

Bertrand Creek Improvement Project
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Bertrand Creek Hydrologic Model Update and Assessment

Draft Final Report

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Abstract

This report describes the Bertrand Creek update of the surface water quantity hydrologic model, TOPNET, which was originally developed as part of the WRIA1 Water Management project. The model update has increased the spatial discretization of model elements, which has resulted in an improved representation of the spatial variability of precipitation, as well as land use and soil based parameters in both the U.S. and Canadian portions of the watershed. After updating the hydrologic model, we conducted a new calibration to the observed streamflow measurements at Bertrand Creek watershed outlet at Rathbone Road, which began in 2003. Nash-Sutcliffe efficiency statistics greater than $E = 0.85$ show that the updated model and calibration are a good representation of the hydrologic system, given the current drainage and groundwater pumping practices. Using a historic climate record of 60 years, the water balance presented illustrates the mean monthly relationships between precipitation, baseflow, soil storage, surface runoff, and irrigation demand. Exceedence probability flow results show that there is a low probability of sustaining both irrigation water use and instream flows without significant water management activities. To understand the potential effects of proposed management solutions, the updated model developed in this work can be used for scenario testing and sensitivity analysis in future work.

Introduction

This work updates the Bertrand Creek Hydrologic Model developed in the WRIA1 Water Management project by focusing on the following activities: sub-basin delineation with additional node locations, calibration to observed streamflow modified by an estimation of consumptive water use, and statistical analysis of model outputs specified to support instream flow negotiations. The first aim of this task is to improve our understanding of the physical hydrology and climate variability of the Bertrand Creek watershed. Another important aim of this task is to document a modeling process which ensures relevance for current and future decision-making, and is transferable to updating other watersheds in the region.

All spatial data inputs of the WRIA1 Water management project have been re-processed for the extent of Bertrand Creek. The data inputs that are the same as the WRIA1 project are the precipitation and temperature time series (end date 5/31/2006). The location of additional nodes for increased sub-basin delineation has been determined using current and future stream gage locations, as well as soil and geologic information. The model parameterization based on soils has been updated based on available SSURGO soils information and preliminary groundwater model work provided by Diana Allen. The model parameterization based on land use and vegetation has been updated only in the Canadian portion (Koole and Steensma, 2007).

Observed streamflow data has been collected and analyzed for use in the calibration of the updated Bertrand Creek model. The two calibration locations are Bertrand Creek at Rathbone Road, and Bertrand Creek at the International border. The water use and irrigation management information available in the Comprehensive Irrigation District Management Plan (WID, 2004) and the Groundwater Investigations of Bertrand and Ten-Mile Creek (Barber et al., 2008), have been used to develop a set of time series of estimated surface water diversions and groundwater pumping streamflow effects for the length of the model calibration periods, at specified model nodes. Water use from Canada has been incorporated into the model using surface water licenses. The estimated effect of surface water diversions and ground water pumping has been added to the observed streamflow to create a naturalized streamflow time series for calibration. The model calibration was conducted with an automatic calibration algorithm called

MOSCEM, which is a multi-objective global optimization software tool. Nash-Sutcliffe efficiency statistics confirm that the calibrated results of the updated model at Rathbone Road are a significant improvement compared to the WRIA1 model. However, the results for both models are not as good at the International border, which has only a low flow seasonal gage for observed records and little information about upstream water use. Further analysis of flow volume error, mean monthly water budget, and exceedence flow analysis show that future modeling could be improved with additional data collection that informs the timing of groundwater pumping on streamflow. However, the updated model is a good representation of streamflow values than can be expected given the current drainage system and use of groundwater for irrigation.

Model Element Update

Sub-basin delineation using stream gage locations, soils, and geology

Locations for surface runoff model outputs were selected in order to design a hydrologic model for long-term use in Bertrand Creek. Model output locations are referred to here as nodes, and the contributing surface area of each node is referred to as a sub-basin. The criteria for selecting nodes in this project included historic stream gage locations, potential future stream gage locations, the confluences of major creek tributaries, and tributary crossings at the International border. Additionally, nodes were added to further subdivide sub-basins with spatially variable soil and geologic properties. First, sub-basins were delineated based on natural stream lines and ditches. The creation of sub-basins by terrain analysis is dependent on the National Elevation Dataset 30-m digital elevation model (DEM), but can be modified by creating digital ditches and walls to force the creation of stream networks and sub-basin boundaries. The stream network was developed by terrain analysis combining natural stream lines and ditch lines in the US portion, with natural stream lines in the Canadian portion.

Figure 1 shows the Bertrand Creek watershed and the node locations connected by the stream network. Figure 2 shows the US portion of the Bertrand Creek watershed

with the node locations, sub-basins, and stream network together with the existing roads and ditches. Figure 3 shows the geology and soils data (hydraulic conductivity) used to add node locations. This step was included with the assumption that each sub-basin should be spatially consistent given physical properties that are converted into parameters such as transmissivity and hydraulic conductivity. The soils data are from the NRCS SSURGO database for Whatcom County; the geology data was provided by David Tarboton and was developed during the WRIA1 project.

The node locations for this project include several categories discussed above. There are 48 nodes and sub-basins.

Historic and Current Stream data locations

- Bertrand Creek at the International Boundary
- Jackman Ditch near H Street
- Bertrand Creek @ Birch Bay-Lynden east
- Bertrand Creek near Lynden - Rathbone Road
- Bertrand Creek Watershed Outlet

Potential Future Stream gages

- Bertrand Creek @ Bertrand at H St Bridge
- Bertrand Creek Intensive Site

Ungaged tributaries at International border

- Border Central Crossing 1 – East of Jackman Ditch
- Border Central Crossing 2 – to Jackman Ditch
- Border East Crossing

Soils

- 1. Coarse grain glacial outwash (CGGOW) is separated from bog in the southeast corner of the watershed.
- 2. Coarse grain glacial outwash (CGGOW) is separated from alluvium in the south of the watershed.
- 3. This location was used to break up a previously large sub-basin where the hydraulic conductivity is spatially variable.
- 4. Fine grain glacial outwash (FGGOW) is separated from CGGOW in the northwest of the watershed.

Confluences

- 32 locations where creeks and tributaries join each other and/or Bertrand Creek. There will be model outputs at each of the sub-basins.

Potential Future Ponds

- West High
- Groen

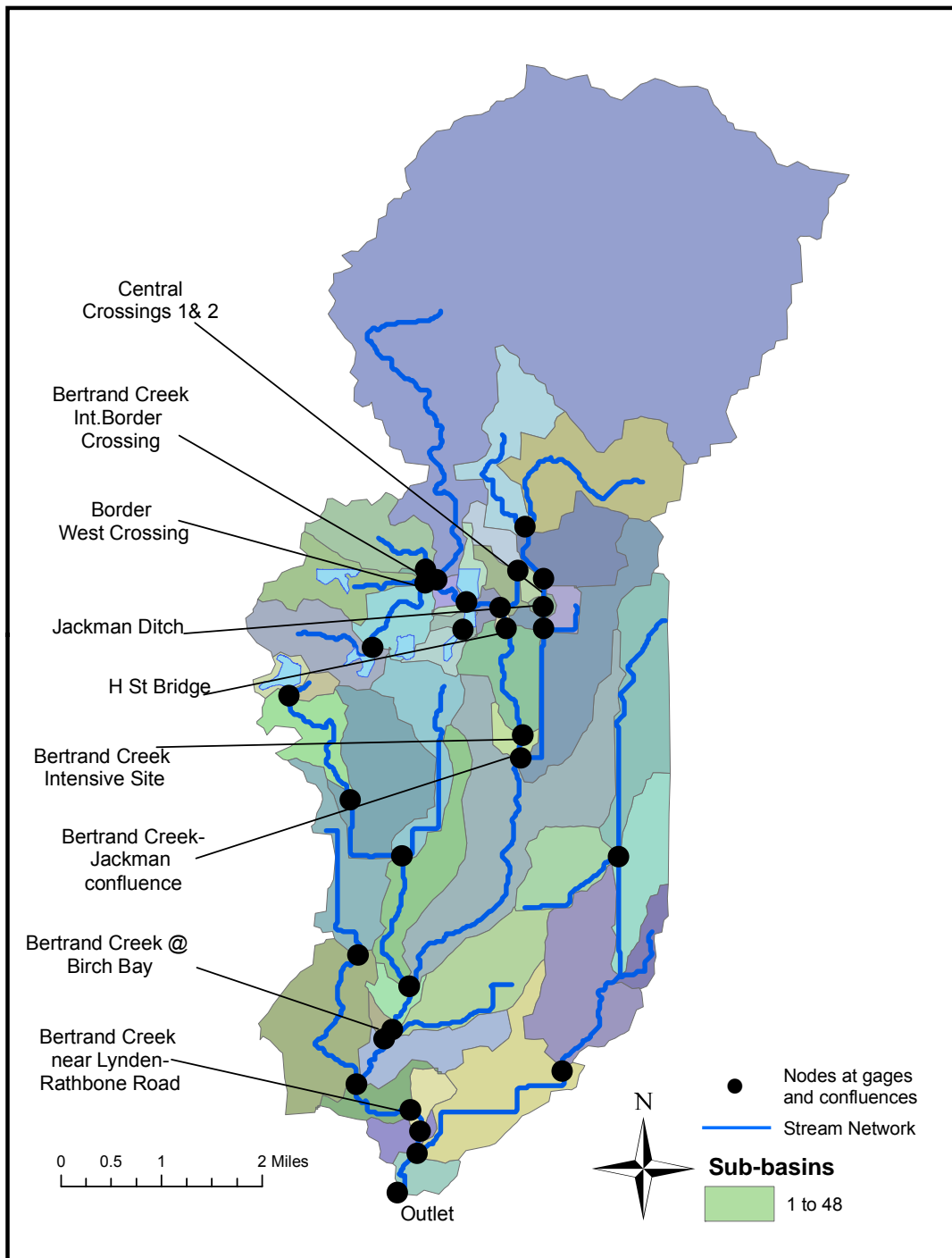


Figure 1. Updated Bertrand Creek Hydrologic model sub-basins and node locations. Nodes without labels are those at confluences or geo-soil locations.

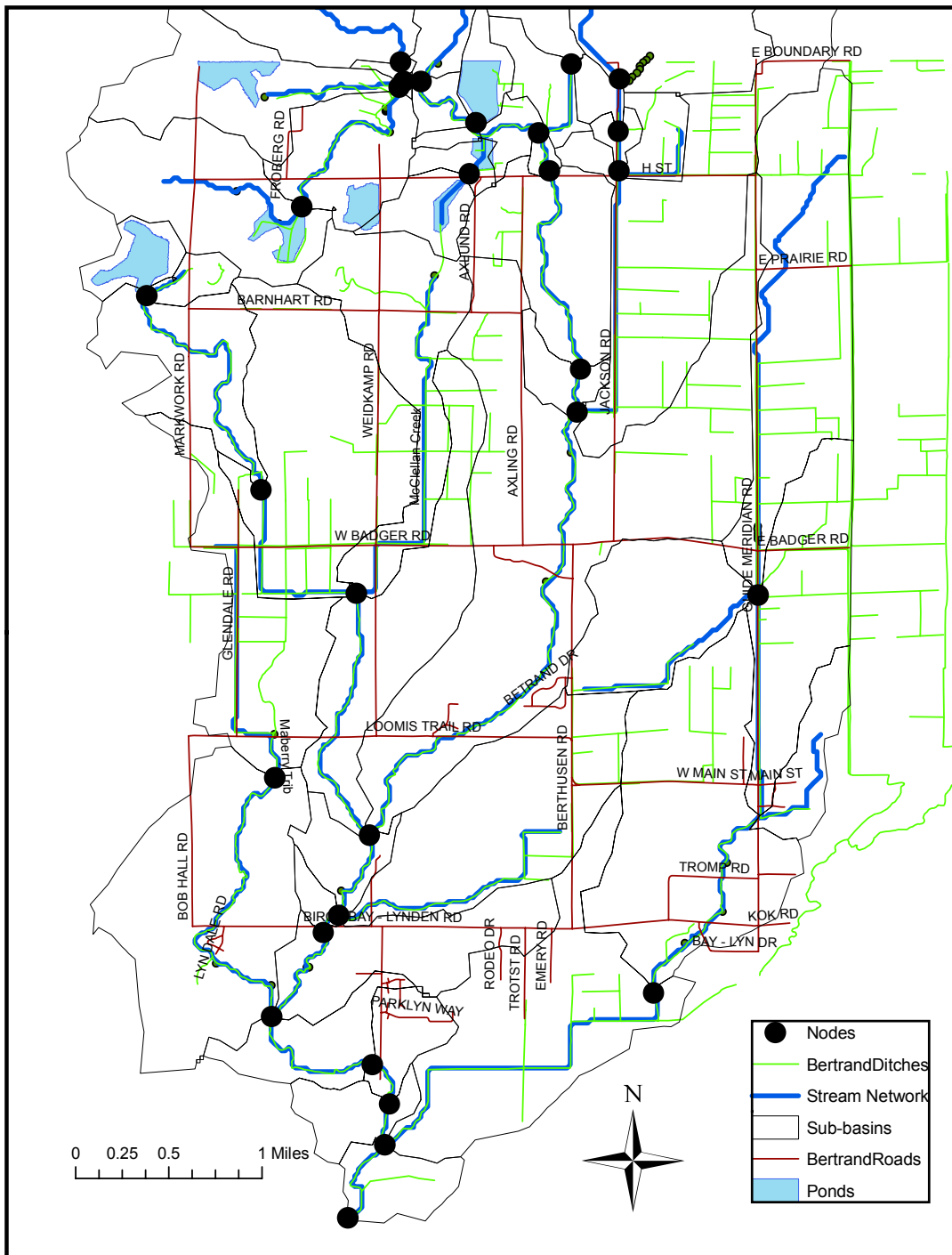
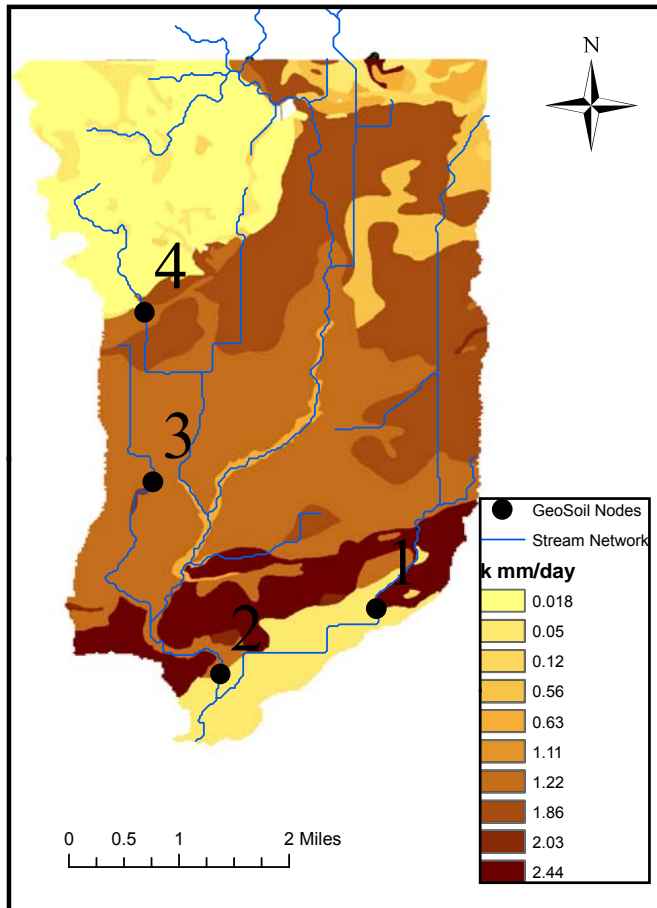
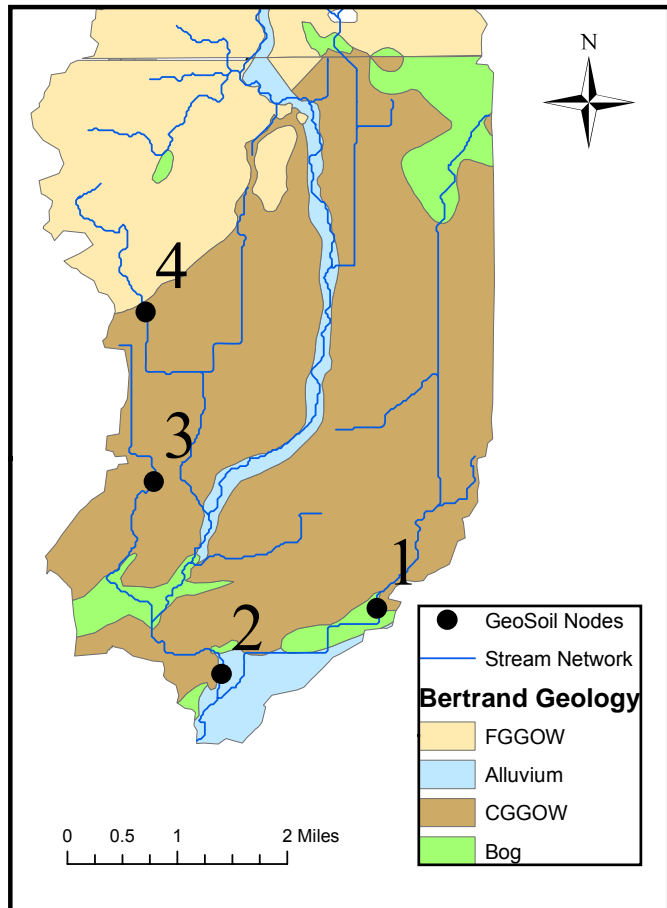


Figure 2. The US portion of the Bertrand Creek watershed with nodes, sub-basins, and stream network shown with existing roads and ditches.



1
 2 Figure 3. Additional nodes based on geology and soil properties (hydraulic conductivity is shown here).

3

Sub-basin delineation for potential future pond sites

During this project, sub-basin delineation was determined based on model utility in the event of future storage pond development. Pond locations were based on the information provided in the Bertrand Creek Surface Storage Reconnaissance Report by Anderson and Welch (2007). There are two ways to model reservoirs or storage ponds, in TOPNET. The first is an instream reservoir where the water source is from the drainage area calculation. The second is as an offstream reservoir; in this case the modeler defines the source sub-basin and defines rules for how much water goes in and out of the reservoir. If a future storage reservoir exists within any of the sub-basins, it can be modeled as a source to the sub-basin where it drains naturally, or to any other sub-basin. Nodes for West High and Groen were included because a node could be located on an existing stream network near the proposed outlet. The other storage reservoir can be modeled within the sub-basins that are currently grouped as confluences.

First, sub-basins were delineated based on natural stream lines and ditches. Next, sub-basins were delineated after modifying the DEM to essentially ‘dig out’ a pond. In some cases, accounting for pond depth affected the sub-basin delineation. In other cases, the pond drainage to specific locations would take significant alternation of the topography. Figure 4 gives a map of the storage pond area with ponds, the stream network, and the final sub-basin (SB) boundaries. The relationship between pond locations and sub-basin boundaries is limited by the natural flow lines determined by terrain analysis using the 30m DEM. If the model network determined by this project is different than the connectivity after building the storage ponds, this can be accounted for in the TOPNET water management component, which allows for any sub-basin to be an instream or offstream reservoir to any other sub-basin.

Site 1: Devries and Site 2: Gully

Based on the natural topography, these sites drain towards Bertrand Creek. In future models, SB30 and SB31 can be made a source of water to McClellan Creek. Gully pond drains south to McClellan Creek from SB 31 to SB 37.

Site 3: Weid-H

This site may be able to drain by gravity towards SB 31. However, if the pond does not exist, it is a contributing area to SB23. For the purposes of this project, this pond area was kept with the natural drainage pattern contributing to SB23. In future models, SB23 can be made a source of water to McClellan Creek.

Site 4: Groen

This is the most attractive site for a future pond considering the relatively large upstream catchment area of SB 24.

Site 5: West High

As indicated by the black sub-basin boundaries, the area of this proposed pond mostly contributes to sub-basin 24, with a southern portion contributing to sub-basin 36. If the pond is dug, gravity flow to the west branch (towards SB36) will be possible. For the purposes of this project, this pond area is the contributing area to SB24, but in future work SB24 can be a source of water to the West Branch.

Site 6: Border

This site contributes to SB 22. More work is required to determine the exact upstream area of this potential pond location.

Site 7: Devries North

Without an existing pond, this area contributes to multiple sub-basins. When it is determined if this pond location will drain easterly towards Jackman Ditch, or south directly into Bertrand Creek, the storage outflows can be directed to the appropriate locations.

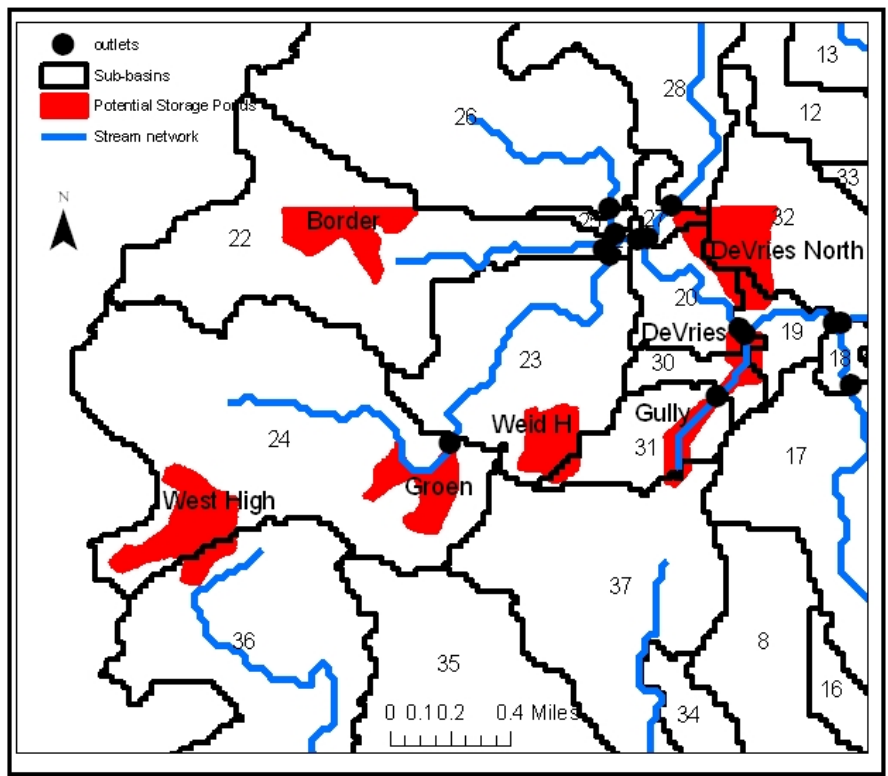


Figure 4. Potential future pond sites in the northwest U.S. portion of the Bertrand Creek watershed.

Model Calibration Update

The observed flows used for calibration of the updated Bertrand Creek hydrologic model include the effect of surface water diversions upstream and groundwater pumping within the watershed. At this time, there is no information on the flow rates of diversions and groundwater pumping distributed throughout the watershed. In order to calibrate the model to observed flows, we have added the estimated effects of surface water diversions and groundwater pumping to the observed flows. The aim is to calibrate the model to current conditions (June 2003- May 2006) and to use the past climate data (1946-2006) as a predictor of the future, given current land use conditions and water use practices. The calibration period starts at the beginning of streamgauge observations at Rathbone Road in June, 2003. The calibration period ends May 2006, at the end of the climate series compiled and formatted by the WRIA1 water management project.

Estimation of the effect of Irrigation requirements on streamflow

The irrigation requirement was estimated as the difference between the crop water requirement and the effective precipitation at each sub-basin. Based on FarmWest methods (www.FarmWest.org) and local climate statistics, the effective precipitation was calculated differently for dry periods, wet periods, and for large rainfall events. For dry periods, the effective precipitation (mm) was calculated as 75% of the incoming precipitation after subtracting 5 mm. For wet periods, the effective precipitation is the total incoming precipitation. For large rainfall events, since some incoming precipitation is lost to deep percolation, subsurface drainage, or surface runoff, the effective precipitation is the total incoming precipitation minus the maximum soil storage capacity. The maximum soil storage capacity was estimated using the drainable plant available moisture content of each sub-basin derived from SSURGO soils data, multiplied by the sub-basin area averaged rooting depth. Rooting depth of 1 ft was assumed for grass, corn and wheat, 2 ft for bush and shrub crops, and 3 ft for trees. The final daily crop water requirement of each sub-basin is the crop coefficient multiplied by the reference grass ET_0 minus the effective precipitation and available stored water in the root zone. The

initial soil storage on June 13, 2003 was estimated as the average of the soil storage on June 13, 2004 and 2005. The potential crop water use assumes 85% on-farm application efficiencies based on the area average application efficiencies for surface water irrigated crops. The area averaged application efficiency for groundwater irrigated crops is closer to 70%, but a more conservative estimate of 85% was used for groundwater crop water requirement estimation. We assume 100% conveyance efficiency and no return flow for both surface and groundwater irrigation estimations.

Figure 5 shows the relationship between potential crop water use, effective precipitation, and the resulting estimated diversion requirement or ‘effective crop water use’ for each of the sub-basins with surface water users. A portion of the effective precipitation is stored in the root zone; this storage pattern is shown in Figure 5. This calculation was repeated for the sub-basins where ground water pumping is used for irrigation.

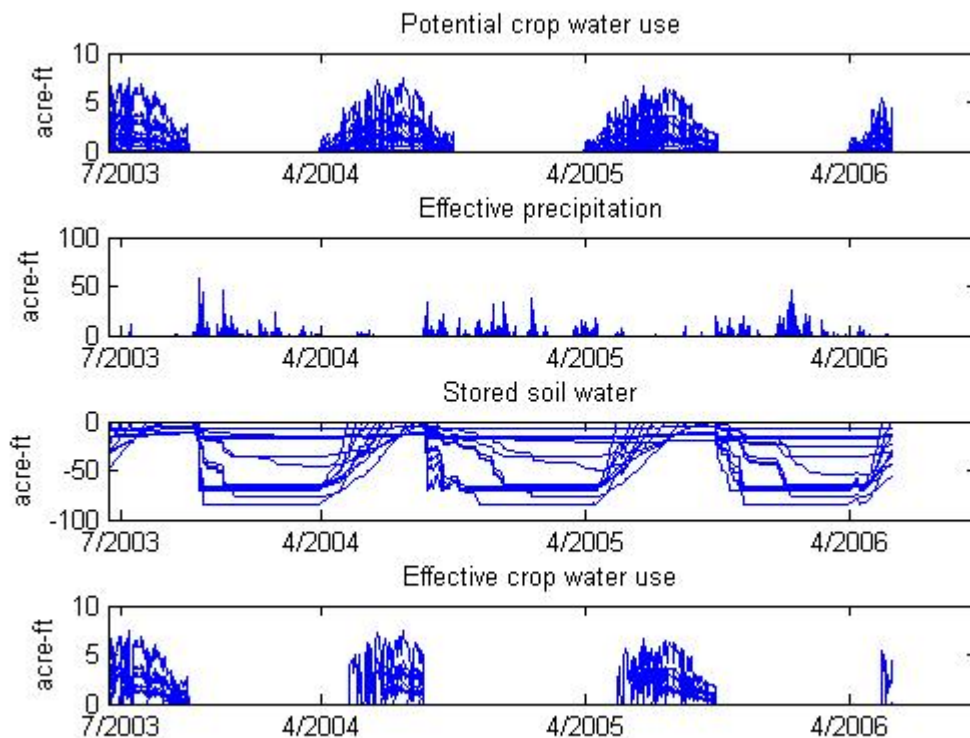


Figure 5. The relationship between potential crop water use, the effective precipitation, the portion of effective precipitation that is stored soil water, and the remaining effective crop water use that must be met by surface water diversion.

Calculation of potential evapotranspiration

As described in the Task 4.1 Report (Tarboton, 2007), the hydrologic model used in this project, TOPNET, calculates reference ET using a standardized form of the ASCE Penman-Monteith equation recommended by the ASCE Standardization of Reference ET Task Committee (Walter et al., 2000; Allen et al., 2005). There are two reference surfaces defined by the standardized form: (1) a short crop with an approximate height of 0.12 m similar to clipped, cool-season grass (ET_0); and (2) a tall crop with an approximate height of 0.50 m similar to full-cover alfalfa (ET_r). The inputs for the calculation of ET_0 and ET_r are air temperature, dew point, wind speed, surface albedo, date, elevation and location (latitude and longitude).

For a comparison, the same TOPNET model inputs were used to calculate ET_0 calculation using the software application REF-ET. The REF-ET program supports reference ET computation guidelines and procedures that were recommended in ASCE Manuals and Reports on Engineering Practice No. 70, "Evapotranspiration and Irrigation Water Requirements" edited by Jensen, et al., (1990) through efforts by the Committee on Evapotranspiration in Irrigation and Hydrology of the Irrigation and Drainage Council of the Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE), and is available at <http://www.kimberly.uidaho.edu/ref-et/>. Figure 1 and Table 1 verify the agreement between ET_0 calculated by REF-ET and TOPNET, which both sum to approximately 30 inches per year for the grass or short reference crop. The alfalfa, or tall reference crop, sums to approximately 37 inches per year during this time period. Statistics comparing the two calculation methods were calculated between 1/1/2004 and 12/31/2005 to develop annual values familiar in ET analyses within the calibration period which was determined by observed streamflow data of Bertrand Creek at Rathbone Road (starts 06/13/2003) and available WRIA1 climate data (ends 05/31/2006). Figure 6 highlights results for water year 2003 to enable visualization of the daily differences between TOPNET and REFET. Table 1 shows the average annual sum of reference evapotranspiration (in/yr), the mean, variance, and standard deviation (mm), and the Nash-Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970) measure of 0.952. This statistic is essentially a sum of square errors normalized by the squared

difference in the time step value and the mean value. The bounds of NSE are $[1, -\infty]$; a value of 1 implies a perfect fit.

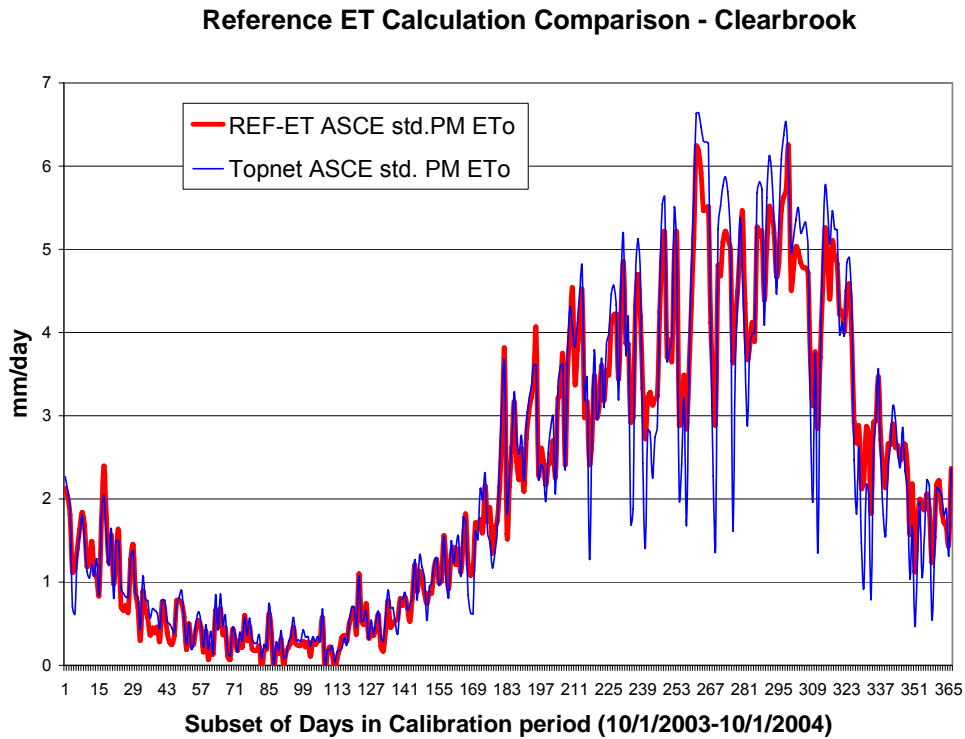


Figure 6. A comparison of the potential ET rates (ET_0) calculated by REF-ET and TOPNET for two of the years in the three year calibration period.

Table 1. Statistics comparing the modeled evapotranspiration of two different standardized ASCE Penman-Monteith calculations over the calibration period (CP): REF ET and TOPNET.

	REF ET	TOPNET
average annual sum	779.5 mm/yr; 30.69 in/yr	784.1 mm/yr; 30.87 in/yr
mean (CP)	2.13 mm; 0.084 in	2.15 mm; 0.085 in
variance (CP)	0.11 mm; 0.004 in	0.12 mm; 0.005 in
standard deviation (CP)	1.69 mm; 0.067 in	1.76 mm; 0.069 in
NSE (1/1/2004-12/31/2005)	0.952	

The main difference between these two calculations is the treatment of the missing solar radiation data. REF-ET uses an air temperature difference approach, while TOPNET uses a calculation that sums net short and long wave radiation. Net shortwave radiation is calculated from radiation at the top of the atmosphere based on date estimated sun angles, surface albedo derived from surface vegetation and atmospheric transmissivity. The atmospheric transmissivity is approximated based on the diurnal temperature range. Net long wave radiation calculations are based on a cloudiness factor with parameters for humid conditions, daily maximum and minimum temperatures and vapor pressure, which is determined from the dew point temperature. While the annual sum of ET_0 calculated by TOPNET and REF-ET is equivalent, the daily differences in calculations can be expected to be more accurate using the TOPNET calculation. REF-ET was designed for use with observed radiation data, while the TOPNET snow and evapotranspiration models require estimations of radiation, but was developed for use in areas where these data are not available.

Estimation of monthly crop coefficients

The most commonly used crop coefficient values are the grass-based K_c curves developed by Jensen et al. (1990) and Allen et al., (1998). Multiplying the reference or potential ET_0 by the K_c results in the crop evapotranspiration (ET_c). The reference ET_0 differs from the ET_c because of differences in ground cover, canopy cover, and aerodynamic properties. These differences are captured by the crop coefficient and change throughout the year. The time series of ET_0 calculated by TOPNET was used to create a continuous daily record of gross irrigation requirements for each crop type by multiplying ET_0 , K_c , and irrigated land area, and dividing by the irrigation efficiency (James et al., 1989). Crop coefficients were obtained primarily from the WSU irrigation guide (EB1513); however, specific information on blueberries during the mid season was obtained from the Ministry of Agriculture, British Columbia. Table 2 shows the crop coefficients for the main irrigated crops.

Table 2. Crop coefficients and irrigation efficiencies used to estimate gross irrigation requirements. CIDMP data (2004) was used to develop the crop coefficient curves.

	Raspberries/ Blackberries	Blueberries	Strawberries	Black Current	Pasture Grass	Potatoes
	Drip = 0.90	Drip = 0.90	Spray = 0.65	Drip = 0.90	Spray = 0.65	Spray = 0.65
Apr	0.40	0.40	0.40	0.45	0.95	0.50
May	1.05	0.88	0.40	0.55	0.95	0.75
Jun	1.20	1.00	0.50	0.80	0.95	1.10
Jul	1.20	1.00	0.30	0.90	0.95	1.10
Aug	1.15	0.96	0.40	0.90	0.95	0.70
Sep	0.85	0.85	0.40	0.85	0.95	0.50

Surface Water Use Estimation

We have estimated the irrigation demand with the potential evapotranspiration (ET) rate calculated by TOPNET using the ASCE standardized Penman-Monteith with grass as a reference crop, an updated estimate of monthly crop coefficients for each land cover type, and the crop distribution and irrigation management information available in the Bertrand CIDMP (WID, 2004). The final surface irrigation requirement is the potential crop water demand minus the effective precipitation and available stored water in the root zone. The estimated surface water diversions have been added to the observed streamflow to create a naturalized streamflow regime for calibration.

Figure 7 shows the sum of potential crop water use, a total of 6784 acre-ft for the approximately three year calibration period. We estimate that approximately 2620 acre-ft of this crop demand would have been met by effective precipitation and stored soil water in the root zone. The remaining 4164 acre-ft of crop demand would have had to be met by surface water diversions. Figure 8 shows that the maximum diversion requirements in the irrigation seasons 2003 and 2004 exceed the sum of surface water permits and certificates, an instantaneous flow rate of 9.9 cfs. The addition of surface water claims would increase this flow rate by 7.7 cfs to approximately 17.6 cfs (WID, 2004). The

2005 irrigation requirements come very close to the sum of permits and certificates. The actual water use, which is currently not directly measured, is expected to be higher than the conservative estimate we have calculated and shown in Figure 8.

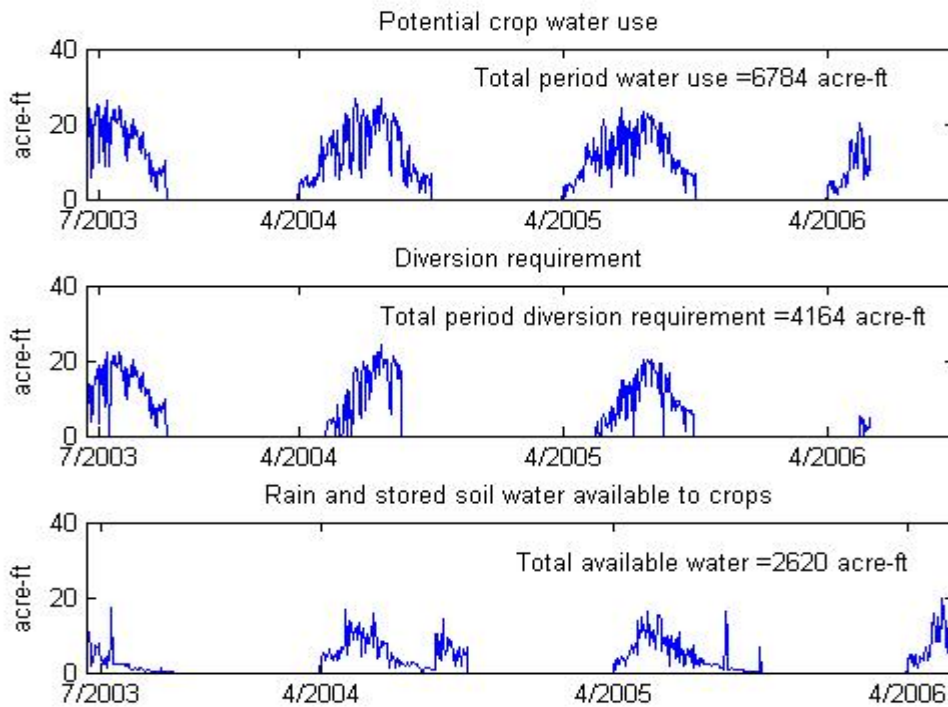


Figure 7. The potential crop water use, diversion requirement, and available water from rain and soil storage, for the sum of surface water irrigated areas in Bertrand Creek.

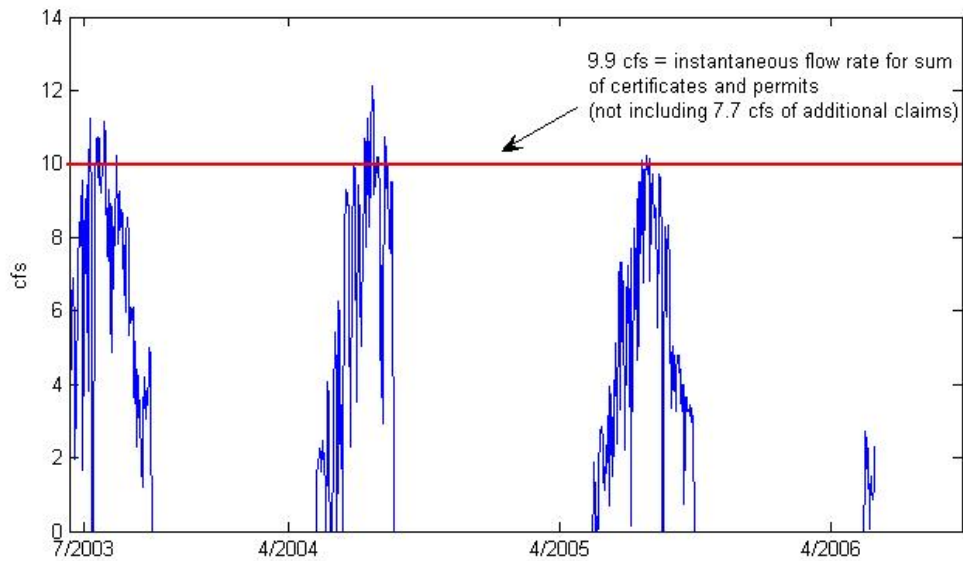


Figure 8. Estimated surface water diversions for the calibration period compared to the instantaneous flow rate for the sum of permits and certificates for surface water diversion of Bertrand Creek in the U.S. portion of the watershed.

Ground Water Use Estimation

Although estimation of groundwater is outside the original scope of this project, recent groundwater modeling of Bertrand Creek (Barber, M. et al., 2008) showed that the 82% of the area of the Bertrand Creek watershed has wells within a response zone greater than 0.1, where at least 10% of groundwater pumping will affect the flow of Bertrand Creek (Table 3). The weighted average area by response zone is 0.4, or 40%, but this does not account for the timing or exact location of which wells are irrigating in which sub-basin. To estimate the daily effect of groundwater pumping on observed streamflow, we are using a conservative estimate that 10% of groundwater pumping used to meet irrigation demand will affect Bertrand Creek flows. The consumptive irrigation demand was calculated in the same way as the surface water use irrigation demand as described in the Irrigation Requirement Estimation section above.

Table 3. Bertrand and Fishtrap Creek combined flow response as the percent area within 1.0 miles of Bertrand Creek (from Table 3-17 of Barber, M. et al., 2008).

Response Zone	Combined Flow Response for Wells within 1.0 mi of Bertrand Creek (%)
0.0–0.1	17.87%
0.1–0.2	14.87%
0.2–0.3	12.35%
0.3–0.4	9.96%
0.4–0.5	8.79%
0.5–0.6	10.20%
0.6–0.7	7.67%
0.7–0.8	7.22%
0.8–0.9	6.53%
0.9–1.0	4.54%

Similar to Figure 7, Figure 9 shows the potential crop water use and additional irrigation requirement after effective precipitation and stored soil water is used to meet crop demand. Although 80% of the Bertrand irrigated area uses groundwater supplies (WID, 2004), a comparison of the diversion requirement in Figure 7 and the pumping requirements in Figure 9, shows that 89% of the total additional irrigation requirement is provided by groundwater. This difference in ratio is due to the accounting for soil water storage and root depth of the different crop types for the respective surface and groundwater irrigated areas.

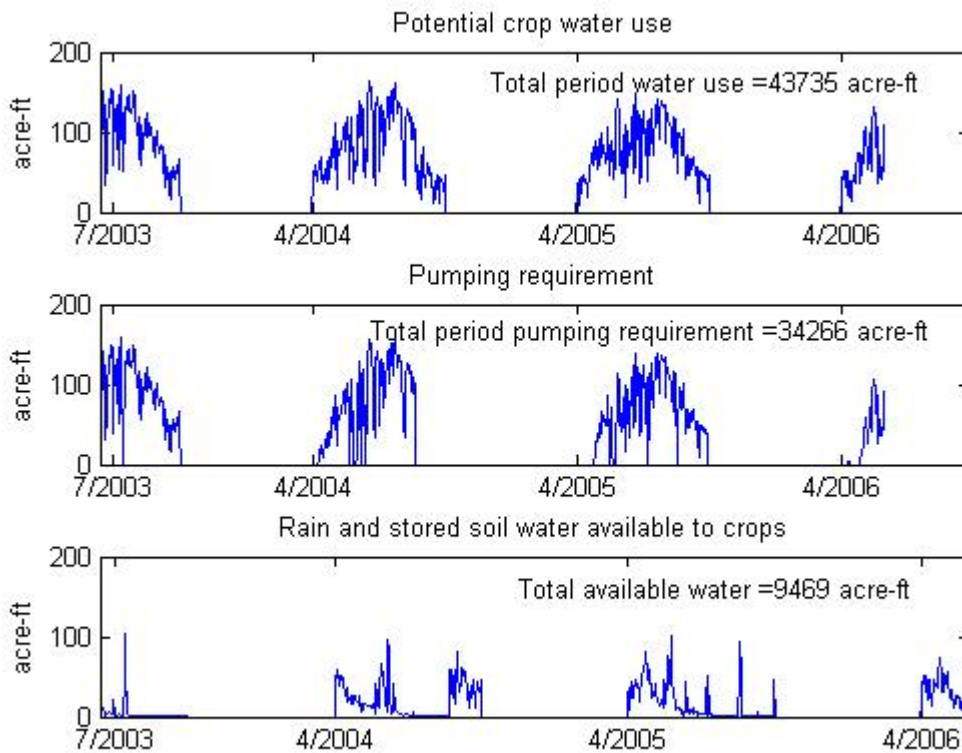


Figure 9. The potential crop water use, diversion requirement, and available water from rain and soil storage, for the sum of ground water irrigated areas in Bertrand Creek.

Observed and naturalized flows at Rathbone Road

Figure 10 shows the hydrograph of observed flows with the hydrograph that results from summing the observed flow with the estimated surface water used for irrigation during the 2005 irrigation season. A continuous time series of ‘naturalized’ streamflow has been created for the calibration time period between 06/13/2003 when the Department of Ecology began collecting data on Bertrand Creek at Rathbone Road, and ending 05/31/2006, when the climate time series available through the WRIA1 watershed modeling project end. The updated Bertrand Creek model will be calibrated to the naturalized streamflow, since surface water diversion data are not directly available as a model input. Plots of the naturalized flows for each irrigation season in the calibration period can be made available upon request.

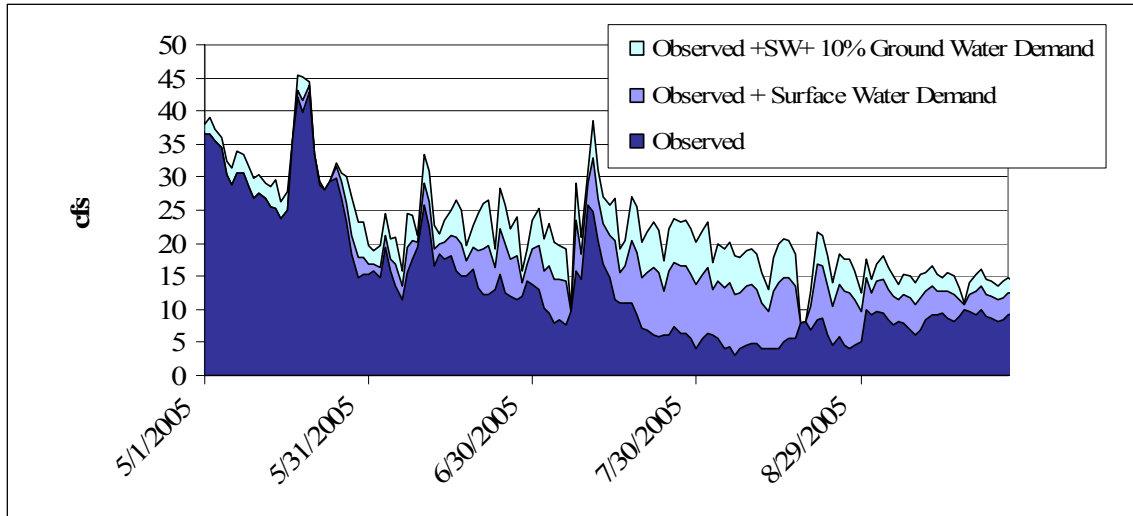


Figure 10. Observed streamflow at the Rathbone Road in the 2005 irrigation season (dark blue) and the addition of the estimated surface water use (medium blue) and the addition of the estimated effect of ground water use on surface water (light blue).

Observed and Naturalized flows at the international border

Surface water licenses for irrigation in the Canadian portion of Bertrand Creek watershed total 228.32 acre-ft per annum (WSD, 2008). For each irrigation season of the calibration period, the total per day was determined given the number of days in the irrigation season of each year (2003, 110 days; 2004, 182 days; 2005, 182 days; 2006, 60 days). The volume per day and the total volume used in the irrigation season from the Rathbone Road data (shown in Figure 10 for 2005), was used to calculate a daily water use ratio. This ratio was used to distribute the total volume per annum of surface water licenses and create a daily surface water use time series. The ratio between the observed streamflow at the International Border and the time series of 10% ground water demand from Rathbone Road was used to create a time series of the groundwater pumping surface water effects at the border. Figure 11 shows these results for the 2005 irrigation season.

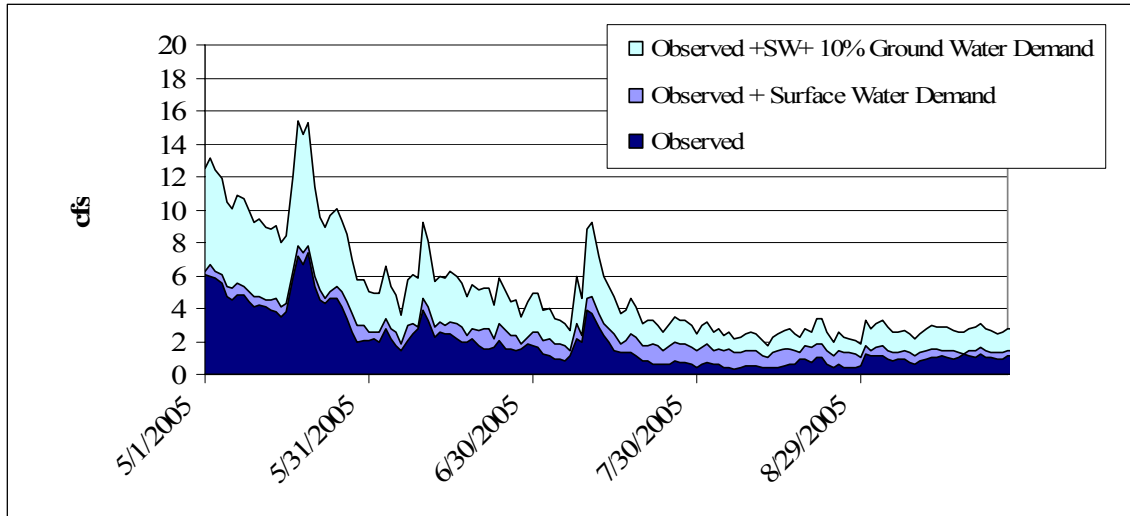


Figure 11. Observed streamflow at the International Border (08MH152) in the 2005 irrigation season (dark blue) and the addition of the estimated surface water use (medium blue) and the addition of the estimated effect of ground water use on surface water (light blue).

Updated calibration framework compared to WRIA1 model calibration

The aim of this section is to clarify how the updated model is calibrated differently than the WRIA1 model and how this affects the calculation of the modeled streamflow. The observed flows used for calibration of the updated Bertrand Creek hydrologic model include the distributed effect of surface water diversions and groundwater pumping, over time and across the watershed. Lack of a time series of daily diversion data has prevented both the WRIA1 model and the updated model from directly representing surface water diversions in the model. However, the updated model includes the estimated irrigation water use and has been added to the observed streamflow to create a ‘naturalized’ streamflow regime for calibration (described in Surface Water Use Estimation and Ground Water Use Estimation sections).

The TOPNET distributed hydrologic model was applied to the 38 mi² Bertrand Creek watershed in this project update, and the 1385 mi² Nooksack basin in the WRIA1 watershed modeling project. The same climate and topography datasets were used in both applications. The land use, soils, and spatial distribution of the Bertrand sub-basins

created very different initial estimates for many of the model parameters. The spatial discretization of the WRIA1 project was 170 drainage basins for the entire area, one for Bertrand Creek watershed. The spatial discretization of the Bertrand Creek update is 46 sub-basins. The increased distribution of the update model from one sub-basin to 46 sub-basins increased the information available for modeling in four important ways: 1) individual precipitation estimates for each sub-basin, 2) individual sub-basin estimates of wetness based on slope and sub-basin area, 3) smaller distances to the stream for each sub-basin, and 4) increased spatial representation of parameters estimated before calibration. Finally, the calibration technique used to calibrate the models is briefly described.

Precipitation Estimates

Table 4 shows the weights assigned to the sub-basins based on their relative distance to different climate stations. The WRIA1 sub-basin representing Bertrand Creek (SB87) is heavily weighted to the Abbotsford Airport, but samples of weights from the updated model (taken from the north, south, east and west) show distinct weighting relationships that better capture the differences among the sub-basin elements and the surrounding climate stations. In the update, the northern sub-basins receive relatively more rainfall inputs from Abbotsford Airport data, where the rest of the sub-basins are modeled with inputs more heavily weighted by the Bellingham Airport, Blaine, and Clearbrook stations.

Table 4. Climate information used by TOPNET to model Bertrand Creek Watershed in the WRIA 1 project (Bertrand Creek is basin 87), and four examples of sub-basins distributed throughout the watershed.

Station Name	ID	Triangulated weights				
		WRIA 1 (Sub-basin 87)	Sample Bertrand Update Sub-basins			
			North	South	East	West
Abbotsford Airport	71108	0.528	0.96	0	0	0.12
Bellingham Int. Airport	450574	0.074	0	0.37	0.02	0.01
Blaine	450729	0.278	0.33	0.29	0.51	0.34
Clearbrook	451484	0.247	0.01	0.34	0.46	0.54

Wetness Estimates

TOPNET models the subsurface storage component using TOPMODEL (Beven and Kirkby, 1979; Beven et al., 1995a) which characterizes the relative saturation based on a wetness index, $\ln(a/\tan\beta)$, where 'a' is specific catchment area and β is the slope angle. The depth of the subsurface is determined by the total soil depth from the soil parameterization. The wetness index is evaluated at each digital elevation model (DEM) grid cell within each sub-basin. The set of values obtained is grouped into on the order of 50 wetness index classes within each model element, each of which is presumed to behave similarly and the depth to water table and potential for saturation excess runoff is evaluated separately for each class (Tarboton, 2007). For locations with large wetness index values, the water table evaluated in the saturated zone component below may up well into and influence the soil moisture content of the soil zone. A histogram of wetness index values over each sub-basin is used to record the proportion of each sub-basin falling within each wetness index class. Figure 12a shows that the single distribution for the WRIA1 representation is in the mid-range of the 46 sub-basins represented in the model update.

Distance to stream

The overland flow distance from each grid cell to the streams is calculated during the model setup using digital elevation model derived flow directions. A cumulative distribution of distances to the stream is calculated for each sub-basin. Figure 12b shows the difference between the longer distances to the stream for the single WRIA1 sub-basin compared to the smaller distances in the smaller sub-basins. This should enable the updated model to better capture the timing and magnitude of the streamflow compared to the single WRIA1 basin.

Spatial representation of parameters

One benefit of using TOPNET for hydrologic modeling of Bertrand Creek is that it is a physically-based distributed model. Spatially distributed soils and land use parameters are used to represent the system. All models are representations of reality. Calibration helps compensate for limited data and knowledge about the system represented by the model. This is done by adjusting parameter values so that modeled results fit observations. These parameters are adjusted in calibration using multipliers, within physically reasonable boundaries, to retain the spatial relationships of soil and vegetative properties of the watershed.

In addition to an increased spatial distribution, the updated model has different calibration parameters. Using soils and land cover information, parameters estimated before calibration, or ‘a priori’, have been derived for each of the sub-basins in the updated model. The calibration multiplier is a single value for each parameter that shifts the a priori parameter values up or down. This retains the spatial relationships among sub-basins originally derived in the model setup. The a priori values determined by soils and land use properties multiplied by the calibration multiplier results in the ‘effective parameter’ set. There was one set of effective parameters for the single WRIA1 sub-basin. There are 46 sets of effective parameters for the 46 updated model sub-basins. The area weighted average of these 46 sets of parameters is presented in Table 2 to allow for comparison to the single WRIA1 effective parameter set.

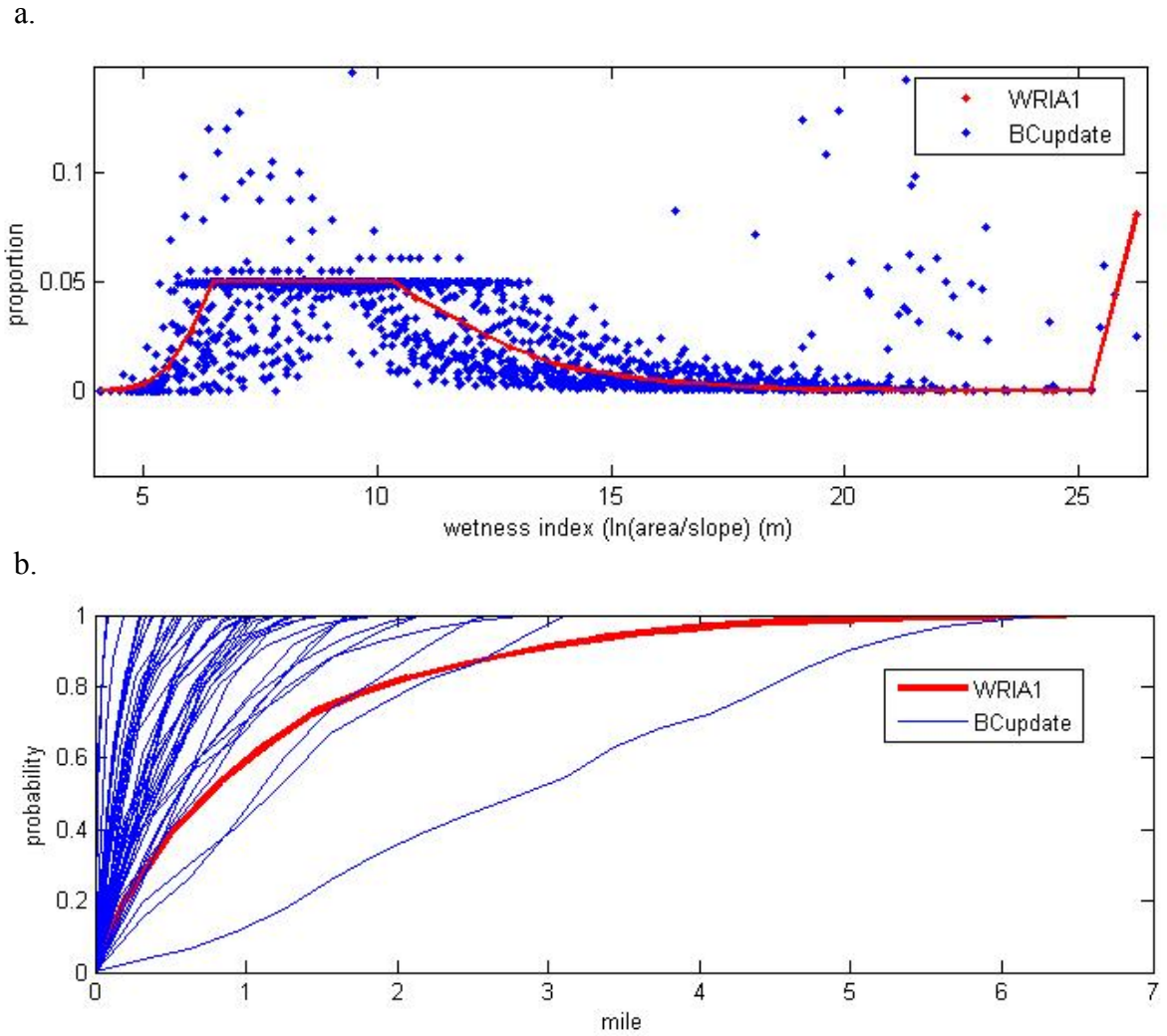


Figure 12. The a) wetness index value plotted against the proportion per sub-basin and b) the cumulative distribution of overland flow distances for the WRIA1 watershed modeling project Bertrand Creek sub-basin (WRIA1) and the 46 sub-basins in the Bertrand Creek model update project (BC update).

Table 5. Effective parameters (a priori * calibration multiplier) for the WRIA1 watershed model and the Bertrand Creek Updated calibration (area averaged).

Notation	Description	WRIA1 multiplier	WRIA1 apriori	WRIA1 effective parameter	Update multiplier	Update apriori	Update effective parameter
f (m ⁻¹)	Saturated store sensitivity	0.55	12.50	6.88	29.05	0.44	12.78
K (m/hr)	Vadose zone vertical saturated hydraulic conductivity	10	0.04	0.43	0.715	0.87	0.62
θΔ1	Drainable moisture content	1	0.31	0.31	16.58	0.04	0.66
θΔ2	Plant available moisture content	1	0.25	0.25	1.9	0.18	0.34
d (m)	Soil Store depth	1	0.60	0.60	0.64	0.32	0.21
c	Soil zone drainage sensitivity	1	1	1	1	1	1.00
ψφ (μ)	Wetting front suction	1	0.45	0.45	1	26.12	26.12
V (m/hr)	Overland flow velocity	0.1	360	36	1	360	360
CC (m)	Canopy capacity	1	0.001	0.001	1	0.0013	0.001
Cr	Intercepted evaporation enhancement	1	1.25	1.25	1	1.31	1.31
Albedo	Incident radiation reflectivity	1	0.20	0.20	1	0.21	0.21
To (m ² /hr)	Soil profile lateral conductivity	45	0.83	37.31	26.52	1.3	34.47
If (m ⁻¹)	Impervious fraction	0.5	0.10	0.05	0.15	0.13	0.02

Calibration Technique

The WRIA1 model was manually calibrated to observed streamflow from locations across the Nooksack River watershed. Observed streamflow from Rathbone Road was not available at the time of this calibration and was not included. Available historical data from Bertrand Creek was used in the model validation, but not directly in the model calibration.

For the updated Bertrand Creek model, streamflow records available beginning in 2003 at Rathbone Road and available during the irrigation season at the International border, were used simultaneously to calibrate the updated model. The Multi-Objective Shuffled Complex Evolution Metropolis (MOSCEM; Vrugt et al., 2003) global optimization algorithm was used as the multi-objective calibration algorithm because of the information provided about the tradeoff involved in optimizing to multiple objectives simultaneously. It is understood that the measured streamflow at these locations reflect stream flow depletions associated with drainage activity and surface and ground water diversions/withdraws. As described in sections above, a continuous time series of ‘naturalized’ streamflow has been created for the calibration time period between 06/13/2003 when the Department of Ecology began collecting data on Bertrand Creek at Rathbone Road, and ending 05/31/2006, when the climate time series available through the WRIA1 watershed modeling project end. The updated Bertrand Creek model was calibrated to the naturalized streamflow, since surface water diversion data and streamflow effects of groundwater pumping are not directly available as model inputs. Additionally, analysis showed that flows at the International border in October of each year on record were twice the available volume of rainfall. During the same time periods, the flows at Rathbone Road were half the available volume of rainfall. Due to this inconsistency, October flows from the border gauge were not used in the calibration.

The WRIA1 manual calibration included 5 calibration multipliers. The updated calibration using the automated MOSEM algorithm was run multiple times with various model setups using 5, 7, 9 and 10 calibration parameters. For each, the model was run up to 10,000 times for each calibration or until the parameter values converged. Results using seven calibration parameters gave the best result. The calibration search algorithm

was repeated four times to increase the certainty that the optimum calibration multipliers were found.

The Nash-Sutcliffe efficiency, E, (Equation 1; Nash and Sutcliffe, 1970) was used as the objective statistic to compare observed (Q_o^t) and modeled (Q_m^t) simulations (at time t) for the calibrations, where \bar{Q}_o is the mean observed flow.

$$E = 1 - \frac{\sum_{t=1}^T (Q_o^t - Q_m^t)^2}{\sum_{t=1}^T (Q_o^t - \bar{Q}_o)^2} \quad (1)$$

The calibration algorithm minimizes the result of 1-E, since the bounds of E are $[1, -\infty]$. The normalization of the difference in error by the difference between the observed and the mean of the observed, allows comparison of results when the observations at different locations have different scales of variability.

Results and Analysis

Calibration Results

Figure 13 shows the calibration results for the entire period at Rathbone Road. The E value of 0.848 is a considerable improvement compared to $E = 0.229$ from the WRIA1 project. In general, $E = 0.7$ can be considered 'acceptable'. Figures in Appendix A show the same results as Figure 13 (Figure A1), and also highlight each water year with distinct E calculations (Figures A2, A3, A4). These plots show the ability of the updated model to capture the streamflow recessions very well; the updated model matches the observations better at Rathbone Road in 2005 ($E=0.835$) and 2006 ($E=0.862$) compared to 2004 ($E=0.747$). Figure 14 compares the model results during the irrigation season for 2004, 2005, and 2006, illustrating that the updated model is able to capture the low flows better in the early part of the irrigation season (April, May, June) and less well in the late summer (July, August, September).

The results at the International border (Appendix A; Figures A1-A5) are currently not as good as at Rathbone Road. This may be because 1) two sub-basins upstream of the gauge may not be a sufficient spatial distribution, or 2) the input data used for spatial parameterization in Canada may not be as accurate as in the U.S, or 3) the naturalization of streamflow using only surface water licenses is not sufficient. Data on surface water extractions and estimates of the groundwater influence on streamflow may be necessary to accurately model Bertrand Creek upstream of the International border. Although the updated model is not an ideal representation of the watershed upstream of the border, the hydrology of the system between the border and Rathbone Road appears to be well represented. Where the hydrology is not represented well is discussed below using monthly flow volume errors. Future work updating the climate data model inputs will allow for an extended modeling record (05/31/2006 – present) that can be used as a validation period for the update calibration.

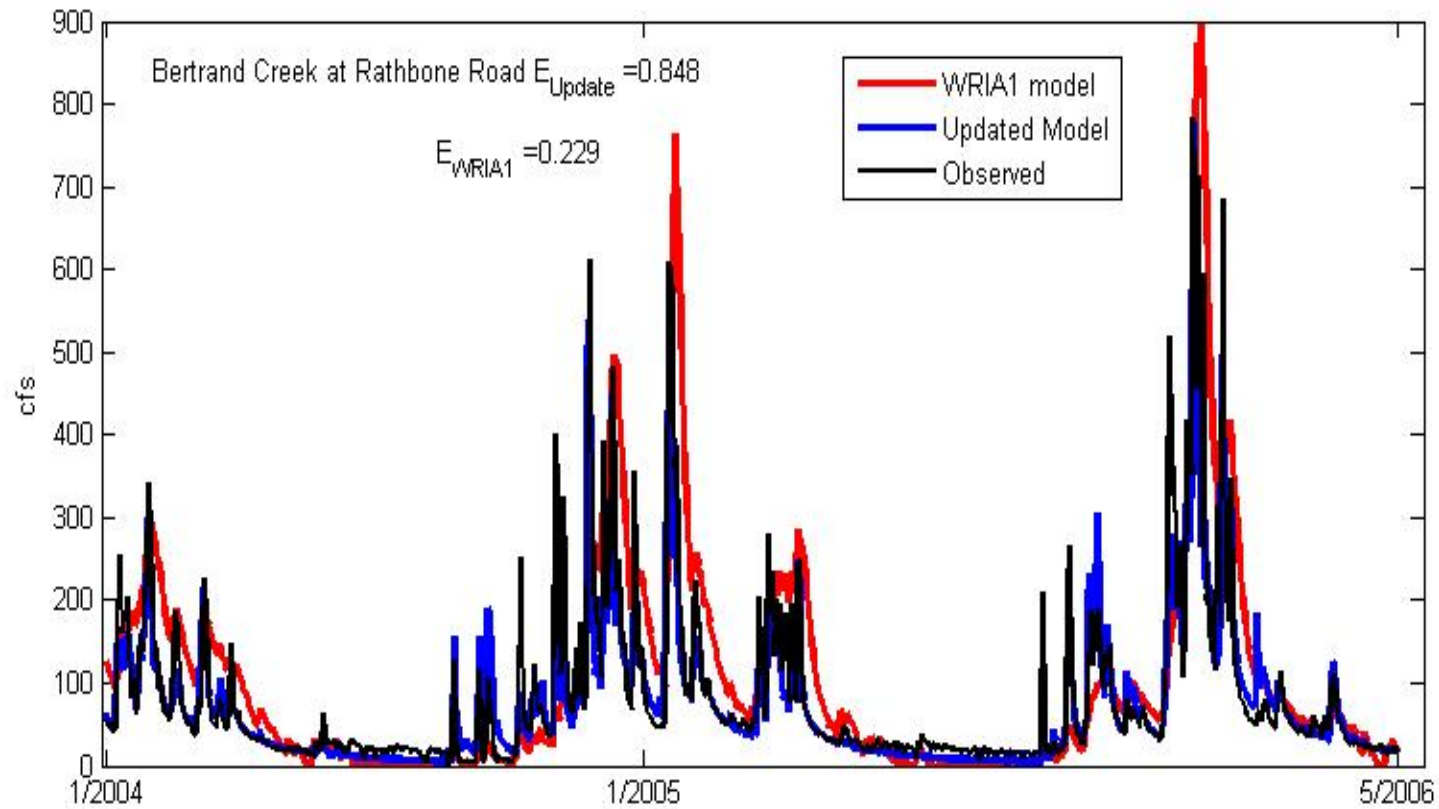
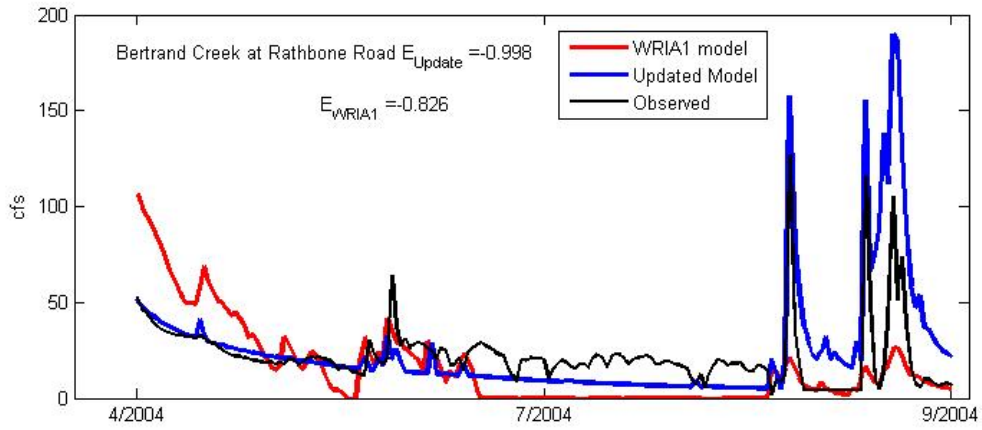
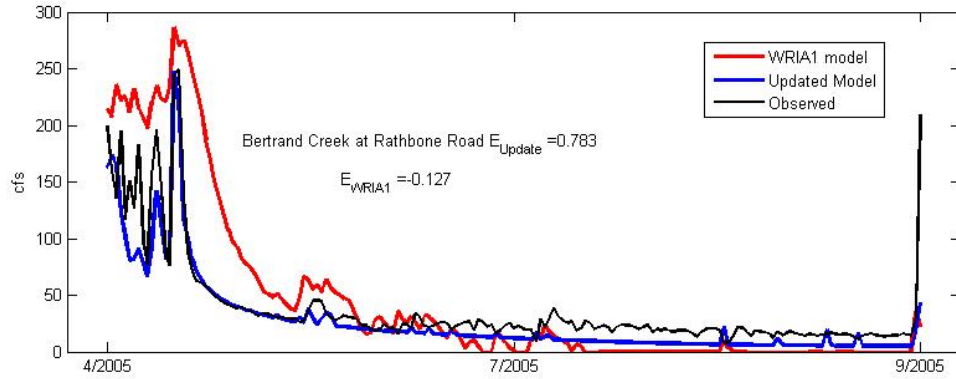


Figure 13. Results for the updated model calibration period at Rathbone Road, not including the first 200 days reserved for starting up the model components. Observed data at the International border are only available during the irrigation season. These results are shown in Appendix A.

a.



b.



c.

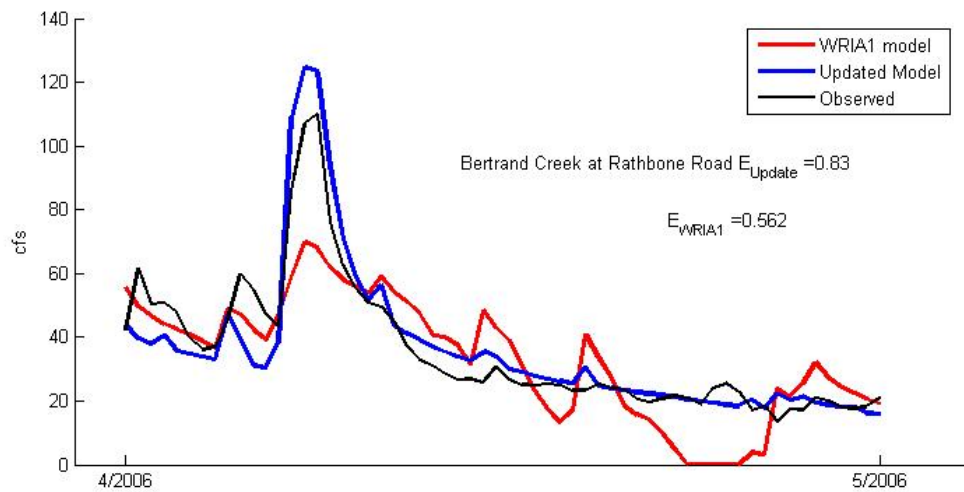


Figure 14. Results for irrigation seasons in a) 2004, b) 2005, and the early part of c) 2006 (until the end of available observed climate data) for Bertrand Creek at Rathbone Road.

Monthly flow volume error

The difference between the observed and the modeled streamflow have been calculated for each time step in the calibration period. The average monthly flow volume error was calculated for Bertrand Creek at Rathbone Road (Figure 15) and at the International border (Figure 16). The observed time series have been ‘naturalized’ by adding the estimated surface water irrigation demand in the U.S. at Rathbone Road, and the licensed surface water extractions upstream of the international border as well as an estimation that 10% of groundwater pumping effects streamflow..

Positive error values imply the observed flows are higher than the modeled flows. Negative error values imply that the modeled flows are higher than the observed flows. At Rathbone Road, on average during the calibration period, the June and July model flow volume may be approximately 12 acre-ft lower (30% error) than the mean observed flows during those months. At Rathbone Road, the September model flow volume may be 13 acre-ft (35% error) higher than the mean observed flows. This suggests that the model representation of the timing and effects of groundwater pumping could be improved with additional data and information about this important component of the watershed system. For the rest of the year, the model is within approximately 10% of the observed flow volume.

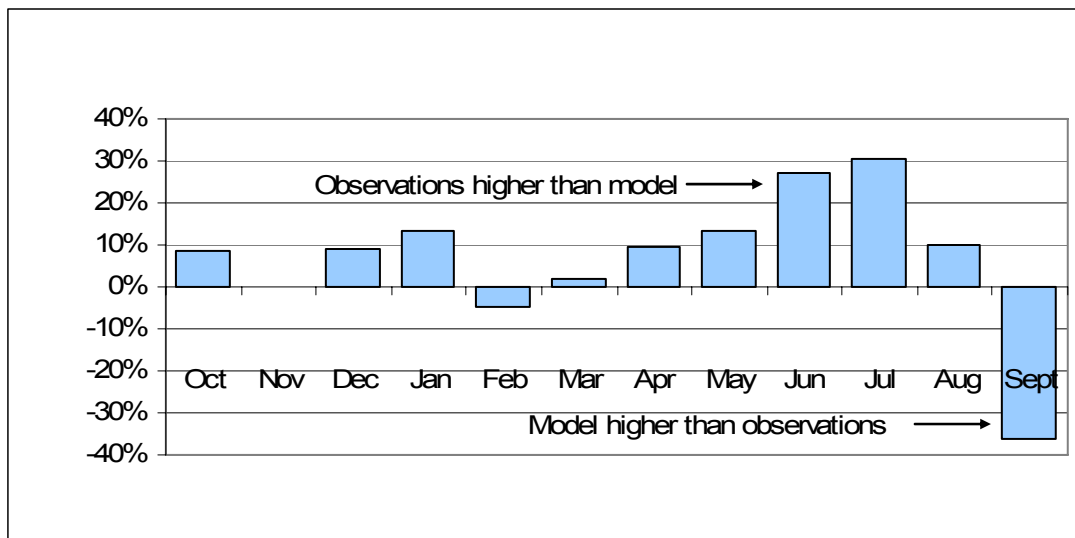


Figure 15. Percent monthly flow volume error at Rathbone Road.

At the international border, the modeled monthly flow volume may be up to 4 acre-ft higher than observed. This is a relatively high error, up to 126% in August, where the model flow volume is higher than the observed. Figure 16 shows the percent monthly flow volume error for the seasonal gage at the International border. The over-prediction of the model suggests that the effects of groundwater pumping are not represented well.

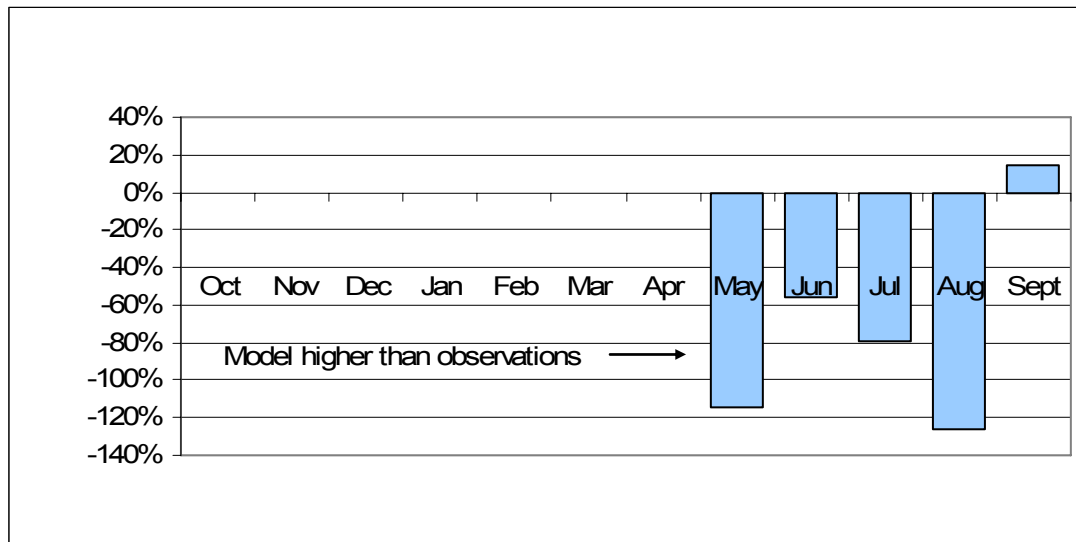


Figure 16. Percent monthly flow volume error at the International Border.

Water Budget Analysis

Using the calibrated parameters determined from the 2003-2006 time period, the updated Bertrand Creek model was run for three different periods: 1) a 60 year run from 1946-2006; 2) a wet run from 1995-1999; and 3) a dry run from 1976-1980. To determine wet and dry periods, a cumulative five year rainfall sum was calculated for the entire length of the climate record to determine the highest and lowest precipitation over a consecutive five year period. Figure 17 shows the resulting mean monthly water balance components resulting from the model run of 60 years. The baseflow represents the subsurface drainage, the surface runoff represents the sum of saturation and infiltration excess runoff generation, and the AET is the actual evapotranspiration. The AET is the potential ET times the crop coefficient and is limited by available water in the upper layer soil storage. The storage is the sum of the available water in the upper layer

soil and the subsurface soil. The storage value represents a *change* in storage, where a negative value means the storage is draining and a positive value means the storage is filling. Figure 18 shows these mean monthly water balance components for the dry period and Figure 19 shows these values for the wet period. The pattern of the relationships between water balance components is generally the same during all periods, although there is overall less total water during the dry period and more during the wet period. The results show that streamflow in June July, and August are entirely provided by baseflow.

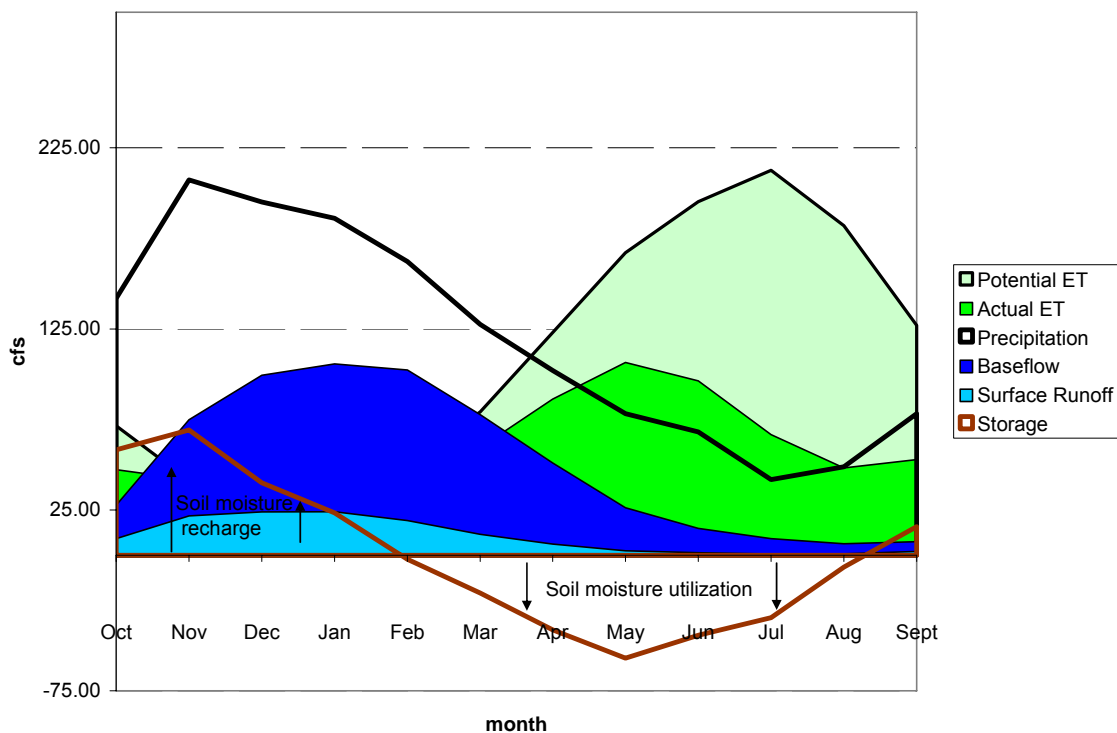


Figure 17. Mean monthly water balance components over 60 years: 1946-2006.

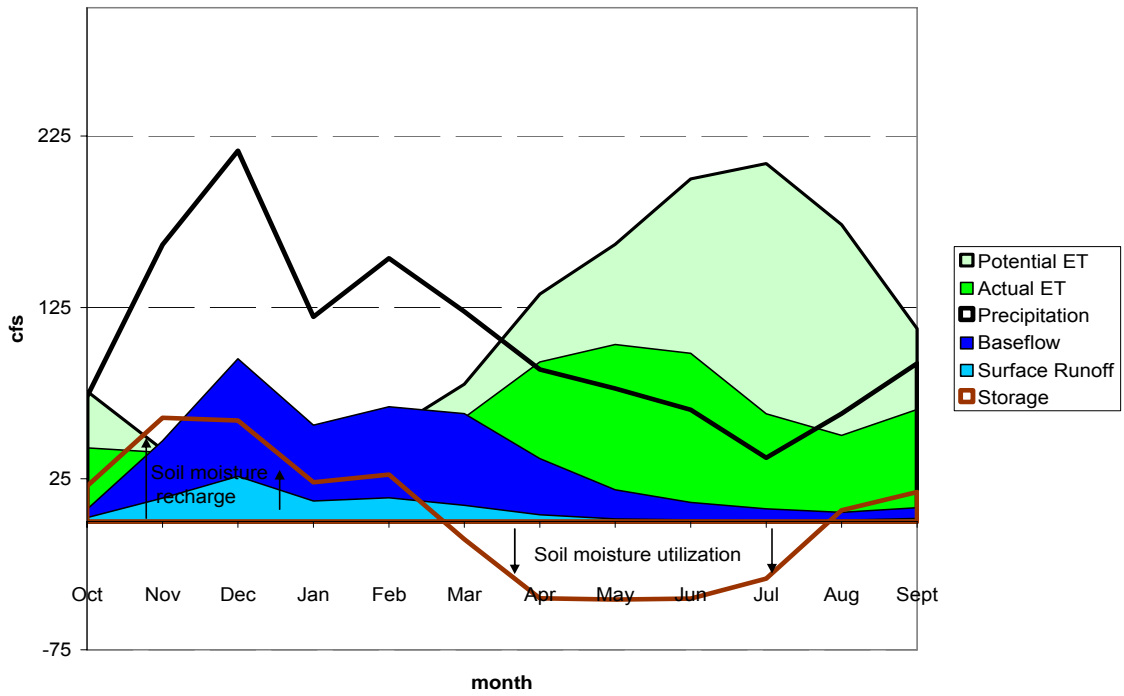


Figure 18. Mean monthly water balance components over a five year dry period: 1976-1980

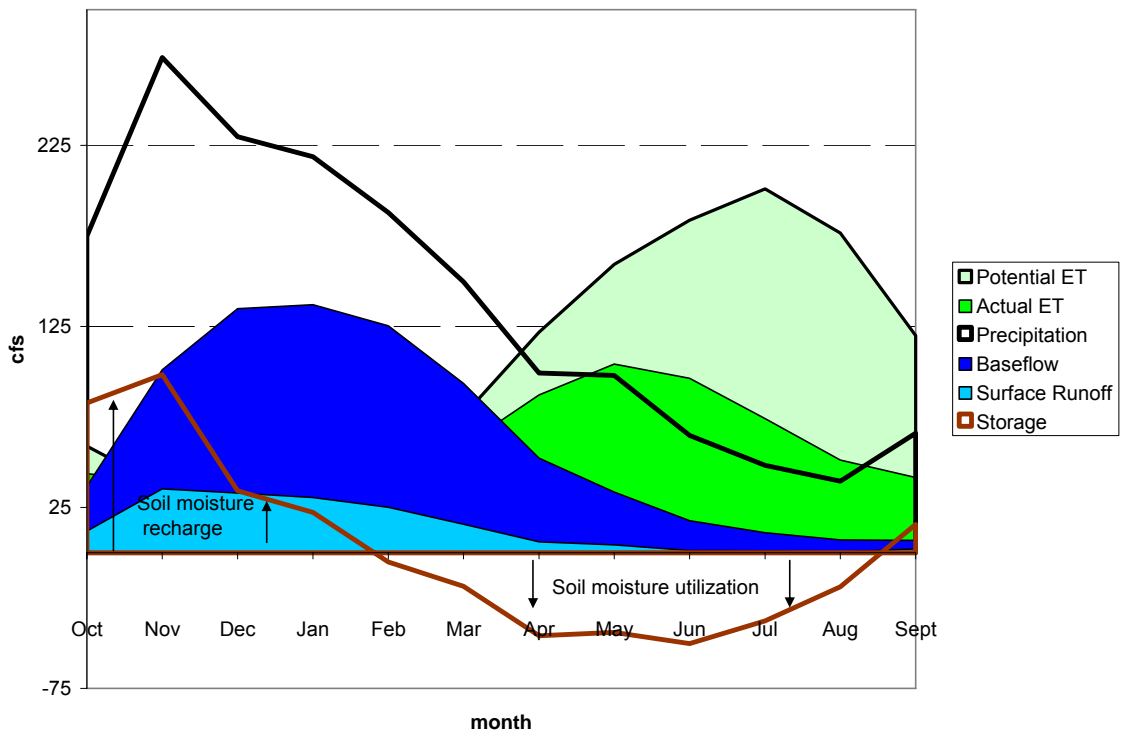


Figure 18. Mean monthly water balance components over a five year wet period: 1995-1999

Historic Climate Variability

To understand the updated model results in the context of historic climate inputs, the four climate stations were used to calculate a spatially interpolated daily rainfall for each sub-basin. The area averages of the sub-basin values were summed to calculate the annual precipitation for the years between 1947 and 2005¹. The average annual precipitation in the Bertrand Creek watershed is 42.4 inches. The long-term record of annual precipitation is shown as a bar chart (Figure 19). The cumulative or sum of the differences between annual precipitation and the long-term average precipitation, highlights climate trends over the different time periods. Figure 20 shows the cumulative departure from the long-term average precipitation, which illustrates that the period 1947-1978 was relatively wet compared with more above average precipitation compared to the time period after 1978. The calibration period was above average in 2003 and 2004, and very close to average in 2005.

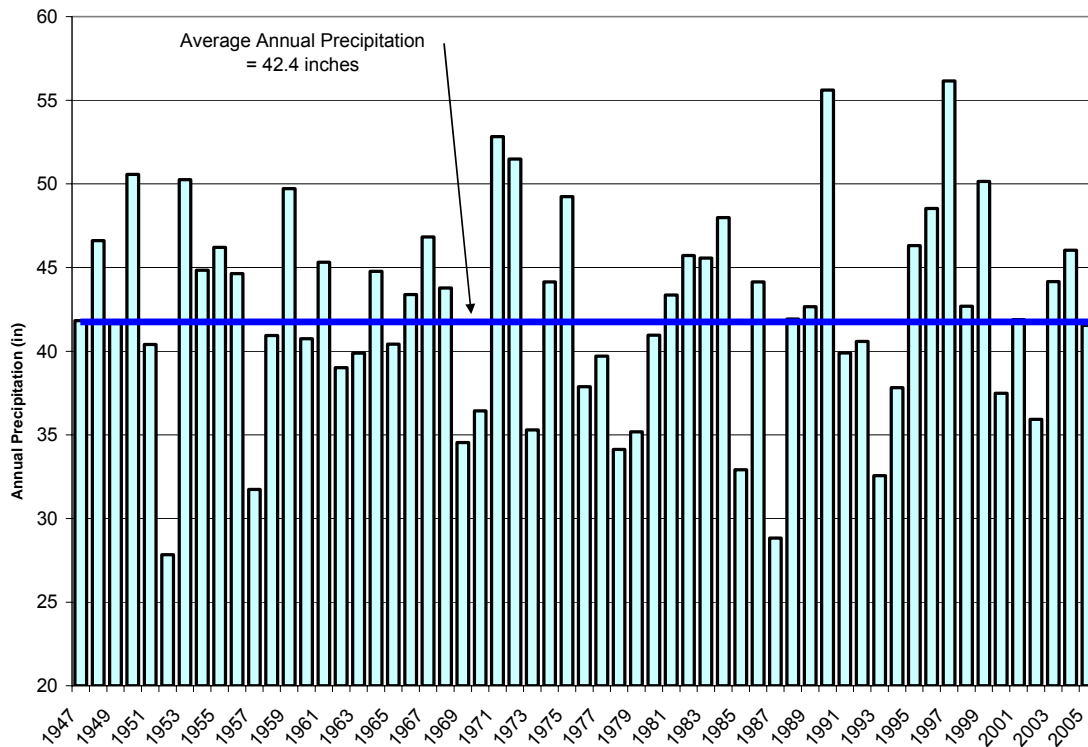


Figure 19. Annual precipitation at Bertrand Creek watershed (1947-2005).

¹ 1946 and 2006 are excluded since there is not a complete year of data in the climate time series used for this project.

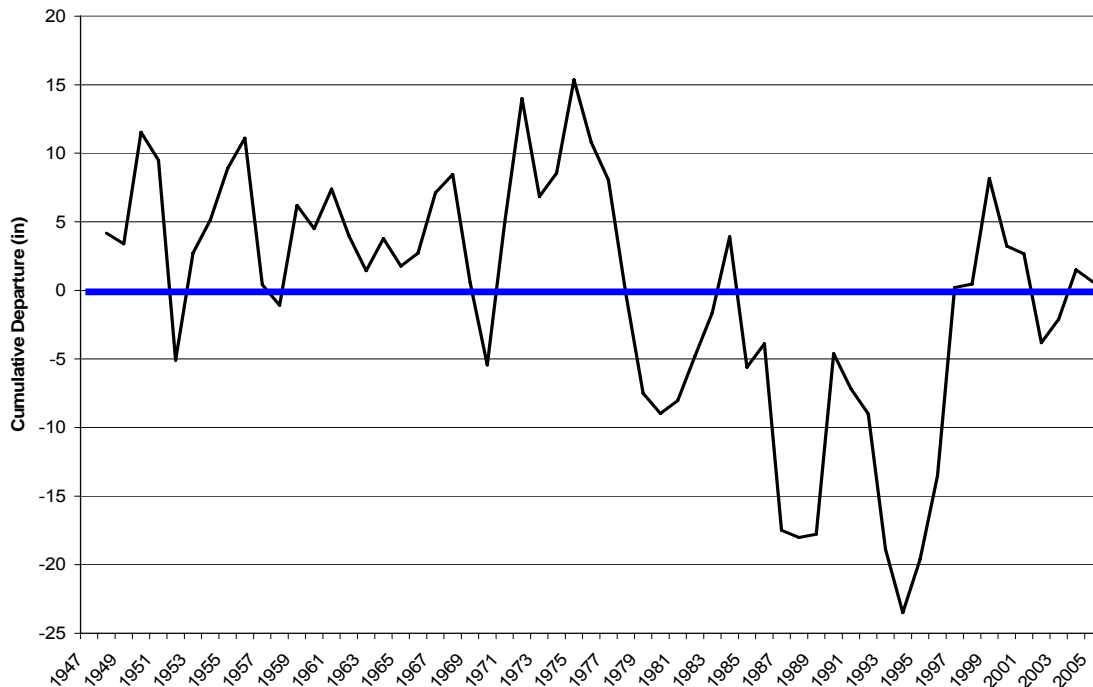


Figure 20. Cumulative departure from long-term average precipitation at Bertrand Creek watershed (1947-2005).

Exceedence Flow Analysis

Exceedence probability of a flow is the probability that a particular flow rate will equaled or exceeded. Low flows have a high probability of exceedence and high flows have a low probability of exceedence. These expectations of flow rates vary month to month, and the exceedence flow analysis presented in this report gives exceedence flow values for each month. Figure 21 shows the exceedence probability values of different flow rates occurring in August and compares these probabilities given data from the 60 year period, the wet period and the dry period at Rathbone Road. August usually experiences the lowest annual flows in the Bertrand Creek, and this is also a time of high crop water demand. For August, the streamflow could be expected to be approximately 1 cfs lower during a dry year or 1 cfs higher during a wet year compared to the expectation of streamflow determined over a 60 year historical period. The annual rainfall over a year may not be a strong indicator of streamflow availability during low flow months, since the sub-surface storage is filled by approximately February every year.

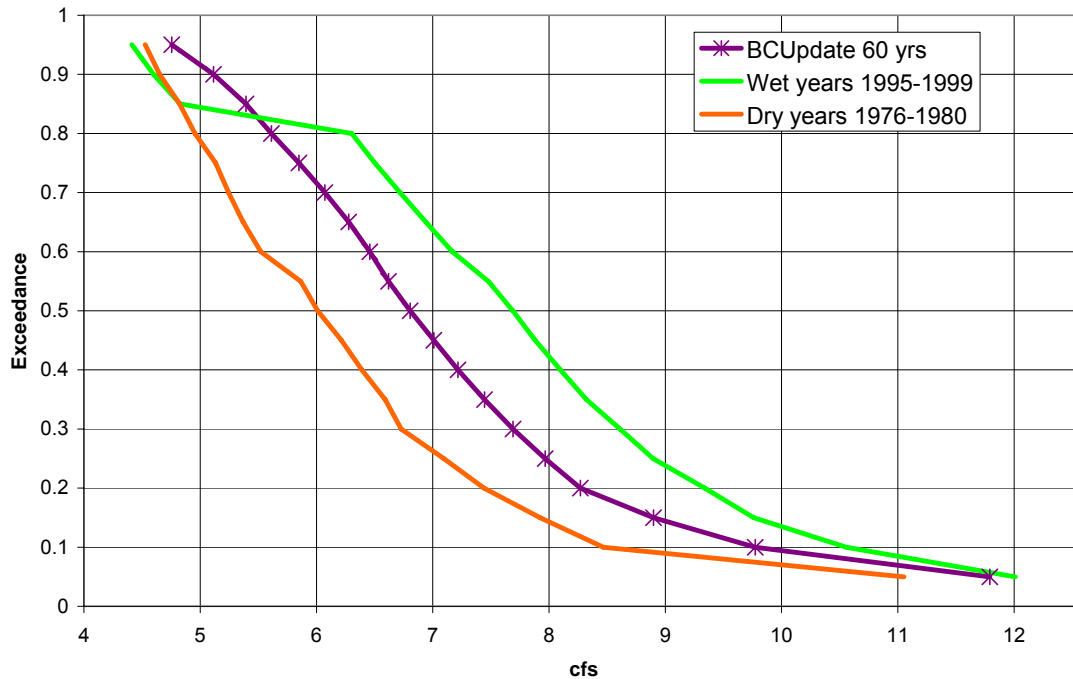


Figure 21. August exceedence probability flows for the updated Bertrand Creek model run of 60 years (purple), a five year wet period (green), and a five year dry period (orange) at Rathbone Road.

Exceedence flows for the lowest flow months calculated using the 60 year model run are shown in Figure 22. Although there is some probability of high flows occurring in September (green line), there is some likelihood that flows may be even lower than in August (magenta line). Figure 23 presents the exceedence probability flows at Rathbone Road and shows the comparison between curves calculated using the updated Bertrand Creek model, the WRIA1 model, and the 60 year historic period and the three year calibration period for each model setup. The WRIA1 model predicts no August flow, approximately 5-7 cfs lower than the updated model. Comparing the updated model results for the calibration period and the 60 year period shows that the calibration period of the updated model was very close to representing a long term expectation of flows.

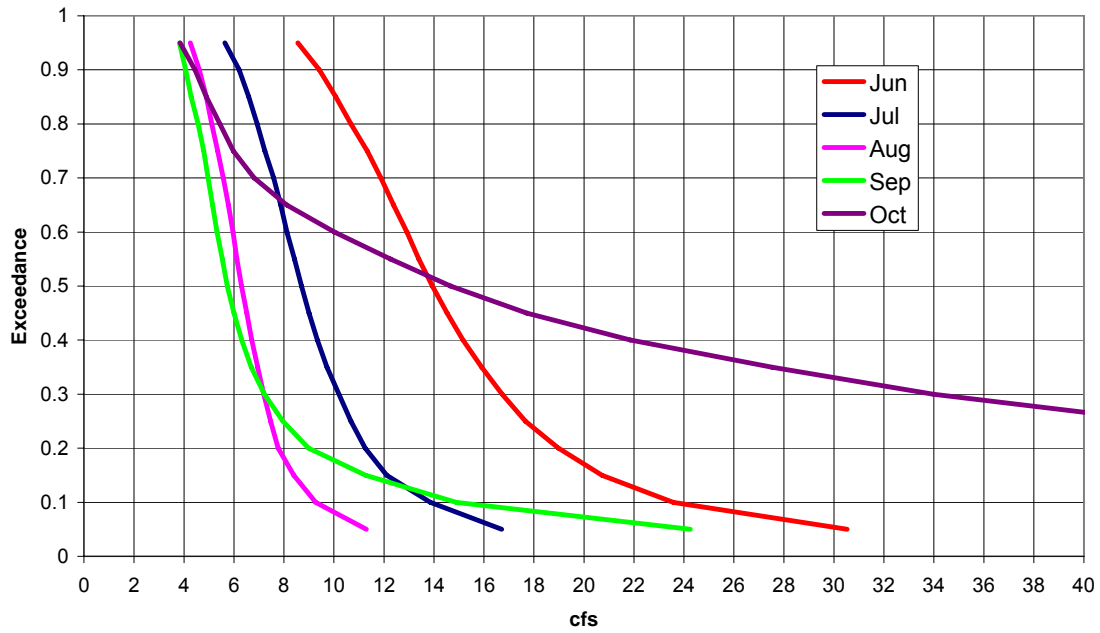


Figure 22. Exceedance probability flows for the lowest flow months of the Bertrand Creek at Rathbone Road.

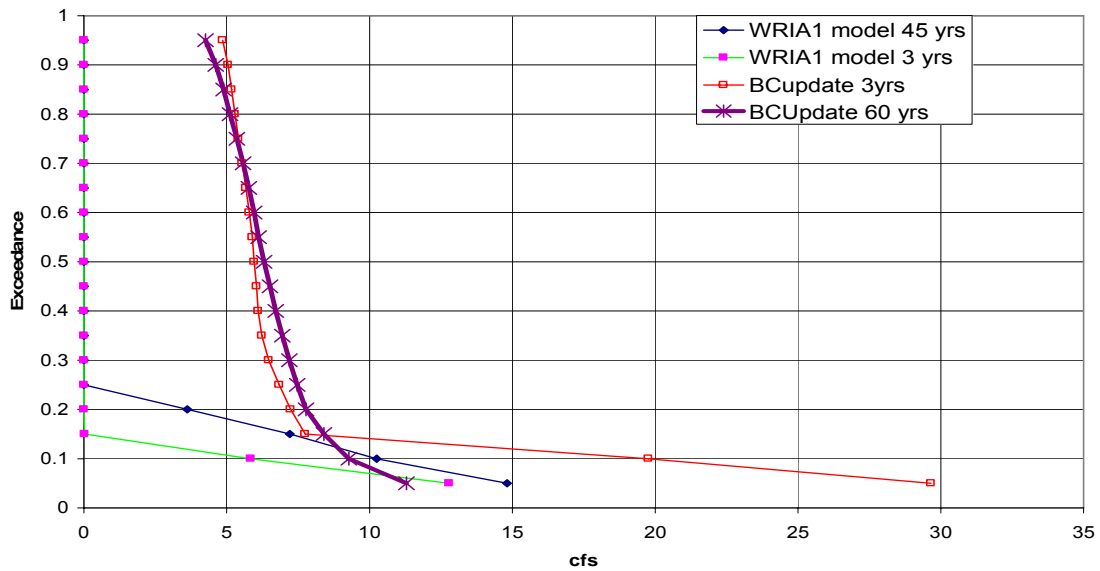


Figure 23. August exceedance probability flows at Rathbone Road compared to the WRIA 1 results and the three year calibration period.

Table 6 shows a comparison of the updated Bertrand Creek model results and the various monthly flow rates under negotiation. The exceedence flows presented are a reflection of the ‘naturalization’ of the model. The streamflow values presented are what can be expected to be used for irrigation, or to stay in the stream. The 10% exceedence flows (EF) from the wet period represents the highest flows expected. The 10% exceedence flows from the 60 year period are more representative of the system since it encompasses more data. These values are slightly lower than the 10% EF from the wet period, except in September when they are slightly higher. The 50% EF is useful for recognizing that flows will be higher than this value only half of the time and lower than these values half the time. If available streamflow is higher than required surface water diversions to meet crop water demand only half of the time, investment in storage capacity would be strongly recommended. For a 90% EF, 90% of the time the flow will be higher and 10% of the time the flow rate will be lower. Calculating the EF statistic from the driest consecutive five year period lowers these 90% EF by less than 1 cfs during low flow months. The observed flows from 2004 -2006 at Rathbone Road are higher than the 50% EF of the winter months, but closer to the 90% EF in the low flow summer months. This difference may be due to unaccounted for surface use and groundwater extractions by the model. The naturalized flows do increase the low flow values by the diversion requirement and 10% of the groundwater pumping. However, the time delay of the effect on streamflow of the groundwater pumping may not be properly represented.

In 1985, the State of Washington Department of Ecology proposed an instantaneous flow rate for Bertrand Creek in the Nooksack Instream Resources Protection Program (IRPP). These flows are very close to the 50% EF of the updated model during the winter months, and very close to the naturalized flows estimated for the summer months. However, the IRPP flows for June, July and August are higher than the 10% EF predicted by the wettest five year period.

The Bertrand WID has proposed a set of ensured flows to be met followed by targeted flows that could be met after various groundwater supplements to streamflow and storage capacity building projects are underway. The ensured flows are closest to the

lowest flows expected from a 90%EF during October of the driest five years. The targeted flows are closest to the 50%EF predicted by the model update given 60 years of climate data.

The Nooksack Tribe and Lummi Nation have proposed a set of desired future flows and acceptable interim flows. In June and July, these flows are closest to the 10%EF for the five wettest years. For the rest of the year, the desired flows are between the 10%EF and 50%EF predicted by the model update given 60 years of data.

Table 7 shows the modeled exceedence probability flows determined by the WRIA1 model and the updated Bertrand Creek model for Bertrand Creek at the International border. The observed flows are from a seasonal gage with values available only during the irrigation season. Naturalized flows include the addition of surface water licenses for streamflow diversion to the observed streamflow. The lack of groundwater pumping information available to use in the model setup and calibration is a likely cause for modeled streamflow that is generally higher than observed streamflow.

Table 6. Modeled, observed and proposed mean monthly streamflow levels in Bertrand Creek at Rathbone Road.

Month	Bertrand Creek Model Update							WDOE	Bertrand WID		Nooksack Tribe & Lummi Nation	
	10% Exc.Flow 5 Wet Yrs	10% Exc.Flow	50% Exc.Flow	90% Exc.Flow	90% Exc.Flow 5 Dry Yrs	Obs.Flow 2004-2006	Naturalized* Flows 2004- 2006	IRPP (1985)	Targeted Flows	Ensured Flows	Desired Future Flows	Accept. Interim Flows
	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
October	136.8	94.2	14.7	4.4	3.6	73.7	73.7	13	20.18	3.5	20.1	18.3
November	265.3	196.3	68.7	18.7	9.9	133.2	133.2	30	74.2	3.5	127.9	76.1
December	313.4	240.0	94.5	36.4	36.6	136.2	136.2	60	74.2	3.5	127.9	76.1
January	286.6	260.5	96.4	40.5	21.1	211.0	211.0	90	74.2	3.5	127.9	76.1
February	274.0	225.4	93.4	43.0	28.6	98.3	98.3	90	74.2	3.5	127.9	103.5
March	181.9	159.5	72.6	38.2	32.2	74.2	74.2	90	50	3.5	127.9	103.5
April	85.9	97.6	46.1	29.3	25.8	63.8	63.8	80	40	3.5	96.7	84.5
May	67.0	45.9	24.4	15.9	13.1	21.1	22.0	50	20	3.5	54.5	48.1
June	29.8	23.6	13.9	9.4	8.3	12.9	17.9	33	12	3.5	32.3	28.8
July	17.9	13.9	8.7	6.2	5.4	6.6	15.0	21	8	3.5	18.8	17.5
August	10.1	9.3	6.3	4.6	4.2	5.3	12.1	13	8	3.5	11.6	9
September	13.7	14.9	5.7	4.1	3.9	14.4	16.8	13	8	3.5	13.2	12.3

*Naturalized flows shown here include the addition of estimated surface water diversion requirement to the observed flows.

Table 7. Modeled, observed and naturalized mean monthly streamflow levels in Bertrand Creek at the International border. The streamflow gage at this location is seasonal and observed values are available during the irrigation season.

Month	WRIA 1 Watershed Model for Bertrand Creek					Updated Bertand Creek model					Observed	Naturalized*
	0.1	0.3	0.5	0.8	0.9	0.1	0.3	0.5	0.8	0.9		
October	22.7	12.4	5.9	3.0	1.6	10.0	6.7	4.3	3.5	2.9	NA	NA
November	101.8	56.2	30.7	16.4	7.3	20.5	14.6	9.4	5.9	4.1	NA	NA
December	195.7	132.9	86.5	47.2	27.8	38.5	25.9	16.8	11.1	7.1	NA	NA
January	210.6	152.5	99.0	68.3	47.3	55.4	37.9	23.9	16.0	10.8	NA	NA
February	182.1	129.6	89.1	64.2	47.7	60.5	44.0	29.3	19.7	15.2	NA	NA
March	120.4	95.7	70.0	51.1	40.0	46.7	36.0	27.0	19.2	14.2	NA	NA
April	81.5	65.3	48.8	36.9	28.8	31.3	24.8	19.8	15.1	12.1	7.9	8.3
May	50.8	35.6	25.3	18.3	14.3	19.4	16.2	13.0	10.4	8.4	5.9	6.6
June	30.1	18.3	12.6	8.9	6.7	12.7	10.7	8.7	7.0	5.7	3.8	4.5
July	15.2	9.7	6.1	3.9	2.8	8.4	7.2	6.0	4.9	4.1	1.7	2.6
August	7.8	5.1	2.9	1.8	1.3	5.9	5.2	4.5	3.8	3.2	1.2	1.9
September	8.8	5.3	3.1	1.6	1.0	5.4	4.4	3.9	3.3	2.8	3.8	4.1

*Naturalized flows shown here include the addition of surface water licenses to the observed flows.

Modeling Agricultural Drainage

There are different types of drains used to remove excess field water. Open ditches can remove large volumes of water and work especially well draining heavy clay soils where the slope is flat. Concrete and tile drains, which function as buried perforated pipes, have become popular for subsurface drainage in the past 30 years. However, it should never be assumed that subsurface drains are functioning properly, since many subsurface drains are clogged after only a few years, especially in areas of finer textured clay soils (Hargreaves and Merkle, 1998). In Bertrand Creek, the small open channels, or ditches, are responsible for most of the early spring water drainage required to warm the soils and begin the initial growth stage of the agricultural season. This artificial drainage removes water from the soil storage, bypassing the groundwater saturated zone, and adds it directly to the streamflow by way of the artificial channel network.

It is currently not known whether the groundwater saturated zone is full at the time of year that artificial drainage is used to dry the root zone. If the groundwater saturated zone is at capacity, the artificial drainage bypassing the saturated zone may only affect the timing of streamflow by a matter of days. If the groundwater zone is below capacity, the artificial drainage may reduce the annual recharge to the groundwater zone and therefore affect the level of baseflow later in the season. It is not possible to determine these effects without a better understanding of the timing of the hydraulic continuity between groundwater and streamflow in Bertrand Creek.

However, we can use the spatial information we have about the ditch network to model the potential differences between a dense network of ditches and a non-ditched stream network. Figure 24 shows the difference between the relatively non-ditched network used in this project to update the model. The total length of ditches and stream channels in the Bertrand Creek is 91 miles. This total includes approximately 80 miles of ditches in the U.S portion and 11 miles of stream channels in Canada. The total length of the ditches and stream channels modeled in this project is 48 miles. Using the total watershed area of approximately 20 mi^2 , the area average distance, L_{full} , between ditches and channels for the full network is 0.2 miles. An area average distance, L_{mod} , between ditches and channels as represented in the model is 0.4 miles. In short, the actual

drainage network is twice as dense as we are currently modeling given the practical limitations of the number of sub-basins represented and parameterized.

We can use the L parameter to estimate the relative difference in drainage discharge we might expect from two different networks. The ‘full’ network is what is currently captured by the model calibration. The ‘less’ dense network has approximately twice the distance between streams.

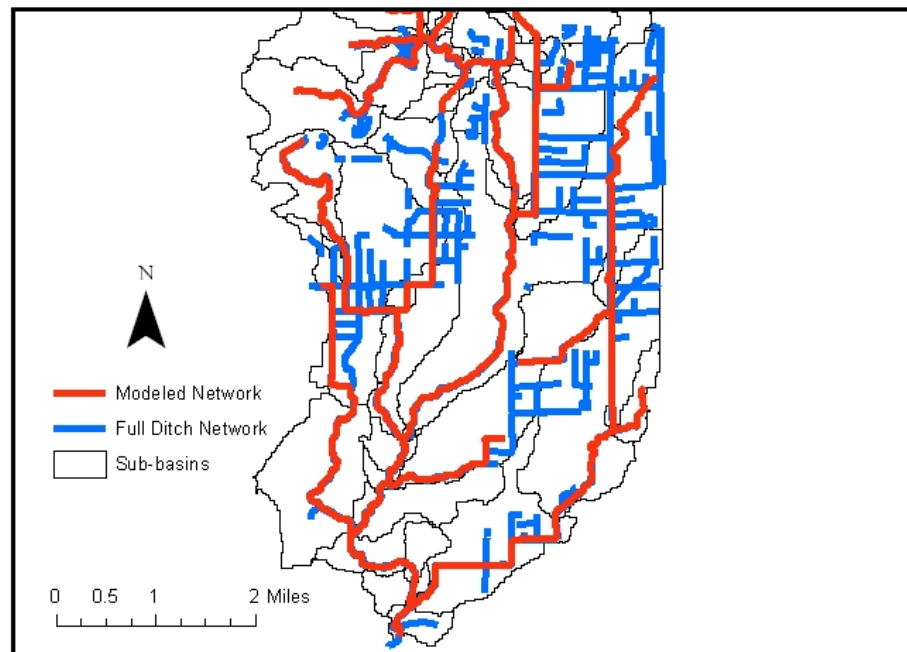


Figure 24. A comparison of the full ditch network used for agricultural drainage in Bertrand Creek and the modified network used in the updated model.

In 2004, Utah State University suggested modeling the agricultural drainage using discharge to a ditch or drain pipe as given by Skaggs (1980) and Cooke et al. (2001):

$$Q = \frac{2K}{L}(m^2 + 2mh_0)$$

where K is the effective horizontal saturated hydraulic conductivity, L the spacing between drains, h_0 the soil/aquifer depth (below the drain) and m the midpoint water table elevation above h_0 . Assumptions in deriving this equation are the same as those used by

Skaggs (1980) and Cooke et al. (2001) and are: (1) Horizontal flow in the saturated zone (Dupuit-Forcheimer); (2) Steady State. The water table profile due to time varying drainage will be approximated using a sequence of steady states, an approach also used by Skaggs (1980) and Cooke et al. (2001). If K , m , and average h_0 are constant area averages, the difference between Q given $L_{full} = 0.4$ and $L=0.2$ will be 50%.

To compare the a change in flows expected between $L = 0.4$ and $L=0.2$, we have kept all updated model components the same, but reduced the K calibration multiplier by 50% to account for the 50% less flows expected from a less dense drainage network. Results from this experiment showed very little sensitivity to the K parameter or change in the resulting streamflow.

The f parameter is the most sensitive parameter in Topnet. It is a measure of the sensitivity of lateral groundwater flow to changes in groundwater level. Its value greatly influences the responsiveness of simulated flow hydrographs and the shape of recession curves (Tarboton, 2007). During the pre-irrigation drainage season, the groundwater table is essentially at the surface. The per unit area baseflow, Q_b , draining the saturated zone derived using the exponential decrease in hydraulic conductivity with depth assumed by TOPMODEL, with T_0 being transmissivity: $Q_b = T e^{-\lambda} e^{-fz}$. Since f is a more sensitive parameter than T , to reduce Q_b by 50%, the calibration multiplier f was reduced by 70% (derived using the natural logarithm).

Figure 25 shows that representing a decrease in drainage by 50% with the adjustment of the f parameter will reduce the highest of the high flows (10-30% exceedence probability for winter months) by approximately 5-10 cfs at Rathbone Road. Figure 26 shows the result during the summer months where fewer ditches results in an increase of approximately 5 cfs. While this result makes intuitive sense, further model development may be required to test this result. The assumption that f parameter adjustment is reasonable for ditch drainage may be reasonable during the high flow season when the ditches are full. However, during the low flow season when the ditches are dry, the reduction in the f parameter may not be appropriate. A model development that allowed for a seasonal parameter adjustment, rather than a constant parameter throughout the year may improve the representation of the ditch function in the Bertrand Creek hydrologic system.

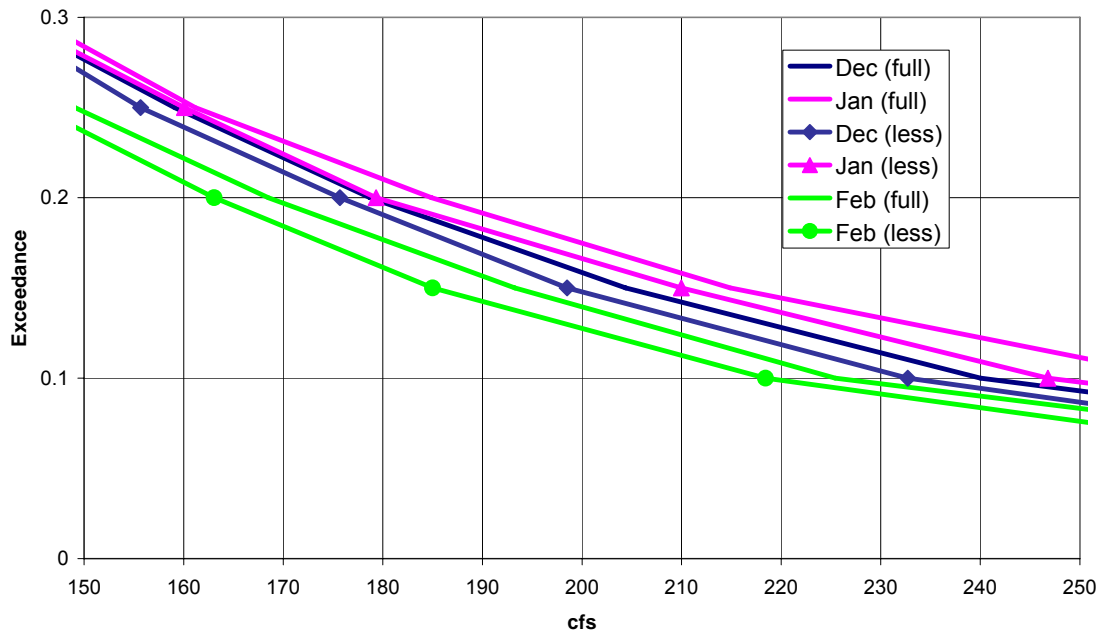


Figure 25. The highest range of flows for winter months comparing the current 'full' ditch network with a 'less' dense network.

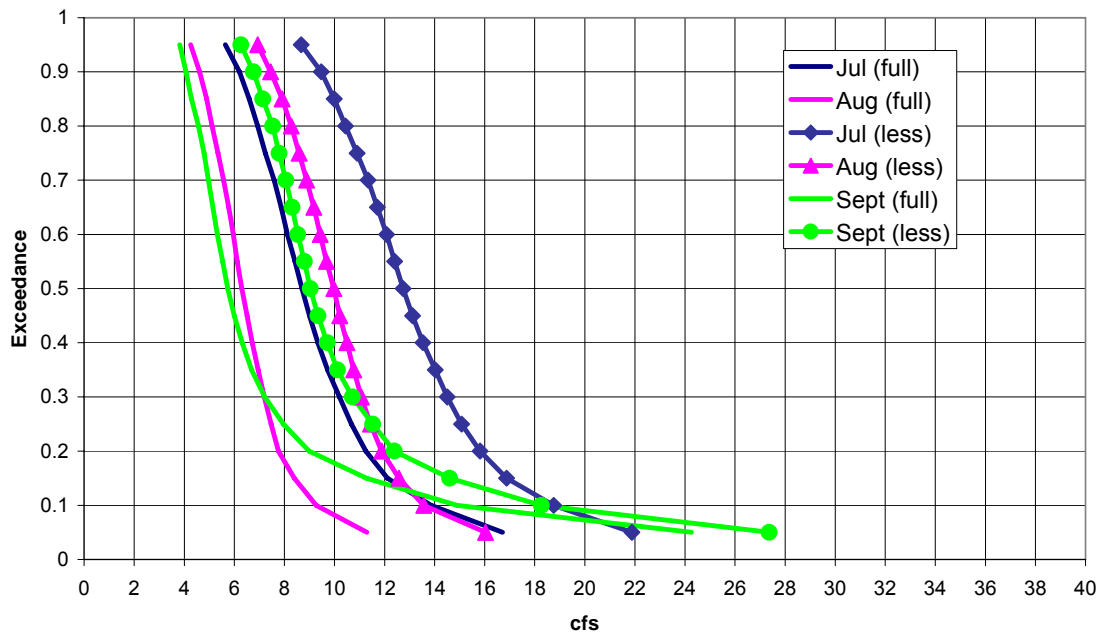


Figure 26. The lowest range of flows for summer months comparing the current 'full' ditch network with a 'less' dense network.

Conclusions and Recommendations

The updated TOPNET hydrologic model for the Bertrand Creek watershed developed in the project is an improvement compared to the WRIA1 watershed project model representation of the watershed. The main difference between the models is the increased spatial discretization of the model focused on Bertrand Creek compared to the WRIA1 model developed for the entire Nooksack basin, and the incorporation of data that has become available since the development of the WRIA1 version of the model. Newly available data used in this project include observations of streamflow at Rathbone Road used for an updated calibration, land use and soils data from the Canadian portion of the watershed used for model parameterization, and data about irrigated area and water sources used for irrigation collected in the Bertrand CIDMP which was used to estimate crop water demand. An important implication of dividing the watershed into 46 sub-basins in the updated model, compared to 1 basin in the WRIA1 model, is that the spatial variability of rainfall is better related to the four surrounding climate stations.

Analysis of precipitation records between 1946 and 2006 show that the 2003-2006 calibration period was very close to average. The Nash-Sutcliffe efficiency measure of 0.85, where a value of 1 is a perfect result and values less than 0.7 are generally not acceptable, confirms a good calibration of the model to Bertrand Creek observed flows at Rathbone Road. The modeled streamflow resulting from a 60 year historic record (1946-2006) can be expected to be a statistically acceptable representation of the current system. Exceedence probability flows reflect that the modeled flows in the low flow months are lower than the naturalized observed flows. Naturalized flows included the estimated effect of surface water diversion and groundwater pumping. The estimated crop water requirements for areas using surface water is close to the sum of certificates and permits for irrigation diversions, however, exceedence probability flows show that this amount of streamflow may be available less than half of the time during low flow summer months.

A drainage modeling exercise comparing the current ditch drainage network to a relatively less dense network with twice the distance between ditches was calculated

using the updated model calibration. Results suggested that given mean monthly averages, the highest flows will be lower by 5-10 cfs and the lowest flows will be higher by close to 5 cfs with a less dense drainage network. Attaining this increase in flow would require disabling the entire ditch network of the watershed, and may better be addressed by management activities such as pond storage or groundwater supplements to streamflow. Addressing the development capacity, contributing area, expected water temperature and economic feasibility of the proposed storage ponds should be considered for future work.

Given the current drainage system and use of groundwater for irrigation, the updated model is a good representation of the Bertrand Creek system. However, an average monthly flow volume error analysis suggests that the over-prediction of the model at the International border and during September at Rathbone Road may indicate that the model is not capturing the delayed effect of groundwater pumping on streamflow. The modeling of low flows in the Bertrand Creek could be improved with a better understanding of the influence of groundwater pumping on streamflow. Knowing the time delay and hydrologic continuity between the groundwater and surface water systems would be very valuable for managing water during low flow months.

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Appendix A: Additional Calibration Result Figures

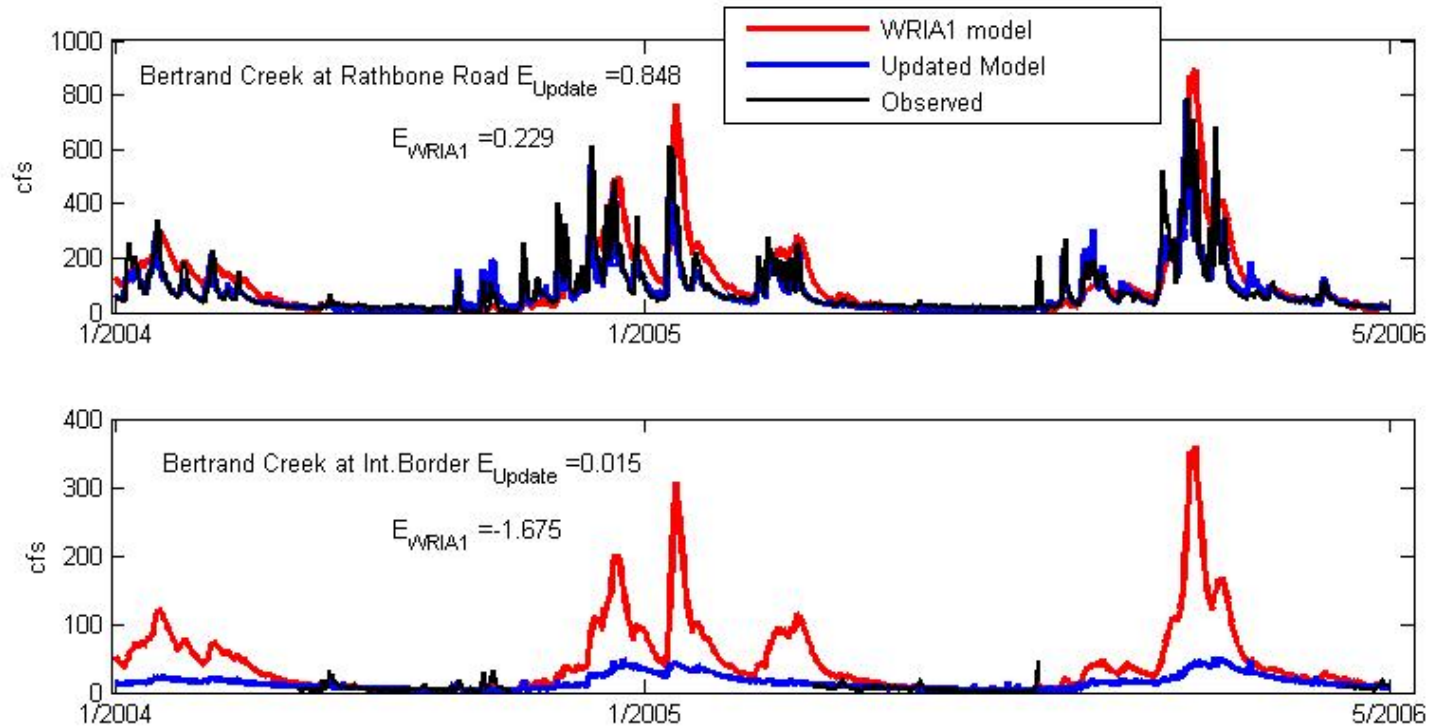
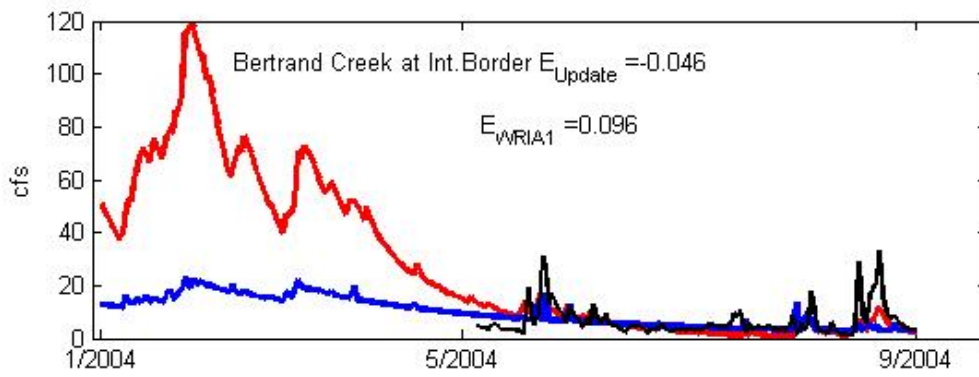
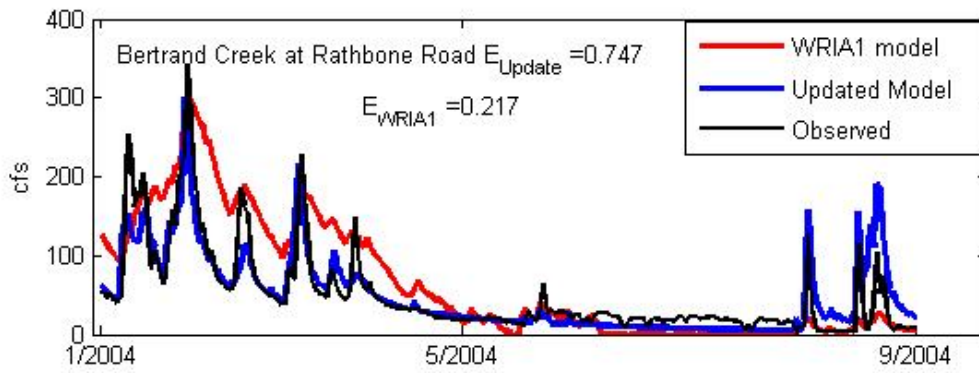
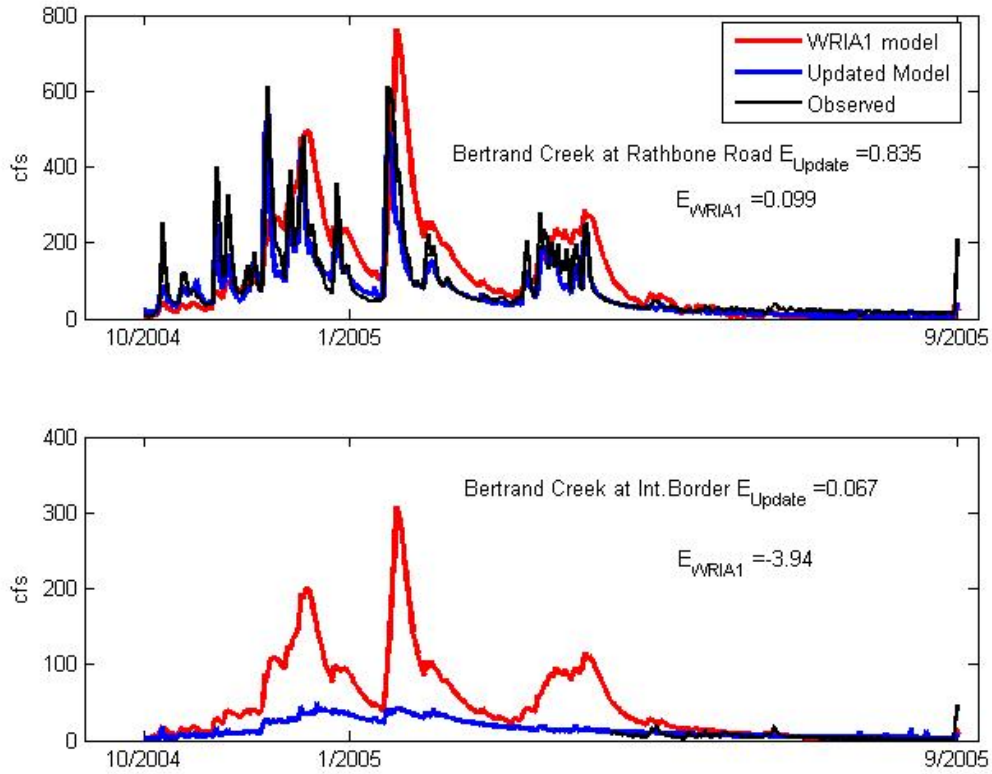


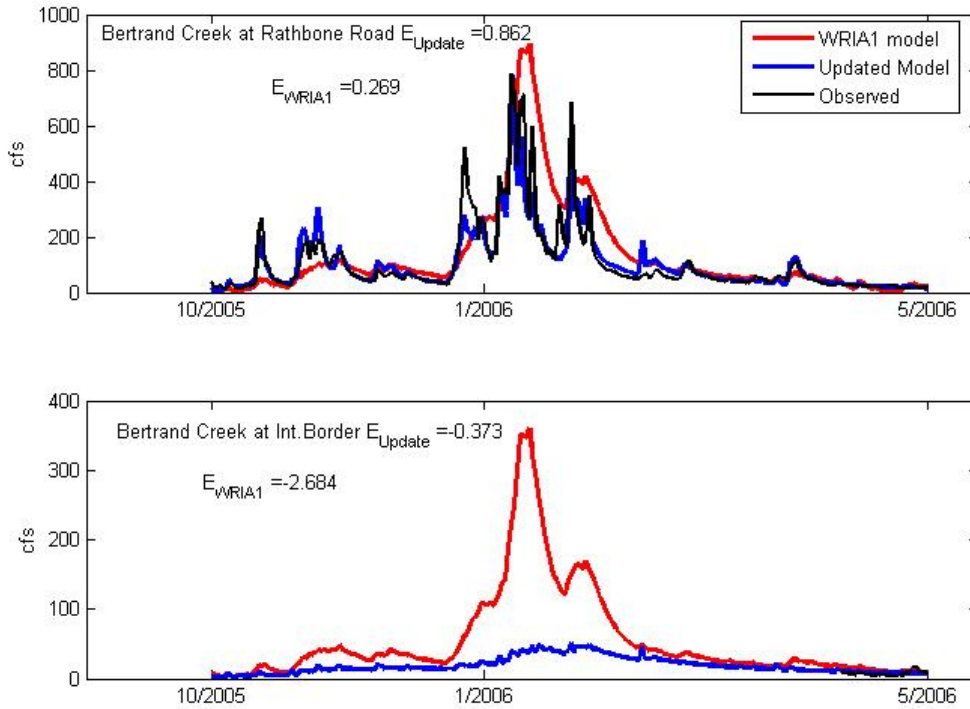
Figure A1. Results for the updated model calibration period, not including the first 200 days reserved for starting up the model components. Observed data at the International border are only available during the irrigation season.



1
 2 Figure A2. Results for the water year 2003. Observed data at the International border are
 3 only available during the irrigation season.

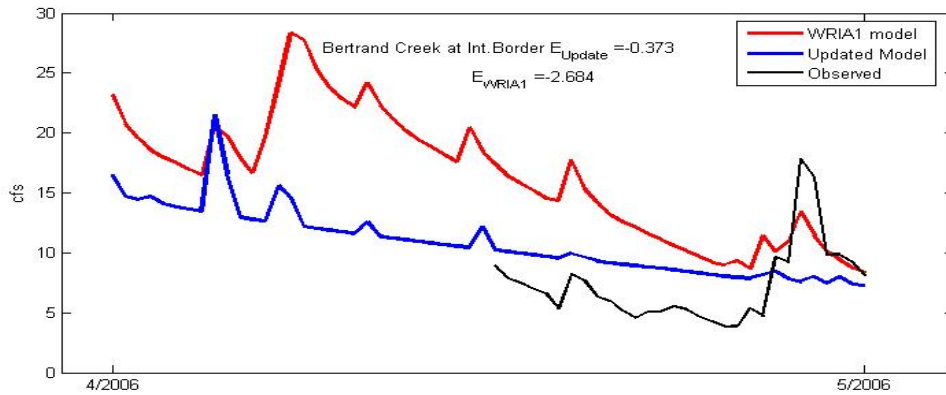


1
2 Figure A3. Results for the water year 2004. Observed data at the International border are
3 only available during the irrigation season.
4

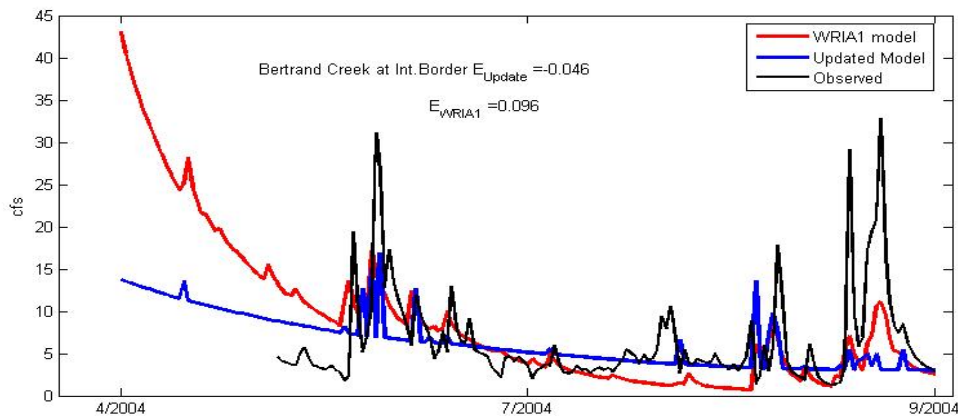


1
2 Figure A4. Results for the water year 2005. Observed data at the International border are
3 only available during the irrigation season.

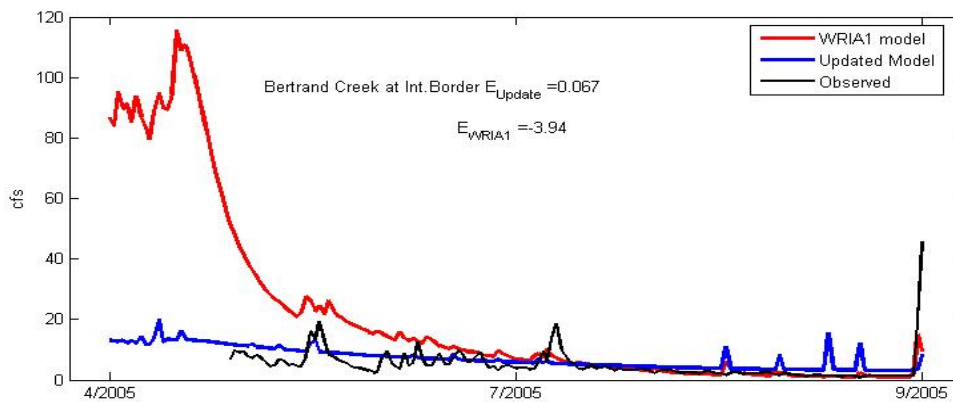
1 a.



2
3 b.



4
5 c.



6
7
8 Figure A5. Results for irrigation seasons in a) 2004, b) 2005, and the early part of c)
9 2006 (until the end of available observed climate data) for Bertrand Creek at the
10 International Border.

11