HYDROGEOLOGICAL ASSESSMENT OF STREAM WATER IN FORESTED WATERSHEDS: TEMPERATURE, DISSOLVED OXYGEN, pH, AND ELECTRICAL CONDUCTIVITY

by

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ABSTRACT

This research focuses on analyzing and modeling pre- to post-harvest variations in stream water quantity (stream discharge) and quality (temperature, dissolved oxygen, pH, and electrical conductivity) in relation to year-round daily weather, for two contrasting study areas. This research is done for the Pockwock-Bowater and Hayward Brook Forest Watershed Projects in Nova Scotia and New Brunswick, with 4 and 5 intensively monitored forest streams, respectively. The Forestry Hydrology Model ForHyM was used for simulating stream temperature, dissolved oxygen, pH and electrical conductivity, and deriving new algorithms for relating: (1) stream temperature to measured air and simulated riparian soil temperature, (2) dissolved oxygen to measured or simulated stream temperature and discharge rate, (3) stream pH and electrical conductivity to simulated variations of gravitational soil moisture content. Stream-to-stream differences in these relationships could be expressed with catchment-specific coefficient adjustments. Catchment-specific adjustments were attributed to substrate differences in water-transmissivity, being low and high for the Pockwock-Bowater and Hayward Brook areas, respectively. Shallow flows would produce a greater sensitivity of stream temperature and dissolved oxygen to the air temperature, lower stream pH, and increase electrical conductivities during each water-flow events. Deeper flows would do the opposite, with electrical conductivities decreasing during each flow event. Harvest effects on stream water quality were generally small, being positive for stream discharge and temperature, variable for electrical conductivity, and difficult to discern for stream pH and dissolved

oxygen due to inconsistent data quality, and restricted harvesting per basin, varying from 0 (control basins) to 46.5 %.

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CHAPTER 1

INTRODUCTION

This thesis is about monitoring and modeling small forest stream discharge and water quality parameters (temperature, dissolved oxygen, pH, and electrical conductivity), for two geologically contrasting study areas, one in Nova Scotia on impervious igneous substrates, and one in New Brunswick, on water-transmissive shales, with calcareous inclusions. The areas involved are:

- the Pockwock-Bowater Watershed Project in central Nova Scotia [2 catchments near Sackville north of Pockwock Lake, and 2 catchments further to the west at Five-Mile Lake (http://map.ns.ec.gc.ca/forest/www/en/who_en.html)], and
- 5 catchments within the Hayward Brook Watershed Study in New Brunswick near Moncton, New Brunswick (Stanley, 2002).

Both areas were subject to detailed pre- and post-harvest stream discharge and water quality monitoring for stream temperature, dissolved oxygen, pH and electrical conductivity. Forest harvesting at the Pockwock-Bowater study area removed about 40 % of the forest cover per catchment areas, while leaving fully treed buffer strips next to each of the monitored streams. Harvesting was even more restricted to small sections along the stream-monitored watersheds of the Hayward Brook study area (about 3 to 15 % per catchment area). The main objective for each study area was to determine the effectiveness of riparian buffer zones and buffer-zone treatments to protect streams against potential adverse tree-harvesting effects along the down-slope stream sections, on either side of the streams. Each study had an un-harvested catchment as the control treatment.

The objectives of this Thesis are:

- to analyze the daily stream discharge, stream temperature, dissolved oxygen, pH and electrical conductivity data that were generated for each of the nine streams of the two study areas by automated monitoring ;
- to relate these data from one stream to the other, and also from the pre- to post-harvest conditions, using the control streams in each of the two areas as baselines;
- to develop and calibrate simple algorithms to represent the daily variation in pre- to post-harvest water quality, by way of hydrological modeling using the daily weather records (air temperature, precipitation) and basic catchment-delineation descriptors (forest cover, catchment area, soil layers, soil type) for model initialization and input;
- to develop a general understanding of the factors that control stream discharge and the four water quality variables in the context of the hydro-geological differences between the two study areas.

This thesis is constructed as follows:

- Chapter 2 reviews existing approaches to model temperature, dissolved oxygen, pH, and electrical conductivity in small forest streams.
- Chapter 3 provides an overview of the two study areas, harvesting methods, and field work done to monitor stream discharge and the four water quality parameters in each of the nine forest streams.

- Chapter 4 describes the Forestry Hydrology Model (ForHyM) and its study-area calibrations for year-round projections of daily stream discharge, soil temperature, moisture, water table and snowpack development and recession.
- Chapters 5, 6, 7, and 8 describe and quantify the monitored temperature, dissolved oxygen, pH and electrical conductivity data for the two study areas, pre- and post harvest, within the general ForHyM hydro-thermal modeling context.
- Chapter 9 summarizes the work done, and suggests further work.

CHAPTER 2

HYDROLOGICAL MODELING OF WATER QUALITY PARAMETERS: OVERVIEW

INTRODUCTION

Stream discharge, temperature and other water quality parameters such as dissolved oxygen, pH, and electrical conductivity are important indicators of stream water quality and aquatic life, and need to be understood and predictable within and beyond the range of observed field data in managing, planning and regulating specific operations within watersheds (Radwan et al., 2003; Cox, 2003). These indicators can now be routinely and automatically monitored by way of fully integrated field-calibrated and computer-controlled sensor systems involving (1) pressure transducers (for stream height measurements to determine stream discharge), (2) thermocouples (for stream temperature measurements), (3) glass electrodes (for pH measurements), (4) electrical conductivity cells (for determining stream electrical conductivity), and (5) dissolved oxygen sensors (See Chapter 3). Monitoring and modeling these indicators refers to the early detection and projection of physical, chemical and biological conditions and changes within streams and other surface waters and groundwater, including those pertaining to microbial, floral and faunal growth rates and mortality caused by pollutants, fertilizers, nutrients and sediments as they are introduced and flow through catchments and stream networks (Gooseff et al., 2005). The purpose of this Chapter is to review:

- Factors that influence stream discharge, temperature, dissolved oxygen, pH, and electrical conductivity,
- A number of water-quality models and related algorithms used to predict these water quality indicators,
- To determine how the information so reviewed can be incorporated into the ForHyM forest hydrology model.

STREAM DISCHARGE

Water quality is much affected by stream discharge, which can quickly vary from storm run-off events to stagnant or near-stagnant conditions in some cases. During times of high turbulent flow, loose sediments if any are picked up, render the water turbid and enhance the electrical conductivity of the water. Also, oxygen drawn in enriches the turbulent water with dissolved oxygen. At these times stream temperatures are more closely associated with soil surface temperatures, since run-off water would thermally equilibrate with surface soils, especially next or stream banks. During low flow periods, biological oxygen demand would lower the dissolved oxygen content, while temperature may either increase (as in isolated pools) or decrease (as in cases of groundwater seep age, and springs). With groundwater seep age, electrical conductivity may also increase or decrease, depending on the electrolyte concentrations of the seeping water on reference to water at or near the soil surface. Generally, water flowing through calcareous soil and substrate layers tends to have a high electrical conductivity, while the opposite occurs with water seeping through igneous and slow-to-weather rock formations, such as granites, and gneiss. Because of these variations, knowing stream discharge rates are very important in terms of understanding changes in stream water quality. To that end, stream discharge either needs to be monitored, or modeled. In all cases, stream requires locating a well-defined and stable flow channel cross-section, and calibrating flow across that section by careful measurements of channel profile and flow velocities at various times, ranging from very low to very high flow conditions. Subsequent automated recording of stream height is then sufficient to determine flow rates across that particular stream channel at any time. Determining the above-stream catchment then generates estimates for flow rates per catchment area, to allow for catchment-to-catchment flow rate comparisons. Some catchments tend to be very flashy, with quick run-off and very little flow in between water-yielding weather events. Other catchments are well buffered, with delayed stream discharge peaks, and very gradual changes in flow rates when there are no water-yielding weather events.

In the absence of direct stream discharge monitoring, there are many hydrological models available for modeling stream discharge based on local weather records. These models vary from simple catchment-based trickle-down models (as in EPD-RIV1 and QUAL2K) to more elaborate two-dimensional hill-slope models (as in HSPF) and complex three-dimensional flow models (as in SWAT). Other models attempt to predict flow across the landscape, involving flow and water quality algorithms to track differences in weather, topography, land-use across watershed scales or orders, from small and identifiable hydrological response units to large river basins. Some of these models are reviewed below within the context of specific water quality assessment algorithms. The model type that is sufficient for the purpose of this thesis is a simple-trickle-down model that allows for the partitioning of water flow into the lateral and downward direction, by soil and subsoil layers, based on the hydrological properties of these layers, i.e., soil bulk density (or pore space or saturation point), soil permeability, field capacity, and permanent wilting point. Of the many available trickle-down models (e.g. QUAL2K, HSPF, EPD-RIV1, WASP) , we chose the ForHyM model, because of its general applicability and ability to model water as well as heat flow through forested watersheds and soils.

STREAM TEMPERATURE

Temperature is a critical parameter in stream ecosystems. Temperature controls rates of metabolism, growth, decomposition, and solubility of gases as well as many processes and biotic interactions (Beitinger and Fitzpatrick, 1979; Beschta et al., 1987). Most aquatic species have a specific range of water temperature that they can tolerate (Caissie et al., 2004). For example, water temperatures exceeding 23°C can affect trout (Lee and Rinne, 1980; Bjornin and Reiser, 1991) and Atlantic salmon populations (Huntsman, 1942; Garside, 1973; Lund et al., 2002). Temporal and spatial variations in stream temperature are the result of multiple factors that interact with one another (Brown, 1969). Direct solar radiation on the water surface is a dominant source of heat energy for streams (Beschta et al., 1987; Sinokrot and Stefan, 1993; Webb and Zhang, 1997), but other sources and fluxes of energy also contribute to stream temperature at a given point as Figure 1 (Johnson and Jones, 2000). Energy sources that influence stream temperatures include energy conduction between stream water and stream substrata (Crittenden, 1978; Hondzo and Stefan, 1994; Evans et al., 1995), evaporation and sensible heat exchange with the atmosphere (Sinokrot and Stefan, 1993; Webb and Zhang, 1997), and advection of water from deep groundwater sources and upstream (Ingebritsen et al., 1992; Webb and Zhang, 1997).

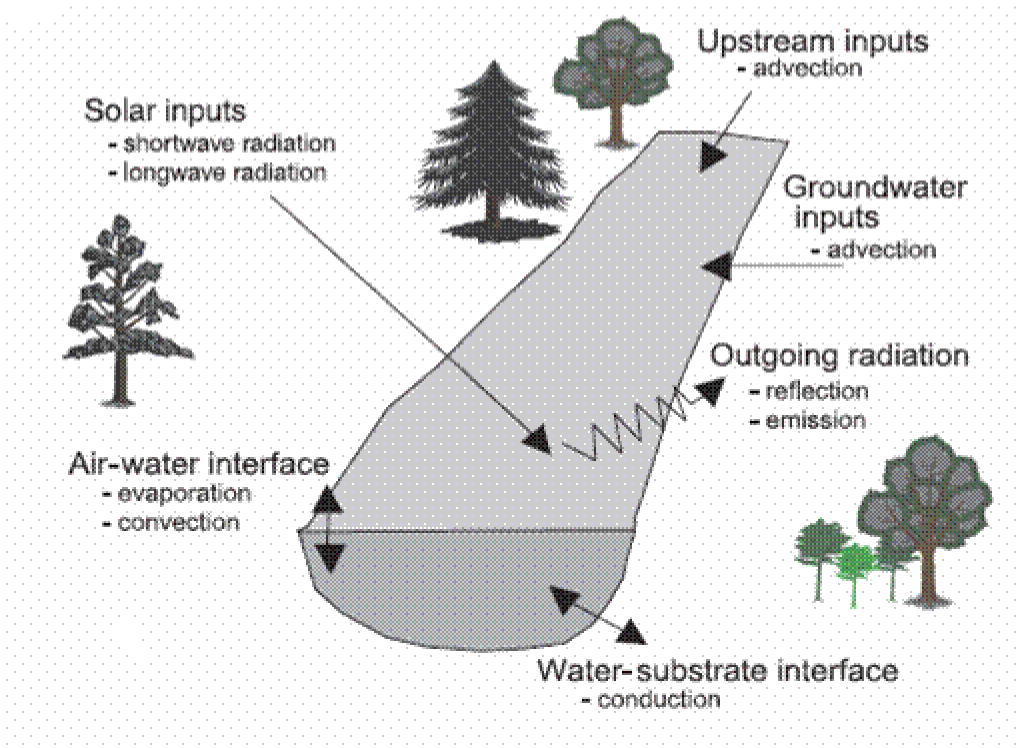

Figure 1.1 Factors influencing stream discharge and temperature (Johnson and Jones, 2000).

Anthropogenic impacts on rivers and streams often lead to a disruption of the thermal regime in streams (St-Hilaire et al., 2000). In the past, logging of large drainage basins has led to both increases in average stream water temperatures (Burton and Likens, 1973; Holtby and Scrivener, 1988) and daily variations (Brown and Krygier, 1970). Also, forest harvesting in riparian areas increases in stream temperatures, with the magnitude of these increases varing among sites and regions (Swift and Messer, 1971; Anderson, 1973; Beschta et al., 1987). Sites where only over story riparian vegetation was removed have smaller increases in stream temperature than where the understory was also removed through burning or herbicide treatments (Levno and Rothacher, 1969; Lynch et al., 1984). The increase in direct solar radiation caused by the removal of streamside vegetation was the main caused of water temperature increases (Van Groenewoud, 1977). Hence, buffer strips of various widths are now left along the stream banks to block solar radiation from entering the stream water (St-Hilaire et al., 2000).

STREAM DISSOLVED OXYGEN

Dissolved oxygen (DO) refers to the volume of oxygen that is contained in water (Radwan, et. al., 2003). A sufficient supply of dissolved oxygen (DO) is vital for all higher aquatic life. The problems associated with low concentrations of DO have been recognized for over a century. Low DO concentration in otherwise well-aerated streams can lead to fish mortality odors, and other aesthetic nuisances (Cox, 2003). Generally, oxygen enters the water by direct absorption from the atmosphere or from photosynthesizing biota of aquatic biota such as algae and macrophytes (Radwan, et. al., 2003). Biological oxygen demand (BOD) refers to the loss of dissolved oxygen in water on account of biological oxygen consumption via respiration. At night, loss of DO due to BOD continues until dawn when dissolved oxygen levels are typically lowest. During the day, DO levels tend to recover again due to photosynthesis within or immediately adjacent to the stream water. In this, temperature is the most important: BOD increases with increasing temperature (Smith, 1990; Radwan et. al., 2003) and colder water has the ability to hold higher amounts of dissolved oxygen than warmer water. In addition, flowing water is more likely to have high dissolved oxygen levels than stagnant water because of water movement at the air-water interface, and especially so in turbulent water (Radwan et. al., 2003).

STREAM PH

The acidity of water is expressed by the pH value, which is the negative logarithm of the hydrogen ion (or proton) activity in water, i.e.:

$$pH = -\log a_{H+} \qquad \text{Eq. 2.1}$$

where a_{H+} denotes hydrogen ion activity, or as an approximation, concentration divided by molarity (Gustafsson et. al., 1995). Stream pH is affected by a number of factors, particularly the concentration of some of the CO_2-system components (CO_2, $H_2CO_3^-$ andCO_3^{2-}) by the way of equilibrium reactions (Stumm and Morgan, 1981). The concentration of CO_2 is a function of the CO_2 pressure of the atmosphere, rate of photosynthesis and respiration of aquatic organisms, including those responsible for the decay of organic matter. Since pH is affected by photosynthesis and respiration, pH values also change daily and are closely related to changes in solar radiation and water temperature (Newmerak and Straskraba, 1985; Box and Jenkins, 1976). However, hydrological and biogeochemical dynamics also affect stream pH and stream chemistry in general (Hill, 1996; Cirmo and McDonnell, 1997): the near-stream zone with its organic soils can be the main source of stream acidity in the form of organic acidity (Bishop, 1994). Stream water pH is also controlled by rise and fall of the soil water table next to the stream: the higher the soil water table, the more the stream water comes in contact with the forest floor, where the pH is lowest. As the water table decreases, more water remains in contact with the adjacent mineral soil, for which the pH gradually increases with increasing soil depth (Morris and Thomas, 1987; Mcneil and Cox, 2007).

STREAM ELECTRICAL CONDUCTIVITY

Electrical conductivity refers to the ability of water to conduct electricity. Salts, as they dissolve in water, break into positively and negatively charged ions, which then conduct the current. The main positively charged ions in stream water refers to Ca^+, Mg^+, Na^+, K^+, Mg^+. The major negatively charged ions are SO_4^{2-} , CO_3^{2-}, HCO_3^- and Cl^- . Streams running through granite, silicon or other igneous rock should typically have an electrical conductivity of 10 to 50 µS / cm. Stream running through limestone formations has an electrical conductivity from 150 to 500 µS / cm. Highest electrical conductivities occur where water flows through regions with salt accumulations, either in arid regions and salts accumulate in the soil or on soil surfaces, as in salt deserts, or in salt marshes, where stream water is affected by tidal flows that extend inlands, and where upwelling groundwater is influenced by ocean water. Ocean water has a value of 53,000 µS / cm. (Jackson Bottom wetlands preserve, http://www.jacksonbottom.org/waterquality_ concepts.htm). Electrical conductivity values as high as 500 µS / cm is acceptable for household and industrial use. A value of 2000 µS / cm is acceptable for irrigation water.

Stream electrical conductivity is affected by soil mineralization. Soil and rocks release ions into the waters that flow through them. The geology of a certain area will determine the amount and type of ions released to the percolating water. Evaporation is another factor: loss of fresh water through evaporation increases the conductivity of a water body through increased ion concentrations. Since the movement of ions increases with increasing temperature, electrical conductivity values are also affected by changes in stream temperature (Morris and Thomas, 1987; Mcneil and Cox, 2007).

WATER QUALITY MODELS FOR STREAMS

In this section, a number of readily accessed water quantity and quality simulation models are reviewed in terms of specific algorithms used to determine each of the above four water quality parameters. The models so reviewed are listed in Table 2.1, together with reference to the particular water quality algorithms that are part of these models.

QUAL2K (Chapra et. al., 2005)

QUAL2K is designed to simulate river and stream water quality. It is a one dimensional, steady-state model. The model represents a river as a series of segmentations which have constant hydraulic characteristics (slope, bottom width, etc.) The model includes water temperature simulation. The heat balance takes into account heat transfers from adjacent elements, loads, withdrawals, the atmosphere, and sediments. Temperature is calculated as:

$$\frac{dT_i}{dt}=\frac{Q_{i-1}}{V_i}T_{i-1}-\frac{Q_i}{V_i}T_i-\frac{Q_{out,i}}{V_i}T_i+\frac{E'_{i-1}}{V_i}\left(T_{i-1}-T_i\right)+\frac{E'_i}{V_i}\left(T_{i+1}-T_i\right)$$

$$+\frac{W_{h,i}}{\rho_w C_{pw} V_i}\left(\frac{m^3}{10^6\ cm^3}\right)+\frac{J_{a,i}}{\rho_w C_{pw} H_i}\left(\frac{m}{100\ cm}\right)+\frac{J_{s,i}}{\rho_w C_{pw} H_i}\left(\frac{m}{100\ cm}\right)$$

(Eq.2.2)

Table 2.1 Stream water quality model summary

	Water quality parameters			
Model	Temperature	Dissolved oxygen	pH	Electrical conductivity
QUAL2K	√		√	
HSPF	√	√		
EPD-RIV1	√	√		
SWAT	√	√		
WASP	√	√		
Spring melt runoff model			√	
TMDL			√	
IPO				√
BC2C				√

where:

T_i = temperature in element i [°C],

t = time [d],

E'_i = the bulk dispersion coefficient between elements i and i + 1 [m^3/d],

$W_{h,i}$ = the net heat load from point and non-point sources into element i [cal/d],

ρ_w = the density of water [g/cm^3],

C_{pw} = the specific heat of water [cal/ (g °C)], Ja,I and

$J_{s,I}$ = the air- and sediment-water heat flux [cal/(cm^2 d)].

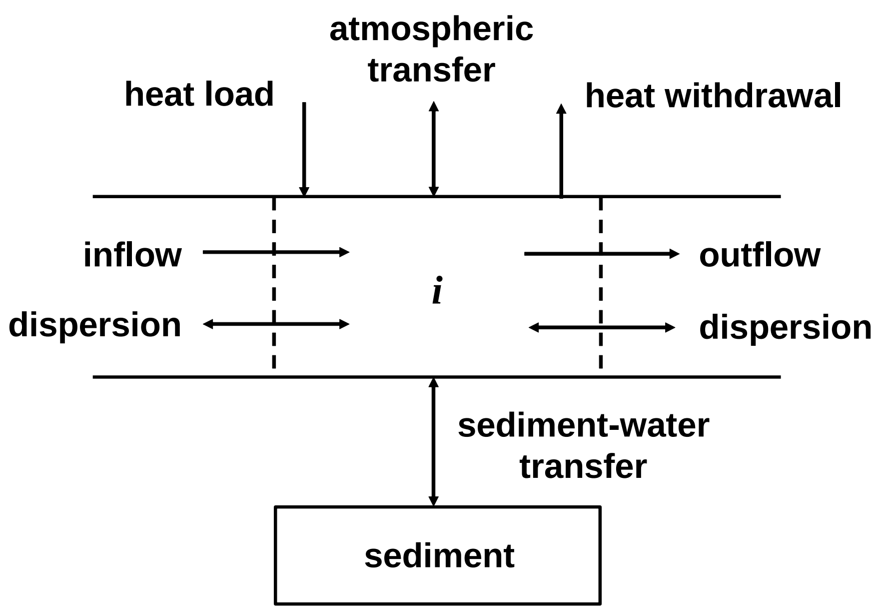

Figure 2.2 QUAL2K stream temperature simulating process.

QUAL2K models pH based on simulations of alkalinity and total inorganic carbon. The model uses the following equilibrium, mass balance and electro neutrality equations to define a freshwater dominated by inorganic carbon (Stumm and Morgan 1996),

$$K_1 = \frac{[HCO_3^-][H^+]}{[H_2CO_3^*]} \quad \text{(Eq. 2.3)}$$

$$K_2 = \frac{[CO_3^{2-}][H^+]}{[HCO_3^-]} \quad \text{(Eq. 2.4)}$$

$$K_w = [H^+][OH^-] \quad \text{(Eq. 2.5)}$$

$$c_T = [H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}] \quad \text{(Eq. 2.6)}$$

$$Alk = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] \quad \text{(Eq. 2.7)}$$

where:

K_1, K_2 and K_w are acidity constants,

Alk = alkalinity [eq L^{-1}],

H_2CO_3 = the sum of dissolved carbon dioxide and carbonic acid,

HCO_3^- = bicarbonate ion,

CO_3^{2-} = carbonate ion,

H^+ = hydronium ion,

OH^- = hydroxyl ion,

C_T= total inorganic carbon concentration [mole L^{-1}].

The brackets [ ] designate molar concentrations.

The equilibrium constants are corrected for temperature by

$$pK_w = \frac{4787.3}{T_a} + 7.1321\log_{10}(T_a) + 0.010365T_a - 22.80 \qquad \text{(Eq. 2.8)}$$

$$\log K_1 = -356.3094 - 0.06091964T_a + 21834.37/T_a + 126.8339\log T_a - 1{,}684{,}915/T_a^2$$

……………………………………………………………………………………..(Eq. 2.9)

$$\log K_2 = -107.8871 - 0.03252849T_a + 5151.79/T_a + 38.92561\log T_a - 563{,}713.9/T_a^2$$

……………

………………………………………………………………………………………(Eq. 2.11)

The five simultaneous equations can be solved numerically for the five unknowns: $[H_2CO_3]$, $[HCO_3^-]$, $[CO_3^{2-}]$, $[OH^-]$, and $\{H^+\}$.

$$\alpha_0 = \frac{[H^+]^2}{[H^+]^2 + K_1[H^+] + K_1K_2} \qquad \text{(Eq. 2.12)}$$

$$\alpha_1 = \frac{K_1[H^+]}{[H^+]^2 + K_1[H^+] + K_1K_2} \qquad \text{(Eq. 2.13)}$$

$$\alpha_2 = \frac{K_1K_2}{[H^+]^2 + K_1[H^+] + K_1K_2} \qquad \text{(Eq. 2.14)}$$

where α_0, α_1, and α_2 = the fraction of total inorganic carbon in carbon dioxide, bicarbonate, and carbonate, respectively. Those equations can then be combined to yield,

$$\text{Alk} = (\alpha_1 + 2\alpha_2)c_T + \frac{K_w}{[H^+]} - [H^+] \qquad \text{(Eq. 2.15)}$$

Thus, solving for pH reduces to determining the root, {H+}, of

$$f([H^+]) = (\alpha_1 + 2\alpha_2)c_T + \frac{K_w}{[H^+]} - [H^+] - Alk \qquad \text{(Eq. 2.16)}$$

where pH is then calculated with pH = $-\log_{10}(H^+)$

The model is not suitable for first or second order forestry stream simulation, since variations of soil texture and effect of canopy and bank shading are not considered in this model.

HSPF (EPA, April 1997)

HSPF, Hydrological Simulation Program was developed in the late 1970s by the EPA. It is a one-dimensional, continuous-simulation, process-oriented hydrologic model. It consists of several water quality models, including the Agricultural Runoff Model (ARM) and the Non-Point Source model (NPS). It is a comprehensive model of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions.

Module PWTGAS of HSPF simulates water temperature of surface, interflow, and groundwater outflows from a land segment. The temperature of each outflow is considered to be the same as the soil temperature of the layer from which the flow originates, except that water temperature can not be less than freezing. Soil temperatures must either be computed in module section PSTEMP or supplied directly as an input time series.

Module PWTGAS of HSPF assumes the dissolved oxygen concentrations of the overland flow is at saturation and is calculated as direct functions of water temperature.

PWTGAS uses the following empirical nonlinear equation to relate dissolved oxygen at saturation to water temperature (Committee on Sanitary Engineering Research, 1960):

$$SODOX = (14.652 + SOTMP*(-0.41022 + SOTMP*(0.007991 - 0.000077774*SOTMP)))*ELEVGC \qquad \text{(Eq. 2.17)}$$

where:

SODOX = concentration of dissolved oxygen in surface outflow (mg/l)

SOTMP = surface outflow temperature (degrees C)

ELEVGC = correction factor for elevation above sea level, calculated by the Run Interpreter dependent upon mean elevation of each segment.

HSPF requires adjustments for many calibration parameters, to be derived from handbook specifications or from field calibrations (Center for Exposure Assessment Modeling (CEAM), National Exposure Research Laboratory-Ecosystems Research Division, Office of Research and Development (ORD), U. S. EPA, 1997).

EPD-RIV1 (U.S. Army Corps of Engineers, 1995)

EPD-RIV1 is a one dimensional, hydrodynamic and water quality model. It is designed for analyzing existing conditions and performing waste load allocation under dynamic conditions. The model consists of a hydrodynamic component. The hydrodynamic component is applied first. The water transport information is saved to a file which is read by the quality component when performing quality simulations.

Temperature is simulated based on either a full heat balance or a simple equilibrium temperature. If the full heat balance approach is chosen, all terms in the heat balance equation are calculated, including: net short-wave radiation, net long-wave radiation, heat loss due to evaporation, and heat transferred by conduction at the water surface and bottom. The temperature calculation in the full heat balance depends on: water temperature predicted during the previous model time step; time of the year and day; site latitude, longitude, and elevation; and local meteorological data. The effect of canopy and bank shading is simulated by specifying a shading coefficient, and solar radiation is reduced by one minus that fraction. In the equilibrium temperature approach, the effects of each term in the heat balance are computed externally and incorporated into an equilibrium temperature and coefficient of heat exchange. Presently, the equilibrium and coefficient are constants.

The external sources and sinks (excluding lateral inflows) for heat are described by

$$H_N = H_s(1\text{- }Cs) + H_L - H_E - H_B \pm H_C \qquad \text{(Eq. 2.18)}$$

where:

H_N = net heat transfer, heat energy surface area-1 time-1

H_S = net short-wave radiation

H_L = net long-wave radiation

H_E = heat loss because of evaporation

H_B = heat loss because of back radiation of the water

H_C = heat transferred by conduction at the water surface and the bottom

Cs = canopy shading coefficient

In the full heat balance, each of the above terms is computed and added to determine the net heat exchange, H_N, which is converted to a rate of temperature change by

$$\Delta T = \frac{H_N * conv}{\rho H C_p} \quad \text{(Eq. 2.19)}$$

where:

ΔT = rate of temperature change, (degrees time^{-1})

ρ = density of water (mass volume^{-1})

C_p = specific heat of water (heat energy mass^{-1} degree^{-1})

H_N = hydraulic depth (Area/Top Width, length)

conv = conversion factor from English to metric units.

EPD-RIV1 simulates dissolved oxygen based on mass balance. Oxygen is produced by algae and macrophytes, transferred by re-aeration, consumed by the death of algae and macrophytes, nitrification, sediment oxygen demands, CBOD, iron, and manganese oxidation. The complete balance of DO reactions is:

(Net rate of accumulation of dissolved oxygen, g/m^3/d)

= (Reaeration) – (CBOD oxidation) – (nitrification) + (DO production from algae/macrophytes) – (DO used in algal/macrophyte respiration) – (Fe oxidation) * (Mn oxidation) – (SOD)

This is stated in equation form as:

(Rate of accumulation of DO g O_2/m^3/day)

$$= D_2 * (DOSAT – DO) – K_1 * CBOD – ONITRI * KN * NH_4N + OPDECY + (ONEQUI * ((NO_3^- - N)/ (NO3\text{-}N + NH_4^+\text{-}N))*(ALGRO + MGRATE) – OPDECY * (1 – FCBOD) * (ALGADK + MDEATH) – OFEDEC * KMNDK * M_N – KSOD \quad \text{(Eq. 2.20)}$$

where:

ALGRO = Algal growth rate, corrected for light, temperature, and nutrient availability, g biomass/m^3 day^{-1}

ALGADK = rate of algal decay, g/m^3/day

DOSAT = Local solubility of oxygen, g O_2/m^3

MDEATH = rate of macrophyte decay, g/m^3/day

OPDECY = Oxygen-to-biomass ratio for oxygen production by algae and macrophytes when ammonia is the nitrogen source

ONITRI = Oxygen-to-nitrogen ratio for ammonia oxidation

OFEDEC = Oxygen-to-iron ratio for iron oxidation

KMNDK = Oxidation rate for manganese, day^{-1}

FCBOD = Fraction of algal and macrophyte decay which goes to CBOD

M_N = Concentration of reduced manganese, g/m^3

ONEQUI = Incrementl increase in oxygen-to-algal biomass ratio for oxygen production by algae and macrophytes when nitrate is used as a nitrogen source

NH_4^+-N = Concentration of ammonium nitrogen, g-N/m^3, C

NO3-N = Concentration of nitrate nitrogen, g-N/m^3, C

MGRATE = Growth rate of macrophytes, g/m^3/day

K_1 = Temperature corrected rate coefficient for aerobic oxidation of CBOD, day^{-1}

SWAT (Arnold et al., 2000)

SWAT (Soil Water Assessment Tool) is a basin-scale hydrologic/water quality model which operates on a daily time step. In-stream water temperature is simulated by the in-stream water quality component. The simulation is based on a relationship developed by Stefan and Preud'homme (1993) through regression analysis of many river observations; the relationship is given by: $T_w = 5.0 + 0.75\ T_a$, where T_w and T_a are temperature of the water and air (C), respectively. SWAT assumes that the impact of other variables on water temperature is not significant.

To determine the dissolved oxygen concentration of surface runoff, SWAT calculations assume that rainfall is saturated with oxygen, and oxygen uptake by the oxygen demanding substances in runoff is subtracted from the saturation oxygen concentration (Neitsch, et. al., 2002). The equation is as below:

$$Ox_{surf} = Ox_{sat} - k_1 \times cbod_{surq} \times \frac{t_{ov}}{24} \qquad \text{(Eq. 2.21)}$$

where:

Ox_{surf} = the dissolved oxygen concentration in surface runoff, mg O2/L

Ox_{sat} = the saturation oxygen concentration, mg O2/L

K_1 = CBOD deoxygenation rate, day -1

$cbod_{surq}$ = the CBOD concentration in surface runoff, mg CBOD/L

t_{ov} = the time of concentration for overland flow, hr

WASP6 (U. S. EPA, 2006)

Dissolved oxygen is simulated by the DUTRO program of WASP6. WASP6 considers the variables participate in the DO balance includes: phytoplankton carbon, ammonia, nitrate, carbonaceous biochemical oxygen demand, and dissolved oxygen. The reduction of dissolved oxygen is a consequence of the aerobic respiratory processes in the water column and anaerobic processes in the underlying sediments.

$$\frac{\partial C_6}{\partial t} = K_2(C_s - C_6) - K_d\left(\frac{C_6}{K_{BOD} + C_6}\right)C_s - \frac{64}{14}K_{12}\left(\frac{C_6}{K_{NIT} + C_6}\right)C_1 - \frac{SOD}{D}$$
$$+ G_{P1}\left(\frac{32}{12} + \frac{48}{14} \times \frac{14}{12}\left(1 - P_{NH_3}\right)\right)C_4 - \frac{32}{12}K_{1R}C_4$$

(Eq. 2.22)

where:

K_2 = Reaeration rate @ 20 C, Temp. Coeff

K_d = Deoxygenation rate @ 20 C, Temp. coeff.

K_{12} = Nitrification rate @ 20 C, temp. coeff

K_{BOD} = Half saturation constant for oxygen limitation

K_{NIT} = Half saturation constant for oxygen limitation

K_{NO3} = Half saturation constant for oxygen limitation

K_{1R} = Phytoplankton resp-iration rate, 20 C, temperature coeff

SOD = Sediment oxygen demand, temp, coeff

G_{P1} = Phytoplankton growth rate

C_s = DO saturation

C_1 = the internally computed NH3, mg/L

C_4 = the phytoplankton biomass in carbon units, mg/L

C_6 = Dissolved oxygen concentration mg/L

Spring melt runoff model (Laudon et. al., 2000)

Laudon, Westling, and Bishop developed a simple pH model to study the effect of spring melt runoff on stream water. pH is calculated based on acid-base modeling method. ANC, a measure of natural water's capacity to consume H^+, is calculated as the difference between the sum of BC and strong mineral acids:

$$ANC = [BC] - 2[SO_4^{2-}] - [Cl^-] - [NO_3^-] \quad \text{(Eq. 2.23)}$$

ANC can also be calculated as:

$$ANC = [HCO_3^-] + 2[CO_3^{2-}] + [RCOO^-] + [OH^-] - [H^+] - n[Al^{n+}] \quad \text{(Eq. 2.24)}$$

By combining two equations: the H^+ concentration of surface water can be calculated as:

$$[H^+] = [HCO_3^-] + 2[CO_3^{2-}] + [RCOO^-] + [OH^-] - [BC] + 2[SO_4^{2-}] + [Cl^-] + [NO_3^-]$$

(Eq. 2.24)

pH is then calculated as $pH = -\log_{10}[H^+]$.

TMDL (Stiles, 2002)

The TMDL model was developed to analysis mine drainage impact on stream water quality. The following relationship was developed through the empirical examination of pH and net acidity data from samples collected in several small watersheds. (Stiles,et al., 2000).

$$pH = -\log_{10}[H^+] = a\max(1, A^2)^{b\,\mathrm{sign}(A)} \quad \text{(Eq. 2.25)}$$

where:

A = net acidity of the stream in mg/L $CaCO_3$ equivalents and

a and b = coefficients, normally calibrated from locally obtained water quality data. If local data are unavailable, a and b are usually close to 6.5 and -0.02 respectively.

IPO (McNeil and Cox, 2007)

McNeil and Cox (2007) analyzed the climatic signal in stream salinity by modeling stream EC using the Interdecadal Pacific Oscillation (IPO). IPO is a general and geographically broad scale climatic indicator representing the influence of climate on hydrology and subsequently stream salinity. The EC series were divided into two overlapping phases: high groundwater level (WL > -7.4) and low groundwater level (WL<=-7.4). In particular,

For WL ≤ -7.4: $EC = -5.86*\Delta IPO + 69.79*WL+829;$ (Eq. 2.26)

For WL > -7.4: $EC = -106.29*\Delta IPO -106.3*WL-434.$ (Eq. 2.27)

BC2C (Dijk, et al., 2004)

The Biophysical Capacity to Change (BC2C) model was developed to compare the impacts of land use change on stream flow and salinity for different parts of the Murray-Darling Basin. The conductivity, which is a representative of stream salinity, is calculated as below (Albert, et al., 2004):

$$\frac{dC}{C} = \frac{Y+dY}{Y}\frac{Q}{Q+dQ} - 1 = \left(1+\frac{dY}{0.308*10^6}\right) / \left(1+\frac{dQ}{4.64*10^6}\right) - 1$$

(Eq. 2.28)

where:

$\frac{dC}{C}$ = The relative change of salinity, (dC/C), Y= total equilibrium salt yield which is calculated by groundwater salinity (Y_G) and precipitation salinity (Y_P).

SYNTHESIS

Comprehensive water quality models for practical small stream water quality simulations require the following design elements:

- specially designed hydrothermal algorithms for small headwater streams and catchment simulations, sensitive to variations in vegetative cover (bare-ground to full canopy), soil texture, watershed slope and aspect
- Daily weather input to allow simulation for daily variations in stream discharge and water quality
- a modular modeling frame, allowing for additions without affecting rest of model structure and its available components
- operational utility and efficiency

Based on this and the above, one may conclude the following about the utility of each model for determining each of the four water quality indicators in small forest streams:

- QUAL2K: this model is not suitable for first- or second-order forest stream and watershed simulations, since variations in soil texture and forest canopy affect the hydrothermal conditions of the stream and its immediate surroundings
- HSPF: The disadvantage of this model is that it has large data and model initialization requirements; its algorithms to relate stream temperature to surrounding soil temperature, and DO concentration to stream temperature instead of detailed and stream-specific energy balance calculations have practical merit, especially if soil

temperatures can be modeled on a small watershed basis or riparian zone basis rather than a stream or stream-segment basis

- EPD-RIV1: EPD-RIV1 is designed for analyzing river or streams waste load allocations ability, relationships between soil, soil interflow, and water quality are not considered.
- SWAT: this model is a continuous time and a long term water yield and water quality model for large catchment areas subject to intense land-use management and soil erosion. The model is not designed to simulate detailed, single-event flood routing but routes flows from the main hydrological response units within large catchment areas. The model requires many carefully constructed data files to track events in each response unit over time
- Spring melt runoff model: this is a simple model specifically developed to study the effect of spring melt runoff on stream pH. Other water quality parameters are not considered.
- TMDL MODEL: the TMDL model analyzes mine drainage impacts on stream water based on predicting the effect of $CaCO_3$ input on water pH. Other water quality parameters are not considered.
- McNeil and Cox MODEL: this model uses the Interdecadal Pacific Oscillation indicator (IPO) to model stream EC. The model focuses on analyzing climatic signal in stream salinity, the relationship between soil water and water quality is not considered.

- BC2C MODEL: the model was developed to compare the impacts of land use change on stream salinity. The model does not directly simulate stream EC, but it is still a contribution for stream EC modeling.

The Forest Hydrology Model (see Chapter 4) is designed meet most of the above design requirements for developing a comprehensive yet operationally practical stream water quality model. As such, it already uses a modular approach in simulating hydrothermal conditions and flow in and through forest soils and small forested catchments from weather records pertaining to daily rain, snow, and air temperatures. The model simulates snowpack accumulation, snowmelt, through-fall, surface runoff, interflow, and base flow. It also simulates daily water-table fluctuations and soil temperatures under varying catchment and cover type conditions, from bare-ground to full softwood and hardwood canopies, and from saturated to non-saturated soil conditions, including soils within the riparian zone. It uses aspect, slope, and soil texture and organic matter levels in its automated derivation of hydrothermal properties such as thermal conductivity, pore space or soil bulk density, field saturation, permanent wilting point and substrate permeability, by soil layer. The model generates stream discharge and soil temperature simulations that could be used to determine stream temperature and DO, as already seen with HSPF. The model also generates water table fluctuations that could be useful in tracking variations in stream pH and electrical conductivity, with high water tables generating low pH, and vice versa.

While is it tempting to estimate stream pH and conductivity from first principles based on aquatic equilibrium expectations regarding soil weathering, biological activities, release of organic acids from within and adjacent to the flowing water, and external acid and base cation inputs, it is still difficult to do that in detail. This is especially so if the calculations were to extend to a wide range of field conditions and catchments, with each catchment having its own unique configurations of forest cover (type and density), soil and bedrock substrates with their inherent differences in mineral composition, texture, permabilities, topography, and land use.

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CHAPTER 3

STUDY AREAS AND STREAM MEASUREMENTS

The objectives of this chapter are to provide:

- an overview of the biophysical features of two study areas, including the harvest operations;
- a description of instruments (Hydrolab monitoring probes) and an overview of the in-stream discharge and water quality monitoring activities;
- an overview of water quality data and quality control;
- a brief summary concerning data treatments by way of regression analyses.

STUDY AREAS

Two study areas are selected in this research, namely the Pockwock-Bowater area in Nova Scotia and the Hayward Brook area in New Brunswick. For each area, four and five watersheds were monitored for stream discharge and water quality (temperature, dissolved oxygen, pH and electrical conductivity), respectively. These watershed were monitored from 1998-2003 (Pock-Bowater area) and 1993 to 1998 (Hayward Brook area) for pre- and post-harvest conditions. Harvesting involved stem-only for parts of the watershed above the stream-monitoring locations, except for ones used as non-harvested controls. Stream monitoring dealt with automated registration of stream discharge and in-stream water quality parameters (temperature, dissolved oxygen, pH and electrical conductivity Stream water was also retrieved through weekly to biweekly grab sampling for checking the automated monitoring results.

For both areas, catchments were selected with relatively undisturbed, mature forest areas, and would be large enough to support first to second order streams to allow for continuous monitoring of stream discharge and water quality. Also, the catchments that were selected for each area would be in fairly close proximity of each other so that there would be no substantial differences between them in terms of forest cover type and soil, climate and hydrothermal conditions. For the Pockwock-Bowater and Hayward Brook study areas, the annual rate of precipitation amounts to 1410 and 1028 mm (about 400 mm occurring from May to September), and average monthly temperatures range from July to January between 18.5 and -6.0, and 19.2 and -9.2, respectively.

The Pockwock-Bowater area involves two locations, with west of Sackville north of the Pockwock Lake, and one further north-west on the western side of Five-Mile Lake in Central Nova Scotia (Hants County). The Pockwock area is part of the Provincial Crown Land, and is managed in cooperation with NSDNR, Elmsdale Lumber, and the Halifax Regional Water Commission. Both areas have the same bedrock geology (impervious middle-devonian granodiorite of the Goldenville formation) and are covered by the same soil type, namely the Gibraltar soil which varies in depth from ridge top (shallow to absent) to deeper soils and regolith formations in depressions and along flow channels. The soil is generally well-drained, and consists of a sandy loam mostly derived from the underlying bedrock. The general area is interspersed with many poorly drained and bogfilled flow channels and depressions. The forest cover in this area varies from spruce-fir vegetation to mixed forests for the most part.

The Hayward Brook area is covered by an 80-year-old Acadian mixed wood forest, with intolerant hardwoods dominating to the south, white pine to the east, and fir-spruce and pine to the north. The area stretches over three kinds of soil, namely Salisbury, Parry, and Sunbury, all mainly derived from the underlying sedimentary bedrock. This bedrock belongs to late carboniferous Pictou group, consisting of terrestrially derived and fairly water-transmissive sediments of varying composition (reddish to greyish sandstones, mudstones, conglomerates, with calcareous inclusions). The Salisbury and Parry soils developed on well to imperfectly drained lodgement tills. The Sunbury soil is well drained and is derived from grey lithic and feldspathic sandstone till with high coarse fragment content (Stanley, 2002).

The above differences in bedrock geology should affect stream discharge and water quality in a contrasting manner:

- deeper water percolation within the Hayward Brook area than in the Pockwock-Bowater area (Stapinsky et al., 2002)
- deeper water percolation implies longer contact time between the percolating water in the substrate minerals
- longer water-mineral contact time should increase the pH, electrical conductivity and mineral content of the percolating water, while removing easily absorbed substances such as dissolved organic matter; in contrast, shorter mineral-water contact time with

water remaining near the surface produces a stream water low in mineral content but dark and acidic (low pH values).

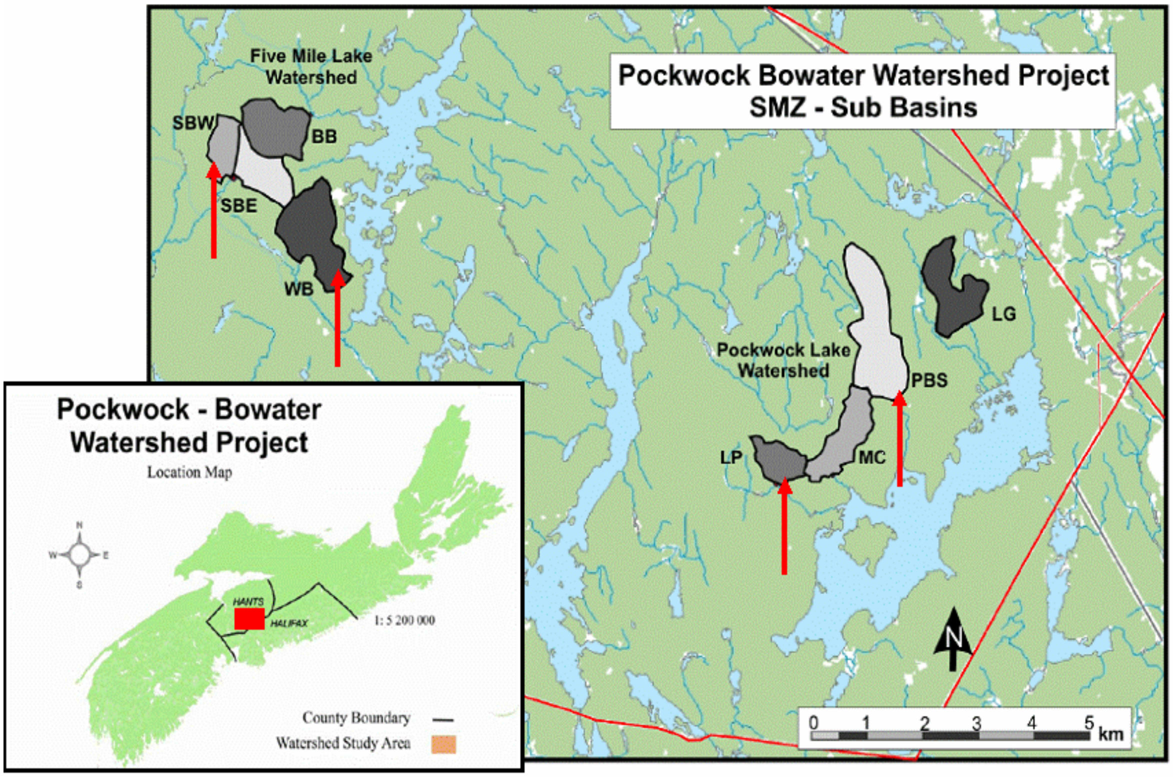

Figure 3.1 Pockwock-Bowater study area, with watersheds borders for 8 streams, of which 4 (Walsh Brook, WB; Sandy Brook West, SBW; Peggy Brook, PB (control watershed) and Long Ponds, LP) were monitored continuously for stream discharge and water quality.

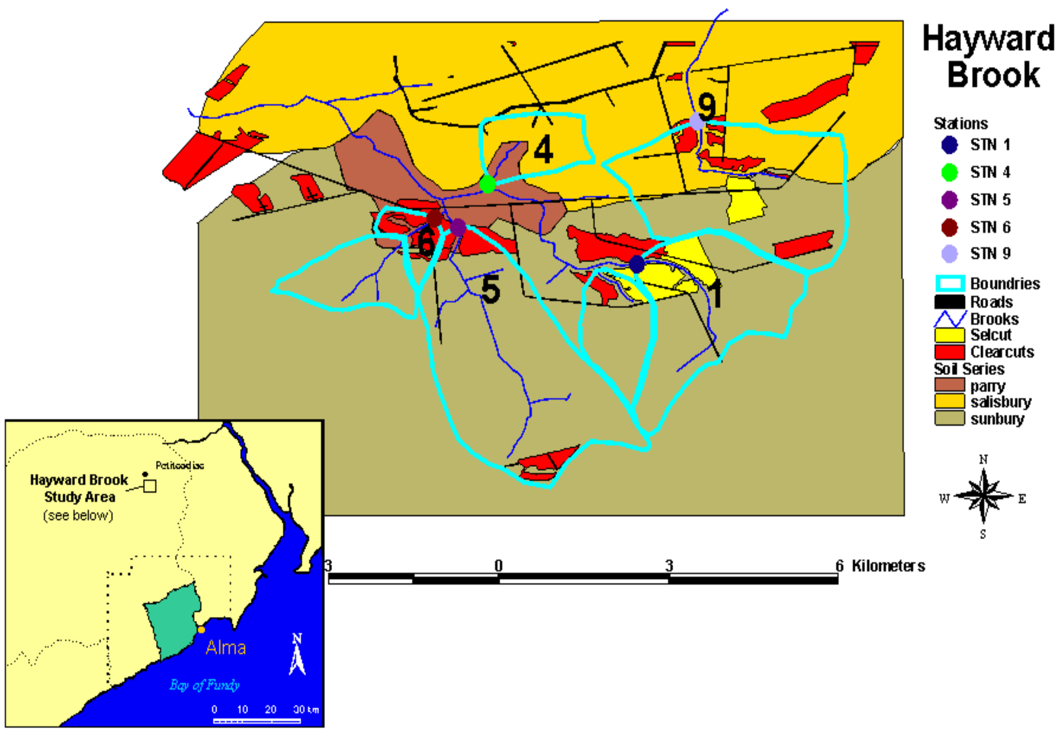

Figure 3.2 Hayward Brook study area, with borders for monitored stream watersheds WS1, WS4 (control watershed), WS5, WS6 and WS9, in relation to soil type and pre-harvest cutting pattern.

HARVEST OPERATIONS

On each study area, one of the catchments acts as a control and no harvesting occurs in that area. The other catchements were harvested (20 to 40 within the Pockwock-Bowater area; 5-20 percent within the Hayward Brook area, Figures 3.1, 3.2 and Table 3.1), leaving a riparian buffer zone along each watercourse. Show Google Earth images: plus wet-areas map.

Table 3.1 Forest harvesting in Pockwock-Bowater and Hayward Brook sub-catchments; compiled from Pockwock-Bowater aerial photographs and results presented by Bourque et al.(Bourque et al., 2001)

	Watershed	Treatment Date	Land Area Harvested (%)	Land Area Harvested (ha)
Pockwock-Bowater	PB	No harvesting	No harvesting	No harvesting
	LP	Spring-summer, 2001	41.6	26.6
	SBW	Spring-summer, 2001	46.5	27.8
	WB	Spring-summer, 2001	39.2	68.4
Hayward Brook	HS1	Spring-summer, 1995	16.8	150.3
	HS4	No harvesting	No harvesting	No harvesting
	HS5	Spring-summer, 1995	3.2	39.2
	HS6	Spring-summer, 1995	15.1	42.2
	HS9	Spring-summer, 1995	11.4	62.4

STREAM MEASUREMENTS (Pomeroy, 2003).

The Hydrolab sensor probes were used to monitor stream water level and in-stream temperature (C), dissolved oxygen, pH, and conductivity (uS/cm) every quarter hour, using a thermistor, a dissolved oxygen probe, a combination glass electrode, and an electrical conductivity cell.

The specifications for the HydroLab Datasonde 4A sensors (http://www.hachenvironmental.com/products/DataSonde4a.asp) are as follows:

Table 3.2 HydroLab sensor specification

	Range	Accuracy	Resolution	Unit
Temperature	-5-20	±0.1	0.01	º C
Specific conductivity	0-100	±1%	4	mS/cm
DO	0-50	±0.2	0.01	mg/L
pH	0-14	±0.2	0.01	mm
Pressure sensor	0-20	± 0.003	0.001	m

The Hydrolab probes were each fully immersed in a pool at sufficient depth to remain under water in each of the nine streams under all times. The probes and associated data recorders were powered by way of solar panels. Each probe location was visited regularly once every 6 to 12 weeks, to check calibration and integrity of each sensor, and to take corrective actions, as needed. Timing between visits was longer during winter when probe locations were covered by a layer of ice. Data were sent from each probe to its automated data recorder. The cumulated output from these recorders was retrieved manually during each site visit, in a format that identified date, sensor location, sensor type, and sensor reading.

The Hydrolab pressure sensor output was calibrated for each stream by installing a metric stream gauge inside the pool selected for stream monitoring, reading that gauge during each site visit, and determining gauge height and water flow (in m^3 / sec, determined from detailed channel cross-section x flow velocity measurements during high, intermediate and low flow conditions.

Figure 3.3 HydroLab Sonde 4A, with water quality sensors.

Grab samples

The streams at each of the study areas were also visited weekly or after major rain events to obtain stream water grab samples. A 1L bottle for pH and conductivity was taken every visit by Environment Canada personnel (Stanley, 2002).

Data quality control

Each of these water quality sensors required calibrations and maintenance. For automated recordings, temperature and electrical conductivity determinations were generally the most robust and subject to the least drifts and other electronic noises. In contrast, the membrane based pH and dissolved oxygen sensors were subject to electrical and electro-chemical noise and drifts. In part, this was corrected for by regular sensor replacements and calibrations, which also required the replacement of reference electrolytes. The dissolved oxygen probe also required a regular replacement of the dissolved oxygen filter membrane.

The resulting data were inspected in terms of erratic readings, sudden shifts, sensor instabilities, and unusual trends. Faulty data associated with one particular stream were brought into alignment with the data from the other streams when these were found to be clean and reliable. For the stream height, temperature and electrical conductivity determinations, only a few data were faulty, and these were easily replaced through substitution by way of regression analysis using the data from the other streams as predictor variables. In contrast, data fragmentation was extensive for the dissolved oxygen and pH data records. For the pH records, the weekly grab sample records were used as reference for re-aligning faulty pH data fragments. Persistent drifts within these fragments were eliminated as much as possible by correcting for the slope from the beginning to the end of the drift-affected fragments. For the dissolved oxygen records, data fragments were re-aligned as much as possible by comparing the DO records from one stream with the DO records from the other streams for the same time periods.

DATA TREATMENTS AND ANALYSIS PROCEDURES

The data were inspected for completeness, and whether the data conformed to general expectations regarding consistent trends across and within each measurement years, and from stream to stream. Consistency of trends (or the lack thereof) was established by way or regression analysis. These analyses served several purposes.

1. to compare each of the stream variable from one stream to all the other streams and vice versa, by study area, and to establish the regression equations among these streams
2. to determine regular and erratic trends, to locate outliers, and to eliminate these or to correct for these, by using the appropriate regression equation for substituting erratic or missing data, by pre- and post-harvest periods, and by study area
3. to derive pre-harvest control-to-harvested regression equations, and to use these equations as unharvested benchmark for the post-harvest data, by study area, and for each stream.

Regression equations were also used to compare actual data with model-calculated values, and to establish the goodness of fit for each stream-model comparison.

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CHAPTER 4

STREAM DISCHARGE

The specific objectives of this chapter are

- to introduce the Forest Hydrology Model ForHyM model with special focus on stream discharge, soil temperature, and groundwater table fluctuations;
- to apply this model to simulate stream discharge, soil temperature and groundwater table fluctuations for the two study areas, by way of stream-specific model calibrations

ForHyM

The ForHyM model was first developed to model thermal and hydrological flows at a monthly scale (Arp and Yin 1992; Yin and Arp 1993). This was followed by a daily version (Bhatti et al., 2000). Since then, the model has gone through further revisions designed to make the model more applicable for a variety of site, soil, and climate conditions (Balland 2002). The newest version of the model can be used to estimate

- Daily solar radiation,
- The daily net level of energy exchange between the ground (snow, soil) and the atmosphere,
- Daily fluctuations in soil moisture and temperature at various depths in the soil,
- Snow pack density, depth and snowmelt amounts,
- Formation and extent (depth) of soil frost,

- Runoff, interflow, stream discharge and daily water table fluctuations.

ForHyM requires two types of inputs (Figure 4.1): daily weather data and soil and catchment characteristics. The required weather inputs refer to mean daily air temperature, and daily rainfall and snowfall. The required catchment inputs refer to:

- latitude (degrees) and altitude (m),
- slope (degrees),
- aspect (degrees),
- catchment area (ha),
- % of catchment area cut,
- forest floor and mineral soil depths of the A, B and C layers (in cm),
- For each layer of the soil, the following parameters need to be specified: texture (sand and clay content), and organic matter and coarse fragment content.

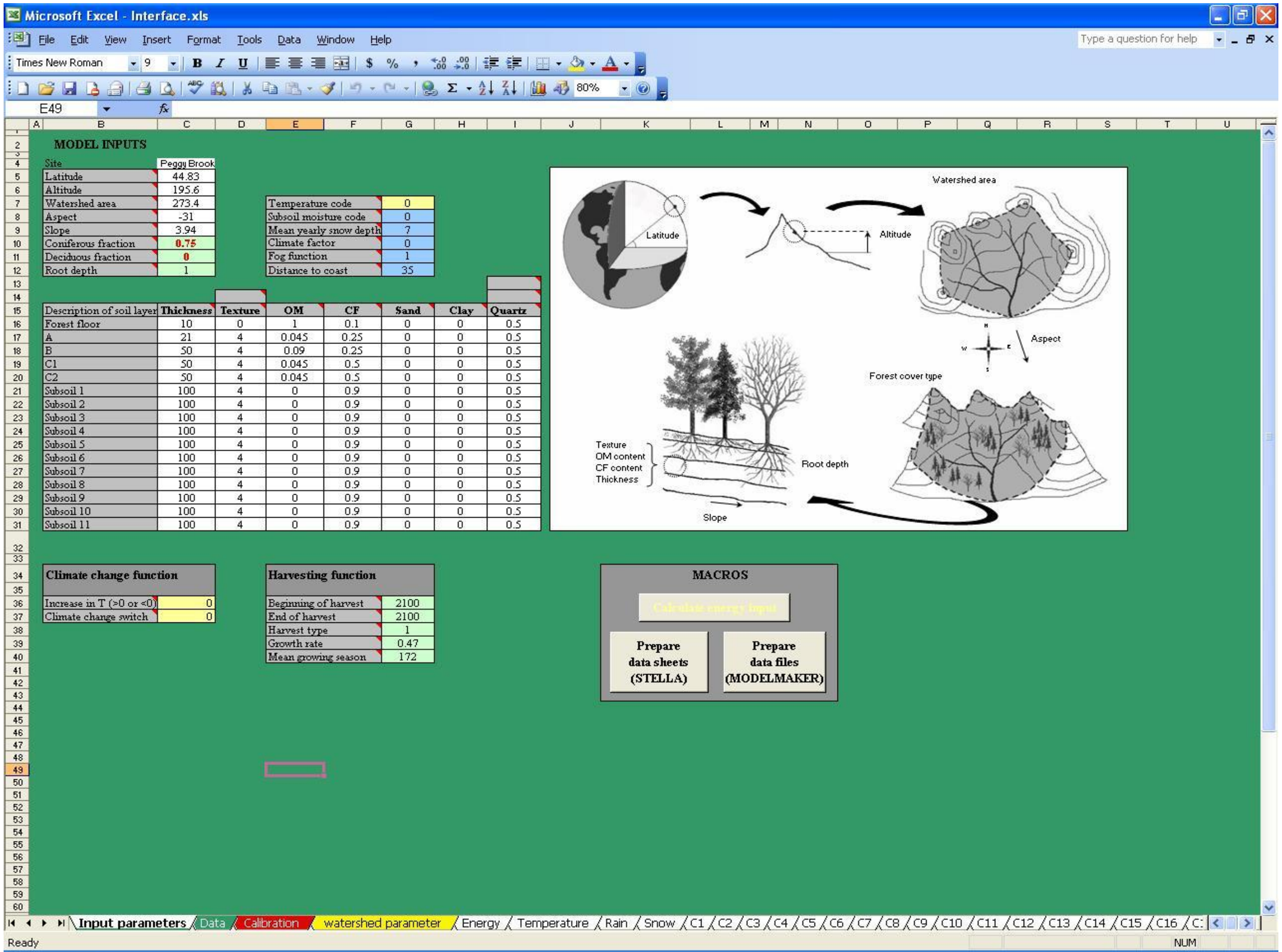

Figure 4.1 ForHyM user interface.

The Forest Hydrology Model has several modules. The hydrology module (Figure 4.2) deals with water flow and water retention calculations. When it rains or snows, part of water is simulated to be intercepted by trees depending on canopy depending on the extent of the canopy leaf area (or leaf area index). When there is snow on the ground, some of the rain is retained by the snowpack. Liquid water that reaches the soil surface either infiltrates the soil or becomes surface runoff. When the soil water content in the forest floor and any other soil layer exceed the field capacity of that layer, water starts to flow as interflow, according to slope and estimated soil permeability conditions. Water that trickles through the forest floor and A and B layers becomes the base flow. Stream discharge is calculated as the sum of run off, interflow, and base flow. All water flows are calculated in terms of mm/year, which are then converted into mm/day. The catchment area specification is used to convert the estimated stream discharge from mm/year (or mm/day) into m3/sec (Figure 4.3). Water that is calculated to exceed the field capacity of the forest floor and thee A, B and C layers at any particular time step in the computations is collectively referred to as the gravitational water, and this water is used as an index of the water table fluctuations. Water that is frozen is not allowed to flow and is not considered to be part of the gravitational water (Figure 4.4).

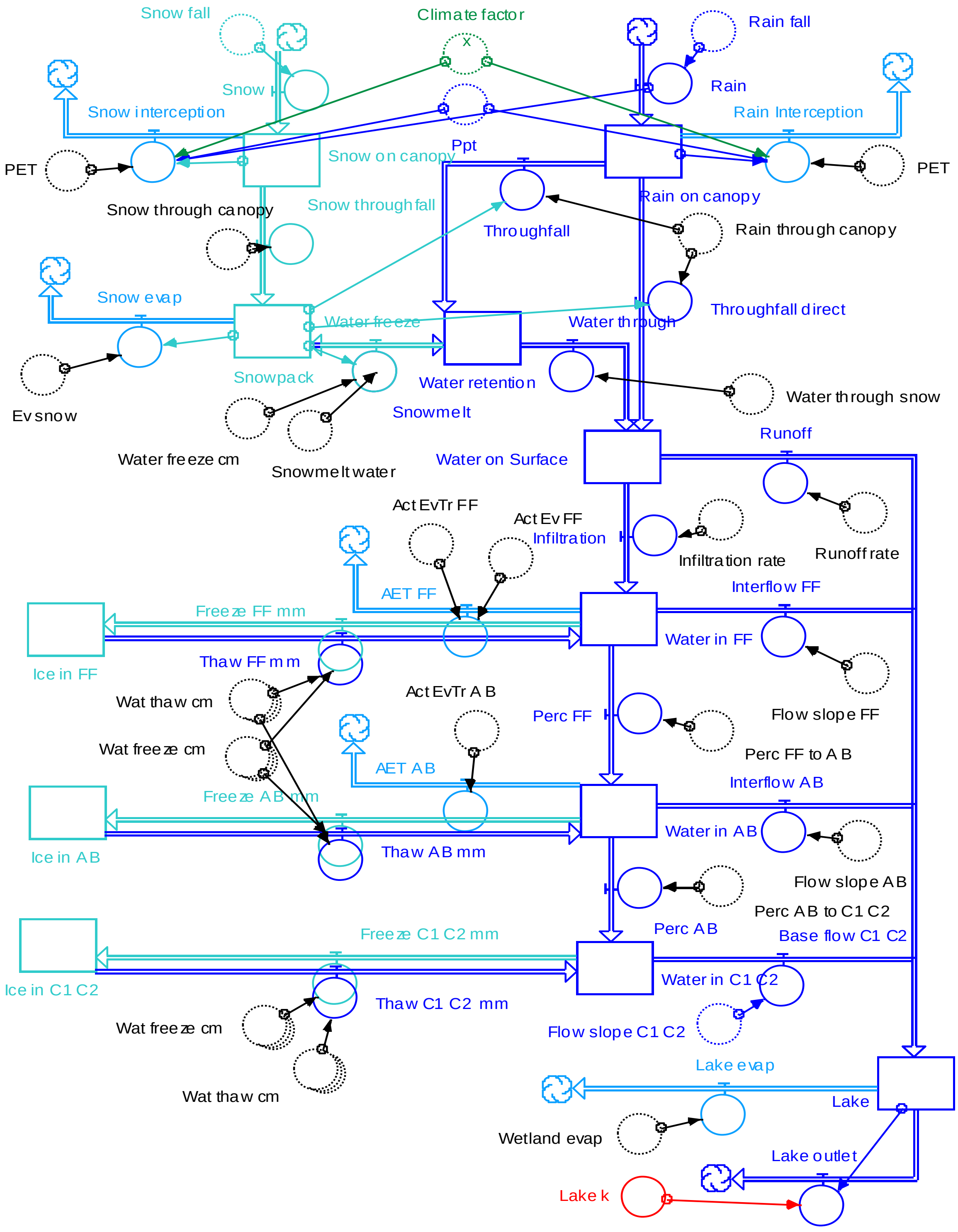

Figure 4.2 Main hydrology sub-modules.

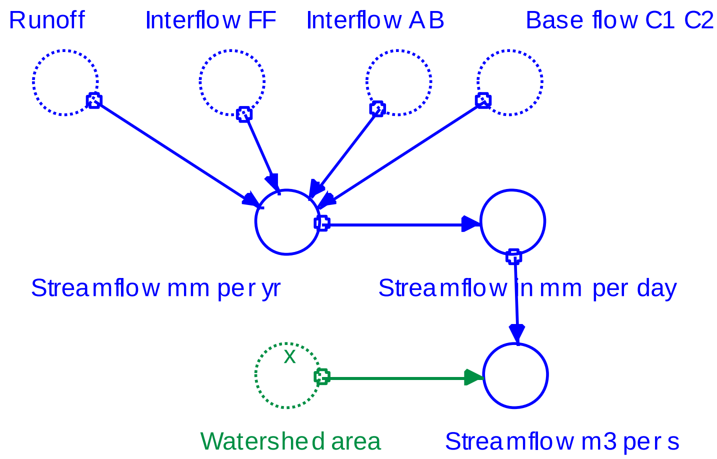

Figure 4.3 Stream discharge sub-module

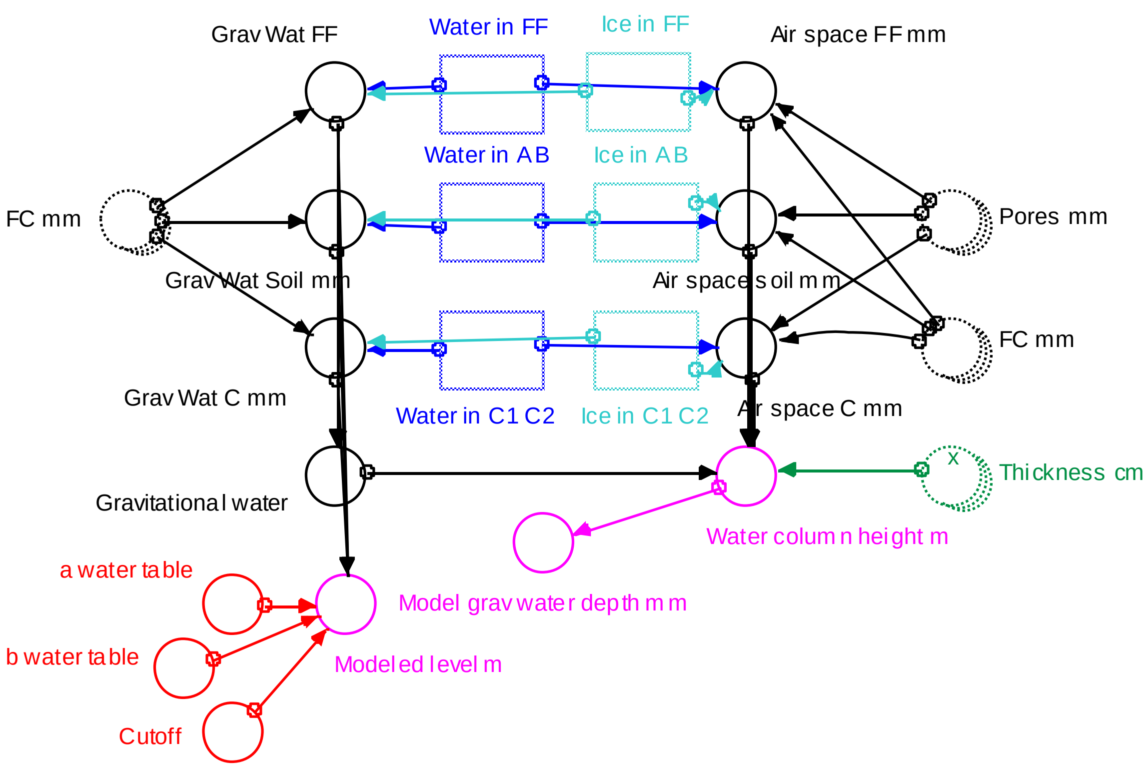

Figure 4.4 Sub-module for estimating the gravitational water content of the soil, summer through winter.

In ForHyM model, soil field capacity of each layer is calculated as follows:

FC_mm = 10 FC_v Layer-thickness_cm, (Eq. 4.1)

where: FC: Field capacity of each soil layer in mm.

FC_v: Volumetric field capacity of the soil (dimensionless, and varies between 0 and 1, 1=100%)

The permanent wilting point (PWP_mm) is calculated in the same way. For details regarding FC_v and PWP_v see Balland et al. (2008).

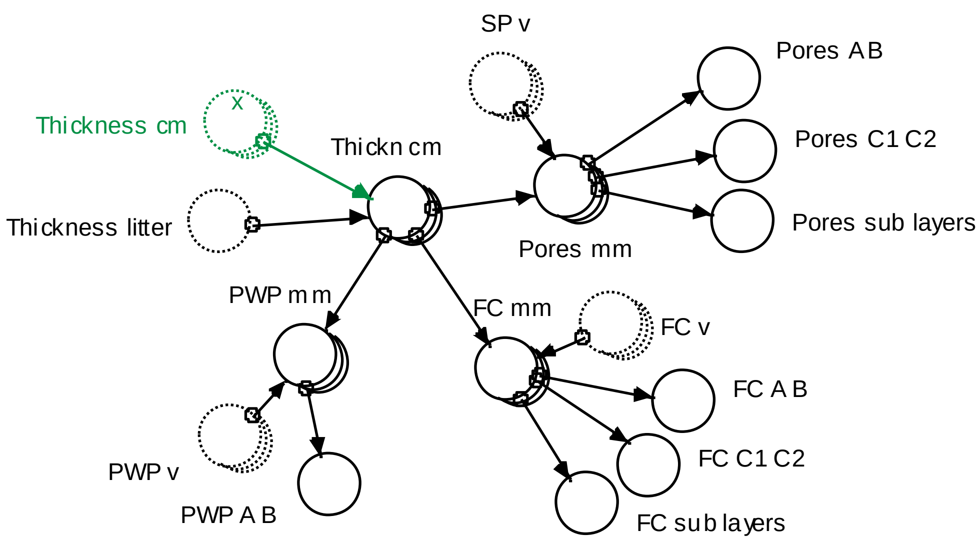

Figure 4.5 Diagram for the field capacity and permanent wilting point calculations.

The ForHyM model User-Interface developed in Excel (Microsoft Corporation 2003; Balland, 2002) contains a panel for stream discharge calibration (Figure 4.6). There are 7 parameters which can be adjusted for the stream discharge calibrations (blue shaded portion of Figure 4.6).

Model calibration	
Water balance at watershed scale	
PETadjustor	1.6
Snow density and snowmelt	
Air temperature adjustor	0.1
Density of fresh snow	0.15
Water flows	
Surface runoff adjustor	0
Infiltration in FF adjustor	1
Interflow in FF adjusor	0.2
Infiltration in A & B adjustor	1
Interflow in A & B adjustor	0.025
Infiltration in C1 & C2 adjustor	1
Interflow (base flow) in C1 & C2 adjustor	2

Figure 4.6 Calibration panel of the ForHyM model User-Interface to estimate runoff and infiltration and percolation rates. The panel is also used to calibrate catchment-specific evaotranspiration rares, the density of fresh snow, and the temperature gradient above the snow surface.

The ForHyM model can also be used to simulate soil temperature at various depths, in the presence and absence of the snowpack (Yin and Arp 1993; Bhatti et al., 2000; Houle et al., 2002). The energy, heat flow and temperature calculations are based on the consideration that the physical and thermal properties of each layer are assumed to be homogenous inside each layer. The calculations start with the energy balance at the ground surface as this balance varies each day based on daily incoming and outgoing ration, air temperature, and heat fluxes. For details concerning the parameterization of the hydro-thermal soil properties such as heat capacity, heat conductivity, soil bulk density, pore space, field capacity, permanent wilting point and soil permeability, see Balland, (2002) and Balland et al. (2008). An overview of the calculations that determine the changing soil temperatures in each soil and subsoil layer is shown in Figure 4.7. The algorithm for these calculations follows the implicit method for solving the second-order difference equation for one-dimensional heat flow equation. This difference equation is based on the principle of energy conservation and on the assumption that heat flow is directly proportional to the temperature gradient between any two adjacent points.

ForHyM CALIBRATIONS

The ForHyM calibrations used the daily records for air temperature, precipitation, snowpack depth and stream discharge to determine the rate coefficients for

- surface run-off,
- forest floor infiltration,
- infiltration into the top soil (A and B soil layers)
- interflow for the top soil, and
- infiltration into the sub soil (C layer),
- baseflow, or flow through the subsoil.

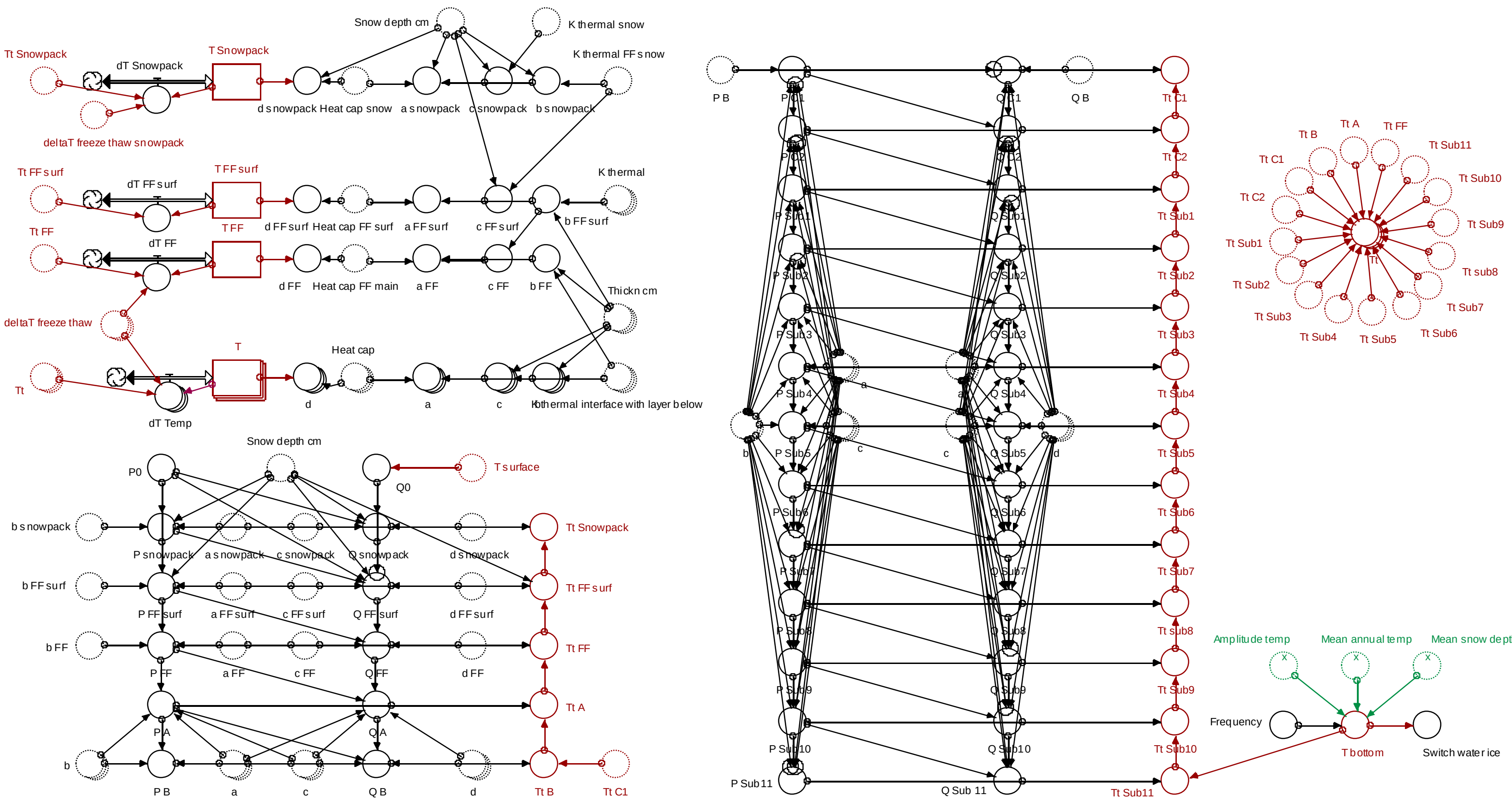

Figure 4.7 Sub-module for estimating soil temperatures at the midpoint of 17 consecutive layers, including the snowpack, the forest floor, the A, B, and C soil layers, and 11 subsoil layers.

The resulting coefficient values are listed in Table 4.1. From these values, it can be concluded that the amounts of water entering the soils and percolating through the soils and subsoils differ substantially between the two study areas. In particular, the various Table 4.1 entries show:

- larger surface flow and interflow coefficient values for the Pockwock-Bowater area than the Hayward Brook area;
- the deep soil percolation coefficient values are larger for the Hayward Brook area than the Pockwock-Bowater area;
- the subsurface flow coefficients are larger for the Hayward Brook area than for the the Pockwock-Bowater area.

Table 4.1 Calibration settings for stream flow paths.

	Pockwock-Bowater				Hayward Brook				
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
Surface runoff	0	0	0	0	0	0	1	1	1
Infiltration in FF	1	1	1	1	2	2	2	2	2
Interflow in FF	0.2	0.2	0.05	0.2	0.005	0.25	0.05	0.05	0.05
Infiltration in A&B	1	1	1	1	2	0.1	2	2	2
Interflow in A&B	0.1	0.025	0.005	0.025	0.0005	0.0005	0.0005	0.0005	0.0005
Infiltration in C	1	1	1	1	2	0.1	2	2	2
Interflow in C	2	2	0.5	2	0.05	0.05	0.01	0.005	0.005
Area	68	273	114	190	508	181	924	356	834
Elevation	162	196	174	190	145	96	95	96	115
Slope	2.7	3.9	4.6	4.5	4.6	2.5	3	4	3

Overall, a good fit could be achieved between measured and the ForHyM-calibrated snowpack depth and stream discharge values (daily and cumulative) for 3 of the catchments at Pockwock-Bowater Watershed and the 5 catchments at Hayward Brook Watershed (Figure 4.8 and 4.9). The exception was the modeled versus actual discharge at LP, with only about half of the expected water flowing through the stream channel at the stream-monitoring location, and with the other half most likely flowing below the stream channel.

The modeled pre- and post-harvest stream flow and soil gravitational water differences (or water table fluctuations) are presented in Figure 4.10 and 4.11 for both areas, assuming complete catchment cutting in each of the two areas. These figures suggest that:

- stream flow and water-table fluctuations would likely increase after harvesting; day-to-day pre-versus post-harvest stream discharge and water-table difference are calculated to be largest during the snowmelt season, because post-harvest snow accumulations are calculated to melt than pre-harvest snow accumulations (see also Balland et al., 2002); this difference was calculated to be considerable for the Hayward Brook area, but less so for the Pockwock-Bowater area on account of fairly fast and shallow water flow (Table 4.1), and also due to more frequent snowmelt events during each winter season; for the Pockwock-Bowater area, snowpack accumulations would be more temporary, and pre- to post-harvest differences regarding snowmelt-induced discharge would be short and flashy.

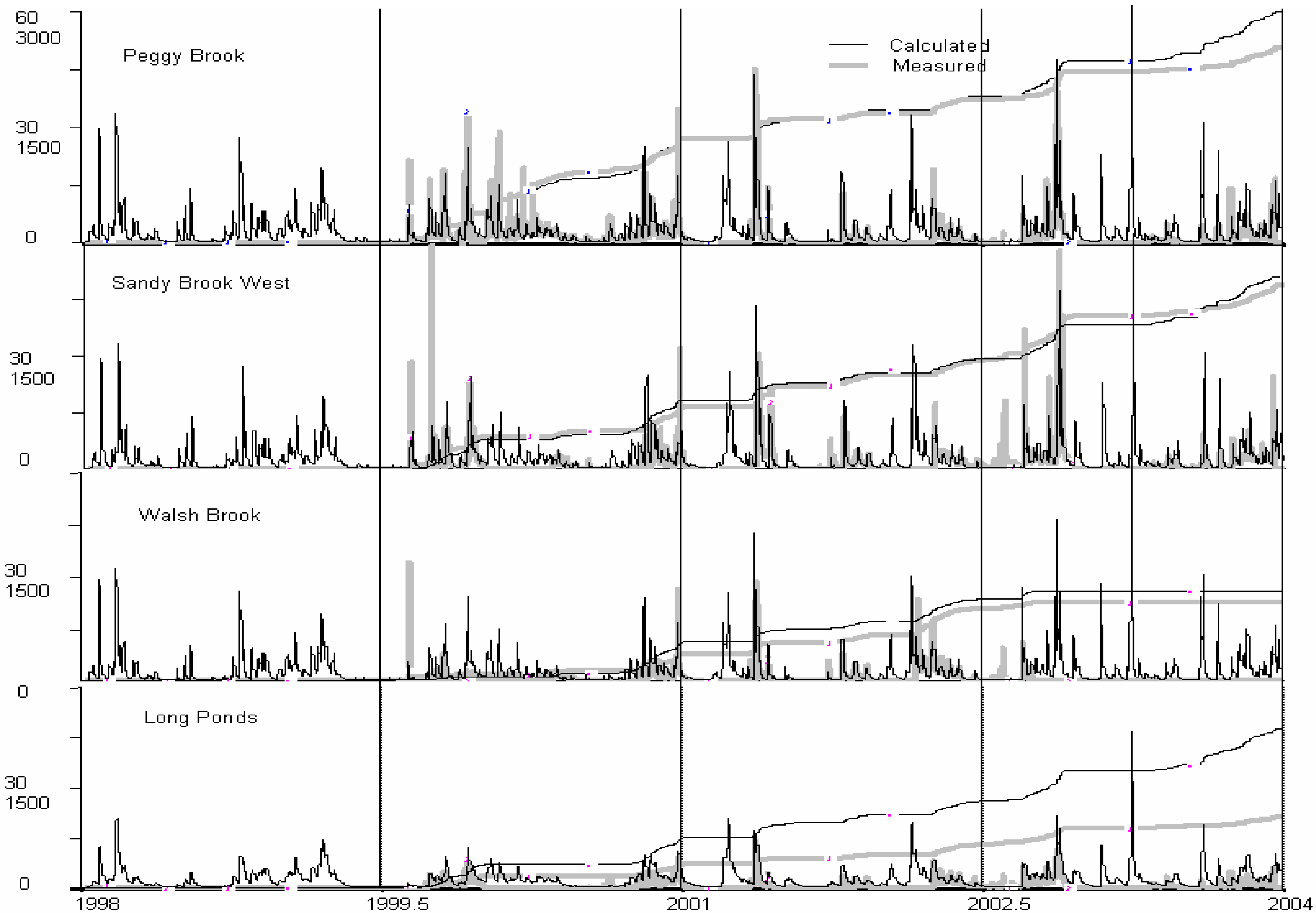

Figure 4.8 Comparison of observed and calculated stream discharge at Pockwock-Bowater.

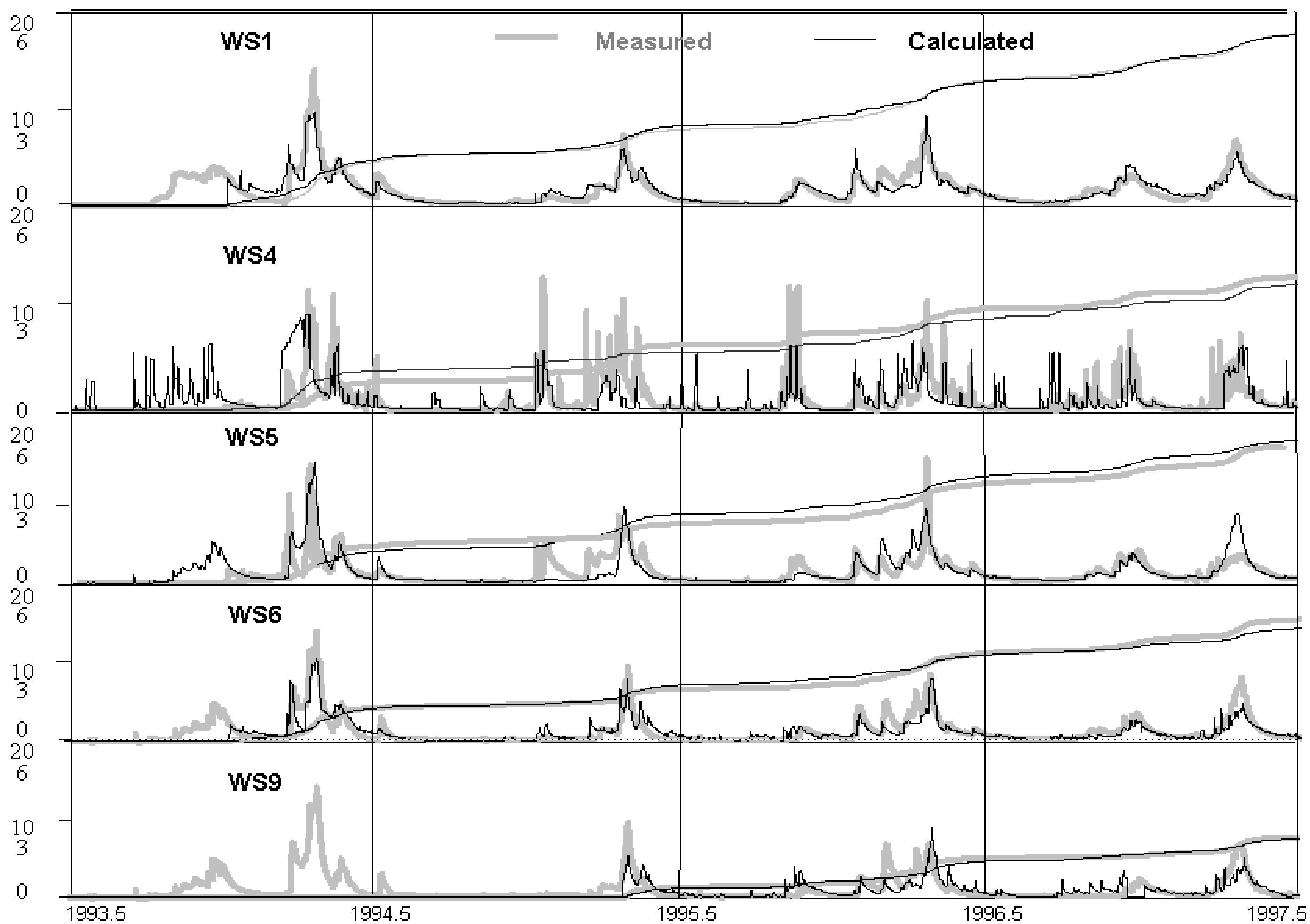

Figure 4.9 Comparison of observed and calculated stream discharge at Hayward Brook

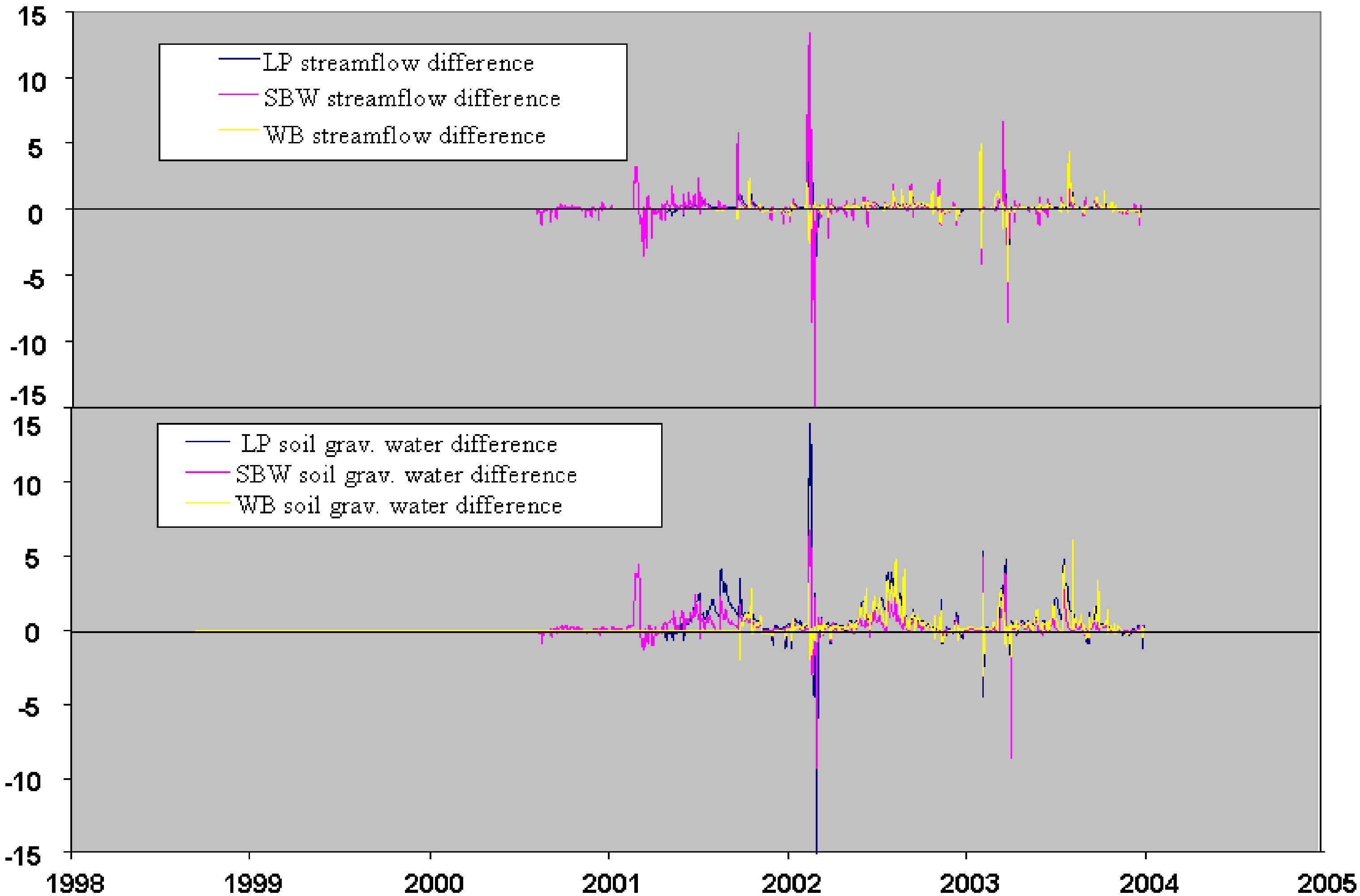

Figure 4.10 Pre- and post-harvest differences in stream discharge and water table levels, for the Pockwock-Bowater Area, NS.

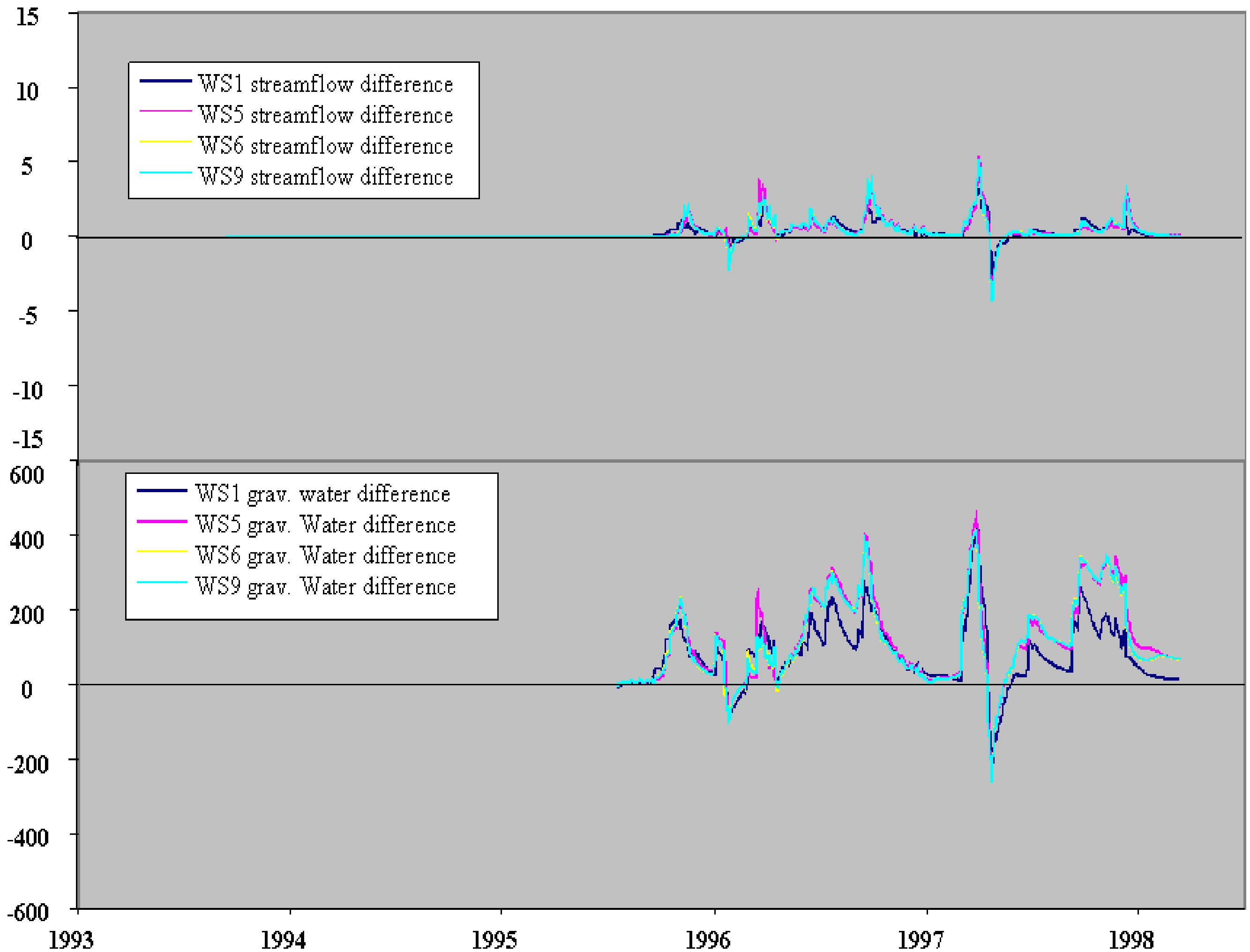

Figure 4.11 Pre- and post-harvest differences in stream discharge and water table levels, for the Hayward Bbrook area, NB.

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CHAPTER 5

STREAM-WATER TEMPERATURE

INTRODUCTION

Stream temperature affects the rate of physical, chemical and biological processes in streams, including the processes of self-purification, and related aesthetic and sanitary stream-water qualities (Feller, 1981; Beschta et al., 1987). In forestry, there are concerns as to harvesting affects air, soil temperatures, and stream temperatures (Brown, 1985). For example, logging along streams and throughout drainage basins can result in has been observed to increase hourly daily and stream-water temperatures, especially during summer (Burton and Likens, 1973; Holtby and Scrivener, 1988; Brown and Krygier, 1970; Hick et al., 1991). This Chapter reports on analyzing and modeling the multi-year pre- and post-harvest stream temperature records from the two study areas. The particular objectives are:

- to determine which principal factors control stream temperature within the study areas, by stream;
- to develop an algorithm that approximates the stream temperature control mechanism, and add that algorithm to ForHyM;
- to document the quality-of-fit between the model results and actual data;

- to discern the effect of partial basin harvesting on post-harvest stream temperatures.

MODELING STRATEGY

It is hypothesized that, for small streams with 100% forest cover, stream water equilibrates thermally with adjacent soil, snow and air fairly quickly, as the water flows through riffles and pools, over logs, rocks, and gravel beds and sometimes underneath the forest floor and soil-, rock- and snow-confined confined flow channels. Full forest canopies above ensure full or nearly full shading thus not allowing direct solar radiation inputs during summer. Hence, post-harvest stream warming if it were to occur during summer would mostly be due to enhanced post-harvest soil and subsoil warming. In winter, when a snowpack is present, there would be additional shading and thermal insulation of the soils and subsoils, and therefore also of the soil and subsoil water. In principle, soil and subsoil temperatures can be modeled with ForHyM for any soil and snow depth, and any particular forest cover type situation (softwood, mixed wood, hardwoods, varying degrees of post-harvest canopy closure from none to complete (Balland et al., 2005). Variations in hydrothermal soil conditions related to water and heat retention and layer-to-layer transferability are automatically taken in account according to soil texture, bulk density, coarse fragments, current moisture content, and the progression of daily weather, year-round. Since the ForHyM simulations address the hydrothermal conditions and transfers at the catchment or forest-stand scale, it is reasonable to suggest that the hydrothermal conditions that are applicable for soil, snow and air at these scales are also reflected by the soil and stream water, at least to some extent. The extent of thermal equilibration between the soil and stream water likely depends on actual flow paths as these vary towards and along the streams, and on the extent of continued water-atmosphere interaction. For example, at and below points of confluence, local stream temperature would the result of stream, soil and ground water mixing, depending on the temperature of each of the contributing flows as these converge in the form of surface run-off, inter flow, or base flow. The combined water would then equilibrate again with the prevailing soil, snow and air temperatures along the flow channel further downstream (Figure 5.1; Hann, 2006).

Based on preliminary model-data comparison, it was determined that the following formulation can be used to simulate the stream temperatures of each of the study-area basins quite well:

$$T_{stream} = (1-a)\ T_{Soil} + a\ \mathrm{SMTH1}\ (T_{Air}, \mathrm{Snowpack}/b) + c\ \sin\ [2\pi\ (\mathrm{year\_fraction}-d)] \quad \text{(Eq. 5.1)}$$

where:

T_{stream} = stream temperature (°C)

T_{Soil} = temperature of subsoil at the depth 230 cm (°C), as calculated with ForHyM.

T_{Air} = daily air temperature (°C), field observation.

Snowpack = depth of snow on the ground (cm), as calculated with ForHyM.

a, b, c, d = adjustable parameters, with “a” determining the differential contributions of air and soil temperatures to the measured stream temperatures, “b” allowing for a damping of the air-temperature influence on the stream temperature when a snowpack is present, “c” used to adjust the amplitude of the sine function characterizing an annual hysteresis loop between the stream temperature and the air and soil temperature fluctuations, and “d” determining the timing of the hysterisis loop in relation to the calendar year, or year fraction (= 0 at the beginning and = 1 at the end of each year).

SMTH1 is a built-in function of Stella (Version 5.1.1, High Performance Systems, Inc.). This function calculates a first-order exponential smoothing of the daily air temperature record exponential time averaging (Version 5.1.1, High Performance

METHODOLOGY

The data for the stream temperatures were compiled, averaged on a daily, monthly, and annual basis, and were cross-referenced by date, to enable direct stream-by-stream comparisons, by study area. Only days with complete data were averaged. The resulting daily time series were inspected and checked for consistent peak-to-peak correspondence. In some case, individual data tracks were re-aligned to conform to the general peak-to-peak pattern when such tracks were in obvious misalignment. Misalignments would be due to improper or shifting thermostat calibrations   Missing data in the resulting dataset were estimated and substituted by way of multiple regression analysis, using the daily temperatures of the other streams of the same study are predictors. The equations used had the following form:

stream_temperature_A = a_0 + b stream_temperature_B + c stream_temperature_C +…

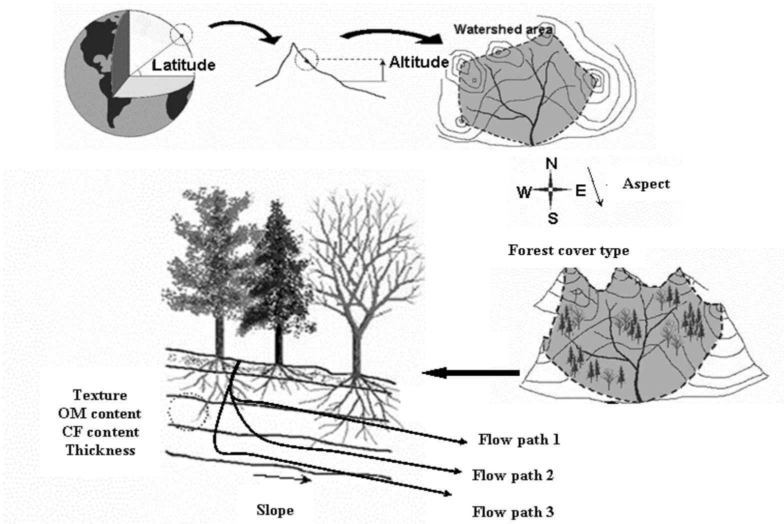

Figure 5.1 Flow paths of water through soils towards the stream, with the amount of water flowing along Flow paths 1, 2, and 3 depending on antecedent soil moisture and changes in soil permeability by soil layer. Water temperature along deep flow paths do not vary as much as water temperatures along shallow flow paths changes in soil permeability by soil layer.

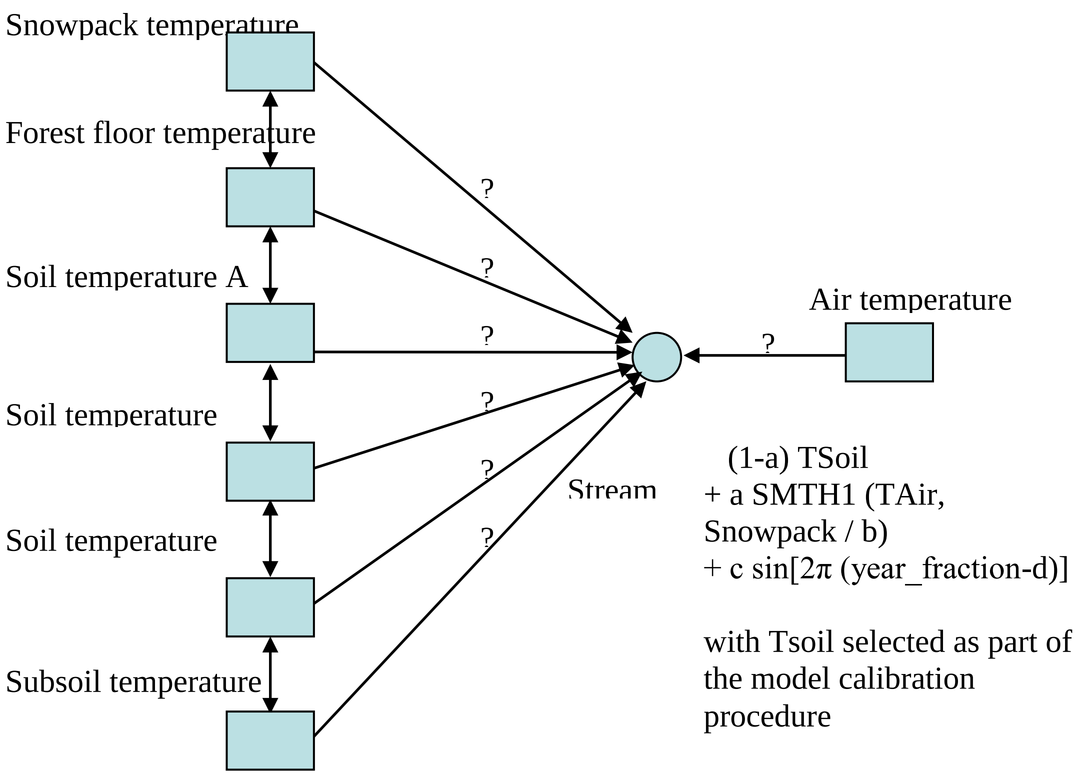

Figure 5.2 Overview of soil and stream temperature considerations with ForHyM. Question marks are directed at determining which combination of soil and air temperatures can be used to best quantify stream temperature through calibration.

This was done separately for the pre- and post-harvest conditions. The resulting time series data were then analyzed further, again through regression analysis, by checking for pre- versus post-harvest stream temperature effects, as follows (e.g.)

$$\text{stream\_temperature\_ SBW} = a_{SBW} + b_{SBW}\ \text{stream\_temperature\_PB}$$
$$+ c_{SBW}\ \{1 + \sin [2\pi\ (\text{year\_fraction} - d_{SBW})]\} + e_{SBW}\ \text{harvest} \qquad \text{(Eq. 5.2)}$$

where the addition of the sine function would account for a residual phase difference between the temperature of the control stream (e.g., Peggy Brook) and the temperature of the harvested basin (e.g., Sandy Brook West), with d_{SBW} as the phase difference between the SBW stream temperature and the calendar year, and c_{SBW} as adjuster for amplitude of a seasonal temperature correction between the two streams.

The “harvest” variable in the above expression quantifies any systematic stream temperature difference between before and after harvesting, with “harvest” set at 0 and 1, respectively. Specific values for the a, b, c and d coefficients were generated for the pre-harvest condition only. The post-harvest analysis then proceeded with the a, b, c and d coefficients already fixed, leaving e as the only adjustable parameter. In this way, the a, b, c and d coefficients were also used to determine the un-harvested stream temperatures in the harvested basins. In turn, doing so allowed for a direct comparison between the harvested and estimated un-harvested stream temperatures. These comparisons were done for the entire post-harvest periods, and also one post-harvest year at a time, to determine how the harvest coefficient would change with each successive post-harvest year, by stream and study area.

The calibrate ForHyM projections for soil temperature and snow pack depth (preceding Chapter) and the actual stream temperature records were used to calibrate the a, b, c, and d coefficients in Equation 5.1, stream by stream. Examples for typical under-, over- and proper stream-temperature calibrations are shown in Figures 5.3, 5.4 and 5.5. In general, if the estimated stream temperatures were too slow to increase in spring and too slow to decrease in fall, and also if the peak estimates were too smooth in general, then the air temperature contributions to the stream temperature would be increased, i.e., parameter "a" would be increased. The smoothing influence of the snowpack on the stream temperature was adjusted by way of the "b" coefficient: increasing its value would decrease the influence of the air temperature on the stream temperature at the stream-monitoring location during each snow season. The calibrations also involved choosing the soil depth at which the soil temperature itself would provide a close match with the stream temperature records. Adjusting the "c" and "d" coefficient in Eq. 5.1 provided additional controls in terms of matching the daily ForHyM-projections, especially for the Hayward Brook area.

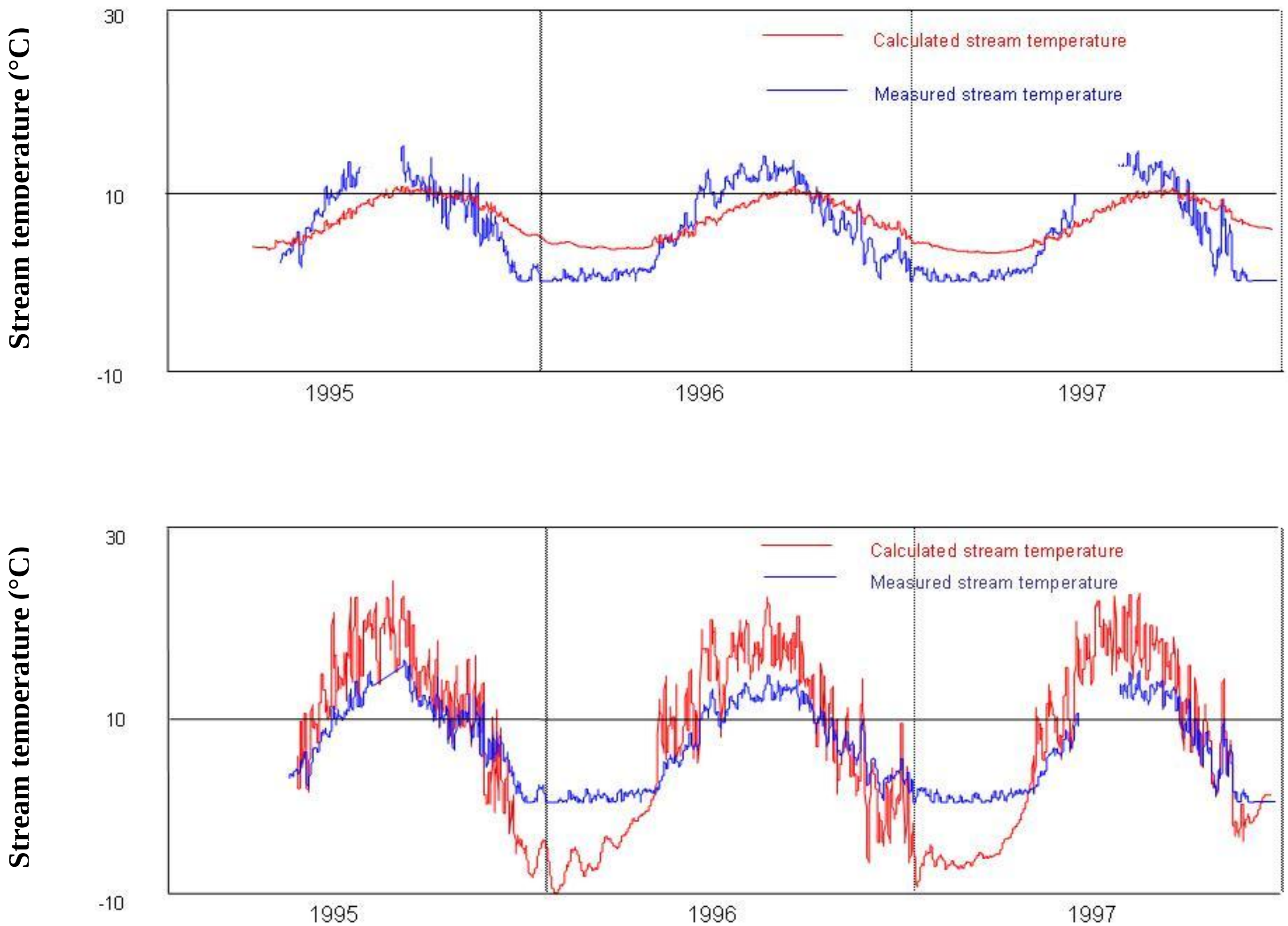

Figure 5.3 Under- and over-estimating the air temperature contribution to the stream temperature.

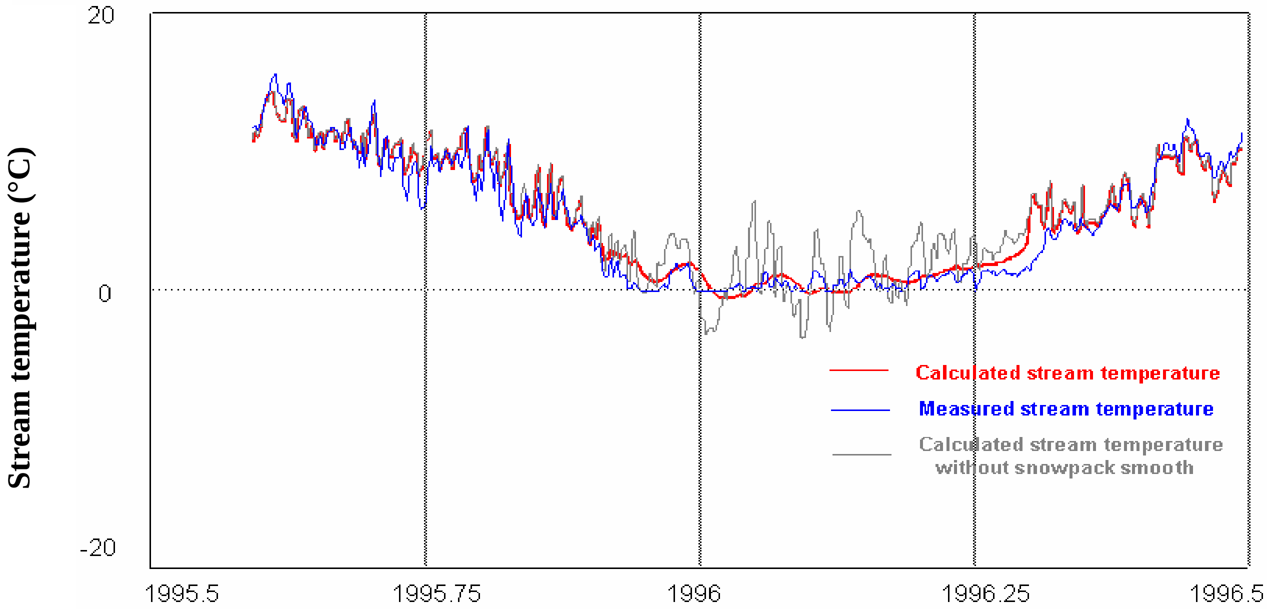

Figure 5.4 Calibration for winter period.

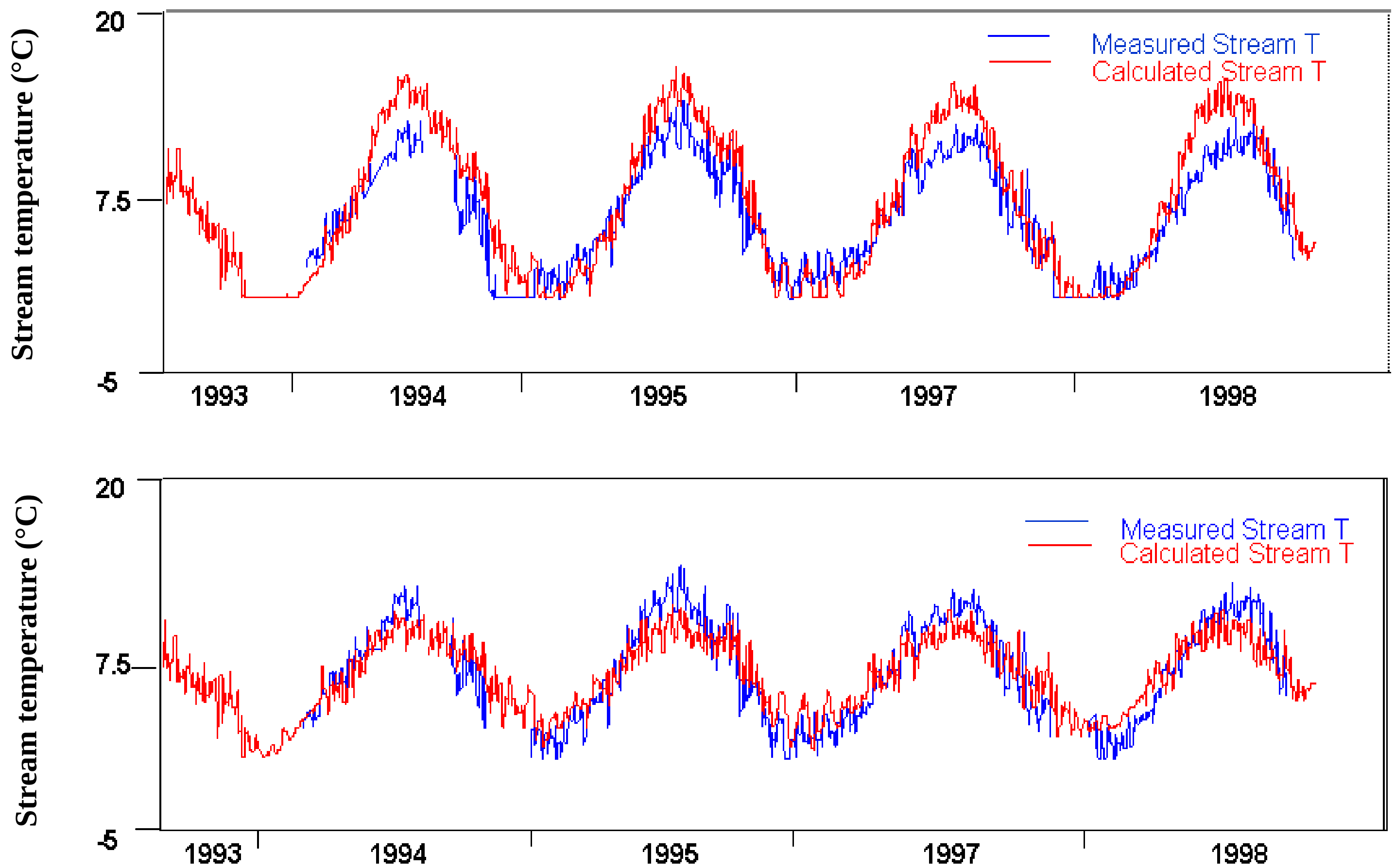

Figure 5.5 Calibration of soil depth.

RESULTS AND DISCUSSION

Stream temperatures, by study areas

Based on the stream temperature records, streams in the Pockwock-Bowater area have warmer temperatures than the streams in the Hayward Brook area during summer, but not during winter, in spite of the cooler air temperatures for the latter during that time of year (Table 5.1). This further supports the interpretation that water runs deeper in the Hayward Brook area, and – once in the soil - is therefore more insulated from the colder air temperature during winter than what would be the case for the Pockwock-Bowater study area.

For the Pockwock-Bowater area, the following equations were obtained to express the pre- and post-harvest stream-temperature relationships between the stream of the control basin and the harvested basins:

Long Ponds stream temperature = (1.18+/-0.08) + (0.66+/-0.01) Peggy Brook + (1.1+/-0.09) sin [2π (year_fraction-0.4)] + (0.03+/- 0.05) harvest, $R^2 = 0.98$.

Sandy Brook West stream temperature = (0.38+/-0.1) + (0.87+/-0.01) Peggy Brook + (0.8+/-0.11) sin [2π (yearfraction-0.4)] + (0.47+/- 0.01) harvest, $R^2 = 0.98$

Walsh Brook stream temperature = (0.47 +/- 0.11) + (0.94+/-0.0) Peggy Brook + (0.96+/-0.12) sin [2π (yearfraction-0.4)] + (0.33+/- 0.05) harvest, $R^2 = 0.96$

Table 5.1 Stream temperature by study areas.

	Pockwock-Bowater				Hayward Brook				
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
Max T_{stream}	19	19.4	17.5	21.7	12.5	14.8	13.2	13.3	14
Min T_{stream}	0	0	0	0	0	0	0	0	0
Average T_{stream} (annual)	7.2	7.3	7	7.7	6	5.7	5.9	5.9	5.8
Average T_{stream} (Jan)	0.2	0.2	0.4	0.1	1.4	1.1	1.9	1.8	1.5
Average T_{stream} (July)	15	15.3	14	16.9	10.1	12.1	10.7	10.9	11.3
Max AET (mm)	26.6	20.2	27	25.8	53.9	54.7	54.6	54.6	54.6
Min AET (mm)	0.04	0.2	0.05	0.05	0.4	0.5	0.4	0.4	0.4
Average AET (mm)	3.3	5.2	3.6	3.8	11.7	11.8	12.1	12.3	12.3
Max Ppt (mm)	69	69	69	69	40.4	40.4	40.4	40.4	40.4
Min Ppt (mm)	0.04	0.2	0.05	0.05	0	0	0	0	0
Average Ppt (mm)	3.9	3.9	3.9	3.9	3	3	3	3	3
Average T_{air} (Jan)	5.3	5.3	5.3	5.3	-9.1	-9.1	-9.1	-9.1	-9.1
Average T_{air} (July)	26.3	26.3	26.3	26.3	19.2	19.2	19.2	19.2	19.2
Average T_{air} (annual)	6.6	6.6	6.6	6.6	6	6	6	6	6

These equations, with R2 > 96 for all three comparisons, represent most of the observed stream-to-stream temperature variations. As well, these equations reveal that the stream temperatures for the LP, SBW and WB lagged the stream temperature of PB: the lag between the PB stream temperatures and the year fraction is 0.25; by the LP, SBW and WB lags are >0.25.

The following equations were obtained for the Hayward Brook study in the same way:

WS1 stream temperature = (2.17+/-0.08) + (0.6+/-0.08) WS4 + (2.29+/-0.06) sin [2π (yearfraction-0.35)] + (0.24+/-0.07)harvest, $R^2 = 0.90$.

WS5 stream temperature = (2.36+/-0.07) + (0.59+/-0.01) WS4 + (0.46+/-0.05) sin [2π (yearfraction-0.22)] + (0.28+/-0.06)harvest, $R^2 = 0.94$

WS6 stream temperature = (1.19+/-0.06) + (0.69+/-0.01) WS4 + (0.16+/-0.06) sin [2π (yearfraction- 0.3)] + (0.43 +/- 0.05)harvest, $R^2 = 0.97$

WS9 stream temperature = (0.6+/-0.05) + (0.8+/-0.04) WS4 + (0.53+/-0.04) sin [2π (yearfraction- 0.26)] + (0.32 +/-0.05) harvest, $R^2 = 0.99$

Again, the regression coefficients of the pre-post harvest variable were positive and also significantly different from zero.

The above regression equations with harvest = 0 were also used to predict what the stream temperatures would have benn in the harvested catchments if harvesting had not occurred. Doing so allows for direct visual comparisons with the actual post-harvest stream temperature measurements. The corresponding plots are shown in Figure 5. 6 and 5.7.

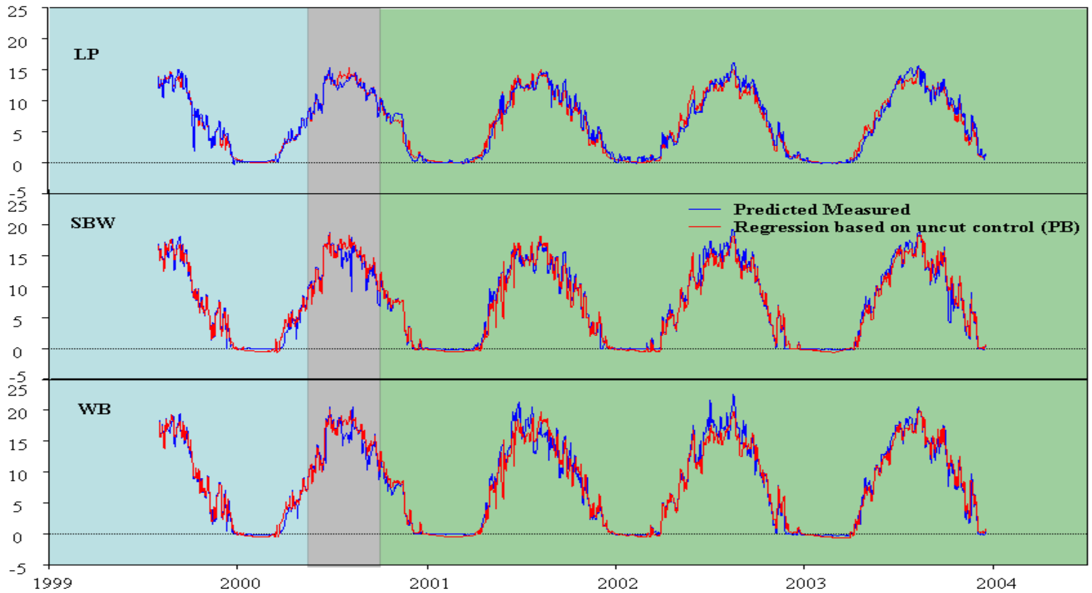

Figure 5.6 Comparison of actual stream temperatures of the 3 harvested basins (Sandy Brook West, Walsh Brook, and Long Ponds) with pre-harvest stream temperature projections based on the uncut control basin (Peggy Brook). Shaded area shows time of harvesting.

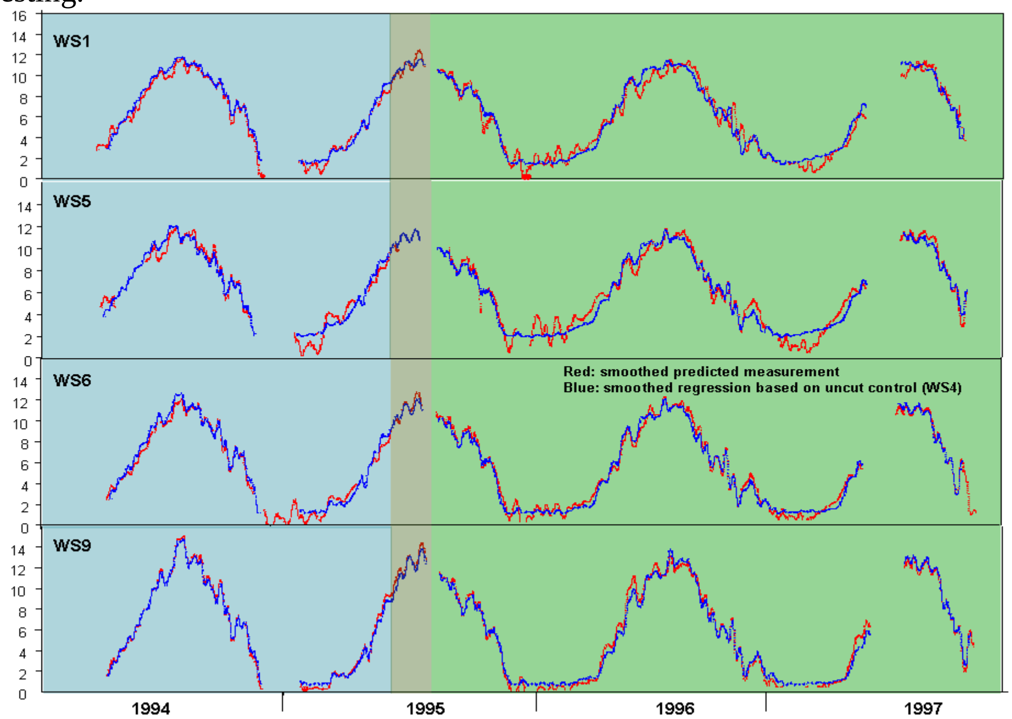

Figure5.7 Comparison of actual stream temperatures of the 4 harvested basins (WS1, 5, 6, 9) with pre-harvest stream temperature projections based on the uncut control basin (WS4). Shaded area shows time of harvesting.

Analyzing the post-harvest stream temperatures by year lead to the harvest coefficient values listed in Tables 5.2 and 5.3. Except for LP, these harvest coefficients are positive at about 0.45C in the year of harvesting, somewhat lower in the following year, and barely significant for the second post-harvest year. Hence, the effect of harvesting on stream temperature was fairly small, fairly short-lived, and would likely not last much longer than 2 years. The exception at LP may be due to the local flow pattern, with only half of the water flowing though the stream channel at the stream monitoring location, and the other half flowing below the channel (preceding Chapter).

Table 5.2 Comparison of normalized summer mean stream temperatures between 1994 (pre-harvest) and 1995 (post-harvest) (Bourque et al., 2001).

Station	1994 (Pre-harvest) (°C)	1995 (Post-harvest) (°C)	T difference (°C)	P-values
Moncton	16.81	16.27	-0.54	P>0.250
WS1	9.62	10.32	0.7	P<0.001
WS4	12.6	12.38	-0.22	P>0.500
WS5	9.93	10.2	0.27	P<0.002
WS6	9.93	10.31	0.38	P<0.001
WS9		11.25		

Table 5.3 Comparison of mean yearly stream temperature difference between pre-harvest (1999, 2000) and post-harvest (2001, 2002 and 2003), Pockwock-Bowater study area.

Catchment	2001 (°C)	2002 (°C)	2003 (°C)	Post harvest (2001, 2002, 2003)
SBW	0.48+/-0.07	0.34+/-0.06	0.15+/-0.06	0.47+/-0.01
LP	0.05+/-0.05	0.09+/-0.06	0.01+/-0.05	0.03+/-0.05
WB	0.44+/-0.08	0.44+/-0.07	0.25+/-0.05	0.33+/-0.05

The results for the Hayward Brook study are similar to those derived by Bourque et al. (2001), who determined that harvesting affected the monitored stream temperatures by 0.27 to 0.7 °C (Table 5.3) for the 1 post-year summer period from June to September.

Table 5.4 Comparison of mean yearly stream temperature difference between pre-harvest (1994) and post-harvest (1995, 1996 and 1997), Hayward Brook study area.

Catchment	1995 (°C)	1996 (°C)	1997 (°C)	Post harvest (1995, 1996, 1997)
WS1	0.47+/-0.07	0.3+/-0.07	0.13+/-0.08	0.35+/-0.01
WS5	0.3+/-0.09	0.29+/-0.07	0.01+/-0.08	0.28+/-0.08
WS6	0.44+/-0.08	0.45+/-0.05	0.13+/-0.06	0.43+/-0.06
WS9	0.51+/-0.06	0.15+/-0.05	0.07+/-0.05	0.32+/-0.05

These results can also be compared with the post-harvest temperature effects in shallow post-harvest groundwater wells (4.4 to 7.6 m deep) by Sleeves (2004), who reported post-harvest well-water increases as high as 2.5 C in the first two to three years following whole-basin harvesting in northern New Brunswick. Here, basin sizes varied from 6 to 30 ha, with wells installed in the confluence area of each catchment, about 5 to 20 m above the first seepage point towards the water-receiving stream below. The well water with its increased post-harvest temperature would then flow into the stream below, where this water would then join with the stream water itself, and would likely cause local stream-water temperature increases during summer and fall (Hann, 2005).

ForHyM CALCULATIONS

The ForHyM calculations were done using the watershed and soil specifications as described in Chapter 3, by study area, for each basin fully harvested according to the specified harvest times, or unharvested.

An overview of the results for snowpack depth, depth and timing of soil frost, as well as actual and ForHyM-calibrated daily stream temperatures are shown in Figures 5.8 and 5.9. These illustrations indicate that frost penetration into the ground is deeper during winters with low snowpack accumulations (e.g., the winter of the year 2000 for the Pockwock-Bowater area), and vice versa (e.g., the winter of the year 2001). Moreover, stream temperatures remain colder longer following winters with deep soil frost than following winters with no soil frost.

For the Hayward Brook area, snowpack accumulations were of sufficient depth for most of the winter, thereby preventing significant the build-up of long-lasting soil, and allowing stream temperatures to warm relatively quickly during each spring. In contrast, streams within the Pockwock - Bowater study area have winter temperatures close to 0°C. This is partly due to winters with low and short durations of snow on the ground, causing soil and stream temperatures to be lower and frozen.

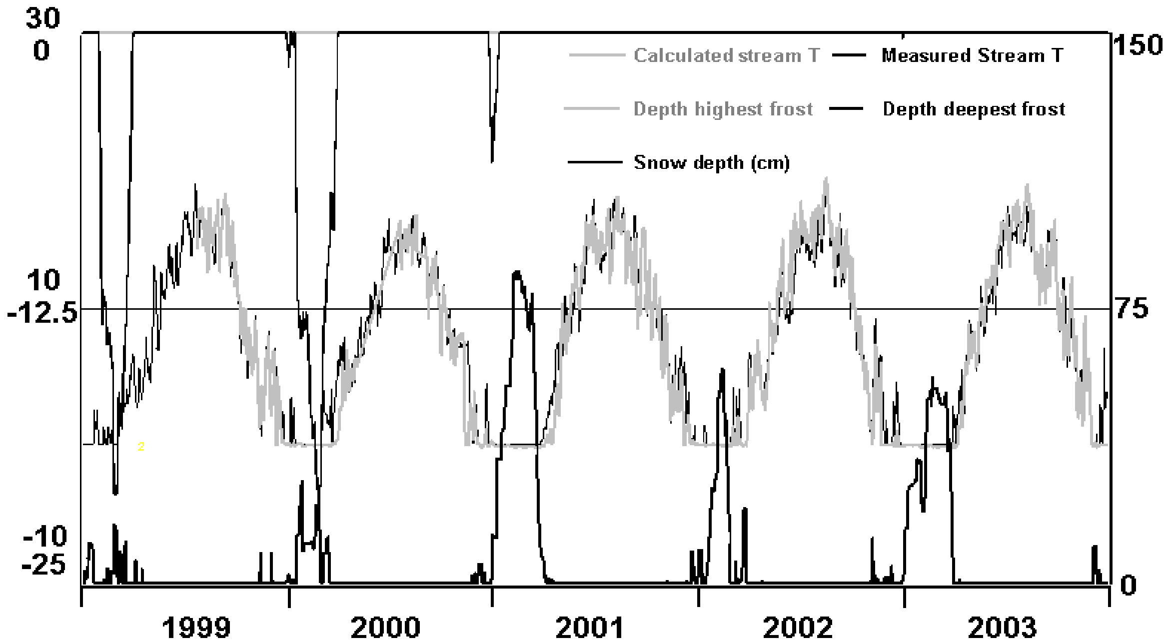

Figure 5.8 Stream temperature with soil frozen depth and snow depth, Pockwock-Bowater study area, NS.

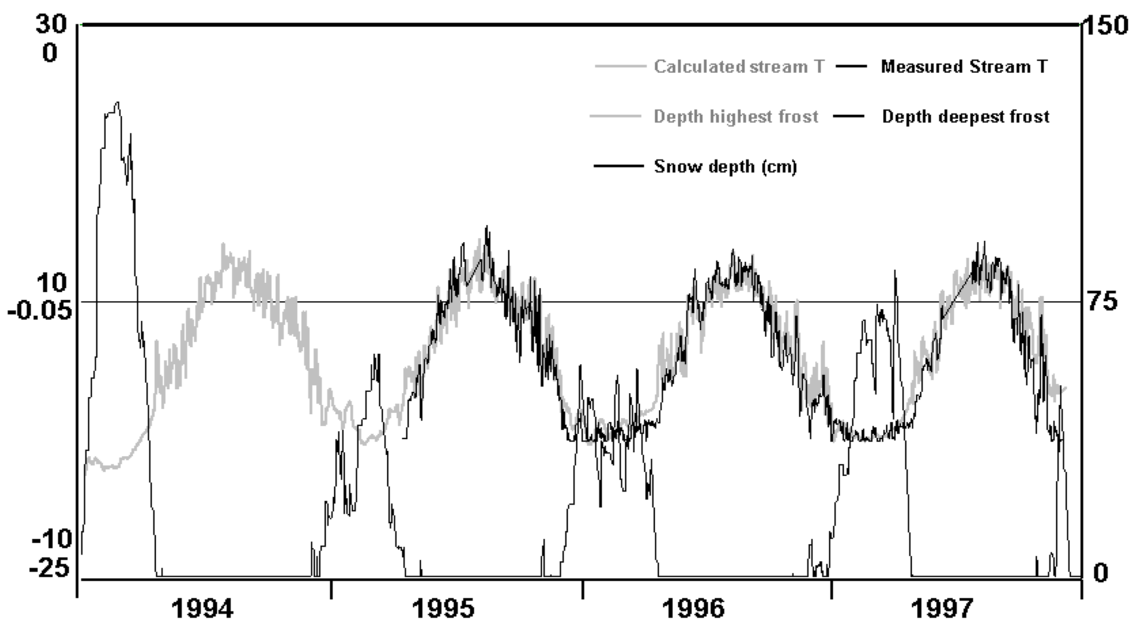

Figure5.9 Stream temperature with soil frozen depth and snow depth, Hayward Brook study area, NB.

Calibrating the coefficients of Equation 5.1 by way of the ForHyM calculation led to the results shown in Table 5.5. In general, the stream temperatures for the Pockwock - Bowater study area were fairly responsive to changes in air temperature throughout the year (coefficient “a” is larger for the Pockwock-Bowater streams than the Hayward Brook streams). This means that water entering the streams in the Pockwock – Bowater study area remained fairly close to the soil surface, summer and winter. To a large extent, and as modeled, this would be due to a low soil and subsoil permeability of the soil and bedrock substrates within the Pockwock –Bowater study area (loamy, on impervious granites). In contrast, the permeability of the soil and bedrock substrates within the Hayward Brook area (sandy loams, on shale) would be large, thereby allowing for fast water infiltration and deeper water percolation, and a greater insensitivity of the stream temperature to the daily air temperature variations.

Table 5.5 Calibration settings for stream temperature parameters.

	Pockwock-Bowater				Hayward Brook				
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
a	0.7	0.72	0.62	0.85	0.25	0.41	0.3	0.31	0.35
b	1000	1000	1000	1000	10000	1000	5000	3500	2000
c	0	0	0	0	1.06	1.34	1.04	1.3	0.6
d	0	0	0	0	0.5	0.3	0.2	0.3	0.2

The calibration of the sine component of this equation was particularly important for improving the stream temperature calculations for the Hayward Brook watersheds, each showing an annual hysteresis loop, with the hysteresis loop delayed by 29, 17, 12, 17, and 12 days for watersheds 1, 4, 5, 6, and 9, respectively (Table 5.5). These calibrations suggest that water that enters the Hayward Brook stream runs - on average - deeper and takes longer to flow through the ground before re-surfacing than the water that enters the streams in the Pockwock-Bowater area.

Actual stream temperatures can be compared with the ForHyM calibrations in Figure 5.10 and 5.11 versus time, and in Figures 5.12 to 5.14 by way of scatter plots showing actual versus the calibration-estimated values. In general, the best-calibrated stream-water temperatures reproduced the observed stream temperature variations fairly well, with R2 > 0.9 for all nine watersheds within the Pockwock - Bowater and Hayward Brook study areas. Of these, the stream labeled "WS9" in Hayward Brook had the highest R2 value (= 0.96), while Walsh Brook ("WB") of the Pockwock-Bowater area had the lowest R2 value (= 0.90). Also note that the Pockwock-Bowater simulations required no hysteresis adjustments, and produced better and more consistent linear regression results than the Hayward Brook simulations (Figure 5.12 and Figure 5.13). In Figure 5.13 and 5.14, actual and measured Hayward Brook stream temperatures using Equation 1 are presented with and without the sine function in Equation 5.1, respectively.

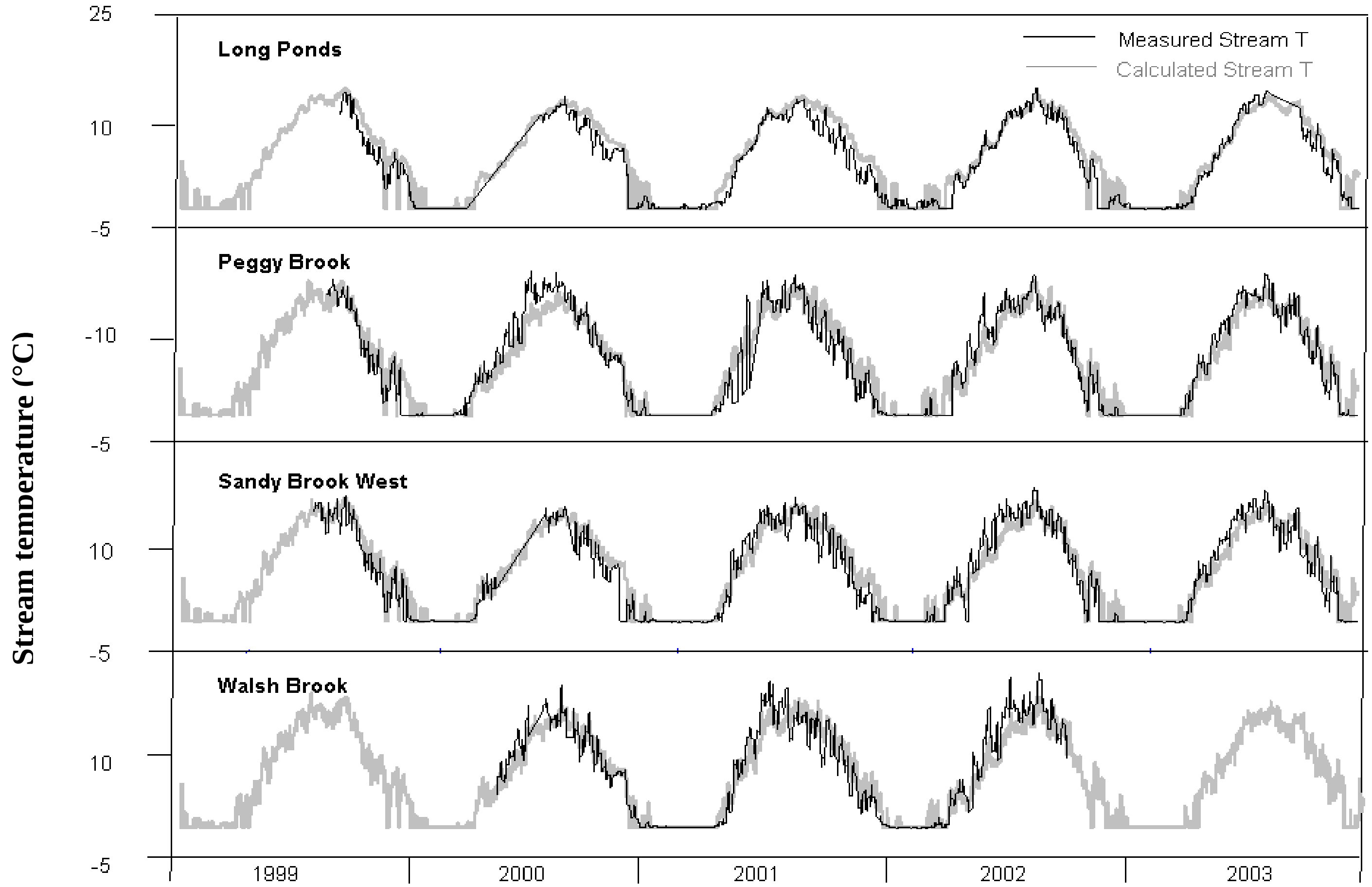

Figure5.10 Actual and predicted stream temperature, Pockwock-Bowater study area, NS.

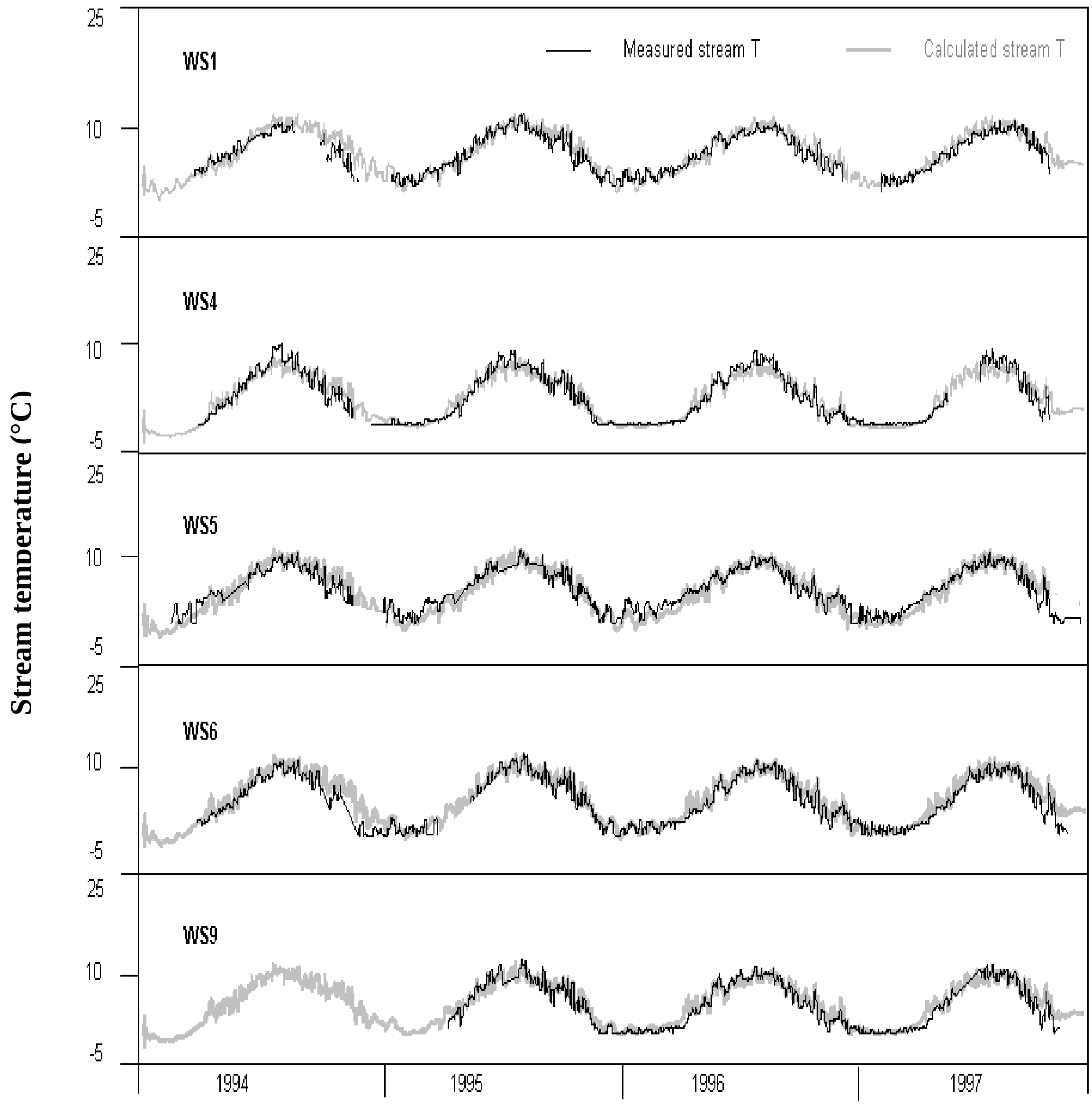

Figure5.11 Actual and predicted stream temperature, Hayward Brook study area, NB.

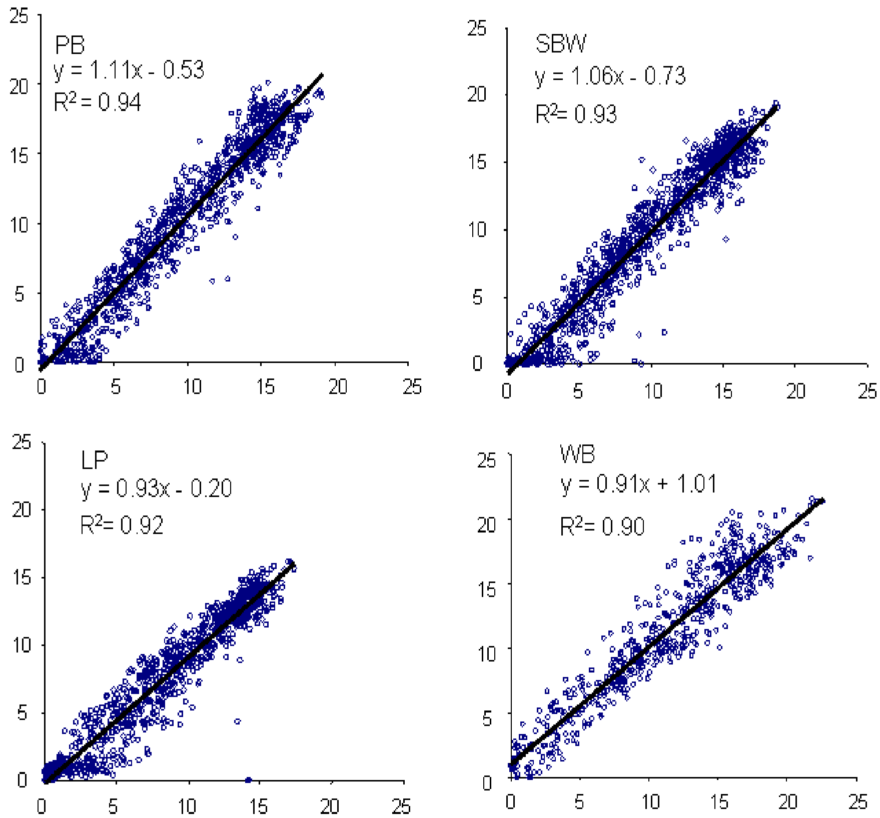

Figure 5.12 Actual and predicted stream temperature correlations with R^2 values, Pockwock-Bowater study area, NS.

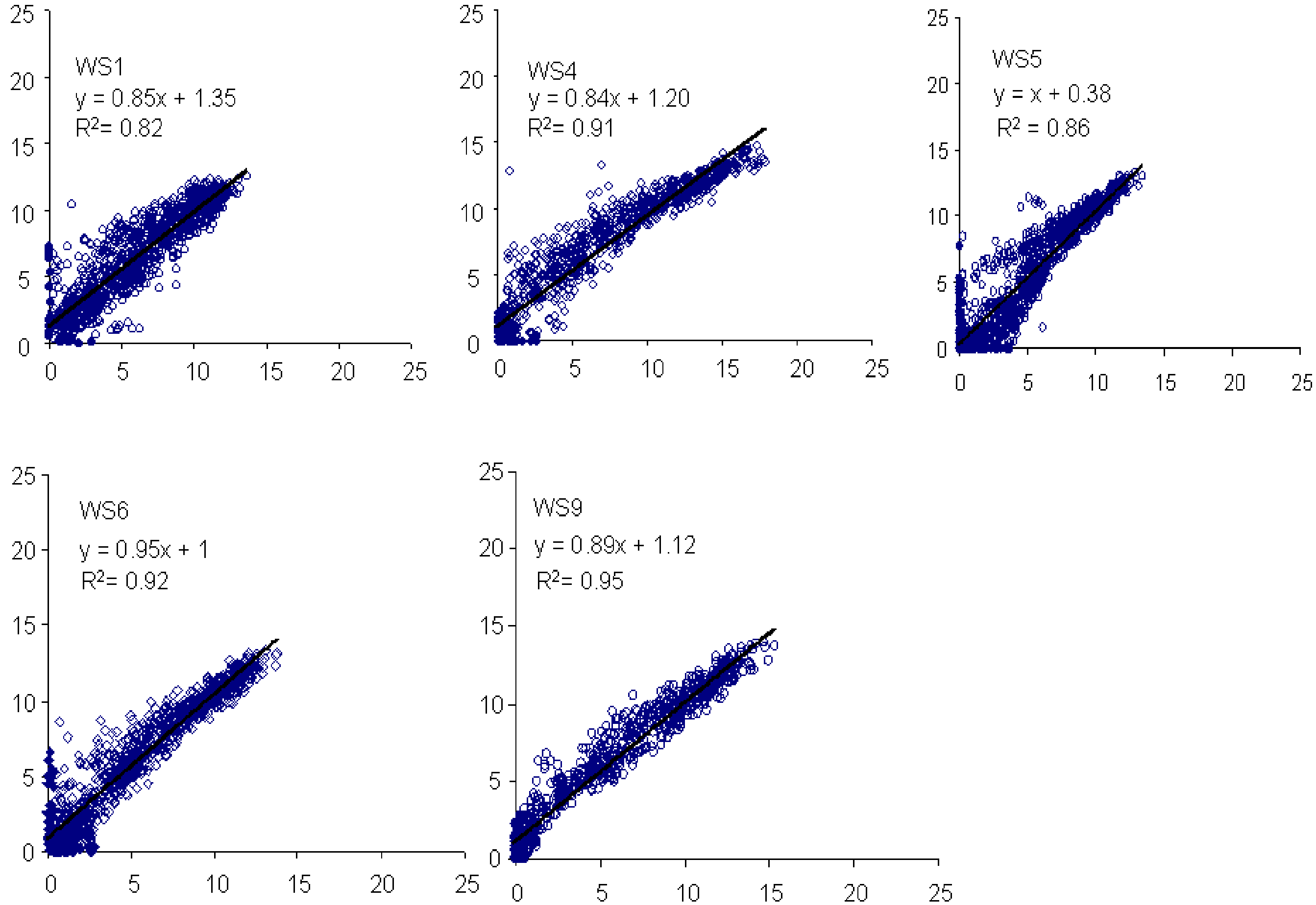

Figure 5.13 Actual and predicted stream temperature (without sine function) correlations with R^2 values, Hayward Brook study area, NB.

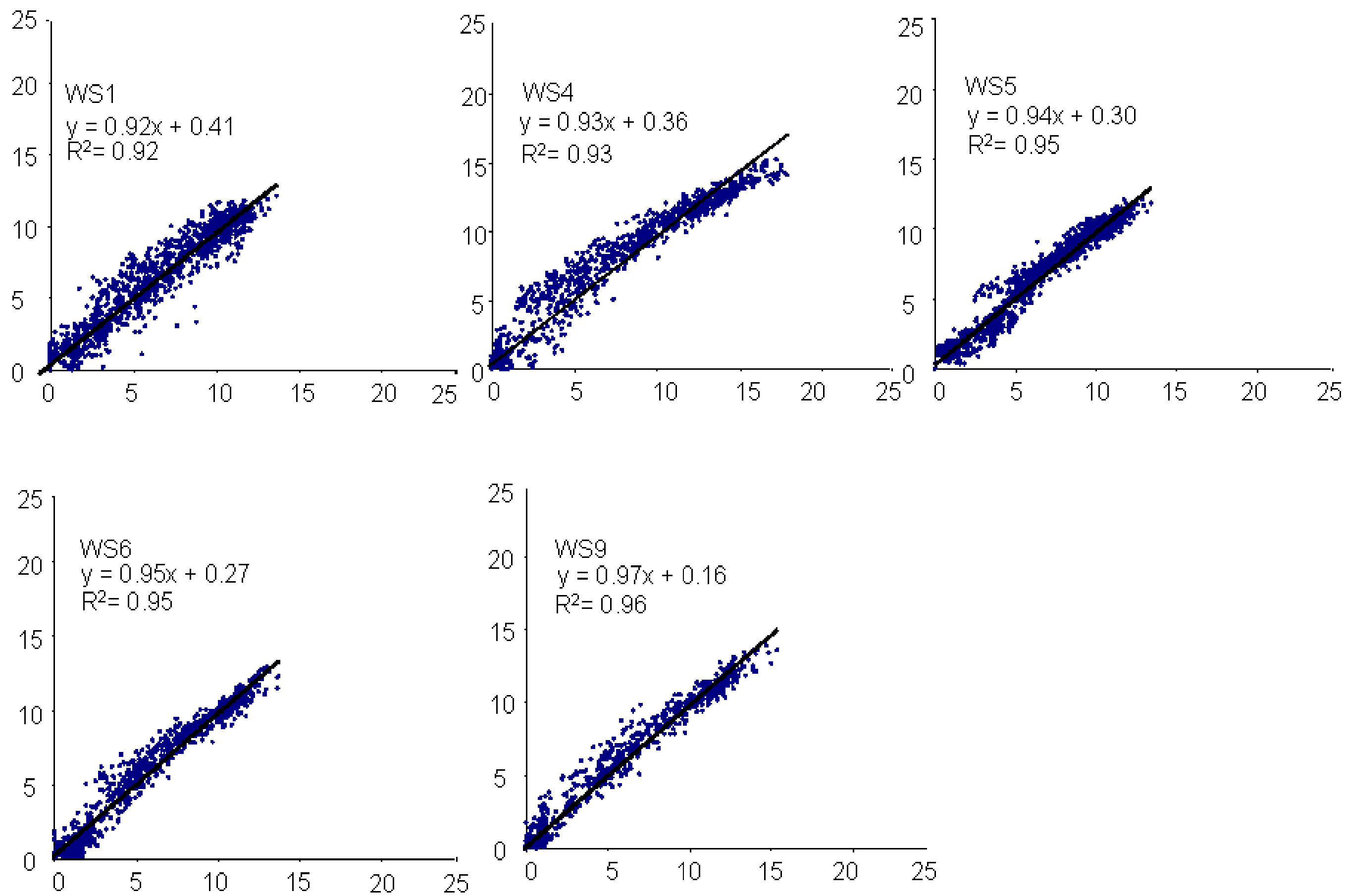

Figure 5.14 Actual and predicted stream temperature (with sine function) correlations with R^2 values, Hayward Brook study area, NB.

Pre- and post-harvest stream temperatures were simulated with the ForHyM model, by using its built-in pre- to post-harvest leaf area index function and complete catchment-wide harvesting for the two study areas. The results were used to determine potential monthly harvest versus no-harvest stream temperature differences. These differences are plotted in Figures 5.15 and 5.16 with the corresponding harvest versus no-harvest snow depth simulations. These plots suggest small but generally positive increases in stream temperature for both study areas, with the largest differences occurring at the beginning and the end of the snow season, mainly due to differences in pre- to post-harvest snow melt differences.

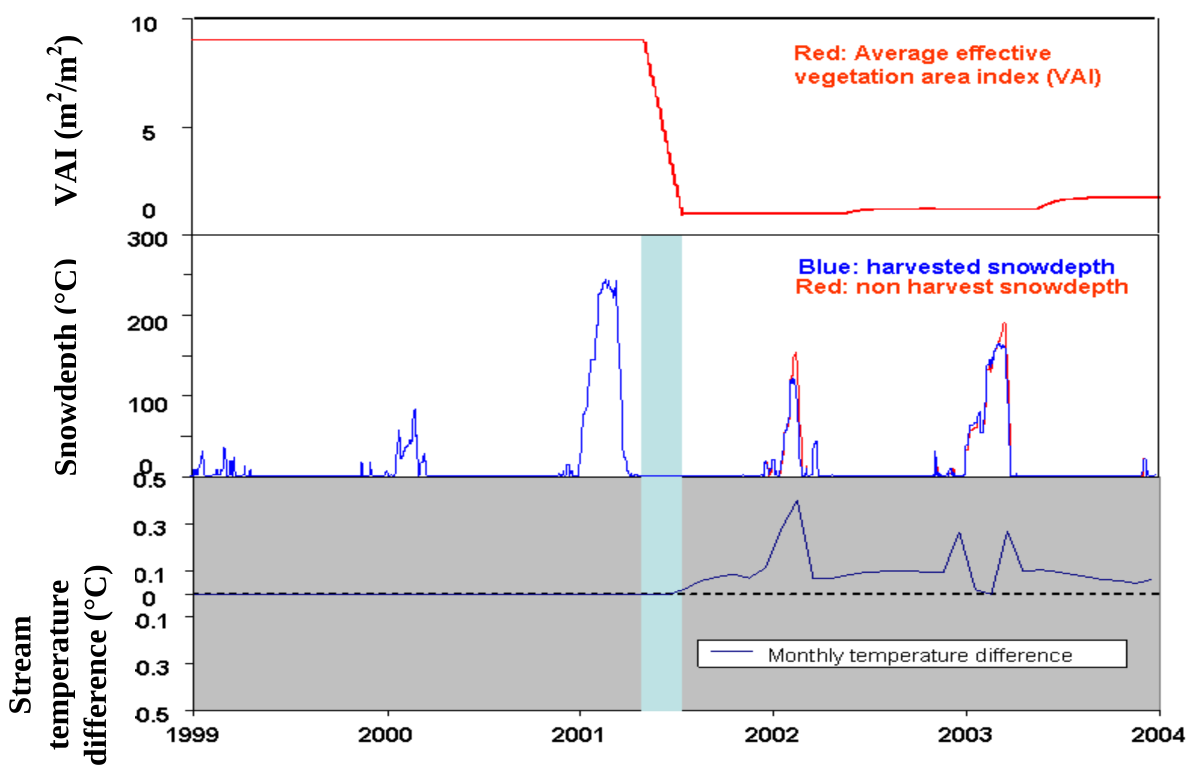

Figure5.15 Pockwock-Bowater pre- and post-harvest snow depth and stream temperature difference. Shaded area shows time of harvesting.

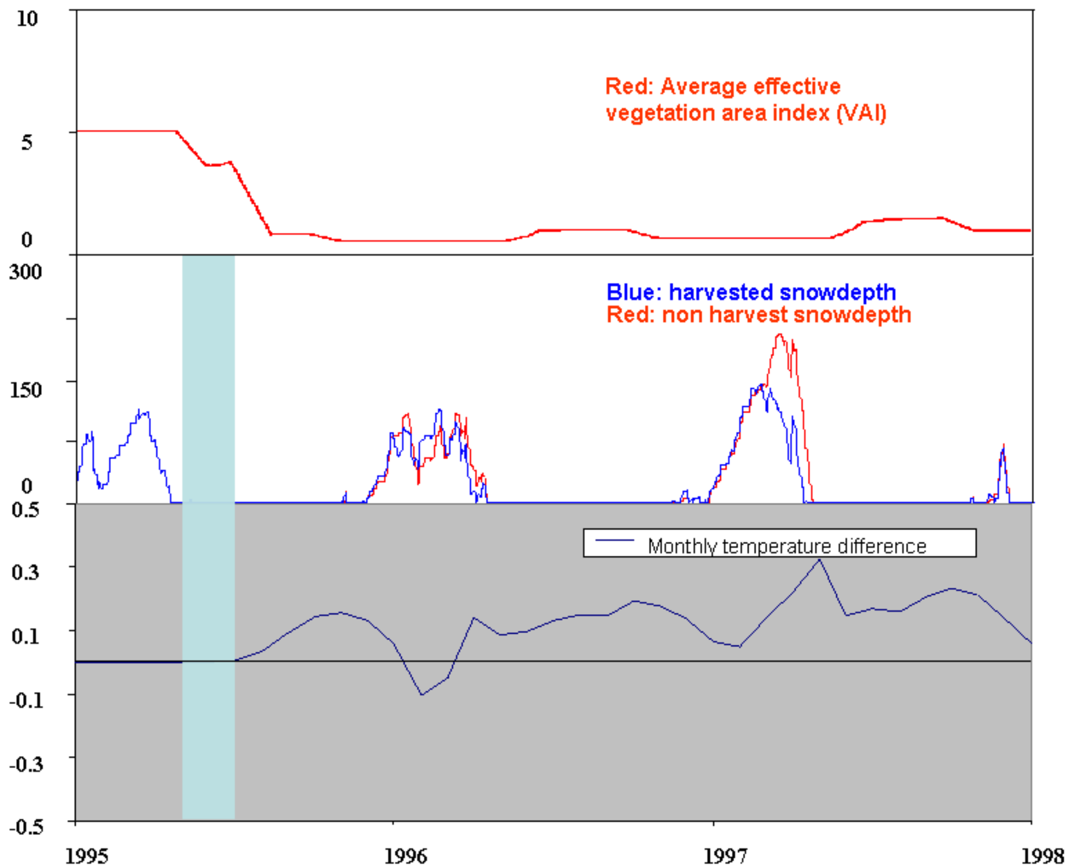

Figure5.16 Hayward Brook Pre and post harvest snow depth and stream temperature difference. Shaded area shows time of harvesting

CONCLUSIONS

The stream temperature, according to the field experiment and the model simulations showed the following seasonal patterns:

(1) Stream temperatures are slightly higher during summer and lower during winter for both study areas.

(2) The summer variations of the Pockwock – Bowater stream temperatures are somewhat larger than those of the Hayward Brook area.

(3) Pockwock – Bowater streams freeze in winter while Hayward Brook streams remain unfrozen.

(5) Harvesting makes the stream water of the Pockwock area less frigid during winter, while the opposite is calculated to occur of the Hayward Brook area.

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CHAPTER 6

STREAM-WATER DISSOLVED OXYGEN

INTRODUCTION

Dissolved oxygen concentration is one of the principal determinants that govern water quality and health of forest streams and lakes. A sufficient supply of dissolved oxygen (DO) is vital for all higher aquatic life (Cox, 2003). In general, oxygen enters stream water in three ways: (1) Oxygen is released in-situ as a by – product from aquatic plant photosynthesis during each day. At night, continued biological oxygen demand reduces the dissolved oxygen level; at dawn, dissolved oxygen levels are typically lowest. In this case, temperature is an important factor: biological oxygen demand increases with increasing temperature, and cold water holds more oxygen than warm water. (2) Oxygen from the atmosphere is mixed into the water through turbulence and through diffusion. The faster the flow, the more dissolved oxygen enters the water. (3) Oxygen is already part of the water as the water enters the stream.

Although field observed data can provide useful information for scientific research, many of the DO responses to weather conditions, geography, human behaviour, and hydrological change are mostly unknown due to difficult or impossible field measurements. Thus, the dissolved oxygen simulation linked with the watershed hydrology model is fundamentally important to

- fill data gaps when field equipment is down,
- calculate dissolved oxygen concentration when management activities expect more data beyond the range of observed field data,
- understand the dissolved oxygen responses to weather conditions,
- understand the dissolved oxygen responses to geographic conditions.

In this case, mathematical models simulating dissolved oxygen must be formulated to give a more dynamic method for research.

The objective of this chapter is to

- find out the principal parameters that can control the rise and fall of stream dissolved oxygen
- explain the modeling strategy of stream dissolved oxygen concentration
- add stream dissolved oxygen simulation to the existing ForHyM model
- test the reliability of the dissolved oxygen model using data from the Pockwock-Bowater watershed, NS and the Hayward Brook watershed, NB.

MODELING STRATEGY

A number of biogeochemical processes control the DO concentration in streams, for example, reaeration, photosynthesis, respiration, nitrification, and sediment oxygen demand (Chapra. et. al., 1998). Most of these field measurements are impossible to get, as usually data collection is a general survey of water quality conditions in the stream system and not the development of a water quality model. This problem forces modelers to use simplified model description with less input and parameters (Radwan et. al., 2003). It is hypothesized that, for small streams, dissolved oxygen concentration is mostly dependent on stream water temperature and the rate of stream flow. Warmer water holds lower amounts of dissolved oxygen while the solubility of oxygen in water increases with colder water temperatures. Also, in fast-moving streams, water is aerated by bubbles as water flows over rocks and gravel beds. For slow moving streams, oxygen enters into water through diffusion, and is not as easily replenished. Water that enters the stream from groundwater is generally oxygenated, unless the groundwater originates from a poorly drained depression further upland. Since stream flow rate can be simulated by the forest hydrology model ForHyM for any particular forest situation, and stream water temperature of small streams can be equated to the temperature of the stream-adjacent soils, it follows that water DO concentration can be simulated for small forest streams with ForHyM, through calibration.

METHDOLOGY

Using observed and predictable data, the equation to calculate stream dissolved oxygen concentration is presented below:

$$DO = a - b * T_{Stream} + c * \log 10 \, (Rate_{Stream}) \qquad \text{(Eq. 6.1)}$$

where:

T_{Stream} = stream temperature (°C);

$Rate_{Stream}$ = Stream discharge rate (mm/day);

a = initial value of dissolved oxygen;

b = stream temperature coefficient;

c = stream discharge coefficient.

The equation was programmed in STELLA (High Performance Systems, Inc., 1998) as the new extension of the ForHyM model, which were calibrated with the field observations. Basically, all 8 catchments at the Pockwock-Bowater and Hayward Brook watersheds use the same equation, but as dissolved oxygen concentration is geologically specified, each catchment was calibrated separately.

RESULTS AND DISCUSSION

The dissolved oxygen concentration in the Pockwock-Bowater study area and the Hayward Brook study area were simulated for a period of 4 years. The dissolved oxygen calculations were performed on a daily basis. In Figure 6.1 and Figure 6.2, the simulation results are compared with the observations for the complete simulation periods. Some years of the observed data were excluded from the simulation results because of the inaccurate field measurements (see Chapter 3). The figures indicate that the general performance of the model is satisfactory in terms of the magnitude of the concentrations and their variability in time. This means that the long term statistics of the modeled concentrations seem to be realistic (Fig 6.3 and 6.4). For specific time moments, the model shows important over- and underestimations of the concentrations. This is due to sources of uncertainty sources involved in the modeling process. Apart from the parameter calibration, uncertainties also arise from the precipitation and temperature data, the hydrological model of the stream temperature simulation, and the dissolved oxygen concentration measurements.

Model calibration is crucial for getting realistic predictions. It includes adjusting model parameters in order to get the best fitted simulations. The model needs to be run several times to get the general view of calculations. Calibration was finished by comparing the field data against model output until the outputs represented the field data well. Three coefficients in Eq.6.1 can be adjusted to get the best fitness.

Table 6.1 Max, min and average DO.

	Pockwock-Bowater				Hayward Brook				
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
Max	26	19.61	20.04	15.97	13.88	13.28	19.43	15.44	16.47
Min	7.08	6.23	1.65	3.05	7.45	7.06	8.56	7.34	8.28
Average Jan	16.51	15.07	17.56	12.72	13.17	11.85	18.47	13.41	15.17
Average July	9.26	9.16	4.35	4.83	8.99	8.13	11.53	9.8	9.99

Table 6.2 Calibration settings for stream DO parameters.

	Pockwock-Bowater				Hayward Brook				
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
a	23	15	19.8	15	12.3	12	19	14	16
b	0.85	0.51	1.2	0.7	0.3	0.3	0.6	0.4	0.45
c	500	500	200	500	100	200	10	150	10
Surface runoff	0	0	0	0	0	0	1	1	1
Infiltration in FF	1	1	1	1	2	2	2	2	2
Interflow in FF	0.2	0.2	0.05	0.2	0.005	0.25	0.05	0.05	0.05
Infiltration in A&B	1	1	1	1	2	0.1	2	2	2
Interflow in A&B	0.1	0.025	0.005	0.025	0.0005	0.0005	0.0005	0.0005	0.0005
Infiltration in C	1	1	1	1	2	0.1	2	2	2
Interflow in C	2	2	0.5	2	0.05	0.05	0.01	0.005	0.005

- a: This coefficient reflects the initial standard of DO concentration. It could be seen as the steady state, saturation concentration of dissolved oxygen at the local temperature and air pressure when the model is initialized.
- b: This coefficient adjusts the effect of stream temperature on the concentration of stream dissolved oxygen.
- c: This coefficient adjusts the effect of stream flow on the concentration of stream dissolved oxygen.

The model results illustrate that dissolved oxygen synchronizes closely with stream temperature, daily and seasonally. Within-catchment flow-path characteristics also influence stream dissolved oxygen. Surface-bound flow tends to have higher oxygen content in winter, and lower oxygen content in summer. For example, the streams of the Hayward Brook area likely receive much groundwater summer through winter, hence these stream have smaller variations in DO concentrations than the streams of the Pockwock-Bowater area.

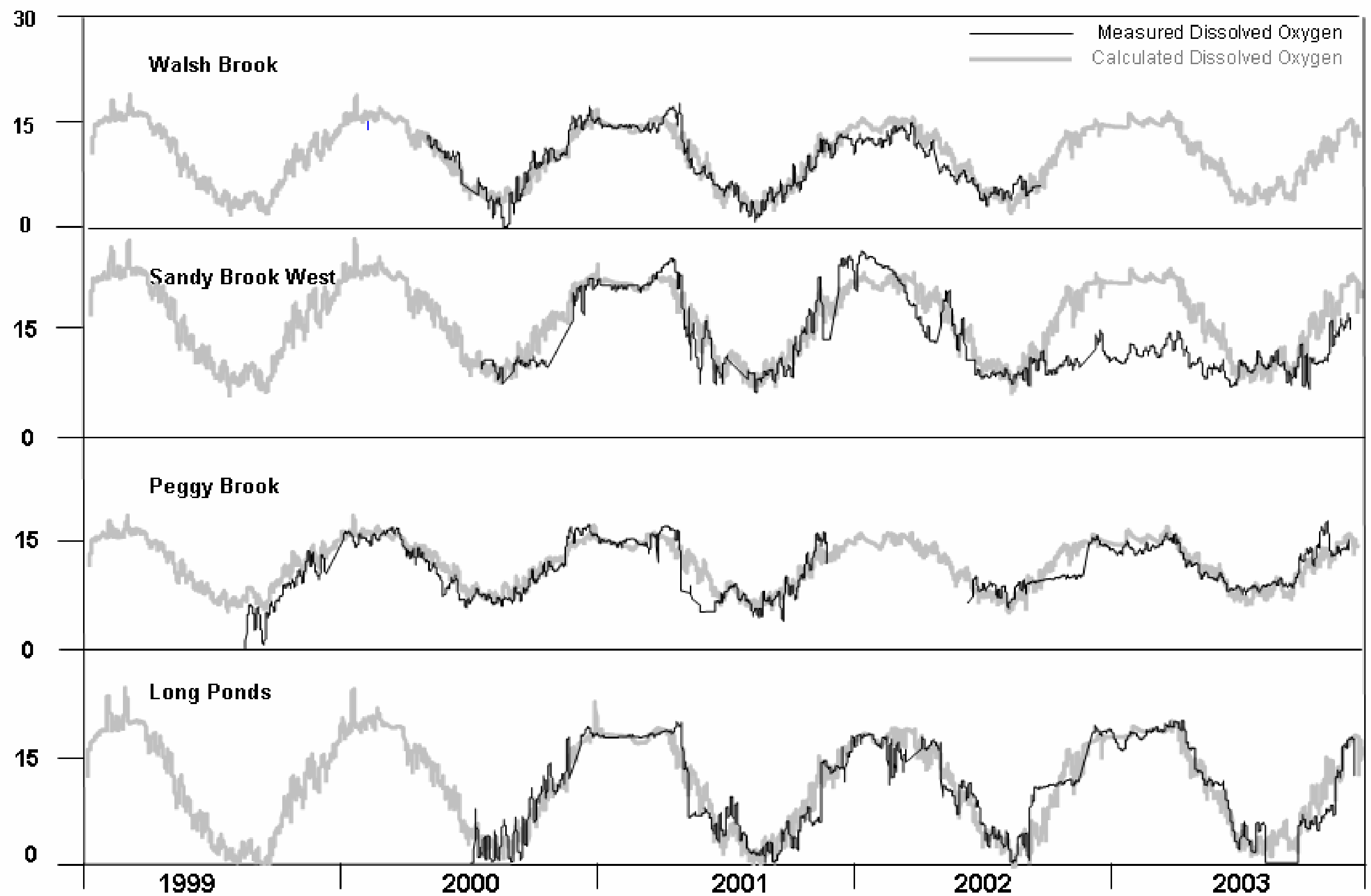

Figure 6.1 Actual and predicted stream DO, Pockwock-Bowater study area, NS.

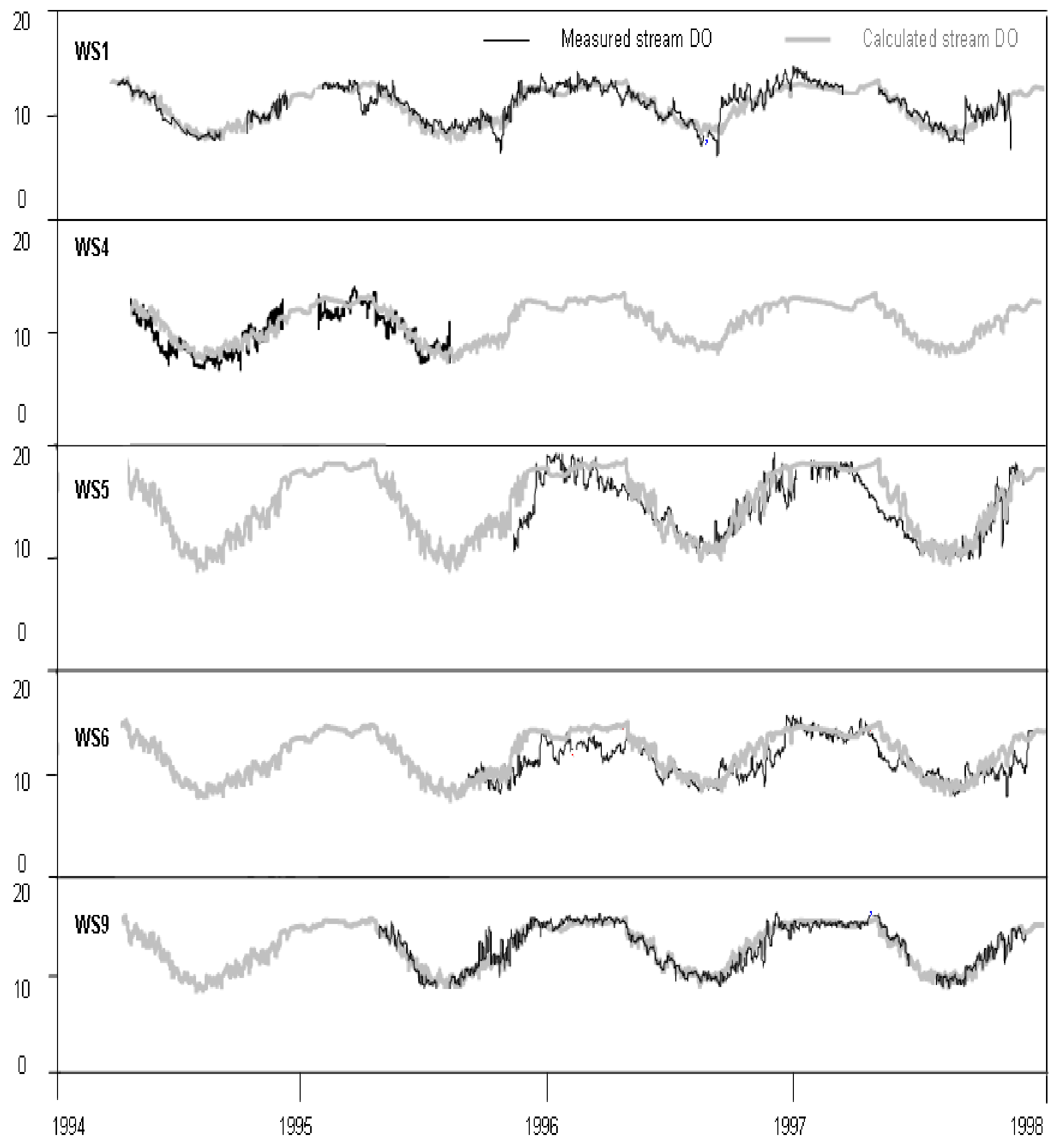

Figure 6.2 Actual and predicted stream DO, Hayward Brook, NB.

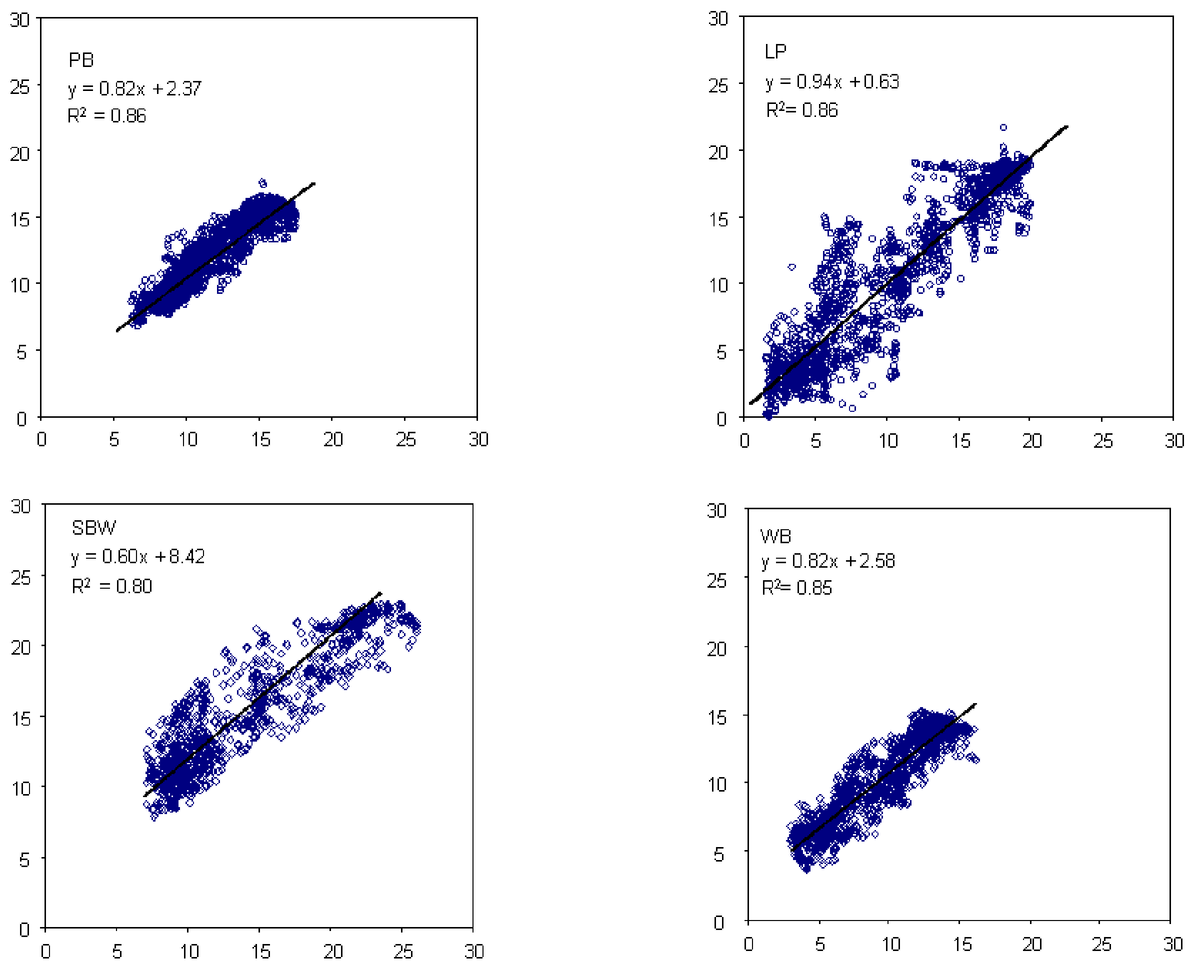

Figure 6.3 Actual and predicted stream temperature correlations with R^2 values, Pockwock-Bowater study area, NB.

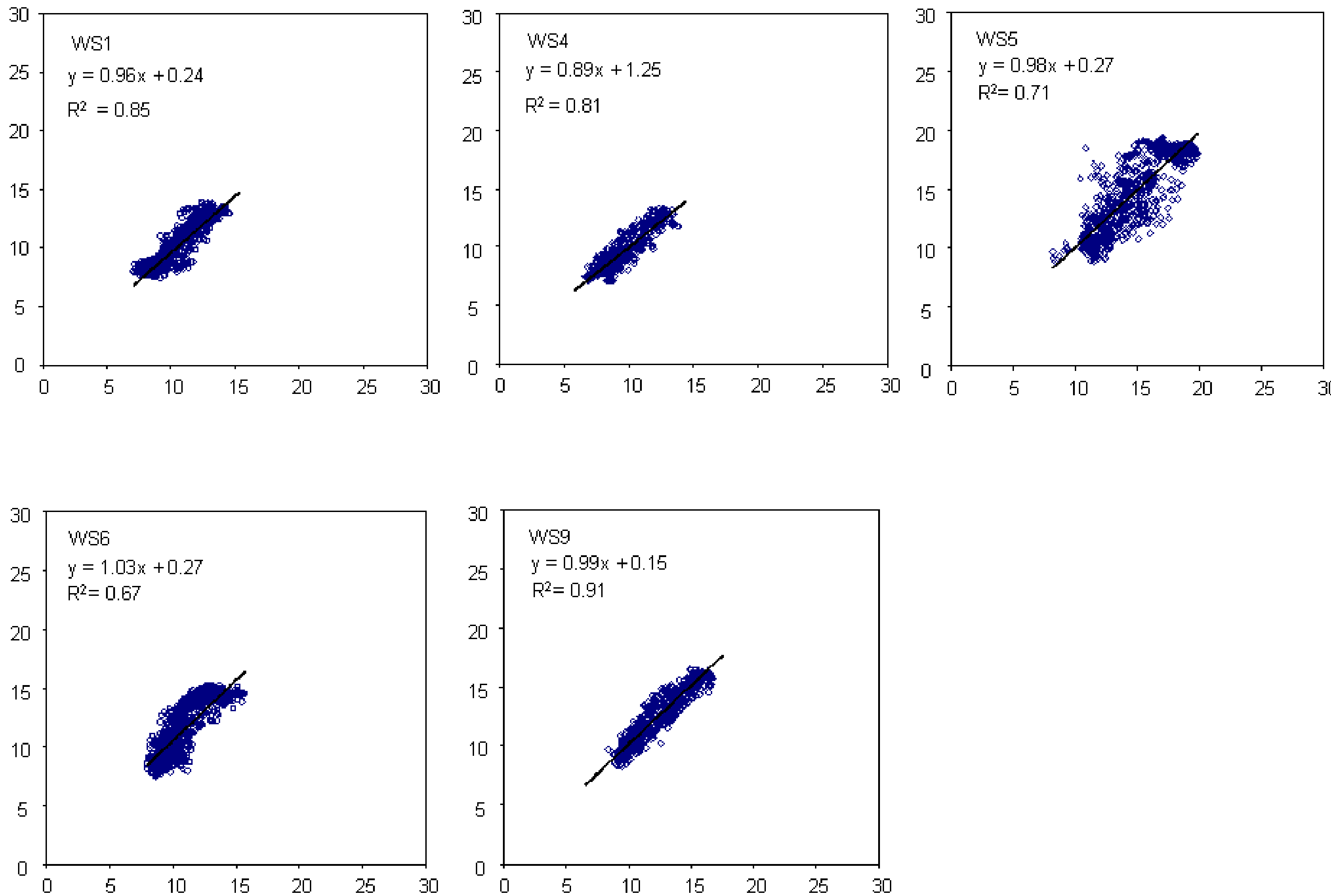

Figure 6.4 Actual and predicted stream temperature correlations with R^2 values, Hayward Brook study area, NB.

During the summer of 1995, harvesting occurred in Watersheds 1, 5, 6, and 9 at Hayward Brook. Sandy Brook West, Long Ponds, and Walsh Brook at Pockwock-Bowater were harvested in June 2000, March 2001, and June 2001, respectively. Watershed 4, Hayward Brook and Peggy Brook, Pockwock-Bowater were left as control areas without harvesting. A regression analysis was done to determine if harvesting would affect the post-harvest in-stream DO concentrations. This analysis was done in three steps:

1. Develop the pre-harvest stream-to-stream DO regression equations, using the control stream as the predictor variables for DO in the streams of the as yet unharvested basins
2. Use these regression equations to project what the DO concentrations would be in the streams of the basins if these basins had not been harvested
3. Compare the actual in-stream DO concentrations of the harvested basins with the DO predictions if the streams in the harvested basins had not been cut.

The following equations and related R^2 values were obtained for the in stream DO concentrations for the Pockwock area, using the in-stream DO concentrations of Peggy Brook as the predictor variable:

LP Stream = (-4.300+/-0.623) – (0.054+/-0.098)* PBDO – (2.244+/-0.250) *sin[2π (yearfraction - 0.3)] + (1.364+/-0.096) * SmthPBDO – (0.050+/-0.226) Summer Harvest – (0.591 +/- 0.221) Winter Harvest**,** R^2 = 0.771.

SBW Stream = (4.728+/-0.570) + (0.674+/-0.082) * PBDO – (2.078+/-0.235) * Sin(2π

(yearfraction-0.3)) +(0.293+/-0.083) * SmthPBDO – (1.560+/- 0.193)

Summer Harvest – (4.286+/-0.232) Winter Harvest, $R^2 = 0.834$

WB Stream = (-0.943+/-0.229) + (0.657+/-0.036) * PBDO – (0.311+/-0.094) * sin[2π

(yearfraction- 0.3)] + (0.325+/-0.035) * SmthPBDO – (1.734+/-0.085)

Summer Harvest – (2.725 +/- 0.122) Winter Harvest , $R^2 = 0.956$

As indicated by the R^2 values, the regression equations represent 77 to 96% of the in-stream DO concentrations within the treatment basins before harvesting. The resulting comparison between actual post-harvest in-stream DO concentrations relative to the DO concentrations projected according to the above equations for the Pockwock-Bowater area are shown in Figures 6.5. In general, no systematic differences are apparent from this comparison. This lack is most likely due to the difficulty in obtaining DO data that are sufficiently consistent from sensor calibration to sensor calibration. Lack of consistency is indicated by a number of features in the plots of Figure 6.5:

1. Unlike the records fort the in-stream temperatures, many parts of the DO concentration tracks were found to be unreliable and have to be dropped, due to frequent DO sensor failings.
2. Sensor failures were also indicated stream-to-stream DO inconsistencies, and erratic data.

For the Hayward Brook, there were even more data inconsistencies including the missing pre-harvest DO data for the control watershed WS4.

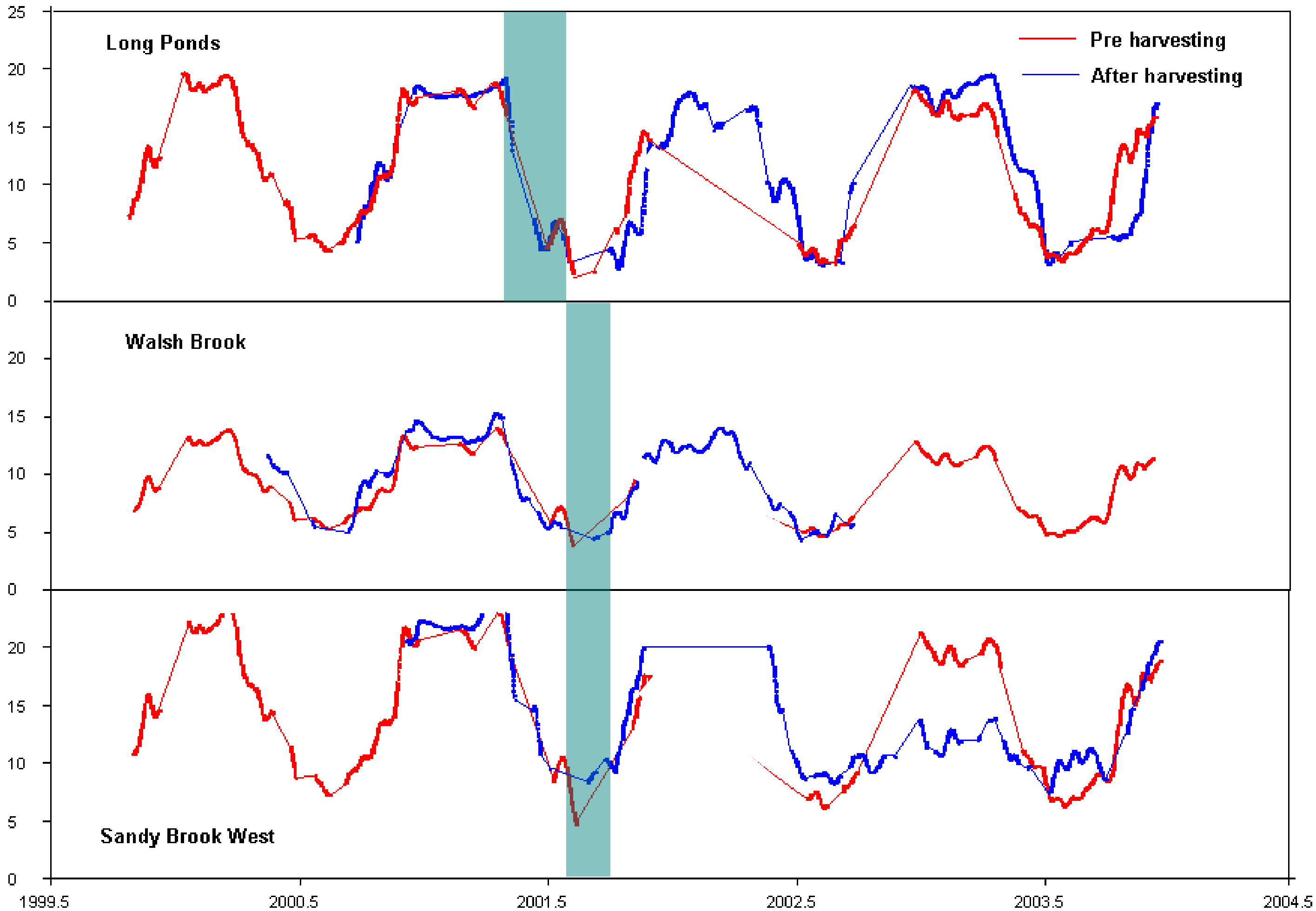

Figure 6.5 Pre and after harvest DO, Pockwock-Bowater, NS. Shaded area shows time of harvesting.

In view of these data shortcomings, the effort moved from data analysis to data re-construction, using the above regression equations. The purpose of the data re-construction was to create a continuous record of daily data based on the existing stream-specific DO data track that were found to be reliable. This re-construction was done in two ways

1. using the above stream-to-stream regression equations;
2. using Equation 6.1.

The results for the regressions and Equation 6.1 are shown in Figures 6.6 and 6.1. As shown, this data re-construction represent the DO trends across the seasons by stream quite well, with the stream-to-stream regression results representing actual DO variations more closely than the smoothed model (Equation 6.1) results. However, the data re-construction does not reveal any consistent pre- to post-harvest DO differences. For example, the resulting model differences between post-harvested and non-harvested DO concentrations in Figure 6.8 reveal no systematic differences for the Hayward Brook study area, and only small, season-dependent differences of up to 0.5 mg/L (max. in summer, and min. in winter) for the Pockwock-Bowater area. These small differences are likely an artifact of the log (discharge) component of Equation 6.1, because log (discharge) would exaggerate the influence of small post-harvest increases in stream discharge rates on DO, especially during summer when stream discharge rates are very low.

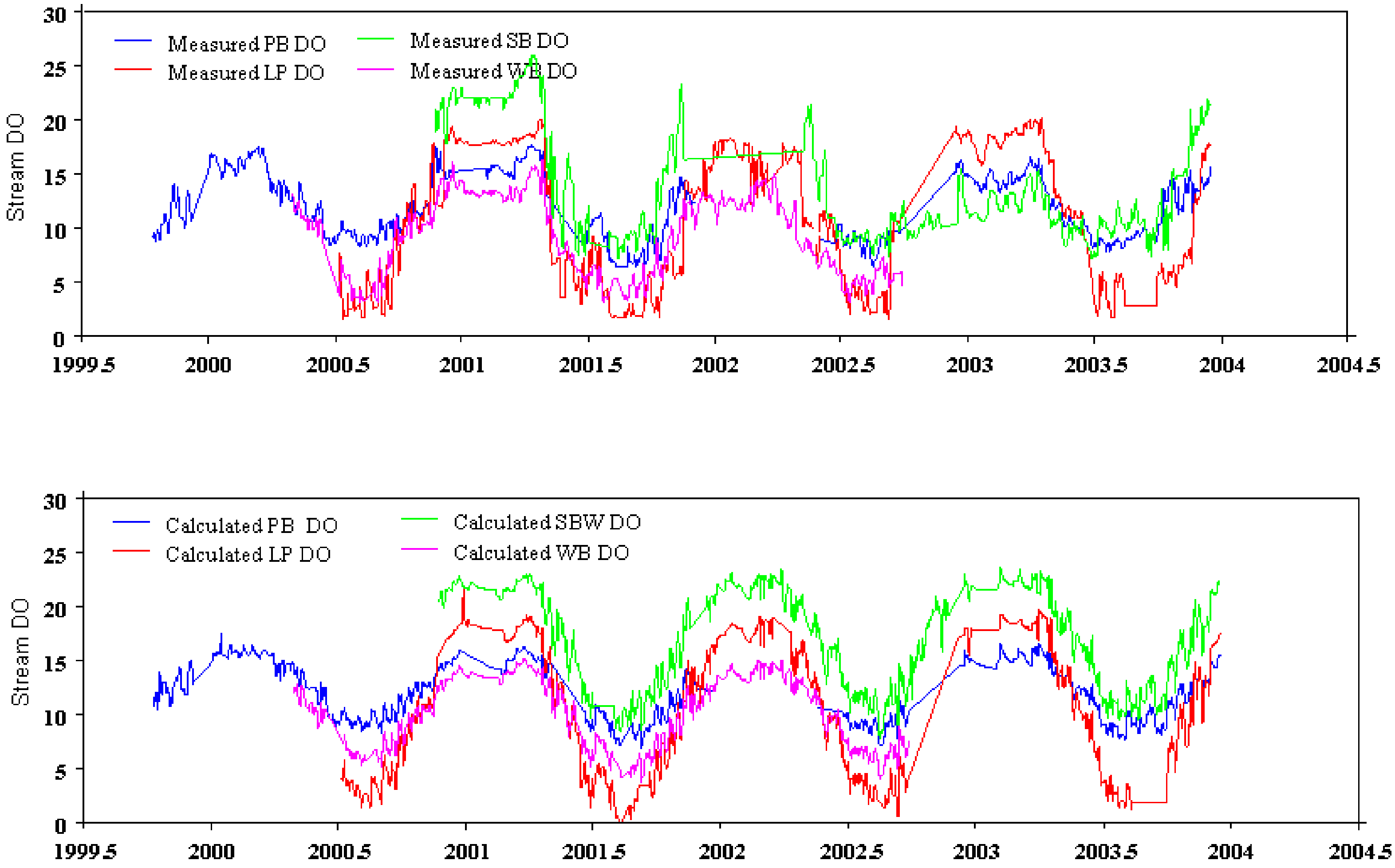

Figure 6.6 Inter-catchment stream DO comparisons, Pockwock-Bowater, NS.

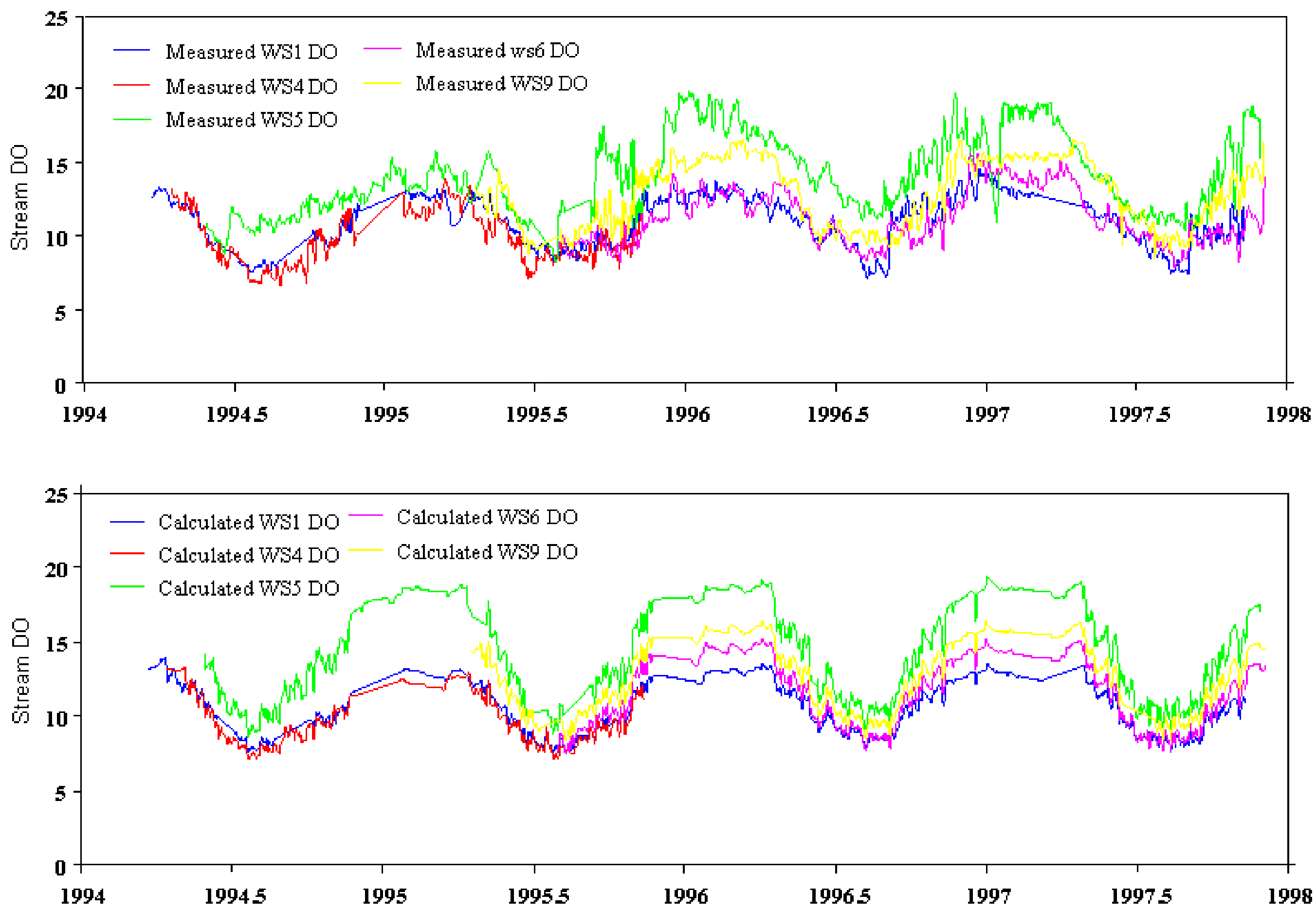

Figure 6.7 Inter-catchment stream DO comparisons, Hayward Brook, NB.

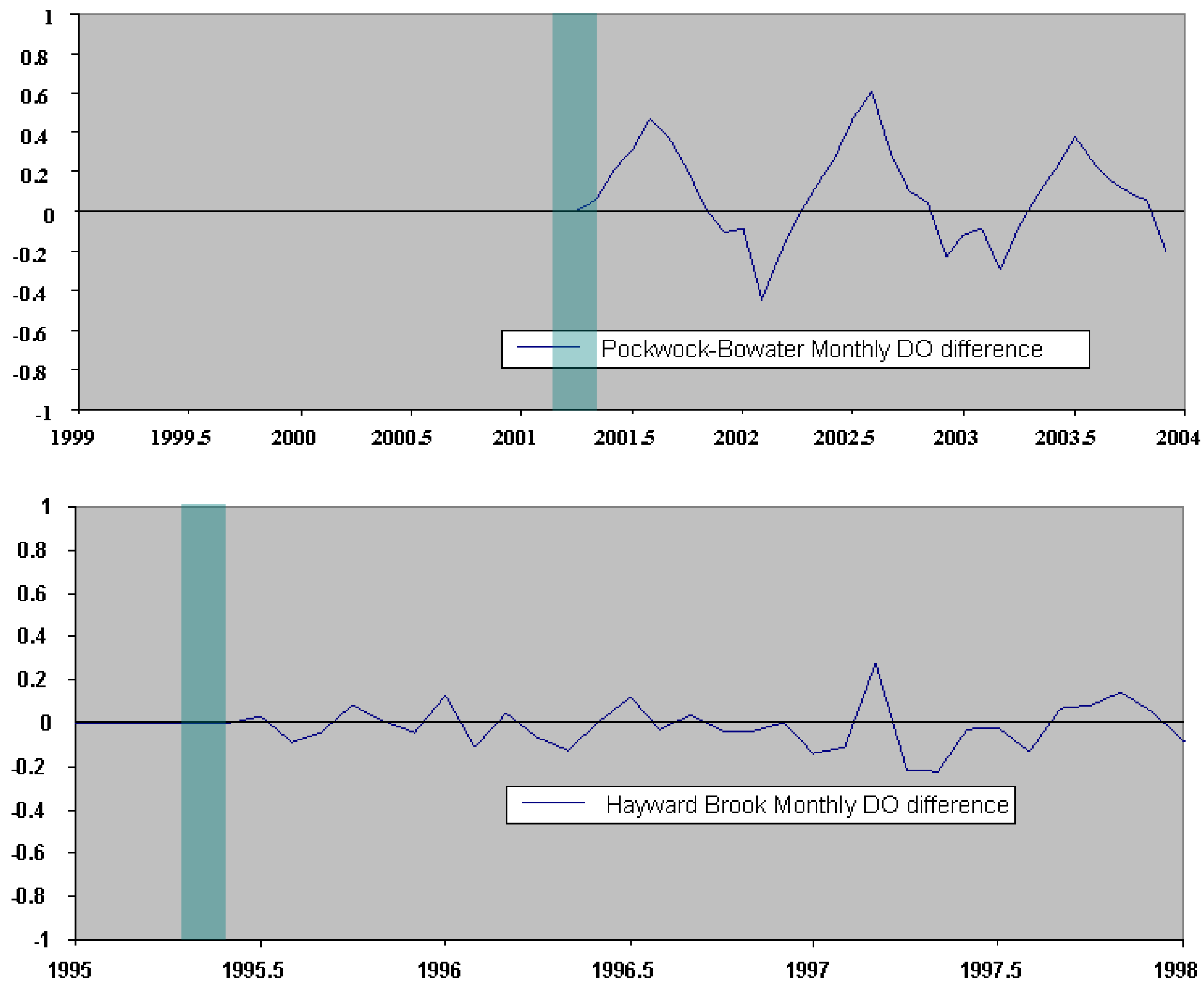

Figure 6.8 Pockwock-Bowater and Hayward Brook Pre and post harvest stream DO difference.

The small modeled DO effects for the Pockwock-Bowater area and the lack thereof for the Hayward Brook area is due to the general flow pattern differences between these two study areas: being more surface controlled in the Pockwock-Bowater area than in the Hayward Brook area, as apparent from the calibration differences for the b and c coefficient of the proposed in-stream model (Table 6.2). The lack of strong post-harvest trends in the DO concentrations would suggest that in-stream DO concentrations are not much affected by forest harvesting. This is undoubtedly due to the fairly small post-harvest temperature effect, as shown and discussed in the preceding Chapter.

CONCLUSION

The dissolved oxygen concentration in the Pockwock – Bowater study area and the Hayward Brook study area were simulated for a period of 4 to 5 years. Observed daily precipitation and air temperature data were used. Observed stream discharge data were used to calibrate ForHyM model hydrological flow calculations. The dissolved oxygen calculations were performed on a daily basis. In Figures 24 and 25, the simulation results are compared with the observations for a complete simulation period. Figures 26 and 27 indicate that the general performance of the simulation is satisfactory in terms of the magnitude of the concentrations and its variability in time.

This study suggests that stream dissolved oxygen can be simulated with the more consistently monitored and modeled stream temperature and discharge variables, with fairly good reliability. For different study areas with various soil texture and drainage characteristics, streams receiving groundwater for the most part would experience lower dissolved oxygen variations across seasons than streams receiving surface water for the most part. The study also suggests that harvest effects on in-stream DO concentrations might occur, but such differences would be quite small, and would not be easily detected, especially not with DO sensors that require frequent servicing and adjustments, including membrane replacements.

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CHAPTER 7

STREAM-WATER PH

INTRODUCTION

Stream acidity or pH has been adopted as a general indicator of the resilience of watersheds and streams against soil acidification in general and atmospheric acid deposition specifically (Bastarache et al., 1996). To that end, continuous monitoring of stream pH could – at least in principle – reveal much about the acid buffering in catchments, as these would vary with substrate type, vegetative cover, topography, soil moisture regimes, daily and seasonal changes in weather, and surface disturbances such as forest harvesting. The purpose of this Chapter is to present and discuss the daily pH records that were generated for each of the 9 streams of the Pockwock-Bowater (for 5 years) and Hayward Brook (for 4 years) study areas. The specific objectives of this chapter are:

- to propose a simple model that relates in-stream pH values to daily hydrothermal variations within soils adjacent to the streams;
- to calibrate this model with the daily in-stream pH data obtained from the Pockwock-Bowater Watershed and the Hayward Brook Watershed Projects;
- to incorporate this model as part of the Forest Hydrology Model ForHyM.

MODELING STRATEGY

Water enters into streams from adjacent soils and subsoils as surface run-off, interflow, or base flow. Once in the stream, the water remains in close contact with the adjacent soil as the water trickles along small and narrow channels, and often branches and combines again in the flatter portions of upslope reaches. During high water conditions, most of the water that flows towards the streams and in the streams is at or close to the organic soil surface layers, which - in the vicinity of the flow channels - are particularly thick, moss-covered and acidic. When the water table drops during the summer on account of basin-wide evapotranspiration, most of the percolating water moves through the less acidic layer of the mineral soil, the subsoil, and aquifers, especially along the regolith-bedrock interface. In addition, upslope depressions and flow channels may dry out so that the overall contact of stream water with the sacrificial soil layers is quite low to absent during summer, depending on the extent of the water table drop. Since soil water table fluctuations can be simulated with ForHyM, it follows that stream water pH can, in principle, be related to the modeled water table fluctuations, through calibration. In general, soil pH is lowest in the forest floor (as low as 3 in some cases), and then increases gradually towards neutral or near-neutral levels with increasing soil depth (Yanni, 1996). Therefore the higher the soil water table is, the lower the pH should be. It is assumed that pH of the soil water and pH of the soil that the stream water contacts before entering the stream and remains in at least partial contact while flowing down the stream are about the same.

METHODOLOGY

The following equation is proposed for the simulation of in-stream pH:

$$\text{In-stream pH} = ax^2 + bx + c \quad \text{(Eq. 7.1)}$$

With a, b, c as adjustable coefficients subject to calibration, and $x = \log_{10}$ (water table_ fluctuation (Chapter 4). The pH-model calibrations were done were based on the data deemed to be reliable. Data reliability or quality assurance assessments were performed by stream-to-stream regression analysis and related time-series and residual analyses. In general data quality ranged from acceptable to poor, depending on pH sensor performances. These could at times be erratic, drifting (upward or downward), jump from on data track into another, or be missing altogether due to poor weather conditions (ice) and vandalism (Walsh Brook, 2003), especially on account of interchanging the pH sensors among the measurement (Smith et. al., 2005). All erroneous data were either eliminated or corrected by adjusting for consistent drifts and jumps. Missing data were substituted where ever possible by way of stream-to-stream regression analysis (Chapter 3). The resulting, quality-checked in-stream time-series data were then compiled, and used for stream-by-stream evaluations (means, ranges) and for determining the above a, b and c coefficients.

RESULTS AND DISSCUSION

Average in-stream pH values and corresponding maximum and minimum values are listed in Table 6.1, by stream and study area. Clearly, the stream water for the Pockwock-Bowater area is considerably and consistently more acidic than the stream water in the Hayward Brook area, by 2 to 4 pH units. Furthermore, in-stream pH values change considerable within the streams over the course of the study periods, with some streams more variable than others. For example, stream pH within the Walsh Brook varied from 3.83 to 6.63, while HS5 only varied from 6.74 to 7.65. In general, in-stream pH values were moore variable for the Pockwock Bowater area than the Hayward brook area. Greater acidity and greater acidity variations are undoubtedly related to the contrasting hydrological flow patterns within the two study areas: mostly at or near the soils surface within the Pockwock Bowater area, and deeper through soils and subsoils within the Hayward Brook area.

Table 7.1 In-stream pH summary.

	Pockwock-Bowater				Hayward Brook				
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
Max	5.75	5.42	5.88	6.63	7.27	7.49	7.65	7.73	7.53
Min	3.78	3.93	4.11	3.83	6.12	5.94	6.74	6.41	6.25
Average	4.37	4.35	4.37	4.63	6.75	6.65	7.34	7.19	6.99

Calibrating Equation with the in-stream pH variations for all of the streams of the two study areas produced the results for the, b and c coefficients in Table 6.2. For the Pockwock-Bowater area, the a coefficient dropped to zero, which means that the in-stream pH values were more or less linearly related to the ForHyM calculations for the water table fluctuations. The calibrations further showed the pH values of Peggy Brook to be most acidic, and confirmed the pH values of Walsh Brook to be the most variable. This suggests that the subsoil of the Walsh Brook basin contains more acid buffering minerals than the other 3 basins for the Pockwock-Bowater area. For the Hayward brook area, the relationship between the in-stream pH values and the calculated water table fluctuations are somewhat curvilinear, suggesting pH saturation values between 7.85 and 9.05 when water tables are fairly low, which is close to the pH of a saturated carbonate system.

Table 7.2 Calibration settings for stream pH parameters.

	Pockwock-Bowater				Hayward Brook				
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
a	0	0	0	0	-0.2	0	-0.3	-0.49	-0.67
b	-1.02	-0.72	-0.73	-1.35	-0.02	-1.5	0.42	0.46	1.17
c	6.26	5.78	6.24	7.3	7.85	10.5	8.12	9.05	8.46

The best fitted results for stream pH for the Pockwock-Bowater watershed and the Hayward Brook watershed are shown in Figure 7.1 and 7.2. Considering the extent of pH data fragmentation, the best-calibrated stream-water pH still reproduced the usable portions of the observed pH variations quite well, with R^2=0.54 being the highest model conformance to the data. The inter-stream actual versus modeled pH scatter plots are shown in Figures 7.3 and 7.4. Altogether Figures 7.1 to 7.4 suggest that the quality of fit changes from poor to acceptable along the following sequence for the Pockwock-Bowater area:

Long Ponds pH > Sandy Brook West pH > Peggy Brook pH >> Walsh Brook

The poor data for Walsh Brook were undoubtedly due to frequent sensor malfunctions, and loss of equipment during the final year. Sensor malfunctions were also prevalent for

Sandy Brook West and Peggy brook, while mostly absent at the Long Ponds stream monitoring location.

For the Hayward brook area, quality of fit decreased along the following sequence: WS1> WS6> WS9>WS4 >WS5. In all cases, the modeled data followed the adjusted trends, by weather events, such that storm events caused quick in-stream pH depressions, followed by slow relaxation towards higher values. Seasonally, pH values were observed and modeled to be highest during summer (when water tables are low), and least during periods of high stream discharge, often during fall and spring, especially for the Hayward Brook area (all basins assumed to be harvested 100%, except the control basin). For the Pockwock-Bowater area, seasonal variations were less pronounced; presumably due milder winter conditions, and because the stream is mainly fed by surface- acidified water year-round.

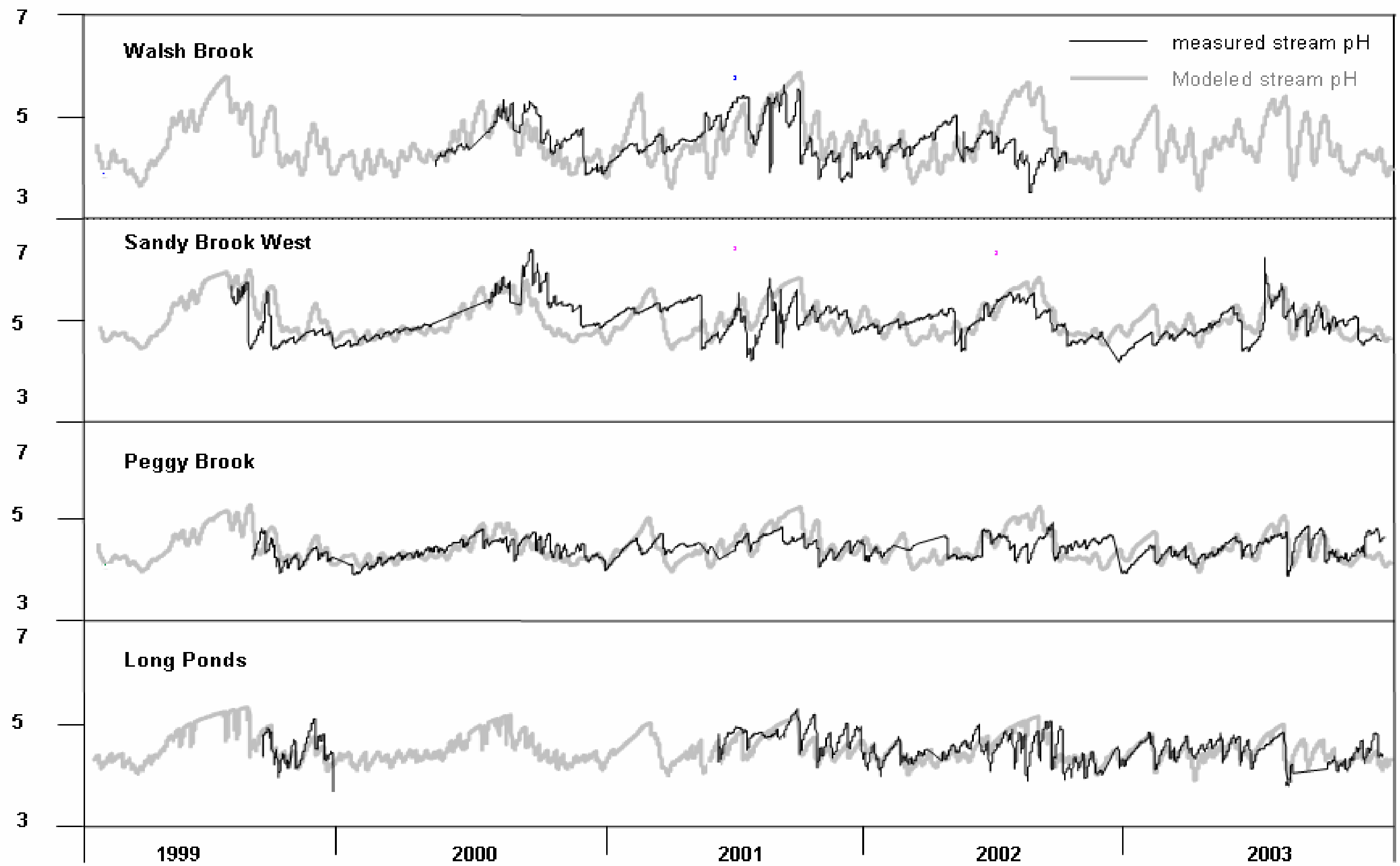

Figure 7.1 Actual and predicted stream pH, Pockwock-Bowater study area, NS.

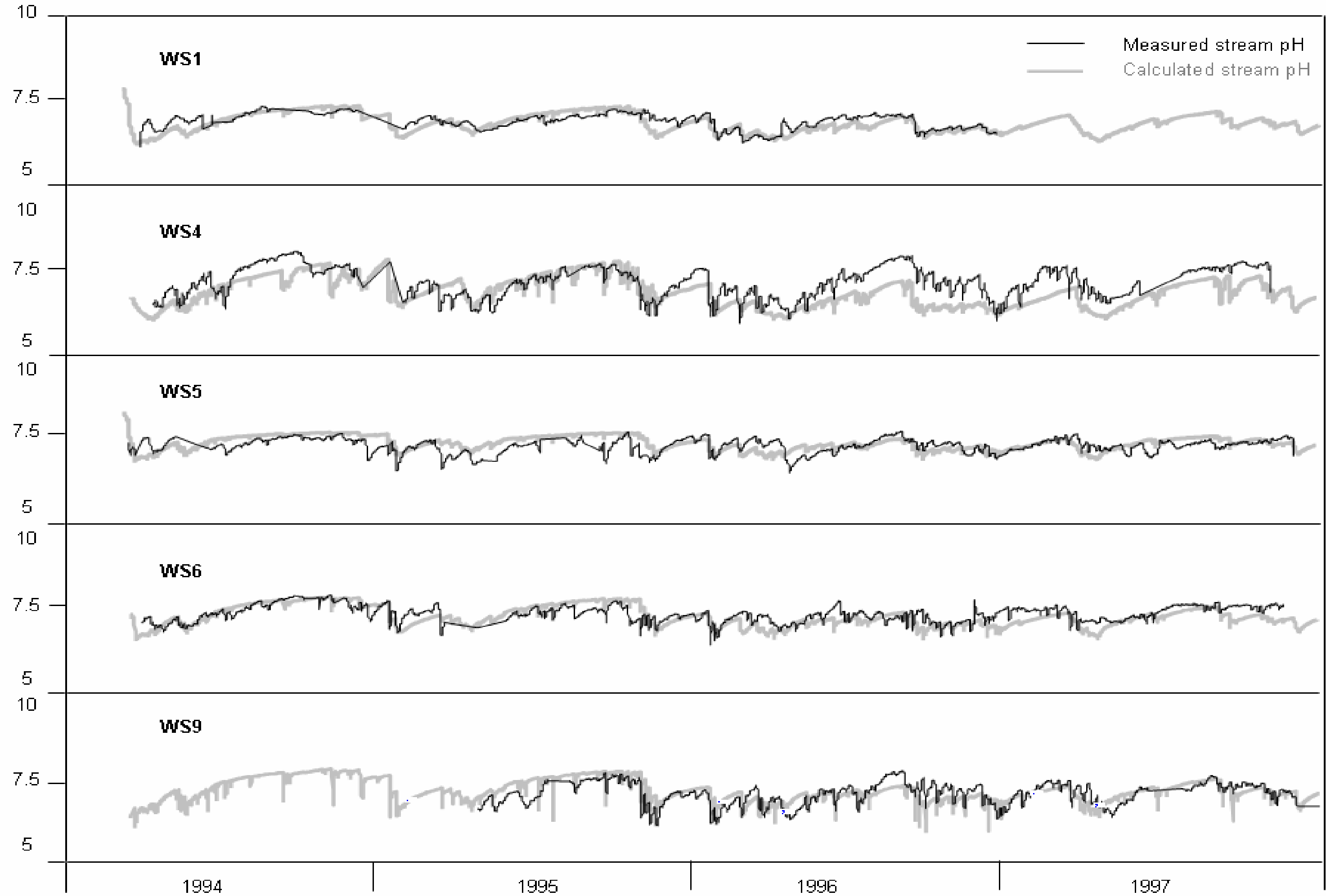

Figure 7.2 Actual and predicted stream pH, Hayward Brook study area. NB.

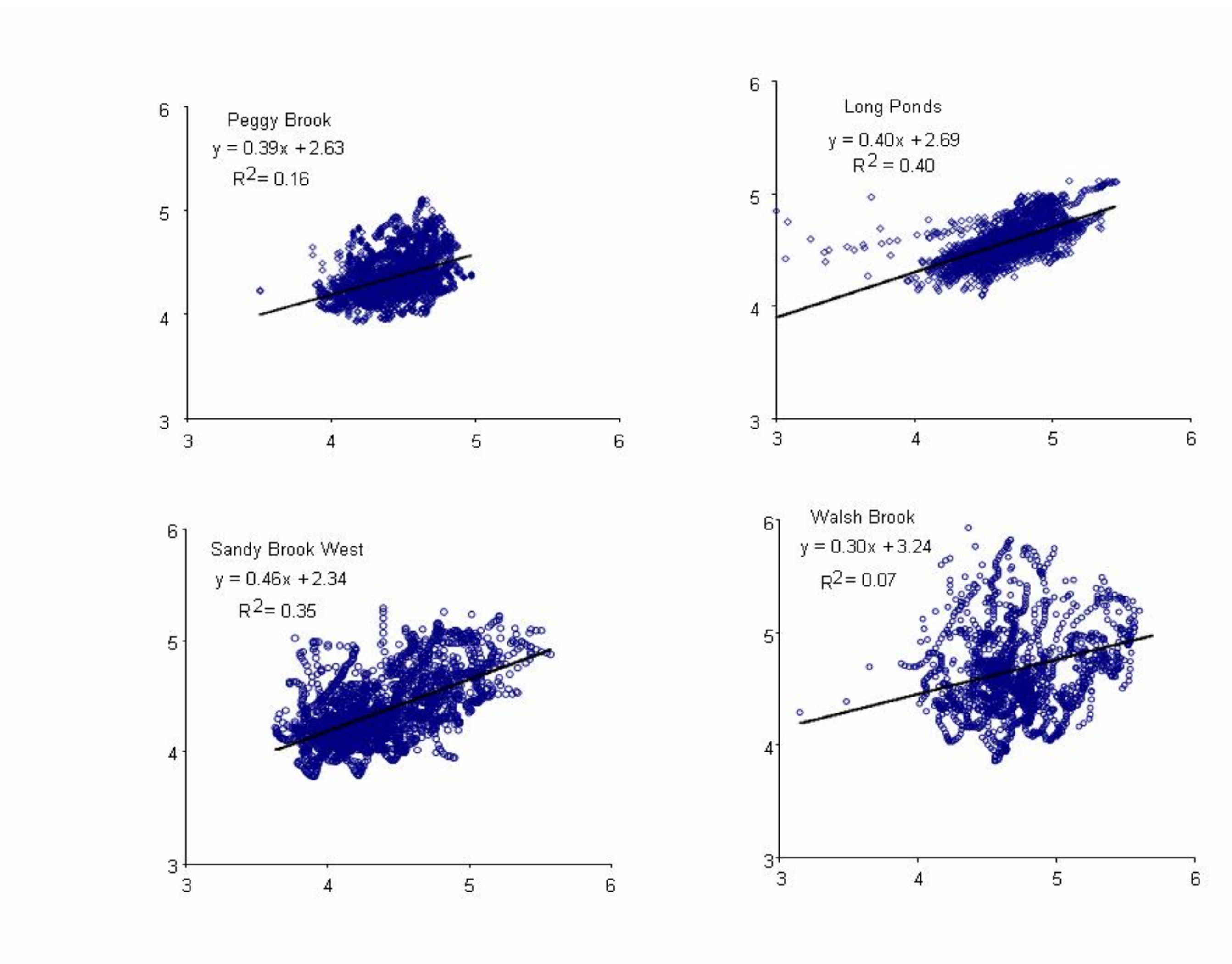

Figure 7.3 Actual and predicted stream pH correlations with R^2 values, Pockwock-Bowater study area, NS.

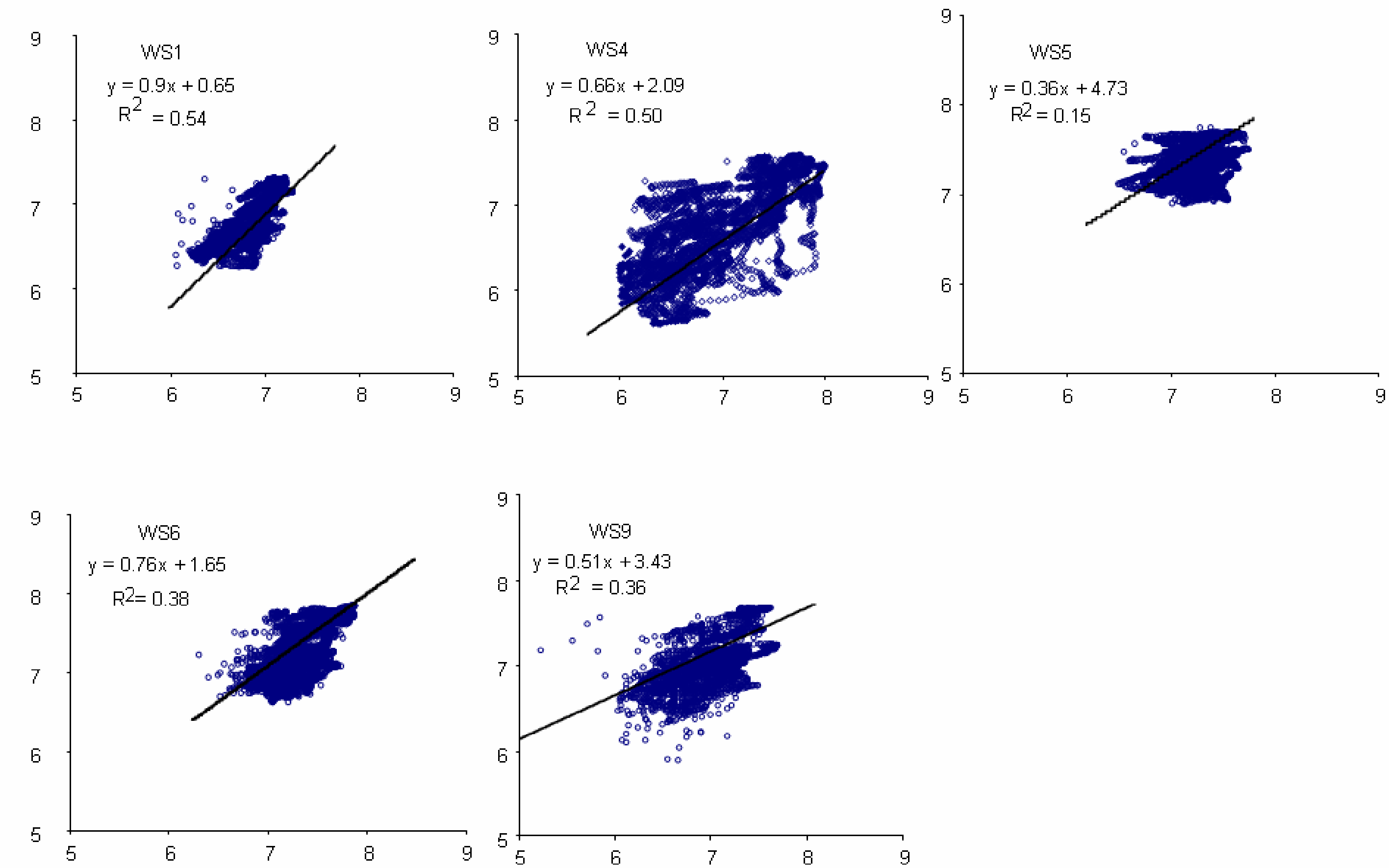

Figure 7.4 Actual and predicted stream pH correlations with R^2 values, Hayward Brook study area, NB.

Inter-stream comparisons of actual-versus-actual and modeled versus-versus-modeled in-stream values are shown in Figure 7.5 and 7.6 for all the nine streams, to further emphasize the in-stream-pH differences between the two study areas: sharp and rapid fluctuations for the Pockwock-Bowater area, and sharp decreases followed with slow and buffered relaxations for the Hayward brook area.

The extent of data fragmentation, however, did not allow for a direct empirical analysis of harvest-induced effects on in-stream pH values. Plotting the modeled differences between 100% harvested and non harvested basins, however, suggest that there would be post-harvest depressions in stream pH during summer at both locations, with the stronger and more persistent effects modeled for the Hayward Brook area than the Pockwock-Bowater area. These differences, as also shown in the same figures, is a numerical consequence of the extra post-harvest water amounts that would accumulate and flow through the post-harvest basins and on a account of the proposed connection of in-stream pH with the catchment specification fluctuations in the water table.

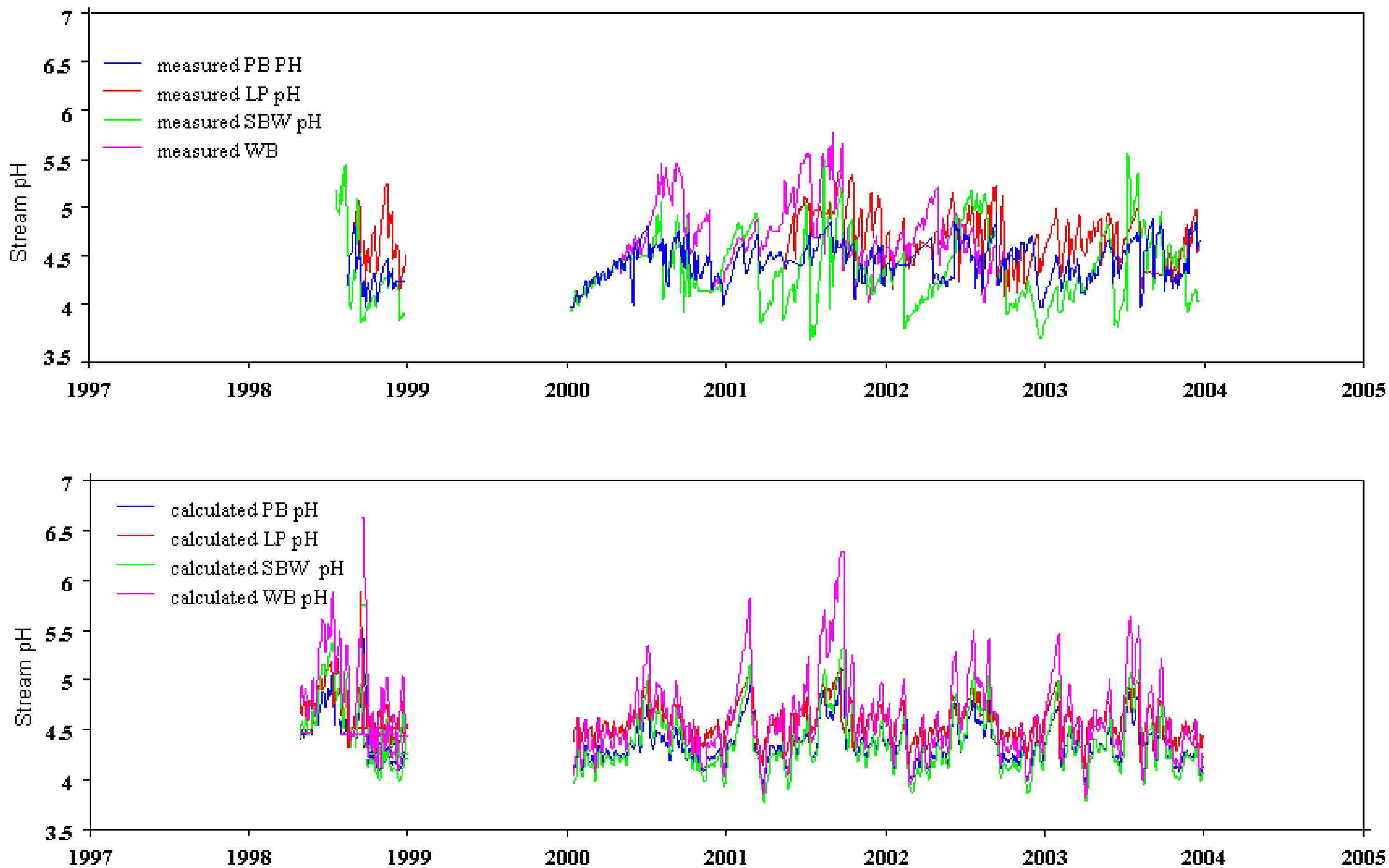

Figure 7.5 Inter-catchment stream pH comparisons, Pockwock-Bowater, NS.

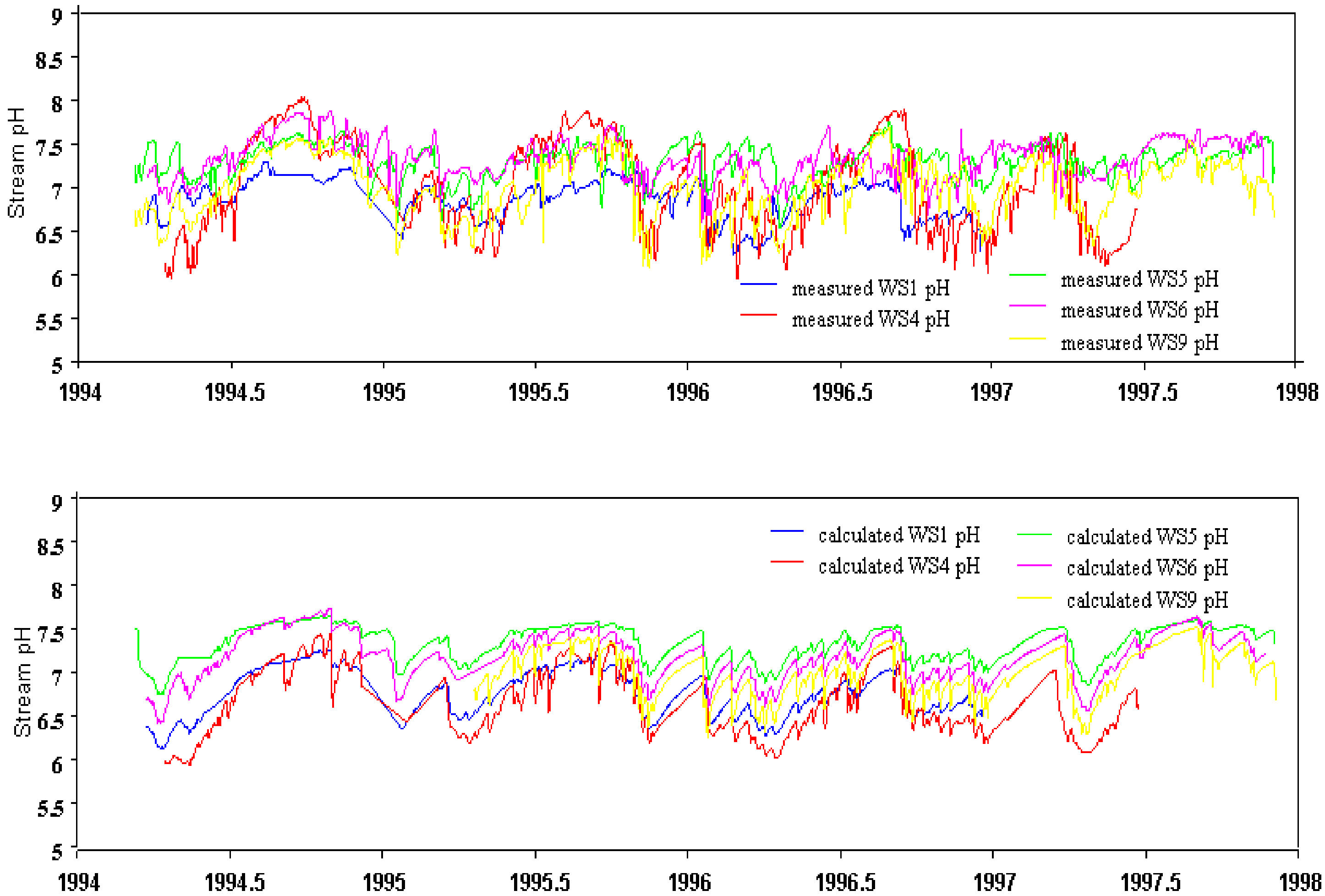

Figure 7.6 Inter-catchment stream pH comparisons, Hayward Brook, NB.

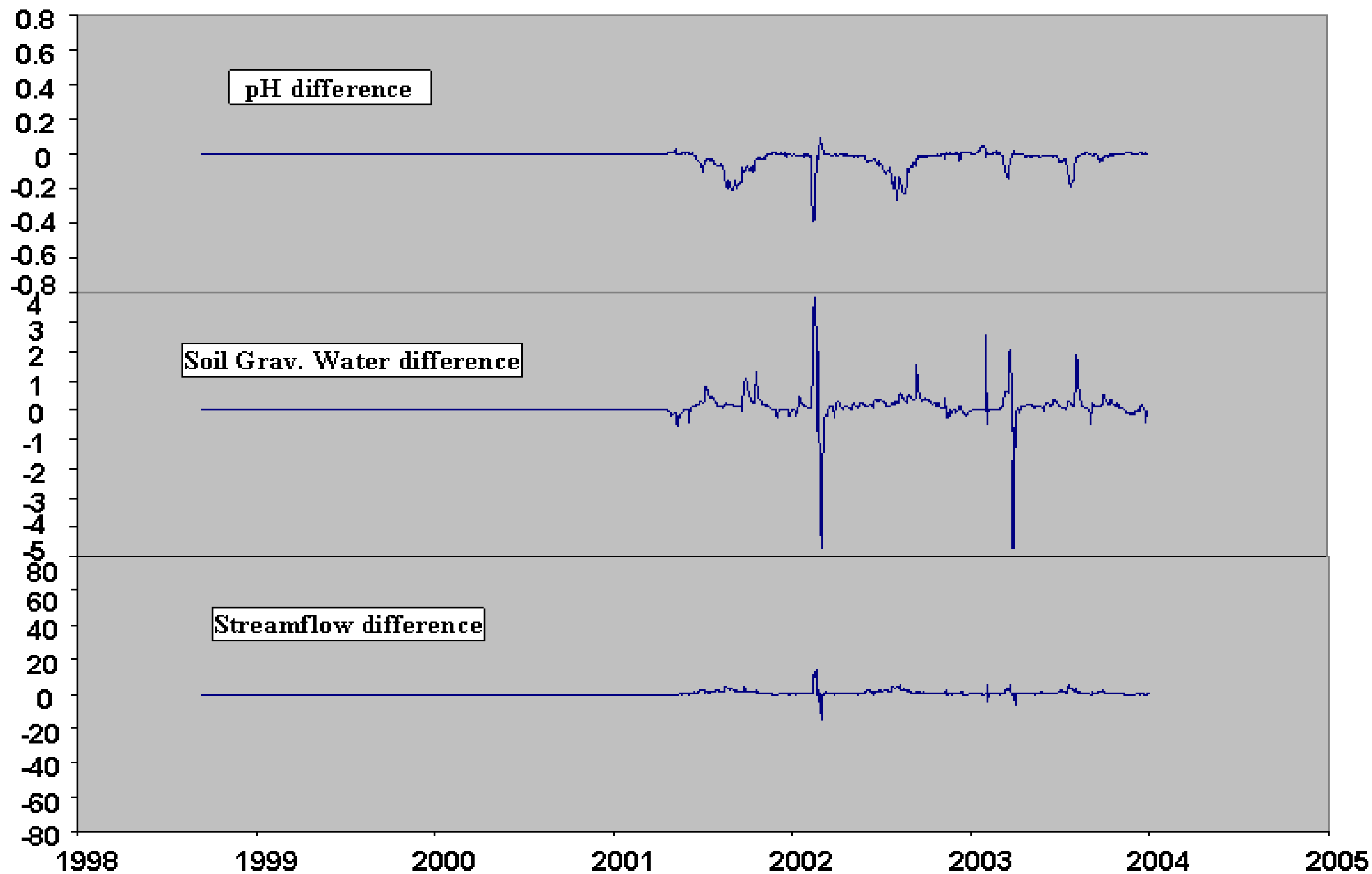

Figure 7.7 ForHyM simulated pre and post harvest difference of pH, soil gravitational water and streamflow, Pockwock-Bowater, NS.

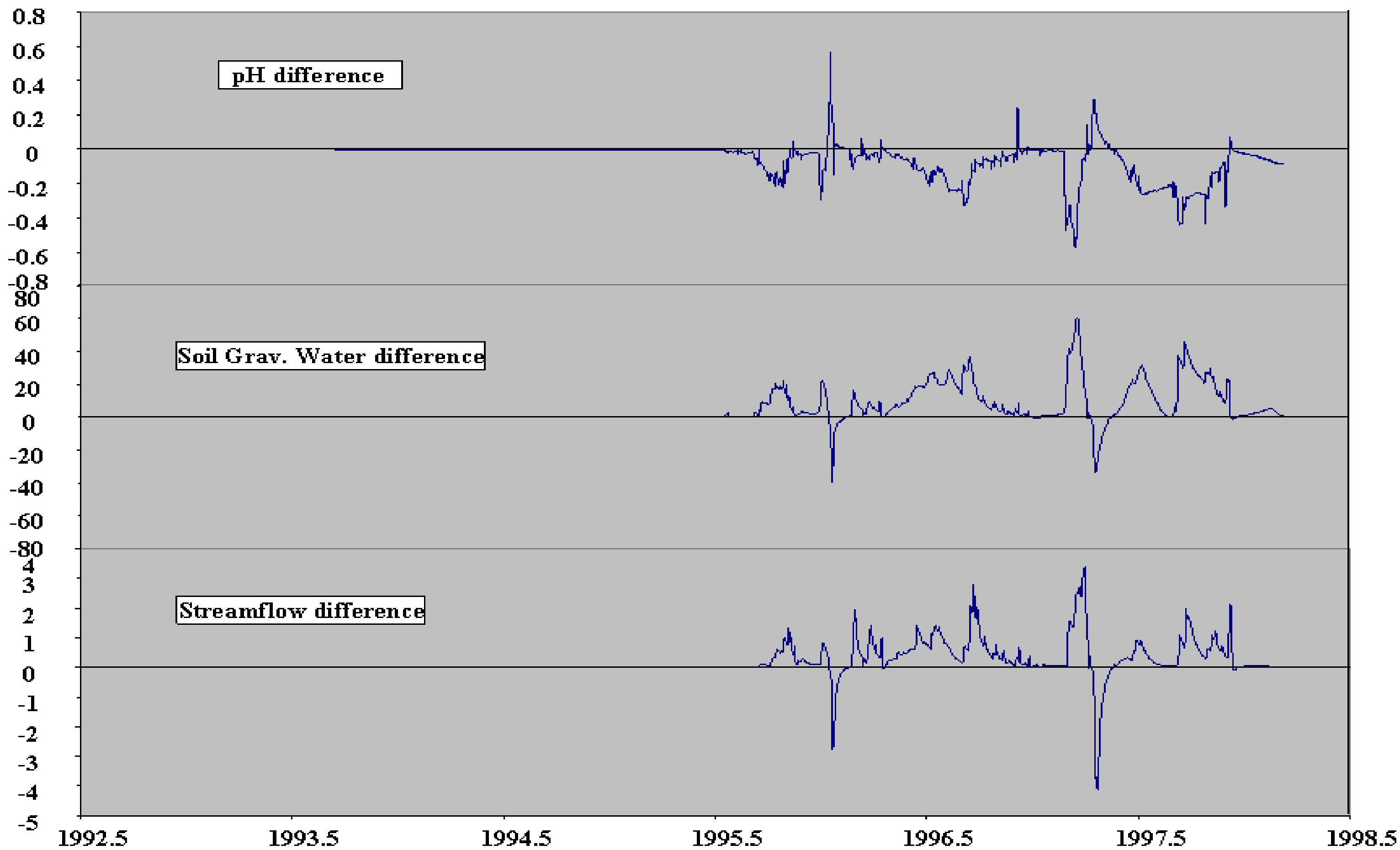

Figure 7.8 ForHym simulated pre and post harvest difference of pH, soil gravitational water and streamflow, Hayward Brook, NB.

CONCLUSION

The stream pH in the Pockwock – Bowater study area and the Hayward Brook study area were simulated for a period of 4 to 5 years. The analysis and the pH calculations were done on a daily basis. For the pH records, data fragmentation is a concern, and this was in most cases brought about by in-field sensor calibrations. From the modeling results, it is concluded that stream pH can be simulated from the rise and fall of the soil water table. Flow paths depths through the basins also appear to affect stream ph, being higher in areas where water percolates deeper and lower where the percolating water remains near the surface before entering the streams.

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CHAPTER 8

STREAM-WATER ELECTRICAL CONDUCTIVITY

INTRODUCTION

Electrical conductivity (EC) a useful indicator of total dissolved solids in stream water, and is commonly used to estimate relative ion load contributions of precipitation and subsurface water in stream hydrographs (Kobayashi, 1986). It is also used to estimate the dilution capacity of catchment discharge (Dingman, 2002). In general, in-stream EC depends on the total of all geochemical ion inputs. Catchment-specific ion inputs refer to precipitation deposition, upper layer soil water solution, and groundwater. Soils play an important role by modifying the chemistry of water that originates as precipitation and groundwater while flowing into the streams (Hendershot et. al., 1992). In-stream processes would further affects the total in-stream ion loads, through the decomposition of dissolved organic matter, and the tendency for dissolved constituents to precipitate as hydroxides, oxalates, carbonates, or leave the stream in gaseous form (CO_2, NOx), depending on in-stream chemical and biological conditions according to pH, redox potential, and overall chemical composition. The particular objectives of this Chapter are:

- to present the daily pre- and post-harvest changes for in-stream EC in each of the 9 monitored streams in the Pockwock-Bowater and Hayward Brook study areas

- To determine how these changes are affected by changes in hydrothermal and vegetation conditions within the catchments of the monitored streams
- To derive a model that simulates these changes by stream and study area, and to introduce that model into the ForHyM calculations,
- To calibrate and compare the ForHyM model results with the in-stream observations.

MODELING STRATEGIES

It is hypothesized that the electrical conductivity of the water in small streams is mainly related to the extent of soil organic matter mineralization and to soil weathering throughout the forest catchments, with additional inputs via atmospheric deposition (wet, dry, gaseous, and particulate). Catchments with low rates of soil weathering tend to have low electrical conductivity. Catchments with calcareous substrates tend to have high soil weathering rates, and therefore produce water with a high electrical conductivity. Soil weathering and soil organic matter decomposition, including the mineralization of forest litter within the organic forest floor, affect the electrical conductivity of the water through release of strong and weak electrolytes, such as inorganic ions and organic acids. Near the coast, stream EC can further be strongly affected by way of seas spray deposition, or the influx of periodic tidal saltwater and occasional storm surges. The more electrolytes are added to the water, the higher the electrical conductivity will be.

For forest streams emerging from uplands, such as the streams of this study, soil weathering and organic matter mineralization rates likely provide the most dominant ion sources, as affected by soil moisture, soil temperature, and substrate type. Contributions to soil and stream water conductivity are therefore expected to be highest when soil temperatures are highest. However, the loss of water in the catchments due to evapotranspiration tends to further increase the actual concentration of electrolytes in the water that remains to percolate through the catchments. This tendency implies that electrical conductivities are also affected by weather and subsequent soil moisture conditions. Since the soil temperature and moisture conditions throughout the catchments basin can be estimated with ForHyM, it follows that the electrical conductivity of water in small forest streams can be simulated as well, through calibration. The following summarizes methods and results that arose from attempts to generate systematic projections of daily in-stream EC using FoHyM output variables such as daily gravitational water, and daily soil moisture and temperature variations, coupled with a seasonal adjuster (a simple sine function) to account for re-occurring seasonal changes with respect to total ion release and uptake by the forest vegetation and perhaps within the streams themselves. The best results this far generated with these attempts were those obtained with using daily gravitational water coupled with a seasonal adjuster as important in-stream EC predictors, for both study areas. The details are summarized and discussed below.

METHODOLOGY

To perform the simulations of total soil ions which are ready to go to small forest streams, the model assumes that ions, together with the water, enter streams from the soils nearby. There are two sources of soil ions, precipitation and soil mineralization. Direct precipitation interception by the streams is considered negligible. For modeling convenience, it is assumed that ions from soil mineralization are added to the soil at a fixed rate; precipitation inputs are added monthly, as measured. The following formula was used to connect ForHyM output with the daily in-stream EC records:

$$\text{Stream EC} = a + b \log_{10} (\text{Grav. Water Depth} - c) * (1 + d \text{ sine} (2 \pi (\text{yearfraction} - e))) \qquad \text{(Eq. 8.1)}$$

where:

Stream EC = stream electrical conductivity concentration,

Grav. Water Depth = soil gravitational water, in mm, and

a, b, c, d, e are adjustable parameters, with e representing the seasonal adjuster for the sine function.

This formulation arose by noting a general association between the ForHyM calculated amounts of gravitational water (which would correspond to likely water table fluctuations within the catchment-specific recharge zones) and in-stream EC.

RESULTS AND DISCUSSION

Average, minimum and maximum EC values for each of the nine streams of the two study areas are listed in Table 8.1 Evidently, EC values are lower for the Pockwock-Bowater area by a factor of two, except for the WS1 stream, the catchment of which is mostly located on Sunbury soil. The other catchments are either located on Parry or Salisbury soils (WS4, WS5, WS6, WS9), or also in part on Sunbury soil but still monitored within the Parry soil area., The higher EC values at WS4, WS5, WS6, WS9 are undoubtedly due to longer contact time between the deeper flowing water and the minerals within in the soils and the sub soils of these catchments, therefore allowing for higher soil weathering inputs on account gradual mineral hydration and subsequent dissolution.

Table 8.1 Stream EC summary.

	Pockwock-Bowater					Hayward Brook			
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
a	65.49	53.98	67.89	63.73	58.91	102.1	101.3	146.8	134.8
b	20.34	19.62	18.9	21.04	13.98	15.47	7.07	12.89	13
c	35.38	30.06	34.03	34.36	35.12	55.67	50.37	73.2	61.21

Direct electrolyte inputs into the streams via precipitation should be negligible. This assumption is reasonable because the Hayward Brook watershed is mainly fed by groundwater. This assumption is borne out by the observed daily and seasonal patterns of electrical conductivity for both study areas, by stream (Figures 8.1and 8.2), as follows:

- There s a distinct seasonal pattern with highest electrical conductivities occurring in late summer and fall for both areas, this is the time when soil temperatures are highest, and soil moisture contents are lowest
- For the Hayward Brook area, there is a gradual increase in electrical conductivity from spring to fall, while, the peaks are mainly centered on late summer and fall for the Pockwock-Bowater area

Individual precipitation events tend to dilute the EC values within the Hayward Brook streams, on account of increased amounts of water flowing through the basins; in contrast, the opposite occurs to the EC for the streams in the Pockwock-Bowater area. In this, many individual EC peaks or troughs are well synchronized with the corresponding gravitational water peaks. All of this suggests that precipitation and snowmelt induced gravitational water peaks likely serve

- To flush accumulated electrolytes from the forest floor and the mineral soils immediately below the forest floor into the streams within the Pockwock-Bowater area;
- To dilute the accumulated electrolytes arising from soil and subsoil soil weathering before these enter the streams of the Hayward Brook area.

Using ForHyM to determine in-stream EC values via Equation 8.1, streams, and adjusting to a, b, c, d and e parameters for each stream, produced the list of best-fitted parameters in Table 8.2, by stream and study area. These calibrations were conducted by ignoring the EC data from 2001.6 to about 2002.2, because the EC peaks during this period were anomalously high compared to the other before and after monitoring periods. This EC anomaly was also observed for Peggy Brook, which served as the non-harvested control basin for the Pockwock-Bowater study area. Without this anomaly, Equation 8.1 was sufficient to replicate about 40 to 50% of the actual daily EC variations for both study areas. Many of the individual EC peaks or troughs were modeled in this way quite well, and these were well synchronized with the corresponding variations in gravitational water. The calibrations, however, fell short in terms of representing the background levels for EC as these appear to change from year to year. Further work is required to determine the cause for these changes from year to year.

Table 8.2 Calibration settings for stream EC parameter.

	Pockwock-Bowater				Hayward Brook				
	SB	PB	LP	WB	HS1	HS4	HS5	HS6	HS9
a	16	13.5	7	12.5	108	192	288	384	372
b	10	11.5	10.5	8.5	-30	-60	-90	-120	-120
c	0	0	0	0	40	40	150	250	250
d	0.5	0.5	0.2	0.55	0	0	0	0	0
e	0.5	0.5	0.6	0.55	0	0	0	0	0

.The following can be noted from the Table 8.2 entries:

- The EC values follow a distinct seasonal pattern on top of the gravitational water influence on EC ($d>0$), but not for the Hayward Brook streams ($d=0$).
- The EC values for the Pockwock-Bowater streams are positively related to the gravitational water fluctuations ($b>0$), while the reverse is true for the EC values of the Hayward Brook streams ($b<0$).
- The EC values of the Hayward Brook streams or 3 to 12 times more sensitive to the gravitational water fluctuations than the EC values of the Pockwock-Bowater streams ($b_{Pockwock}<b_{Hayward}$).
- Within the Pockwock-Bowater area, the LP stream has the least dependency on seasonal EC contributions ($d=0.2$ as opposed to 0.5 or 0.55)

These differences by study area are again mainly related to the hydrological flow paths of the water as it percolates through the catchments toward the streams. For the Pockwock-Bowater area, water remains close to the surface, and receives ion loads from the soil layers at the surface, at a rate which appears to depend on the availability of water to flush these surface layers, and on the availability of ions within these layers as affected by season, being particularly high during the fall of each year. For the Hayward Brook area, water percolates deeply through the soil and subsoil. Here, the ion load of the percolating water appears to be related to the contact time between water and slowly dissolving minerals. At Hayward Brook, periods of high water flow suppress this contact time, thereby causing in-stream EC reductions, invariably.

Actual versus calibrated values are shown in the time series plots in Figures 8.1 and 8.2, and also in the scatter plots of Figures 8.3. and 8.4. In general, the EC scatter plots have higher R^2 values for the Hayward Brook area (0.63 to 0.84) than for the Pockwock Bowater area (0.37 to 0.50).

The extent of actual and modeled in-stream EC stream-to-stream synchronization (Figures 8.6 and 8.7) is quite remarkable for both study areas, suggesting that weather and season dominate the release of electrolyte from each stream-monitored catchment, in concert with the movement of gravitational water through the catchments.

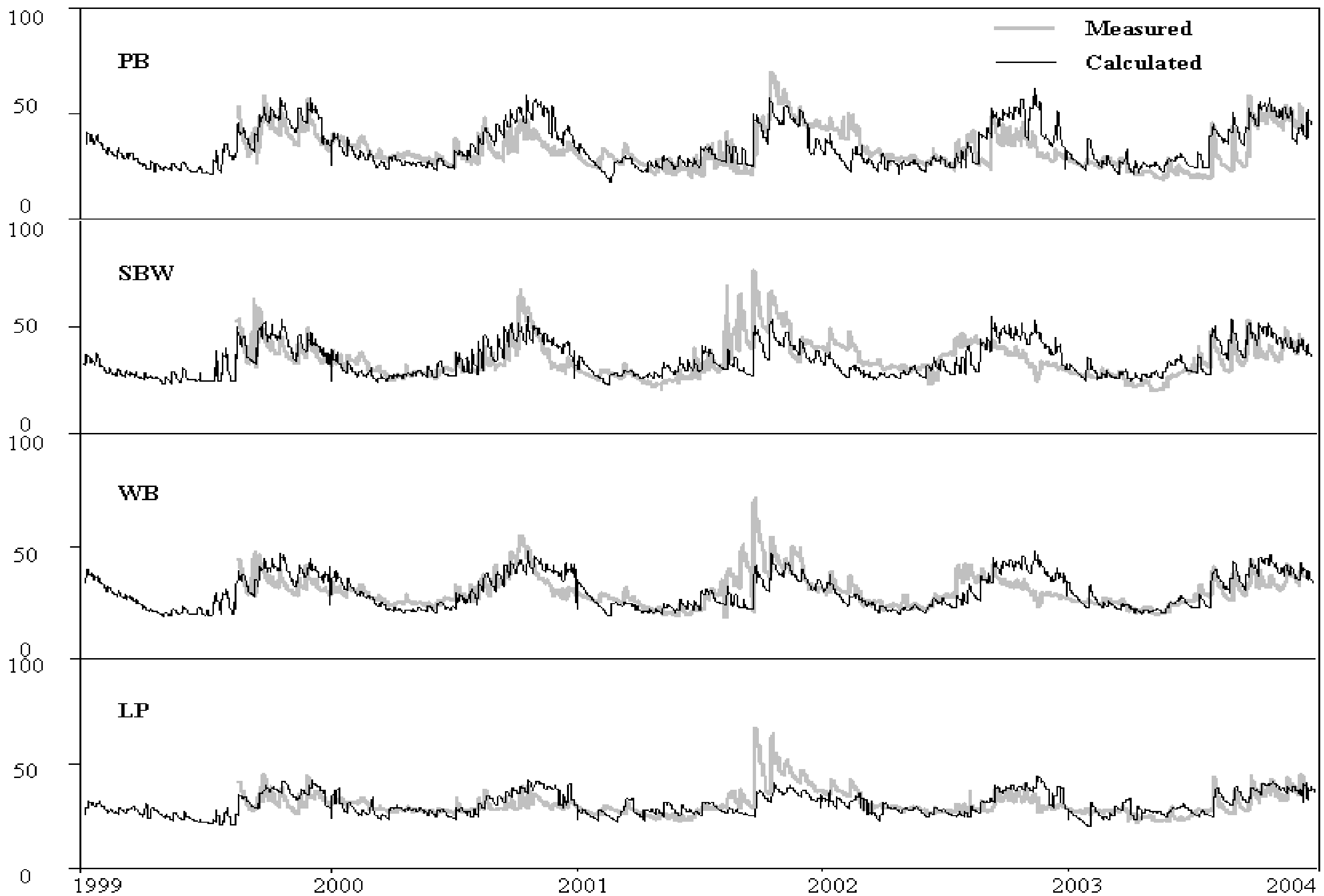


Figure 8.1 Actual and predicted stream EC, Pockwock-Bowater study area, NS.

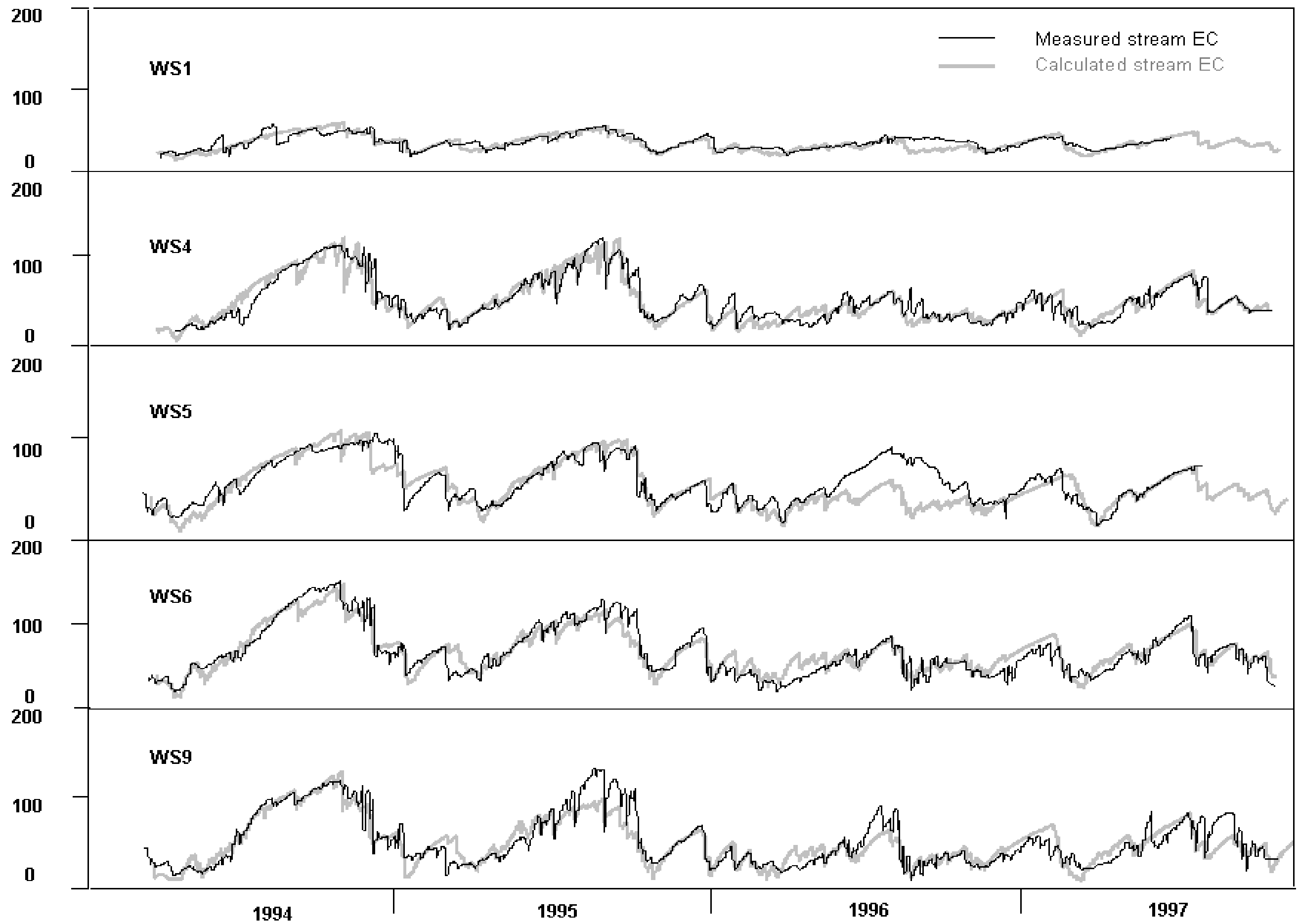


Figure 8.2 Actual and predicted stream EC, Hayward Brook study area, NB.

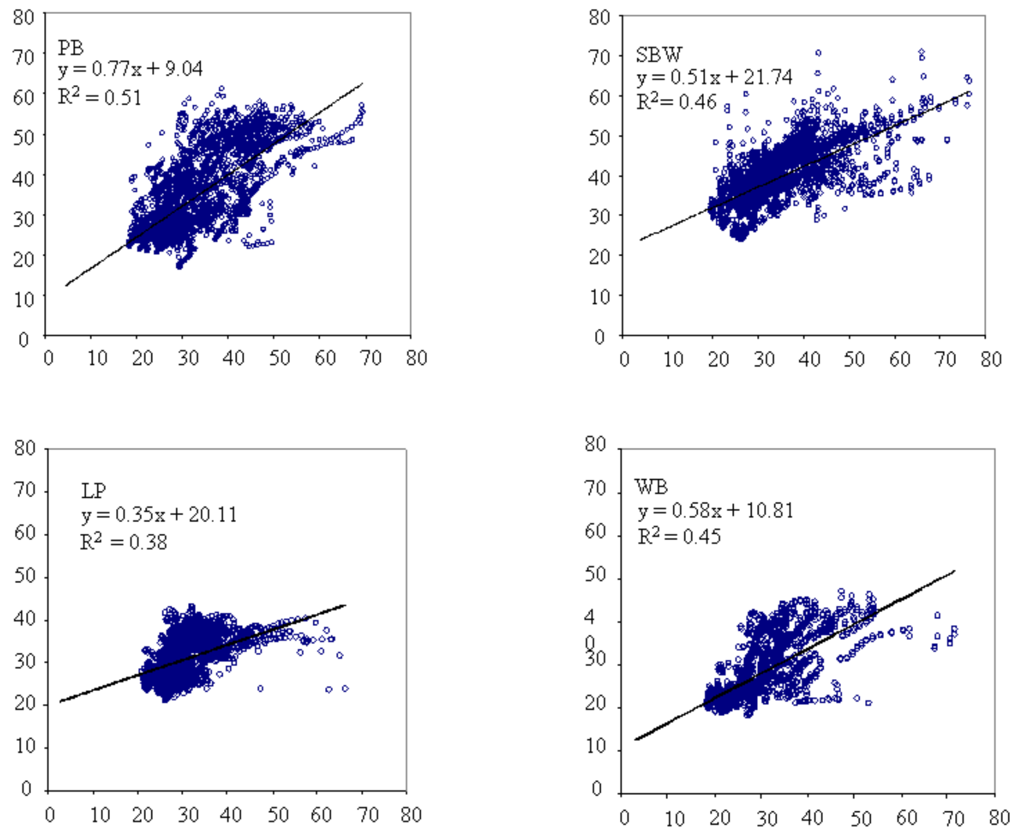


Figure 8.3 Actual and predicted stream EC correlations with R^2 values, Pockwock-Bowater study area, NS.

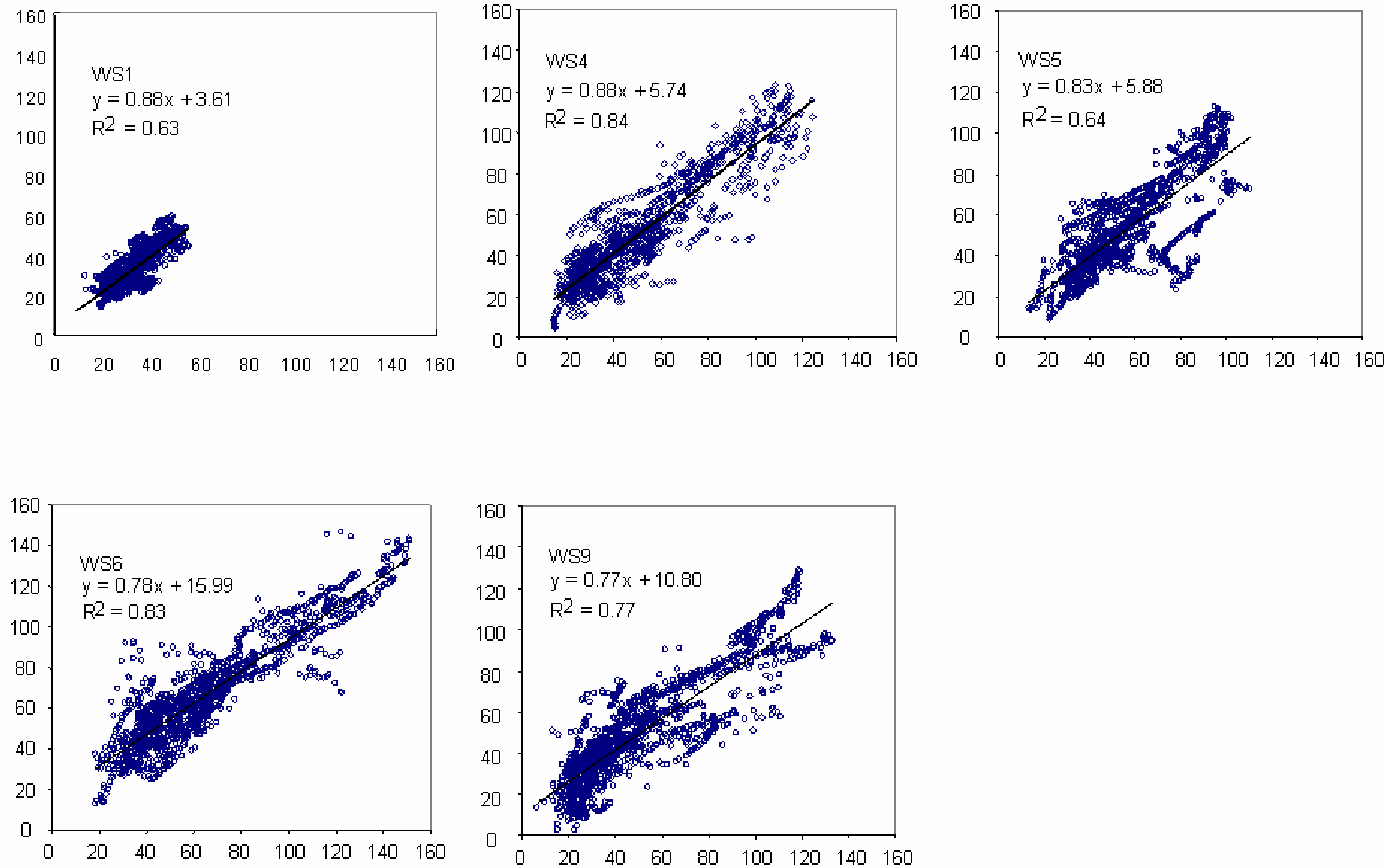


Figure 8.4 Actual and predicted stream EC correlations with R2 values, Hayward Brook, NB

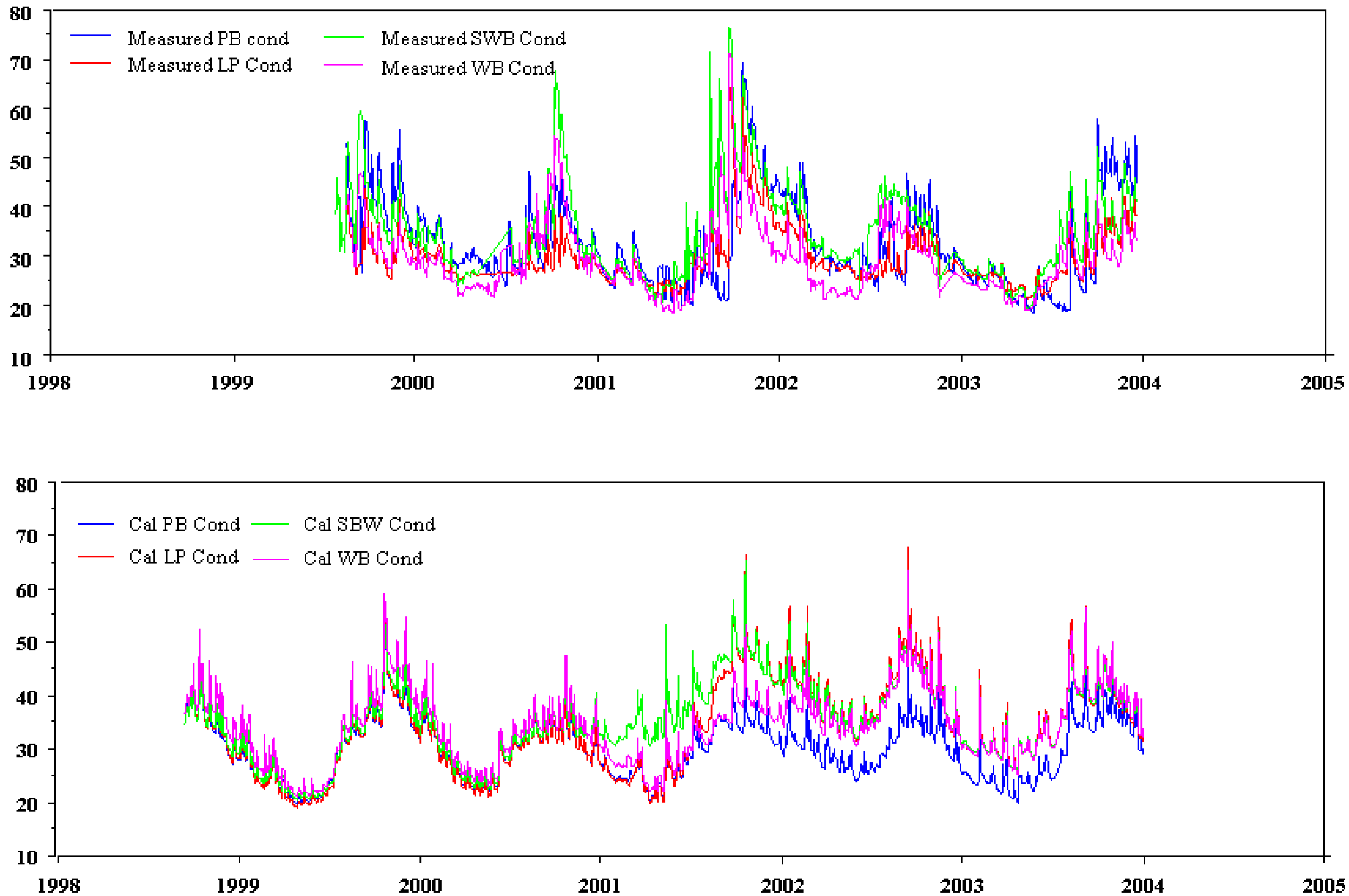


Figure 8.5 in- stream EC comparisons for the Pockwock-Bowater area: actual on top, and modeled on bottom. Peggy Brook is the control basin.

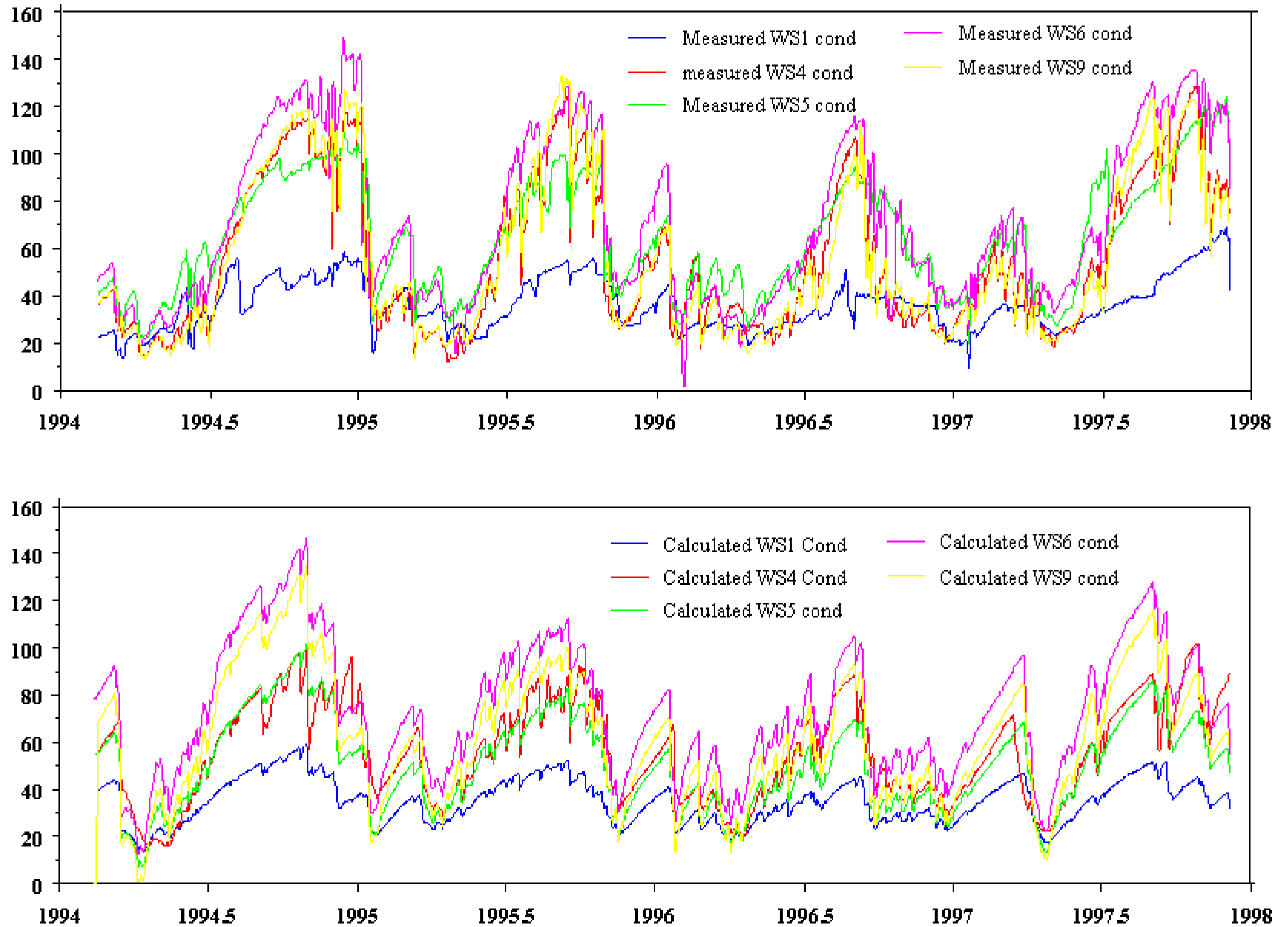


Figure 8.6 In- stream EC comparisons for the Hayward Brook area: actual on top, modeled on bottom) WS4 is the control basin.

The plots in Figures 8.5 and 8.6 reveal little in terms of likely extent of harvesting on in-stream EC values. However, the harvest contributions to the in-stream EC variations come into focus by way of the following direct stream-to-stream equations, where the “harvest” variable toggles from 0 (unharvested condition)) to 1 (harvested condition), with the harvested condition coming into effect for the post-harvest period:

Long Ponds stream conductivity = (13.80 +/- 0.48) + (0.53+/-0.02) PeggyBrook - (1.66+/-0.18) sin [2π (yearfraction-.15)]) – (0.10 +/- 0.02) SmthPeggyBrook + (2.67+/- 0.18) harvest, $R^2 = 0.72$.

Sandy Brook West stream conductivity = (15.62+/-1.13) + (0.78+/-0.04) PeggyBrook – (2.95+/-0.37) sin [2π (yearfraction-.15)] – (0.29+/-0.04) SmthPeggyBrook + (3.29+/-0.46) harvest, $R^2 = 0.52$

Walsh Brook stream conductivity = (25.13 +/- 0.80) + (0.61+/-0.03) PeggyBrook – (4.62+/-0.28) sin [2π (yearfraction-0.15)] – (0.50+/-0.03) SmthPeggyBrook + (0.98+/- 0.27) harvest, $R^2 = 0.48$

WS1 stream conductivity = (21.83+/-0.47) + (0.12+/-0.01) WS4 – (2.38+/-0.29) sin [2π (yearfraction-0.15)] + (0.16+/-0.02) SmthWS4 – (0.81+/-0.34) harvest, $R^2 = 0.71$.

WS5 stream conductivity = (11.62+/-1.28) + (1.08+/-0.05) WS4 – (1.93+/-0.48) sin [2π (yearfraction-0.15)] + 0.23 SmthWS4 – (0.24+/-0.57) harvest, $R^2 = 0.84$

WS6 stream conductivity = (4.56+/-1.29) + (1.21+/-0.05) WS4 – (3.05+/-0.48) sin [2π (yearfraction- 0.15)] + (0.23+/-0.03) SmthWS4 – (1.92+/-0.57) harvest, $R^2 = 0.92$

WS9 stream conductivity = (-1.13+/-0.55) + (0.89+/-0.01) WS4 – (0.80+/-0.34) sin [2π (yearfraction- 0.15)] – (0.16+/-0.02) SmthWS4 – (1.62+/-0.40) harvest, R^2 = 0.96.

Note that the harvest component of the above equations has a positive sign for the Pockwock-Bowater area, and a negative sign for the Hayward Brook area. Hence, harvesting tends to increase the post-harvest in-stream EC values in the former area, and tends to decrease post-harvest in-stream EC values in the latter area. Apparently, harvesting increased the effectiveness of water to flush post-harvest electrolytes for the Pockwock-Bowater area. For the Hayward Brook areas, the extra post-harvest water tends to dilute the electrolyte solutions that would enter the streams via deep percolation. Figures 8.7 and 8.8 show the in-stream EC comparisons for the un-harvested and harvested conditions, for each stream. For the Pockwock-Bowater area, there are distinctive positive peaks, but only within the first year after harvesting. For the Hayward Brook, there are distinctive negative EC peaks, but again only within the first year after harvesting.

The extent to which Equation 8.1 replicates these post-harvest effects is shown in Figure 8.9, by way of the corresponding harvested – non-harvested in-stream EC calculations, by study area, using the appropriate parameter values from Table 8.2, and assuming 100% basin-wide harvesting. These plots show the positive / negative post-harvest EC responses for each basin, but the calculations project these effects to last longer than what is suggested by the direct

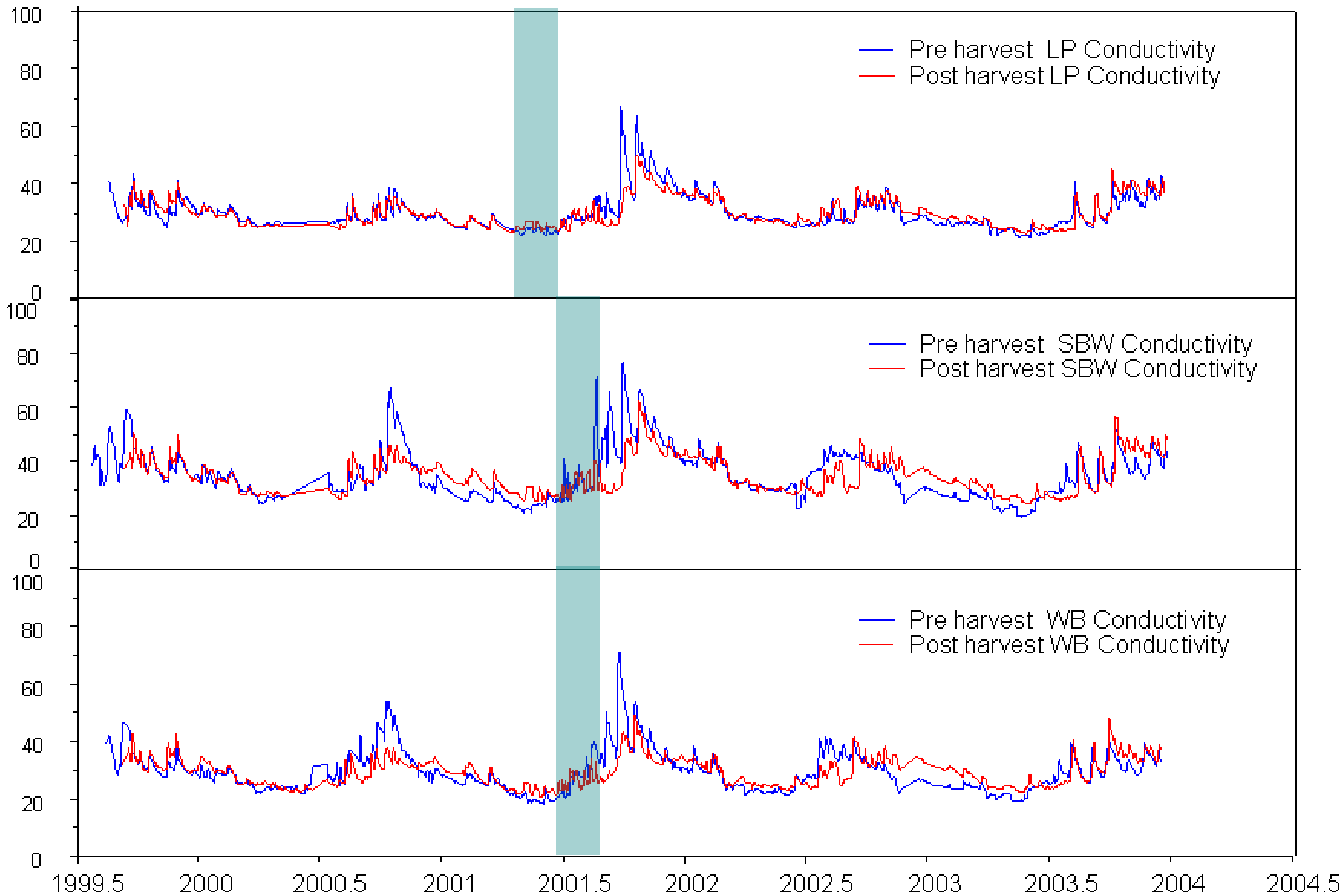


Figure 8.7 Pre and after harvest EC, Pockwock-Bowater, NS.

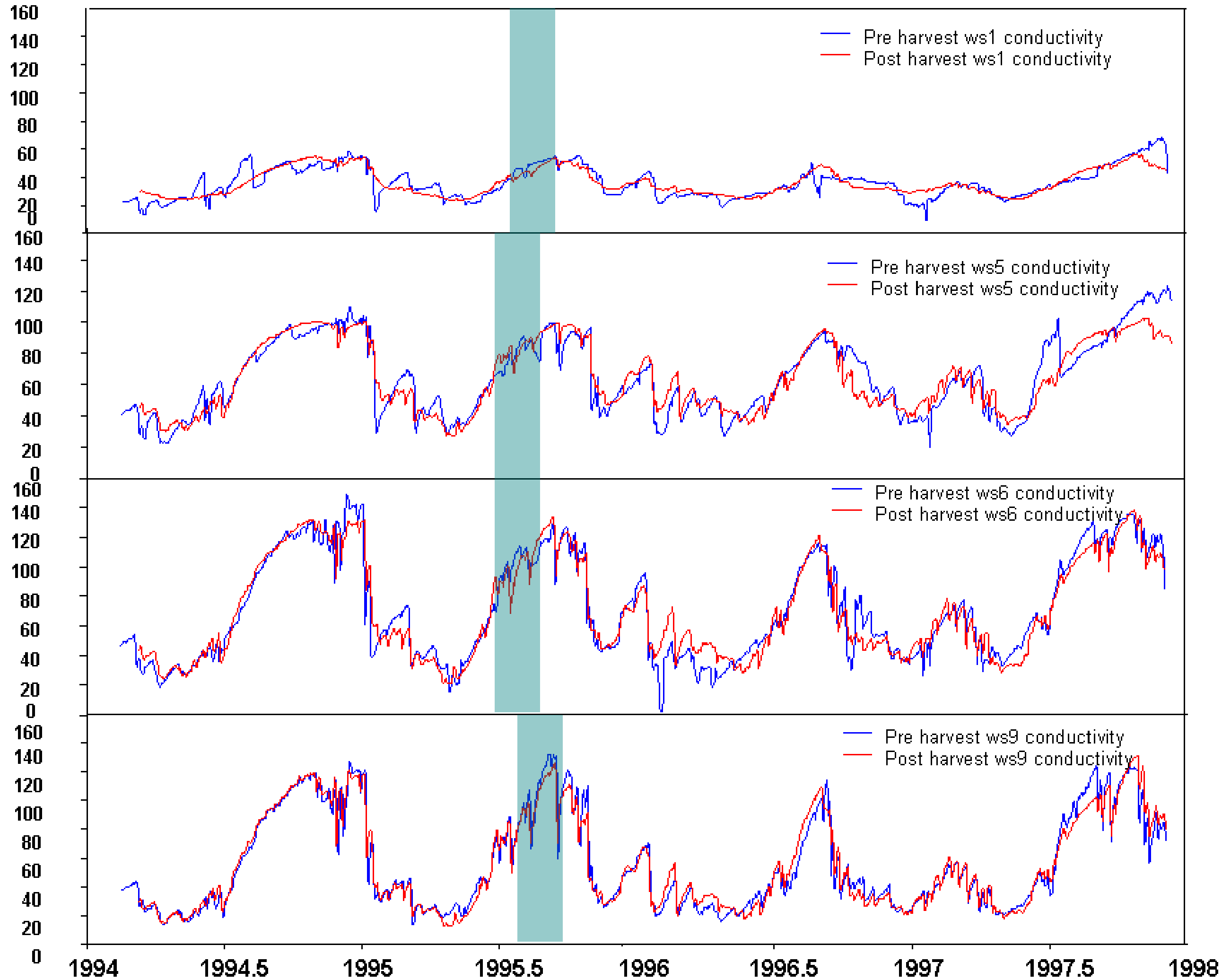
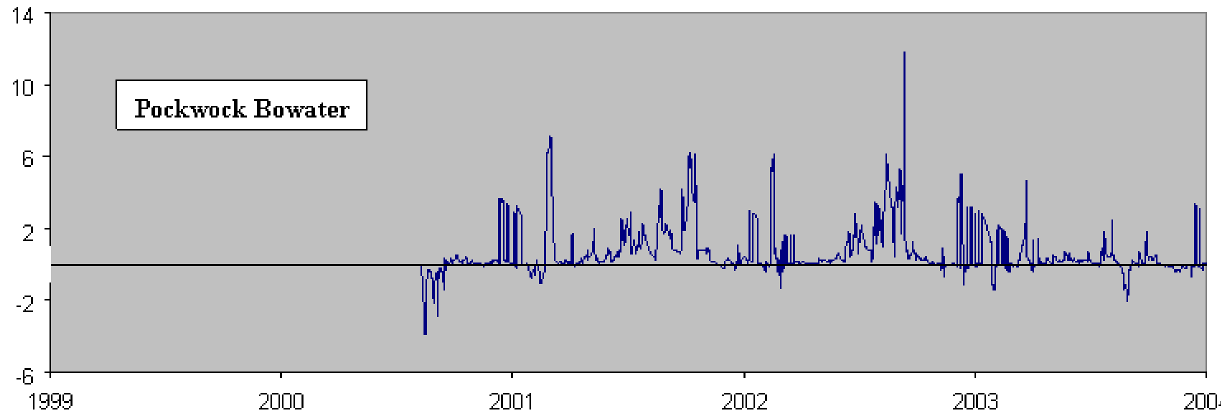


Figure 8.8 Pre and after harvest EC, Hayward Brook, NB.



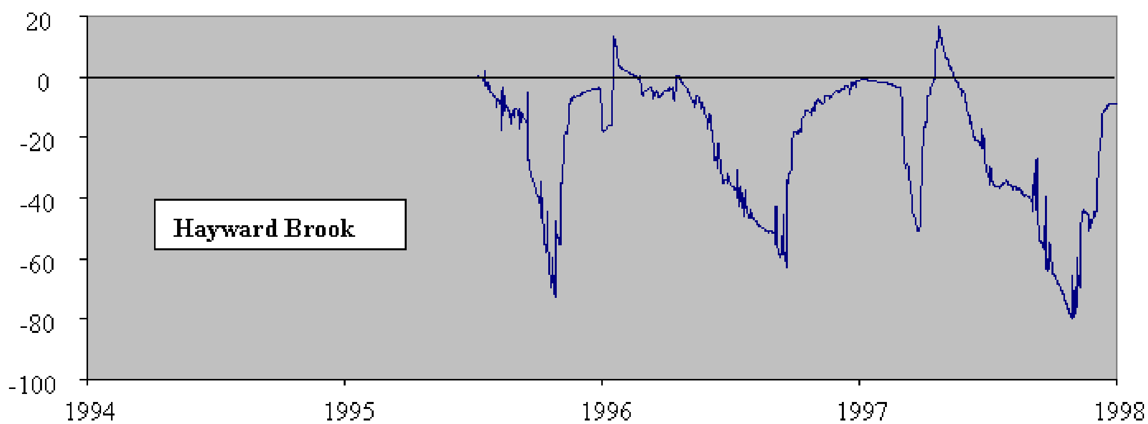


Figure 8.9 ForHyM simulated pre and post harvest difference of stream EC.

stream-to-stream projections shown in Figure 8.7 and 8.8, because of the longer lasting harvest effect on the gravitational water calculations (Figure 4.11).From this, it is evident that Equation 8.1, as written, is still limited in terms of correctly projecting post-harvest changes of the in-stream EC values.

CONCLUSIONS

Stream electrical conductivities in the Pockwock-Bowater study area and the Hayward Brook study area show a contrasting behavior in their response to incoming precipitation and snowmelt: for the former, EC values invariably increase with increasing gravitational water; the opposite occurs for the latter. This can be directly attributes to the differences in substrate permeability, being very low for the former, and water transmissive for the latter. For the former, electrolyte release from decaying matter on top of the mineral soil is most likely the driving factor for enhanced electrolyte entry into the soil and stream solution whenever the soil gets wet again. For the latter, the same factor tends to dilute the electrolyte concentrations of the electrolyte enriched groundwater enter s the stream. When there is little surface water coming to the streams, the EC values remain high. When there is much surface water entering the stream, the EC values decrease.

The EC data suggest positive and negative responses to harvesting, which is again related to the substrate permeability, and the increased amount of post-harvest water to either enhance the flushing of plant-released electrolyte, or to decrease the high electrolyte concentrations that would enter the streams from the permeable soil substrate.

The proposed equation to link the in-stream EC values to the amount of gradational water accounts for about one half the field-monitored EC values. The equation is, however, insufficient in correctly projecting the short-term nature of the post-harvest EC responses fro either the impermeable or pervious subsoil conditions.

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CHAPTER 9

THESIS SUMMARY, ORIGINAL CONTRIBUTIONS AND SUGGESTIONS FOR FUTURE WORK

THESIS SUMMARY

This thesis presents and analyzes in-stream monitoring records for stream discharge, temperature, dissolved oxygen, pH and electrical conductivity for 9 streams located in two areas with contrasting hydro-geological substrates, referring to a granitic and therefore fairly impermeable substrate for the Pockwock-Bowater area, and water-transmissive shale associated with the Hayward brook area. This contrast led to the following interpretations:

- Faster run-off and interflow within the Pockwock-Bowater area led to warmer streams during summer and colder streams during winter than within the Hayward Brook area.
- Warmer in-stream temperature led to faster dissolved oxygen draw-down during summer for the Pockwock- Bowater streams than for the Hayward brook area.
- Deeper water flow led to higher in-stream pH and electrical conductivity values for the Hayward Brook area than the Pockwock-Bowater area.

In terms of post- versus pre-harvest or unharvested comparisons, harvest effects were generally small and could only be detected within the first post-harvest year. Actual different were noticeably restricted to stream discharge, temperature, and electrical conductivity. These effects were somewhat more pronounced for the Pockwock-Bowater area than the Hayward Brook area. Post-harvest changes were not observed for pH and dissolved oxygen in a significant or systematic manner. To some extent, clear pre-to post-harvest difference were in part obscured by frequent sensor malfunctions, especially for the pH and dissolved oxygen probes.

For the most part, all of the observed daily variations in stream discharge temperature, dissolved oxygen, pH and electrical conductivity could be modeled, based on fairly simple but stream-specific relationships between the water quality variables, and calibrated ForHyM outputs for stream discharge, soil temperature, moisture, or gravitational water equivalents. These relationships, together with their and R^2 values and calibrated coefficient values are summarized in Table 9.1. The following can be observed:

- Daily stream temperatures can be simulated from measured air temperatures and ForHyM simulated soil temperatures. By region, differences in the soil-stream temperature relationships are affected by the hydrological pathway of the water. With deeper flows, stream temperature is less sensitive to air temperature than with shallow flows.
- Daily in-stream DO values can be simulated with daily ForHyM stream discharge and stream temperature simulations. Generally, DO values are highest in winter and lowest in summer, which is opposite to temperature, as to be expected. Groundwater-fed streams have lower daily DO variations than streams fed by surface water.

- In-stream pH values can be simulated with daily ForHyM simulations of the amount of gravitational water that exists in the soil and is en route to the streams. This water provides an index for the local water table fluctuations. When the water table is high, the water equilibrates with the pH of the forest floor. When the water table is low, the water equilibrates with the pH of the lower soil layers.
- In-stream electrical conductivity is also affected by the amount of gravitational water that exists within each catchment on a daily basis. However, this relationship is quite complicated. For the catchments on impermeable substrates within the Pockwock-Bowater area, the relationship between EC and soil gravitational moisture is positive. The opposite occurs on the water-transmissive shales of the Hayward brook area. For the Pockwock-Bowater area, high moisture conditions likely lead to a greater solubilization of previously mineralized electrolytes, particularly in the fall, due to the weather-determined drying and wetting cycles at and within the soil surface. For the Hayward Brook area, high moisture conditions lead to electrolyte dilution, as more water mixes with the electrolyte-rich groundwater. In the ForHyM formulation for the in-stream simulations, these differences are accounted for by entering the proper coefficients as detailed in Table 8.2.

It is interesting to note that the pre- to post-harvest differences were, in general, quite small, and therefore difficult to discern from many catchment- and stream-specific variations including inadvertent measurement errors. Pre- and post-harvest differences, however, were anticipated to be small on account of

1. Only cutting a small percentage of the stream-monitored basins within the Hayward brook area,
2. Leaving a treed buffer zone next to each permanent flow channel within each catchment.

It is expected that the effects on especially stream temperature and dissolved oxygen would have been larger otherwise, especially during summer.

SUGGESTIONS FOR FUTURE WORK

Gathering data with the Hydrolab probes was somewhat problematic on account of frequent sensor malfunctioning. Data quality checking and data recovery would have been easier and more complete if the same sensors would have been used for the same location throughout the whole monitoring periods for the Hayward Brook and Pockwock-Bowater areas. Moving the sensors among the stream-monitoring locations spread sensor-specific biases from one location to another in a non-traceable manner. In general, the sensors that respond to electrical signals only, such as the temperature, electrical conductivity and the pressure transducers used for stream height gauging, were fairly reliable. The electrochemical pH and dissolved oxygen probes were found to be less reliable. Newer electrodes for dissolved oxygen that do not need membrane replacement will likely be better than the dissolved oxygen probes used for the two study areas. Upon periodic downloading, all data records should be inspected, to determine whether any sensor malfunctioning had indeed occurred. Sensors that malfunction should be replaced to avoid further compromising of the data. Ideally, with wireless technology, incoming data should be monitored on screen on a weekly if not daily basis. Any malfunctioning that would be observed this way should than trigger a field visit, to either determine the cause of the malfunction, or simply replace the sensor(s) that produced erratic results.

It is difficult to calibrate the ForHyM calculations based on stream discharge alone. Ideally, each coefficient that determines, e.g., amount of run-off, infiltration, percolation, interflow or base flow, would have one specific number for a particular stream. However, many of these coefficients are linked to one another, thereby making it difficult to select a particular set of numbers that is unique, without making arbitrary calibration choices. In general, monitoring, e.g., snowpack depth, soil moisture and temperature somewhere in the basin not too far from the stream monitoring location for logistic reasons would increase the confidence in the stream discharge calibrations, if these calibrations would also produce a good fit for the daily variations in snow pack depth, soil moisture and temperature as well.

It should be interesting to know if the calibrations generated for the in-stream temperature, electric conductivity, dissolved oxygen and pH by study area could be applied to other streams as well. Doing so is a very distinct possibility because Since Hydrolab probes and other similar probes are being used at many other locations, world wide. Additional calibrations of the relationships generated in this thesis would show whether these relationships also apply elsewhere. In addition, each new stream-specific calibration would generate additional information as to how the best-fitted coefficients can specifically be related to hydro-geological and vegetative catchment attributes, in general.

Additional work could be done of the in-stream EC records, especially to determine the inter-annual changes in the EC baseline. This research has shown that the inter-annual baseline variations are not simply due to soil temperature and moisture changes alone, or some other hydro-thermal variations. Since EC variations depend on the extent of electrolyte loading and release per study area and/or per stream catchment, it is possible that the EC variations are due to changes in, e.g., atmospheric deposition, annual variations in canopy conditions, especially due to insect activities, annual variations in litter fall, litter decomposition, and tree growth. Differences in tree growth would translate to inter-annual differences in electrolyte (nutrient) uptake. A year with low electrolyte losses and low in-stream EC values may indicate a year of good tree growth, with a healthy forest. Conversely, a year with high EC base-line values could suggest a disturbance in nutrient cycling due to a variety of physical or biological tree-stress factors.