOTNER UNITS P3 TO P5, P8 TO P10 AND F1 TO F20
About Peak Flows
Save Data To Excel
Return to Results

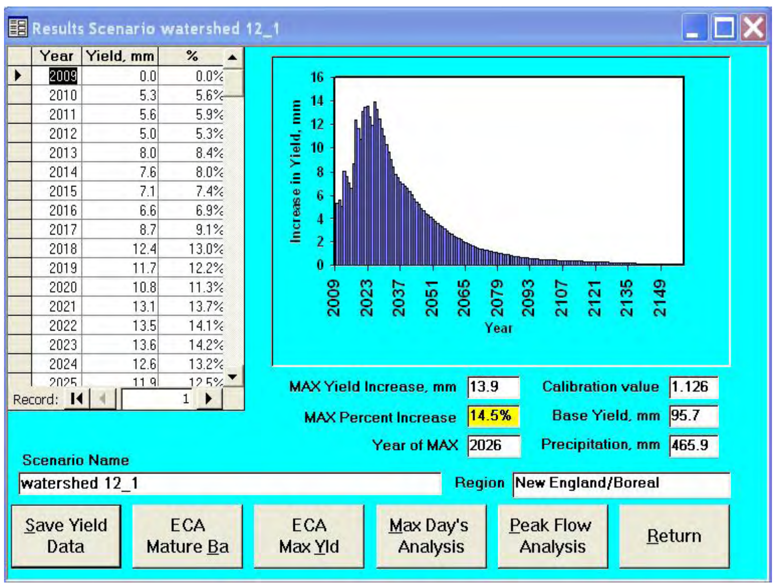

Results Scenario watershed 5
Year | Yield, mm | %
2017 | 0.0 | 0.0%
2018 | 0.3 | 0.4%
2019 | 0.4 | 0.4%
2020 | 1.0 | 1.0%
2021 | 2.0 | 2.2%
2022 | 3.5 | 3.9%
2023 | 4.1 | 4.5%
2024 | 3.9 | 4.3%
2025 | 3.8 | 4.2%
2026 | 4.0 | 4.4%
2027 | 3.8 | 4.2%
2028 | 3.7 | 4.0%
2029 | 3.5 | 3.8%
2030 | 3.4 | 3.7%
2031 | 3.2 | 3.5%
2032 | 3.1 | 3.3%
Record: 1
Increase in Yield, mm
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2017 2031 2045 2059 2073 2087 2101 2115 2129 2143 2157
Year
MAX Yield Increase, mm 4.1
Calibration value 1.173
MAX Percent Increase 4.5%
Base Yield, mm 91.6
Year of MAX 2023
Precipitation, mm 465.9
Scenario Name
watershed 5
Region New England/Boreal
Save Yield Data
ECA Mature Ba
ECA Max Yld
Max Day's Analysis
Peak Flow Analysis
Return

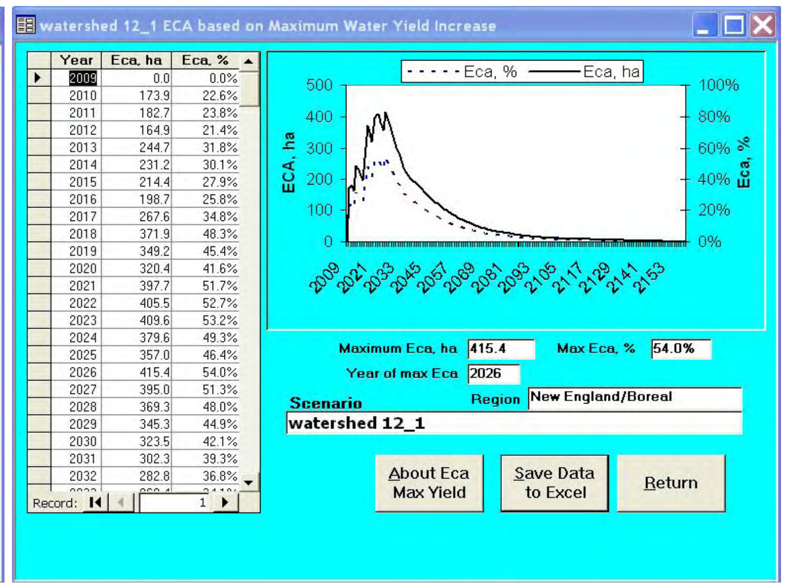

watershed 5 ECA based on Maximum Water Yield Increase
Year | Eca, ha | Eca, %
2017 | 0.0 | 0.0%
2018 | 116.7 | 6.3%
2019 | 128.4 | 6.9%
2020 | 343.5 | 18.5%
2021 | 717.6 | 38.6%
2022 | 1250.7 | 67.3%
2023 | 1469.0 | 79.0%
2024 | 1398.9 | 75.2%
2025 | 1353.7 | 72.8%
2026 | 1408.3 | 75.7%
2027 | 1343.8 | 72.3%
2028 | 1277.5 | 68.7%
2029 | 1215.5 | 65.4%
2030 | 1155.9 | 62.2%
2031 | 1097.9 | 59.0%
2032 | 1042.6 | 56.1%
2033 | 992.5 | 53.4%
2034 | 948.0 | 51.0%
2035 | 913.9 | 49.1%
2036 | 891.5 | 47.9%
2037 | 883.0 | 47.5%
2038 | 880.6 | 47.4%
2039 | 875.9 | 47.1%
2040 | 855.3 | 46.0%
Record: 1
Eca, %
Eca, ha
ECA, ha
1600
1400
1200
1000
800
600
400
200
0
100%
80%
60%
40%
20%
0%
Eca, %
2017 2029 2041 2053 2065 2077 2089 2101 2113 2125 2137 2149 2161
Maximum Eca, ha 1469.0
Max Eca, % 79.0%
Year of max Eca 2023
Scenario
Region New England/Boreal
watershed 5
About Eca Max Yield
Save Data to Excel
Return

Watershed 12_1

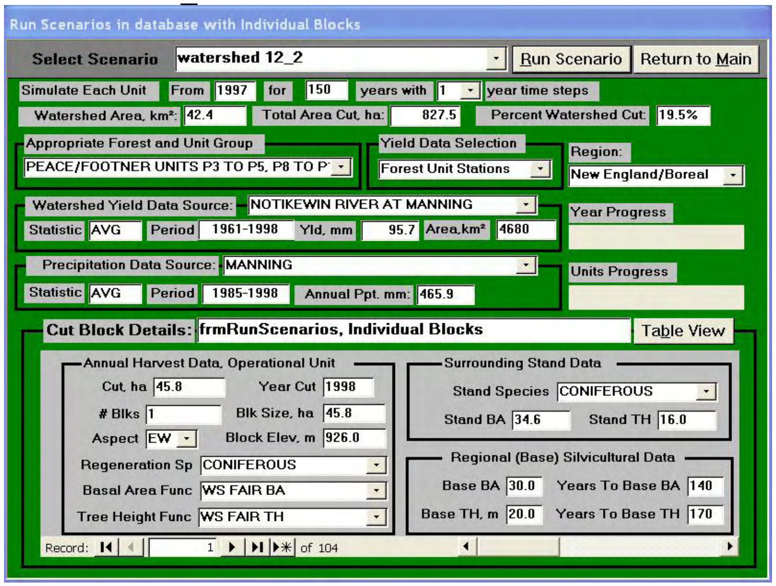


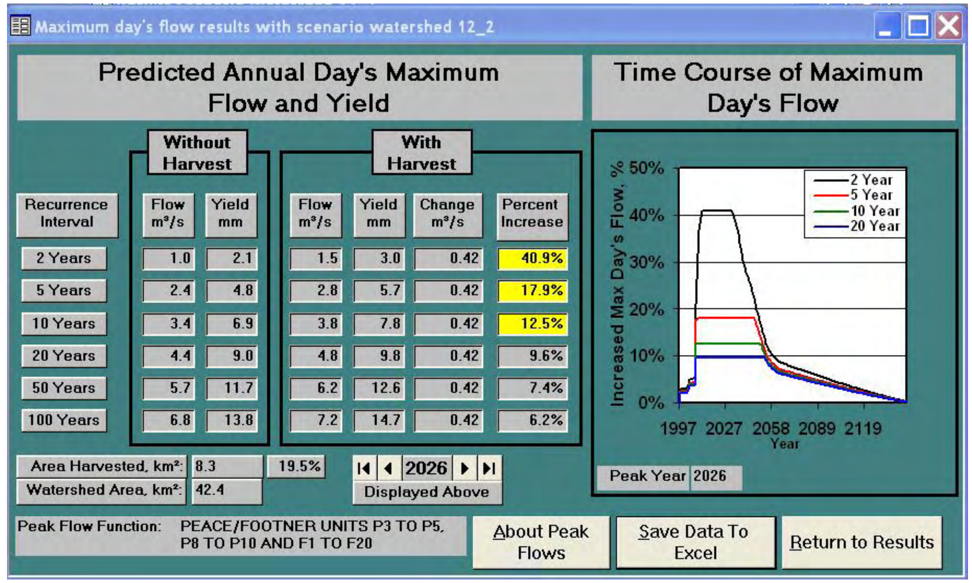


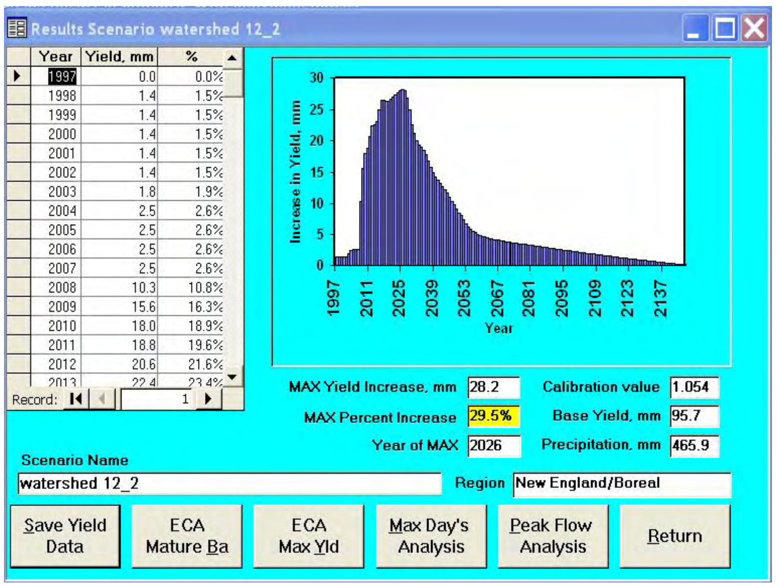


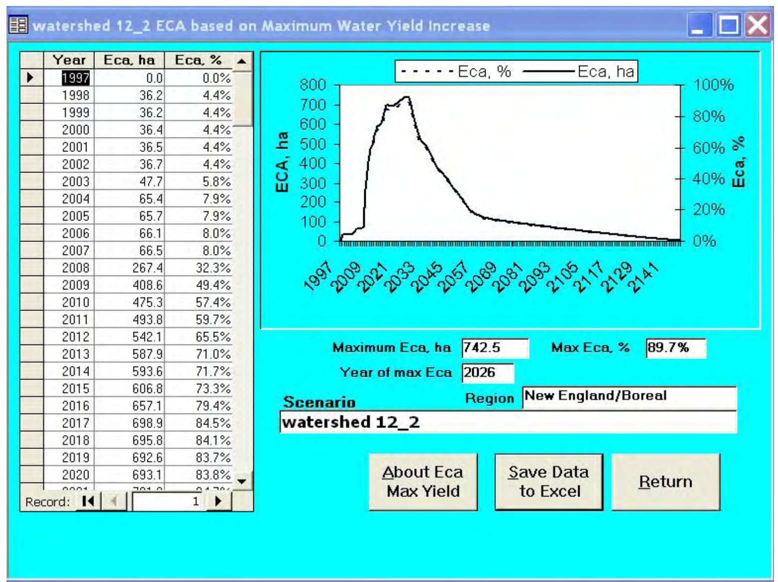


Watershed 12_2

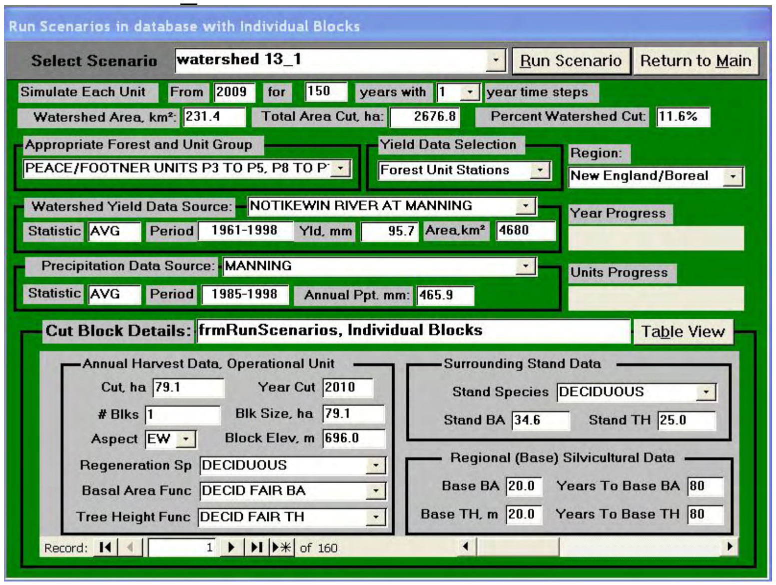


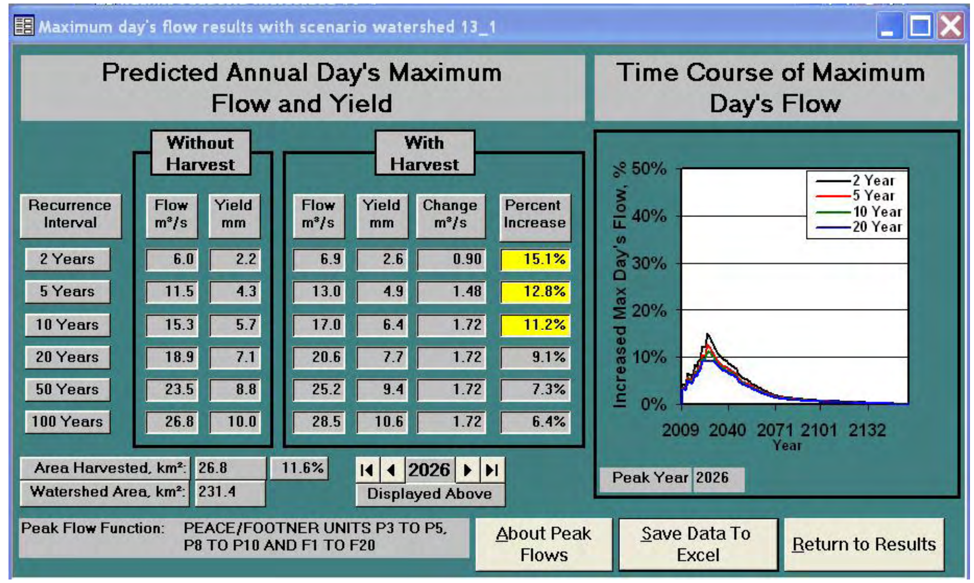


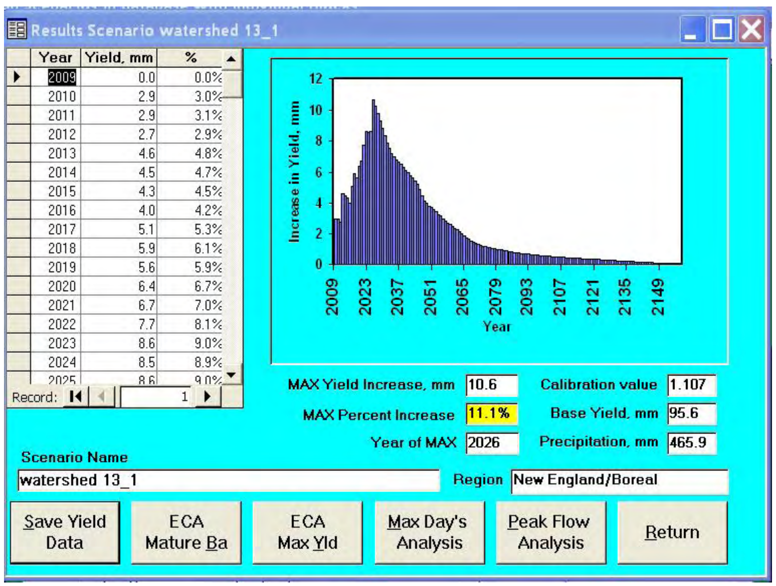


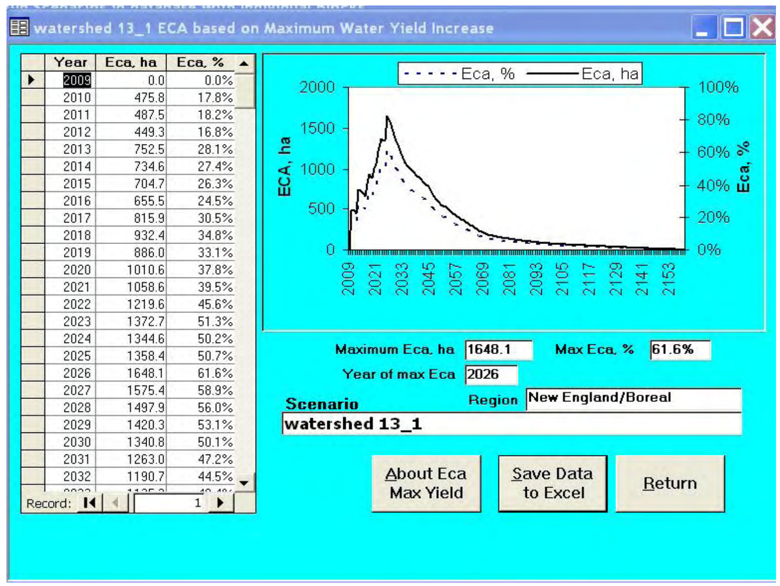


Watershed 13_1

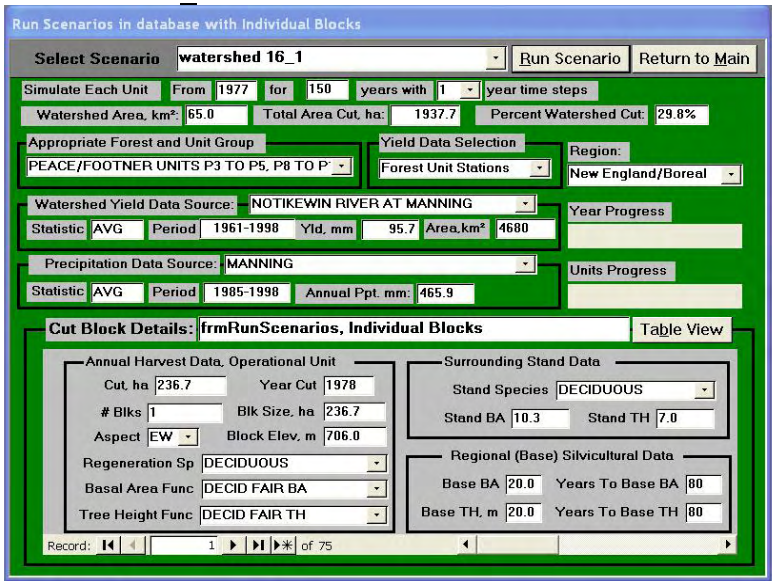


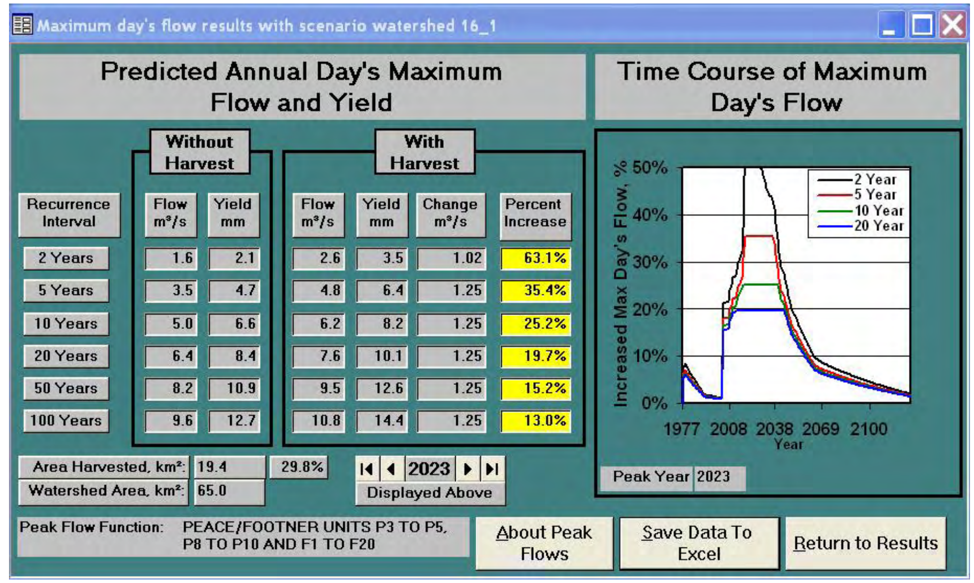


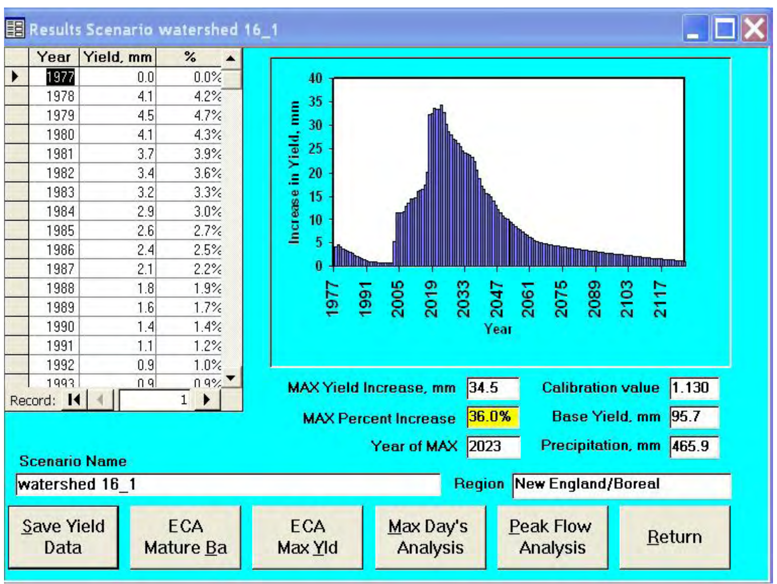


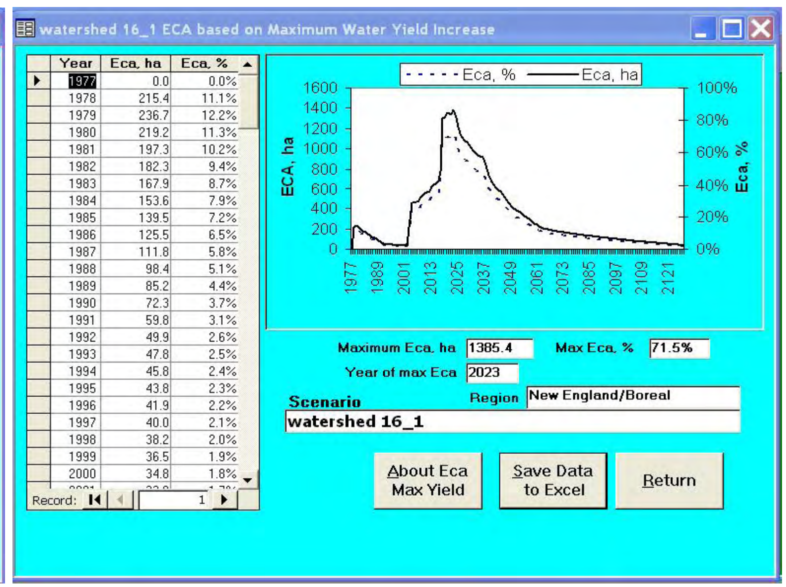


Watershed 16_1

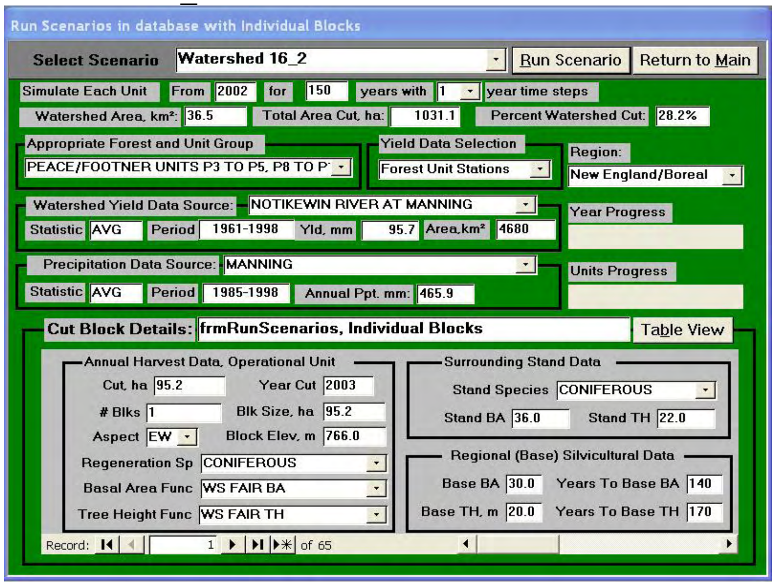


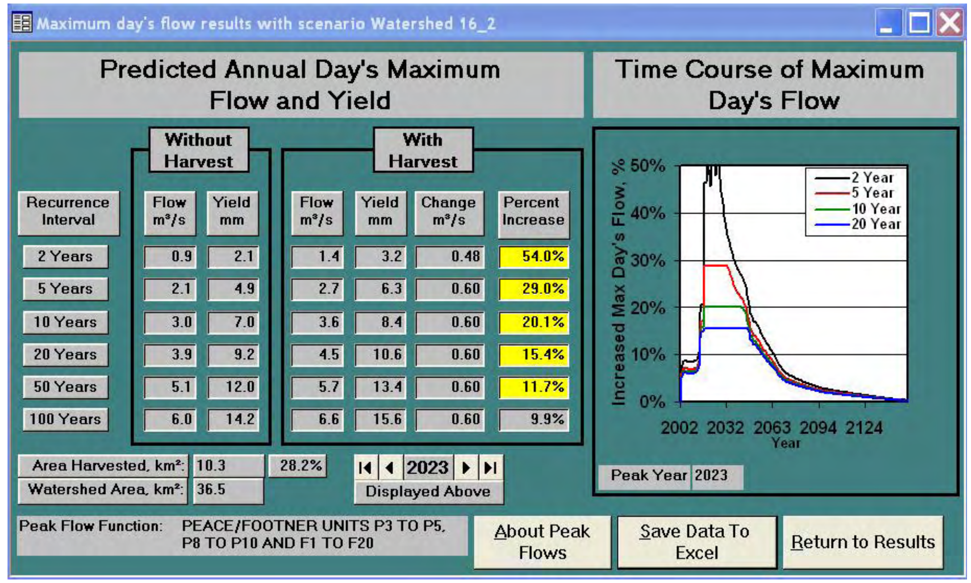


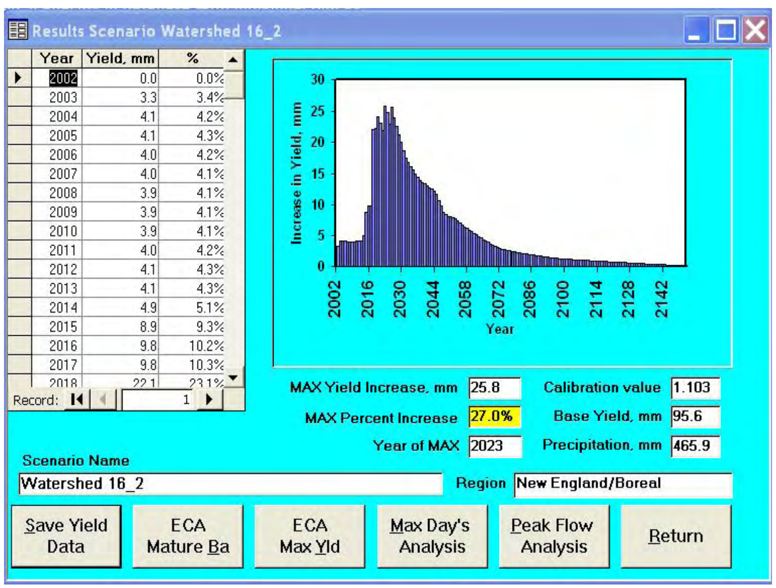


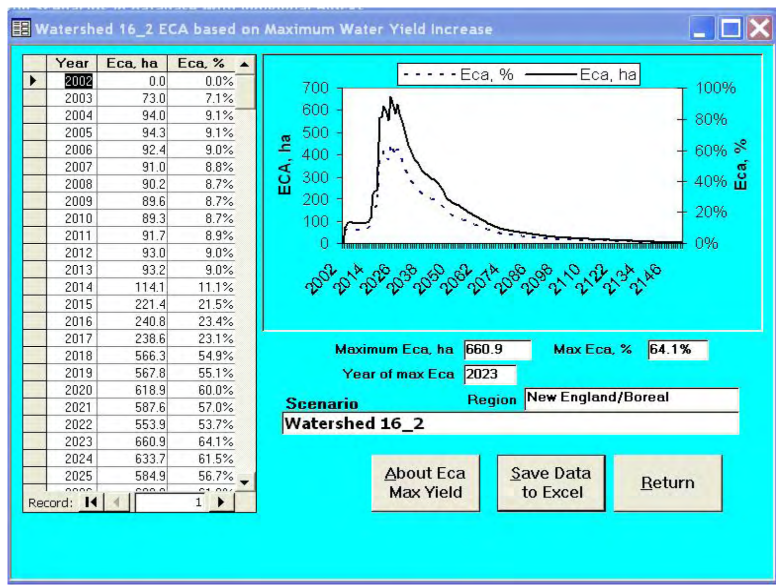


Watershed 16_2

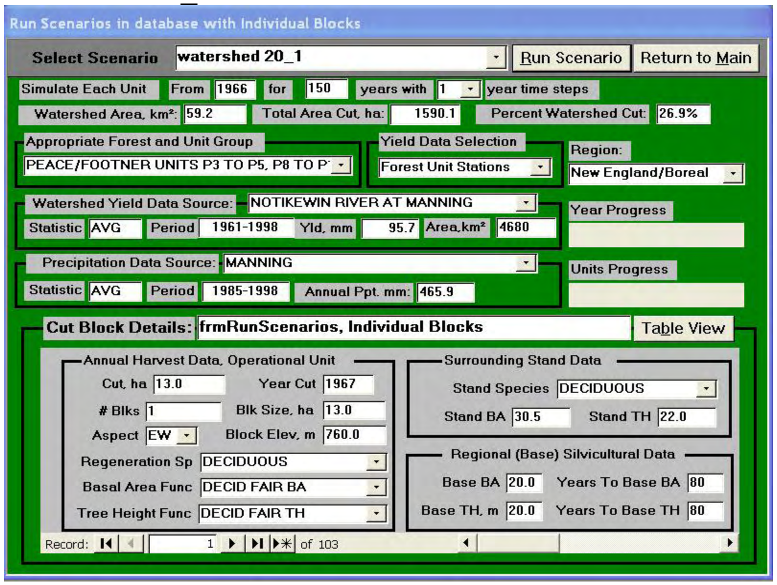


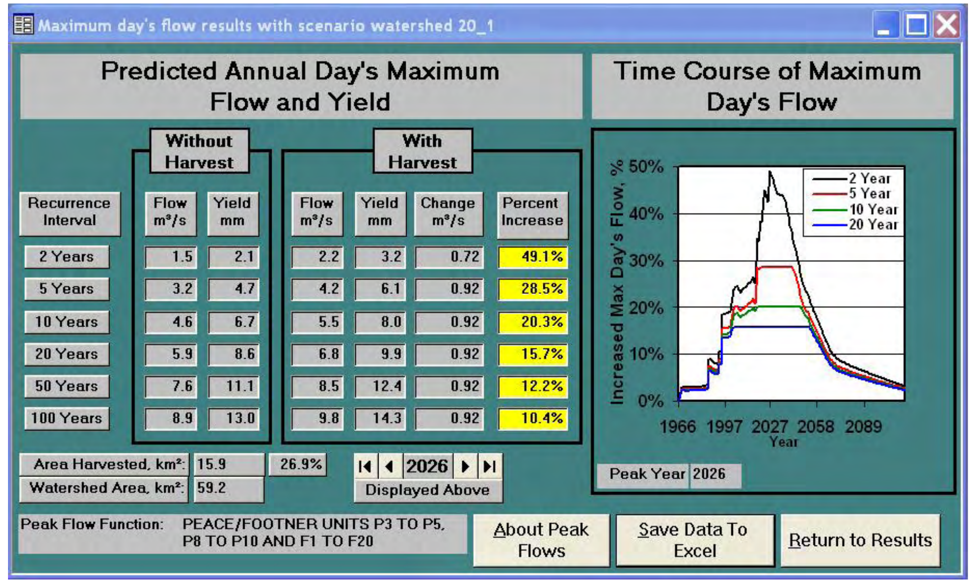


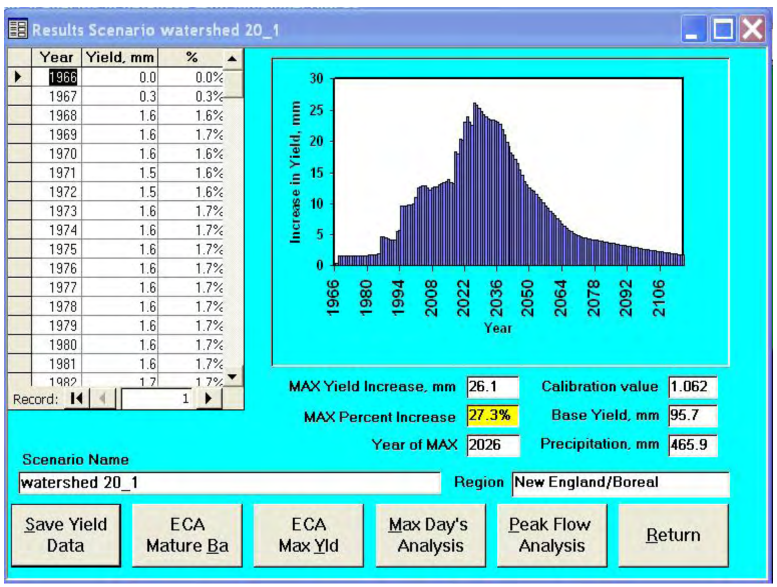


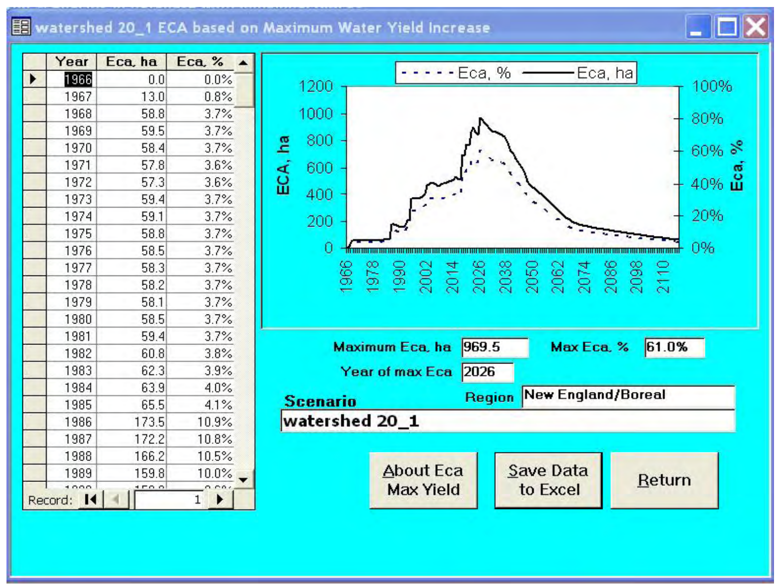


Watershed 20_1

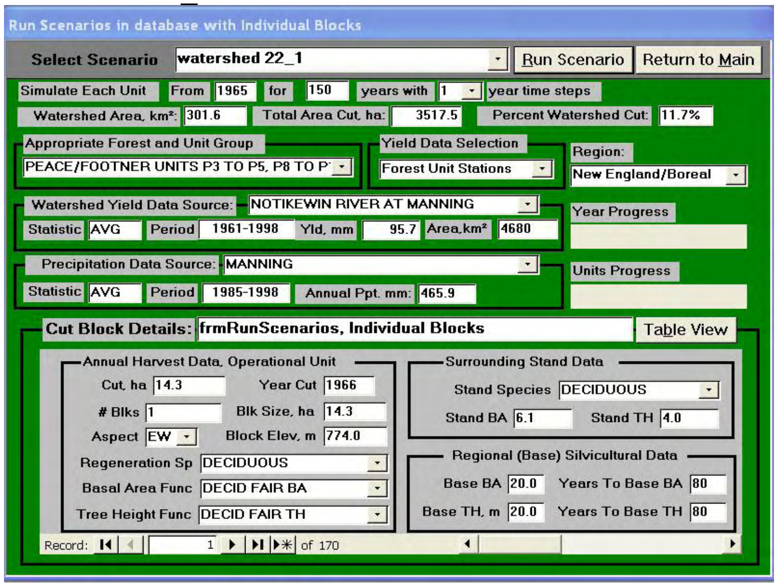


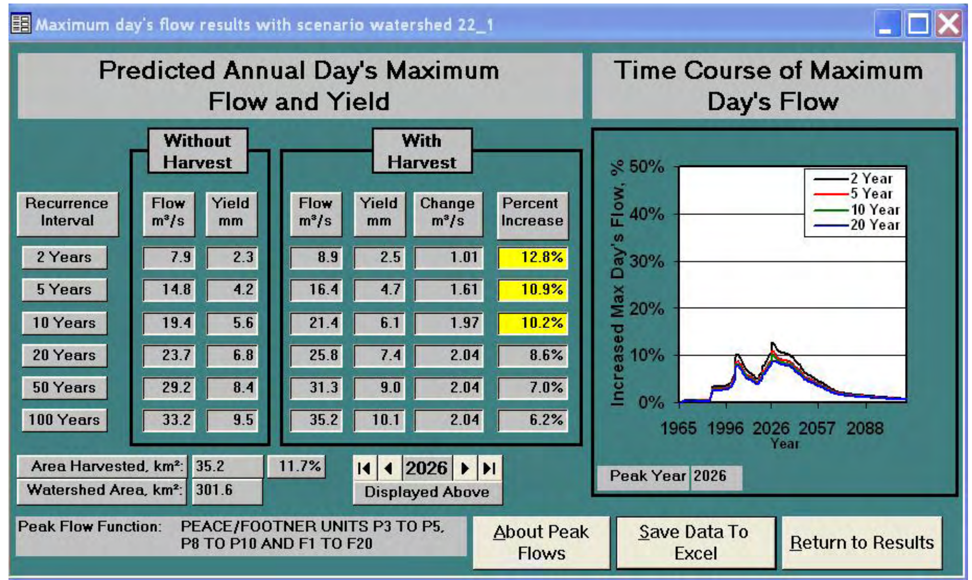


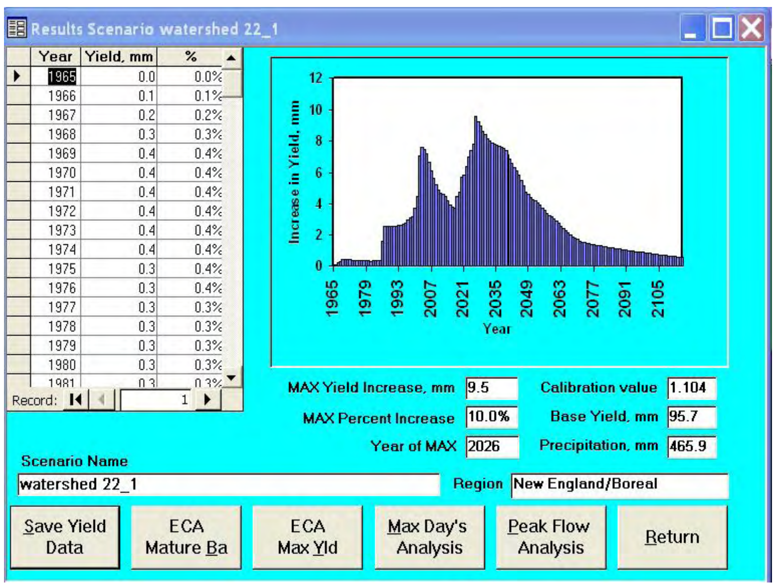


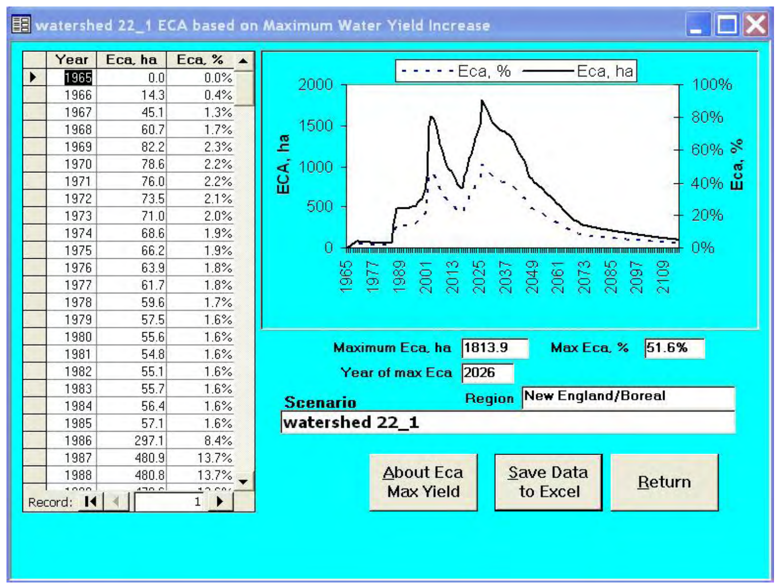


Watershed 22_1









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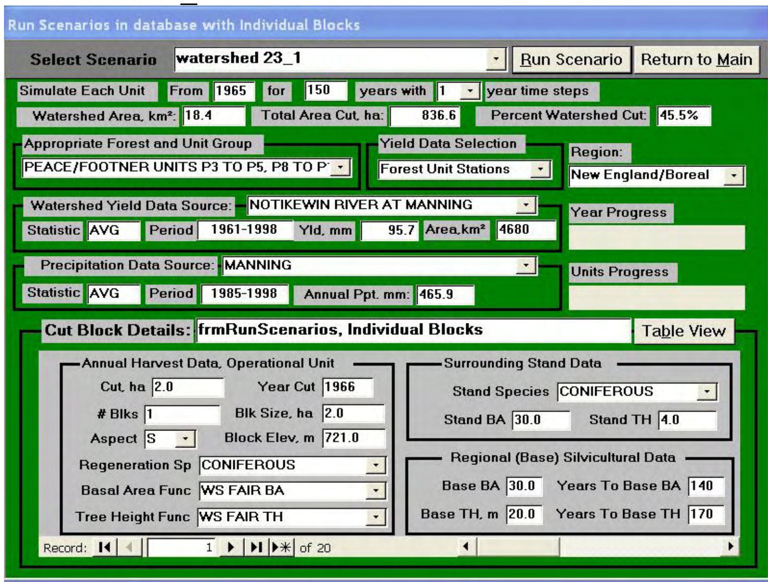
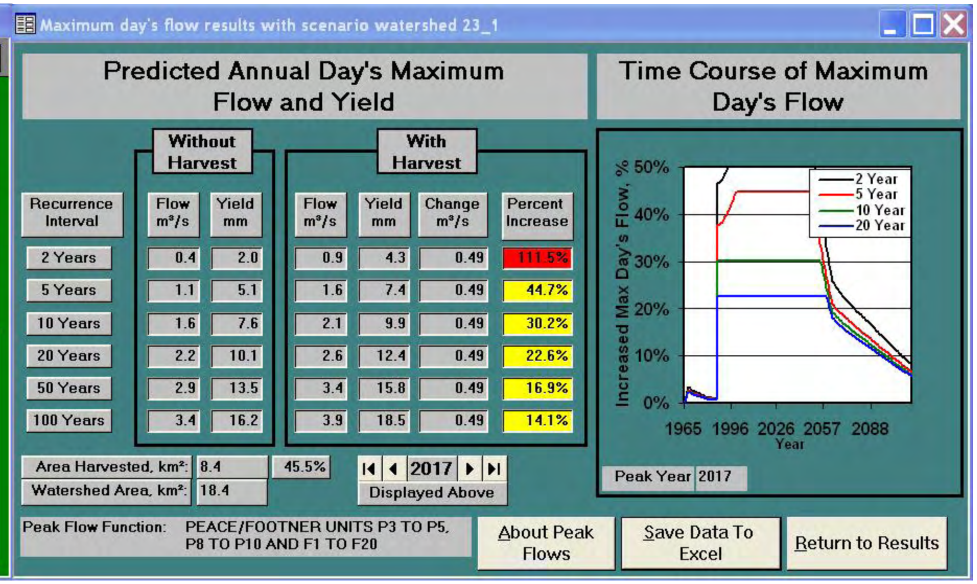
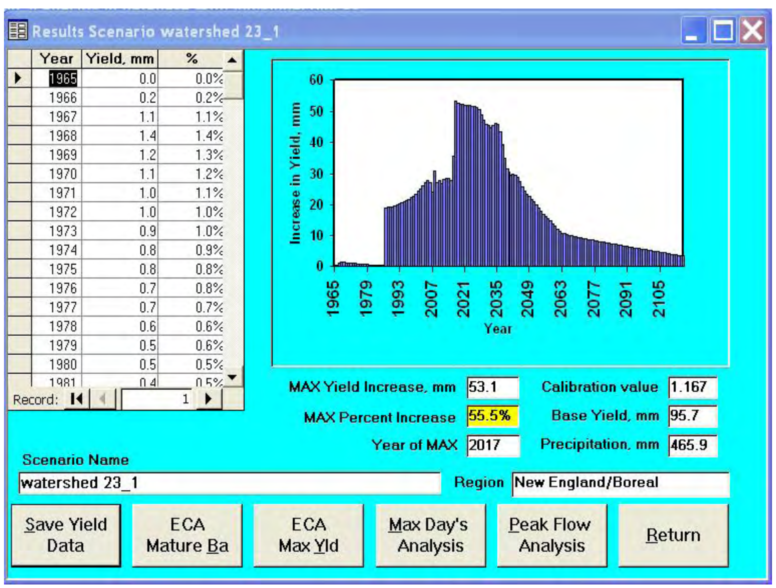
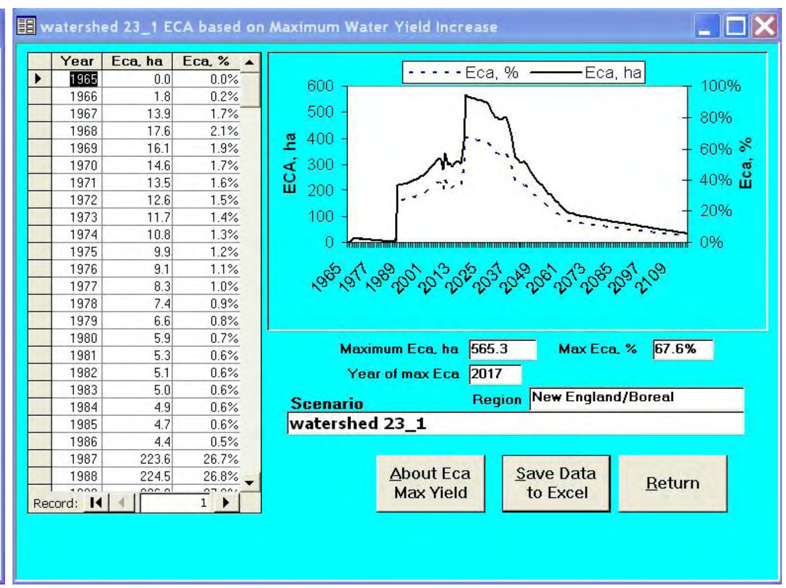
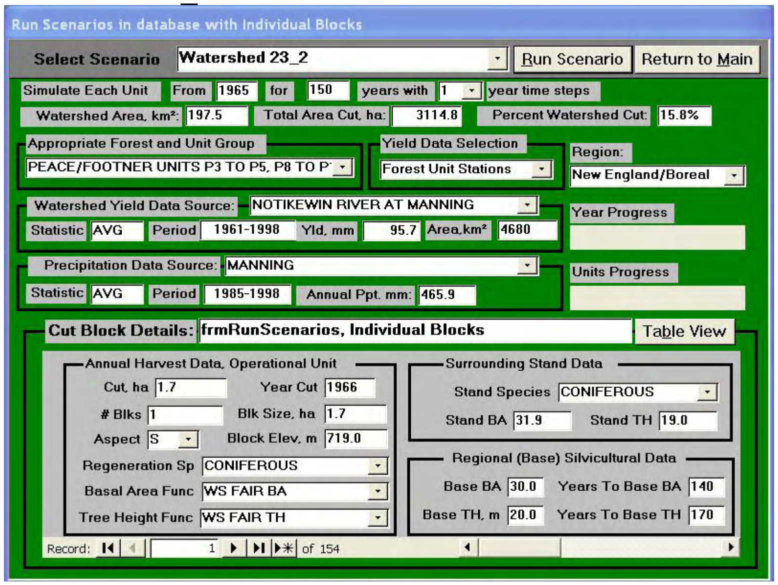


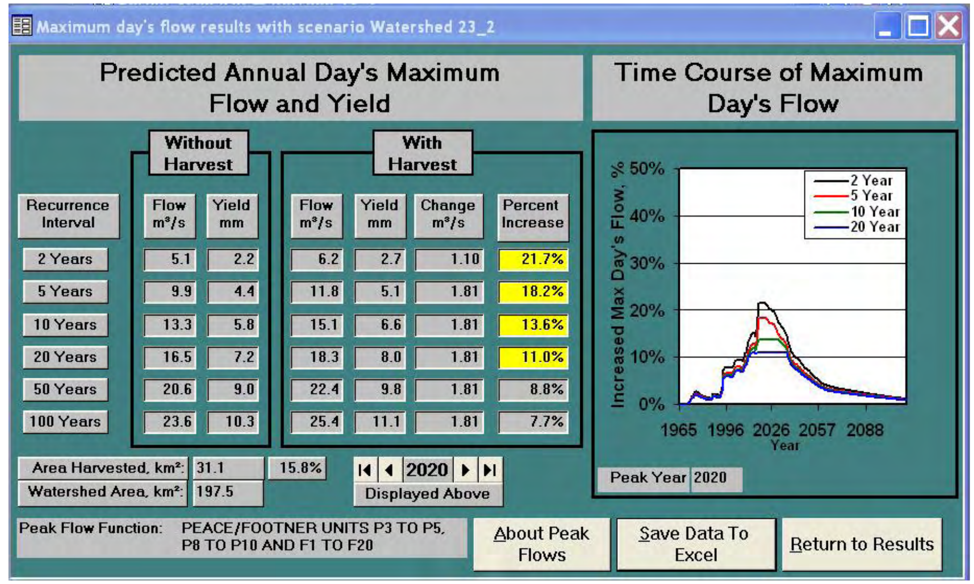


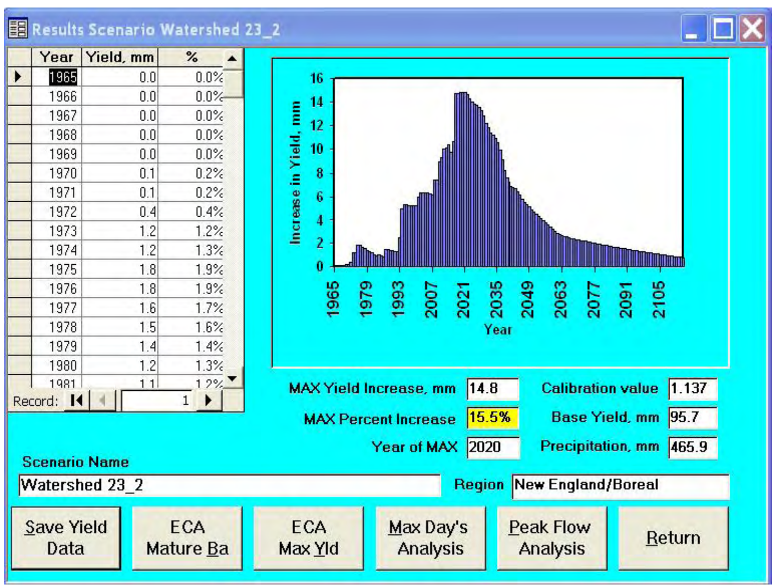


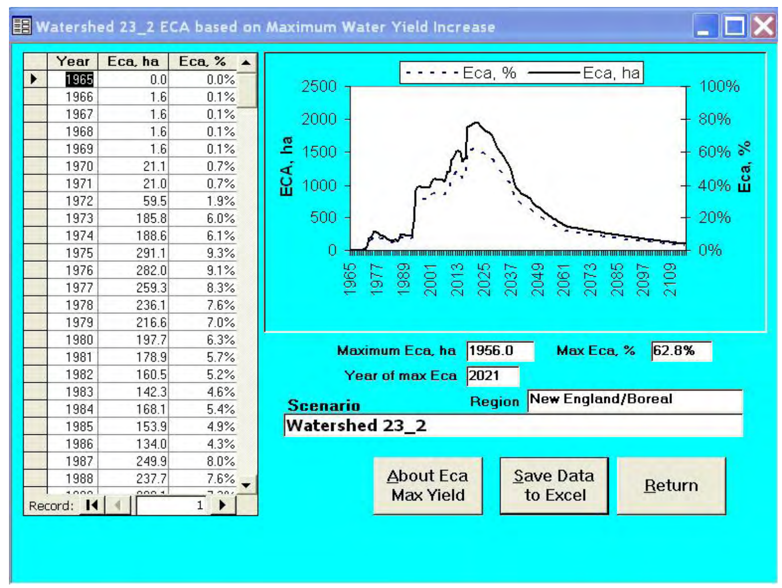


Watershed 23_2









Watershed 16