MODELLING THE EFFECTS LOGGING ROADS ON THE STREAMFLOW OF A MOUNTAINOUS, SNOW DOMINATED WATERSHED

by

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B.Sc., The University of Arizona, 1996

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTERS OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

Department of Forest Resources Management; Faculty of Forestry

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

August 2003

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Date August 14, 2003

ABSTRACT

Logging roads have the ability to alter streamflow by converting subsurface flow paths to surface flow paths. The two primary mechanisms by which this occurs are the interception of subsurface flow at road cuts and production of infiltration excess overland flow on road surfaces. The impact of subsurface flow interception in a snow dominated regime, at basin and sub-basin scales, was explored in this study with the application of the hydrologic model, Distributed Hydrology-Soil-Vegetation Model (DHSVM). Sensitivities of the model to road cut depth, increased stream density and increased road density were also examined in addition to the comparison of modelled versus observed tributary flow. Redfish Creek and two of its sub-basins are the subject watersheds located in the Kootenay Mountains of the British Columbia interior. At the 26 km^2 scale of Redfish Creek basin, no substantial alteration in annual yield or annual peak flow occurred resulting from the presence of 16 km of logging roads. There was also no appreciable change due to modelled minimal stream extension to culverts connected to the stream via surface flow or the addition of skid trails and an abandoned road both modelled in the form of increased road density. Greater changes occurred at the sub-basin scale. Redfish Upper Tributary, in a 1 km^2 sub-basin, experienced decreases of less than 5% in annual yield and annual peak flow. The largest changes occurred for the South tributary, in a 0.8 km^2 sub-basin. The annual yield increased by 19.6% and the annual peak flow increased by 11.3%. Redfish Creek model sensitivities to the refinements in representing logging roads and their effects are greater at smaller scales. As compared against a roadless model, the addition of logging roads to Redfish Upper tributary did not noticeably improve the fit of modelled flows with observed flows.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

This research would not have been possible without the help and support of many people. I would firstly like to thank my advisor, Dr. R. Daniel Moore, who saw me through the completion of this thesis. I greatly appreciate his patience equally as much as his invaluable guidance. Additional thanks go out to Dr. Roy Sidle for his input and support. I am also thankful for Dr. Younes Alila's belief in me and the role he played in my acceptance to the graduate program.

Adam Stonewall is especially deserving of recognition. He has been a very important part of my life and has supported me with love through all the successes and supposed catastrophes. He fills many roles in this accomplishment: field assistant, technical advisor, lab mate and confidant.

This work would not have been possible without the technical assistance of those that are or were associated with the University of British Columbia: Jos Beckers, Jerry Maedel, Erik Schiefer, Harry Verwoerd, and Andrew Whitaker. Emilee Fanjoy, Peter Jordan, and Dave Toews of the Ministry of Forests were of great help. Valuable support was also provided by the Civil Engineering Department at the Univeristy of Washington namely Laura Bowling, Jonathan La Marche, Pascal Stork, and James Van Shaar. Thanks goes to the field assistance of Dino Gnoto without whom I'd still be trying to finding my way out of Redfish Creek watershed. The camaraderie of my fellow computer lab mates, Takashi Gomi, Joyce Kim, David Luzi, Ahmed Mtiraoui, Julie Orban, and Yuzhang Wang, made my work even more enjoyable.

My appreciation goes out to my best friends of many years Zulma Biddle and Jeanie Comstock for knowing that I would eventually finish. Thanks also to each member of my family who hoped I would eventually finish.

Many thanks to the Research and Development Department of Stormwater Management Inc. who have been very supportive and understanding through the final stages of my work.

CHAPTER 1: INTRODUCTION

1.1 Overview

The effects of forestry activities on streams are of great interest to those researching and preserving stream health. Logging roads may alter streamflows in different ways than forest harvesting. Removing the forest cover alters vertical exchange processes such as interception loss, snowmelt and transpiration (Bosch and Hewlett, 1982; Gray and Prowse, 1993). However, road construction more drastically affects the lateral movement of water downslope to stream channels. Roads intercept subsurface flows at road cuts and route them more rapidly as surface flow via ditches, culverts, and natural drainage features (Wemple, 1994, Croke and Mockler, 2001.). In addition, constructed haul roads are typically highly compacted, and the resulting low permeability can inhibit the infiltration of rainfall on road surfaces, thereby producing Hortonian overland flow (Gardner and Chong, 1990). In these ways, logging roads may affect peak flow timing and magnitude, annual yield quantities, and low flow levels. There is currently vigorous debate about the hydrologic effects of logging roads and their significance in relation to downstream flooding (Jones and Grant, 1996; La Marche and Lettenmaier, 1998). This debate is fueled, in part, by the paucity of field experiments that have focused on forest roads, in isolation from the effects of forest removal and natural catchment processes. Given the considerable cost involved and time required to conduct properly controlled catchment-scale experiments, it is unlikely that this situation will be rectified in the near future. An alternative approach to field experiments to assess relative impacts is the application of computer simulation models.

The general objective of this research was to apply a physically based, spatially distributed hydrologic model to examine the effect of logging roads on streamflow at the basin and sub-basin scales in Redfish Creek, a mountainous, snowmelt-dominated watershed located in the West Kootenay region of British Columbia, Canada. The remainder of this chapter reviews runoff generation in forested catchments, with attention to the effects of forest roads. It then introduces the application of the Distributed Hydrology-Soil-Vegetation Model (DHSVM) for predicting the hydrologic effects of forest practices, then ends with the specific objectives of the research.

1.2 Runoff Generation and the Effects of Forest Roads

Fundamental to analyzing the potential results of forest management practices on the hydrologic regime is the understanding of physical mechanisms operating in the geographic area of interest. Many physical processes are involved in the conversion of rainfall and snowmelt to streamflow. Most pertinent to this study is runoff generation through subsurface flow, the dominant mechanism of temperate, forested mountainous terrain.

Research has contributed to advancing theories of watershed response to runoff. Since the infiltration capacity for the undisturbed forest floor is typically much higher than rates of input from snowmelt and rainfall, Hortonian overland flow is not often observed. Betson (1964) suggested a partial area concept in which a relatively constant portion of the basin contributes to direct runoff. Hewlett and Hibbert (1967) promoted the variable source area concept, in which direct runoff is produced by rapidly draining soils which would extend the length of stream channels and expand contributing riparian zones. Areas contributing to direct runoff are not constant but expand and contract with the progression of rainfall events. More recently a hydrogeomorphic concept of runoff generation has been proposed based on studies in Japan (Sidle et al., 2000). This model suggests non-linear responses in subsurface flow and discharge from geomorphic hollows dependent on antecedent moisture (Sidle et al., 2000, 2001; Tsuboyama et al., 2000). For all of the modern runoff concepts, runoff delivery to forest streams is dominated by subsurface flow (Bonell, 1993).

Aspects of forest subsurface characteristics allow for the rapid conveyance of snowmelt and rainfall to stream channels. It has been shown that macropores, as a preferential flow pathway, are integral to subsurface flow of forested watersheds (Chamberlin, 1972; Mosley, 1982; Sidle et al., 2001). Macropores that form preferential flow networks in the soil matrix are associated with live and decayed plant roots and borrowed paths of small animals. The macropore presence contributes to an effective hydraulic conductivity higher than the hydraulic conductivity of the soil matrix alone (Germann and Beven, 1981; Buttle and House, 1997). Mosley (1982) showed that macropores are capable of transmitting a large portion of subsurface flow in forest soils in New Zealand. However, he found it difficult to characterize the temporal and spatial contribution of macropores in transmitting stormflow. At a hillslope segment approximately 10 m wide, Hutchinson and Moore (2000) found that macropores can shift water flow across a slope, and dominate over the often assumed topographic controls on subsurface flow. Sidle et al. (2000; 2001) noted that preferential flow networks may develop and 'self-organize' in response to increasing antecedent moisture.

Preferential flow paths also influence snowmelt related throughflow. At a site in coastal British Columbia, Kim et al. (2003) observed unsteady state subsurface flow response to snowmelt. The activation of preferential flow paths was suggested as the cause of the throughflow response. Roberge and Plamondon (1987) show that pipe flow contribution can be a significant component of snowmelt throughflow when activated over the short time periods when the saturation level reaches the mineral-organic soil contact at a site 80 km north of Québec City. Both studies report fluctuations in throughflow rates that mimic the diurnal patterns of snowmelt. Kim et al. (2003) also found that the timing of hillslope throughflow peaks either matched or preceded streamflow peaks during diurnal snowmelt cycles.

The presence of logging roads interrupts the natural basin hydrology through two primary mechanisms: Hortonian overland flow operating on road surfaces and the interception of subsurface flow at road cuts. Due to compaction, the infiltration capacities for road surfaces are much less than those found on undisturbed forest soils. The reduction of hydraulic conductivity, which controls infiltration, indicates a reduction in infiltration capacities. Ziegler and Giambelluca (1997) measured median saturated hydraulic conductivities of 146.1 mm/h for forested surfaces and 2.3 mm/h for road surfaces in the mountains of Thailand. For a range of road surface textures in three western US states, Luce and Cundy (1994) estimated hydraulic conductivities ranging from 5×10^{-5} to 8.82 mm/h. The reduced infiltration capacities of roads produce Hortonian runoff that is routed either to a ditch or the fill slope. Water carried down the road, to the ditch and through a culvert, has the potential to travel quickly as surface flow. This may result in shortened travel time to the stream channel and higher peak flows.

In most paired catchment experiments, forest cutting has occurred either at the same time as or shortly following road construction. It is therefore not possible in most studies to separate the two effects statistically. In the few studies where there was a delay between road construction and harvesting, the period of road-only treatment was short, typically one or two years. In a study in the Oregon coast range, the only significant change in peak flow was in a 0.4 km^2 watershed in which roads occupied 12% of the total area (Harr et al., 1975). No statistically significant change in peak flow occurred in the other study watersheds, where roads occupied only 3-5% of the watershed areas. Ziemer (1981) did not detect a change in streamflows resulting from the addition of logging roads that covered approximately 5% of a

4.24 km^2 basin in northern California. King and Tennyson (1984) found a significant increase (30.5%) in the 25% exceedence flow for an 83.8 ha watershed in northern Idaho where roads occupied 3.9% of the area. However, their statistical approach placed their analysis under question (Teti and Northway, 1986).

The hydrologic influence of flow interception depends on two factors: (1) the proportion of downslope flow that is intercepted, and (2) the connectivity between the road drainage system and the stream network. The proportion of intercepted flow will depend on soil depth, geology and the depth of the road cut. Megahan (1972) found that troughs installed along road cuts in two first-order watersheds in the Idaho batholith collected a significant amount of intercepted flow. He also estimated that approximately 65% of the subsurface flow passed below the road possibly by way of fractures in the bedrock. Whereas Hutchinson and Moore (2000) showed that essentially all of the downslope flow from a hillslope segment underlain by compacted till was intercepted at a road cut. King and Tennyson (1984) found that a midslope road was capable of intercepting 67% of the subsurface flow from the watershed. About 61% of the road length had cut slopes greater than 6 m in vertical height.

Several studies have estimated the increase of stream density due to stream channel extension caused by surface flow connectivity of road systems (Montgomery, 1994; Wemple, 1994; Croke and Mockler, 2001). Ditchflow draining directly to a stream-crossing culvert and to drainage relief culverts that flow to an incised gully creates an efficient method of flow delivery to the stream channel. Increasing the speed of flow to the stream channel may result in a general desynchronization of stream flows or shorter time to peak. In the H.J. Andrews Experimental Forest in the western Cascades of Oregon, the estimated drainage density increase due to stream extension in Lookout Creek was 48% and the increase in Blue River was 50% (Wemple et al., 1996). In an examination of the effect of road drainage concentration, Montgomery (1994) found that a 1.2 km^2 basin located in southern Sierra Nevada, California had an increased drainage density from 2.8 to 4.4 km/km^2 due to roads.

1.3 Modelling Effects of Forest Operations on Watershed Hydrology

1.3.1 Evaluation of Available Models

Modelling anthropogenic effects, such as the presence of logging roads and land use change, on streamflow requires the application of a distributed physically based model. A distributed model allows for spatial variation of watershed parameters such as soil and vegetation. For example, modelling the impact of logging roads can be accomplished by applying variables that rerouting subsurface flow in specified areas of the basin after model calibration. Whereas variable changes in a lumped model affect the entire watershed, a physically based, distributed model allows for a physical and spatial representation of hydrologic mechanisms. Without a physically based approach to modelling, calibration would be based on developing empirical or statistical relations between parameters and generated streamflow. Empirical models may be effective in predicting streamflow given meteorological inputs. However, the model would not be capable of accurately predicting effects of land use on streamflow since it does not rely on physically based governing equations.

The DHSVM (Wigmosta et al, 1994) is well suited for the objective of modelling the impacts on basin hydrology due to spatial variation of logging practices in a snowmelt dominated regime (Whitaker et al., 1998). As a distributed, physically based model, DHSVM contains the subroutines required to meet the study objectives. The subroutines simulate snowmelt, precipitation interception by vegetation, evapotranspiration, sublimation, subsurface percolation, saturated subsurface flow, overland flow and channel flow. Most importantly, a road algorithm is contained within the model that allows for an analysis of road influences on streamflows.

1.3.2 Previous Application of DHSVM to Redfish Creek

A snowmelt dominated watershed has been modelled using DHSVM Whitaker et al. (2002, 2003). Located in the Kootenay Mountains near Nelson, British Columbia, Redfish Creek drains a 26 km^2 south facing watershed. The experimental watershed is contained in the West Arm Demonstration Forest controlled by the Ministry of Forests, Nelson District (Figure 1). Four climate stations are located in Redfish Creek watershed. Alpine, Burn, Cabin, and Ross climate stations are shown in Figure 2. Stream gauge locations for Redfish Creek and a Redfish Upper Tributary are also shown.

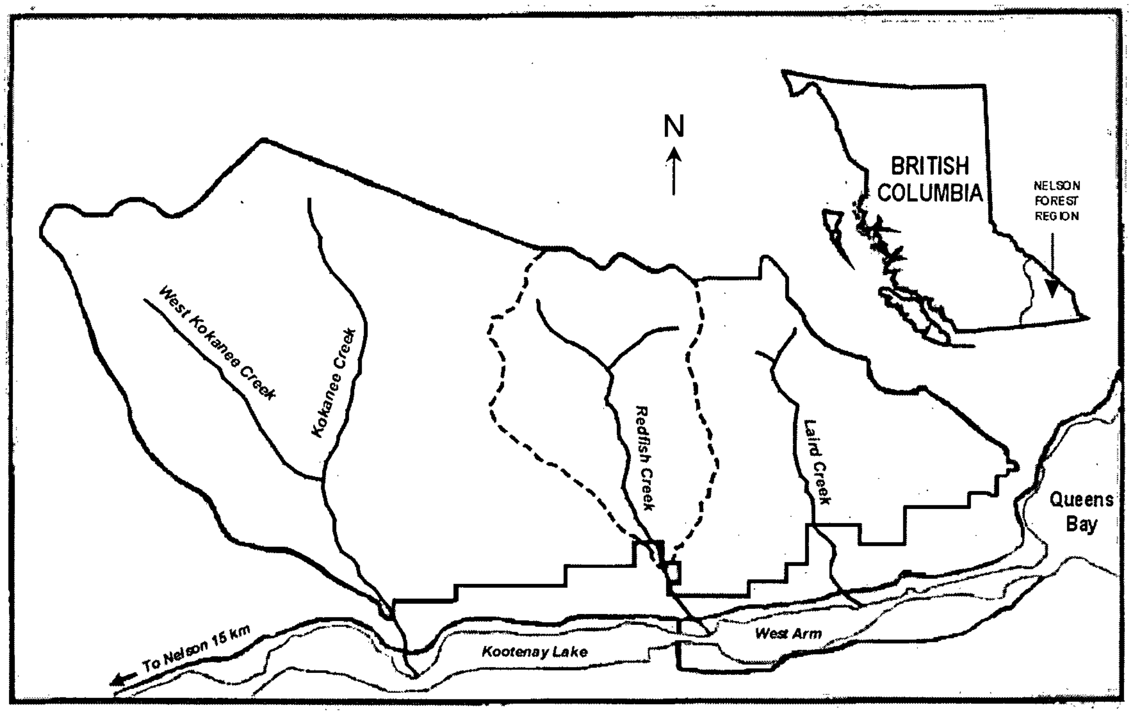


Figure 1. West Arm Demonstration Forest
(courtesy of Ministry of Forests)

The first study applied to Redfish Creek using DHSVM involved the evaluation of peak flows changes due to harvesting within varying elevation bands (Whitaker et al., 2002). It was found that the greatest increases to peak flows occurred for vegetation removal within the upper 80-40% of the watershed, in other words, excluding the lower 20% and upper 40% of the watershed area. Whitaker et al. (2003) conducted a subsequent study assessing the ability of DHSVM to model internal hydrologic processes such as tributary runoff generation and the spatial and temporal distribution of snow accumulation and melt.

1.3.3 Incorporating Road Effects in DHSVM

The original version of DHSVM, which was applied by Whitaker et al. (2002, 2003), did not incorporate algorithms to represent the hydrologic effects of forest roads. A more recent

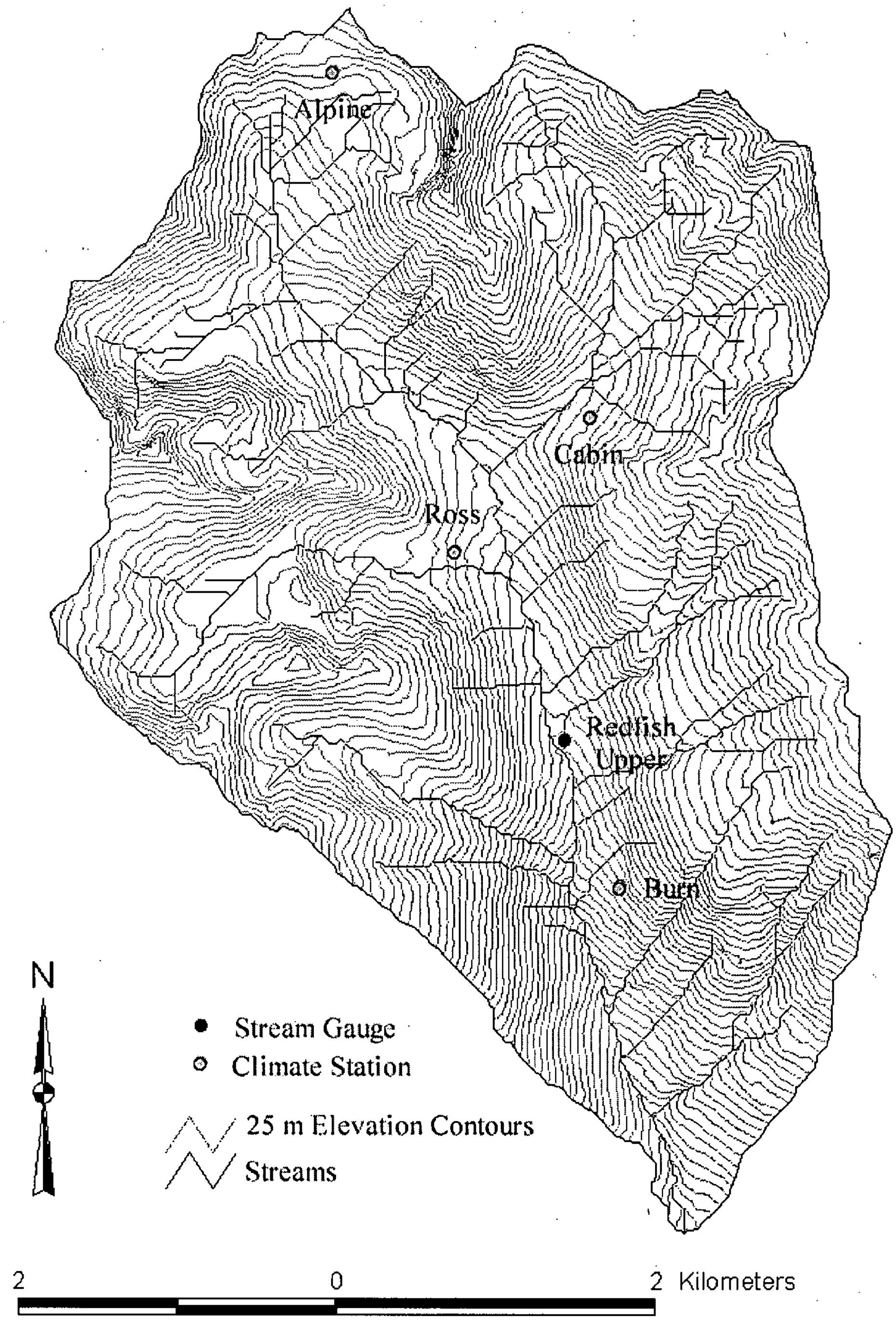


Figure 2. Locations of tributary gauge and climate stations in Redfish Creek watershed

version of DHSVM has been developed, which includes such algorithms (Wigmosta and Perkins, 1997). Two studies focusing on the use of the road algorithm were performed in the Department of Civil Engineering at the University of Washington (Bowling and Lettenmaier, 1997; LaMarche and Lettenmaier, 1998). The modelling objective of Bowling and Lettenmaier (1997) was to test the ability of DHSVM's road algorithm to simulate logging road effects on runoff response. DHSVM was applied to the adjacent watersheds of Hard and Ware Creeks, located in the Deschutes River basin of Western Washington. Hard Creek is a 2.31 km^2 watershed containing 11.4 km of roads. Streamflow extension caused by the road presence resulted in a 63.5% increase in stream channel density to 5.9 km/km^2 in Hard Creek. Ware Creek is a 2.83 km^2 watershed containing 10.7 km of roads. Streamflow extension caused by the road presence resulted in a 52.3% increase in stream channel density to 5.6 km/km^2 in Ware Creek.

A 2 ha contributing area was selected as the threshold for channel initiation for a 30 m resolution DEM (Bowling and Lettenmaier, 1997). A 2-hour time step was applied. Data used to test the model during calibration include monitored peak culvert discharge for six culverts in each basin. The model tended to overpredict culvert discharge for the largest stormflows. The occurrence of culvert discharge as simulated by the model tended to agree with field observations. Following calibration, a series of scenarios were run. According to DHSVM, the addition of the road network to the existing vegetation resulted in a 10% and 8% increase in the 10-year return period flow in Hard and Ware Creeks, respectively. Adding the existing road network and vegetation to pristine watersheds resulted in 18% and 22% increases in the 10-year flows in Hard and Ware Creeks, respectively.

The modelling objective of LaMarche and Lettenmaier (1998) was to simulate the effect of logging roads and forest harvesting on peak flows. Through modelling, they also examined the effect of vegetation and topography on road-generated runoff. The study site is the Upper Deschutes River basin that encompasses Hard and Ware Creeks of the Bowling and Lettenmaier (1997) study. Fourteen named and eight unnamed tributaries (totaling 15 km^2) are included in the 149 km^2 drainage area of the Upper Deschutes. The road densities for the 14 named tributaries range from 3.2 km/km^2 to 5.0 km/km^2. The drainage density due to roads in the tributary watersheds increased from a range of 3.3 km/km^2 to 4.1 km/km^2 to a range of 3.5 km/km^2 to 4.4 km/km^2.

As with the Bowling and Lettenmaier (1997) study, a 2 ha contributing area was used as the channel initiation threshold for a 30 m resolution DEM (LaMarche and Lettenmaier, 1998).

However, a 3-hour step was used. Initial model results over-predicted culvert response. After calibration, percent changes in the 10-year return flow were examined by comparing simulations of the current vegetation state with and without roads. Changes ranged from 2.5% to 10.1% for the 14 named tributaries. Percent changes in the 10-year return flow were then examined through simulations of a pristine vegetation state with and without roads. Changes ranged from 2.6% to 12.2% for the 14 named tributaries. In this case, the modelled road effects appeared to be relatively independent of the vegetation state. Modelled comparisons of similar sub-basins with differences in the percent of connected culverts showed a difference in the percentage increase in the 2.3-year return flow.

1.4 Specific Objectives and Approach of this Study

This study presents the first application of DHSVM, including its road algorithms, in a snowmelt-dominated watershed. The specific objectives were:

1. To examine the sensitivity of streamflow to the addition of roads at the scale of the entire Redfish Creek basin, as well as sub-catchments, including changes to peak flows and annual yield.
2. To explore the sensitivity of the model to variations in road cut depth.
3. To examine the effect of surface flow connections from culverts to the steam network.
4. To examine hydrologic influence of skid trails and abandoned roads.
5. To contrast the effect of logging roads on tributary flow against observed flow

CHAPTER 2: METHODS

2.1 Redfish Creek Site Description

Redfish Creek watershed was previously glaciated. The soils overlie Jurassic, granitic bedrock of the Nelson Batholith. The upper elevations fall within the Engleman spruce - subalpine fir biogeoclimatic zone. The lower elevations are within the interior cedar - hemlock biogeoclimatic zone.

The Burn climate station, located at an elevation of 1290 m, recorded an average annual precipitation of 1040 mm based on data for water years 1993-1997. Approximately 15% of the precipitation fell as snow assuming a rain-snow threshold of 0 C. The Cabin climate station, located at an elevation of 1735 m, recorded an average annual precipitation of 1580 mm of which approximately 45% fell as snow. In addition to four total climate stations within the watershed (Figure 3), an additional climate station, Seed Tree, is located approximately 1 km east of the basin outlet. Runoff peaks are generated by snowmelt and rain on snow events.

Forest harvesting occurred during the years 1966, 1969-1974, 1987-1988, and 1990, with road building taking place approximately a year prior to harvesting each area. By 1993, harvested areas occupied 10% of the watershed area. Of the roads in the watershed, 16 km are active and 3 km are unused and overgrown.

2.2 Distributed Hydrology-Soil-Vegetation Model (DHSVM)

Developed at the University of Washington, DHSVM (Wigmosta et al, 1994) explicitly solves the water and energy balance for each grid cell specified by a digital elevation model (DEM). Meteorological parameters from up to five base stations are adjusted by the model according to lapse rates for application to different elevations in the basin. Precipitation interception is simulated through use of a two layer canopy model. Snow accumulation and ablation calculations for intercepted snow are controlled by a single layer energy balance model. A two layer energy balance model is applied to ground snow. Shortwave and longwave radiation budgets are utilized for each energy balance. The Penman-Monteith formula is used to calculate evapotranspiration. Model conditions are updated according to user defined time steps.

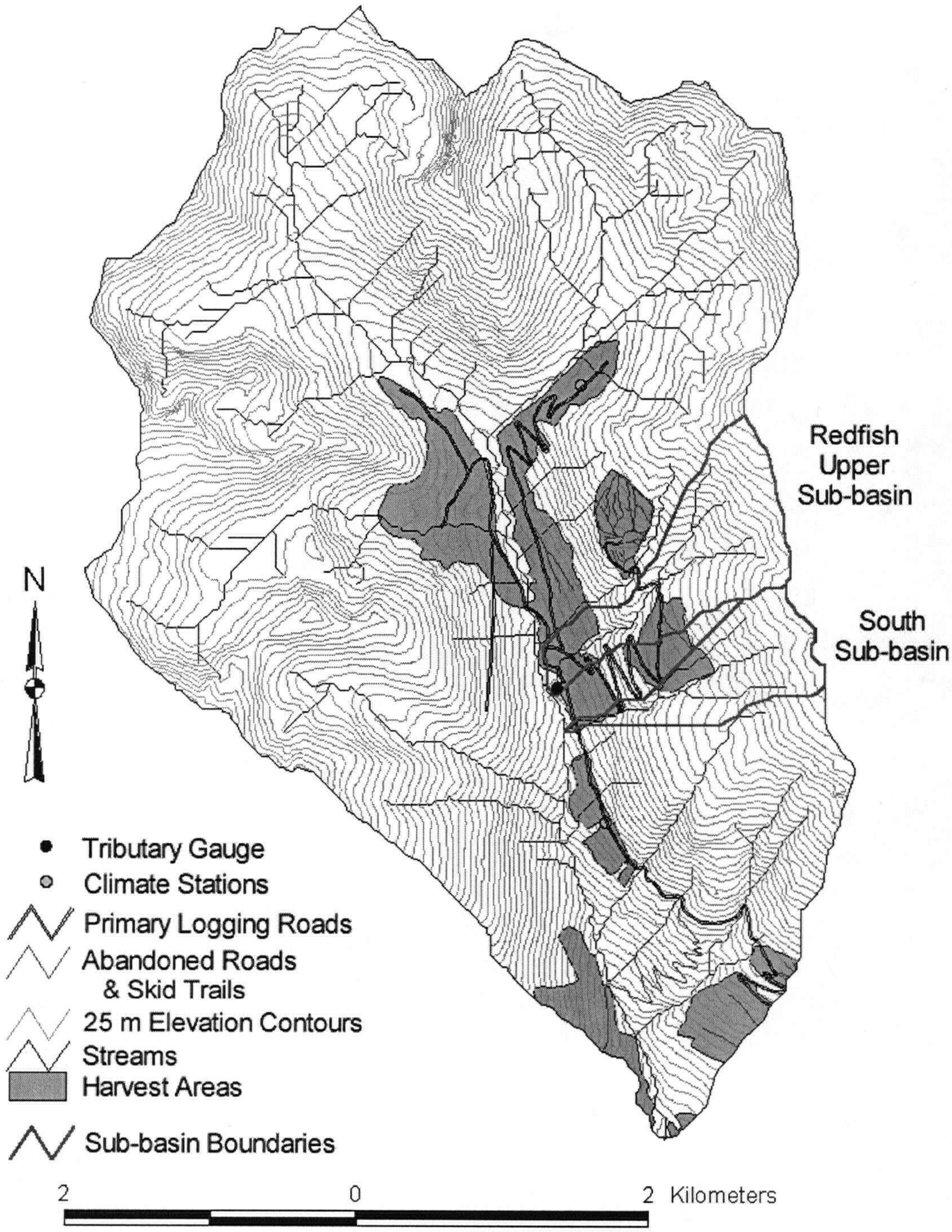


Figure 3. Features of Redfish Creek watershed

All throughfall and snowmelt enter the soil. Vertical movement of soil water in the unsaturated zone is calculated using Darcy's law. Grid cell water table is recharged by this flux. Lateral subsurface flow (slope parallel) relies on hydraulic gradients applied to cells based on the local ground surface slope derived from the DEM. The model assumes lateral saturated hydraulic conductivities decrease exponentially with depth as suggested by Beven (1982).

Subsurface flow is intercepted by the stream channel for routing to the basin outlet. The stream channel is generated by the DEM based on the number of contributing upslope cells. Subsurface flow contribution to streamflow is determined by the water table location relative to the channel bottom. The Muskingum-Cunge routing scheme is used to route water downstream.

The road algorithm operates similarly to the channel routing algorithm (Wigmosta and Perkins, 1997). Roads are essentially treated as an extension of the stream network. Interception of subsurface flow at road cuts is determined by the water table location relative to the cut depth. Ditch flow is routed according to the Muskingum-Cunge method. Once flow enters the ditch, it will not be allowed to reinfiltrate through ditch bottoms. Flow in ditches will either be added to streamflow at stream crossings or reinfiltrated at cross drain culvert locations. Extending the stream network to a cross drain location simulates flow released by culverts that directly connects to streams via overland channels. The road surface is modelled as crowned and impermeable.

The model allows for various output options. Streamflow can be assessed at user specified tributaries, culverts and ditch segments. Basin maps of calculated variables can be generated. An example of map outputs include precipitation, snow water equivalent, water table depth, and saturated subsurface flow. The model can also be run for a chosen cell in the basin to examine internal physical processes without investing time to run the model using the entire basin.

2.3 Hydrologic Model of Redfish Creek

2.3.1 Data Requirements

A large amount of data is required to operate DHSVM due to its high degree of physical representation. A range of spatial and temporal data constitutes the input files. Data relating to the distribution of elevation and parameters relating to soils, vegetation, roads and streams are needed. A range of meteorological data is also required to drive the model. The data required to develop a hydrologic model of Redfish Creek was acquired through the Ministry of Forests, Nelson District.

Meteorological input establishes quantity of inputs and the partitioning within the water balance of the basin. Data required by the model include air temperature, wind speed, humidity and incoming longwave and shortwave radiation. Hourly climate data for October 1992 to December 1997 from the Burn and Cabin climate stations were utilized for the initial Redfish Creek modelling applications (Whitaker et al., 2002, 2003). The climate data were quality checked only for 1997. Gaps in the climate data were resolved by Whitaker and Alila (2000) through estimations based on climate data from Nelson and Castlegar, located approximately 30 km southeast and 65 km southeast, respectively, of Redfish Creek watershed.

Additional temporal data are available for comparison against model outputs. Snow course and hourly streamflow data were used to calibrate and test the model. Streamflow data for the Redfish Upper Tributary are also available for the comparison of model performance on a smaller scale. Hourly data for the 1 km^2 tributary spans late April through October for 1995-97.

Of the spatial data required by the model, the DEM is one of the most important components. Information derived from the DEM is applied to a range of model routines. For example, topography is a controlling factor in the distribution of precipitation. Lateral water movement also depends on topography. The 25 m resolution DEM used for Redfish Creek was derived from a 1:20,000 TRIM (Terrain Resource Information Mapping). Ninety percent of the elevations fall within 10 m of actual elevations. The rectangular DEM consists of 100,800 pixels. The Redfish Creek drainage comprises 41,331 of these pixels for a drainage area of 25.83 km^2 (Whitaker and Alila, 2000).

A map containing the distribution of vegetation classes along with the attributes associated with each class are used by the model to determine vegetative effects on meteorological input and water movement. Modelled effects of vegetation include precipitation interception, evapotranspiration, and the attenuation of solar radiation and wind speed. The vegetation attributes include trunk space, constants for aerodynamic and radiation attenuation, height of vegetation layers, summer and winter leaf area index (LAI), stomatal resistance ranges, albedo, the percentage of roots within soil layers and the depth of soil layers, or root zones. The forest cover map used in the original Redfish Creek modelling project was derived from a Ministry of Forests operational forest cover map consisting of 53 vegetation classes based on species, presence or absence of overstory and understory, vegetation height, stand age and crown closure. Whitaker and Alila (2000) derived additional data required by the model, such as LAI, from available literature. The 53 vegetation classes were merged into 14 classes to allow easier calibration and shorter model run time. Table 1 and accompanying Figure 4 show the distribution of the applied vegetation classes.

Table 1. Key characteristics of the fourteen vegetation types (courtesy of Whitaker and Alila, 2000)

Veg. Type	Description / Species	Stand Age (years)	Overstory Height (m)	Canopy Closure (0-1.0)	Leaf Area Index (LAI)
1	Vegetation absent (tundra-rock)	N/A	N/A	N/A	N/A
2	SubAlpine (subalpine-BS)	200	12	0.2	2.5
3	Balsam-Spruce (BS-20-3)	180	21	0.3	3.0
4	Balsam-Spruce (BS-20-5)	140	22	0.5	3.5
5	Balsam-Pine (BPL-20-8)	130	20	0.8	5.0
6	Balsam-Spruce (BS-30-6)	170	30	0.6	4.5
7	Balsam-Spruce (BS-36-4)	260	36	0.4	4.0
8	Cedar-Hemlock (CWH-30-7)	160	27	0.65	7.0
9	Cedar-Hemlock (CWH-40-7)	170	39	0.7	7.0
10	Douglas-fir-Larch-Pine (FDLPL-30-7)	115	29	0.7	6.0
11	Clearcut-no overstory	8	0	0	0
12	Clearcut-early regeneration	10	2	0.1	2.5
13	Clearcut-shelterwood	10	15	0.1	2.5
14	Regenerated clearcut	38	15	0.2	3.0

Soil attributes are obtained through soil depth and soil type maps. Information provided by these maps and their associated attributes contribute to calculations of soil moisture content, percolation and lateral subsurface flow. Attributes required for each soil type include lateral saturated hydraulic conductivity and its exponential decrease with depth, maximum infiltration rate and soil surface albedo. Information pertaining to each soil layer specified by the root zones include porosity, pore size distribution, bubbling pressure, field capacity, wilting point, bulk density, vertical conductivity, thermal conductivity and thermal capacity. Soils and terrain information originating from Kutenai Nature Investigation Ltd. were developed to create the

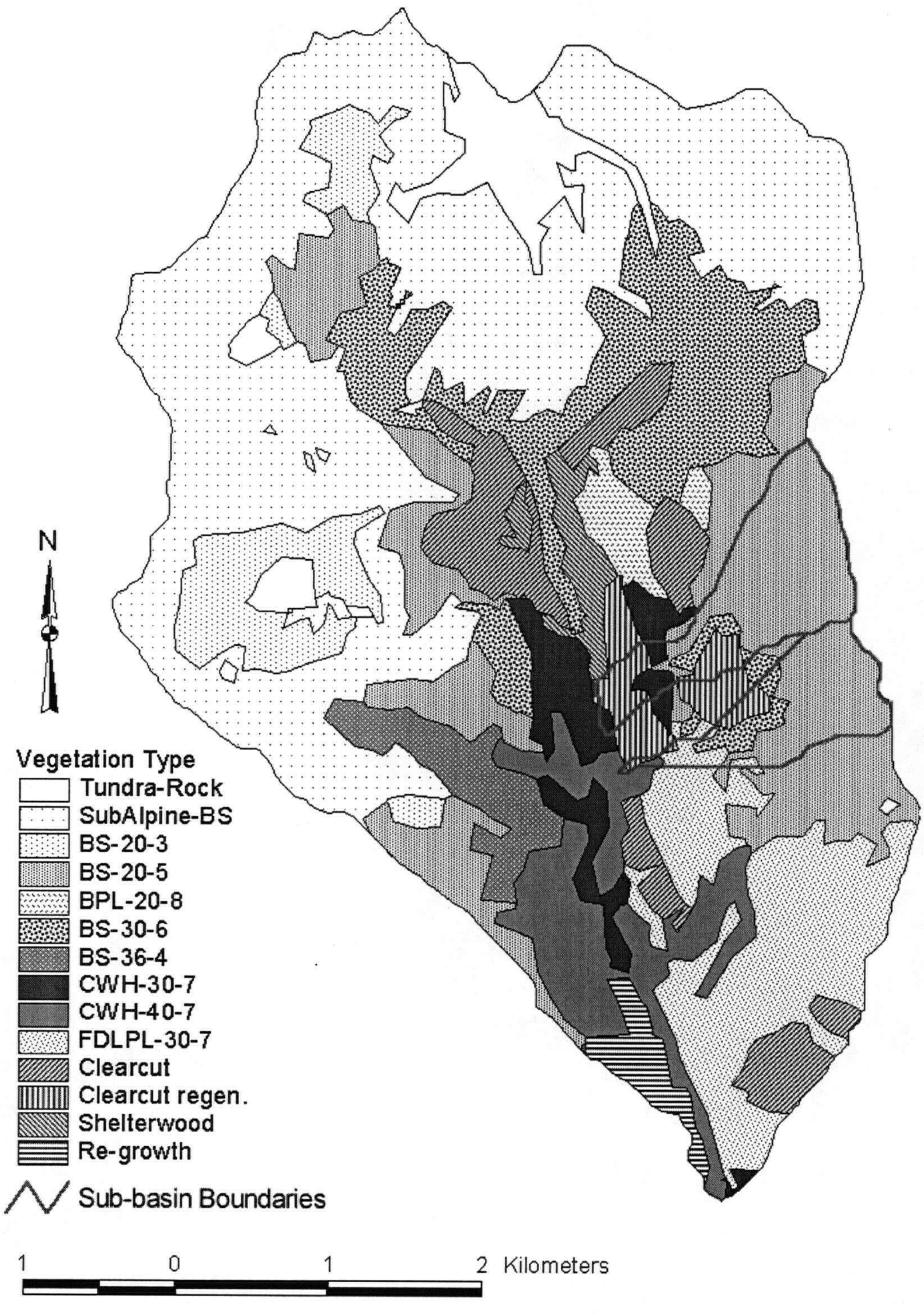


Figure 4. Vegetation types for Redfish Creek watershed

input files. Derivation of soil parameters were based on percent sand and clay content. As with the vegetation data, the soils data were merged into seven soil types to allow easier calibration and shorter model run time. Table 2 with accompanying Figures 5 and 6 show the distribution of soil classes.

Table 2. Key characteristics of the seven soil types (courtesy of Whitaker and Alila, 2000)

Soil Type / Genetic Material	Soil Layer	Texture	Coarse Fragment Content >2mm (% by vol.)	Porosity	Field Capacity	Vert. Sat. Hydraulic Conductivity (m/s)
Colluvium	1	fSL	54	0.45	0.24	1.1e-5
(C)	2	cSL	66	0.4	0.17	1.6e-5
	3	LS	76	0.4	0.17	3.3e-5
Colluvial-	1	SiL	40	0.49	0.33	3.8e-6
Fluvial	2	SiL	55	0.45	0.33	3.8e-6
(CF)	3	SL	65	0.4	0.21	1.2e-5
Fluvial	1	fSL	23	0.45	0.24	1.1e-5
(F)	2	SL	29	0.4	0.21	1.2e-5
	3	LS	36	0.4	0.17	3.3e-5
Morainal	1	L	32	0.46	0.27	7.4e-6
(M)	2	SL	48	0.4	0.21	1.2e-5
	3	SL	54	0.4	0.21	1.2e-5
Weathered	1	L/SL	24	0.46	0.24	1.0e-5
Bedrock	2	cSL	29	0.4	0.17	1.6e-5
(D)	3	cSL	39	0.4	0.17	1.6e-5
Colluvium-	1	SL	61	0.45	0.21	1.2e-5
Bedrock	2	SL/LS	82	0.4	0.17	2.3e-5
(CR)	3	LS	92	0.4	0.17	3.3e-5
Organic	1	L	25	0.46	0.27	7.4e-6
(O)	2	SL/LS	38	0.4	0.17	2.3e-5
	3	SL/LS	52	0.4	0.17	2.3e-5

Three input files are required to describe the stream network. The stream class file provides channel routing parameters such as stream width, depth and friction coefficient. Each stream segment is assigned a stream class in the stream network file. Channel routing parameters for individual segments and stream segment orders for flow routing calculations are also contained in this file. The stream map file locates stream segments in grid cells. Segment location is expressed in terms of grid cell column and row number. The straight line stream channel length in cells, stream bank height and stream channel width are also specified by the stream map file.

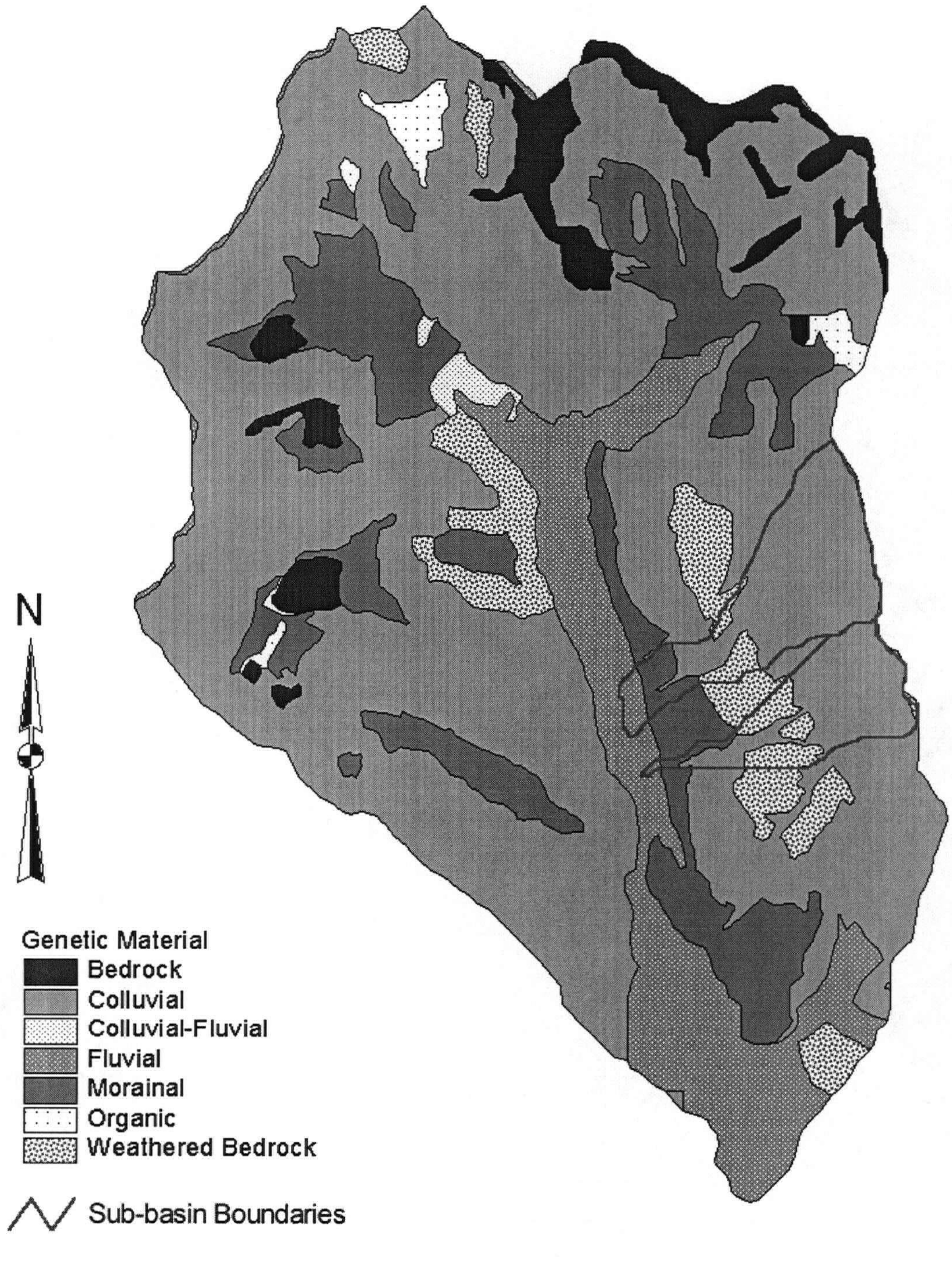


Figure 5. Genetic material classification used to determine soil types for Redfish Creek

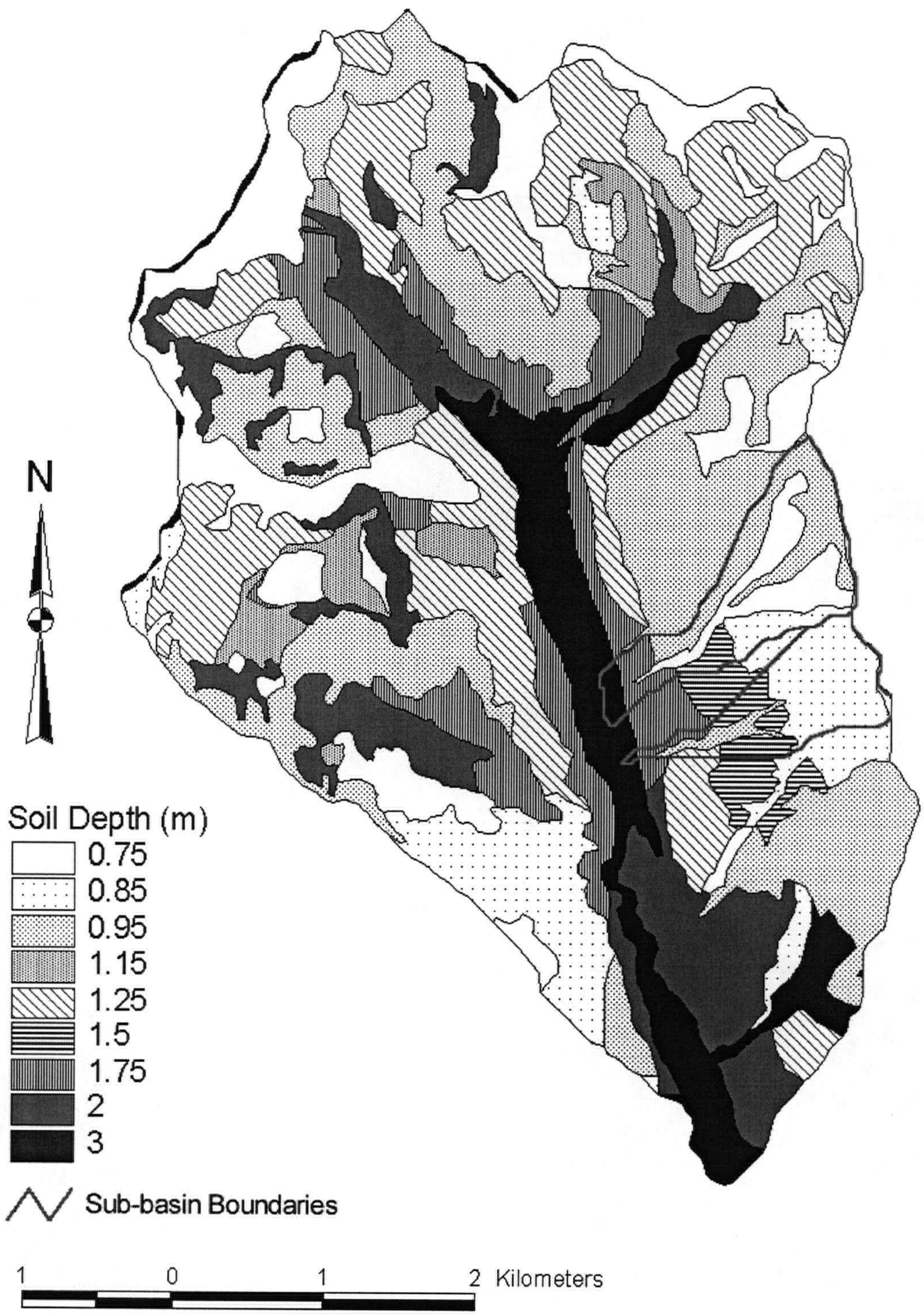


Figure 6. Soil depth for Redfish Creek watershed

As stated previously, the road network is treated as an extension of the stream network. The input needed to operate the road algorithm is similar to that of the streams. The road class file provides channel routing parameters such as ditch width, depth and friction coefficient. The crown type may also be specified but has not been incorporated into model calculations. Each road segment is assigned a road class in the road network file. Also included in this file are channel routing parameters for individual segments and road segment orders for ditch flow routing calculations. The road map file correlates road segments with cells for the quantification of intercepted flow. Segment location is expressed in terms of grid cell column and row number.

2.3.2 Redfish Creek Model Calibration

The calibrated model used in this study is described in Whitaker et al. (2001). Calibration of the Redfish Creek model is summarized in the following paragraph and detailed by Whitaker et al. (2003), who made further applications of the calibrated model, including a slight enhancement to the calibration, using an updated version of DHSVM. Although neither the final calibration nor updated DHSVM version was used in this study, the calibration information of Whitaker et al. (2003) is relevant to the calibrated model used for this study.

The calibration process addressed annual streamflow yield through adjustment of precipitation input to the system; occurrence of seasonal peak flows through separation of rain and snow using a temperature threshold, and by adjustment of albedo curves; effect of vegetation on snow cover through analysis of snow water equivalence distribution; and hydrograph fit through designating values for parameters controlling lateral hydraulic conductivity. A 4-year period from October 1992 to September 1996 was used for the initialization of basin conditions and calibration. As the first six months are very sensitive to the initial conditions applied to the start of the model, they were not used for calibration. The last year of available data (October 1996 to December 1997) was used to test model output response to parameter changes during calibration.

Included among the variables controlling snow accumulation are those involving the partitioning of precipitation into snow and rain. The separation was set such that precipitation below -0.5 °C falls as snow. Above 0.5 °C precipitation occurs as rain. A combination of snow and rain occurs between the thresholds. Due to the high elevation of the Redfish Creek, snow water equivalent is not very sensitive to these thresholds since snow typically falls at temperatures much lower than freezing (Whitaker et al., 2003).

Hourly temperature and precipitation lapse rates were calculated to model approximate precipitation distribution and, in turn, snow pack distribution (Whitaker and Alila, 2000). Temperature lapse rates were determined based on the available records for a pair of four climate stations located in the Redfish Creek watershed. In addition to the Burn and Cabin climate stations, partial records from the Alpine station, located in the northern part of the basin at an elevation of 2050 m, and Seed Tree station, located just south of the basin at an elevation of 850 m, were used. For those time periods in which multiple pairs of overlapping information exist, the pair with the greatest elevation difference was used to determine the temperature lapse rate. Precipitation lapse rates were first defined according to a monthly time scale. The monthly rates were then applied to hourly precipitation data to calculate hourly precipitation lapse rates. An upward adjustment of the precipitation lapse rates corrected deficiencies in snow accumulation at the Cabin and Burn sites based on comparisons of pixel scale simulated snow-water equivalence with snow course data at those locations (Whitaker et al, 2001).

To adjust timing of seasonal melt, albedo curves were redefined within the DHSVM code. Snow albedo determines the absorption of solar radiation by the snow surface. Albedo values applied by DHSVM are based on number of days from the last snow event (Wigmosta et al, 1994). Initially, early season melt was under predicted and late season melt was over predicted. The albedo curves were lowered to better simulate timing of melt. Melt calibration based on albedo curve changes were performed by contrasting modelled SWE for pixels at the Burn and Cabin locations to available snow surveys. Maps of snow cover extent, developed from air photos, were also compared to model generated maps of snow water equivalent (Whitaker and Alila, 2000).

Vegetation related variables affecting snow accumulation and melt in forested areas were determined based on available literature as referenced by Whitaker et al. (2003). Comparisons of simulated and measured SWE for the clear-cut and forested areas of Upper Burn, located north of the Burn climate station at an elevation of 1435 m.

The variables controlling saturated lateral hydraulic conductivity were the most sensitive variables controlling subsurface water movement (Whitaker and Alila, 2000). Two components involved in modelling this parameter are maximum saturated hydraulic conductivity in the top of the soil profile and its exponential decay with depth (Beven, 1982). These components were assumed constant throughout the basin. The calibration process involved maximum saturated hydraulic conductivities ranging from 2 x 10^{-4} to 2 x 10^{-3} m/s and exponential decay coefficients from 1.0 to 2.0 (Whitaker et al, 2001). Calibration resulted in a maximum saturated hydraulic conductivity of 5 x 10^{-4} and an exponential decay coefficient of 2.0. Generated maps of water table depth were examined in addition to comparisons between simulated and observed streamflows to determine that a realistic distribution of saturated depth was attained.

A fairly good fit exists between simulated and observed streamflows at the basin mouth. However, there are discrepancies between simulated and observed flows for the Upper Redfish Tributary. Modelled tributary flows have a much flashier response to snowmelt and rainfall. The flows also tend to overestimate observed flows. These differences may be attributed to less precise delineation involved with smaller drainage areas, the sensitivity of small basins to the spatial variability of soil properties, spatial variability of snowmelt runoff, or the presence of roads in the tributary that where not included during calibration (Whitaker and Alila, 2000; Whitaker et al, 2001; Whitaker et al., 2003). An additional factor could be the inability of DHSVM to capture flow generation processes at smaller scales.

2.4 Incorporation of Roads in the Redfish Creek Model

2.4.1 Methods Overview

The research approach largely involved computer simulations of hydrological processes and response at the basin and sub-basin scales. Model simulations of the hydrology of Redfish Creek incorporating the road network were compared to a base simulation that did not include the road network. Field data were collected to derive input parameters required by the road algorithm. After collection, the data were used to create a database for application to a geographic information system (GIS). Three input file sets were produced which relate to the impact of logging roads and skid trails.

The first set of files represent the operational logging roads alone. The second set builds on the first set by incorporating stream extensions to those culverts that are connected to the stream via surface flow. The remaining set incorporates skid roads and abandoned roads with the logging roads and stream extensions of the second set. The skid roads and the abandoned roads were represented as logging roads. These three file sets were incorporated with the input files used for the original model calibration that preceded this study. Streamflow output from the model runs were contrasted against each other and the streamflow generated from the original pre-road calibration to measure the sensitivity of the model to its road algorithm. Streamflow from two sub-catchments were examined in addition to the flow at the basin mouth. Observed tributary flow was contrasted against tributary flow generated from the third input set.

2.4.2 Field Data Collection

Field data were collected during a 2-week period in July and a 1-week period in October 1999. Roads were traversed twice during the initial fieldwork. Points of interest were flagged and labeled during the initial traverse of road branches. Flagged features, which were mapped using a global positioning system (GPS), include points of ditch flow diversion and conversion, culverts, cross ditches, areas where no ditch existed, seeps visible at the cut slope, and ephemeral streams. Road surveys were performed during the second traverse. The parameters measured include road width, ditch width, ditch depth, road cut length, vertical road cut height, road cut slope, and vertical depth to a confining layer. Ditch roughness was qualitatively described using a rating system of 1 (smoothest) to 4 (roughest). Values of ditch roughness ranged from 0.030 to 0.045 and were assigned based on ditch descriptions in the field notes. This range of values is typically applied for moderately rough sandy bed characteristics to rougher cobbly channels with boulders. These characteristics were observed at a smaller scale for the ditchlines. The crown types noted for the road include insloped, outsloped and crowned. Survey points were established approximately every 200 m or after a significant change appeared in one of the parameters.

Areas below culverts, cross ditches, and switch back turns were examined for surface flow connectivity to the stream. Most drainage relief culverts carried little if any water at the time of field data collection due to the lack of rainfall. In addition, it was often difficult to tell whether connectivity existed due to dense vegetation that obscured views downslope. Downslope topography in combination with erosion directly below the culvert and distance to the stream were used to assess likelihood of connectivity noted as none, low, moderate or high. Culverts were considered to be connected where there was substantial erosion directly below the culvert on a continuously steep hillslope with a relatively short distance to the stream. Omitted from consideration were those culverts for which, in absence of detailed field descriptions, there is a flow length of 150 m or greater to the stream.

Following the second traverse, a GPS was used to map the road and feature locations that were flagged earlier. The GPS utilized was a Trimble GeoExplorer II set at a position dilution of position (PDOP) of 6.0. The PDOP is an error assessment of position reading based on of the triangulation between the GPS and satellites. If the PDOP exceeded 6.0, measurements cannot be read. The resulting map of road and feature locations is the foundation of the electronic database that is processed via GIS to generate two of the three required road input files.

Additional road surveys were performed on skid trails and an abandoned road during the final field visit. Measurements were taken upon crossing switchbacks of the abandoned road segments as the hillslope was traversed from the operational logging road down to the main stem of the stream. Locations of road survey points on the abandoned road were not mapped because vegetation obstructed GPS reception of satellite signals. Skid trails located in a clearcut on the east side of the catchment behave hydrologically as roads without a ditch. Small road cuts present along the trails justify their representation as roads in the model. Road surveys were also conducted to characterize two general skid trail types: one that is wider and was likely more heavily used and one that is narrower and was less used.

2.4.3 Application of Field Data

A series of GIS scripts developed at Battelle Memorial Institute facilitated the development of DHSVM road input files based only on road placement relative to a DEM along with assumed road and ditch parameters (Wigmosta and Perkins, 1997). Although field data are not required to create road input files for DHSVM, they provide more accurate input data against which outputs can be compared for the purposes of assessing general modelling accuracy.

Measurements of ditch width and depth, estimates of ditch friction coefficient (Manning's n) and crown type were direct inputs to the model. Road width and cut slope information were used in conjunction with road locations and the DEM to calculate road cut depth and width within the GIS. Mapped road positions were used to overlay model cells to determine which cells are to be accessed by the road algorithm. Ditch flow directions were noted in the field to correct computer generated discrepancies of the flow directions determined through GIS assisted calculations involving road locations relative to the DEM. Inputs of accurate flow directions are of greater importance than detailed road parameter measurements due to model sensitivity (James VanShaar, personal communication 1999). Culverts and cross ditches were mapped as hydraulic sink locations for model input. Evidence of connectivity based on field observations was represented through the inclusion of stream extensions to the original stream network input files.

Field observations were made to assess the validity of model-generated flow paths. The model may not account for true water movement or pathways due to scale effects or model assumptions. For example, accuracy of ridge and valley locations depends on the accuracy of the DEM, and subtle topographic features in the field may not be well represented by a DEM due to the pixel size. DHSVM assumes that no infiltration occurs in ditches; however, significant loss of flow resulting from ditch infiltration was noted in the field. Additional field data collected includes road cut depth, the depth of confining layers within the exposed road cut, location of ephemeral streams, the presence of subsurface flow at road cuts, and presence or absence of a ditch. The depth of a confining layer within the road cut was compared against the soil information used in the initial model calibration. Ephemeral streams and seeps were compared against the location of DEM-generated streams that do not appear as perennial streams in the field. Seep locations were also compared to model-generated maps of water table depth. The locations of ditch absence were noted since DHSVM does not model roads without at least a minimal ditch presence.

2.4.4. Preparation of Input File Sets for the Existing Road Layout

Three input file sets, developed from the field data, modelled the current roads and their stream channel extensions. With each model run, varying detail was added to modelling the logging road affect on streamflows (Table 3). Input file sets include files representing the existing logging roads, stream networks including stream channel extensions to connected culverts, abandoned roads, and skid trails.

The road files were generated from field data through the use of ArcView and ArcINFO GIS. These applications also enabled the alteration of the existing DEM-based stream network to account for surface flow from selected culverts to the stream. Modified stream input files were created as a result. ArcView GIS was applied to alter input soil maps to represent areas of lowered infiltration rate at skid trail locations.

Table 3. Series of Model Runs Performed

Model Runs	
A	Original calibrated model
B	Original calibrated model + existing loging roads Ba: shallow road cuts Bb: observed road cuts Bc: road cut depth = soil depth
C	Original calibrated model + existing loging roads (Bb) + stream extension
D	Original calibrated model + existing loging roads (Bb) + stream extension + abandoned roads ans skid trails (modelled as logging roads)

Initial editing of raw data and creation of a road database were accomplished through ArcView GIS. GPS data relative to the existing logging roads were imported to ArcView. Using this application, roads located on the east side of the basin were shifted approximately 25 m northward to improve their fit against contours of the basin and stream crossing locations. To guide road placement, elevations of road survey points, obtained through GPS, were contrasted against the elevation contours derived from the DEM. Roads were then divided into segments for which the ArcView database associates road segments with a road class. Each road class is an integer with the associated road parameters of ditch width, ditch depth, ditch roughness (Manning's roughness coefficient), crown type road width and cut slope. Exporting pertinent data from ArcView to a text file generated the road class input file. Although road width and cut slope are not explicitly included in the road class input file, they are required to calculate parameters that must correspond to the DEM. The database was then applied within ArcInfo GIS to generate the remaining road input files. The GIS scripts used to generate the road network file utilized the DEM and the digital map of road segments to create an order for flow routing computations. Segment length was also calculated as an additional parameter to the Muskingum-Cunge routing method. The length of the operational logging roads added to the model is 15.9 km.

The remaining road input file was generated though scripts that accessed information from the DEM, the digital map of road segments, and their associated parameters. The resulting road map file associates road segments with their respective grid cells. The road cut depth and width, segment length within a cell, and its aspect within the cell were calculated using the DEM, road width, cut slope, ditch width and depth. The parameters contained within this file help to determine the quantity of intercepted flow for each road segment. A total of 119 sink locations, representing culverts and other features that route flow from ditches, were specified by the map file, 20 of which were stream crossing culverts.

Road input files were edited prior to conducting model runs. A previous application of the road routines resulted in overestimation of intercepted subsurface flow as a result of cut depths specified as deeper than the soil depth (La Marche and Lettenmaier, 1998). Consequently, the road map input file was first edited such that any road cuts deeper than the soil were changed to equal the soil depth. The road map file was further edited to create three versions differing in general road cut depths. The first version contained original ArcINFO generated cut depths that were often equal to the ditch depth, and were therefore much shallower than the road cuts observed. The cut depths of the second version were based on the field notes. In the third version, cut depths were defined equal to soil depths to simulate a worst-case scenario of maximum subsurface flow interception.

The stream network was extended to culvert locations to represent surface flow extending below culverts to the stream. Cross ditches and switch back bends were also examined for connectivity. The culverts were identified as connected based primarily on field note descriptions. For example, if a culvert appeared to drain into a perennial or ephemeral stream in the field that was not represented as a stream in the stream input files, the culvert was selected for incorporation to the stream network via surface flow. Additional culverts were selected based on interpretation of field notes in conjunction with stream network proximity and hillslope gradient. Further examination of field notes led to deletion of many culverts, that were initially designated as connected, from the stream extension process. A conservative estimate of 19 out of 99 non-stream crossing culverts, cross ditches and switch back bends were modelled as connected to the stream network via surface flow. An existing set of stream input files were edited to include stream channel extensions. The total stream length increased by approximately 3% from, 64.3 to 66.4 km, resulting in a slight increase in drainage density by 3%, from 2.49 to 2.57 km/km^2.

Adding further detail to modelling the existing condition involved the inclusion of skid trails and abandoned logging roads. The surveyed, abandoned road, eastern skid trails, and additional abandoned, and unsurveyed roads and skid trails were modelled as logging roads. The additional roads and skid trails were selected based on their high level of visibility on aerial photos. The road database developed for the operational logging roads was expanded to include these additional roads and skid trails. The total road length increased from 15.7 to 25.7 km. This database was run through GIS to create an extended set of road input files. The stream network that includes stream extensions to connected culverts was also utilized in this model run.

2.4.5 Modelling Logging Road Impact

Road effects were tested through application of the three data sets corresponding to runs B through D. Sensitivity to various modelling details was examined via the three model runs that incorporated files associated with road and skid trail impact with the original input files for the calibrated model developed by Whitaker et al (2000) that did not include roads. The calibrated data set includes the stream network, vegetation parameters, soil parameter, and climate parameter. Conclusions on road effects were based on changes in streamflows for the basin and sub-basin scales.

Streamflows resulting from the varying road cut depths of runs Ba through Bc were compared to the stream flows of run A, the original calibrated model without roads. Streamflow differences between the B runs and run A were plotted for the basin mouth and two tributaries (Figure 3,). The road input corresponding to run Bb, in which road cut depths represent field conditions, was incorporated into the remaining simulations involving the existing logging roads. Output and analysis for runs C and D were conducted in a similar manner to those of runs A and B.

Results of model runs Bb and C assessed the modelled impact of existing operational logging roads. Run C differed from run B by the inclusion of stream channel extensions to connected culverts. A comparison of flow simulations (Bb and C) illustrated the modelled result of incorporating stream channel extensions in the examination of road effects.

Model run D was comprised of the input to run C with skid trails, abandoned roads, and unsurveyed roads modelled as logging roads. Simulated flows at the basin mouth in run D were compared to those for run C in order to examine the collective effect of all roads and trails on streamflows versus the effect of active access roads and spurs.

2.4.6 Comparison With Redfish Upper Observed Flows

Whitaker et al. (2001) sited the omission of logging roads to be a possible reason for the modelled overestimate of Redfish Upper tributary flows. The remainder of this study contrasts observed tributary flow against tributary flow generated from the third input set, which incorporates the primary logging road, stream extensions, skid trails and abandoned roads. This was done to determine whether the addition of roads decreased the overestimated flow of the roadless scenario to provide a better approximation of the observed flows.

CHAPTER 3: RESULTS

3.1 Overview of Progressive Modelling Refinements

The following results are described in order of the model runs with a focus on annual and seasonal changes to streamflow characteristics such as annual yield, snowmelt, low flows, and peak flow. Subsequent topics include examination of specific runoff events such as snowmelt and rainfall induced peaks.

Induced streamflow changes can be related to the differences in modelled feature extent displayed in Table 4. The modelled road length for Run D includes skid trails, abandoned roads, and unsurveyed roads in addition to the primary logging roads. The sinks include cross-draining and stream-crossing culverts, switchback bends, and cross ditches. Stream network length does not include the length of ditch contributing intercepted flow to stream crossing culverts or culverts connected to the stream network by way of surface flow.

Table 4. Extent of modelled features

Redfish Creek Basin (25.8 km^2)	**Run A**	**Run B**	**Run C**	**Run D**
Modeled road length (km)	0	15.7	15.7	25.7
Road density (km/km^2)	0	0.61	0.61	1.00
Number of sinks	0	150	150	187
Stream network length (km)	64.3	64.3	66.4	66.4
Stream drainage density (km/km^2)	2.49	2.49	2.57	2.57
Redfish Upper Sub-Basin (1.15 km^2)				
Modeled road length (km)	0	1.73	1.73	1.92
Road density (km/km^2)	0	1.50	1.50	1.67
Number of sinks	0	17	17	17
Stream network length (km)	3.51	3.51	3.69	3.69
Stream drainage density (km/km^2)	3.05	3.05	3.21	3.21
South Tributary Sub-Basin (0.75 km^2)				
Modeled road length (km)	0	0.18	0.18	0.20
Road density (km/km^2)	0	0.24	0.24	0.27
Number of sinks	0	4	4	5
Stream network length (km)	3.34	3.34	3.37	3.37
Stream drainage density (km/km^2)	4.45	4.45	4.49	4.49

Results focus on water year 1995 so as not to overwhelm the results content. This year was chosen based on the simple rise and fall pattern of streamflow associated with the seasonal snow pack melt. Changes to annual yield and peak flows are respectively shown in Table 5 and Table 6, for Redfish Creek, Redfish Upper Tributary, and South Tributary. The figures referenced in this chapter, Figures 7 to 27, are located in Appendix A. Graphical and tabulated results for the remaining years are located in Appendix B, shown in Figures 28 to 51 and Tables 7 to 18. As modelled Redfish Upper tributary flows had shown discrepancies when compared to observed flows, this chapter concludes with the presentation of modelled versus observed Redfish Upper tributary flows.

3.2 Run B – Addition of primary logging roads and model sensitivity to cut depth

As the alteration of streamflow characteristics resulting from the addition of primary logging roads is difficult to detect based on graphing the Run B set of streamflows against that of Run A (the base simulation without roads), the following figures display the effect of roads as differences between the simulated streamflows relative to the streamflow of Run A, which is shown at the bottom of the figures. Discharge differences of the three cut depth types are displayed in an overlain fashion in order to contrast their differences relative to Run A.

3.2.1 Redfish Creek streamflows

As shown in Figure 7, the addition of primary logging roads produces little change in Redfish Creek streamflow. Discharge increases relative to the reference run begin during the early part of the melt season and persist through the peak of the melt season. Flow differences then decrease through the remainder of the melt season through the low flow period, with occasional spikes of increased flow during the period of snow accumulation. Spikes of increased and decreased flows are scattered through the year.

The addition of logging roads with road cuts that represent the minimal road cuts, equal to ditch depth (Figure 7.a.) increased the annual Redfish Creek yield for 1995 by less than 0.1%. The average annual yield for 1994 to 1997 also increased by less than 0.1%. Water year 1993 was omitted from consideration, as the first six months of the simulation were sensitive to initial

Table 5. Changes to 1995 annual yield for Redfish Creek, Redfish Upper Tributary and South Tributary

Run	Redfish Creek			Redfish Upper Tributary			South Tributary		
	1995			1995			1995		
	Annual Yield (m^3)	Annual Yield Change	Average Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Average Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Average Annual Yield Change
A	23663270	-	-	1364539	-	-	724426	-	-
Ba	23668591	< 0.1%	< 0.1%	1352956	-0.8%	-1.1%	743526	2.6%	4.6%
Bb	23646097	-0.1%	-0.1%	1320816	-3.2%	-3.5%	859650	18.7%	19.6%
Bc	23650959	-0.1%	-0.2%	1328498	-2.6%	-3.0%	875188	20.8%	21.3%
C	23654371	> - 0.1%	-0.1%	1312695	-3.8%	-4.2%	847947	17.1%	18.0%
D	23651554	> - 0.1%	-0.1%	1320220	-3.2%	-3.4%	842308	16.3%	17.0%

Average annual yield (AY) Change = 100 x (AYRun - AYRunA) / AYRun A
As stated in Whitaker et al. in Hydrological Processes (2003) in regard to the calibration process, "The first 6 months of simulation, notably the outflow hydrograph, were sensitive to the model initial conditions, and were not considered in the calibration." Therefore, the average annual yield change does not take water year 1993 into account.

Table 6. Changes to 1995 annual peak flow for Redfish Creek, Redfish Upper Tributary and South Tributary

Run	Redfish Creek			Redfish Upper Tributary			South Tributary		
	1995			1995			1995		
	Annual Peak (m^3/s)	Annual Peak Change	Average Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Average Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Average Annual Peak Change
A	6.3292	- -	-	0.4326	-	-	0.3170	-	-
Ba	6.3364	0.1%	0.1%	0.4281	-1.0%	-1.1%	0.3174	0.1%	5.4%
Bb	6.3506	0.3%	> - 0.1%	0.4124	-4.7%	-3.1%	0.3344	5.5%	11.3%
Bc	6.3525	0.4%	-0.2%	0.4136	-4.4%	-2.9%	0.3366	6.2%	11.5%
C	6.3753	0.7%	0.6%	0.4227	-2.3%	-1.3%	0.3340	5.4%	10.8%
D	6.3989	1.1%	0.7%	0.4224	-2.3%	-0.2%	0.3311	4.4%	9.2%

Average annual peak (AP) Change = 100 x (APRun - APRunA) / APRun A

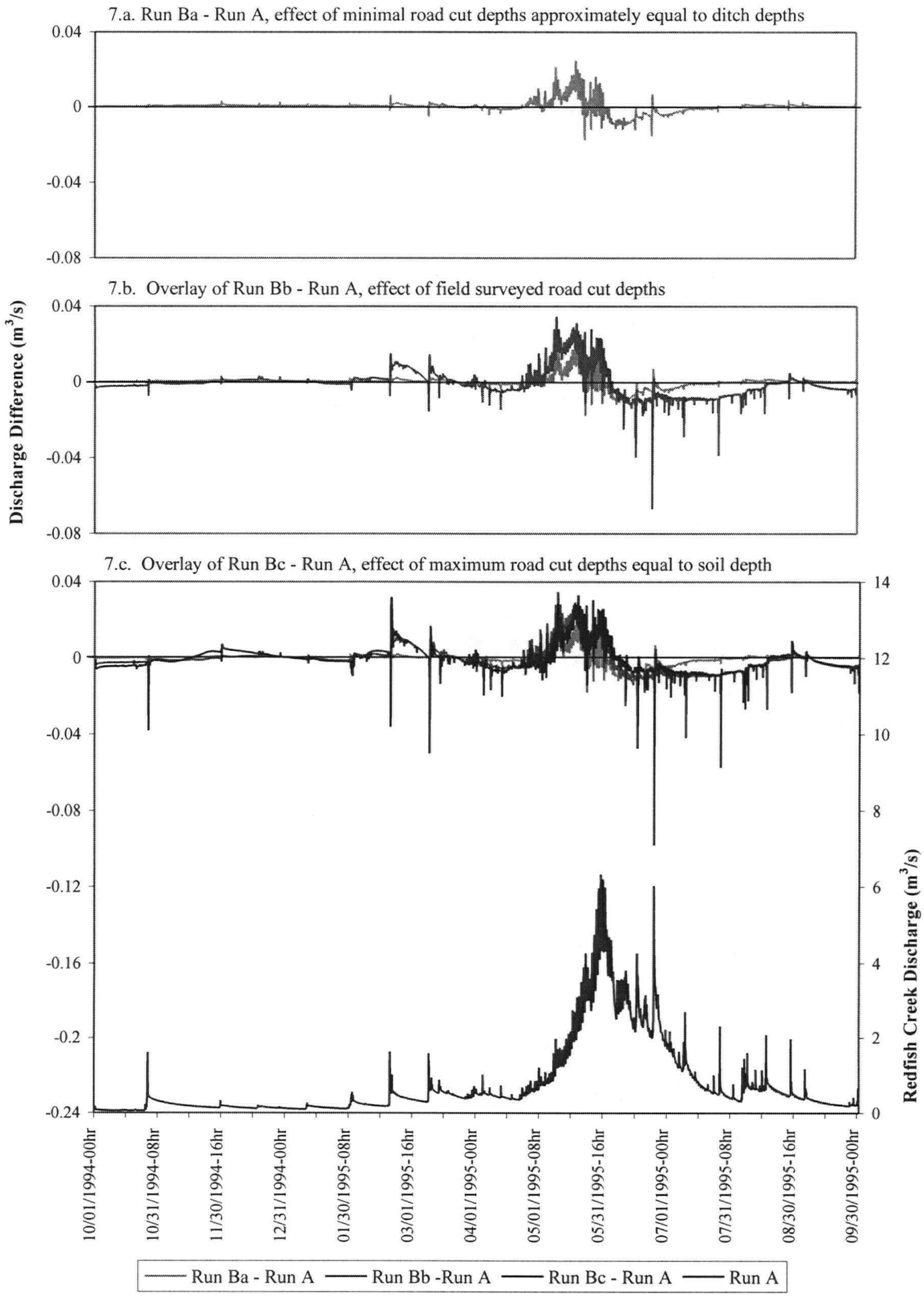


Figure 7. Discharge differences for Redfish Creek due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1995

conditions (Whitaker et al., 2003). Annual peak flow for 1995, and similarly the average annual peak flow for 1993 through 1997, increased by 0.1%.

The addition of logging roads with field-defined road cuts resulted in a slightly greater impact on Redfish Creek streamflow compared to that of the Run Ba (Figure 7.b). The increased flows during the beginning of the melt season are higher and persist further into the melt season. The decrease in streamflow, beginning at end of the melt season, lasted approximately a month longer than the impact resulting from Run Ba. For the scenario of Run Bb, annual yield for 1995 and the average annual yield for 1994 to 1997 decreased by 0.1% compared to that of Run A. The 1995 peak flow increased by 0.3%. However the average annual peak flow, for 1993 through 1997, decreased by less than 0.1%.

The effects of setting cut depths equal to the soil depth are similar to those modelled in Run Bb (Figure 7.c). The increased flows during the beginning of the melt season are higher than that of Run Ba and lower that that of Run Bb. These increased flows continue later into the melt season than for Runs Ba and Bb. The Run Bc annual yield for 1995 decreased by 0.1% and the average annual yield for 1994 to 1997 decreased by 0.2% compared to that of Run A. The 1995 peak flow increased by 0.4%. However the average annual peak flow, for 1993 through 1997, decreased by 0.2%.

A closer look at the effect of the primary logging roads on the snowmelt generated annual peak flow for 1995 shows a sinusoidal pattern of discharge difference between the road imposed simulations and the roadless scenario (Figure 8). Run Ba yielded dominantly increased discharges over the 24-hour period of diurnal streamflow response to snowmelt. Decreased discharge occurred at the midpoint in streamflow recession. Runs Bb and Bc generally increased flows compared to Run A, with Run Bc having a slightly greater impact. The timing of the annual peak occurrence was not affected by the presence of primary logging roads for any year of Redfish Creek streamflows for Runs Ba, Bb, or Bc.

The differences resulting from the addition of primary logging roads during a peak flow resulting from a rain-on-snow event is shown in Figure 9. The decreases in streamflows, represented in Figure 9.a., fluctuate with the rainfall intensity shown in Figure 9.b. The magnitude of peak flow decreases are reduced with decreased cut depth representation. Increasing cut depth, from Run Ba to Bc, was associated with a greater reduction in peak flow.

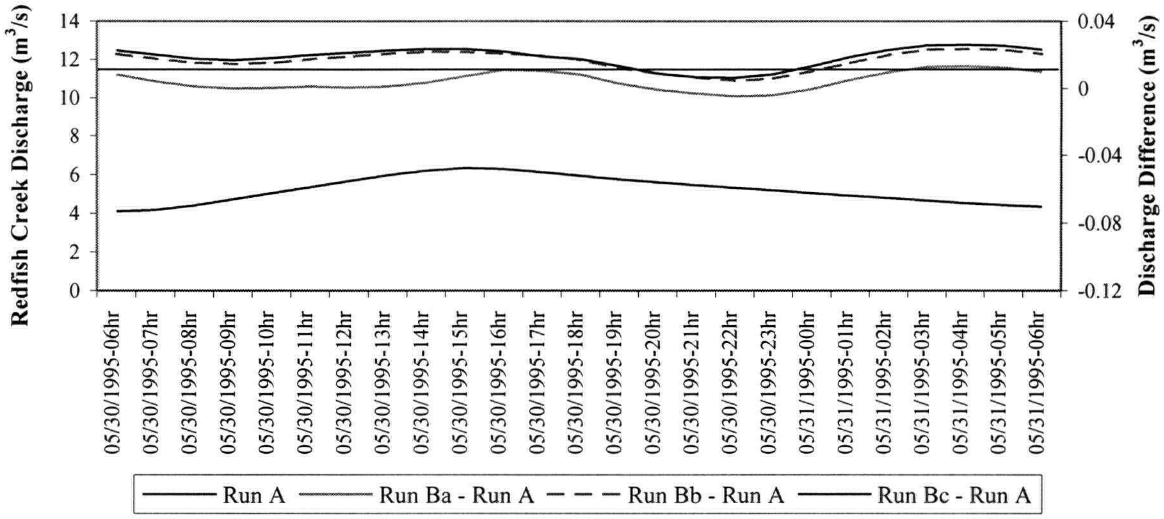


Figure 8. Discharge differences during the annual snowmelt peak for Redfish Creek due to the varying road cut depths of Runs Ba, Bb, and Bc in 1995

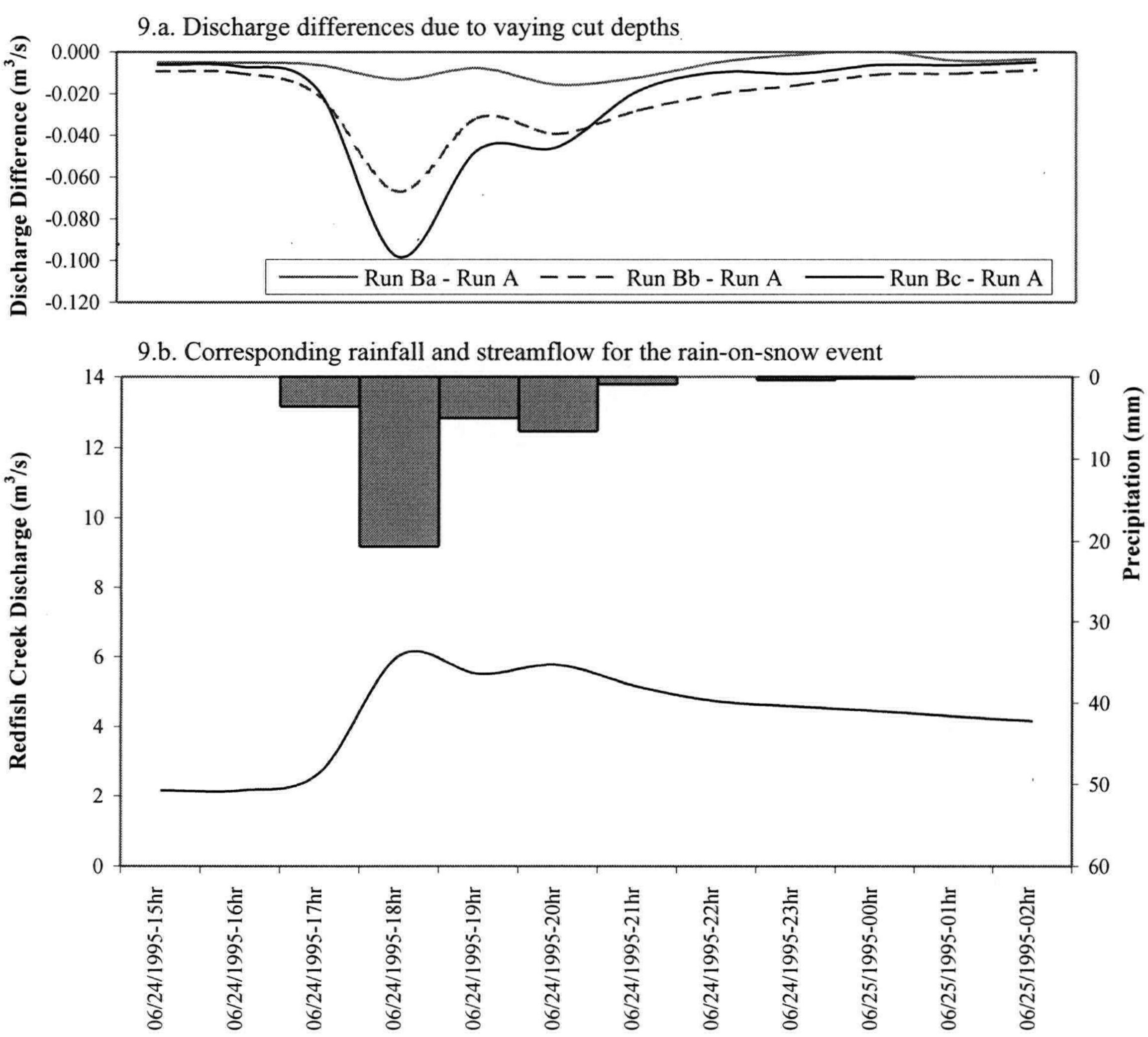


Figure 9. Discharge differences during a rain on snow event for Redfish Creek due to the varying road cut depths of Runs Ba, Bb, and Bc in 1995

3.2.2 Redfish Upper tributary flows

As shown in Figure 10, the addition of primary logging roads results in an overall decrease to Redfish Upper tributary flows. The greatest decreases occur during the melt season. As with the discharge differences for Redfish Creek, there are occasional spikes of increased flow during the period of snow accumulation for Runs Bc and Bb.

With the addition of minimal road cut logging roads (Figure 10.a.), the annual Redfish Upper flow yield for 1995 and the average annual yield for 1994 to 1997, decreased by 0.8% and 1.0%, respectively. Annual peak flow for 1995 and the average annual peak flow for 1993 through 1997 decreased by 1.0% and 1.1% respectively. For the case of this tributary flow, the annual peak flow is the rain-on-snow event of late June and not the peak flow resulting from the snowmelt of late May, as it is for the Redfish Creek streamflow.

The addition of logging roads with field-defined road cuts produced a slightly greater impact to Redfish Upper tributary flows compared to that of Run Ba (Figure 10.b). The reductions in flow relative to Run Ba are greater through the melt season. The scenario represented by Run Bb decreased annual Redfish Upper tributary yield for 1995 and the average annual yield for 1994 to 1997 by 3.2% and 3.5%, respectively, compared to that of Run A. The 1995 peak flow decreased by 4.7%. Average annual peak flows for 1993 through 1997 decreased by less than 3.1%.

The effects of the addition of primary logging roads with cut depths equal to the soil depth are similar to those caused by Run Bb, although there are occasionally larger decreases to tributary peak flows resulting from Run Bb. Run Bc annual yield for 1995 decreased by 2.6% and the average annual yield for 1994 to 1997 decreased by 3.0% compared to that of Run A. The 1995 peak flow decreased by 4.4%. For 1993 through 1997, the average annual peak flow decreased by 2.9%.

The change to the snowmelt-induced streamflow peak for the Redfish Upper Tributary is displayed in Figure 11. A dip in decreased streamflows is common among the three road cut scenarios. Unlike the Redfish Creek streamflows, in which the greater changes were induced by deeper road cuts, the greatest decrease for the Redfish Upper Tributary is shown for the field-defined road cut scenario and not the scenario with the deepest road cuts. The largest decrease in discharge occurred approximately two hours following the peak flow.

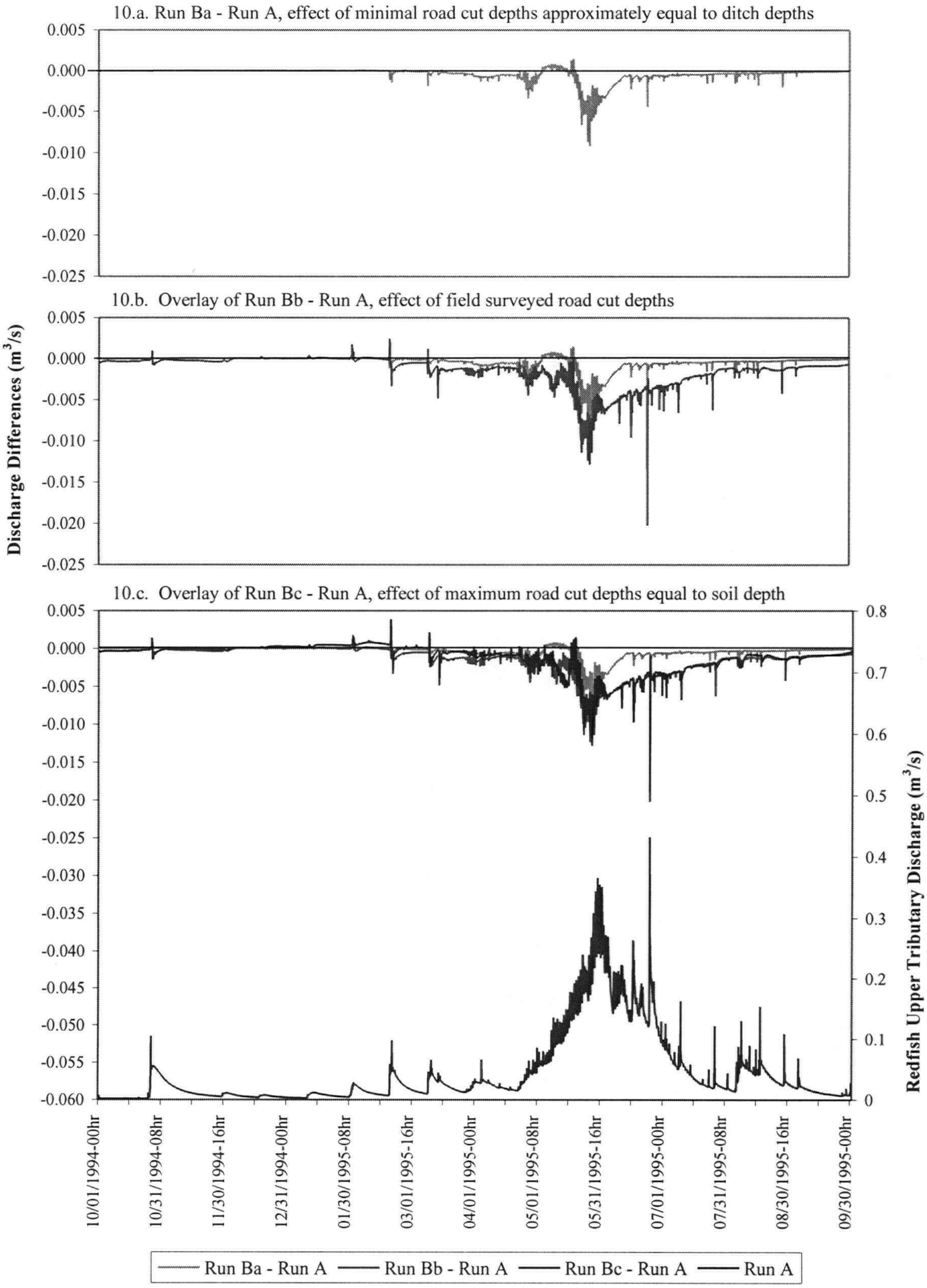


Figure 10. Discharge differences for Redfish Upper Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1995

The Redfish Upper 1995 annual peak flow resulted from a rain-on-snow event. As with the response difference to Redfish Creek streamflows, the differences to Redfish Upper Tributary fluctuate with the fluctuating rainfall rates (Figure 12). Run Bb has a slightly greater impact of decreased peak tributary flow than Run Bc. The timing of the annual peak occurrence was not affected by the presence of primary logging roads for any year of Redfish Upper Tributary streamflows for Runs Ba, Bb, or Bc.

3.2.3 South tributary flows

The addition of primary logging roads results in an overall increase to the South tributary flows, as displayed in Figure 13. The greatest increases occur during the melt season with the largest differences occurring approximately two weeks prior to the tributary peak of the snowmelt season. For the period of increased flows during the melt season, the minimal road cut scenario yielded a shorter duration than of increased flows than either of deeper road cut scenarios. There are spikes of increased discharge changes for peak flows resulting from rainfall events.

The addition of logging roads with minimal road cuts, results in increased flows during the rise of tributary flows at the beginning of the melt season (Figure 13.a). The increase in flows tapers to zero with the conclusion of seasonal melt. The annual South tributary flow yield for 1995 and the average annual yield for 1994 to 1997 increased by 2.6% and 4.6%, respectively. Annual peak flow for 1995 and the average annual peak flow for 1993 through 1997 decreased by 0.1% and 5.4% respectively. As with Redfish Upper Tributary, the annual peak flow is the resulted from the rain-on-snow event of late June.

The addition of logging roads with field-defined road cuts is shown in Figure 13.b. as the line showing greater change to tributary flows. Similarly to the impact of the minimal road cuts, the largest increases to flows occur during the rising limb of the seasonal snowmelt hydrograph. The scenario represented by Run Bb increased annual south tributary yield for 1995 and the average annual yield for 1994 to 1997 by 18.7% and 19.6%, respectively, compared to that of Run A. The 1995 peak flow increased by 5.5%. Average annual peak flows for 1993 through 1997 increased by 11.3%.

The addition of primary logging roads with cut depths equal to the soil depth produced slightly greater changes to streamflow than those caused by Run Bb (Figure 13.c). Run Bc

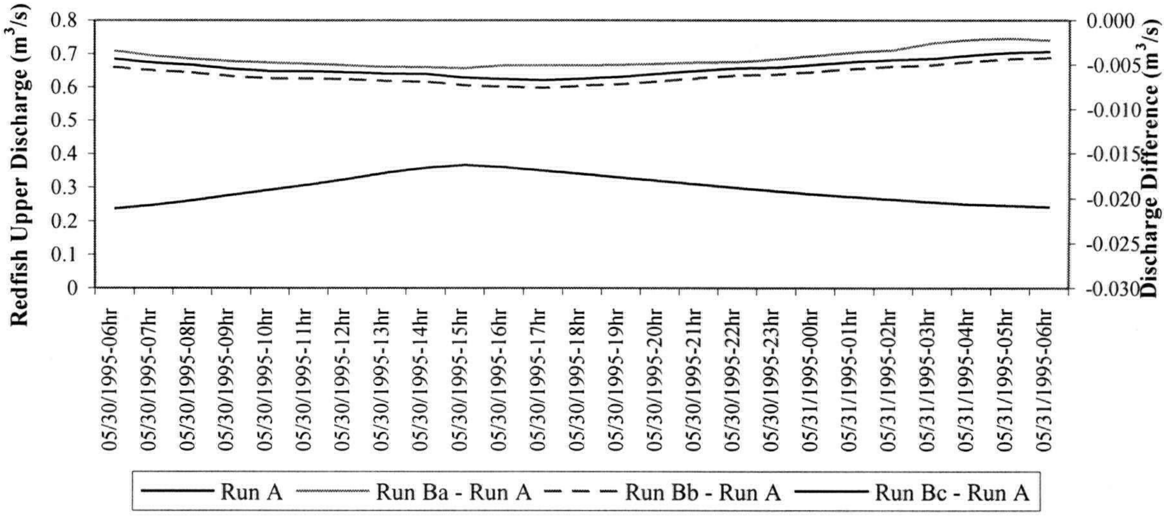


Figure 11. Discharge differences during the annual snowmelt peak for Redfish Upper Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc in 1995

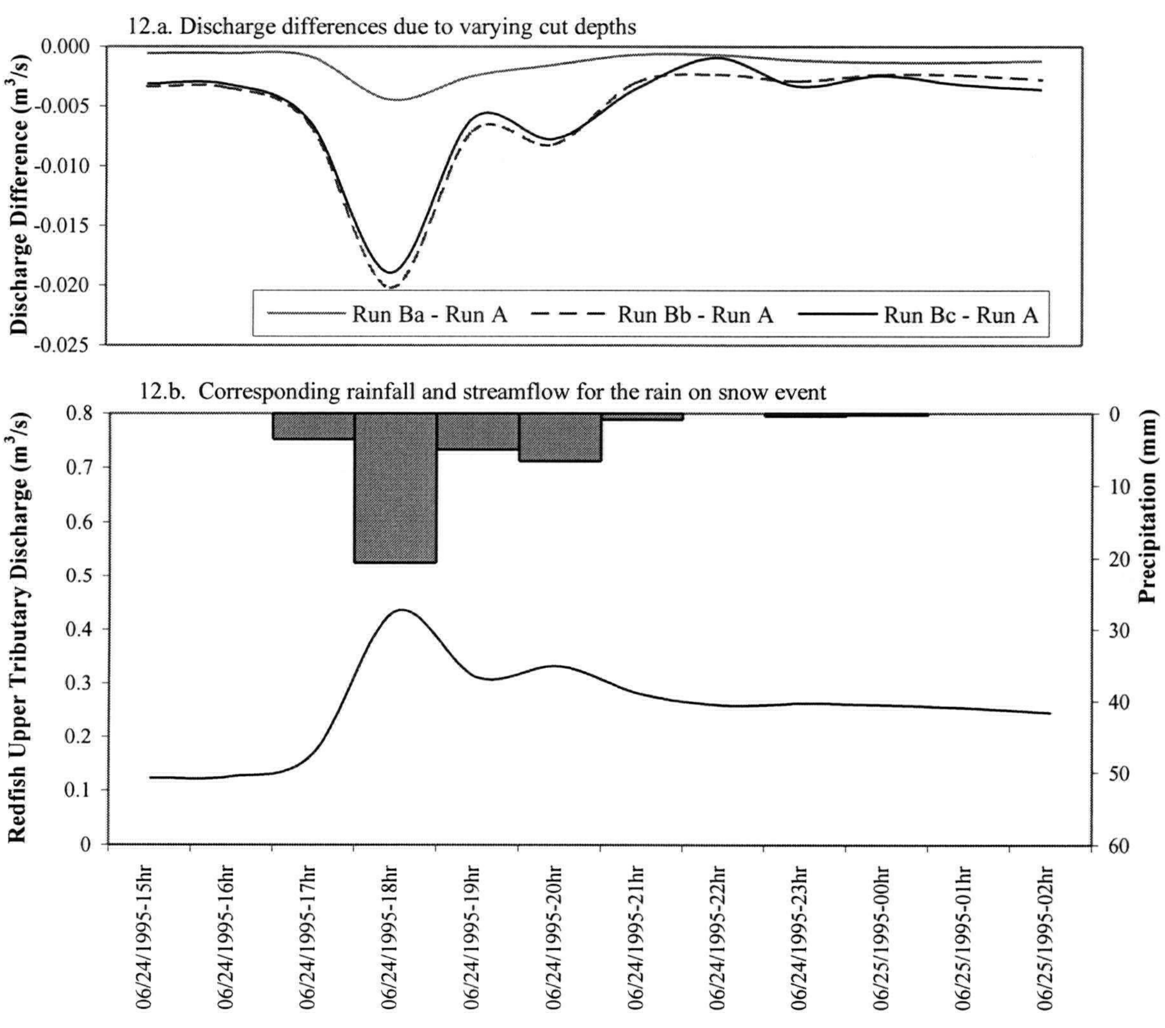


Figure 12. Discharge differences during a rain on snow event for Redfish Upper Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc in 1995

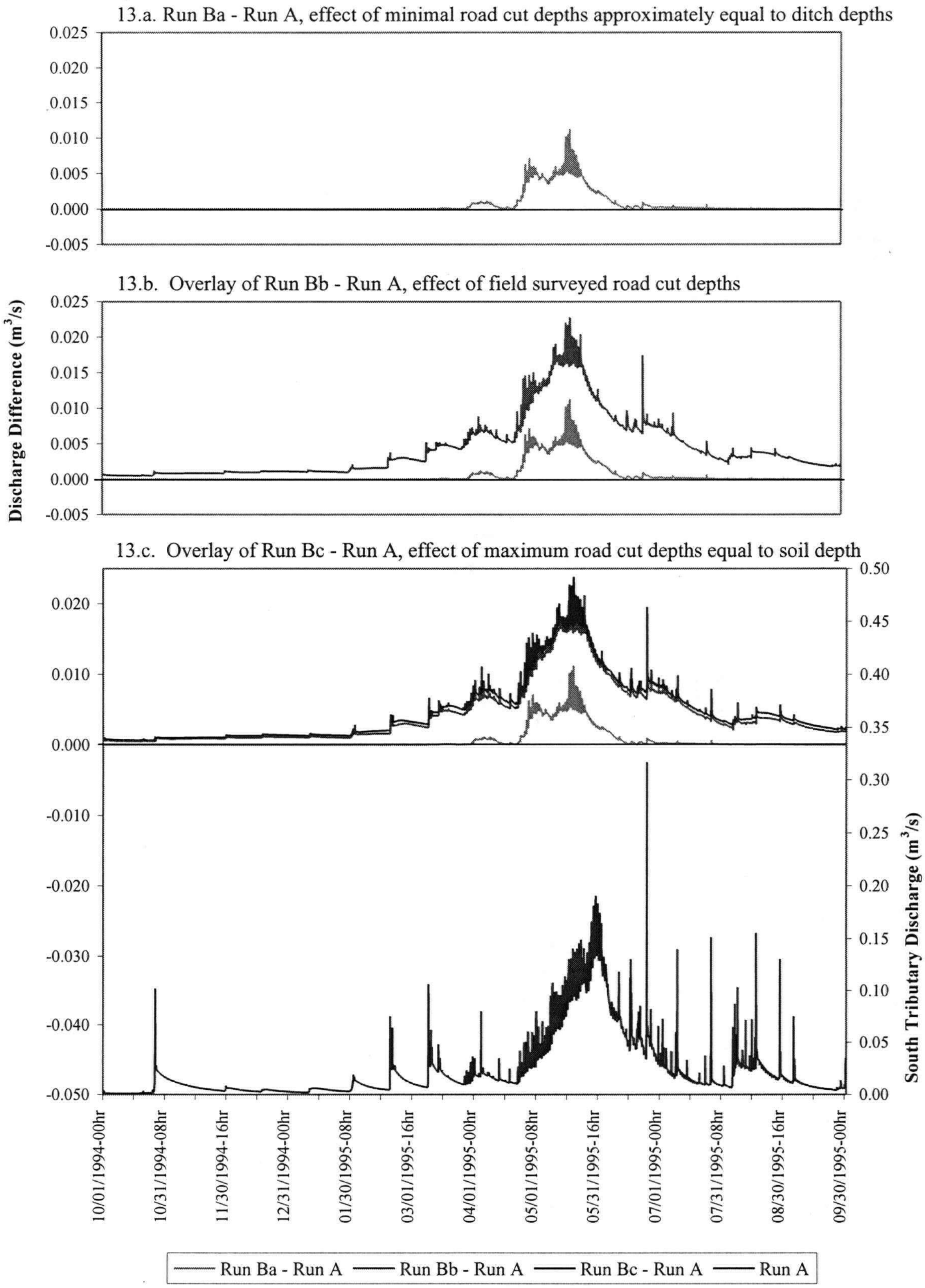


Figure 13. Discharge differences for South Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1995

annual yield for 1995 increased by 20.8% and the average annual yield for 1994 to 1997 increased by 21.3% compared to that of Run A. The 1995 peak flow increased by 6.2%. For 1993 through 1997, the average annual peak flow increased by 11.5%.

The change to the snowmelt induced streamflow peak for the South Tributary is displayed in Figure 14. For the three runs, there is a fairly consistent change to streamflow over the 24-hour flow period, with a nearly indiscernible dip to the increased flows corresponding to the flow peak of Run A. Run Ba shows the least amount of change to the streamflow. The increased changes due to roads imposed in Runs Bb and Bc are nearly identical with Run Bc resulting in slightly greater change.

The South Tributary annual peak flow resulting from a rain-on-snow event is displayed in Figure 15. Changes resulting from Run Ba show little alteration to tributary flows, unlike the changes resulting from Runs Bb and Bc, which exhibit greater sensitivity to rainfall rates. Run Bc has a slightly greater impact on increased peak tributary flow than Run Bb. The addition of logging roads for all B runs resulted in a 10-day advance of the South Tributary annual peak during water year 1997.

3.3 Runs Bb, C and D – Comparison of the effect of primary logging roads, stream network expansion, and skid trails and abandoned roads

As in the case of the contrasting streamflow changes due to varying road cut depths, the streamflow changes resulting from expanding the stream network and adding skid trails and abandoned roads are difficult to detect based on graphing the resultant streamflows against those of Run A, the base simulation without roads. Therefore, the following figures are laid out similarly to that of the previous figures. The streamflow results from Runs Bb, C, and D are shown as differences between the simulated streamflows relative to the streamflow of Run A that is shown at the bottom of each figure. The results from Run Bb, the scenario with road cuts representing field-defined measurements, represent the effects of the primary logging roads, alone, on streamflow. Discharge differences are displayed in an overlain fashion in order to contrast their differences relative to Run A.

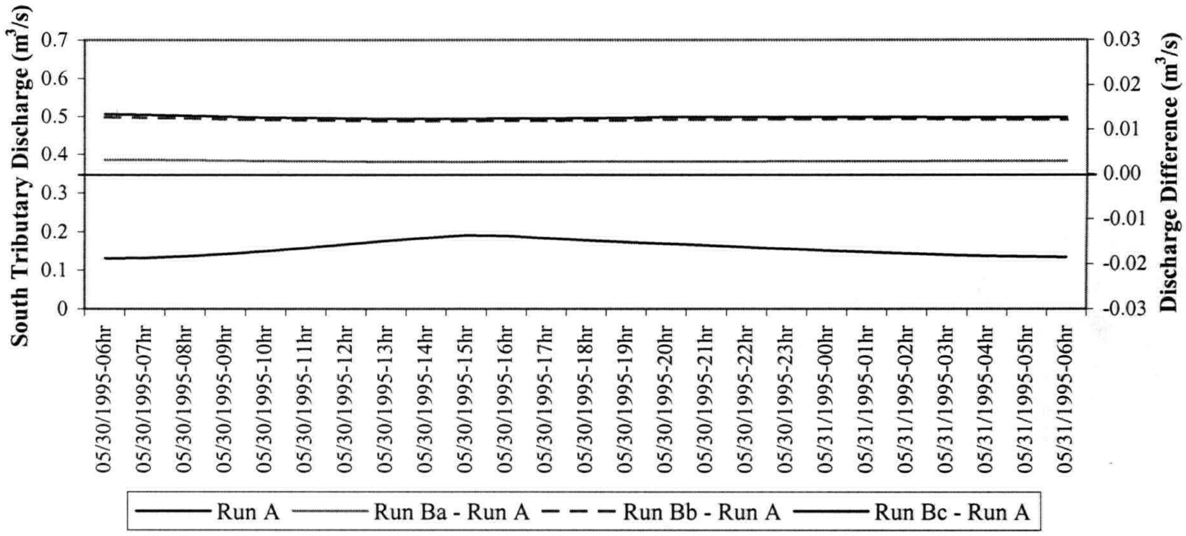


Figure 14. Discharge differences during the annual snowmelt peak for South Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc in 1995

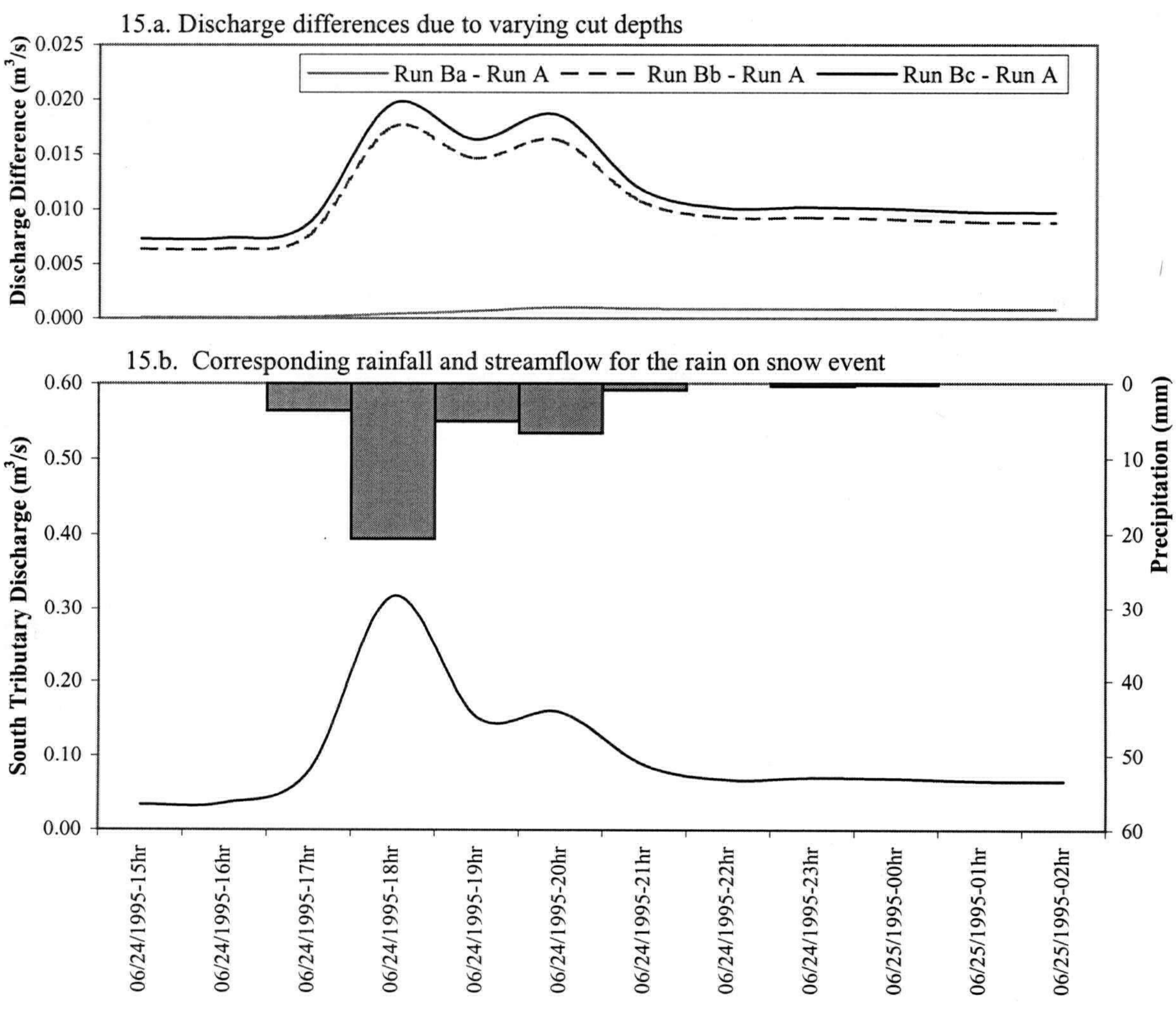


Figure 15. Discharge differences during a rain on snow event for South Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc in 1995

3.3.1 Redfish Creek streamflows

The resulting streamflow of the three model runs exhibit a similar response pattern during the snowmelt season (Figure 16). Discharge is slightly increased during the beginning of the melt season through the melt water peak. During the recession of the annual melt flows, the three modelled discharges show slightly decreased flows. Results of model Runs C and D, however show an opposing response to rain-on-snow and rainfall events compared to Run Bb. later during the water year. The peaks resulting from these events are generally reduced for Run Bb but are increased for Runs C and Run D.

Extending the stream network to represent culverts connected to streams via surface flow resulted in streamflows that are more responsive to diurnal snowmelt and rainfall events, as shown in Figure 16.b., in comparison to flows resulting from just the addition of primary logging roads with field defined road cut depths, shown in Figure 16.a. Incorporating stream extensions decreased the 1995 Redfish Creek yield by less than 0.1% in comparison to the roadless scenario, whereas the logging roads alone decreased the flows by 0.1%. The average annual yield for 1994 through 1997 is decreased by 1.5% and 1.3% for Runs Bb and C, respectively. The 1995 peak flow increased by 0.3% and 0.7% for runs Bb and C, respectively. The average annual peak flow, for 1993 through 1997, decreased by less than 0.1% for Run Bb and increased by 0.6% for Run C.

Discharge changes resulting from the addition of skid trails and abandoned roads to primary logging roads and stream extensions are shown as the overlying graph in Figure 16.c. The rainfall induced streamflow peaks of the skid trail and abandoned road scenario show a lesser difference than the scenario including stream extensions with primary logging roads. The scenario represented by Run D decreased annual yield for 1995 and the average annual yield for 1994 to 1997 by 0.1% compared to that of Run A. The 1995 peak flow increased by 1.1% and the average annual peak flow for 1993 through 1997 increased by 0.7%.

A closer look at the effect of the primary logging roads on the snowmelt generated annual peak flow for 1995, displayed in Figure 17, shows a sinusoidal pattern of discharge difference between the roadless scenario and Runs Bb, C, and D. The impact of Runs C and D are more pronounced than that of Run Bb. The results of Runs C and D exhibit the greatest amount of increased streamflow just prior to the peak and the greatest amount of decrease during streamflow decline over the 24-hour period of diurnal streamflow response to snowmelt. The

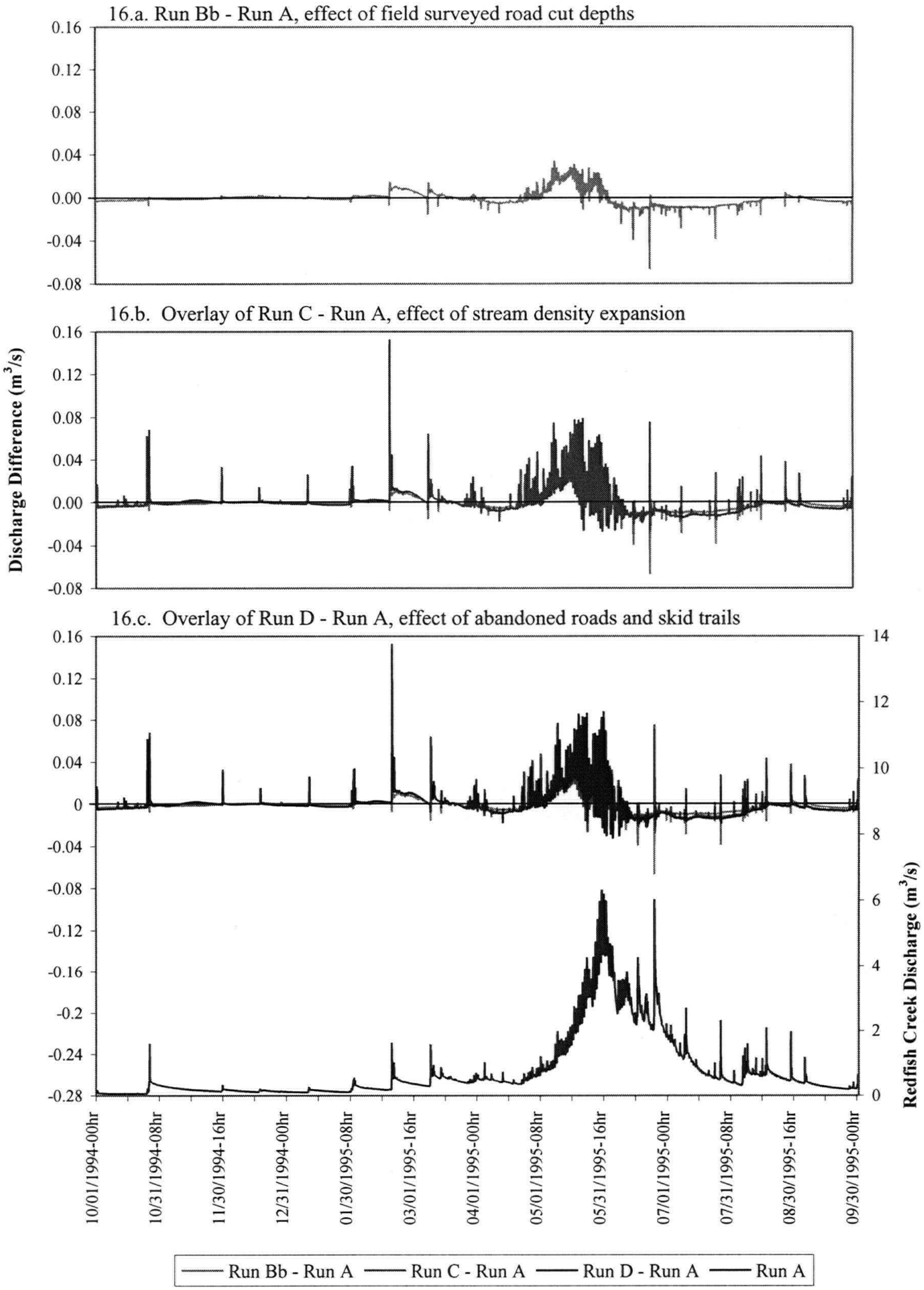


Figure 16. Discharge differences for Redfish Creek due to the varying simulation scenarios of Runs Bb, C, and D during water year 1995

addition of roads, as expressed through Runs Bb, C, and D, do not impact the peak to the extent that the timing of the peak flow was altered.

The differences resulting from the addition of primary logging roads during a rain-on-snow peak flow event are shown in Figure 18. The streamflow changes fluctuate with the rainfall intensity. The addition of logging roads (Run Bb) decreases the peak flow by 1.1%, while the stream network expansion and addition of skid trails and abandoned roads has the opposite effect, increasing the peak flow by 1.3% and 1.2 % respectively.

3.3.2 Redfish Upper tributary flows

The addition of primary logging roads results in generally decreased flows, with slight increases to rain-on-snow events during the period of snow accumulation. Results from Run C (Figure 19.b) show that increasing the stream length by 5% from 3.51 to 3.69 km results in higher flows for rain-on-snow events than the results of Run Bb. Increasing the road length by 11% from 1.73 to 1.92 km in Run D results in a greater sensitivity to snowmelt around the seasonal snowmelt peak. Unlike the responses to Runs Bb and C, Run D yields more variable changes to diurnal snowmelt fluctuations, with occasional increases of streamflow during the seasonal snowmelt.

As with the effect of stream network extension on Redfish Creek, streamflows are more responsive to diurnal snowmelt and rainfall events when the stream network is extended (Figure 19.b), in comparison to flows without stream network extensions and with primary logging roads with field-defined road cut depths (Figure 19.a). Incorporating stream extensions decreased the 1995 Redfish Upper Tributary yield by 3.8% in comparison to the roadless scenario, whereas the logging roads alone decreased the flows by 3.2%. The average annual yield for 1994 through 1997 is decreased by 3.5% and 4.2% for Runs Bb and C, respectively. The 1995 peak flow decreased by 4.7% and 2.3% for runs Bb and C, respectively. The average annual peak flow, for 1993 through 1997, decreased by 3.1% for Run Bb and decreased by 1.3% for Run C.

Discharge changes resulting from the addition of skid trails and abandoned roads to primary logging roads and stream extensions are shown as the overlying graph in Figure 19.c. The response of Run D to rain-on-snow events during the period of snow accumulation is nearly identical to that of Run C. Although the snowmelt modelled by Run D shows fluctuation

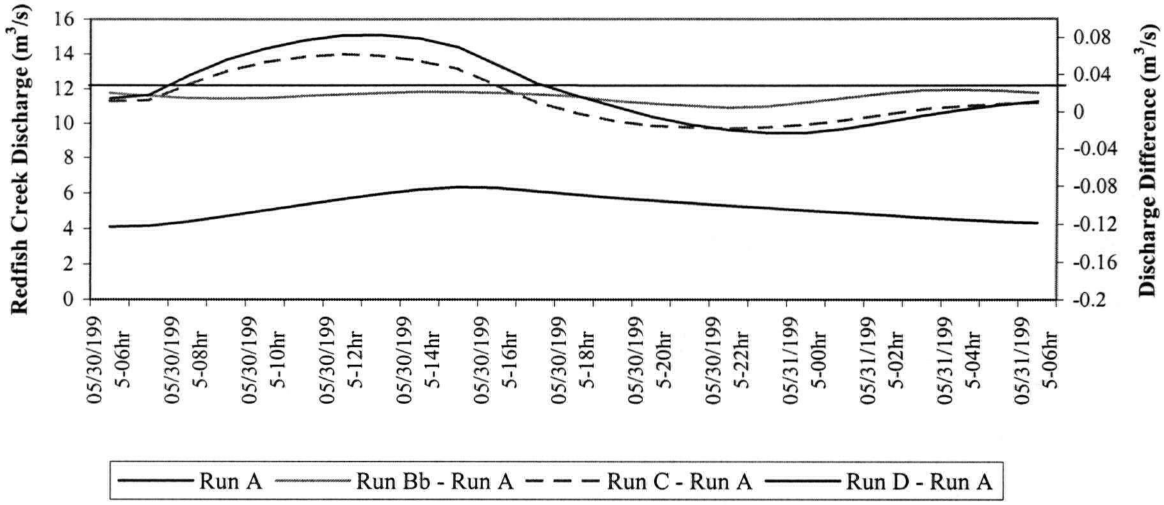


Figure 17. Discharge differences during the annual snowmelt peak for Redfish Creek due to the varying simulation scenarios of Runs Bb, C, and D in 1995

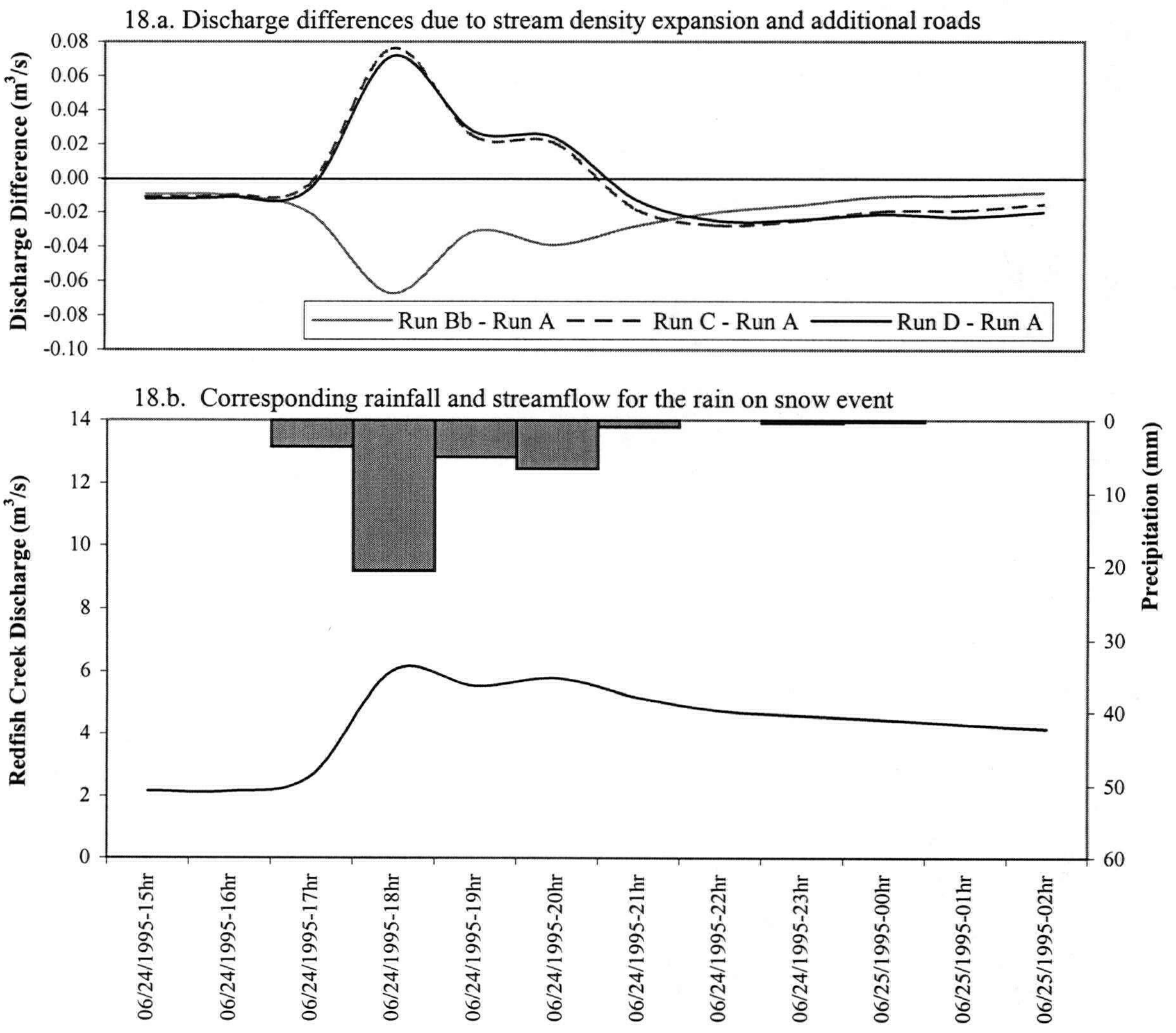


Figure 18. Discharge differences during a rain on snow event for Redfish Creek due to the varying simulation scenarios of Runs Bb, C, and D in 1995

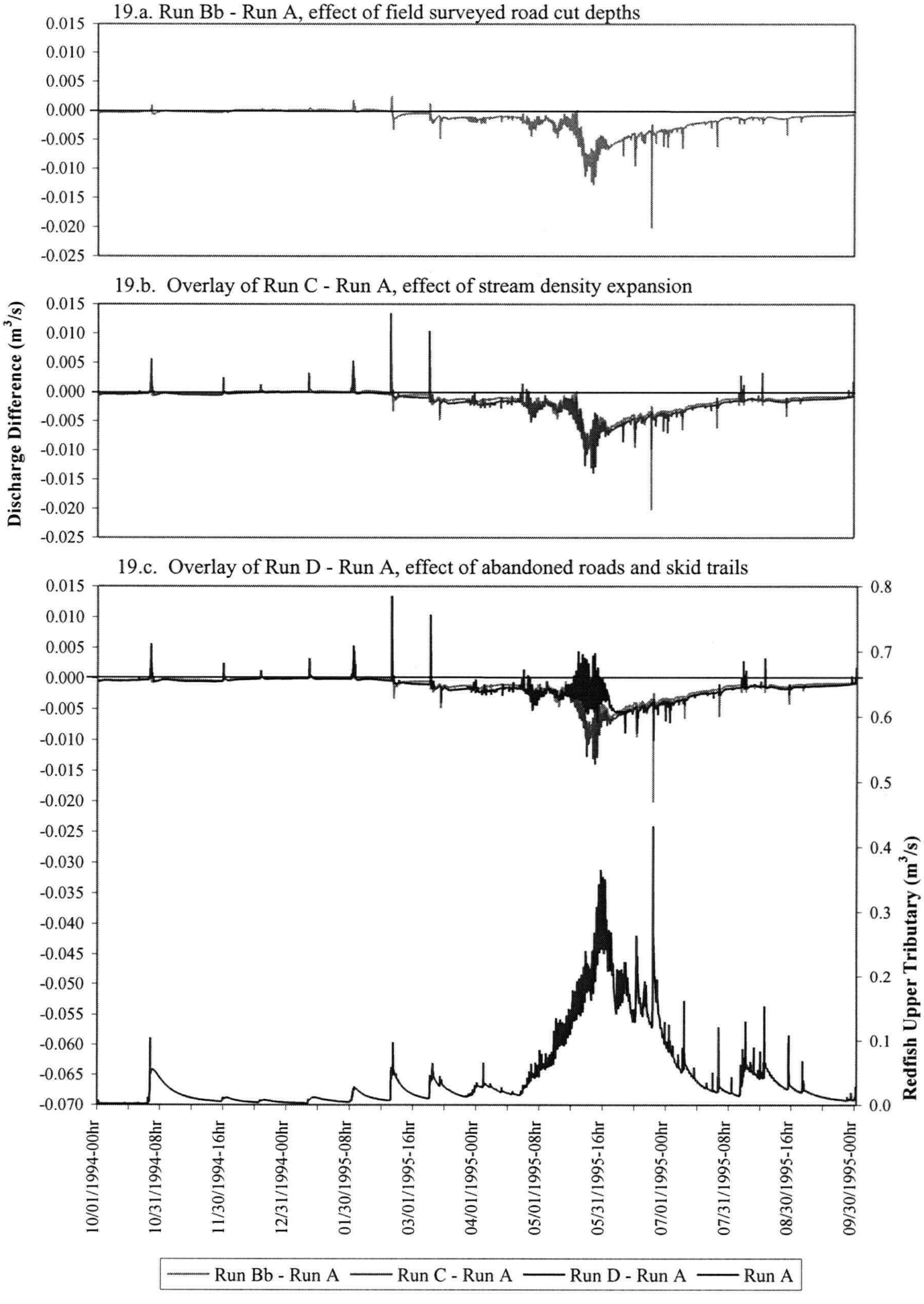


Figure 19. Discharge differences for Redfish Upper Tributary due to the varying simulation scenarios of Runs Bb, C, and D during water year 1995

between positive and less negative differences as compared with Run C, the difference from Run A annual yield is just 0.6% more than that of Run C. For the scenario represented by Run D, annual yield for 1995 and the average annual yield for 1994 to 1997 decreased by 3.2% and 3.4%, respectively, compared to that of Run A. The 1995 peak flow decreased by 2.3% and the average annual peak flow for 1993 through 1997 decreased by 0.2%.

The change to the peak snowmelt induced streamflow for the Redfish Upper Tributary is displayed in Figure 20. The addition of the stream extensions in Run C causes a slightly greater sensitivity in decreased streamflow than the simulation of the main logging road impact of Run Bb, although the magnitude of decrease is similar. The addition of skid trails and abandoned roads decreased the negative difference to Run A streamflows.

As shown in Figure 21, the addition of stream extensions resulted in a reduced change in the 1995 annual peak flow caused by a rain-on-snow event, compared to that induced by the addition of roads alone. Including the skid trails and abandoned roads only slightly increased the negative difference resulting from the combined effect of modelling the main roads and stream extensions as compared with Run A streamflows.

3.3.3 South tributary flows

The streamflow responses to Runs Bb, C, and D are nearly identical. The greatest differences between the streamflows of Run A and those of Runs Bb, C, and D occur approximately two weeks prior to the seasonal snowmelt peak. Following the peak increase in streamflows, it is evident that these differences are slightly reduced from Run Bb to Run D. The increases to the rain-on-snow generated peak were also slightly reduced with the small addition of stream length on top of the main logging roads and further reduced with the addition of skid trails and abandoned roads.

The expansion of the stream network contributing to South tributary flows, as shown in Figure 22.b, results in increases to both annual yield and annual peak flow. These increases are less than those induced by Run Bb, the addition of logging roads alone (Figure 22.a). Incorporating stream extensions increased the 1995 South Tributary yield by 17.1% in comparison to the roadless scenario, whereas the logging roads alone increased the flows by 18.7%. The average annual yield for 1994 through 1997 is increased by 19.6% and 18.0% for Runs Bb and C, respectively. The 1995 peak flow increased by 5.5% and 5.4% for runs Bb and

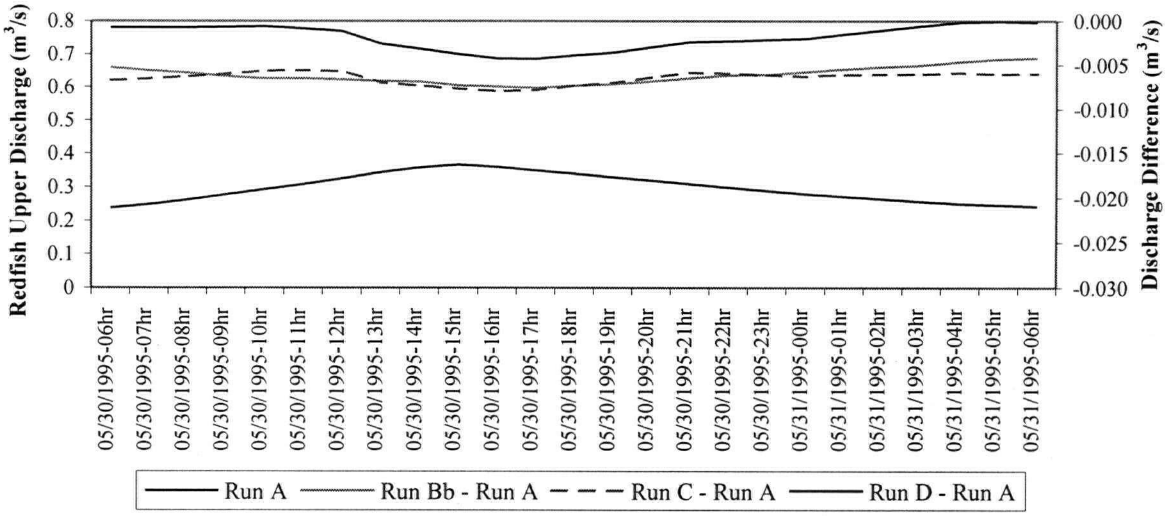
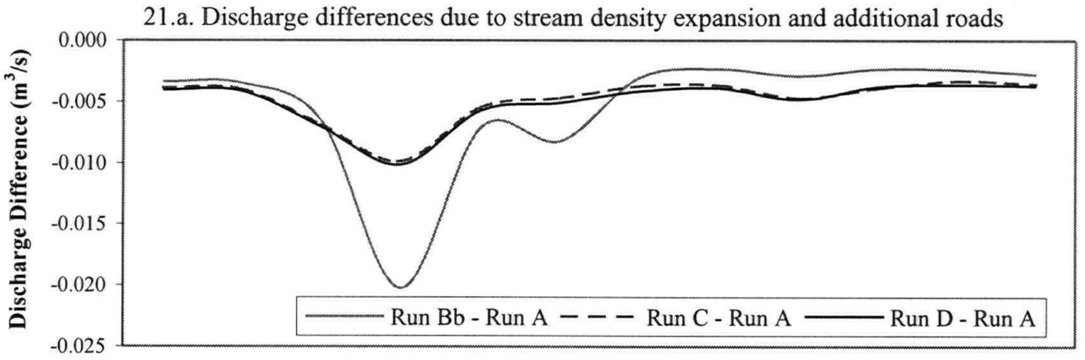


Figure 20. Discharge differences during the annual snowmelt peak for Redfish Upper Tributary due to the varying simulation scenarios of Runs Bb, C, and D in 1995



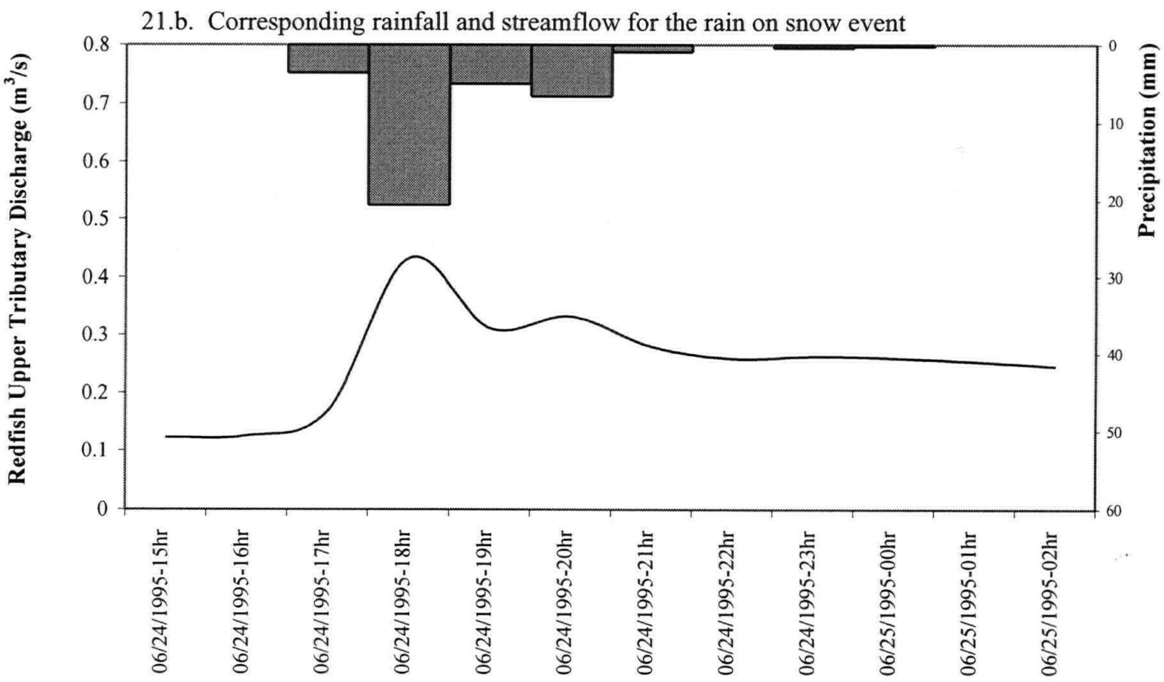


Figure 21. Discharge differences during a rain on snow event for Redfish Upper Tributary due to the varying simulation scenarios of Runs Bb, C, and D in 1995

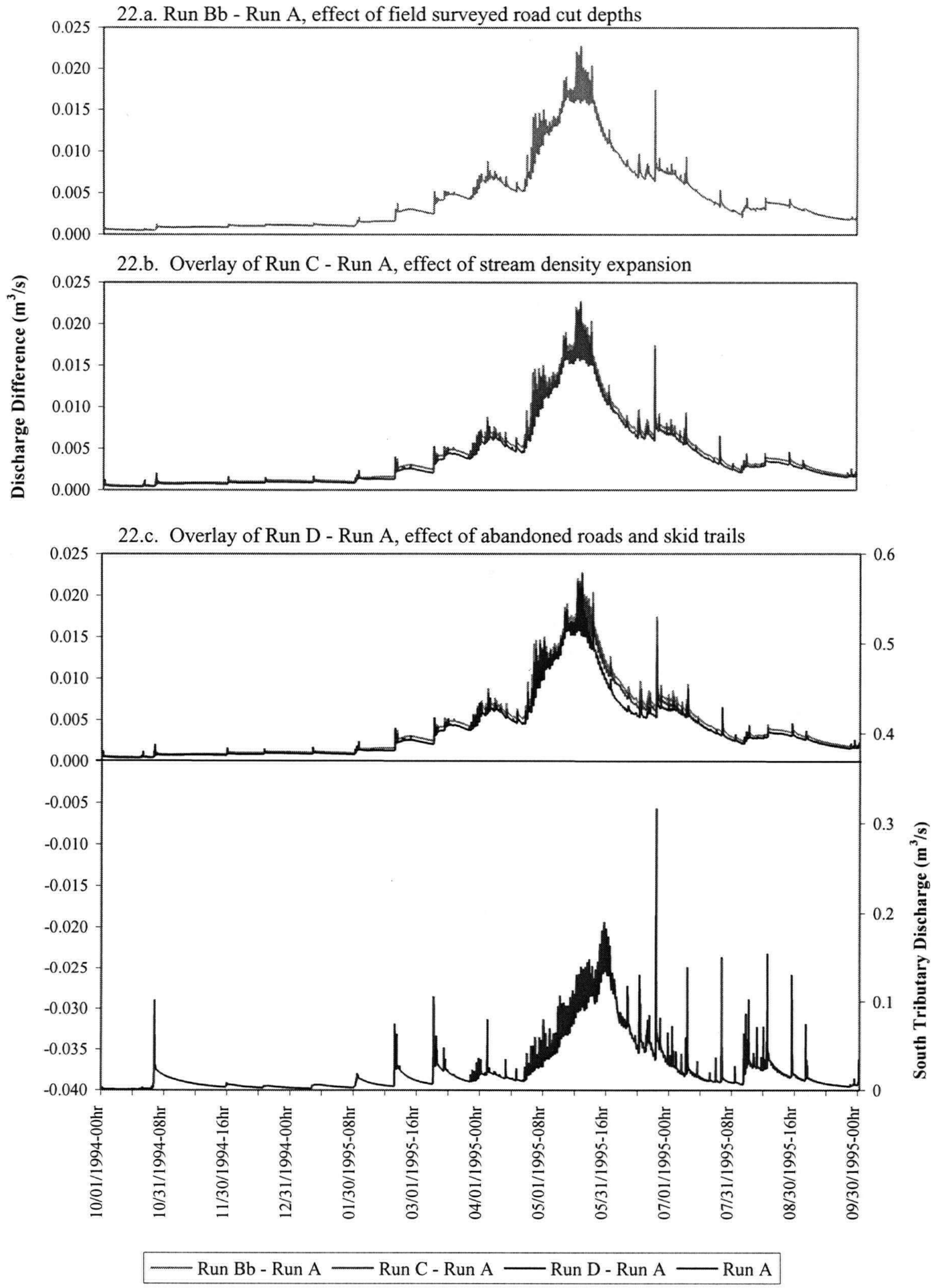


Figure 22. Discharge differences for South Tributary due to the varying simulation scenarios of Runs Bb, C, and D during 1995

C, respectively. The average annual peak flow, for 1993 through 1997, increased by 11.3% for Run Bb and increased by 10.8% for Run C. The only change to peak flow timing occurred for water year 1997. For the roadless scenario, peak flow occurred June 11. The peak occurred ten days earlier on June 11 for Runs Bb and C.

The addition of skid trails and abandoned roads to primary logging roads and stream extensions only slightly diminish the increased South Tributary response to the addition of main logging roads and stream extensions (Figure 22.c). The scenario represented by Run D increased annual yield for 1995 and the average annual yield for 1994 to 1997 by 16.3% and 17.0%, respectively, compared to Run A. The 1995 peak flow increased by 4.4% and the average annual peak flow for 1993 through 1997 increased by 9.2%. As compared with the roadless scenario, the annual peak flow date was approximately three weeks earlier, on May 17.

The change to the peak snowmelt induced streamflow for the South Tributary is displayed in Figure 23. It appears that streamflow changes resulting from the slight expansion of the stream network, Run C, and the further addition of road length, Run D, serve to just slightly reduce streamflow increases.

As shown in Figure 24, the addition of stream extensions reduced the 1995 rain-on-snow generated annual peak flow compared to the streamflow change induced by the addition of roads alone. Including the skid trails and abandoned roads only slightly reduced the increased difference resulting from the combined effect of modelling the main roads and stream extensions as compared with Run A streamflows.

3.4 Redfish Upper Tributary modelled and observed flows

As modelled Redfish Upper tributary flows had shown discrepancies when compared to observed flows, this chapter concludes with the presentation of modelled versus observed Redfish Upper tributary flows. The changes modelled by Run D, representing logging roads and related features, as contrasted with observed flows are displayed in Figures 25, 26, and 27 for water years 1995 through 1997. Although the addition of the logging roads and related features appears to reduce flows as compared with the original Run A roadless model, the modelled flows remain appreciably higher than the observed flows.

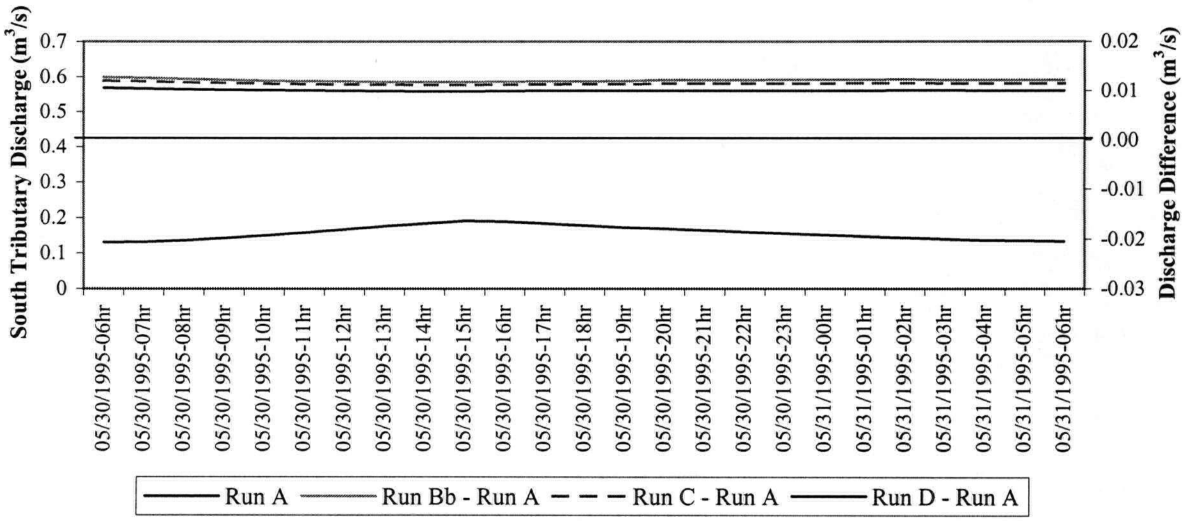


Figure 24. Discharge differences during a rain on snow event for South Tributary due to the varying simulation scenarios of Runs Bb, C, and D in 1995

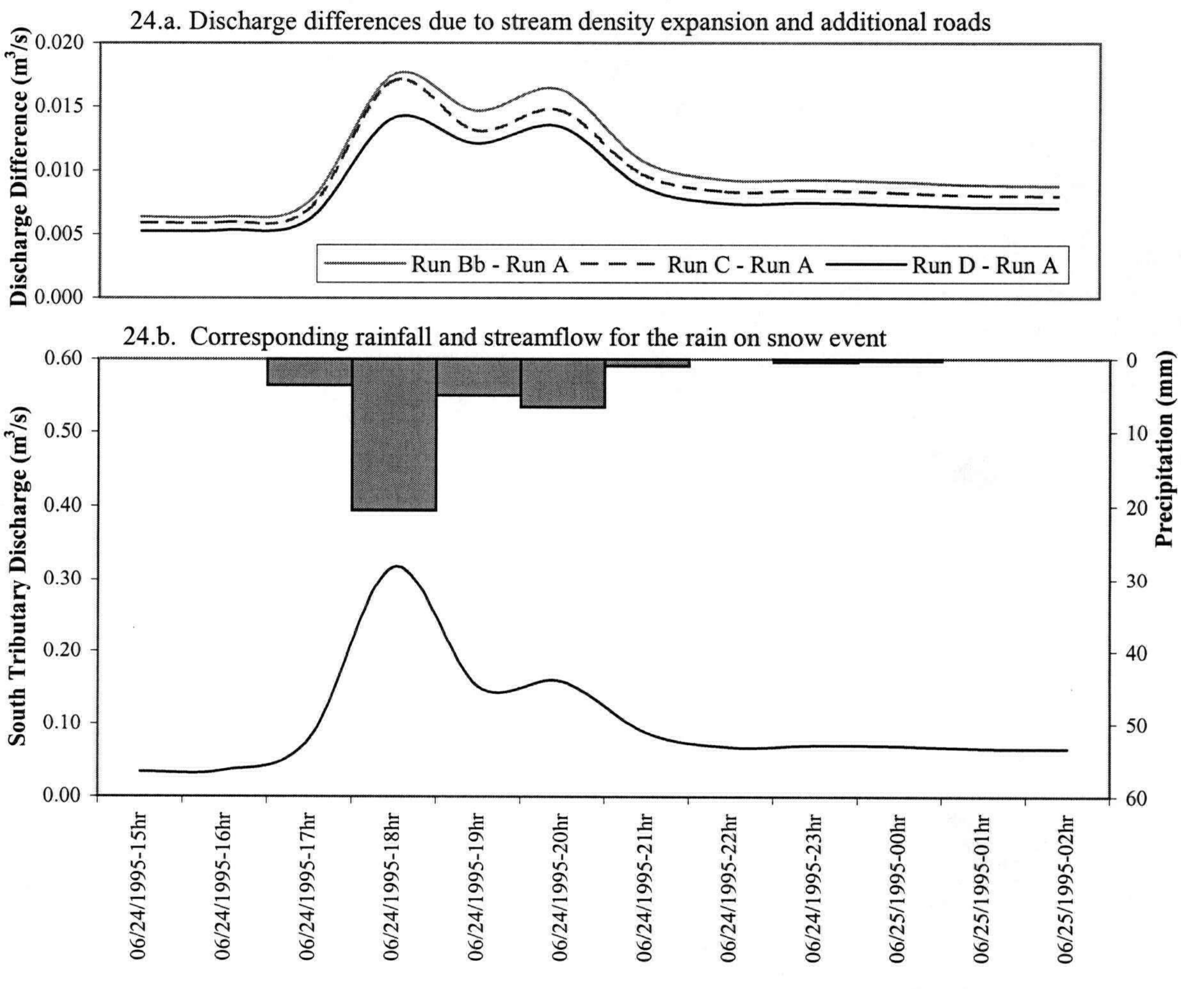


Figure 23. Discharge differences during the annual snowmelt peak for South Tributary due to the varying simulation scenarios of Runs Bb, C, and D in 1995

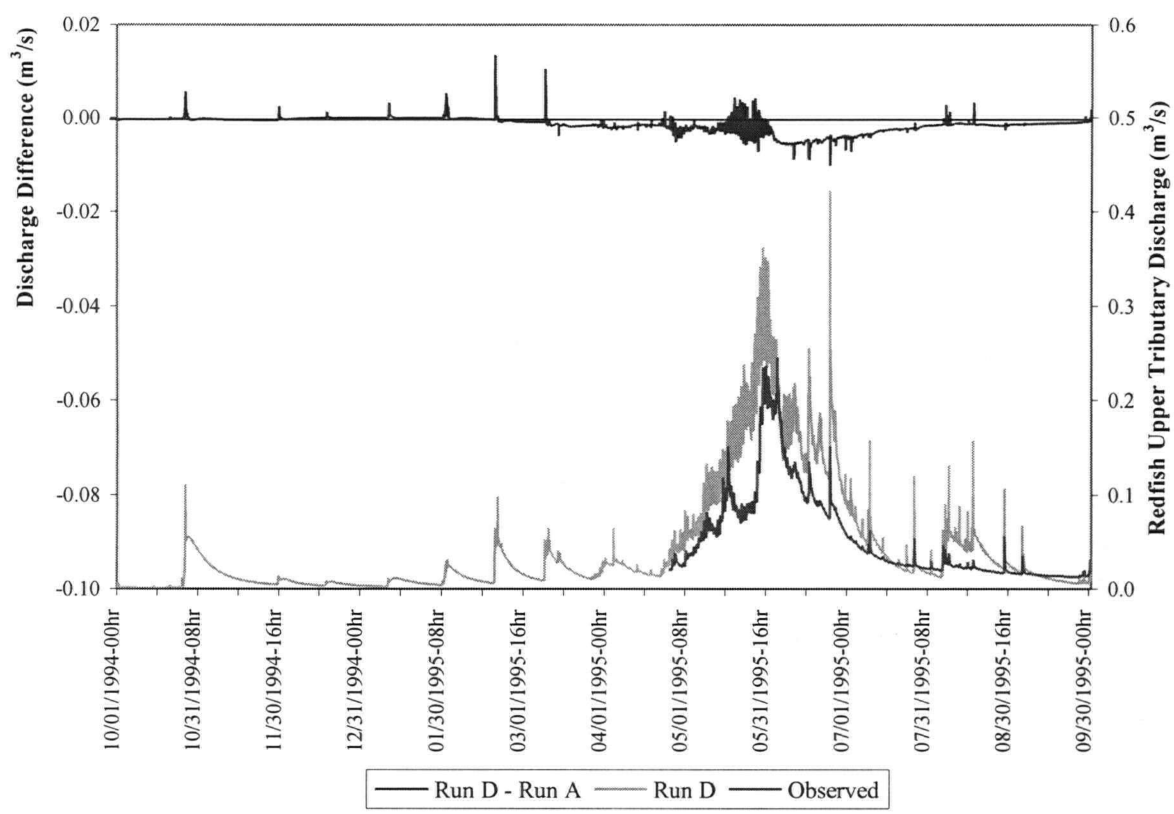


Figure 25. Modelled Redfish Upper Tributary response to logging roads compared with the modelled roadless scenario and observed flow for water year 1995

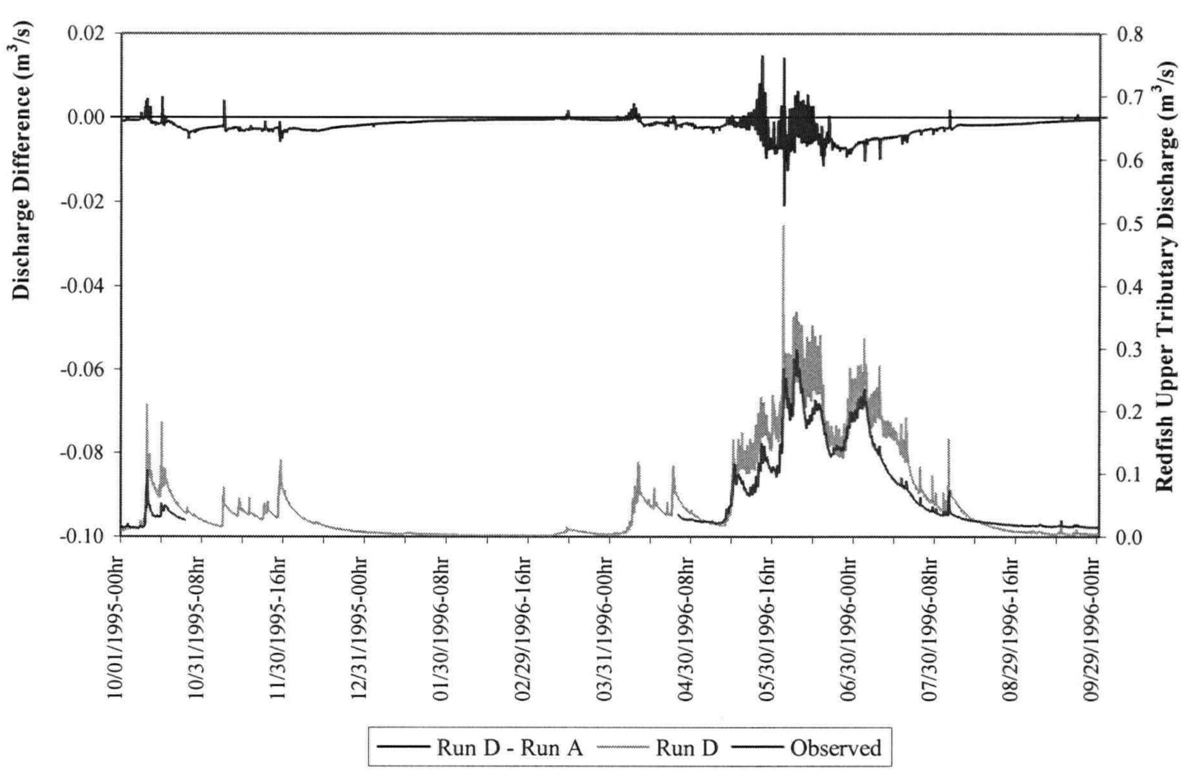


Figure 26. Modelled Redfish Upper Tributary response to logging roads compared with the modelled roadless scenario and observed flow for water year 1996

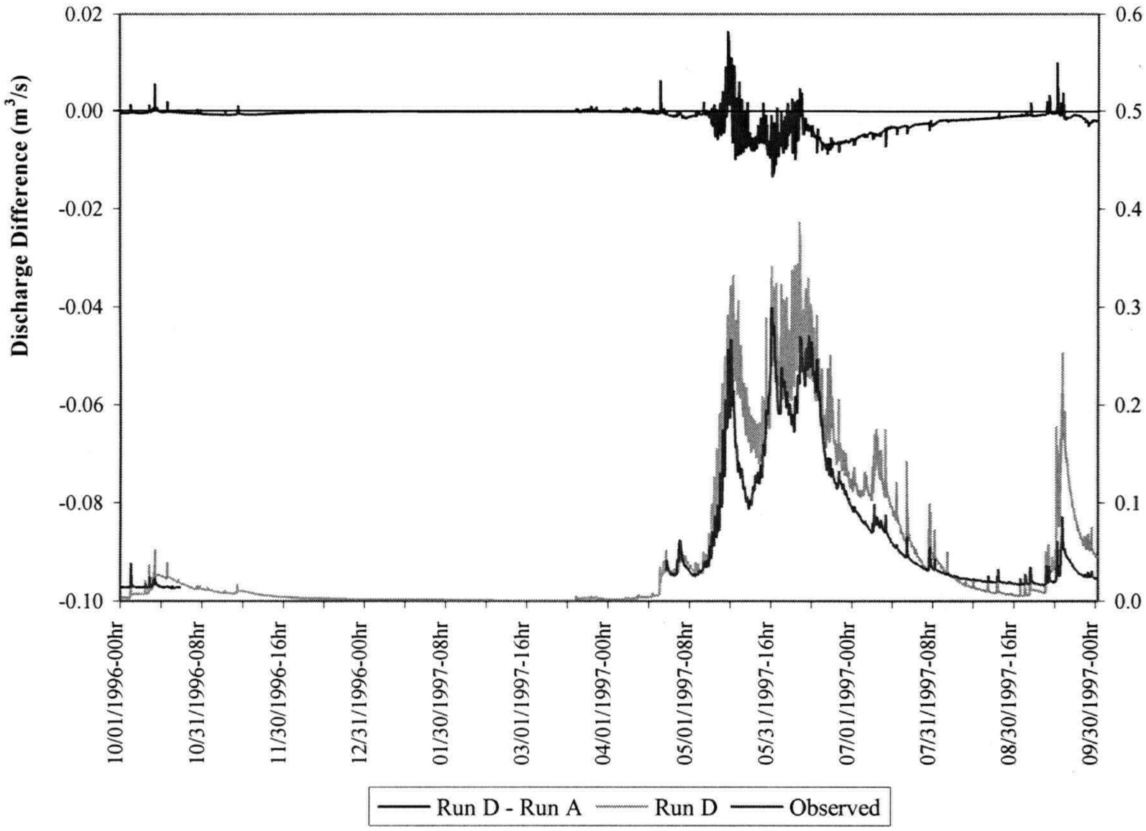


Figure 27. Modelled Redfish Upper Tributary response to logging roads compared with the modelled roadless scenario and observed flow for water year 1997

CHAPTER 4: DISCUSSION

4.1 Overview

This chapter will focus on the objectives outlined in the introduction, which include the examination of modelled streamflow response to the addition of roads, road cut depth variation, stream network extension to culverts connected via surface flow, and the addition of skid trails and abandoned roads. The sub-basin model with enhanced road features will also be compared with observed streamflows. The discussion is focused primarily within the context of basin and sub-basin scale differences with references to the average annual yield and average annual peak changes.

4.2 Streamflow response to the addition of logging roads at the basin and sub-basin scale

At the scale of Redfish Creek basin (25.8 km^2), no substantial change to streamflow was observed in terms of annual yield and annual peak flow with the addition of primary logging roads, whereas greater changes to tributary flows were observed. The degrees to which logging roads affect these streamflows are likely due to various factors such as logging road density, expansion of the basin contributing area, and particularly, road location with respect to streams.

The lack of considerable alterations to Redfish Creek streamflow is consistent with previous field studies showing insignificant change to streamflows when logging road area occupies 5% or less of the watershed area (Ziemer, 1981; Harr et al., 1975). Based on running width, logging roads occupy less than 1% of the Redfish Creek watershed area.

Redfish Creek tributaries appear to be more sensitive to the effects of logging roads than the whole Redfish Creek basin. The annual yield and annual peak changes for were greater for the South Tributary than for Redfish Upper. Relative to the roadless case, the South Tributary experienced increases in annual yield and annual peak, whereas Redfish Upper showed decreases. The degrees of streamflow changes were not proportional to the percent of the sub-basin area covered by road, suggesting that, in the case of these two sub-basins, percent roaded area has little affect in determining streamflow impact at the sub-basin scale. The difference in relative changes is more likely due to road location and changes in contributing area.

The differing results for the adjacent sub-basins superficially suggest that subsurface flow was transferred from Redfish Upper Tributary to the South Tributary by means of the logging road, similar to the case for the DHSVM-derived model of the Carnation Creek watershed, where water was transferred between two neighbouring sub-basins via a road (Wigmosta and Perkins, 2001). However, upon examining the topography surrounding the sub-basins and the potential subsurface flow path alteration due to the logging road, it appears that subsurface flow was not directly diverted from one sub-basin to another by the logging road and thus would not be an explanation of the simulated tributary flow changes. The common boundary of the sub-basins is located well above (600 m) the road location so there is no direct interception and transfer from one sub-basin to another by way of roads. The presence of roads increased the contributing area of the sub-basins according to road altered sub-basin boundaries. These boundaries were determined using road and culvert locations and cell to cell flow paths based on surface topography. The resulting South Tributary contributing area potentially increased by approximately 20%. This may account for the increased flow of the South Tributary for the road scenarios. The increased contributing area of the South Tributary extends out onto the hillslope that separates it from the Redfish Upper sub-basin. The expansion of the South Tributary contributing area does not cause a decrease in the road-altered Redfish Upper contributing area.

The slight increase in Redfish Upper contributing area is contrary to the decrease in tributary flow. This may be an artefact of the DHSVM multiple flow path routing routine (Wigmosta et al., 1994). As not all the water contained by a cell is transferred to the most downslope neighbour, but may distribute amongst all adjacent downslope cells, effective subsurface flow boundaries are larger than those based on cell to cell transfer of subsurface flow. The complexity of the multiple flow path is compounded with the presence of the switchbacks located on the hillslope between the two basins. The switchbacks are capable transferring flows between subsurface and surface paths by the conversion of subsurface flow to surface flow at road cuts and the subsequent transfer of surface flow back to subsurface flow at ditch discharge locations, thereby returning flow to the subsurface for potential interception by a lower switchback. Considering the increased potential for contributing area expansion given the multiple flow paths, it is possible that a transfer of flow did occur between the sub-basins, resulting in the decreased Redfish Upper tributary flows.

4.3 Model sensitivity to cut depth variations

The sensitivity of modelled annual yield and annual peak flows due to variations in logging road cut depth was greater in the smaller catchments. The low road density associated with Redfish Creek watershed inhibits a sensitivity analysis of cut depth because the addition of primary logging roads results in a negligible impact on streamflow regardless of cut depth. The greater South tributary flow changes may be influenced to some degree by the expansion of the contributing area to the South Tributary. The larger the contributing area increase, coupled with increasing road cut depth, the greater the potential to intercept subsurface flows.

It is intuitive that deep road cuts would intercept larger volumes of subsurface flow; such effects were demonstrated by Wigmosta and Perkins (2001). Deeper road cuts would therefore pose potentially greater affects to streamflow. However, such relationships were not consistent in Redfish Creek and its tributaries. The deepest cut depth scenario did not create the greatest impact on annual snowmelt and rain-on-snow peaks for Redfish Upper Tributary. The scenario incorporating the field-defined road cuts generated the largest change to these tributary flows. It may be that subsurface flow, which would have been intercepted and routed to Redfish Upper sub-basin in the case of the road cut depth equalling the soil depth, is passing below the road surface to either flow down the hillslope away form the Redfish Upper sub-basin or is intercepted by lower switchback road cuts for distribution away from the sub-basin. This phenomenon may, in part, explain the lesser decrease in annual yield and peak flow for the field-defined scenario as compared with the deepest cut depth scenario.

4.4 Effect of surface flow connections from culverts to the stream network

The primary effect of extending the stream network to connected culverts should be an increase in streamflow responsiveness, expressed as a shortened time to peak and increased magnitude of peak flows (Wemple et al., 1996). However, for all of the catchments examined in this study, changes to either the average annual yield or peak caused by stream network extensions were less than 2% in addition to the effect of the primary logging roads with field specified road cuts. Further, although slight increases to annual streamflow peak did occur in Redfish Creek and Redfish Upper Tributary, there was no decrease in the time to peak for either snowmelt or rain-on-snow events at both scales. A decrease in the time to peak may have occurred if a greater portion of downslope flow was intercepted by connected ditch-culvert systems, whereas a conservative, but field based, approach was taken to determine the connectivity of culverts. It is also possible that changes in timing of runoff peaks could be detected by employing a smaller temporal resolution instead of use of hourly time steps.

4.5 Hydrologic influence of skid trails and abandoned roads

The addition of skid trails and abandoned roads produced some change in the annual yield of Redfish Upper and South tributaries, over and above the effects of adding the channel extension. As compared against the base scenario without roads, Redfish Upper annual yield increased slightly from –4.2%, for the stream extension scenario, to –3.4% after the addition of skid trails and abandoned roads. The South Tributary annual yield decreased from 18.0% for the stream extension scenario to 17.0%. The addition of an abandoned trail on the hillslope between the two sub-basins may transfer subsurface flows away from the South Tributary to the Redfish Upper Tributary.

Only minimal changes to annual peaks were observed at the Redfish Creek basin scale, probably because less than 1% percent watershed is covered by primary logging roads, abandoned roads, and skid trails. Even though the low permeability of the road is not represented in the model, it is unlikely that such an addition to the model would have changed the results given the scale of the basin and the low proportion of roads.

4.6 Enhancement of sub-basin model with road features

The addition of logging roads did not substantially improve the modelled representation of observed Redfish Upper tributary flows. The addition of roads reduced the streamflows that were overestimated in the unroaded simulation, but only by a negligible amount in compared with observed flows. The base scenario without roads had flashy peaks compared to observed flows. The addition of roads, more notably with channel extensions, increased modelled tributary flow responsiveness. Other sources of error that potentially contributed to the overestimation of Redfish Upper tributary flows include high natural variability of soil characteristics, hillslope flow paths that differ from DHSVM's flow path algorithm and DEM inaccuracy (Whitaker et al., 2001). It is also possible that parameters controlling precipitation, snow accumulation, or snowmelt may have been inaccurately specified for the model.

Whereas inaccurate soil representation in the model would likely have a greater effect on the timing of flows, the inaccurate definition of contributing area and specification of precipitation parameters affect streamflow yield. Subsurface flow routing can be controlled by the topography of the confining layer at the bottom of the soil profile (Hutchinson and Moore, 2000), as well as complex patterns of preferential flow (Sidle et al., 2000). DHSVM and other models assume that subsurface flow paths conform to surface topography. Differences between true and modelled flow paths will affect stream yield to some extent. The modelled flow path is dependent largely on the DEM, which underscores the potential impact of DEM errors. Studies have also shown substantial variability of hydrologic modelling results based on differing horizontal and vertical scales (Zhang and Montgomery, 1994; Kenward et al., 2000). Lack of sufficient topographic detail, which can only be expressed with higher resolution DEMs, can lead to inaccurate flow path representation.

As seen with the potential to alter annual yield in the South Tributary, road placement relative to the DEM is also an important factor for sub-basins. Two of three switchback bends, located on an adjacent hillslope, deposit flow intercepted from the hillslope directly to the South Tributary sub-basin. The increase in South Tributary contributing area is also dependent on the location of roads and culverts. An error in the DEM was detected during the initial overlay of road locations, acquired by GPS, and stream locations, digitized from aerial photos. The east side of the Redfish Creek watershed topography appeared to be displaced northward by almost 50 m. Road placement error could have resulted from shifting the east side logging roads location to better align with the topography.

CHAPTER 5: CONCLUSION

5.1 Summary of main findings

For the snow dominated regime of Redfish Creek watershed, the impact of logging roads on annual and peak streamflows was generally very minor; these minor changes varied with basin size and topography. The low density of logging roads produced negligible changes at the scale of Redfish Creek watershed.

Redfish Upper Tributary experienced decreases of less than 5% in annual yield and peak flow, while the South Tributary experienced larger changes in the form of a 19.6% increase in annual yield and an 11.3% increase in annual peak flow following the addition of primary logging roads with field specified road cuts. A complex interaction between the multiple flow path subsurface flow routing routine and redistribution of subsurface flows at the switch back bends that were located at the edge of the sub-basin boundary likely resulted in the Redfish Upper flow reductions. An increased contributing area of approximately 20% due to the presence of logging roads likely caused the increased South tributary flows.

Increased sensitivity to road cut depth accompanied those scenarios in which modelled streamflows show notable changes due to the general presence of logging roads. The greatest sensitivity was found for annual flow from the South Tributary; increases ranged from 2.6% for the minimal cut depth scenario to 20.8% for road cuts equal to soil depth.

The addition of culvert connectivity through stream density expansion and skid trails and abandoned roads did not impart notable additional streamflow changes to any of the watersheds examined. The lack of change resulting from stream density expansion may be due to a small amount of stream length added to the existing stream network. However, all streamflows became more responsive to the increased surface flow efficiency resulting from the increased stream density. The addition of skid trails and abandoned roads appeared to cause the transfer of a portion of subsurface flow from the South Tributary to Redfish Upper Tributary.

The addition of logging roads to Redfish Upper Tributary did not noticeably improve the simulated flows compared with observed flows. The source of tributary flow overestimation may lie in possible errors in the DEM, precipitation inputs, and/or melt rates.

5.2 Suggestions for further research

Although this project has generated some insights into the effects of roads on streamflow in a snowmelt-dominated mountain catchment, the results are specific to the current road network in Redfish Creek, and may not be applicable to catchments with greater road densities, especially at higher elevations. Some of the issues that deserve further investigation are outlined in the next paragraph.

The streamflow impact of varying road densities should be examined to explore the relationship between road density and peak flow changes. Variations in study site characteristics, such as a high plateau catchment with lower relief and a more synchronised snowmelt timing of annual snowmelt, would develop further understanding of potential road impacts in snow dominated regimes. Another avenue of continued research involves contrasting the effects of multiple and single flow path algorithms in determining the road impacts on subsurface path and contributing areas.

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Appendix

Tabulated and Graphed Results for 1993, 1994, 1996, and 1997

Table 7. Redfish Creek annual yield changes resulting from road cut depth variation

Run	1993		1994		1995		1996		1997		Average Annual Yield Change
	Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	
A	18061182	-	22340069	-	23663270	-	31693984	-	26689987	-	-
Ba	18069179	< 0.1%	22348290	0.0%	23668591	< 0.1%	31684555	< -0.1%	26705268	0.1%	< 0.1%
Bb	18054418	< 0.1%	22295368	-0.2%	23646097	-0.1%	31616365	-0.2%	26670189	-0.1%	-0.1%
Bc	18064548	< 0.1%	22284086	-0.3%	23650959	-0.1%	31606329	-0.3%	26669474	-0.1%	-0.2%

Annual yield (AY) Change = 100 x (AYRun - AYRunA) / AYRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr)
As stated in Whitaker et al. in Hydrological Processes (2003), page 209, in regard to the calibration process, "The first 6 months of simulation, notably the outflow hydrograph, were sensitive to the model initial conditions, and were not considered in the calibration." For this reason, only the later 6 months of water year 1993 have been considered for yield.

Table 8. Redfish Creek annual peak flow changes resulting from road cut depth variation

Run	1993		1994		1995		1996		1997		Average Annual Peak Change
	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	
A	9.2558	-	4.1678	-	6.3292	-	7.0964	-	6.3708	-	-
Ba	9.2503	-0.1%	4.1767	0.2%	6.3364	0.1%	7.1206	0.3%	6.3744	0.1%	0.1%
Bb	9.2406	-0.2%	4.1672	< 0.1%	6.3506	0.3%	7.0767	-0.3%	6.3714	< 0.1%	< 0.1%
Bc	9.2378	-0.2%	4.1458	-0.5%	6.3525	0.4%	7.0547	-0.6%	6.3706	< 0.1%	-0.2%

Annual Peak (AP) Change = (APRun - APRunA) / APRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr)

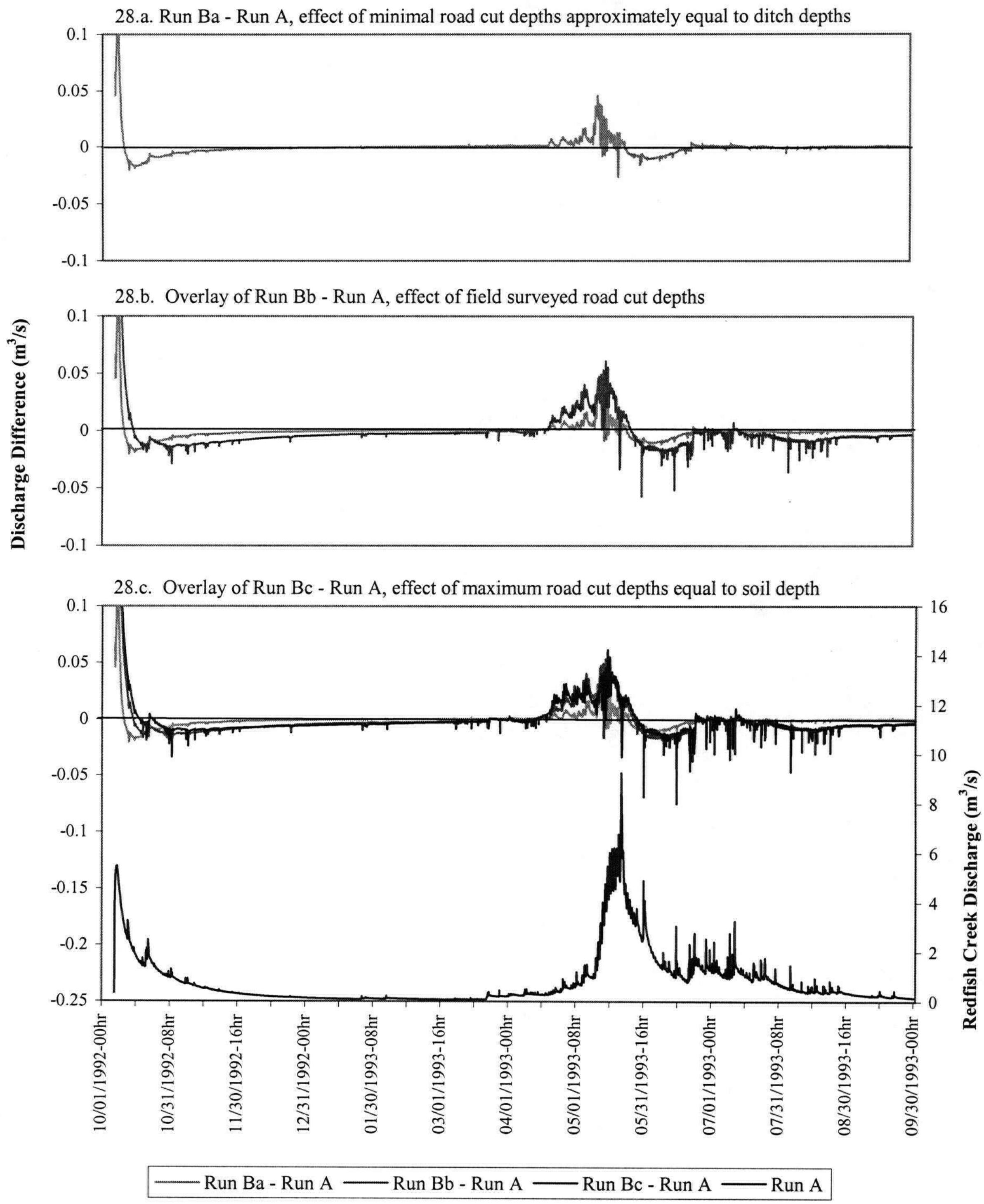

Figure 28. Discharge differences for Redfish Creek due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1993

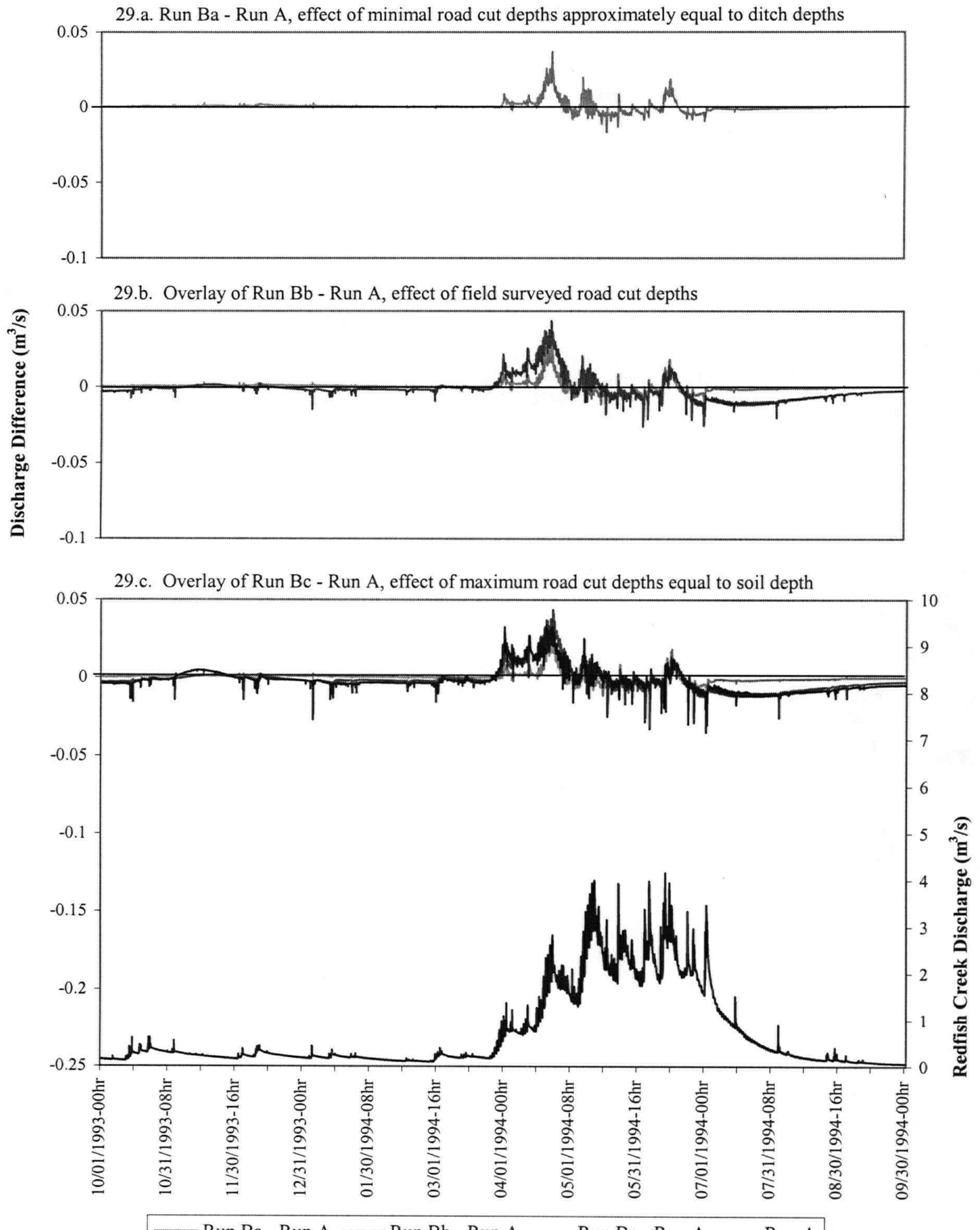

Figure 29. Discharge differences for Redfish Creek due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1994

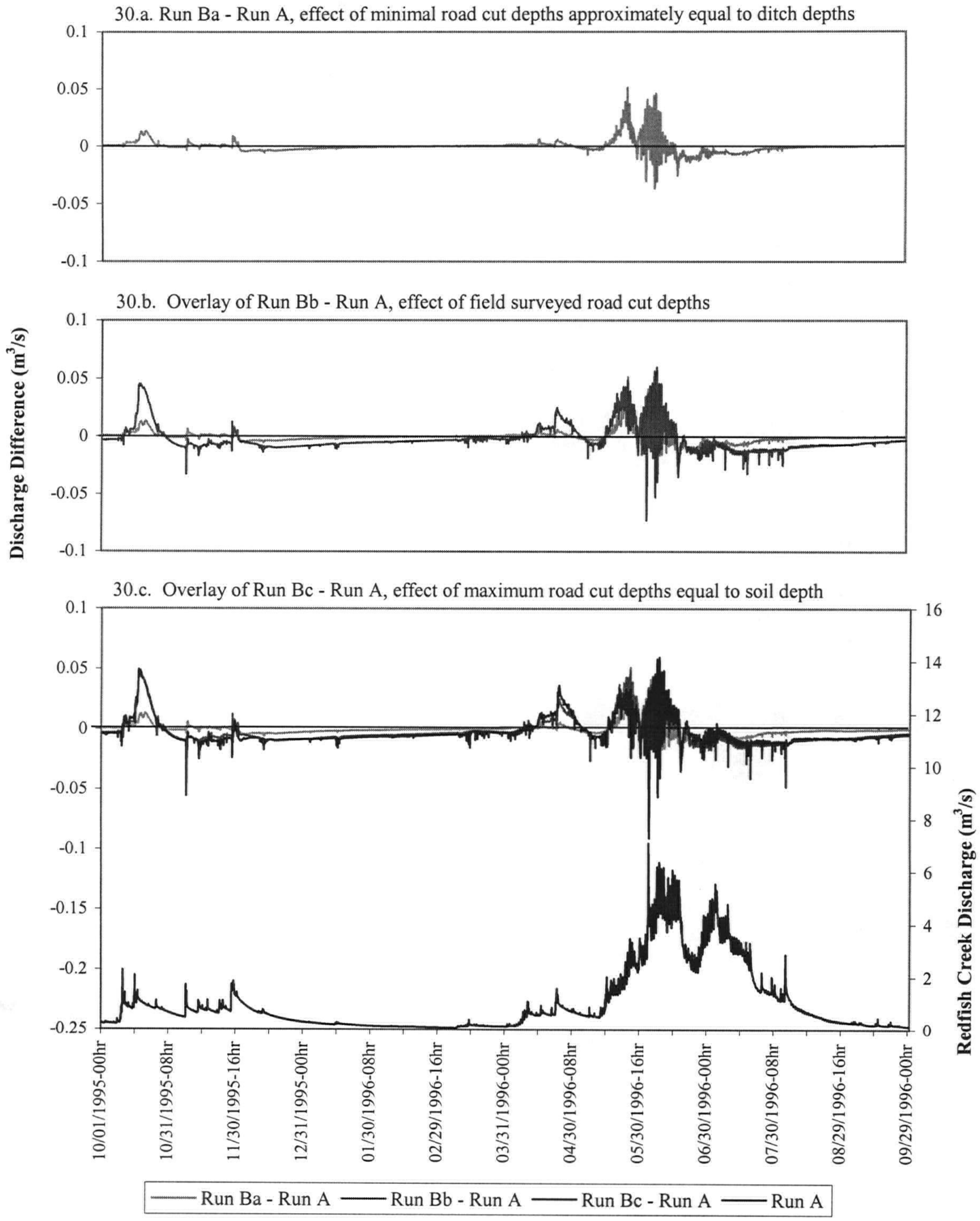

Figure 30. Discharge differences for Redfish Creek due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1996

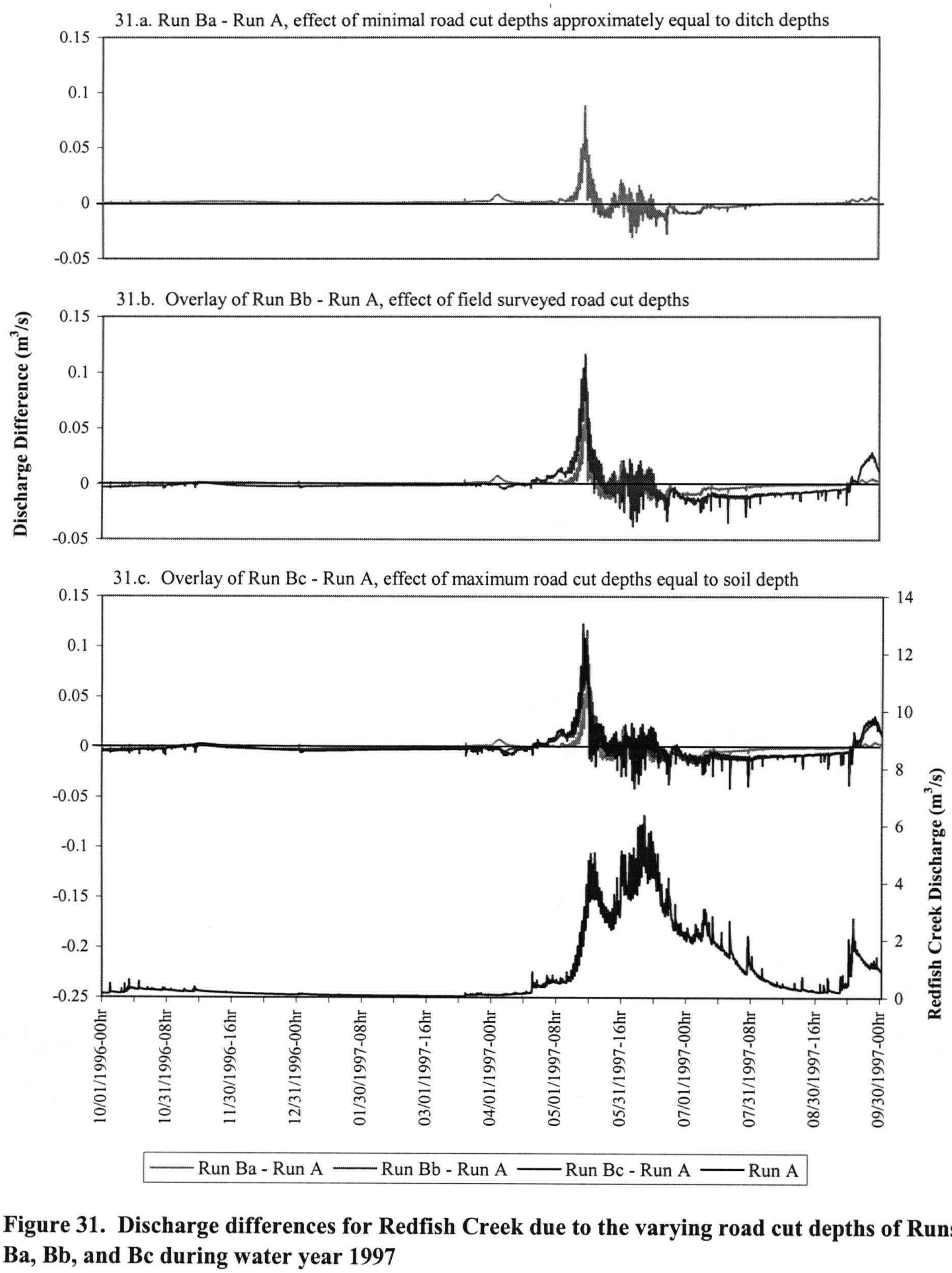

Figure 31. Discharge differences for Redfish Creek due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1997

Table 9. Redfish Upper Tributary annual yield changes resulting from road cut depth variation

Run	1993		1994		1995		1996		1997		Average Annual Yield Change
	Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	
A	1071400	-	1254865	-	1364539	-	1759679	-	1540701	-	-
Ba	1059460	-1.1%	1243640	-0.9%	1352956	-0.8%	1736623	-1.3%	1522049	-1.2%	-1.1%
Bb	1036557	-3.3%	1208460	-3.7%	1320816	-3.2%	1692341	-3.8%	1489103	-3.3%	-3.5%
Bc	1040482	-2.9%	1216860	-3.0%	1328498	-2.6%	1700955	-3.3%	1496604	-2.9%	-3.0%

Annual yield (AY) Change = 100 x (AYRun - AYRunA) / AYRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr)
As stated in Whitaker et al. in Hydrological Processes (2003), page 209, in regard to the calibration process, "The first 6 months of simulation, notably the outflow hydrograph, were sensitive to the model initial conditions, and were not considered in the calibration." For this reason, only the later 6 months of water year 1993 have been considered for yield.

Table 10. Redfish Upper Tributary annual peak flow changes resulting from road cut depth variation

Run	1993		1994		1995		1996		1997		Average Annual Peak Change
	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	
A	0.5829	-	0.2711	-	0.4326	-	0.4833	-	0.3828	-	-
Ba	0.5688	-2.4%	0.2709	-0.1%	0.4281	-1.0%	0.4776	-1.2%	0.3796	-0.8%	-1.1%
Bb	0.5638	-3.3%	0.2629	-3.0%	0.4124	-4.7%	0.4682	-3.1%	0.3781	-1.2%	-3.1%
Bc	0.5656	-3.0%	0.2628	-3.1%	0.4136	-4.4%	0.4696	-2.8%	0.3778	-1.3%	-2.9%

Annual Peak (AP) Change = (APRun - APRunA) / APRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr)

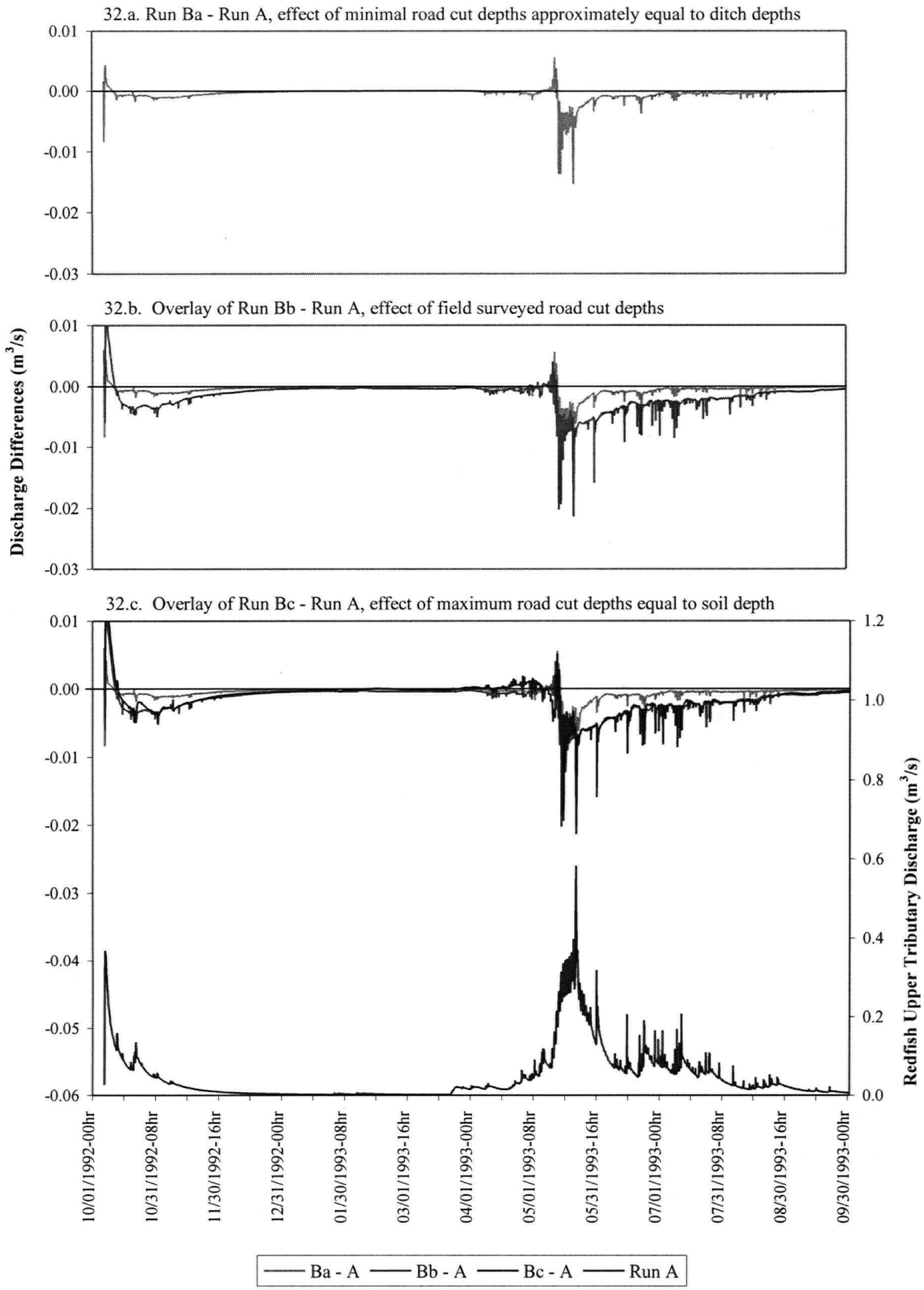

Figure 32. Discharge differences for Redfish Upper Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1993

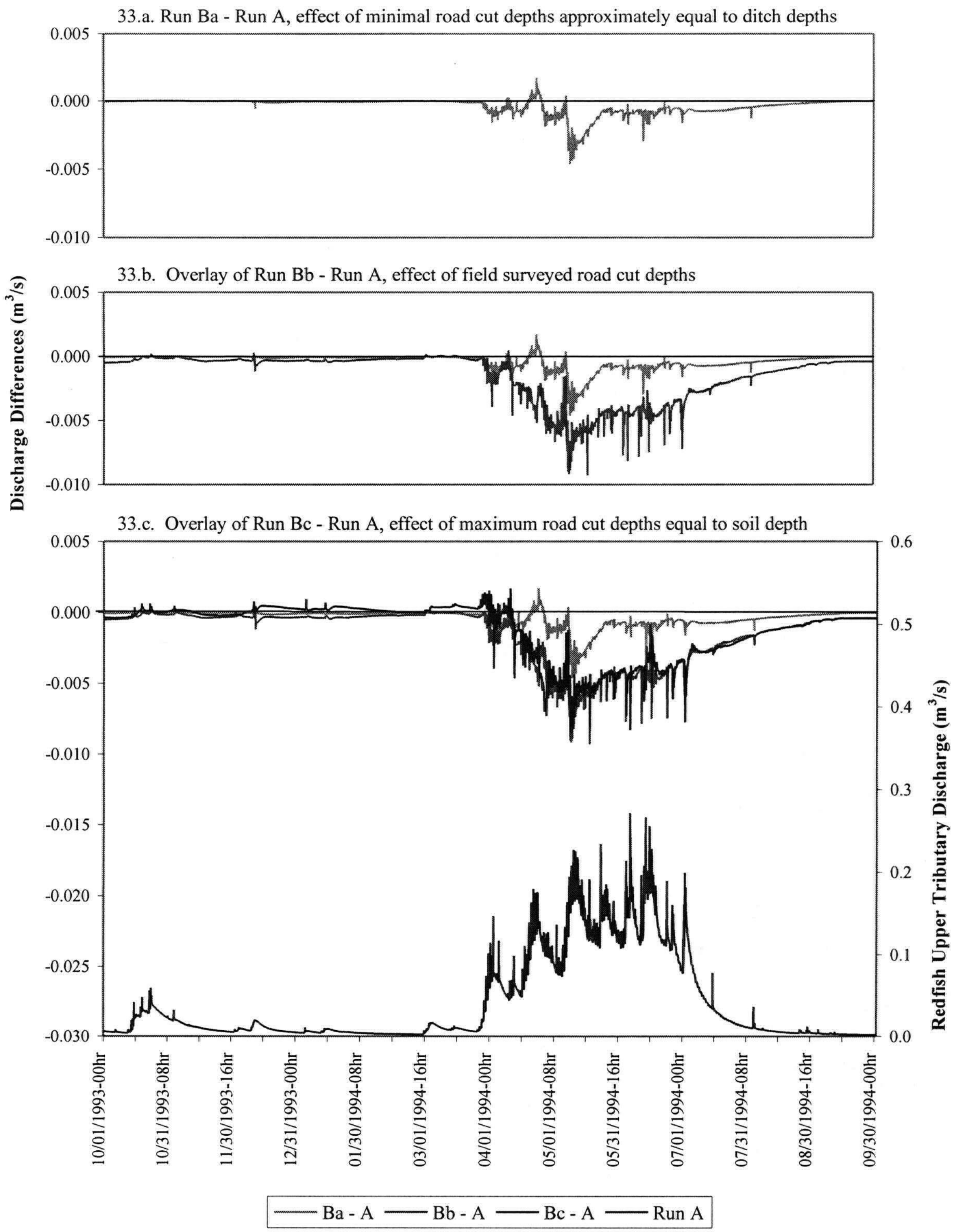

Figure 33. Discharge differences for Redfish Upper Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1994

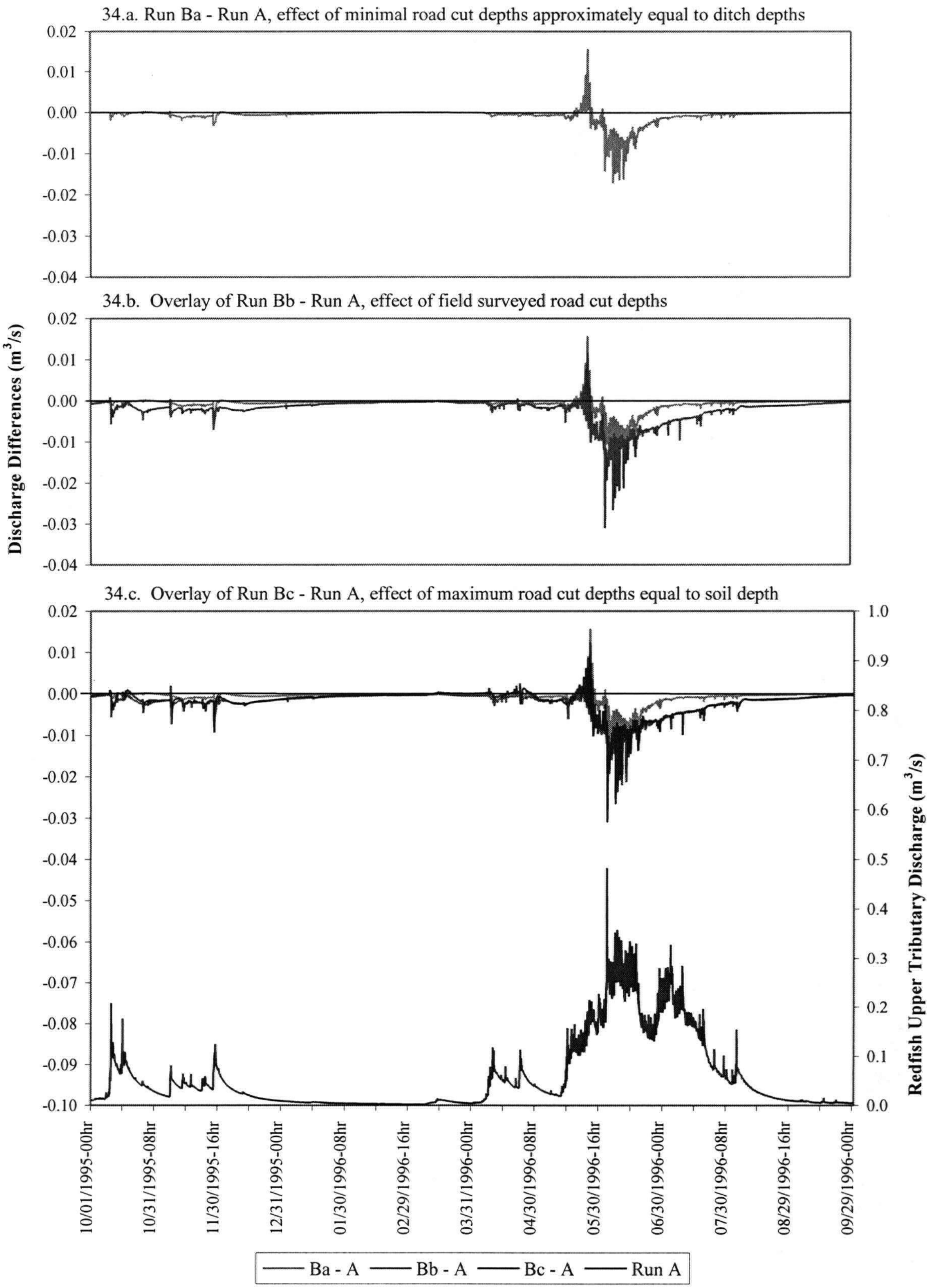

Figure 34. Discharge differences for Redfish Upper Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1996

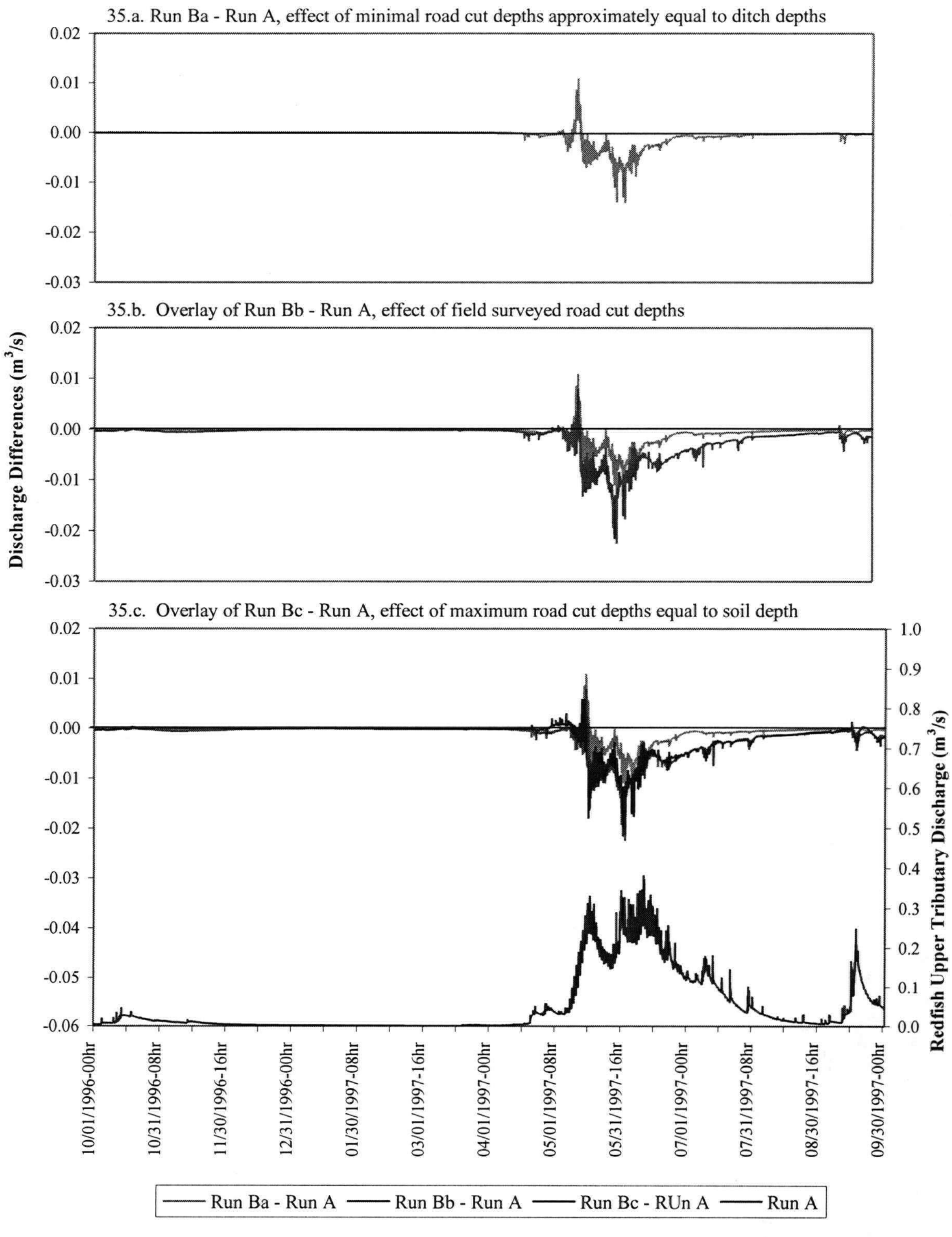

Figure 35. Discharge differences for Redfish Upper Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1997

Table 11. South Tributary annual yield changes resulting from road cut depth variation

Run	1993 Yield (m^3)	1993 Annual Yield Change	1994 Annual Yield (m^3)	1994 Annual Yield Change	1995 Annual Yield (m^3)	1995 Annual Yield Change	1996 Annual Yield (m^3)	1996 Annual Yield Change	1997 Annual Yield (m^3)	1997 Annual Yield Change	Average Annual Yield Change
A	604069	-	694441	-	724426	-	1075998	-	857044	-	-
Ba	624850	3.4%	717141	3.3%	743526	2.6%	1143442	6.3%	910949	6.3%	4.6%
Bb	714938	18.4%	833716	20.1%	859650	18.7%	1297046	20.5%	1019919	19.0%	19.6%
Bc	724579	19.9%	847327	22.0%	875188	20.8%	1313654	22.1%	1032158	20.4%	21.3%

Annual yield (AY) Change = 100 x (AYRun - AYRunA) / AYRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr)
As stated in Whitaker et al. in Hydrological Processes (2003), page 209, in regard to the calibration process, "The first 6 months of simulation, notably the outflow hydrograph, were sensitive to the model initial conditions, and were not considered in the calibration." For this reason, only the later 6 months of water year 1993 have been considered for yield.

Table 12. South Tributary annual peak flow changes resulting from road cut depth variation

Run	1993 Annual Peak (m^3/s)	1993 Annual Peak Change	1994 Annual Peak (m^3/s)	1994 Annual Peak Change	1995 Annual Peak (m^3/s)	1995 Annual Peak Change	1996 Annual Peak (m^3/s)	1996 Annual Peak Change	1997 Annual Peak (m^3/s)	1997 Annual Peak Change	Average Annual Peak Change
A	0.3150	-	0.2365	-	0.3170	-	0.3907	-	0:2508	-	-
Ba	0.3345	6.2%	0.2431	2.8%	0.3174	0.1%	0.4260	9.0%	0.2725	8.7%	5.4%
Bb	0.3513	11.5%	0.2661	12.5%	0.3344	5.5%	0.4360	11.6%	0.2893	15.3%	11.3%
Bc	0.3521	11.8%	0.2656	12.3%	0.3366	6.2%	0.4369	11.8%	0.2897	15.5%	11.5%

Annual Peak (AP) Change = (APRun - APRunA) / APRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr).
The annual peak for year 1997 changed from 6/11/97 for Run A to 6/01/97 for Runs Ba, Bb, and Bc.

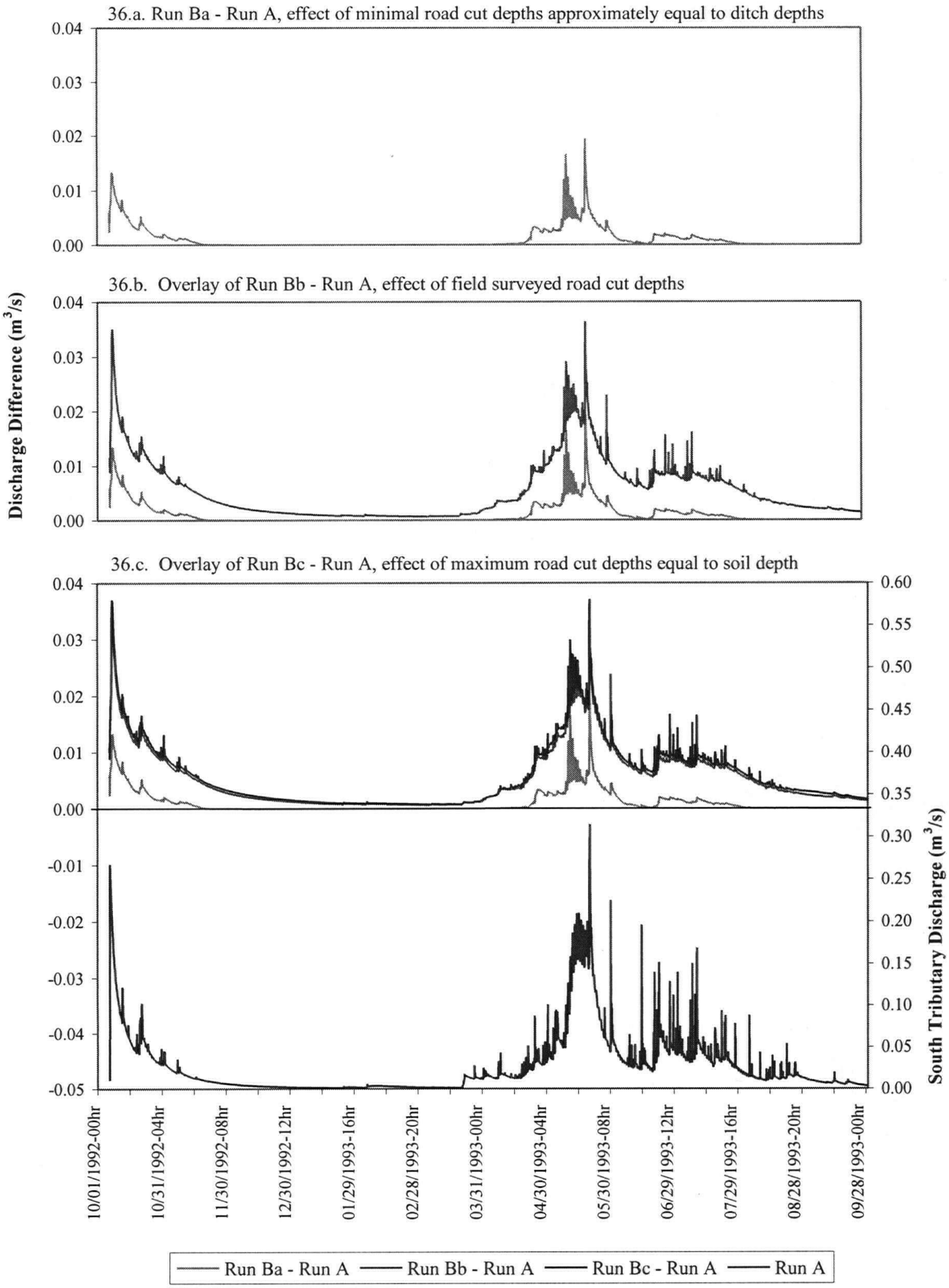

Figure 36. Discharge differences for South Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1993

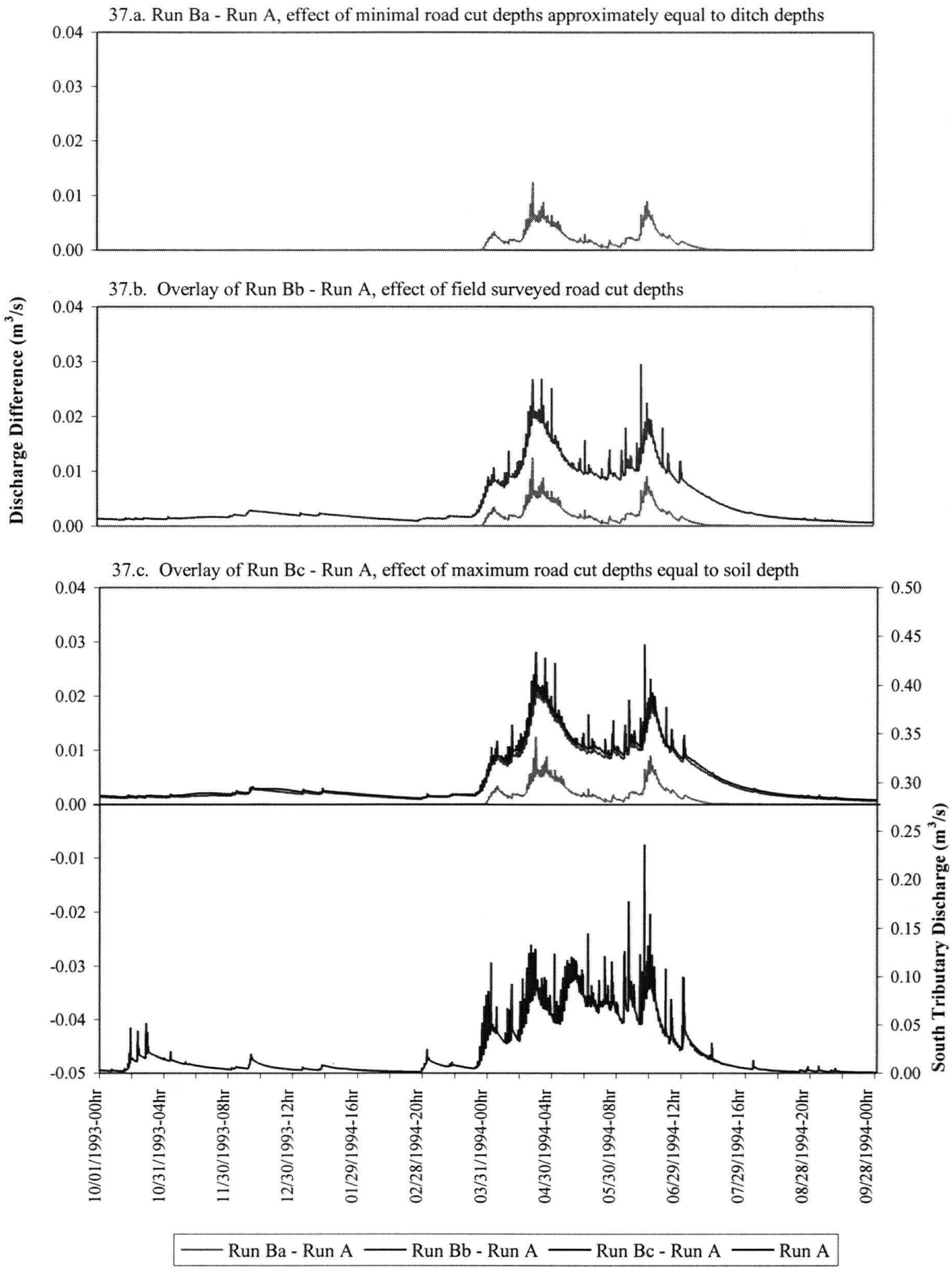

Figure 37. Discharge differences for South Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1994

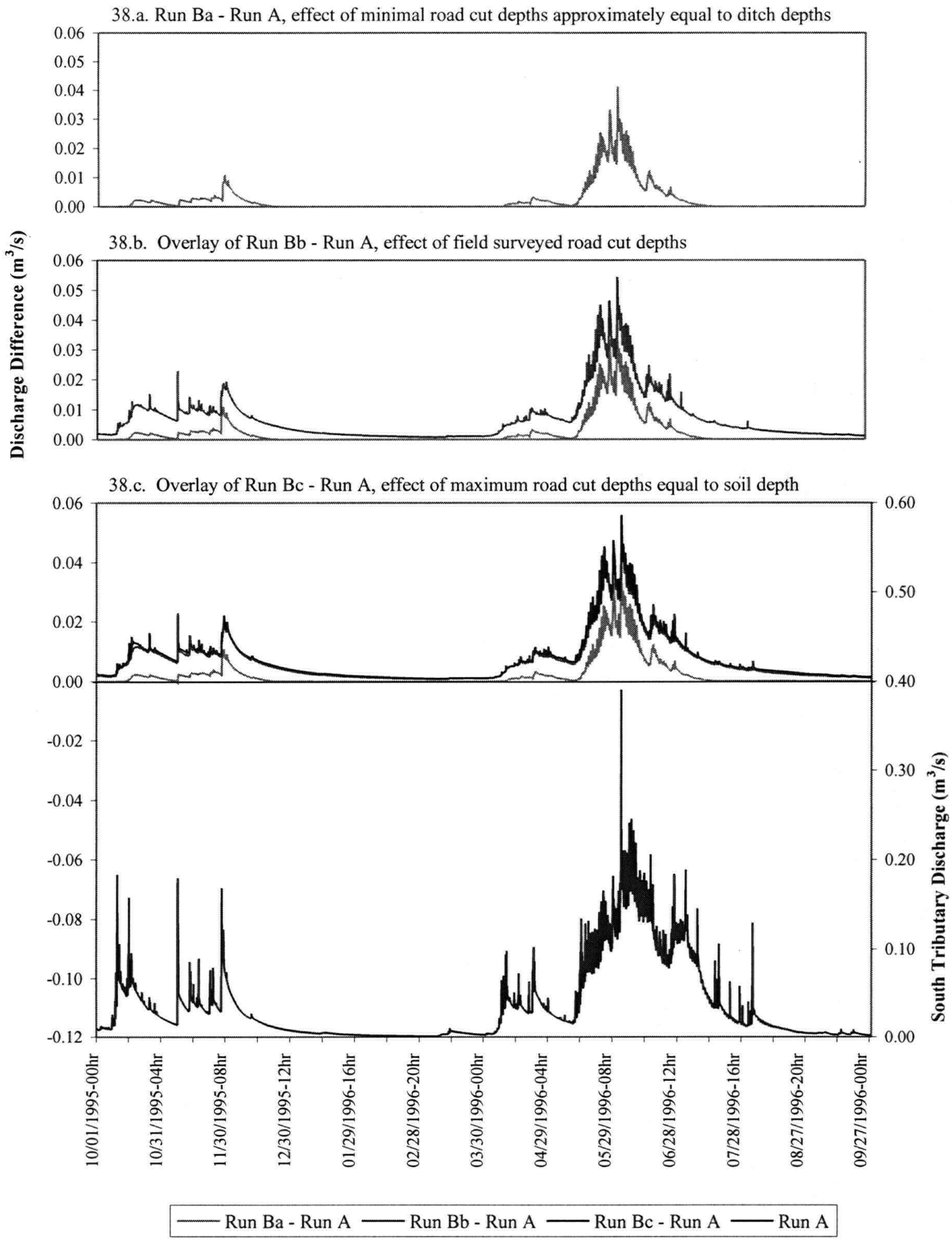

Figure 38. Discharge differences for South Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1996

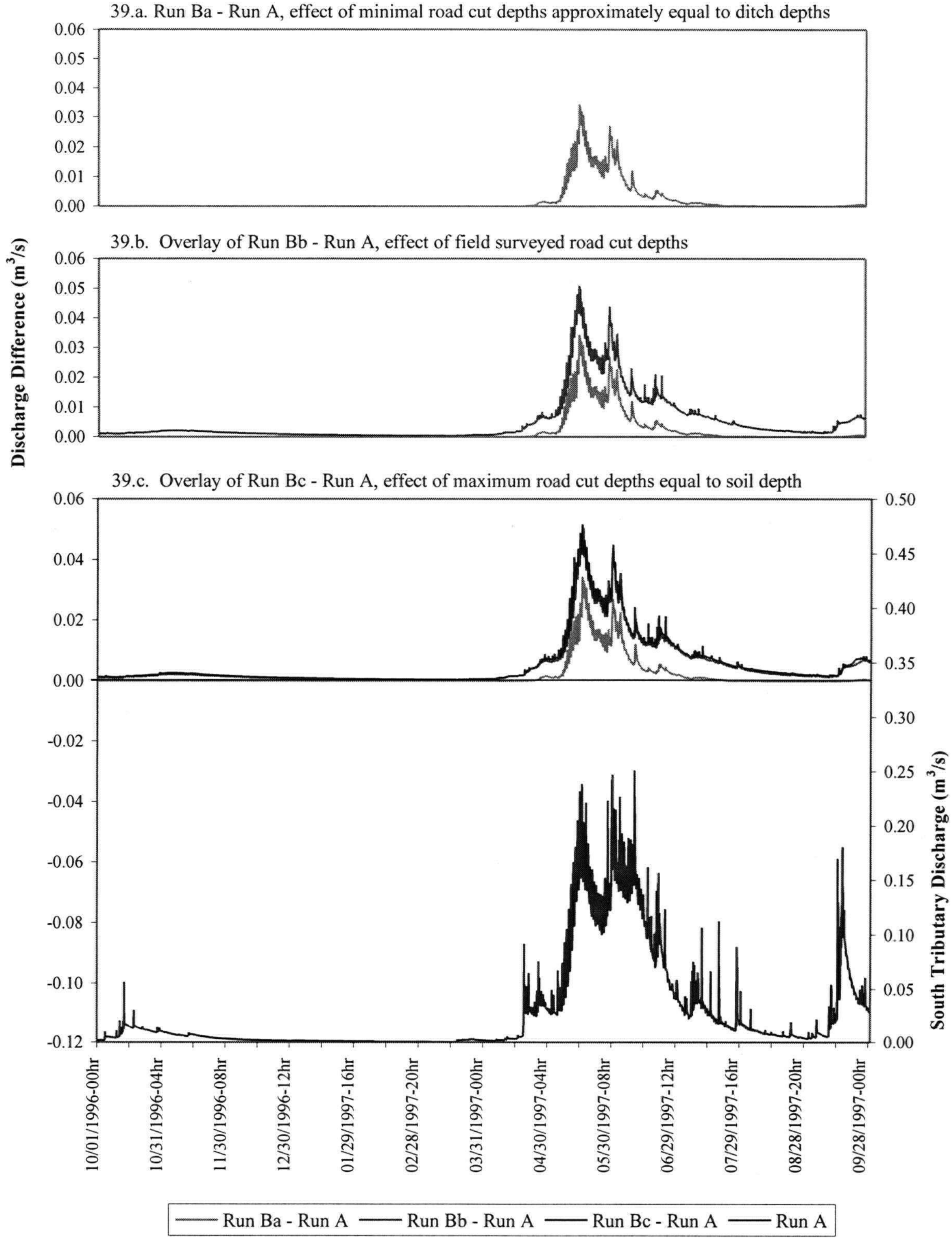

Figure 39. Discharge differences for South Tributary due to the varying road cut depths of Runs Ba, Bb, and Bc during water year 1997

Table 13. Redfish Creek annual yield changes resulting from stream extension, skid trails and abandoned roads

Run	1993		1994		1995		1996		1997		Average Annual Yield Change
	Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	
A	18061182	-	22340069	-	23663270	-	31693984	-	26689987	-	-
Bb	18054418	< -0.1%	22295368	-0.2%	23646097	-0.1%	31616365	-0.2%	26670189	-0.1%	-0.1%
C	18061999	< 0.1%	22291170	-0.2%	23654371	< -0.1%	31615011	-0.2%	26682560	< -0.1%	-0.2%
D	18061458	< 0.1%	22291386	-0.2%	23651554	< -0.1%	31609923	-0.3%	26679599	< -0.1%	-0.2%

Annual yield (AY) Change = 100 x (AYRun - AYRunA) / AYRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr)
As stated in Whitaker et al. in Hydrological Processes (2003), page 209, in regard to the calibration process, "The first 6 months of simulation, notably the outflow hydrograph, were sensitive to the model initial conditions, and were not considered in the calibration." For this reason, only the later 6 months of water year 1993 have been considered for yield.

Table 14. Redfish Creek annual peak flow changes resulting from stream extension, skid trails and abandoned roads

Run	1993		1994		1995		1996		1997		Average Annual Peak Change
	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	
A	9.2558	-	4.1678	-	6.3292	-	7.0964	-	6.3708	-	-
Bb	9.2406	-0.2%	4.1672	< -0.1%	6.3506	0.3%	7.0767	-0.3%	6.3714	< 0.1%	< -0.1%
C	9.2647	0.1%	4.1869	0.5%	6.3753	0.7%	7.1897	1.3%	6.3883	0.3%	0.6%
D	9.2686	0.1%	4.1892	0.5%	6.3989	1.1%	7.1956	1.4%	6.4028	0.5%	0.7%

Annual Peak (AP) Change = (APRun - APRunA) / APRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr).

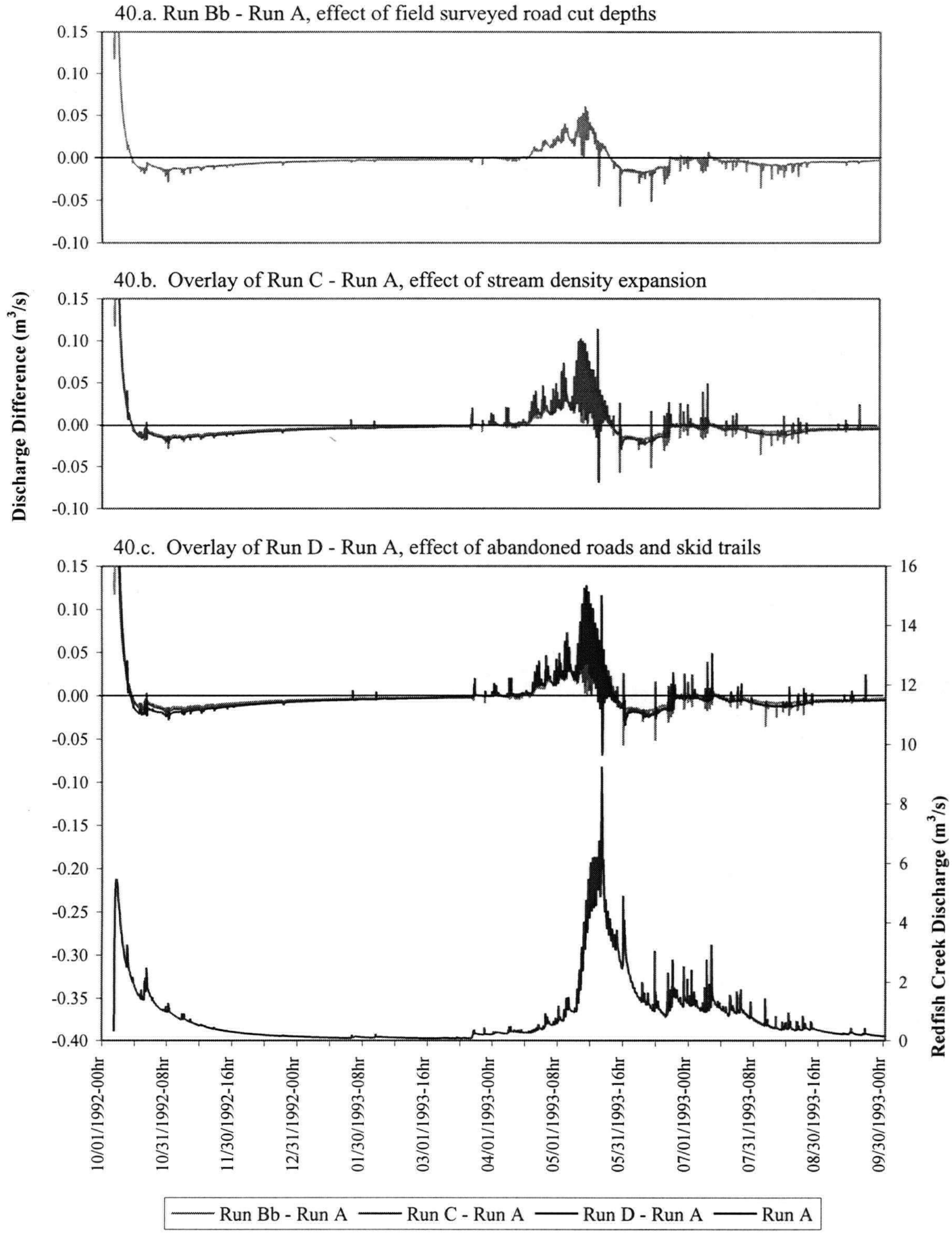

Figure 40. Discharge differences for Redfish Creek due to the varying simulation scenarios of Runs Bb, C, and D during water year 1993

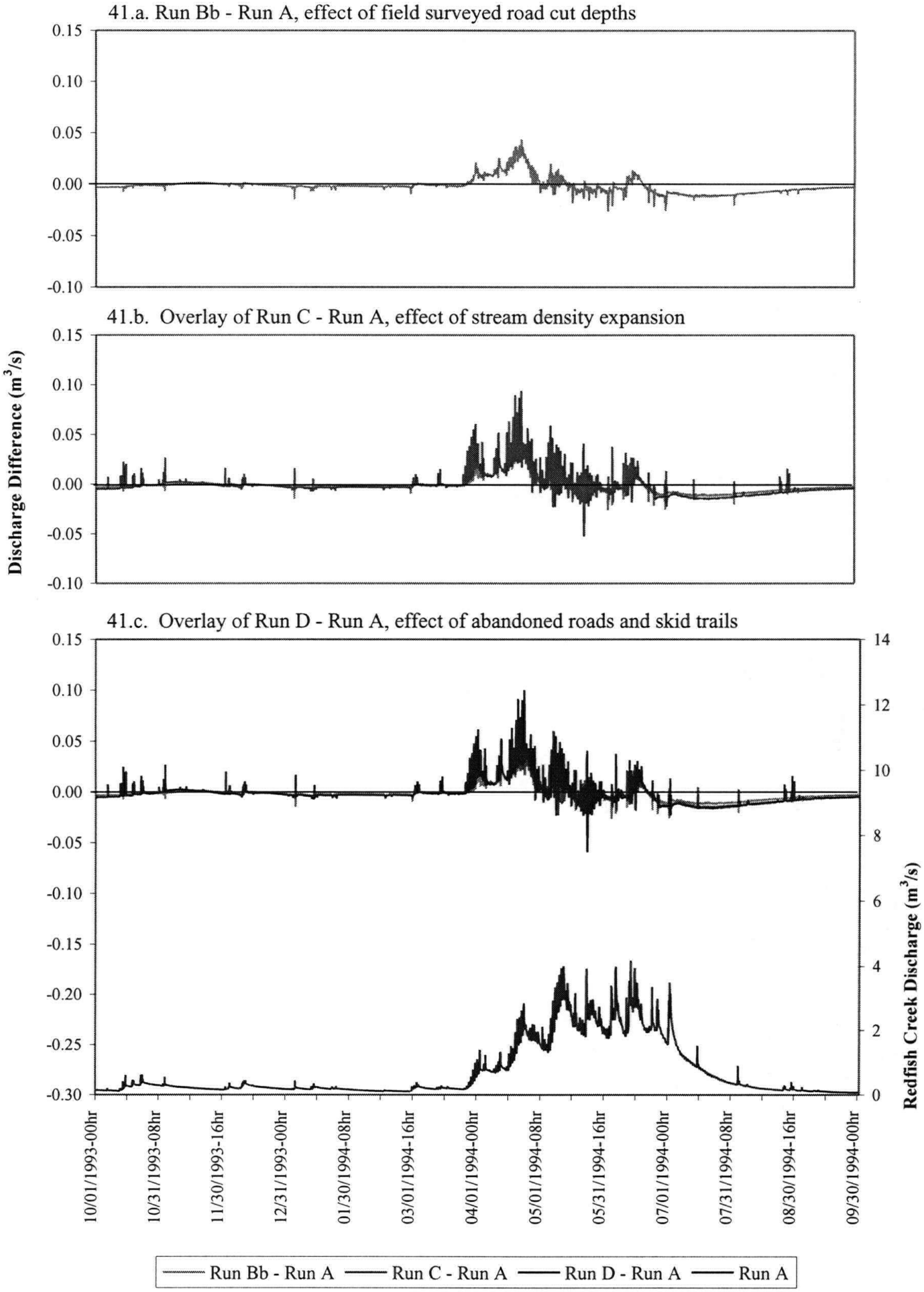

Figure 41. Discharge differences for Redfish Creek due to the varying simulation scenarios of Runs Bb, C, and D during water year 1994

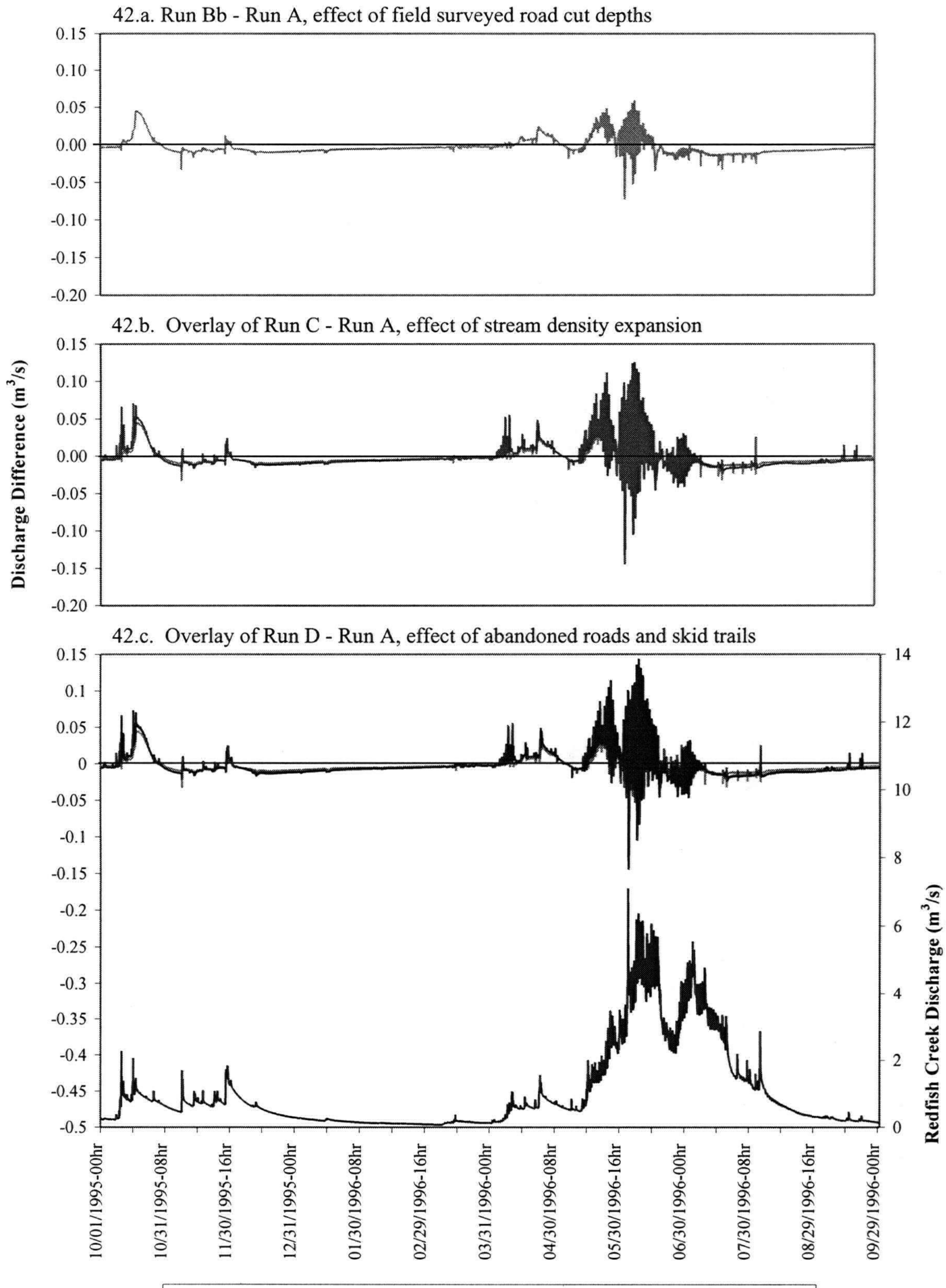

Figure 42. Discharge differences for Redfish Creek due to the varying simulation scenarios of Runs Bb, C, and D during water year 1996

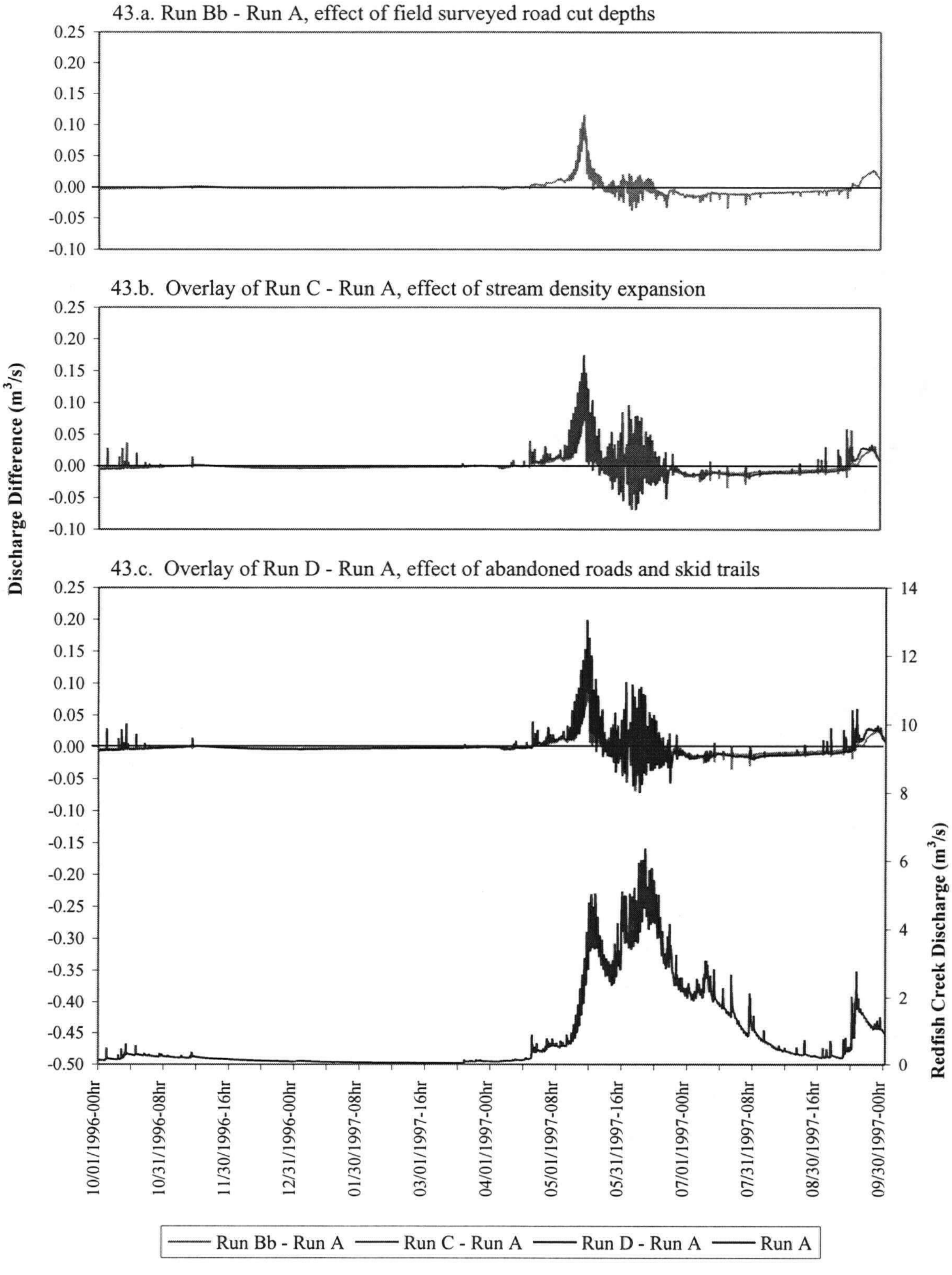

Figure 43. Discharge differences for Redfish Creek due to the varying simulation scenarios of Runs Bb, C, and D during water year 1997

Table 15. Redfish Upper Tributary annual yield changes resulting from stream extension, skid trails and abandoned roads

Run	1993		1994		1995		1996		1997		Average Annual Yield Change
	Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	
A	1071400	-	1254865	-	1364539	-	1759679	-	1540701	-	-
Bb	1036557	-3.3%	1208460	-3.7%	1320816	-3.2%	1692341	-3.8%	1489103	-3.3%	-3.5%
C	1030319	-3.8%	1200427	-4.3%	1312695	-3.8%	1679398	-4.6%	1480045	-3.9%	-4.2%
D	1039232	-3.0%	1204544	-4.0%	1320220	-3.2%	1696846	-3.6%	1498362	-2.7%	-3.4%

Annual yield (AY) Change = 100 x (AYRun - AYRunA) / AYRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr)
As stated in Whitaker et al. in Hydrological Processes (2003), page 209, in regard to the calibration process, "The first 6 months of simulation, notably the outflow hydrograph, were sensitive to the model initial conditions, and were not considered in the calibration." For this reason, only the later 6 months of water year 1993 have been considered for yield.

Table 16. Redfish Upper Tributary annual peak flow changes resulting from stream extension, skid trails and abandoned roads

Run	1993		1994		1995		1996		1997		Average Annual Peak Change
	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	
A	0.5829	-	0.2711	-	0.4326	-	0.4833	-	0.3828	-	-
Bb	0.5638	-3.3%	0.2629	-3.0%	0.4124	-4.7%	0.4682	-3.1%	0.3781	-1.2%	-3.1%
C	0.5665	-2.8%	0.2664	-1.7%	0.4227	-2.3%	0.4855	0.4%	0.3815	-0.3%	-1.3%
D	0.5766	-1.1%	0.2664	-1.7%	0.4224	-2.3%	0.4977	3.0%	0.3876	1.3%	-0.2%

Annual Peak (AP) Change = (APRun - APRunA) / APRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr).

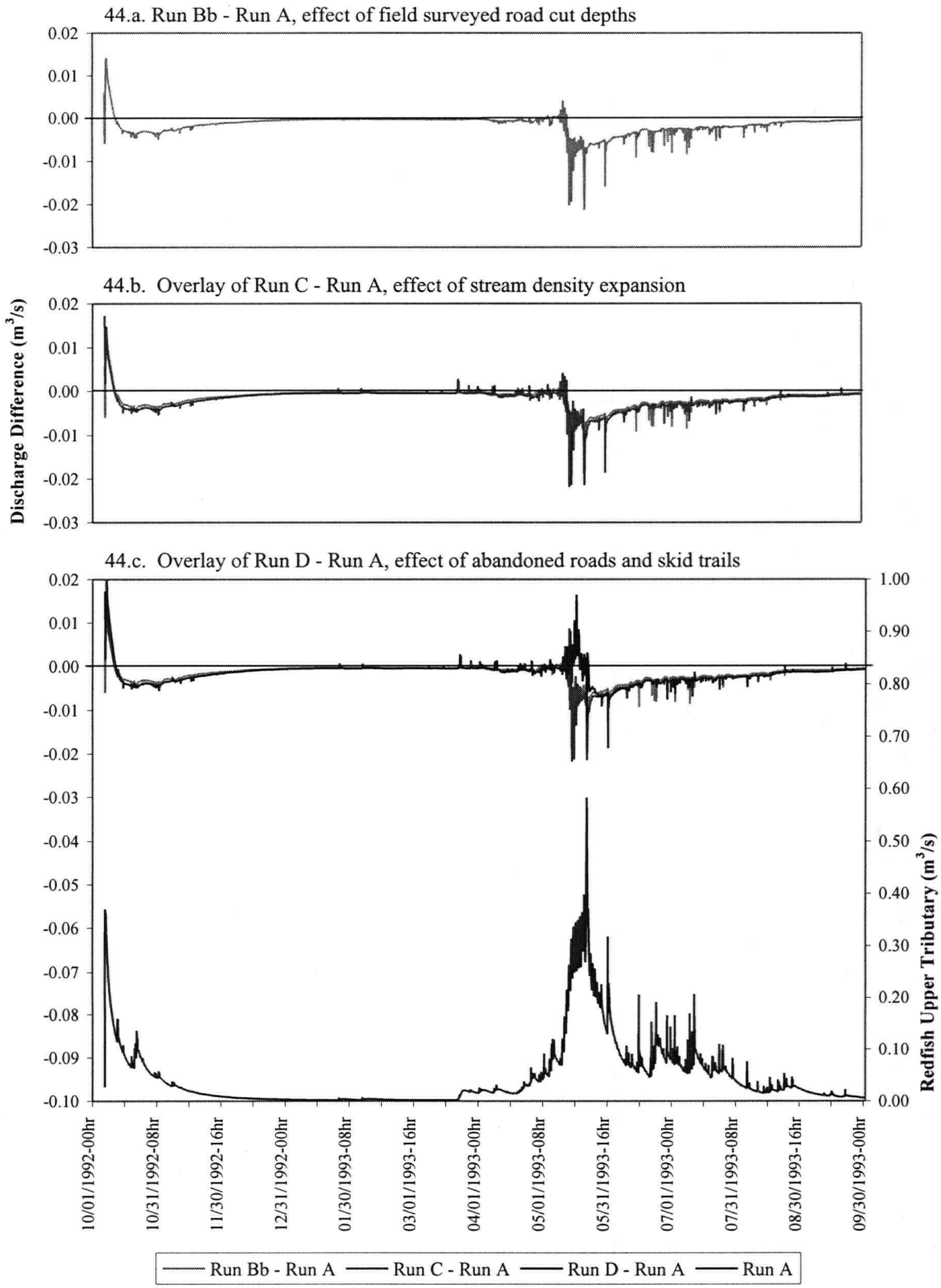

Figure 44. Discharge differences for Redfish Upper Tributary due to the varying simulation scenarios of Runs Bb, C, and D during water year 1993

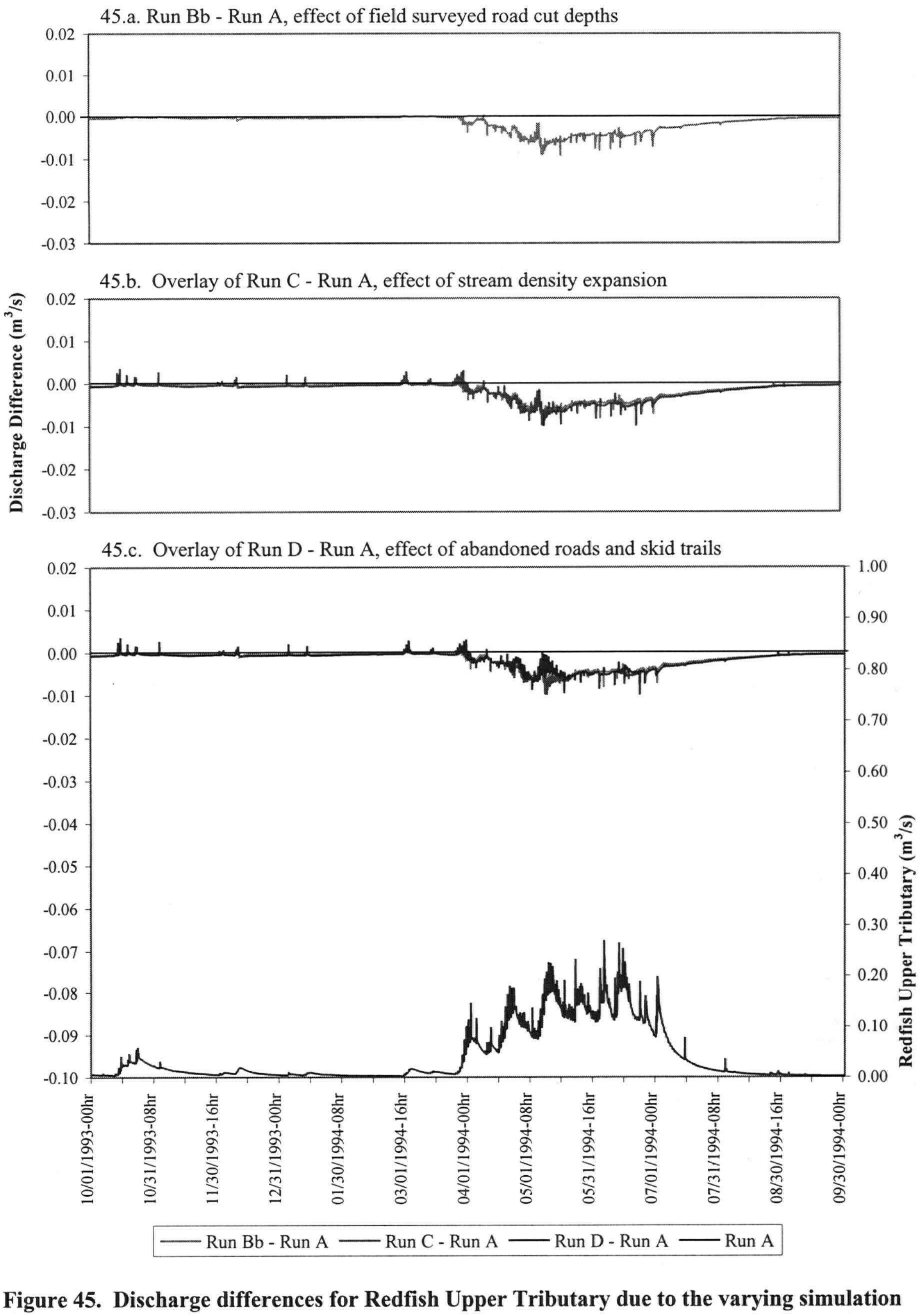

Figure 45. Discharge differences for Redfish Upper Tributary due to the varying simulation scenarios of Runs Bb, C, and D during water year 1994

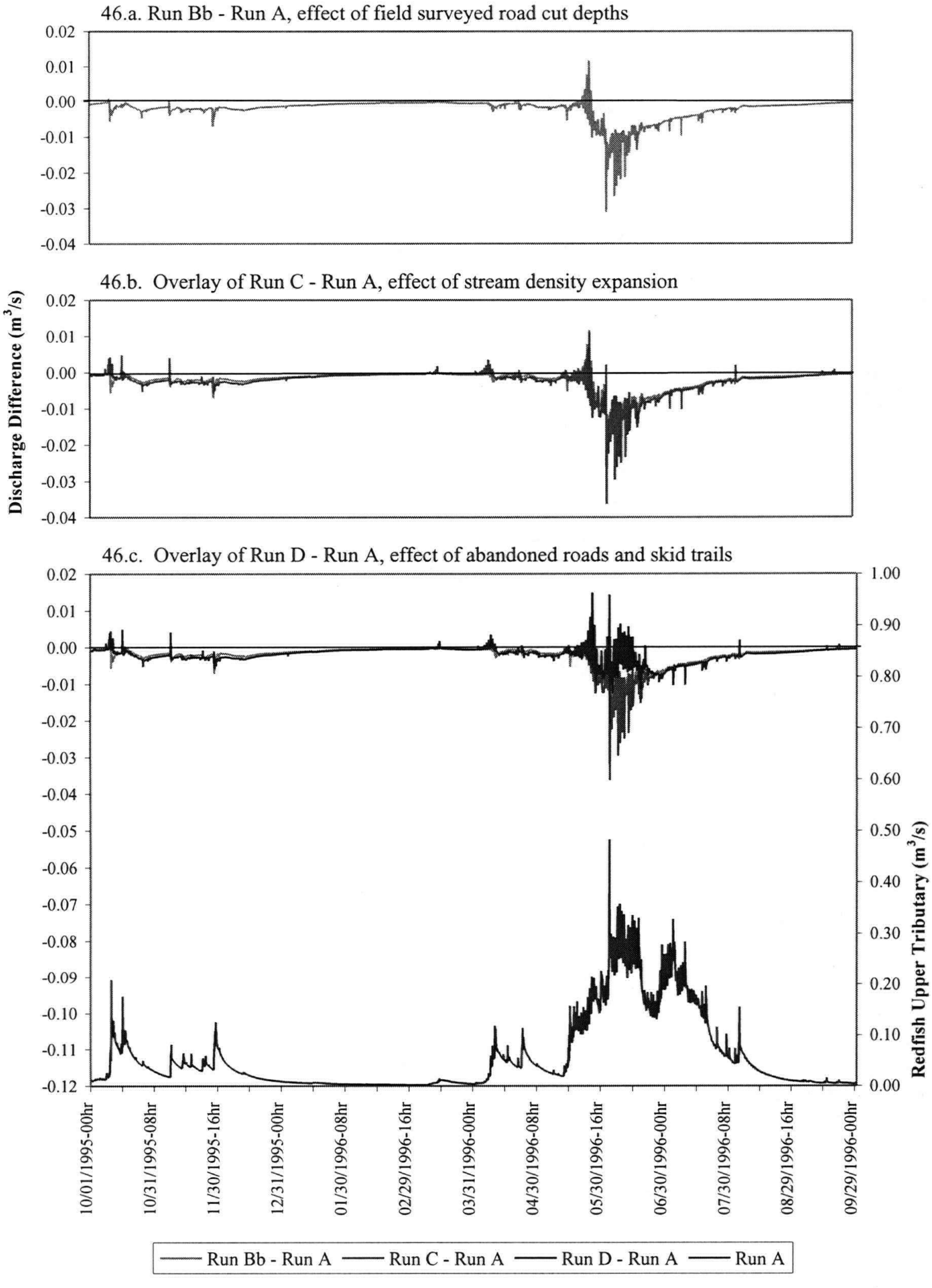

Figure 46. Discharge differences for Redfish Upper Tributary due to the varying simulation scenarios of Runs Bb, C, and D during water year 1996

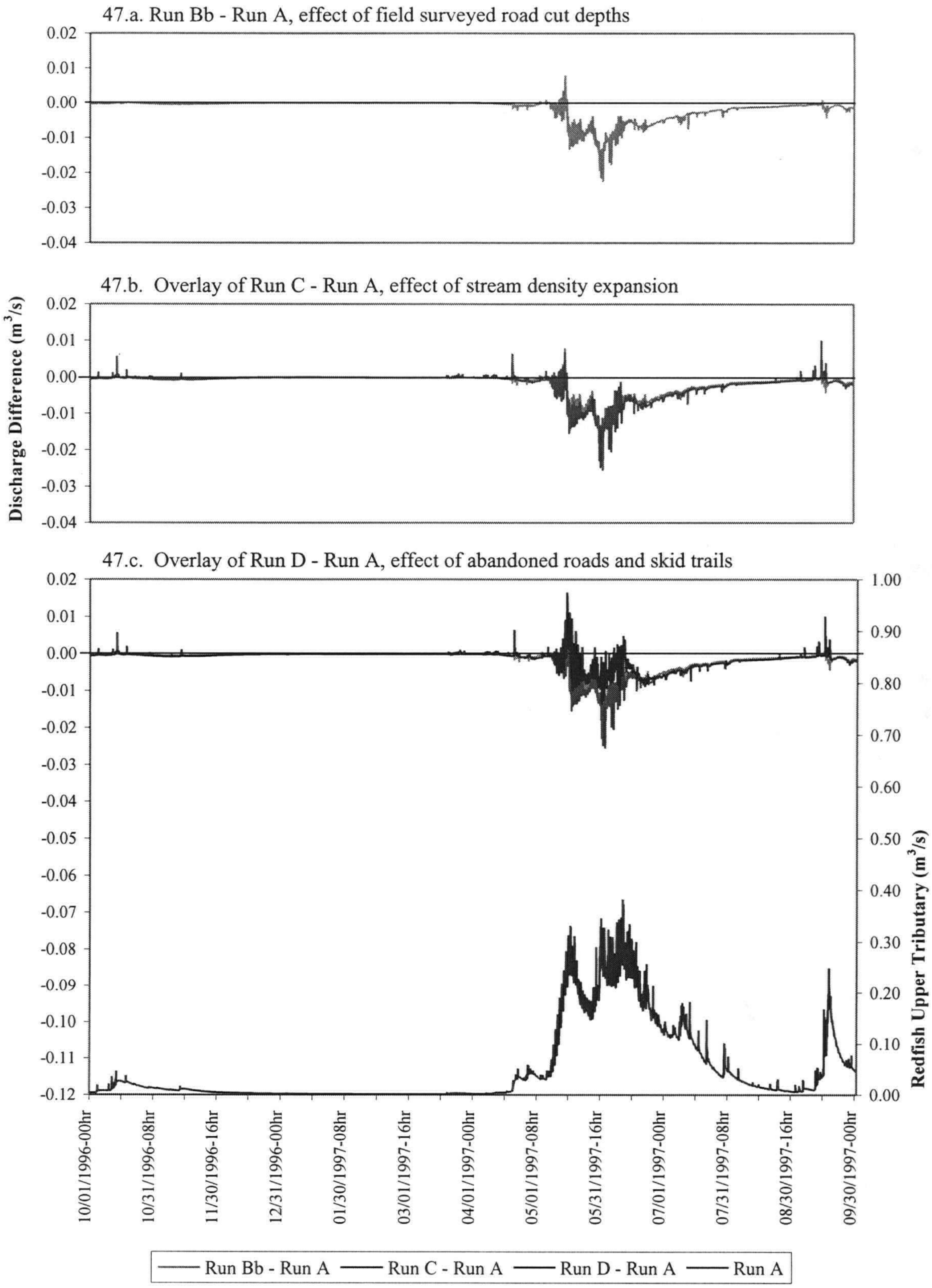

Figure 47. Discharge differences for Redfish Upper Tributary due to the varying simulation scenarios of Runs Bb, C, and D during water year 1997

Table 17. South Tributary annual yield changes resulting from stream extension, skid trails and abandoned roads

Run	1993		1994		1995		1996		1997		Average Annual Yield Change
	Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	Annual Yield (m^3)	Annual Yield Change	
A	604069	-	694441	-	724426	-	1075998	-	857044	-	-
Bb	714938	18.4%	833716	20.1%	859650	18.7%	1297046	20.5%	1019919	19.0%	19.6%
C	706447	16.9%	821930	18.4%	847947	17.1%	1280656	19.0%	1008091	17.6%	18.0%
D	699571	15.8%	818830	17.9%	842308	16.3%	1267638	17.8%	993580	15.9%	17.0%

Annual yield (AY) Change = 100 x (AYRun - AYRunA) / AYRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr)
As stated in Whitaker et al. in Hydrological Processes (2003), page 209, in regard to the calibration process, "The first 6 months of simulation, notably the outflow hydrograph, were sensitive to the model initial conditions, and were not considered in the calibration." For this reason, only the later 6 months of water year 1993 have been considered for yield.

Table 18. South Tributary annual peak flow changes resulting from stream extension, skid trails and abandoned roads

Run	1993		1994		1995		1996		1997		Average Annual Peak Change
	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	Annual Peak (m^3/s)	Annual Peak Change	
A	0.3150	-	0.2365	-	0.3170	-	0.3907	-	0.2508	-	-
Bb	0.3513	11.5%	0.2661	12.5%	0.3344	5.5%	0.4360	11.6%	0.2893	15.3%	11.3%
C	0.3490	10.8%	0.2627	11.1%	0.3340	5.4%	0.4374	12.0%	0.2883	14.9%	10.8%
D	0.3365	6.8%	0.2625	11.0%	0.3311	4.4%	0.4316	10.5%	0.2840	13.2%	9.2%

Annual Peak (AP) Change = (APRun - APRunA) / APRun A
Year 1993 values are from February 1, 1993 (00 hr) to September 30, 1993 (23 hr).
The annual peak timing differences are shown below for WY 1997:

Run A	Run Bb	Run C	Run D
6/11 - 10 hr	6/1 - 1 hr	6/1 - 1 hr	5/17 - 14 hr

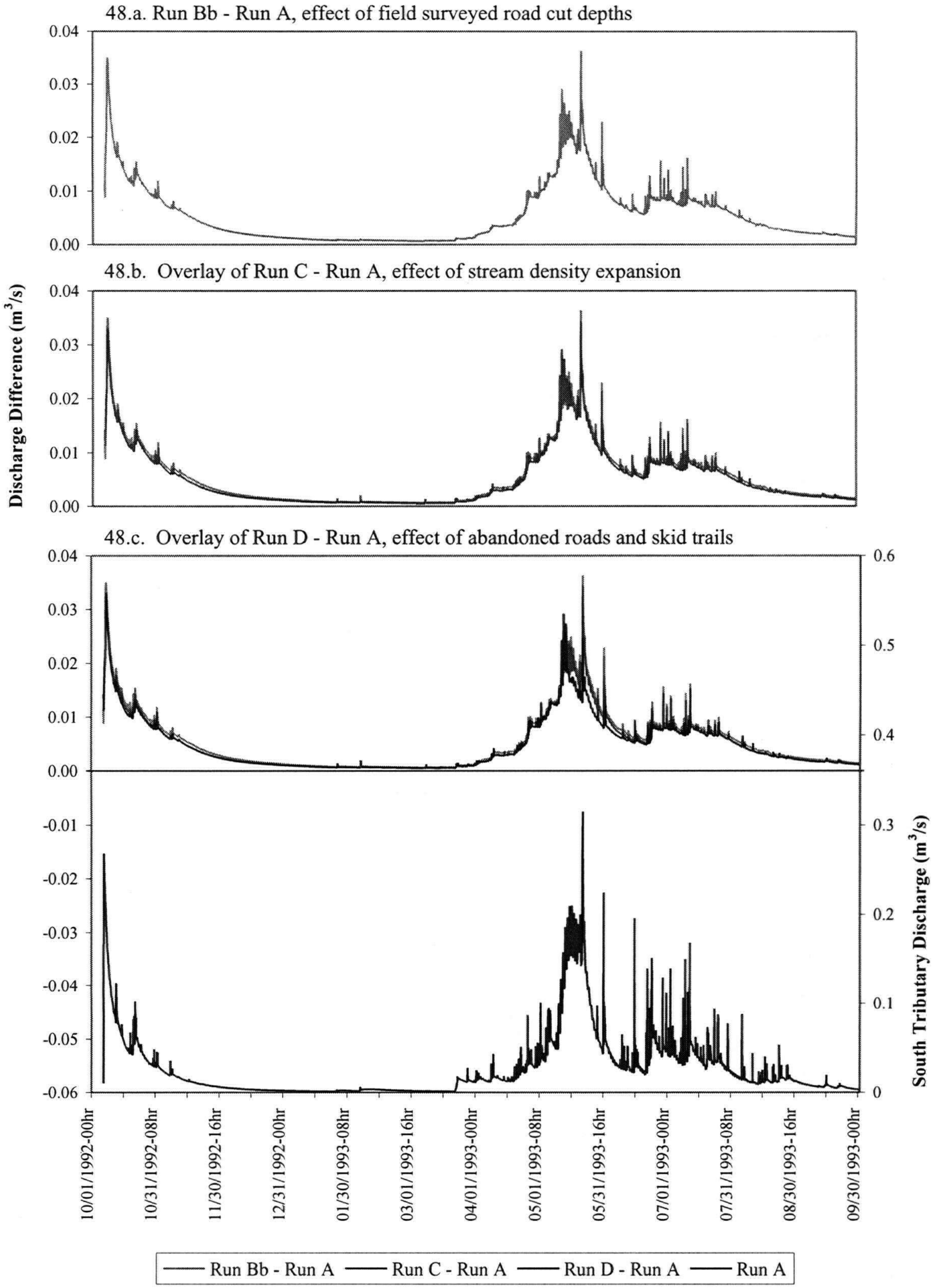

Figure 48. Discharge differences for South Tributary due to the varying simulation scenarios of Runs Bb, C, and D during 1993

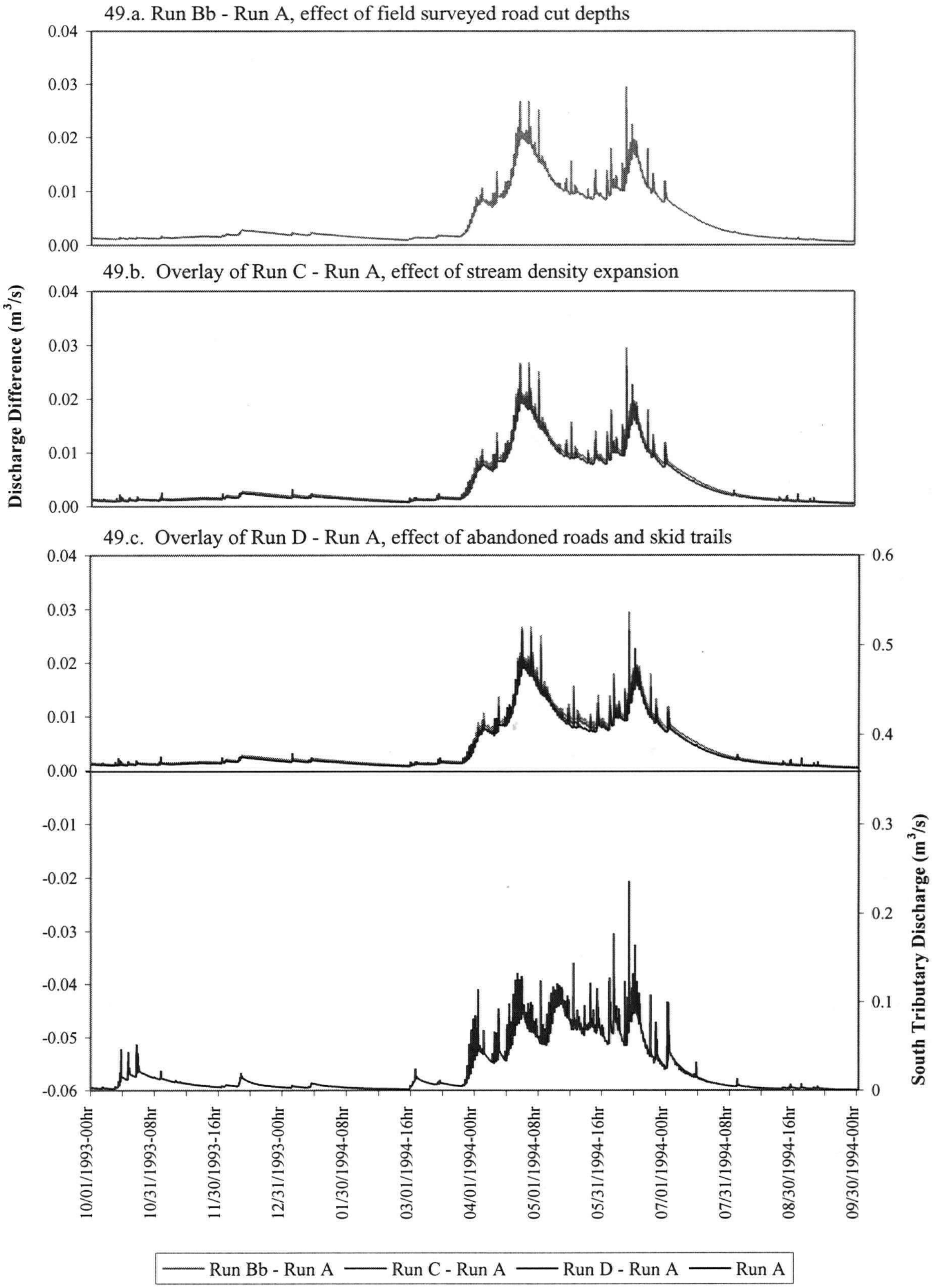

Figure 49. Discharge differences for South Tributary due to the varying simulation scenarios of Runs Bb, C, and D during 1994

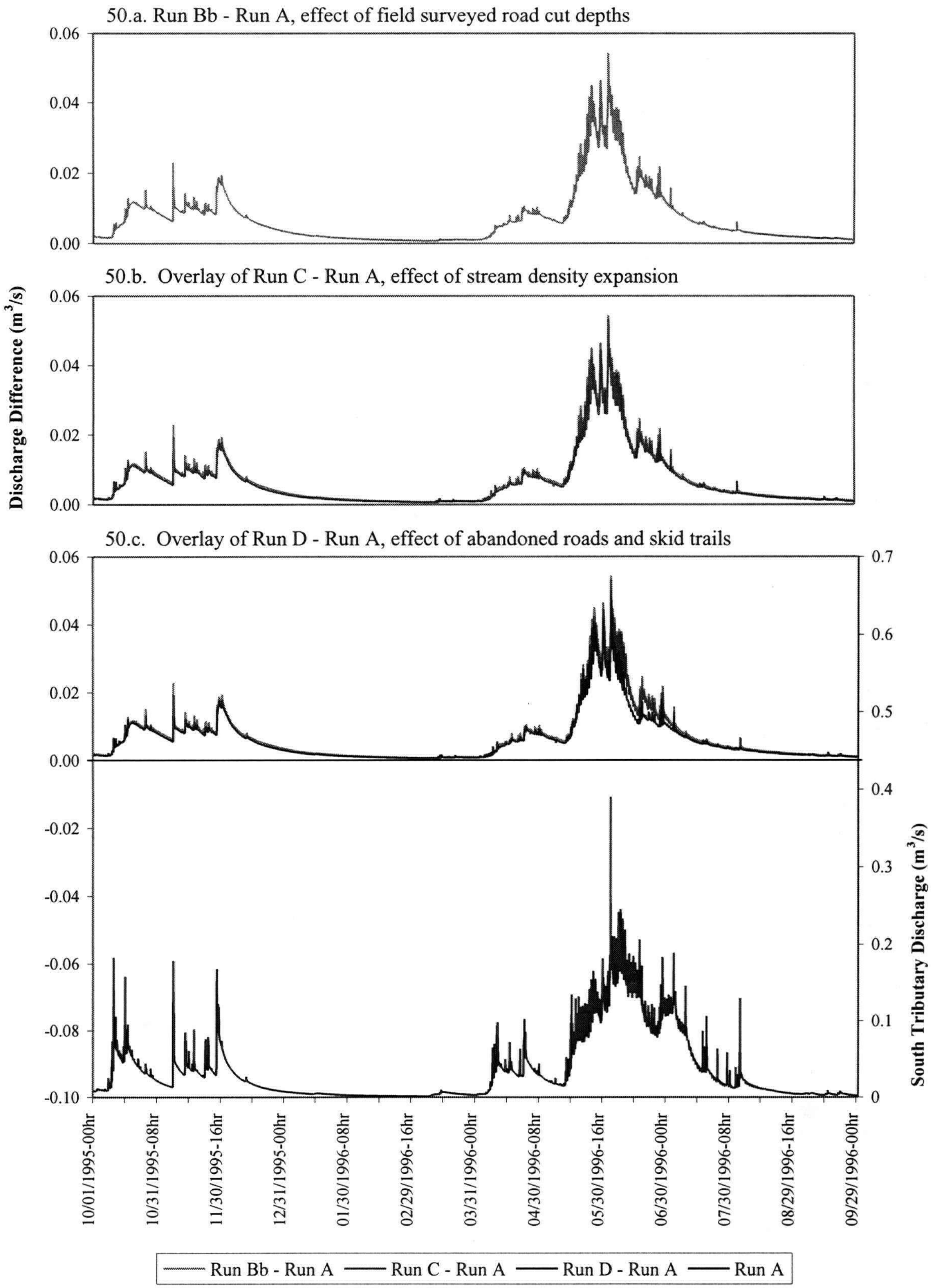

Figure 50. Discharge differences for South Tributary due to the varying simulation scenarios of Runs Bb, C, and D during 1996

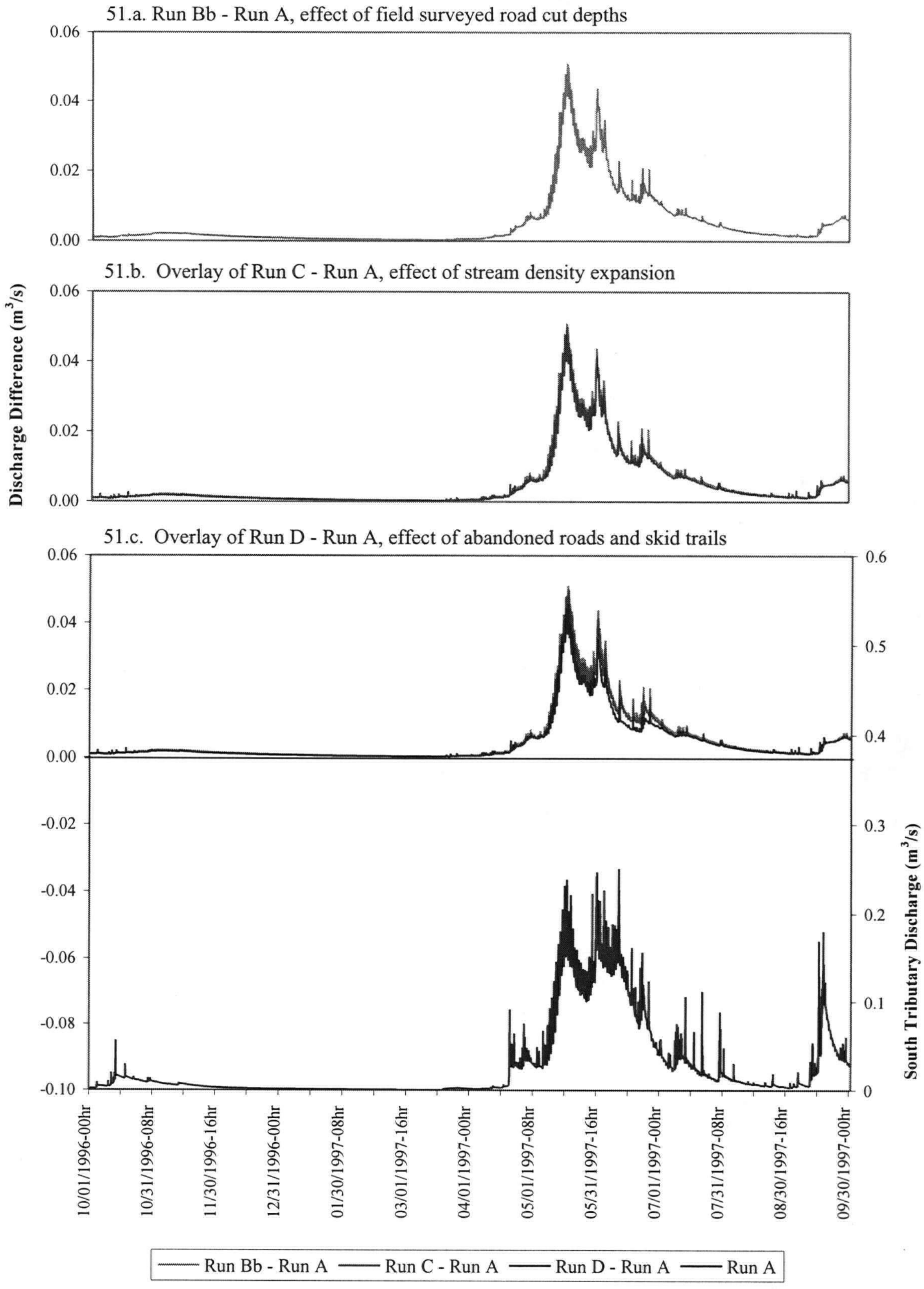

Figure 51. Discharge differences for South Tributary due to the varying simulation scenarios of Runs Bb, C, and D during 1997