

PRE- AND POST-HARVEST GROUNDWATER TEMPERATURES,
AND LEVELS, IN UPLAND FOREST CATCHMENTS IN NORTHERN
NEW BRUNSWICK

by

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ABSTRACT

This Thesis investigates the effects of forest harvesting on shallow groundwater temperatures and levels, at 10 small upland catchments within two study areas in northern New Brunswick, Canada. Three harvesting treatments were implemented: 1) whole-tree, 2) stem-only, and 3) stem-only with extra slash added . One study area was located near Gounamitz Lake, and was characterized by well-drained soils and tolerant hardwood stands. The other study area was located near Island Lake, and was characterized by poorly-drained soils and mostly coniferous tree species.

Monitoring wells were placed at the base of each catchment, just above the seepage areas on the flow accumulation lines. In each well, shallow groundwater levels and temperatures were recorded every two or four hours by automated probes.

Shallow groundwater levels, and well temperatures, increased on all treated catchments following harvesting. Mid-summer water table peaks increased by as much as two meters relative to the controls. Well temperatures increased by as much as 2.5 °C, and temperature increases were advanced by as much as three months. However, differences from one treatment to the other were not obvious.

The hydrology model, ForHyM was calibrated to reproduce the shallow groundwater level fluctuations observed on all catchments. The model was also used to: 1) estimate the depth at which shallow groundwater flows, 2) determine the causes of changes in the shallow groundwater temperature patterns, and 3) calculate increases in soil temperatures resulting from canopy removal.

Key words: clearcutting, harvesting, groundwater flow, shallow groundwater, water temperature, soil temperature, groundwater levels, hydrology, model, whole-tree, stem-only, slash, soil permeability, wells, upland catchments, watersheds.

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CHAPTER 1

INTRODUCTION AND OBJECTIVES

Recently, concerns about impacts of forest harvesting on groundwater have increased because of steadily increasing harvest intensities, as facilitated by increased harvest mechanization (Maliondo *et al.* 1990; Sterner 1991). With whole-tree harvesting, for example, each tree is severed at the stump and is then moved as a whole to the roadside for further processing. Intensive harvesting involves the use of heavy machinery and leaves much of the soil within, and around, the harvested catchment exposed. This likely changes the hydrological dynamics of the harvested sites in terms of:

- increased run-off versus soil percolation in areas of soil compaction (Kozlowski 1999)
- greatly reduced evapotranspiration from complete removal of the forest vegetation, especially during the initial post-harvest years (Riekerk 1989)
- altered snow accumulation due to reduced canopy interception (Troendle and King 1985)
- earlier timing of snowmelt events (Hornbeck *et al.* 1997)
- increased stream water flow (Hibbert 1967; Verry 1972)
- increased ion concentrations in groundwater and streams (Pierce *et al.* 1972 ; Likens *et al.* 1970; Martin *et al.* 1985; Jewett 1995; Kubin 1995; MacLean-Jones 1997; Stanley 2002)

- increased stream turbidity and sedimentation (Cornish 2001; Pomeroy 2002; Martin and Hornbeck 1994)
- decreased solar insolation, and – hence – increased summer maximum soil temperatures (Mahendrappa and Kingston 1994)
- increased stream temperature (Ringler and Hall 1975; Rishel *et al.* 1982; Bourque and Pomeroy 2001).

This research of this Thesis focuses solely on pre- and post-harvest changes in groundwater temperatures and levels in small forested catchments in relation to upslope soil substrate permeability. In this context, small refers to catchments between 5 to 30 ha, which is the size of many forest cutblocks in this study's region. At this scale, it is quite feasible to experimentally determine the extent to which forest harvesting affects groundwater temperatures and water table fluctuations in upslope forest locations.

Generally, there is little information on assessing the cumulative effects of clear-cutting on shallow groundwater temperature and water table fluctuations. For example, Hewlett and Fortson (1982) suggested that groundwater should be monitored for elevated temperatures following harvesting to narrow down the causes of elevated stream temperatures in positions down-slope from the harvest operations. Curry and Devito (1996) and Curry and Noakes (1995) suggested that there should be more studies on groundwater behavior within forested landscapes. Curry *et al.* (2002) stated that, “.... we need a better understanding of the hydrological connections between forests and streams in the north temperate landscape and the effects of various forestry activities on the hydrology and biology of a watershed and its streams”.

Most reported investigations regarding impacts of forest harvesting have focused on streams with year-round discharge. To achieve year-round discharge conditions, however, targeted catchment areas are generally much larger than 5 to 30 ha. In this case, the cutting of the entire area by way of an experimental watershed approach necessitates cutting across a wide range of forest conditions, from uplands to lowlands, from well to excessively well drained locations to poorly drained conditions in wetlands adjacent to streams, and across several forest types. As such, the ensuing results are difficult to interpret in terms of specific forest operations by single forest type and soil substrate. Often, only partial cuts are undertaken in the catchment area above the hydrological measurement station. When watersheds are not completely harvested, the interpretation of the results is even more confounded by way of dilution, where the water from the cut and uncut areas combine to reduce the groundwater signal as it would exist at the subcatchment level below the actually cut area. Hence, large watershed studies that are particularly aimed at discerning impacts of forest harvesting on streamwater temperatures and discharge have produced variable results (Hibbert 1967; Swift and Messer 1971; Bosch and Hewlett 1982; Hewlett and Fortson 1982; Martin *et al.* 1985; Martin *et al.* 2000). Further compounding the interpretation of study results is the fact that previous research has come from a variety of locations around the world. Differing results between forest studies are often attributed to differences in climate, forest type and geography, thereby necessitating more studies to encompass more of this variability (Weetman and Webber 1972; Martin *et al.* 1981; Silkworth and Grigal 1982; Maliondo 1988; Briggs *et al.* 2000).

The main reasons for the scarcity in small-scale groundwater studies of forested uplands are most likely related to the following:

- the renting of costly well-drilling equipment,
- the uncertainty of actually striking water in terrains that are generally difficult to drill, and where access to suitable drill locations is hampered without major trail preparations,
- obtaining agreements between researchers and landowners regarding access, location, harvest schedule, and harvest method,
- the procurement of reliable in-situ equipment for measuring groundwater parameters, and the service and maintenance of this equipment,
- unfamiliarity with standardized measurement protocols for generating reliable data about the groundwater.

Nevertheless, research that relates forest operations to groundwater parameters immediately below the forest operations is important, because harvest-induced changes to groundwater parameters are, in principle, easily parameterized at this scale, and the parameters so obtained can, in turn, be used to estimate the resulting changes in forest stream water quality and quantity, with and without down-stream dilution effects. Steeves (2001) has already shown that there exists a close correlation between the water chemistry of groundwater and of the stream water immediately below the harvested forested area.

GOAL AND OBJECTIVES

The goal of this research is to determine impacts of current harvesting practices on sub-catchment groundwater tables and temperatures, as affected by forest harvesting and soil substrate. Shallow groundwater tables and temperatures were measured for two consecutive years for the pre- and post-harvest conditions, in forested sub-catchments. Two forest areas were involved: one for tolerant hardwoods and a highly permeable soil substrate, and one with a mostly coniferous stand and a soil substrate of low permeability (Case 2001). For each study area, sub-catchments were subjected to the following treatments:

- whole-tree harvest,
- conventional, stem-only harvest,
- conventional, stem-only harvest with extra slash added from the whole-tree harvest catchment, and
- no-harvest (control).

The extra slash treatment was implemented in an attempt to magnify the impacts of post-harvest slash cover on groundwater tables and temperatures. Specifically, this Thesis addresses the following objectives:

1. To quantify the impact of forest harvesting method on shallow groundwater temperatures and water table fluctuations.
2. To identify differences in groundwater responses due to the harvest of two forest types (tolerant hardwoods versus softwoods).
3. To characterize the influence of soil permeability on shallow groundwater hydrology.

4. To reproduce the pre-harvest measurements, and post-harvest responses, of water temperature and water table levels with a portable forest hydrology model.
5. To evaluate post-harvest vegetative recovery.

The approach taken was experimental based on a multiple paired catchments design. Paired catchment studies compare similar catchments before and after inducing a change, with one of the catchments left unaltered as a control (McCulloch and Robinson 1993). Briggs *et al.* (2000) have suggested that paired catchment studies have been key in advancing our knowledge on the impacts of intensive forest harvesting. Here, watersheds or catchments are defined as “...areas that appears on the basis of topography to contribute all the water that passes through a given cross section of a stream” (Dingman 2002). The subsurface water tends to follow the contours of the landscape which act as the catchment boundaries, although there are situations where neighboring catchments may provide minor contributions (Lee 1980; Peck and Williamson 1987; Dingman 2002).

THESIS OUTLINE

The Thesis structure is outlined in Fig. 1.1. Thesis background, objectives and literature review are summarized in Chapters 1 and 2. Chapter 3 introduces the study areas, and the procedures employed within the experimental watershed study. This includes:

- the criteria that were used in locating the study areas,
- details on the installation of monitoring wells and equipment,
- particulars on the implementation of the harvesting treatments, and
- the procedures and methods of data collection, and preparation for analysis.

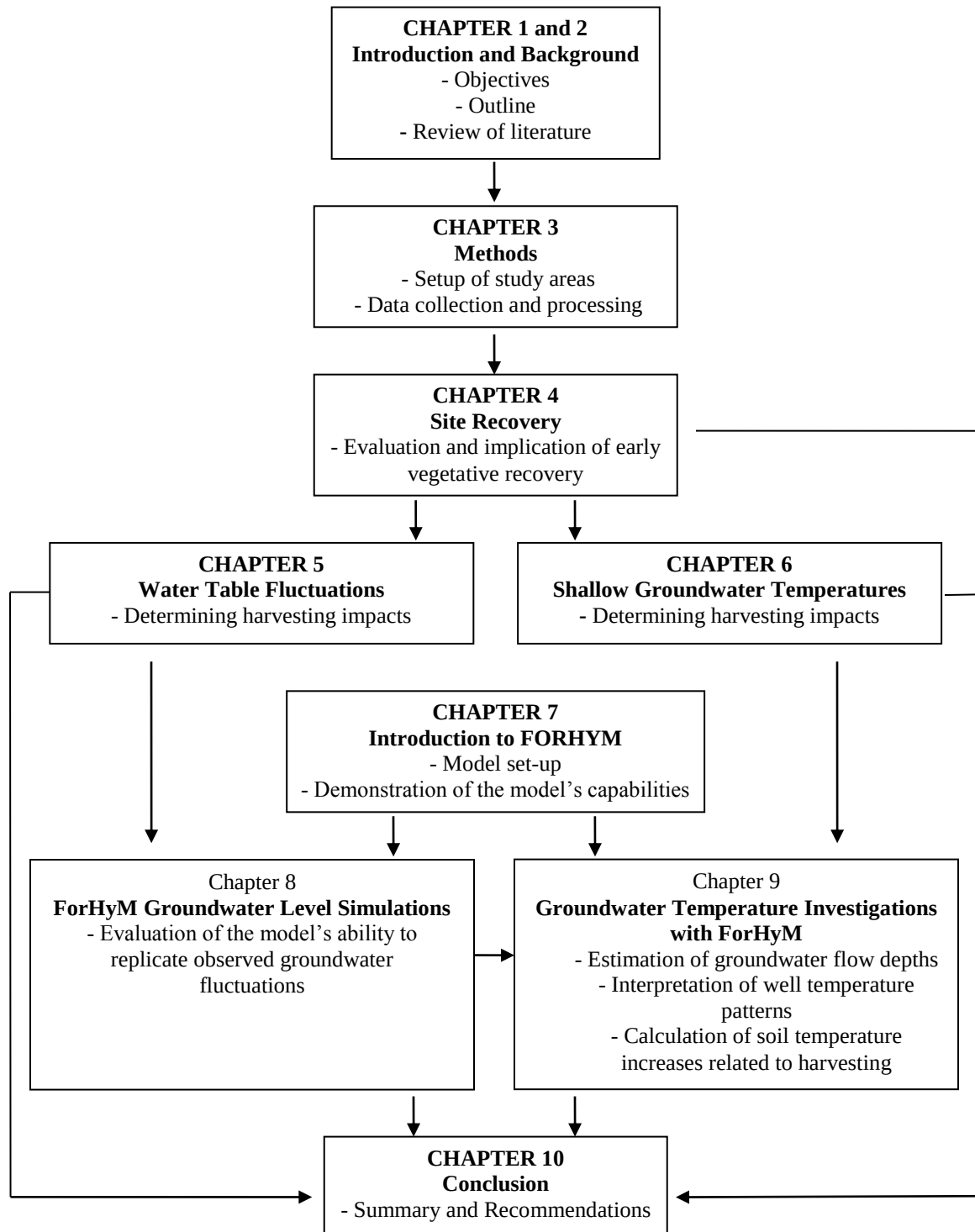


Fig. 1.1. Thesis layout and flow.

Chapter 4 presents the results of vegetation surveys conducted after the harvesting treatments. This lays a foundation for the following Chapters, which explain differences in harvesting hydrological responses among, and between, catchments at the two study areas, as well as predict future recovery. Chapter 5 provides a detailed analysis of the measured water table levels. Chapter 6 provides a detailed analysis of the Thesis-generated groundwater temperature data. Chapter 7 introduces a computer model (i.e., FORHYM) by summarizing details about the inner workings of this model, and its required inputs. In Chapter 8, the FORHYM model is used to compare measured water-table fluctuations with the modeled results. In Chapter 9, the FORHYM model is used as an investigation tool. In addition to calculating soil temperature change resulting from harvesting, the model compares measured water-table temperatures with computer-generated simulations for soil temperature, soil moisture, and snow pack accumulations. The implications and recommendations that were generated from this study are summarized in Chapter 10.

CHAPTER 2

LITERATURE REVIEW

INTRODUCTION

Groundwater plays a key role in the regulation, viability and productivity of forest streams. For example, groundwater provides the stability that is essential to aquatic life and influences fish movements, habitat location, selection of redd sites, fish survival, egg to embryo survival, growth, and reproductive success (Cunjack and Power 1986; Marten 1992; Snucins *et al.* 1992. Schofield 1993; Sinokrot and Stefan 1993; Curry *et al.* 1995; Curry and Devito 1996; Power *et al.* 1999). Also, groundwater provides critical protection from freezing in the winter, and stable, cool temperatures in the summer (Curry *et al.* 1995; Power *et al.* 1999). Essentially, groundwater provides connectivity between the stream environment and the surrounding terrestrial environment. Therefore, it is important to monitor groundwater flowing from managed and unmanaged forests, to determine impacts of land use on aquatic systems. However, studies on effects of forest harvesting on shallow groundwater levels are few (Trousdel and Hoover 1955; Holstener-Jorgensen 1967; Taniguchi 1997). Therefore, much of this review chapter relates to the harvesting impacts on water based on previous streamwater studies. The validity of this approach is, in general, supported by Urie (1971), who suggested that many forest harvesting impacts on streamwater can be interpreted as groundwater effects.

This chapter has the following objectives:

- to review the literature on post-harvest stream and groundwater temperatures
- to review the literature on post-harvest stream discharge and groundwater levels

POST-HARVEST INCREASES IN STREAM AND GROUNDWATER TEMPERATURES

Streamwater temperatures have been identified as perhaps the single most important water quality parameters (Bowles *et al.* 1977). For example, increased temperatures can affect the palatability of water for humans (Corbett *et al.* 1978; Szlyk *et al.* 1989). Increased stream temperatures may contribute to the fouling of water through algal blooms (eutrophication). Fouling interferes with recreation and reduces levels of dissolved oxygen (Brown and Krygier 1967; Corbett *et al.* 1978; Brady and Weil 1996). High water temperatures, and – therefore – low dissolved oxygen levels have been identified as the most important factor limiting trout distribution, well-being and survival (Eschner and Larmoyeux 1963; Beitinger and Fitzpatrick 1979; Baltz *et al.* 1987). High water temperatures have also been shown to affect fish movements, rearing success, egg development, species competition, growth rate and mortality (McCormick *et al.* 1972; Beschta *et al.* 1987; Tang and Boisclair 1995; Magoulick and Wilzbach 1998). As temperatures approach lethal limits, rates of predation by fishes, and subsequent growth, are reduced (Baldwin 1957; Clark 1969).

Any sustained stream temperature increase (or decrease) is likely to affect the timing of critical life cycle stages of aquatic species. For example, Hokanson *et al.* (1973) determined that optimal temperature for incubating trout eggs occurred at 6 °C, with a critical upper limit of 12.7 °C. For adult brook trout, most researchers agree that optimal

temperatures range between 12.4 and 15.4 °C, with a critical upper limit between 17.9 and 20.0 °C (Baldwin 1957; Stroud 1967; McCormick et al. 1972; Hokanson et al. 1973; Magoulick and Wilzbach 1998). Holtby (1988) and the US Department of the Interior (1968) reported that increased stream temperatures increase the growing season for several aquatic species. These increases may translate into better survival for some species, but reduced survival for others. Problems may arise when the changes in stream temperature alter the timing of life cycle events for a particular species, but the surrounding environment continues to follow a normal seasonal pattern.

With respect to forest operations, most studies have shown post-harvest increases in temperatures from 0.3 to 11.1 °C (Eschner and Larmoyeux 1963; Gray and Edington 1969; Hewlett and Fortson 1982; Harr and Fredriksen 1988; Holtby 1988; Stott and Marks 2000; Bourque and Pomeroy 2001; Macdonald *et al.* 2003). Such a wide range is in part due to location and climate. For example, the lowest recorded increases (0.3-0.7 °C) occurred in the cooler climate of northern North America (Bourque and Pomeroy 2001).

Largest stream temperature increases are usually associated with removal of all trees up to the streambank. When this is done, stream temperature is directly related to increased solar radiation input (Brown and Krygier 1967; Brown and Krygier 1970; Barton *et al.* 1985). As a result, many jurisdictions introduced legislation to buffer forest streams, by disallowing indiscriminate removal of trees from within stream buffer zones. A few studies were designed to examine the shading effectiveness of these buffers. Even with buffers in place, small increases in post-harvest stream temperatures have been measured (Martin *et al.* 1985; Bourque and Pomeroy 2001). To account for this, it was

suggested that these increases may, in part, be due to changes in surrounding air temperatures (Cluis 1972), or perhaps from increases in post-harvest soil temperatures (Eschner and Larmoyeux 1963; Hewlett and Fortson 1982).

Studies specifically centered on monitoring post-harvest soil temperatures *have* indeed shown that soil temperatures are affected by the removal of the forest canopy and slash cover, both of which act as an insulating layer over the soil. As a result, summer soil temperatures are typically higher in cut areas, and highest in areas void of slash (Donnelly *et al.* 1991; Mahendrappa and Kingston 1994; Proe *et al.* 1994; McInnis and Roberts 1995; Messina *et al.* 1997). Because of the insulating effect of forest canopies and slash piles, seasonal and daily temperature amplitudes are reduced (Lundkvist 1988; Mahendrappa and Kingston 1994; Proe *et al.* 1994). The insulating effect results from the blocking of incoming solar radiation during the summer, and from a reduced loss of heat stored in the soil during the winter. Clearcut soil temperatures have been measured as much as 6-7 °C higher than uncut controls, and soils that were left without slash cover have been found to be as much as 4 °C higher than soils that were covered with slash (Johnson *et al.* 1985; Smethurst and Nambiar 1990).

A significant amount of heat can be transferred to the stream-water from the surrounding stream banks and bed (hyporheic zones) (Brown 1969; Bowles *et al.* 1977; Jobson 1977; Sinokrot and Stefan 1993; Hondzo and Stefan 1994). Similarly, it is possible that heat transfers will take place from the soil to the groundwater, and the groundwater, in turn, would move this extra heat into the streams. Brosofske *et al.* (1997)

support this theory, demonstrating that there is a strong relationship between soil and streamwater temperatures.

The time required for stream temperatures to recover to pre-harvest levels varies. Johnson and Jones (2000) found it took 15 years, but most studies have found recovery to occur within 3-4 years (Swift and Messer 1971; Harr and Fredriksen 1988; Curry *et al.* 2002). The variability in the post-harvest temperature recovery time is probably due to the magnitude of the immediate post-harvest temperature change, and the rate of post-harvest regeneration.

POST-HARVEST INCREASES IN STREAMFLOW AND GROUNDWATER LEVELS

Many studies have shown increases in streamflow leaving forest catchments subject to harvesting, and a few studies have shown increases in water table levels (Eschner and Larmoyeux 1963; Hibbert 1967; Holstener-Jorgensen 1967; Urie 1971; Burger and Pritchett 1988; Martin *et al.* 2000). These increases are, for the most part, due to reduced evapotranspirational losses (Urie 1971; Riekerk 1989; Sun *et al.* 2001). When trees are removed from a site, less precipitation is intercepted, and therefore, there should be less water evaporated back to the atmosphere. Also, tree removal means plant uptake and transpirational loss of water will be reduced on the site. The effect that these reductions in evapotranspiration will have on shallow groundwater levels may be dependant on the topographic position of the catchment. Upland catchments that have little or no lateral drainage restrictions may not experience large, sustained increases in water table levels. Large, sustained post-harvest increases are more likely on flat, lowland catchments where excess water that passes through the soil is slower to pass water converging areas (Pritchett and Fisher 1987; Meng, personal communication, June 2003).

The impacts of tree removal on groundwater levels and stream flow are likely also dependant on; 1) the species of tree removed; 2) intensity of harvest; and 3) the area harvested. Different tree species will have different rates of water uptake and transpiration. Conifers often have greater leaf areas and maintain these transpiration surfaces for a greater portion of the year than deciduous trees (Hewlett 1958; Dunne and Leopold 1978; Pritchett and Fisher 1987). Greater surface areas also lead to higher interception rates, which increase evaporative losses from a forest stand as well (Hewlett 1958; Helvey 1971; Dunne and Leopold 1978). The net post-harvest effect may be a greater increase in down-slope water tables below coniferous catchments than deciduous (Pritchett and Fisher 1987; Douglass 1983). Hewlett (1958) and Holstener-Jorgensen (1967) suggest that the type of species removed dictates the magnitude of water table change because of species-specific rooting depths; deeper rooting species will consume more soil water. The *intensity* of harvest could also influence the magnitude of water level increases. Holstener-Jorgensen (1967), Urie (1971) and Trousdell and Hoover (1955) all found that neither shelterwood harvesting nor strip cutting result in water table increases as large as clearcutting. Similarly, the magnitude of water table change depends on the amount of area and density of the stand harvested (Verry 1986).

Forest harvesting also advances the timing of snowmelts (Hornbeck *et al.* 1997). These advances occur as canopy shade is lost, and snow surfaces melt faster. The advanced snowmelts have been found to alter the timing of spring streamflows (Hornbeck *et al.* 1986; Martin *et al.* 2000).

Previous research has found that post-harvesting streamflow increases can vary by as much as 31-418%, or by 112-450 mm, in either the year following harvesting, or in

the year of maximum increase (Eschner and Larmoyeux 1963; Hibbert 1967; Bormann *et al.* 1968; Verry 1972; Aubertin and Patric 1974; Nicolson *et al.* 1982; Martin *et al.* 2000; Swank *et al.* 2001). Studies on groundwater have produced similar results. For example, Holstener-Jorgensen (1967) measured harvesting-induced water table increases of up to two meters. In most cases, these increases were expected to last from 4-6 years, but could last as much as 12-15 years (Aubertin and Patric 1974; Verry 1986; Martin *et al.* 2000; Swank *et al.* 2001).

Increases in water-table levels of the groundwater, and related increases in stream flow can have both positive and negative effects: Excess water flow during summer low-flow periods may be beneficial to aquatic life downstream. It may also be beneficial to humans in instances where the water is being used for recreation or as a source of drinking water. On the negative side, increased water flows may increase the incidence of streambank erosion. This is especially true for high-flow run-off events. Also, increased flows can carry with them increased amounts of nutrients away from the catchments (Bormann *et al.* 1968).

Aside from its influences on streamwater, any increases in groundwater table levels that may occur will mostly have negative implications. One of the few benefits of elevated water tables would be in cases where the groundwater is being extracted for human use. Otherwise, elevated water tables may hinder forest operations, kill roots, alter vegetative communities and contribute to increased water temperatures (Trousdel and Hoover 1955; Ahlgren and Hansen 1957; Holstener-Jorgensen 1967; Pritchett and Fisher 1987). If the water tables rise closer to the soil surface, harvesting machinery may cause severe rutting, which leads to another set of problems. In extreme circumstances,

harvesting operations may not be able to operate in an area at all for the wetter portions of the year. Water tables rising into, or above, the rooting zones of forest vegetation can lead to drowning of the roots. This often increases mortality in the short-term, and leads to a change in vegetation in the long-term. Curry *et al.* (2002) suggest that as water tables rise closer to the soil surface, they have the potential to further magnify any existing water temperature increases by bringing the water closer to unimpeded solar radiation inputs.

CHAPTER 3

STUDY SETUP: TREATMENTS AND DATA COLLECTION

The purpose of this chapter is to provide an overview of the two study areas.

Specifically, this chapter provides details on the following:

- 1) A description of the control and treated catchments.
- 2) The process of locating the catchment boundaries within the broader watershed area. This includes the steps that were taken to delineate the catchment boundaries.
- 3) The positioning of the wells within each treatment basin, to allow for continuous groundwater monitoring.
- 4) The installation of the wells and the well monitoring probes.
- 5) The protocol used for data collection from the wells, and for establishing daily weather conditions (air temperature, precipitation in the form of rain and snow) at each of the two study areas.
- 6) Data processing.
- 7) Harvesting procedures.

STUDY AREAS

Two study areas were selected on industrial crown-licenses in northern New Brunswick (Fig. 3.1). Both areas were selected within relatively undisturbed, mature forest areas, each to be subjected to current forest management practices (Case 2001).



Fig. 3.1. Location of study areas within the province of New Brunswick, Canada.

The two areas were selected so that there would be differences in bedrock geology and forest cover type between them. The aim was to locate, within each study area, four or five catchments that were close to each other so that geological, climate, soil, slope, aspect, size and stand characteristics would not vary greatly between these catchments. Because the study was designed to determine impacts from harvesting operations, the

target size for the catchments was roughly between 10 and 30 hectares (ha), to reflect current cutblock size, as commonly used by the forest companies that operate in the region. Both study areas experience similar climatic conditions, with annual rainfall of 700.3 mm, average snowfall of 317 cm, and average monthly temperatures between -13.6 and 16.8 C (van Groenewoud 1983).

Gounamitz Lake

Gounamitz Lake (GL) is located in northwestern New Brunswick (N 47.57; W 67.64) (Fig. 3.1). The merchantable tree species consisted almost entirely of sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula alleghaniensis* Britt.), with a small component of spruce at lower slope positions (Fig. 3.2). There are indications that portions of this area were selectively harvested with the removal of softwoods, possibly in the early 1900's.

The GL study area falls within the Thibault Forest Soils Unit (Colpitts *et al.* 1995). These soils are derived from calcareous sedimentary rock, and are deposited as loose glacial tills (Colpitts *et al.* 1995). The soils within this study area are almost exclusively either Orthic humo-Ferric Podzols or Orthic Ferro-Humic podzols based on the Canadian Soil Classification System (Soil Classification Working Group 1998), and range from moderately well to rapidly drained based on a standard drainage key developed by Jones *et al.* (1983) (Case 2001). Soil texture varies little with depth, ranging from loam to sandy loam (Table 3.1). The terrain is characterized by fairly uniform, gently rolling slopes, which make the boundaries of each subcatchment easily distinguishable from neighboring ones (Fig. 3.3).

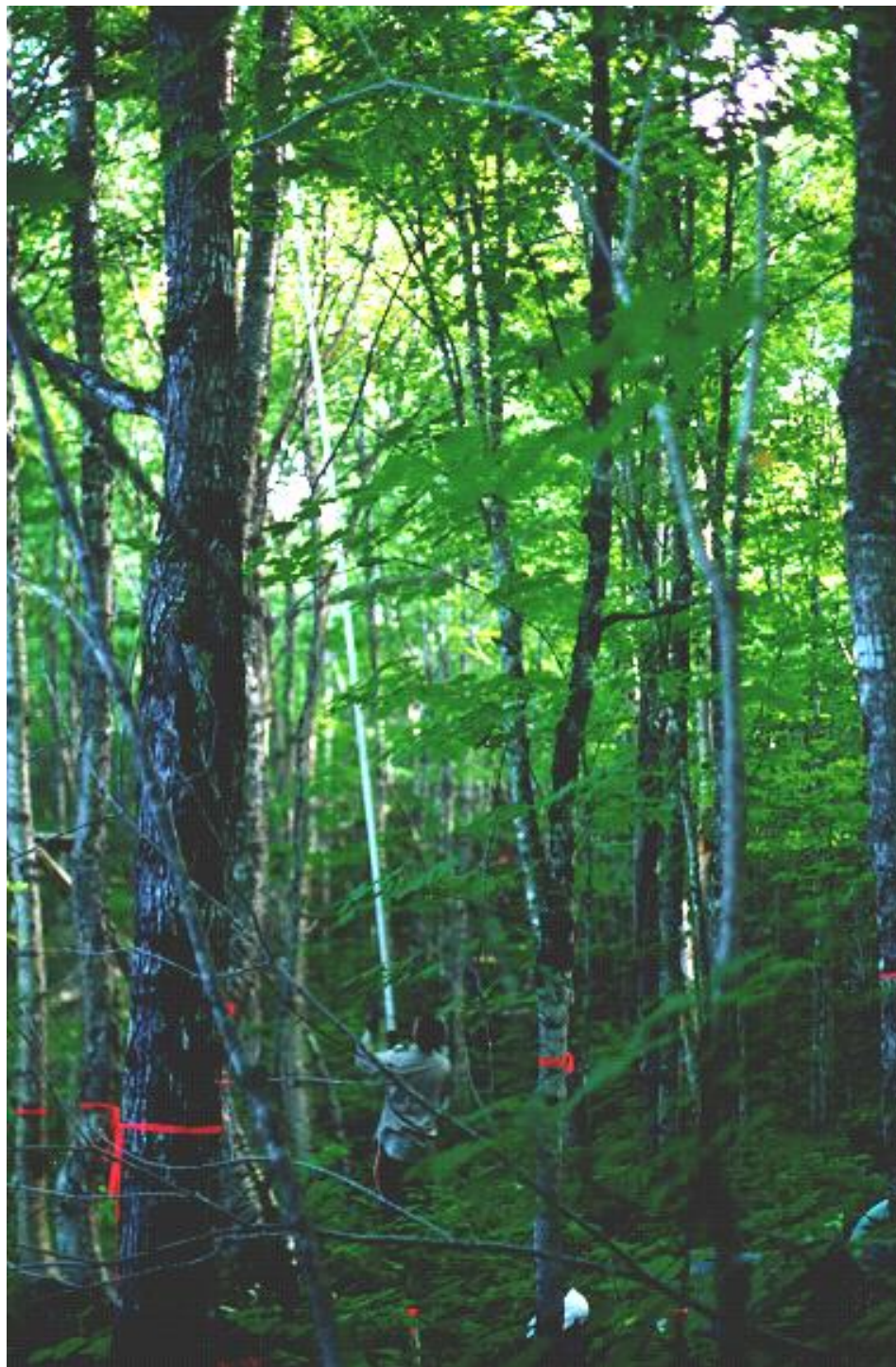


Fig. 3.2. Pre-harvest forest stand conditions at Gounamitz Lake.

Table 3.1. Mean physical property data for the forest floor (FF), A, B, and sub-soil (SS) layers at the Island Lake (IL) and Gounamitz Lake (GL) study sites (adapted from Case 2001).

	Thickness cm		Coarse Fragments %		Sand %		Silt %		Clay %		Texture ^a	
	<u>IL</u>	<u>GL</u>	<u>IL</u>	<u>GL</u>	<u>IL</u>	<u>GL</u>	<u>IL</u>	<u>GL</u>	<u>IL</u>	<u>GL</u>	<u>IL</u>	<u>GL</u>
FF	9.85	3.89	n/a		n/a		n/a		n/a		n/a	
A	11.80	10.69	45.00	39.04	46.84	41.28	35.99	48.40	17.16	10.25	L	L
B	19.05	21.92	48.54	51.83	55.67	63.18	29.16	29.07	15.18	7.73	SL	SL
SS	17.20	19.10	53.61	65.67	65.51	63.89	20.60	25.33	13.89	10.77	SL	SL

^a Texture classification according to the National Soil Survey Committee of Canada (1974)

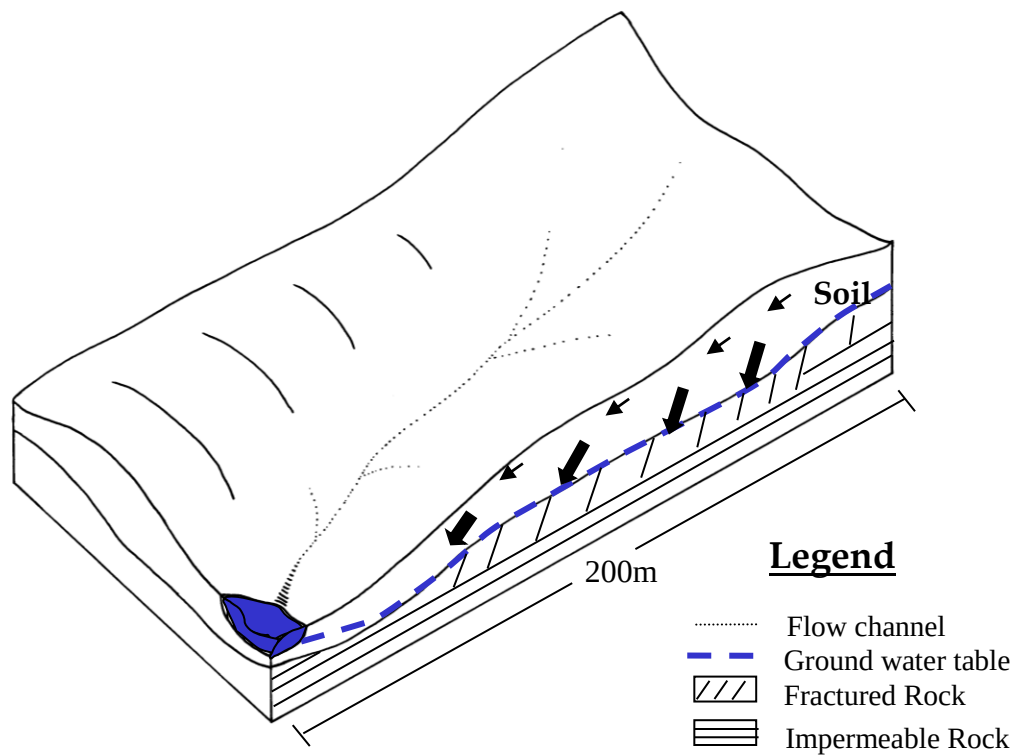


Fig. 3.3. Terrain conditions and hydrologic flow at Gounamitz Lake. Vertical water flow through the subsoil is greater than lateral surface and subsurface flow (adapted from Case 2001).

Island Lake

The Island Lake (IL) study area is located in north-central New Brunswick (N 47.68; W 66.47) (Fig. 3.1). The merchantable tree species are mainly black spruce (*Picea mariana* [Mill.] BSP), balsam fir (*Abies balsamea* [L.]), eastern white pine (*Pinus strobus* L.), and trembling aspen (*Populus tremuloides* Michx.), with a lesser component of white spruce (*Picea glauca* [Moench] Voss), jack pine (*Pinus banksiana* Lamb.), white birch (*Betula papyrifera* Marsh.), and eastern white cedar (*Thuja occidentalis* L.) (Fig. 3.4). Some, or all, of this area was clearcut between 1930 and 1940 (Case 2001).

According to Colpitts *et al.* (1995), IL falls within the Popple Depot Forest Soils Unit. The soils in this study area are loam or sandy loam (Table 3.1), and are derived from felsic-volcanic rocks that with high percentages of quartz and alkali (sodium and potassium rich) feldspars. The soil parent material is compacted glacial till (Colpitts *et al.* 1995). As such, the soils are much fairly impermeable, especially in lower slope positions, leading to varied soil substrate conditions ranging from rapidly to poorly drained (Case 2001) (Fig. 3.5). Soil substrate variability is also evident in the soil classification, with roughly half of the study area represented by Orthic Humo-Ferric Podzols, and the other half belonging to various groups within the Brunisolic order (Case 2001). This study area is characterized by frequent and hummocky rock outcrops on the upper-slope positions, with a few, small, isolated locations on the lower slope where the groundwater approaches the ground surface, thereby creating soft soil conditions (Fig. 3.5). Watershed boundaries and flow accumulation lines in this highly variable terrain are often ill-defined (Fig. 3.6).



Fig. 3.4. Pre-harvest forest-stand conditions at Island Lake.



Fig. 3.5. Fine scale terrain conditions at Island Lake. Above: Rhyolitic outcropping on upper slope positions of the subcatchments. Below: Wet conditions resulting from impermeable till in depressions at lower slope positions.

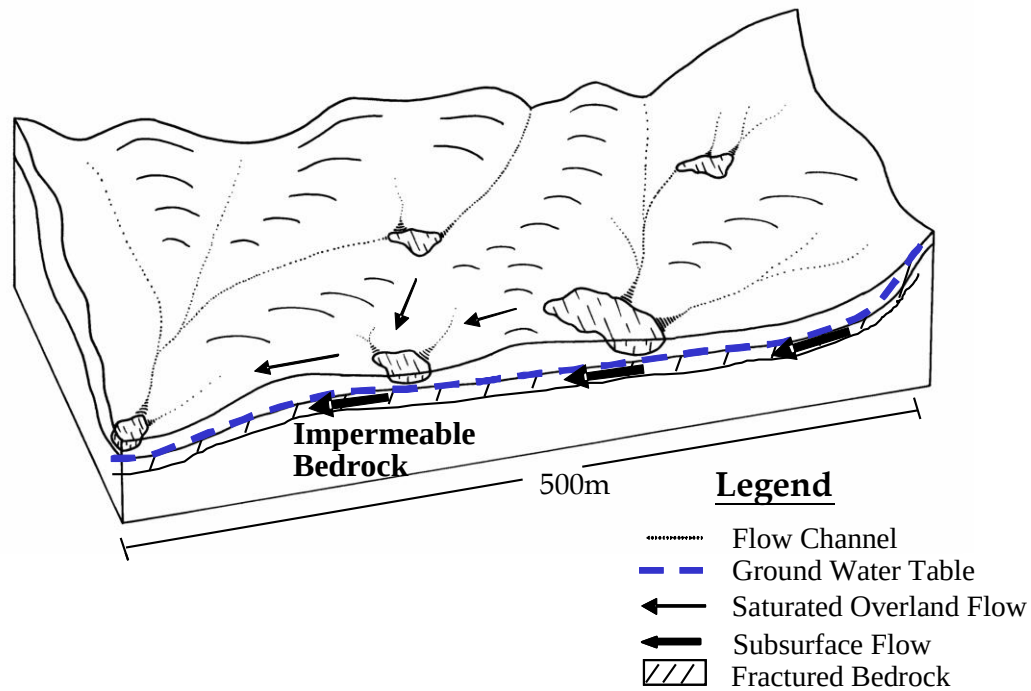


Fig. 3.6. Terrain conditions and hydrologic flow at Island Lake. Lateral surface and subsurface water flow is greater than vertical flow through the subsoil (adapted from Case 2001).

CATCHMENT DELINEATION

At the onset of this study, digital elevation data were obtained from Service New Brunswick. These data were used to generate a digital terrain model (DTM) for each of these two study areas. This was done with MapInfo software (MapInfo Corporation 1995), in conjunction with Vertical Mapper (Northwood Geoscience Ltd. 1996). The resulting DTMs were used to delineate the approximate locations of catchment boundaries. However, the DTM generated boundaries had limited accuracy, because of limited geo-spatial resolution, with elevation data sampled at approximately 70 m intervals (Watermark Industries Inc. 1997, cited in Finley *et al.* 1999). The DTM-generated boundaries were subsequently compared with local air-photos, which were

viewed with a stereoscope, to ascertain the overall correspondence between the DTM catchment boundaries, and the stereo view. There was general agreement, but there were also ambiguities that could not be resolved with certainty. Hence, the catchment boundaries as determined from the DTM were considered to be tentative, and these boundaries were then flagged in the field, using a hand-held Global Positioning System Unit (GPS), programmed with the computer-generated catchment boundaries. The fieldwork proceeded by correcting the tentative boundaries, through re-flagging once the actual boundaries were determined by marking the locations of highest ground next to the tentative lines.

HARVEST TREATMENTS

In total, boundaries for five catchments were located at GL (Fig. 3.7). One of these catchments was designated for a whole-tree harvest, a second was designated for a conventional, stem-only harvest, and a third established for an extra-slash harvest. Boundaries for two other catchments were established to serve as controls. Areas within the established catchment boundaries ranged from 6 to 12.5 ha, and all catchments within the area had similar slopes and aspects (Fig. 3.8 and Table 3.2).

At IL, boundaries were located for three catchments that were designated for the same three harvesting treatments. One other catchment was established to serve as a control (Fig. 3.9). A fifth catchment was also located, but this catchment was unmonitored, and remains in reserve for future experiments. The four monitored catchments ranged in size from 7.4 to 30.0 ha, with similar mean slopes and aspects (Fig. 3.10 and Table 3.2).

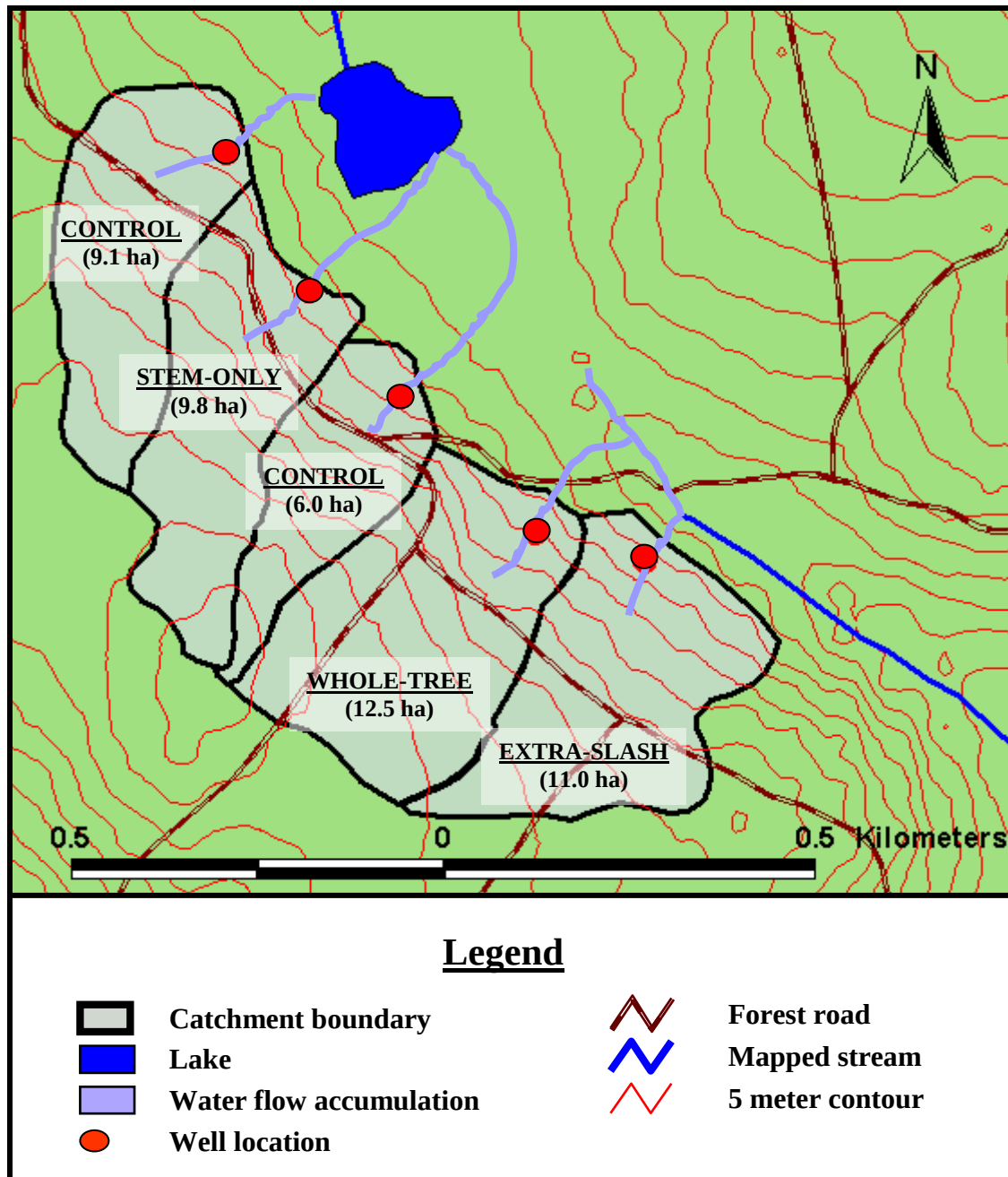


Fig. 3.7. Catchment boundaries and location of wells at Gounamitz Lake. The catchment boundaries are mapped based on a post-harvest aerial photograph and the Digital Elevation Model (DEM) for New Brunswick. Water flow accumulation line locations are estimated based on the DEM and field observations. Well locations are mapped from coordinates obtained with handheld Global Positioning System units.

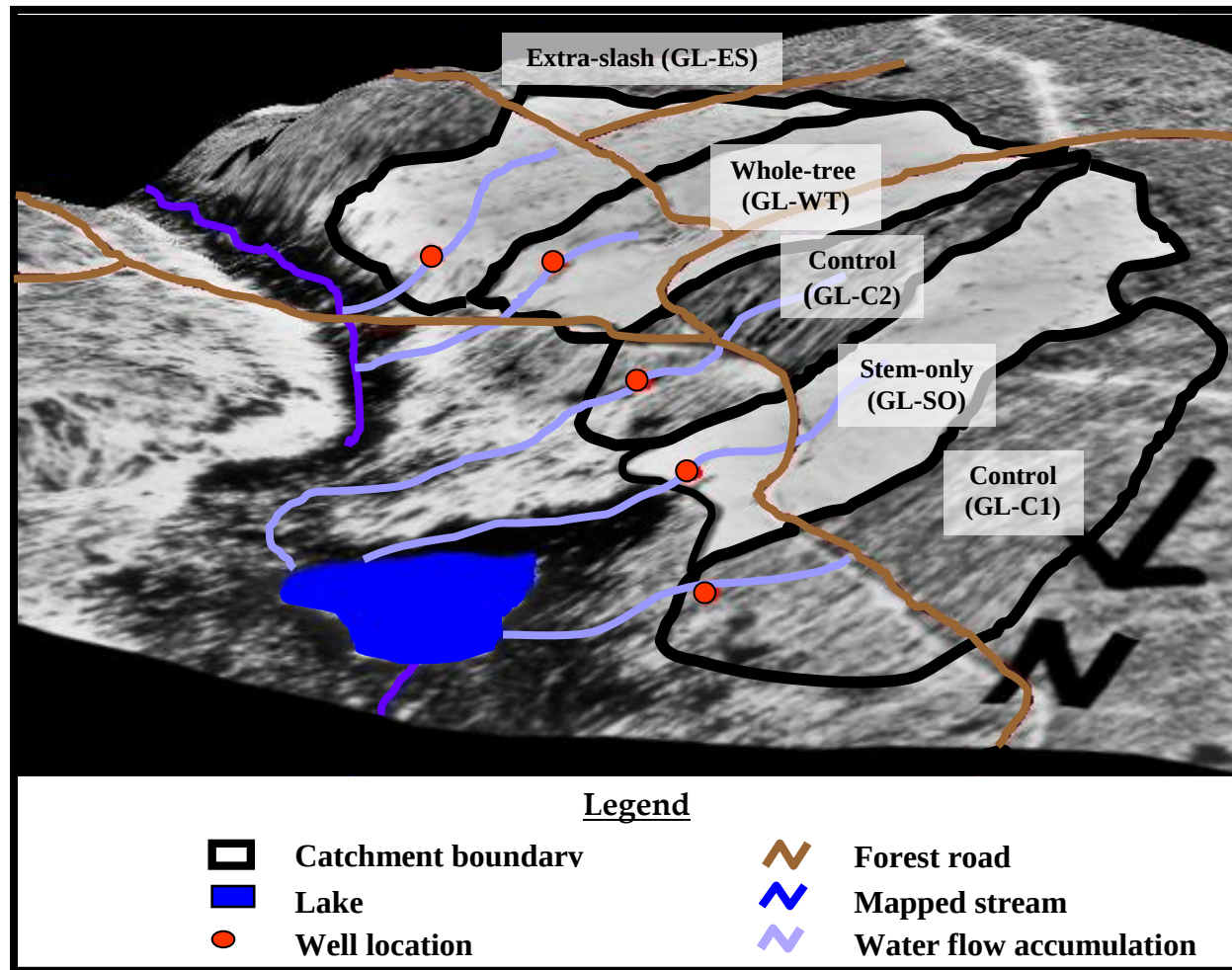


Fig. 3.8. Three-dimensional (3D) display of harvested catchments at Gounamitz Lake. Image was created using ArcView (Environmental Systems Research Institute Inc. 2002) and ArcView Image Analysis (Environmental Systems Research Institute Inc. 1999) to overlay an aerial photograph on a 3D display. Note: topography exaggerated by a factor of three for illustration purposes.

Table 3.2. Characteristics of the study catchments, and their associated wells, within the two study areas.

Characteristic	Gounamitz Lake					Island Lake					
	Control	Control	Stem-only	Whole-tree	Extra-slash	Control	Unmonitored	Stem-only		Whole-tree	Extra-slash
								Upper well	Lower well		
Abbreviated label	GL-C1	GL-C2	GL-SO	GL-WT	GL-ES	IL-C	N/A	IL-SO1	IL-SO2	IL-WT	IL-ES
Total area (ha)	9.1 ^a	9.8	6.0 ^a	12.5	11	30	30	30.6 ^a	7.4 ^a	11.5	20.1
Catchment area above well (ha) ^b	8.3 ^a	8.7	5.2 ^a	10.9	9.7	14.4	15.2	30.6 ^a	7.4 ^a	10.2	18.4
Well depth (m)	6.1	6.1	5.8	5.2	6.1	4.4	5.6	N/R	7.6	6.1	6.2
Average aspect ^c	63.8	105.3	41.1	67.4	49.2	214	213.2	237.4	168.7	227.6	217.7
Average slope (degrees) ^c	4.1	4.8	6.4	4.4	4.5	3.2	3.2	8.4	3.9	5.8	5.4

^a estimate based on Digital Elevation Model for New Brunswick and calculated with the Geographic Information Systems (GIS) software, ArcView (Environmental Systems Research Institute Inc. 2002).

^b best estimate based on knowledge of site terrain conditions.

^c calculated with the GIS software, ArcView (Environmental Systems Research Institute Inc. 2002).

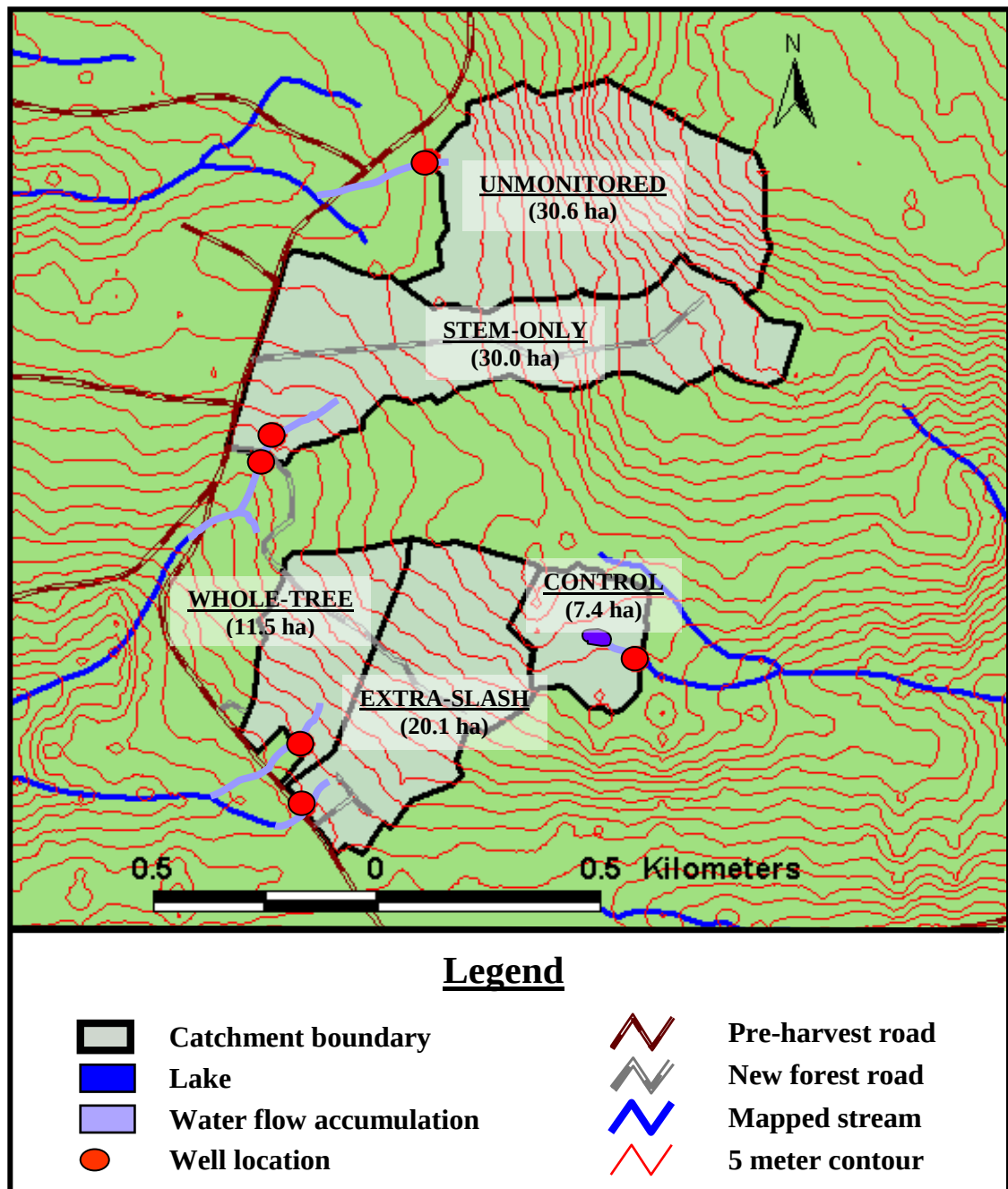


Fig. 3.9. Catchment boundaries and location of wells at Island Lake. The catchment boundaries are mapped based on a post-harvest aerial photograph and the Digital Elevation Model (DEM) for New Brunswick. Water flow accumulation line locations are estimated based on the DEM and field observations. Well locations are mapped from coordinates obtained with handheld Global Positioning System units.

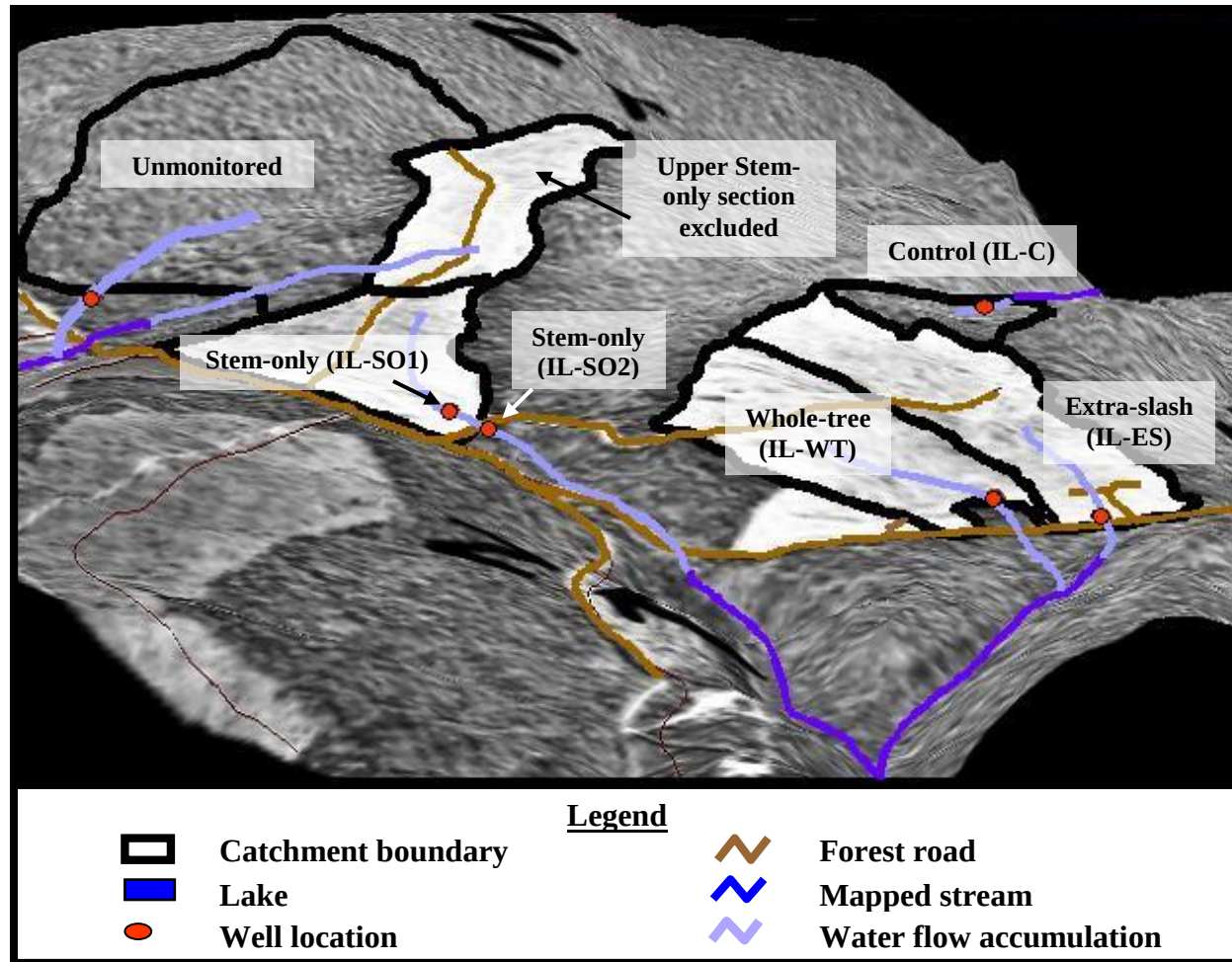


Fig. 3.10. Three-dimensional (3D) display of harvested catchments at Island Lake. Image was created using ArcView (Environmental Systems Research Institute Inc. 2002) and ArcView Image Analysis (Environmental Systems Research Institute Inc. 1999) to overlay an aerial photograph on a 3D display. Note: topography exaggerated by a factor of three for illustration purposes.

Stem-only harvesting is also known as conventional harvest. This method, as its name implies, is the traditional, and most common, form of clearcutting (Muir 2002). With this type of harvest, only the merchantable stem portions of the trees are removed from the cutblock. The limbs, top and any undesired portions of the tree are cut off and left where they fall. Whole-tree harvesting is defined for this study as the removal of all above ground portions of the tree. The tree is severed at the stump and the entire tree is moved to the roadside, where the tree is processed and prepared for transport. In this way, more biomass is captured per unit area of forest. The extra-slash treatment involves the use of stem-only harvesting, and adding extra slash from the neighboring catchment that was subjected to whole-tree harvesting. This technique is not a normal harvesting treatment, but was used to explore whether extra slash would further modify post-harvest catchment responses in groundwater tables and temperatures.

Gounamitz Lake

Harvesting operations at GL began on August 22nd, 2000 and were mostly complete by the first week of September, 2000. Two main harvesting systems were implemented to administer the three harvest treatments (Fig. 3.11).

Stem-only Harvest

Chainsaw crews were used on the stem-only catchment for felling and delimbing of trees. The stems were dragged roadside by one of three types of wheeled skidders used: Timberjack 230D; Timberjack 240D; and Tree Farmer C6D. At roadside, the stems were cut to desired length for transport with a CC-100B Tanguay 5025 slasher.



Fig. 3.11. Forest machinery used in the harvest of treatment catchments at Gounamitz Lake. Harvesting on the whole-tree catchment involved felling and piling of felled trees with a feller-buncher (a), movement to roadside with grapple skidders (b), delimbing with a delimber (c), and cutting to desired lengths with a slasher (e). Harvesting on the stem-only and extra-slash catchments involved felling and delimbing with chainsaws, movement of wood to roadside with cable skidders (d), and cutting of boles to desired lengths with a slasher.

Whole-tree Harvest

Trees on the whole-tree catchment were cut from the stump and placed in bunches with a tracked, Case 1187C feller-buncher. A wheeled, John Deere 748G grapple skidder was used to drag these bunches to roadside, with branches still attached. At roadside, the trees were delimbed with a Pierce delimber mounted on a Daewoo Solar 220 LC-3 excavator. The delimbed stems were then cut to desired length with the CC-100B Tanguay 5025 slasher.

Extra-slash Harvest

Harvesting on the extra-slash catchment took place with the same harvesting system used on the stem-only catchment. Following harvest, slash deposits left from the roadside delimbing at the whole-tree catchment were moved onto the extra-slash catchment with grapple skidders. The grapple skidder operators attempted to create a fairly even distribution of slash across the catchment. However, it was noticed that the operator had missed slash along one section of the road that may have amounted to up to one half of the catchment's slash. This situation could not be corrected before the end of this study.

Island Lake

Harvesting operations at IL began on August 18th, 2000 and were mostly completed by the first week of September, 2000. Three different harvesting systems were implemented to administer the three harvest treatments (Fig. 3.12).

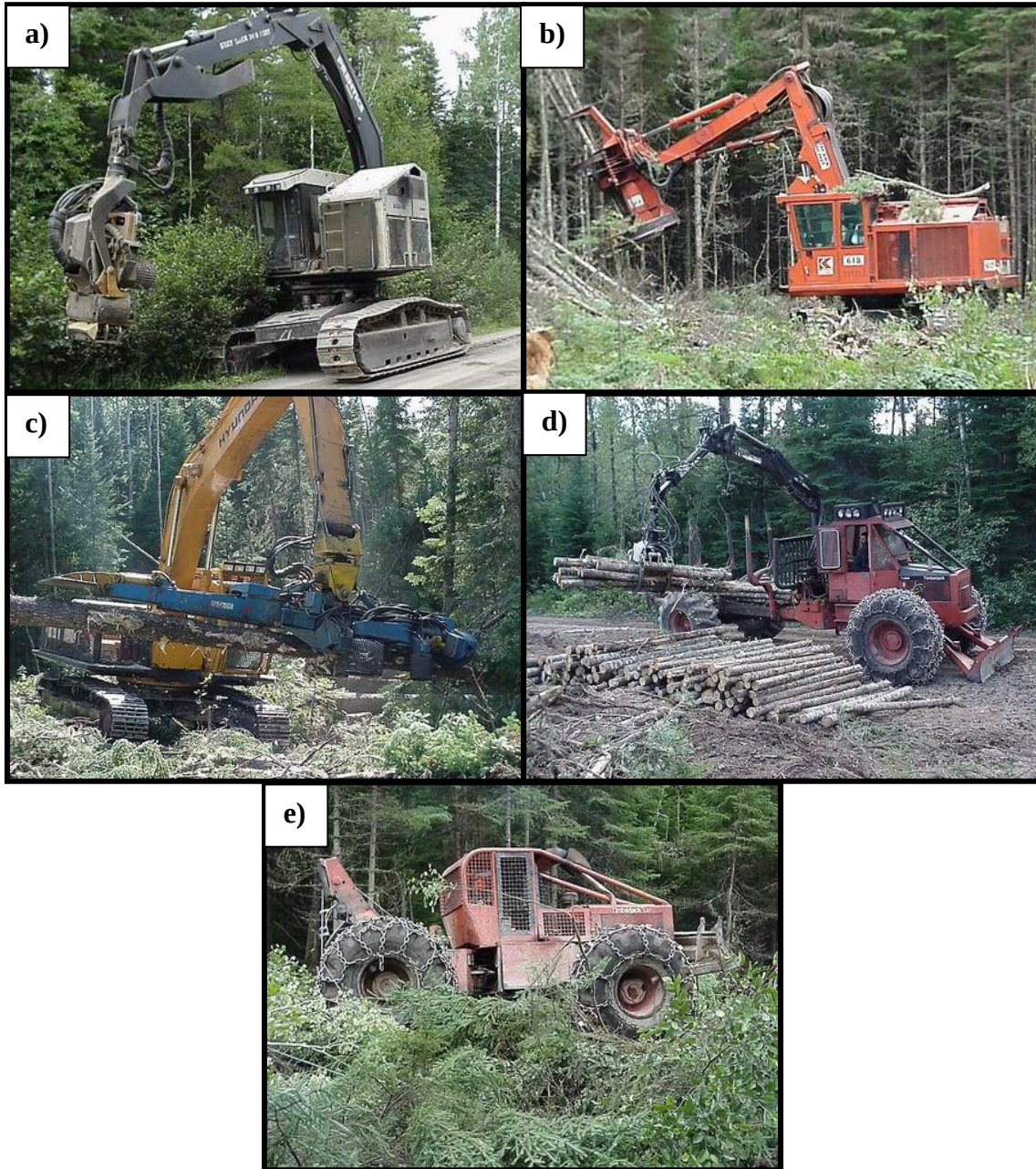


Fig. 3.12. Forest machinery used in the harvest of treatment catchments at Island Lake. Harvesting on the extra-slash catchment was conducted using a single-grip harvester (a) to fell, delimb and cut the boles to desired lengths, with a forwarder (d) carrying the wood to roadside. Harvesting on the stem-only catchment involved felling and piling of felled trees with a feller-buncher (b), delimbing and cutting boles to desired lengths with a Horner processing head (c), and the movement of wood to roadside with a forwarder (d). Harvesting on the whole-tree catchment involved felling with chainsaws, movement of wood to roadside with cable skidders (e), delimbing with a delimeter, and cutting of boles to desired lengths with a slasher.

Stem-only Harvest

On the stem-only catchment, trees were cut from the stump and placed in piles by a tracked, Koering Waterous 618 feller-buncher. The trees were then delimbed, cut to desired lengths, and placed in piles on the cutblock by a Hornet processor mounted on a tracked, Hyundai Robex 290 LC-3 excavator. A wheeled, Timberjack 230 Turbo was then used to pick up the piles of logs and carry them to roadside for transport to the mills.

Whole-tree Harvest

Trees on the whole-tree catchment were felled by chainsaw crews. The trees were then drug roadside, with the limbs attached, by wheeled, Timberjack 230D cable skidders. At roadside, the trees were delimbed with an unknown delimeter and the stems were then cut to desired lengths by an unknown make and model of slasher.

Extra-slash Harvest

On the extra-slash catchment, one, tracked, Prentice 620-Fb single-grip harvester was used to remove the trees from the stump, delimb, and cut the stems to desired length on the cutblock. The harvester left the cut stems in piles at the sides of the extraction trails where they were picked up and carried to roadside by a wheeled, Timberjack Turbo forwarder. After harvesting, roadside slash from the whole-tree harvested catchment was brought onto the extra-slash catchment by a grapple skidder. The skidder adhered closely to the existing extraction trails, and deposited the slash as small, scattered piles throughout the cutblock.

Following the removal of trees on the treatment catchments, it was discovered that the catchment boundaries for the IL stem-only harvest treatment were not accurately located. The dense pre-harvest forest cover had prevented the field crews from seeing a

ridgeline. As a result, the true catchment is approximately half the size of the harvested area for that treatment (Fig. 3.10 and Table 3.2).

DIFFERENCES BETWEEN CATCHMENTS

Two sets of indices were created to highlight differences between catchments that were important for the interpretation of the groundwater temperature and level results of this study.

Solar Radiation Index

A Forest Hydrology extension for ArcView (Environmental Systems Research Institute Inc. 2002) was used to calculate an index for the potential incoming solar radiation (in W/m^2) for each catchment. This extension was designed at the University of New Brunswick to calculate potential solar radiation inputs based on latitude, elevation, season, shading effects of surrounding terrain, slope, and aspect, in the absence of cloud cover (Meng, personal communication, 23 March 04). Since summer maximum temperatures were of greatest interest, the radiation index was calculated for July 1st.

The estimates of solar radiation, as received by each catchment (cloud-free conditions, July 1.) are listed in Table 3.3. In general, there was very little difference in potential radiation between catchments within each study area. However, there were larger differences between study areas, with GL receiving more sun.

Soil/Water Contact Time Index

The size, shape, and slopes of the catchments are important parameters that may have influenced shallow groundwater temperatures at the location of each well. The longer the water would be in contact with the soil as it travels downslope to the well

Table 3.3. Index of potential incoming solar radiation on catchments the a) Gounamitz Lake and b) Island Lake sites. Solar radiation indices were calculated for July 1st using ArcView (Environmental Systems Research Institute Inc. 2002).

a)	Catchment	Radiation Index (watts/m ²)
	GL-C1	1048.5
	GL-C2	1037.4
	GL-SO	1046.6
	GL-WT	1052.7
	GL-ES	1047
b)	Catchment	Radiation Index (watts/m ²)
	IL-C	1013.8
	IL-SO1	1011.4
	IL-SO2	1012.2
	IL-WT	1020.2
	IL-ES	1023.4

locations, the more its temperature should reflect that of the soil (Brosfske *et al.* 1997). Therefore, harvesting-induced soil temperature increases should be best reflected in shallow groundwater with the longest travel times. Likewise, soil and substrate permeability should also contribute to groundwater temperature because of the amount of time required for the groundwater to drain.

To address variability between catchments in the soil/water contact time as water drained, a single index was created to address catchment slope and shallow groundwater travel distances. Each catchment's slope was divided by the distance between its monitoring well, and the ridge on the far side of the catchment, producing an index value for that catchment. The index values shown in Table 3.4 represent the estimated length of time one catchment's shallow groundwater was in contact with the

Table 3.4. Indices reflecting the estimated length of time that shallow groundwaters are in contact with the soils as they drain catchments on the a) Gounamitz Lake and b) Island Lake sites. Index values are calculated by dividing catchment's slope by the distance from its monitoring well to the ridge on its far side.

a)			
Catchment	Travel Distance(m) ^a	Slope (degrees)	Soil/Water Contact Time Index ^b
GL-C1	467	4.1	0.0088
GL-C2	454	6.4	0.0141
GL-SO	500	4.8	0.0096
GL-WT	432	4.4	0.0102
GL-ES	405	4.5	0.0111

b)			
Catchment	Travel Distance(m) ^a	Slope (degrees)	Soil/Water Contact Time Index ^b
IL-C	310	3.9	0.0126
IL-SO1	452	3.2	0.0071
IL-SO2	518	3.2	0.0062
IL-WT	466	5.8	0.0125
IL-ES	690	5.4	0.0078

^a Average distance from the monitoring well to the upper catchment boundary.

^b Calculated by dividing the catchment slope by the water's travel distance.

soils, relative to the other catchments. A lower index value means a longer soil contact time.

WEATHER DATA

When examining fluctuations in water parameters, it is important to consider local weather conditions when determining cause/effect relationships. In this Thesis, weather information is used to help explain and predict the behavior of shallow groundwater temperatures and levels.

A weather station was set up near each of the two study areas. However, numerous problems were encountered in the collection of data, including problems with

tree blow-downs on instrumentation, unreliable power sources (especially at sub-zero temperatures) and animal disturbance (gnawing of cables, and knocking instrumentation to the ground). All of this prevented the collection of continuous on-site weather records regarding precipitation and air-temperatures. Instead, weather data from various Environment Canada and New Brunswick Department of Natural Resources and Energy (NBDNRE) weather stations in the areas surrounding the study areas were used (Fig. 3.13). Most of these stations had short gaps in the temperature and precipitation records during the time period of this study. Complete weather records are required for running the hydrological model ForHyM, to simulate, *inter alia*, snowpack depth, snow melt, soil moisture and temperature, and water table fluctuations of the groundwater. Using relationships between various combinations of weather stations, complete weather data sets were obtained for each study area by gap filling. Missing values were generated by way of multiple regression analysis, with weather data from the near-by weather stations being used to produce the best-fitted predictor equations for the weather station nearest to each of the two study areas. Appendix I provides further details on how the final weather records were constructed.

WELL INSTALLATION

In the summer of 1998, wells were drilled within each of the catchments at both study areas, and well casings were installed. The wells were located near the base of each catchment, on top of the flow accumulation line (Fig. 3.7 and 3.9). These wells were drilled through the till and into the bedrock, where water finally started to flow freely and pour into the borehole. The deepest well was approximately 7.6 m deep (Table 3.2).

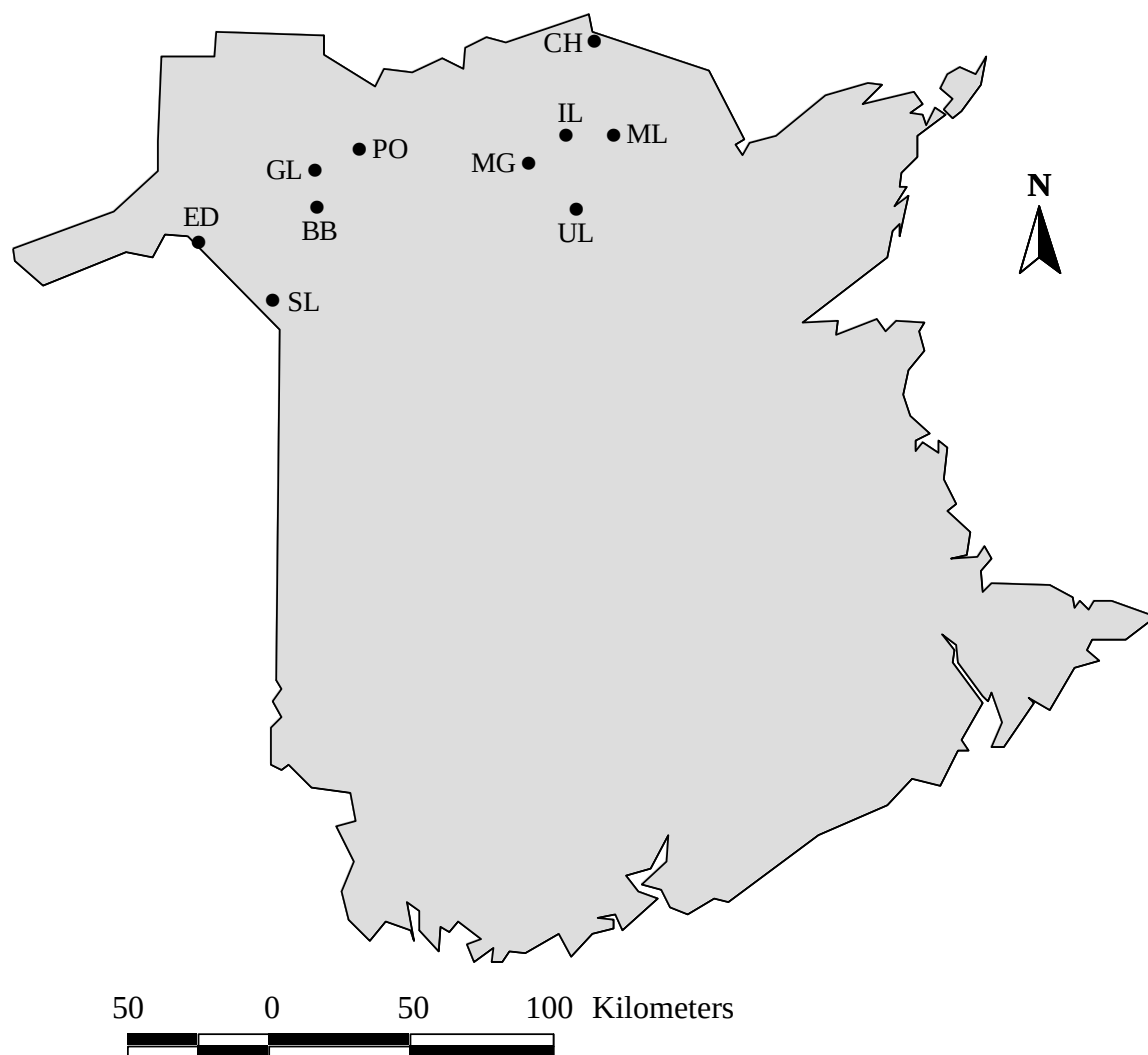


Fig. 3.13. Locations of weather stations from which weather information was used for model input, and their proximity to the study areas. GL = Gounamitz Lake study area, IL = Island Lake study area, ED = Edmundston station, SL = St. Leonard station, BB = Boston Brook station, PO = Petit Ouest station, CH = Charlo station, MG = Mulligan Gulch station, UL = Upsalquitch Lake station, and ML = McRae Lake station.

At IL, a number of the wells that were drilled in the first year started to dry during the height of the summer. For these cases, new wells were drilled in the next year, each located further down the flow accumulation line. In all, five operational wells were established at IL (Fig. 3.9). Two of the wells were located near the base of the stem-only catchment. The other catchments had one well each (Fig. 3.9).

MEASUREMENT PROTOCOL

Each well casing was equipped with two plastic pipes, and one data probe (Fig. 3.14). These pipes were installed to provide two methods by which water samples could be collected. One of the plastic pipes placed in the wells was fitted with a foot-valve at the base so that rapid vertical movement of the pipe would bring the water to the surface and purge the well if needed. The other pipe was used with a hand-held pump to collect water samples. The water samples so collected were, for the record, all analyzed for major cations and anions, as well as pH, electrical conductivity, and dissolved organic carbon. Part of the resulting data have been analyzed by Steeves (2001).

In addition to the plastic pipes, each casing contained an electronic probe for automated data collection (Fig. 3.15). All probes were obtained from In-Situ Inc., Laramie, WY, USA. At GL, the well on the first control catchment (GL-C1) (Fig 3.8), was equipped with a TROLL 8000 Multi-Parameter probe. The other GL wells were equipped with TROLL 4000 probes. At IL, all the wells were equipped with TROLL 4000's except the one on the ES catchment, which was equipped with a TROLL 8000 probe.

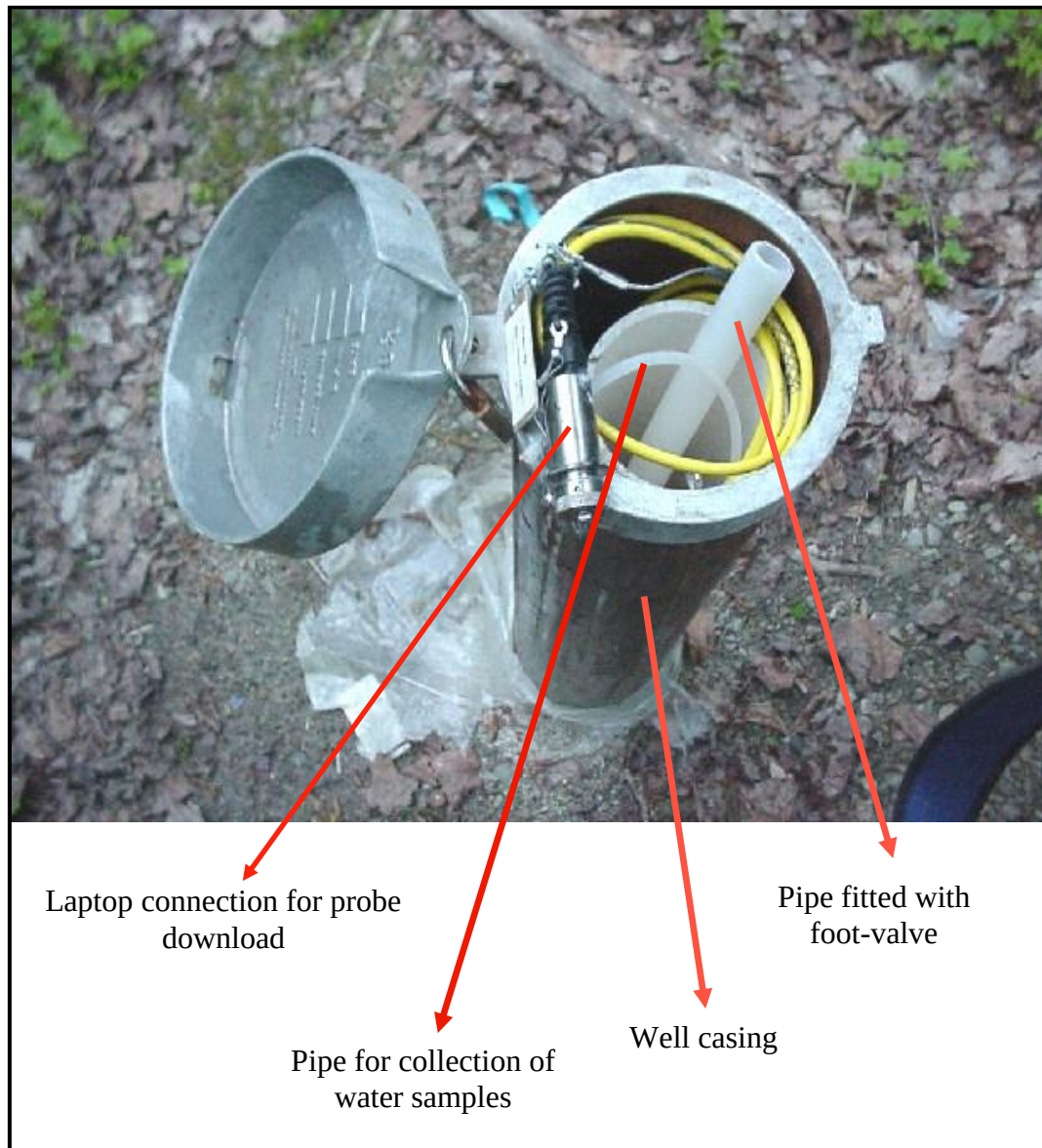


Fig. 3.14. Well fitted with equipment used for groundwater measurements and water sample collection.

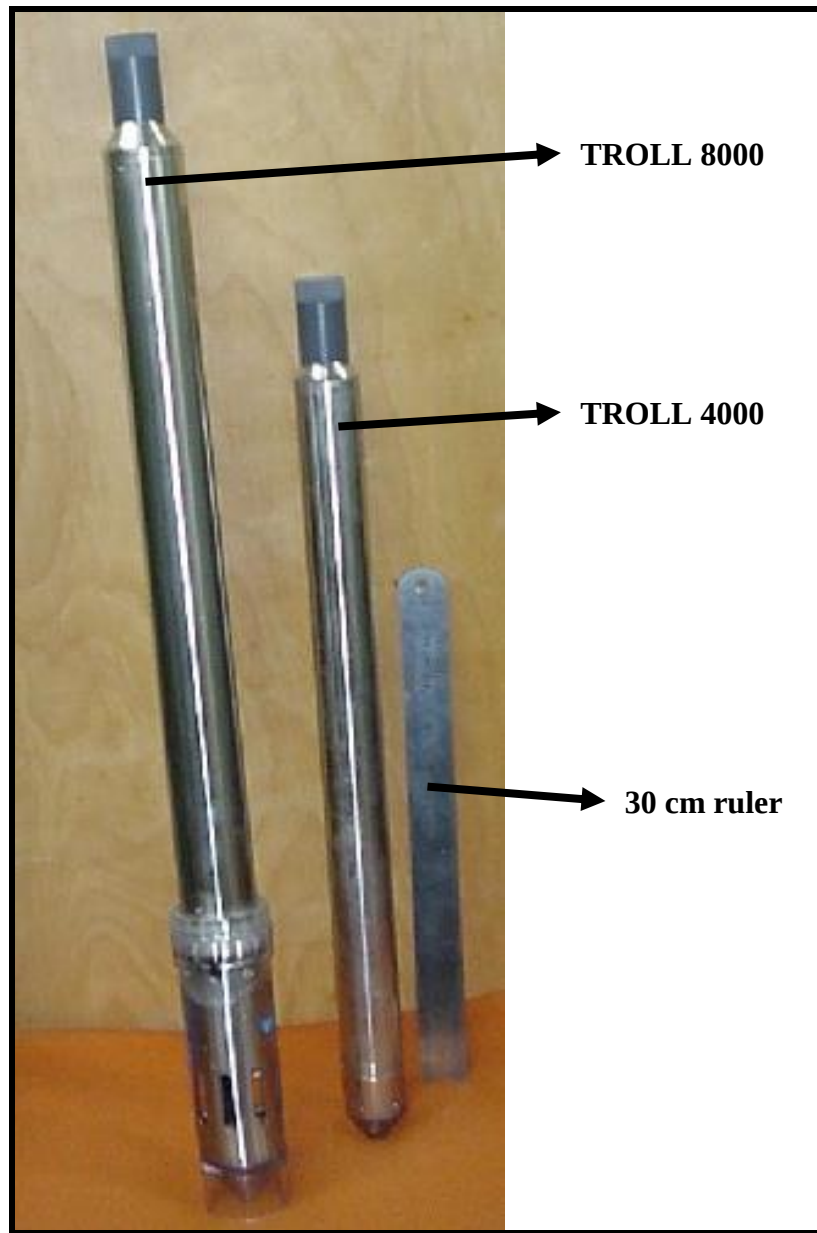


Fig. 3.15. Data collection probes obtained from In-Situ Inc., Laramie, WY, USA, and used for automated collection of water temperature and changes in water table level.

The probes were placed near the bottom of the wells to reduce the possibility of the water table dropping below the level of the probe's sensors. The sensors were programmed to measure temperature and water table fluctuations every two or four hours. This frequency was chosen in an attempt to capture as much change in temperature and water table as possible without sacrificing an unnecessary amount of the probe's battery power. While water temperature readings were not expected to change much during the day, the level of the shallow groundwater table could – in principle - change quickly and drastically.

Water table fluctuations were determined automatically with an internal pressure transducer that monitored atmospheric pressure above and below the water table, at the location of the probe head. The difference between these pressures was automatically converted into depth of water above the pressure sensor.

Probe measurements recorded for two years pre-harvest and two-plus post harvest years. The only exceptions were the two wells containing the TROLL 8000's. Because of limited initial funding and large start-up costs, these probes had to be purchased one year later. Therefore, first year temperature and water table level data are missing for these two wells. The dates during which the probes recorded data are presented in Table 3.5.

All temperature and water table level measurements were stored within the probe's internal memory and were downloaded onto a laptop computer once, or twice, each summer.

DATA QUALITY MANAGEMENT

Data was downloaded from each probe onto a laptop computer using Win-Situ software (In-Situ Inc. 1997a) supplied with the probes. Altogether, each probe contained

Table 3.5. Dates of probe data collection, excluding erroneous measurements.

Well	Parameter	Probe data collection	
		Start	End
GL-1	Temperature Water table	Aug. 24, 1999 Aug. 24, 1999	Apr. 8, 2002 Nov. 12, 2002
GL-2	Temperature Water table } }	Aug. 15, 1998	Nov. 12, 2002
GL-3	Temperature Water table } }	Aug. 15, 1998	Nov. 12, 2002
GL-4	Temperature Water table } }	Aug. 15, 1998	Nov. 12, 2002
GL-5	Temperature Water table } }	Aug. 15, 1998	Nov. 12, 2002
IL-1A	Temperature Water table } }	Aug. 15, 1998	Nov. 12, 2002
IL-1B	Temperature Water table } }	Aug. 24, 1999	Nov. 12, 2002
IL-3	Temperature Water table } }	Aug. 24, 1999	Nov. 12, 2002
IL-4	Temperature Water table } }	Aug. 15, 1998	Nov. 12, 2002
IL-5	Temperature Water table } }	Aug. 24, 1999	Nov. 12, 2002

approximately 13,000 to 31,000 data points, depending on the length of time the probe was active, and the frequency of measurement recording. The raw data were converted from the original “BIN files” format to “text” using the Win-Situ Data Manager software (In-Situ Inc. 1997b). Another program, called Modelmaker (Cherwell Scientific Ltd. 1999), was used to convert the text files into mean, twice-daily values (noon and midnight) for temperature and water table height. This was necessary because the number of daily measurements varied by well, and by year, as programmed into the probes, and

the timing of the measurements were not synchronized. The resulting twice-daily values were assembled in spreadsheet format for data analysis, with each well having one column for temperature, and one for water table levels. Other columns were designated for year, year fraction, month day, and pre- and post-harvest index. Each row represented one temperature reading.

The data, as downloaded from the probes, had to be examined for errors. When the data points for temperature and water level changes were plotted against time, several suspect measurements were evident by either sharp, upward and downward spikes, sudden shifts, or flat-lines. Three main causes were identified for these errors:

- Repositioning of the probes: Over time, soil particles settled on the bottom of the wells and began to cover the base of the probes. In these wells, the probes had to be lifted slightly to avoid covering of the probe's sensors. These slight height adjustments caused shifts in the probe's measurements of water table level, giving false impressions of drops in the water table levels because of decreased water pressure. These errors in the water table levels were corrected by shifting the erroneous data points back into place.
- Errors incurred during probe downloads: False data spikes occurred when the probes were removed for maintenance and data downloading. Downloading interfered systematically with the probe's next temperature measurement, regardless of whether or not the probe had been re-submersed in time for measurement. Any erroneous data were removed. With sample points taken every two or four hours, the deletion of such data was not serious, because the raw data were further converted into daily averages.

- Dry wells: When water levels in the upper SO well at IL (IL-SO1) dried up, measurements of zero were recorded. These zero measurements were removed from the data set.

Temperature measurements from the first control at GL (GL-C1) became erratic on April 8th, 2002, just over 3.5 years into the study, and continued to produce erroneous measurements for the remainder of the study. This probe was found to be running low battery power, which may be a possible explanation for the erroneous recordings. All temperature measurements taken by this probe after April 8th, 2002 were, therefore, deleted (Table 3.5). Loss of data from the end of the study, combined with the lack of data for the first year of the study, left about 2.5 years of solid data for this control catchment (GL-C1). However, GL had a second control well (GL-C2), from which four full years of data were obtained. The second control was used as a predictor to fill the missing data points from the first control, by way of regression analysis. For details of this regression analysis, see Appendix II.

Except for the occasional error reading obtained during probe maintenance, no water level measurements were discarded from the data set. However, three blocks of data from the two IL-SO wells were ignored when establishing well-to-well relationships. These sections of the data set contained erratic measurements occurring as a result of snowmelt and spring thaw. From the upper SO well (IL-B1A), measurements taken between April 27th and May 19th, 1999, and between April 12th and May 21st, 2000 were ignored. From the lower SO well (IL-B1B), measurements taken between March 31st and July 6th, 2000 were ignored.

Finally, when the automated probes were installed in the wells, they were placed at varying depths below the water table. In order to facilitate comparisons of water levels between catchments, the resulting data sets needed to be shifted. For GL, the water level measurements were shifted by an appropriate number so that they all began at the same level when the study was initiated in August of 1998. At IL, only two of the probes were installed at the beginning of the study in 1998. The others were installed one year later. Here, the data sets were shifted so that all winter baseline levels were the same.

CHAPTER 4

POST-HARVESTING VEGETATIVE RECOVERY

INTRODUCTION

As part of the study area description, this Chapter addresses the following objectives:

- to evaluate early post-harvest recovery of vegetation.
- to assess post-harvest slash distribution.

Generally, it is expected that type of forest harvesting affects the rate of post-harvest forest recovery, and thereby affects the recovery rate of water quality and quantity to pre-harvest conditions. The rate of forest recovery depends on specific successions of vegetative regeneration, from herbaceous to tree species (Swift and Messer 1971; Marks and Bormann 1972; Aubertin and Patric 1974; Boring *et al.* 1981; Cox and Van Lear 1985). Hydrologically, post-harvest catchment recovery is more or less attained once the regenerating vegetation has developed a full canopy, thereby re-establishing pre-harvest micro-climate conditions at canopy level, at the ground-level, and below the ground. Full canopy is needed to re-establish pre-harvest rates of shading, interception, and evapotranspiration (Marks and Bormann 1972; Verry 1972; Aubertin and Patric 1974).

There are studies showing that vegetation regrowth following whole-tree harvesting is generally most rapid and thorough (Fahey *et al.* 1991; McInnis and Roberts 1994; Karlsson *et al.* 2002). The reason for this is the removal of greater volumes of slash. When left on the site, slash tends to hinder plant re-establishment, by acting as a physical barrier, and by limiting the amount of heat and light reaching the soil (Lundkvist 1988; Fahey *et al.* 1991; McInnis and Roberts 1994; Olsson *et al.* 1996; Karlsson *et al.* 2002). Therefore, the harvesting method implemented may not only determine the extent of the immediate post-harvest impact on water quality and quantity, but also the rate at which water quality and quantity recover to pre-harvest levels.

METHODS

Two forest recovery surveys were done, one in October 2001 and one in August 2002, i.e., one and two years following the harvest of the treatment basins. Slash distribution was also assessed in 2002 survey.

The October 2001 survey involved systematic sample plots across the treatment basins, laid out on transects 100m apart, oriented east to west, with a sample plot every 50m. The sample plots were circular with a 1.26m radius (area = 5m²). Within these plots, number and species of all commercial trees species of identifiable size were tallied (Table 4.1).

The August 2002 survey was laid out along transects placed 100 m apart, positioned so that they would cross the path of the extraction equipment (i.e., skidders and forwarders) at an angle of about 45°. Sampling was based on 1x1 meter survey plots, similar to those used in previous regeneration surveys (Fig. 4.1) (Roberts 1989, Roberts

Table 4.1. Estimated numbers of merchantable tree species on study sites one to two years following harvesting treatments based on sample counts.

Site	Survey Number	<i>Abies</i> balsamaea (L.) Mill.	<i>Acer</i> rubrum L.	<i>Acer</i> saccharum Marsh.	<i>Betula</i> sp.	<i>Fagus</i> grandifolia Ehrh.	<i>Picea</i> sp.	<i>Populus</i> sp.	<i>Pinus</i> sp.	<i>Thuja</i> occidentalis L.
IL-WT	1	32125	10313	0	10250	0	3875	36250	563	0
IL-SO	1	2807	2667	0	737	0	842	12456	211	0
IL-ES	1	37909	1591	0	10591	0	909	15045	409	45
IL-WT	2	2895	11053	0	21842	0	263	22368	0	0
IL-SO	2	323	2258	0	5914	0	4301	8280	108	0
IL-ES	2	3390	2712	0	1695	0	2373	8644	339	0
GL-WT	2	1316	6316	18158	7632	42368	0	1842	0	0
GL-SO	2	1875	6563	38750	22188	21875	0	0	0	0
GL-ES	2	476	3571	18571	5476	2619	0	2619	0	0



Fig. 4.1. A typical 1x1 meter sample plot containing vegetation and slash.

and Dong 1993). These plots were positioned every 30 m along the transects. Within each plot, vegetation and slash loading was assessed using the following categories:

- *Number of stems* – the number of merchantable stems located within the plot.
These stems included all sizes and ages, where the species could be identified to at least the Genus.
- *% moss* - the percentage of the plot covered by mosses.
- *% herbaceous* –the percentage of the plot covered by the vegetation of herbaceous species (ex: ferns, *Solidago* spp.).
- *% woody vegetation* –the percentage of the plot covered by the vegetation of species having woody stems (ex: *Acer spicatum*, *Vaccinium* spp.). Merchantable tree species was also included in this category.

- % *grass* - the percentage of the plot covered by grasses.
- % *raspberry* –the percentage of the plot covered by raspberry plants.
- *Slash* – The occurrence of harvesting residues within the plots was noted, along with the depth of the pile. Depth was categorized as either <20cm, 20-50 cm, or >50 cm. Two individuals conducted the slash survey, each working independently using slightly different criteria. One surveyor recorded the approximate area within each sample plot that was covered by each depth category of slash. This information was used to estimate the portion of each catchment buried under each slash category. The other sampler only recorded the presence or absence of slash. Slash was recorded as present if there was a significant amount (approx. $\geq 10\%$ of plot covered), and the slash within each plot was categorized as one depth, determined by the majority within the plot.

RESULTS AND DISCUSSION

Gounamitz Lake

Following harvesting, the GL catchments were quickly blanketed with a dense cover of raspberries (Fig 4.2). This blanket was largely responsible for the high “total vegetative cover” figures found on all catchments (Table 4.2). The total vegetative cover was greatest on the WT and SO catchments, with only 1% more coverage on the WT catchment (Table 4.2). The ES catchment had a significantly lower total vegetative cover than either the WT or SO catchments. The ES catchment also had the lowest stocking level, defined as the percentage of sample plots that contained at least one merchantable



Fig. 4.2. Raspberry regeneration at Gounamitz Lake in the third summer following harvesting.

tree species, and significantly fewer merchantable tree stems than the other catchments (Table 4.3).

The low levels of vegetative growth on the ES catchment can be explained, at least in part, by the slash levels on the catchment. High levels of slash on the ES catchment may be acting as mulch. Results indicate that the slash level on the ES catchment was significantly higher than the WT catchment, but not significantly higher than the SO catchment (Table 4.4). Although not significant at a 90% confidence level, Table 4.4 suggests that the SO catchment also had considerably less slash than the ES

Table 4.2 a) Estimated percentages of study sites covered by vegetation based on sample plots established two years following harvesting treatments.

Site	Moss (%)	Herbaceous (%)	Woody (%)	Grass (%)	Raspberry (%)	Total vegetative cover (%)
GL-WT	1	25	33	7	46	113
GL-SO	1	26	26	3	56	112
GL-ES	0	12	25	5	53	95
IL-WT	0	33	45	5	10	92
IL-SO	5	22	18	2	5	51
IL-ES	4	26	33	3	5	71

Table 4.2 b) Statistical significance of differences in total vegetation cover between the six different treatment areas subjected to harvesting.

	P-value					
Catchment	GL-WT	GL-SO	GL-ES	IL-WT	IL-SO	IL-ES
GL-WT	1	0.8945	0.0202 ^b	0.0273 ^b	<.0001 ^b	<.0001 ^b
GL-SO		1	0.0694 ^a	0.0739 ^a	<.0001 ^b	<.0001 ^b
GL-ES			1	0.6865	<.0001 ^b	0.0005 ^b
IL-WT				1	<.0001 ^b	0.0102 ^b
IL-SO					1	0.0029 ^b
IL-ES						1

^a Significant at a 90% confidence interval.

^b Significant at a 95% confidence interval.

Table 4.3. a) Sampling intensity and presence of tree regeneration on study sites one - two years following harvesting treatments.

Site	Survey Number	Size (ha)	# of sample plots	Plot size (m ²)	% of total area sampled	Stocking % ^a	# of merchantable tree stems / ha ^b
IL-WT	1	11.5	32	5	0.139	100	93375
IL-SO	1	29.7	57	5	0.096	84	19719
IL-ES	1	20.1	44	5	0.109	100	66500
IL-WT	2	11.5	38	1	0.033	84	58421
IL-SO	2	29.7	93	1	0.031	47	21828
IL-ES	2	20.1	59	1	0.029	58	19661
GL-WT	2	12.5	38	1	0.030	84	77632
GL-SO	2	9.8	32	1	0.033	78	91250
GL-ES	2	11	42	1	0.038	60	33333

^a percentage of total sample plots containing one or more merchantable tree stems.

^b Merchantable Stems were defined here as tree species that are commercially viable in New Brunswick.

Table 4.3 b) Statistical significance of differences in the number of merchantable stems per hectare between the six different treatment areas subjected to harvesting.

		P-value								
	Catchment	First Survey			Second Survey					
		IL-WT	IL-SO	IL-ES	GL-WT	GL-SO	GL-ES	IL-WT	IL-SO	IL-ES
First Survey	IL-WT	1	0.0001 ^b	0.2973						
	IL-SO		1	0.0016 ^b						
	IL-ES			1						
Second Survey	GL-WT				1	0.6611	0.0645 ^a	0.5399	0.0012 ^b	0.0039 ^b
	GL-SO					1	0.0023 ^b	0.2418	<.0001 ^b	<.0001 ^b
	GL-ES						1	0.2040	0.1549	0.0381 ^b
	IL-WT							1	0.0122 ^b	0.0186 ^b
	IL-SO								1	0.7388
	IL-ES									1

^a Significant at a 90% confidence interval.

^b Significant at a 95% confidence interval.

Table 4.4 a) Slash remaining on treatment sites following harvesting.

Site	Slash level ^a						
	% of site covered				Frequency of occurrence (% of samples) ^b		
	1	2	3	Total	1	2	3
GL-WT	8.8	4.4	0.0	13.2	28.6	4.8	0.0
GL-SO	4.4	3.8	17.4	25.6	66.7	13.3	0.0
GL-ES	12.5	7.5	8.1	28.1	50.0	27.8	0.0
IL-WT	18.3	5.3	0.0	23.6	34.8	0.0	0.0
IL-SO	28.8	5.6	0.1	34.5	54.2	8.3	0.0
IL-ES	28.3	4.3	4.1	36.7	46.7	3.3	0.0

^a level 1: ≤ 20cm deep; level 2: 20-50cm deep; level 3: >50cm deep; Total = sum of the three levels.

^b percentage of sample plots in which approximately ≥10% of the surface area was covered by slash.

Table 4.4 b) Statistical significance of differences in total slash cover between the six different treatment areas subjected to harvesting.

	P-value					
Catchment	GL-WT	GL-SO	GL-ES	IL-WT	IL-SO	IL-ES
GL-WT	1	0.2302	0.0908 ^a	0.2700	0.0208 ^b	0.0134 ^b
GL-SO		1	0.8140	0.8777	0.3871	0.3064
GL-ES			1	0.6705	0.4627	0.3465
IL-WT				1	0.2985	0.2265
IL-SO					1	0.7836
IL-ES						1

^a Significant at a 90% confidence interval.

^b Significant at a 95% confidence interval.

catchment. Also, general visual observations of the catchments by the surveyors confirm that slash cover appeared denser and thicker over much of the ES catchment, than it was on the other two treatment areas, where thinner slash deposits allowed the penetration of some vegetation.

Insignificant statistical significance between slash levels on the ES and SO catchments may have been due to the small sample size involved. It is also possible that the *act* of adding extra slash to the ES catchment alone may have contributed to the low stocking and stem counts here, because heavy equipment was used to drag slash from roadside processing sites, onto the ES catchment. Here at GL, the extra slash was not moved onto the catchment at time of harvest, but in the following spring. Therefore, there is a possibility that there were newly established seedlings that were destroyed by the operation.

The comparatively low total vegetative cover on the ES catchment after two post-harvesting years suggests that this catchment could incur greater post-harvesting hydrological change in the years immediately following harvesting than the other two catchments. Since there also appeared to be fewer trees regenerating on this catchment, it appears that recovery will continue to be slow well into the future. The accuracy of this prediction depends largely upon the influence of species competition on the regenerating tree species. Although the WT and SO catchments have a greater number trees regenerating, there is also a greater potential for competition from other forms of vegetation here, which could lead to much higher mortality rates among the commercial tree species.

Island Lake

At IL, there were significant differences between the total vegetative cover measured on all catchments (Table 4.2). The WT catchment had the highest percentage of its soil surface covered in vegetation, followed by the ES and SO catchment. In terms of tree species present, there was generally poor agreement between the two post-harvest surveys conducted, with the first tally having the larger count (Table 4.3). There are four possible explanations for this discrepancy:

- Mortality: Many young seedlings may have died from predation, exposure, competition, etc. between the first and second surveys.
- Surveyor accuracy: The first survey was conducted by forest industry personnel who have more training and experience in identifying tree seedlings. This may explain why approximately 10 times more balsam fir (*Abies balsamea* [L.] Mill.) seedlings were tallied in the first survey (Table 4.1); young balsam fir seedlings look very much like some moss species, particularly *Polytrichum* sp., to an untrained eye.
- Sampling intensity: The percentage of the treatment catchments surveyed the first time was approximately three times greater than the second (Table 4.3).
- Survey plot locations: The locations within the treatment catchments that the sample plots fell also may have contributed to the discrepancies. During the survey, a patchy distribution of many species was observed. This was especially true for: (i) white birch (*Betula papyrifera* Marsh.), which responded to areas of forest floor removal with intense germination;

(ii) red maple (*Acer rubrum* L.), which produced large clusters of stump sprouts; and (iii) aspen (*Populus* sp.), which produced large, scattered patches of root suckers. Survey plots that fell on these dense patches of regenerating species would skew survey results.

Regardless of these differences, it was found that both surveys had the highest stem counts on the catchment subjected to whole-tree harvesting (Table 4.3). These differences were significant at a 95% confidence interval for all cases except the second survey's comparison of WT with ES at IL.

The proliferation of tree species and other vegetation on the WT catchment may be explained by this harvesting method. Although not always significant statistically, the results in Table 4.4 suggest that whole-tree harvesting was, by design, effective in minimizing slash left on the catchment, thereby minimizing the mulching effect of the slash. Also, trees were extracted from this catchment using cable skidders that likely caused more soil and stump damage from dragging stems compared to the other two catchments where wood was removed on the back of forwarders. Damage to stems and roots likely promoted root suckering and stump sprouting (del Tredici 2001), and dragging stems would have scarified the soil, thereby creating a good microenvironment for seed germination of some species (McInnis and Roberts 1994).

Both surveys found that the SO catchment had the lowest stocking (Table 4.3). This catchment also had the least total vegetative cover, lowest stem count in the second survey, and a large slash load (Tables 4.2, 4.3, and 4.4). On this catchment, vegetative recovery may have been greatly influenced by slash cover and choice of harvesting

equipment. Three harvesting machines were used here, compared to two on each of the WT and ES catchments. A third machine was also used on the ES catchment, but only for depositing the extra-slash. Also, the grapple skidder used followed already-established harvesting trails. On the SO catchment, the increased traffic that would accompany the use of a greater number of harvesting machines most likely resulted in greater soil compaction, which would further hinder vegetative recovery (Kozlowski 1999).

The early proliferation of vegetation on the WT catchment suggests that its hydrological recovery responses to harvesting may be the fastest among the treated catchments. Since this catchment also has the highest number of tree species (Table 4.3), it should also make the quickest recovery to pre-harvest conditions as well, but only if the dense competing vegetation would not entirely suppress the regenerating seedlings. In contrast, based on the vegetation surveys, the SO catchment may be the slowest to recover to pre-harvest hydrological conditions.

Differences Between Study Areas

GL had the highest percentage of area covered in vegetation two years following harvesting, owing mostly to the proliferation of raspberry GL following harvest (Table 4.2). GL also had the greatest number of tree species two years after harvest (Table 4.3). Higher tree counts occur at GL because of sprouting from the maple (*Acer* sp.) and beech (*Fagus* sp.) stumps.

At GL, post-harvest vegetative recovery is fast, but this may delay the regeneration of a full forest canopy due to suppression competing vegetation. The opposite is true at IL, where stem counts, and vegetative cover in general, are comparatively lower (based on the second survey).

Based on these differences in vegetative recovery, IL could incur a greater initial hydrological response to harvesting. If low tree counts at this study area result in slow forest recovery, the hydrology at IL may also be slower to recover to pre-harvest levels.

CONCLUSIONS

The results of the post-harvest vegetative recovery survey suggest that, among the GL catchments, early vegetative recovery after two post-harvest years is poorest on the ES catchment. This suggests that this catchment has the potential for the strongest, early hydrological response to harvesting. Not only did the ES catchment have the lowest total vegetative cover after two post-harvest years, but it also had the lowest tree stocking and fewest trees/ha, which could translate into slow forest recovery. Among the catchments at IL, the WT had the fastest vegetative recovery suggesting that it could be the first to return to pre-harvest hydrological conditions.

Two years following harvest, vegetation was much denser at GL, largely because of profuse raspberry regeneration. There were also more tree seedlings at GL. As a result, IL may take longer to reach canopy closure, and a return to pre-harvest hydrological conditions.

CHAPTER 5

RESPONSE OF SHALLOW GROUNDWATER LEVELS TO HARVESTING INTERVENTIONS

INTRODUCTION

This Chapter presents an examination of the pre- and post-harvest water table fluctuation data as automatically recorded in the wells at the bottom of each of the experimental catchments. The following objectives are pursued, as outlined in Fig. 5.1:

- to compare water table fluctuations within the wells, between study areas, and between catchments.
- to determine to what extent harvesting, harvest type, and basin-specific attributes affect the water table fluctuations.

Several methods were used to visualize and discern inter-catchment differences in post-harvest water-table responses. These methods refer to:

- a time-series display and peak-to-peak synchronization of the water table records across the catchments.
- an inter-catchment evaluation of the synchronized records, by way of regression analysis.
- a no-harvest prediction of the water-table fluctuation of the harvested catchments (see Bliss and Comerford, 2002).
- A specially designed method used to learn whether the records, when accumulated over time, would diverge, in response to harvesting.

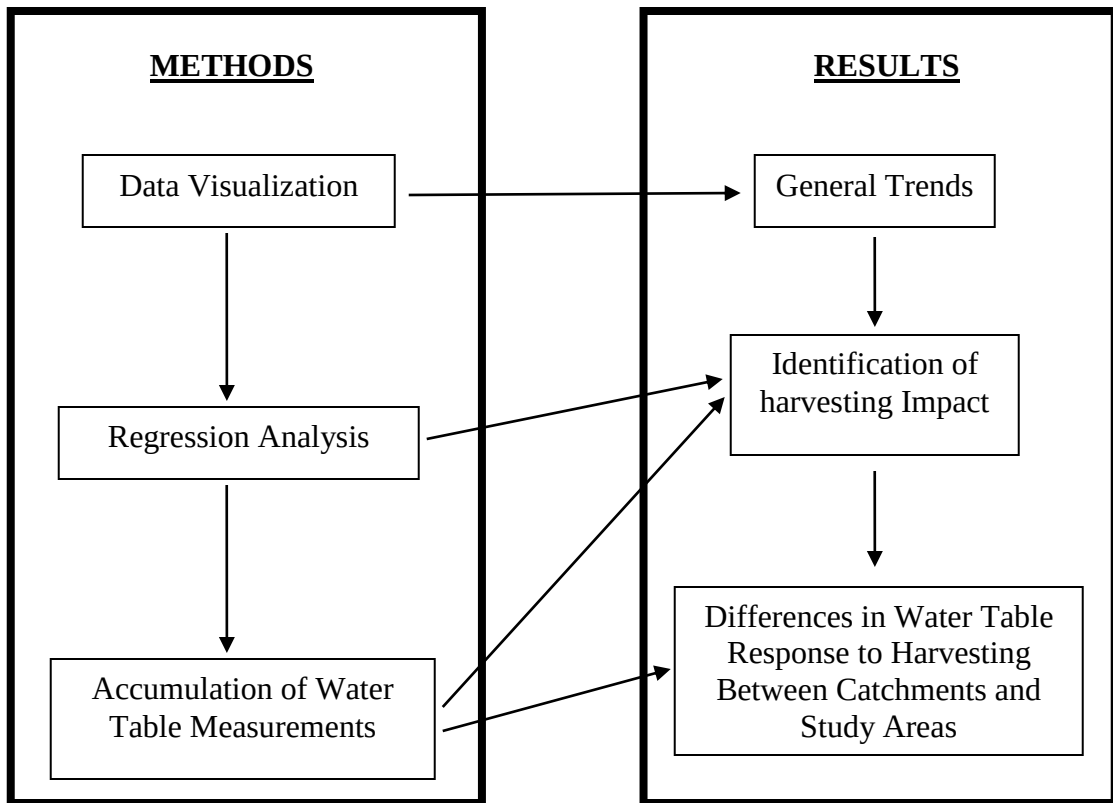


Fig. 5.1. Flowchart of visualizing and analyzing water-table levels at the two study areas.

- a ranking and evaluating of the resulting accumulation differences, by harvest type and catchment attributes.

METHODS

Visualization

All of the corrected, completed, and standardized water table records (Chapter 3) were plotted versus time, from the beginning to the end of the recording period, by catchment, and by study area. Inspection of the resulting plots revealed that there was variability between the catchments within each study area in the timing, magnitude, and duration of water table level changes. Before the inter-catchment relationships were

established using regressions (see “Regression Analysis” below), the data sets for some wells had to be synchronized and smoothed. For example, at GL, water level changes in the GL-ES were particularly flashy, thereby signaling an earlier and more magnified response to hydrological events than in the other wells. In this case, synchronization and smoothing produced considerable conformity of GL-ES with the other GL wells, especially for the pre-harvest period. At IL, groundwater levels within the control well were flashier than in the other wells. In this case, the control well was smoothed first, followed by synchronization and base-line-to-peak standardization with respect to the other wells.

Regression Analysis

With the control catchments as predictor variables, Linear Multiple Regression analysis was used to predict water table levels during the post-harvesting time period under a no-harvest scenario, based on the completed, synchronized, smoothed, and standardized data. (Appendix III).

Accumulation of Water Level Measurements

The unsynchronized and unsmoothed water level measurements were cumulated and graphed over time to better quantify the impacts of harvesting treatments on shallow groundwater levels. Plotting the cumulated data produced monotonically increasing plots for each well, where each plot had its own slope. The cumulated plots were then standardized to produce the same slope for the pre-harvest period, using the control well as reference. To do this, the last pre-harvest cumulative measurement from each catchment was forced to have the same value, by multiplying all the data of a particular

well by the same well-specific slope-correction factor. Thereby, any difference in harvesting's impact among the different treatments showed itself as a clear, post-harvest divergence of the resulting plots. The standardized cumulated data were then compared with the straight line corresponding with the pre-harvest data. The points that corresponded to this line were subsequently subtracted from the cumulated data, to plot the resulting pre- and post-harvest differences, to produce a "Cumulative Difference Index" for each well (Fig. 5.2).

RESULTS AND DISCUSSION

Data Visualization

Figure 5.3 shows the raw water-table records for all wells from the two study areas. At GL, shallow groundwater table level fluctuations were closely synchronized with each other, suggesting that the catchment characteristics that affect the flow of water through these catchments are fairly uniform throughout the study area. However, during some periods of the year, the water levels within the ES catchment dropped faster than levels within the other catchments. This suggests that the ES catchment was better drained. For example, approximately 15 meters below the monitoring well, there is a small embankment descending into a stream channel. It is possible that this embankment allowed the water in the ES well to drain at a greater rate.

IL water table responses were generally less flashy than at GL, but here there was greater variability in water table fluctuations between the five catchments:

- The water levels on the control and upper SO wells rose relative to the other wells in response to each precipitation and snowmelt event. This suggests that

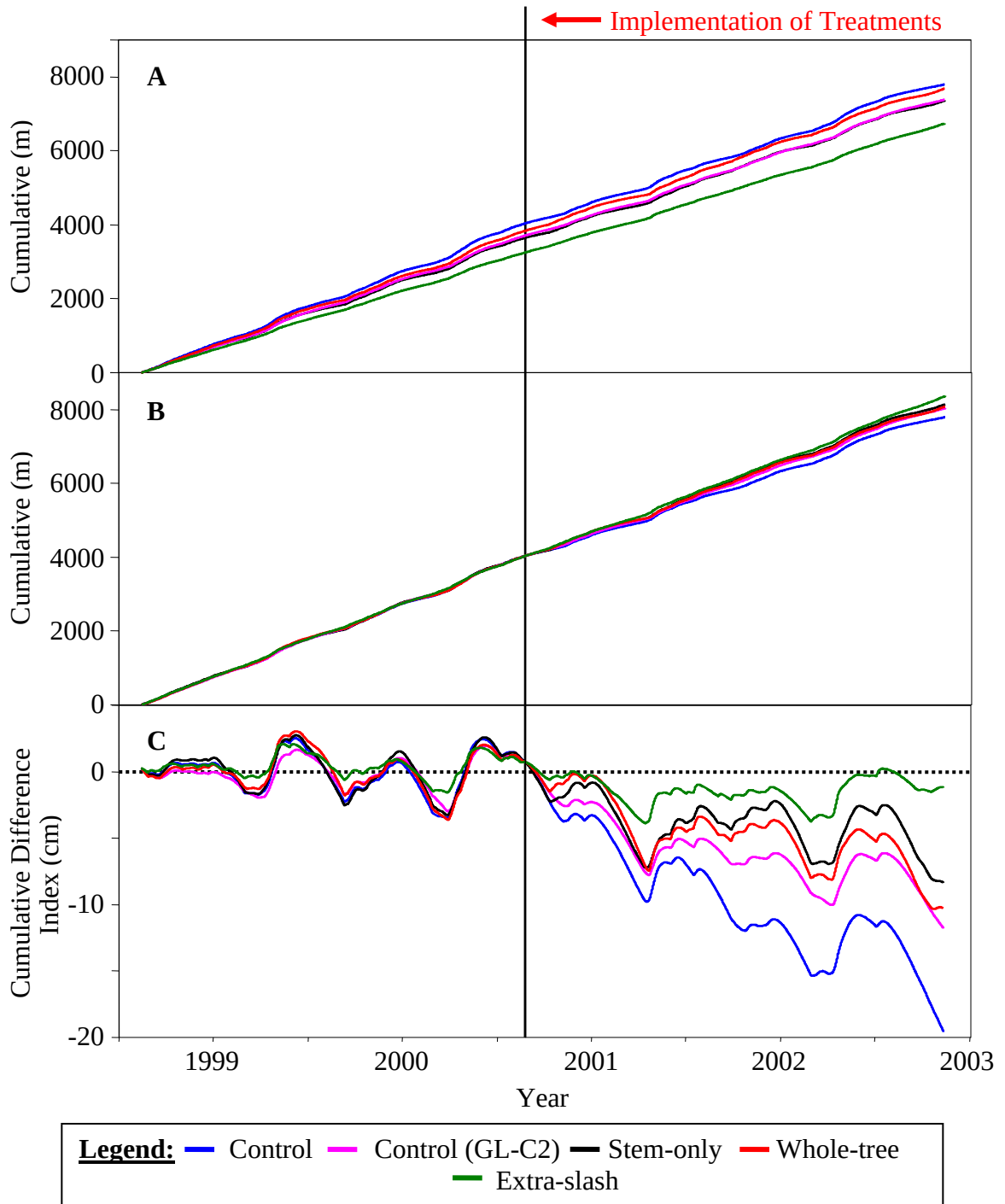


Fig. 5.2. Steps involved in constructing Cumulative Difference Index: A = accumulation of water table levels, B = Standardization of pre-harvest values, and C = subtraction of best-fit pre-harvest trend line from standardized cumulative values.

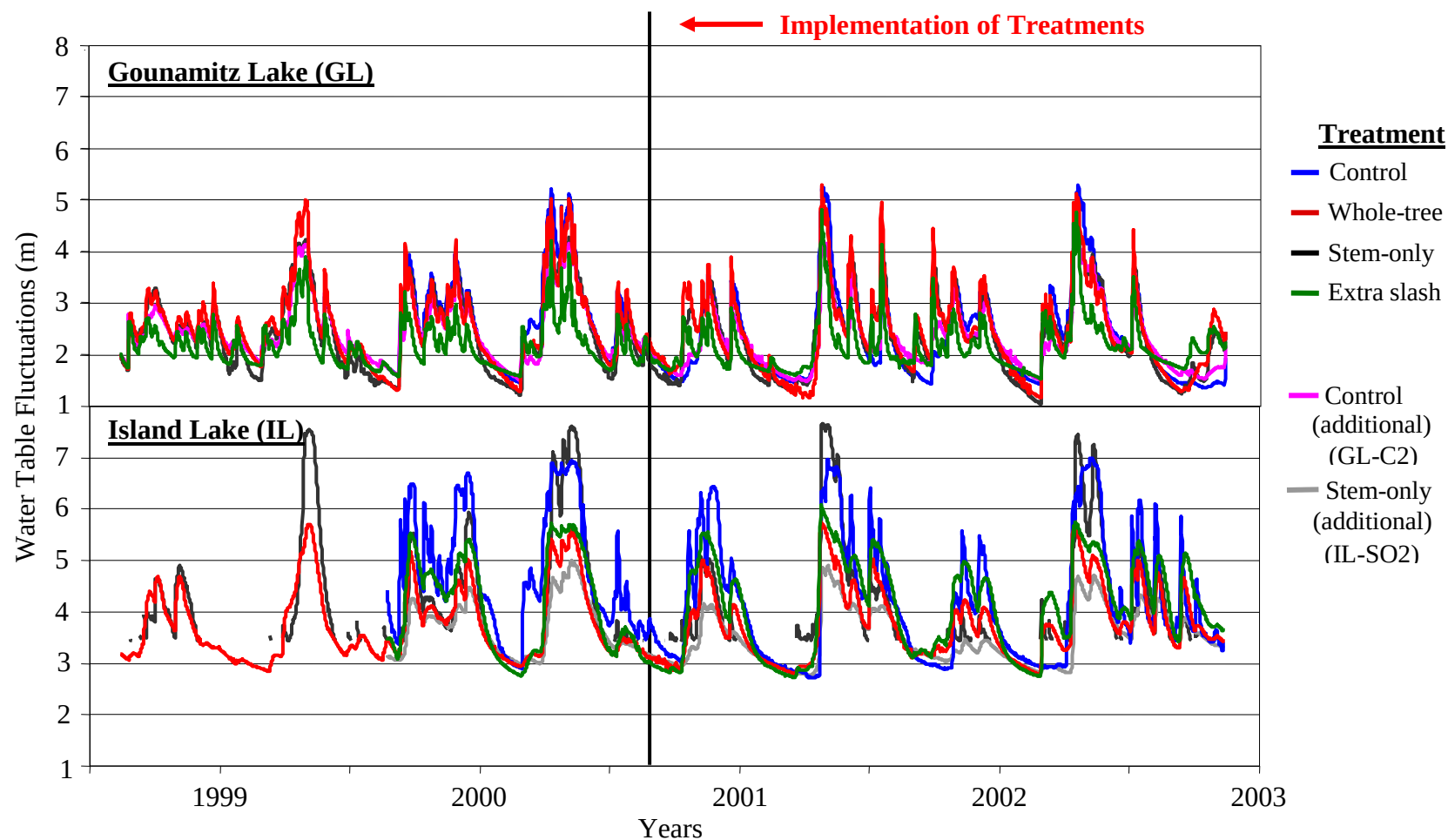


Fig. 5.3. Overview of shallow groundwater table fluctuations in wells on 10 catchments at the Gounamitz Lake and Island Lake study areas.

there was less substrate pore space in the vicinity of these wells in comparison with the other wells at IL.

- There were also considerable differences in the *timing* of the fluctuations. Fluctuations on the control catchment were about 3.5 days ahead of fluctuations measured in the WT, ES and upper SO (IL-SO1) wells, and seven days ahead of fluctuations measured in the lower SO well (IL-SO2) (Appendix III). Assuming that the substrate permeability is fairly similar throughout the study area, these timing differences were likely caused by differences in the distance that water must flow to reach the monitoring wells. The catchment configurations at IL supported this suggestion, because travel distances at IL were much more variable than at GL (Table 3.4 and Figs. 3.7 and 3.9). At IL, travel distances are particularly short for the control catchment, thereby allowing for quick well responses (Fig. 5.3). Although travel distances were not greatest for water entering the lower SO well, the timing of the fluctuations was most delayed here. Positioning of this well in relation to the larger catchment area suggested that the water that arrived at this well could, in part, have also originated from other catchments further above.

Seasonal patterns in the water-table fluctuations were very evident, and common to both study areas. In each case, water tables rose the most during spring snowmelt. Within six weeks of snowmelt, water tables subsided quickly, and remained relatively low during the growing season, only to rise again toward the end of the growing season.

With the beginning of winter, the water tables declined again until the spring. This pattern was undoubtedly related to high vegetative evapotranspiration demands in the summer, and snow accumulation and freezing in the winter. Thawing during winter produced occasional peaks, depending on the intensity of the thaw, as observed and described elsewhere (Balland 2002).

Harvesting-Induced Changes in Shallow Groundwater Table Levels

According to the plots in Fig 5.3, no obvious harvesting effects were visible at either at GL or IL: water tables on harvested catchments changed little with respect to non-harvested controls after treatments were implemented. Water tables at IL in the summer of 2002, however, were a possible exception. Here, water table levels on harvested catchments remained above the control water level more so than during the preceding years.

To better identify and quantify harvesting-induced change in water table levels, the synchronized and smoothed data sets for each well were plotted against regression projections of a no-harvest scenario based on the control catchments (see Appendix III), thereby allowing for a baseline comparison of the post-harvest effect (Figs. 5.4 and 5.5). Inspecting these plots showed that harvesting produced a general water table rise, especially at IL. Prior to harvesting, all measured water levels closely matched the levels predicted from the control catchments. Post-harvest increases varied considerably between years and catchments. The largest increase was approximately two meters, and occurred in the GL WT catchment during the second fall following harvesting (Fig. 5.4). At GL, the two controls were used to predict the water levels of each other. As expected, predicted levels during the post-harvest period on each control catchment fit

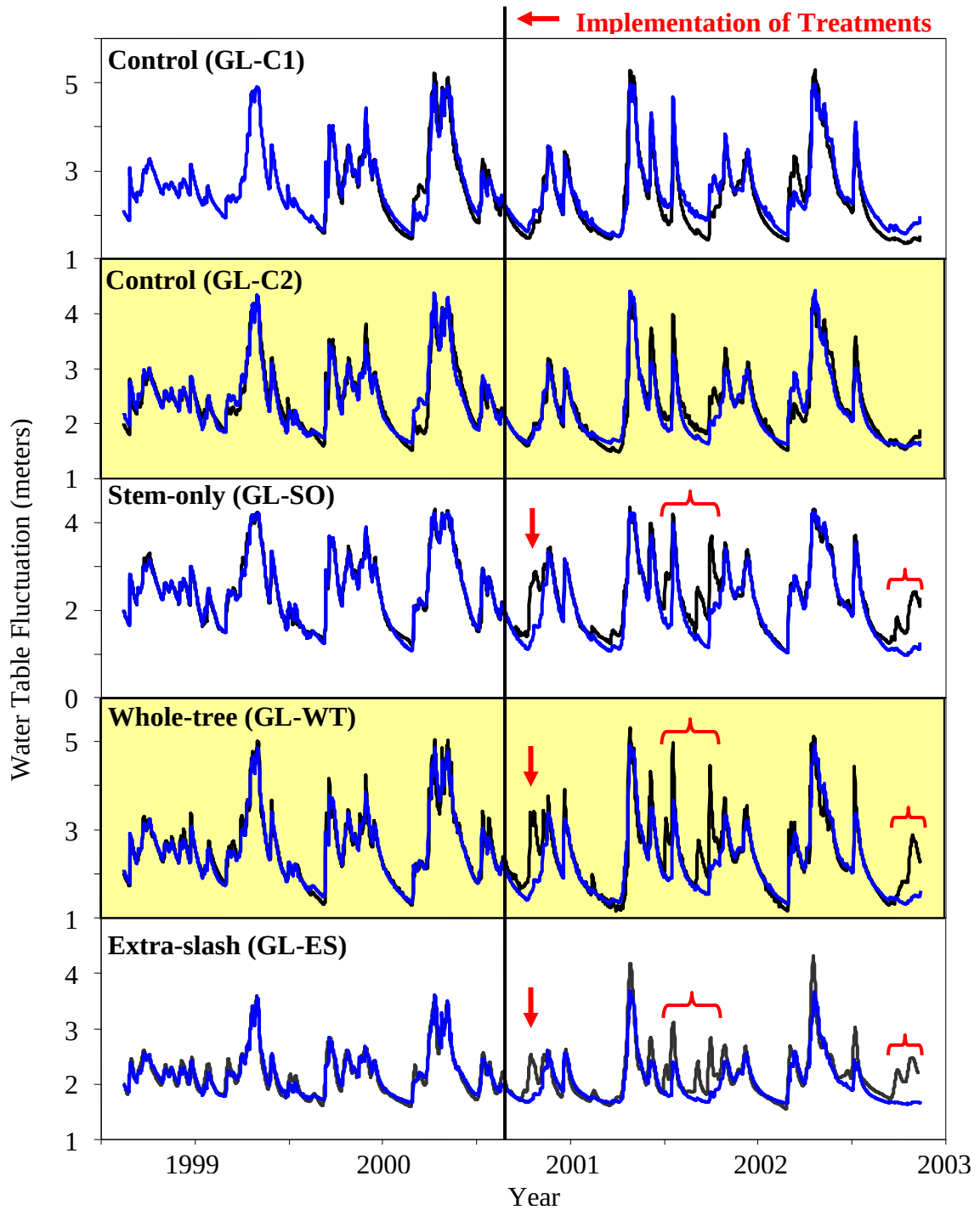


Fig. 5.4. Measured fluctuations in water table levels on the Gounamitz Lake catchments compared with levels predicted (using regressions with the control catchments) to occur in the absence of harvesting. Note: the measured data for the Extra-slash catchment have been smoothed using SPSS (SPSS Inc. 2002) to obtain better predictions from the control.

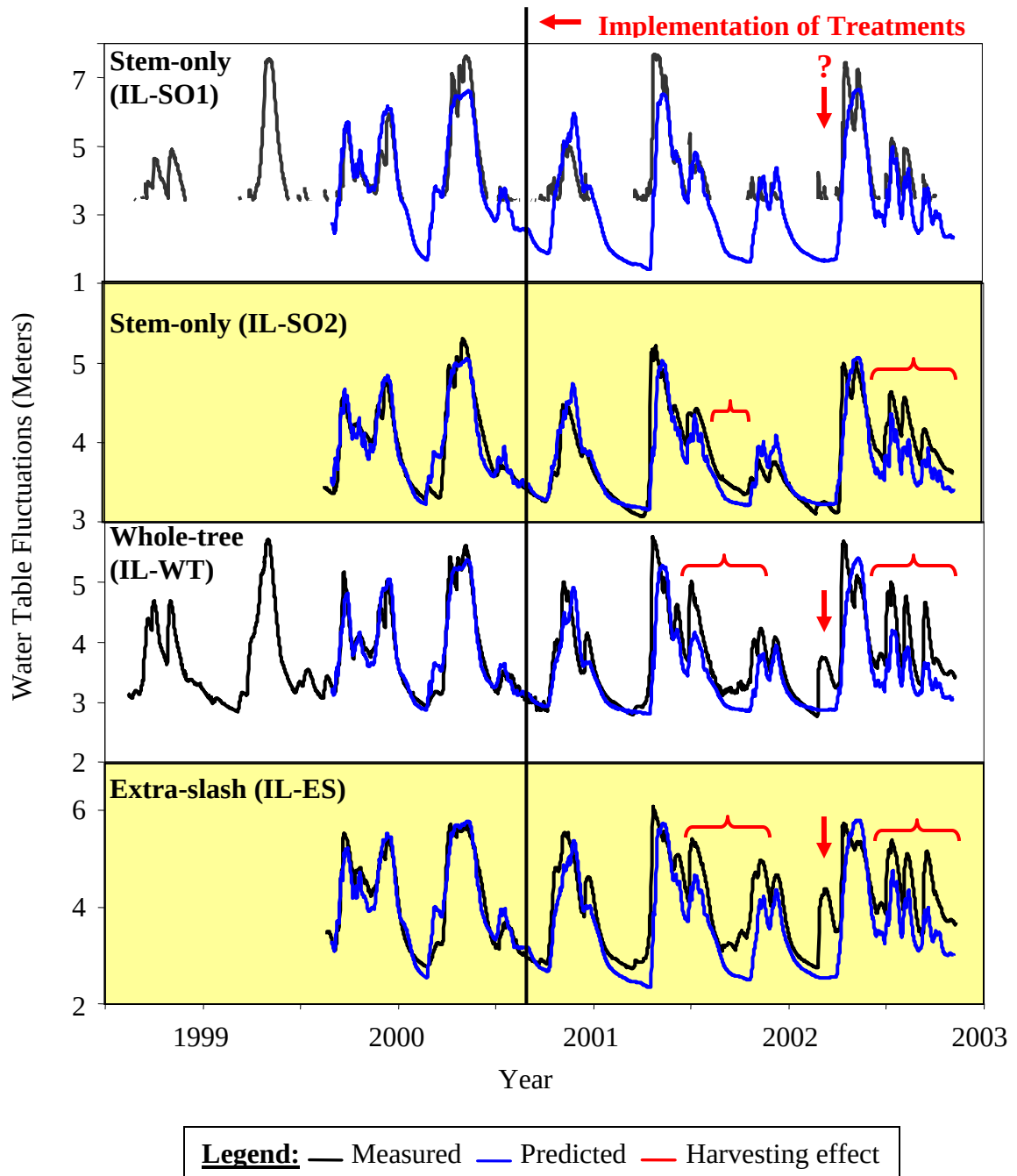


Fig. 5.5. Measured fluctuations in water table levels on the Island Lake catchments compared with levels predicted (using regressions with the control catchments) to occur in the absence of harvesting.

closely with the measured values (Fig. 5.4). All the treated catchments showed a noticeable increase in water level during the month of October 2000, immediately

following the removal of trees. The next notable increase on all treated catchments began around the first of July 2001. Measured water levels then remained elevated over much of the summer and into the fall, dropping back to predicted levels around the middle of October of that year. Water levels then closely matched predicted levels until mid-September, 2003, when they once again rose above predicted levels, and remained so until mid-November when the study period ended.

At IL, harvesting also caused water levels to periodically increase (Fig. 5.5). Here, water levels on the WT and ES catchments reacted similarly to harvest. On these catchments, there were no noticeable harvesting impacts until early June 2001, when water tables rose and remained elevated for most of the summer, and into the fall. Levels returned to normal around the middle of November, but became elevated once again for the month of March, 2002. From the first of April until the first of June, 2002, measured levels were similar to predicted levels. Beginning around the first of June, 2002, levels once again rose above expected levels and remained so until the study period ended in mid-November. Water levels on the SO catchment did not appear as affected by harvesting as levels on the WT and ES catchments. Levels from the lower well on the SO catchment (IL-SO2) were noticeably higher than predicted levels for a two-month period between mid-August and mid-October, 2001, and from the first of June, 2002 until the end of the study that fall. In contrast, a comparison of predicted levels and measured data from the upper SO well (IL-SO1) revealed little obvious change, because there was much missing data. However, even here, the comparison suggested that water levels could have been elevated in March of 2002 as a result of the harvest.

Differences between Study Areas and Catchments in Water Table Response to Harvesting

Figure 5.6 shows the results of displaying the observed harvesting impact on the water-table fluctuations by way of the cumulative differences between the measured data and the pre-harvest trend lines. These plots are characterized by a clear pre-harvest conformity, except for seasonal variations, and are followed by a clear post-harvest divergence pattern. In this pattern, the controls decreased the most from the zero-deviation line, while the post-harvest responses remained above the control line. The IL control well registering a drop about three times larger than the GL control well. Several possible explanations for the post-harvest water level responses, as illustrated in Fig. 5.6, are presented here:

- The overall drop in water table levels across all wells could be weather induced. However, cumulative differences between daily precipitation records or the air temperature records, and the related pre-harvest trend line, revealed no substantial change in pre- and post-harvest weather. In fact, precipitation increased somewhat during 2001 (also shown in Figure 5.6 for reference purposes).
- Harvesting in one sub-catchment could have increased wind exposure and therefore increased evapotranspiration in the adjacent non-harvested controls in the summer, thereby causing lowered water levels. With increased air circulation following harvesting, more water would be lost from the

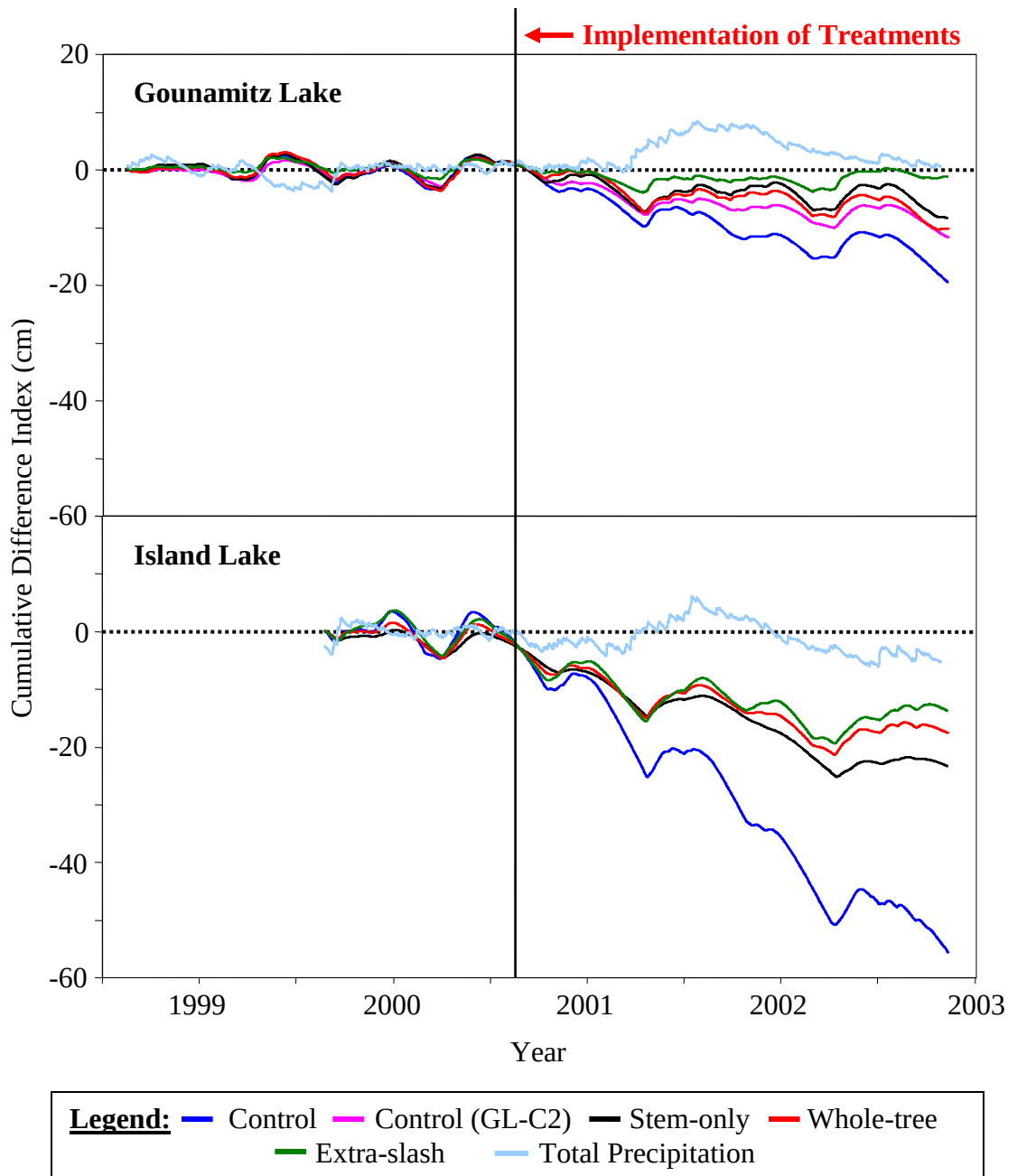


Fig. 5.6. Change in cumulative water table levels and total precipitation at the two study areas. The slopes of the cumulative water levels were adjusted so that the pre-harvest slopes equaled zero for all sites. Cumulative precipitation is water equivalents in millimeters.

vegetation and upper soil levels, leaving less to percolate into the water table (Lockaby *et al.* 1994; Lockaby *et al.* 1997). However, the opposite may occur in winter, where snow

drifting from the cut areas into the adjacent wooded areas may add more water to the controls (Jewett 1995).

- Decreases in summer evapotranspiration within the harvested catchments, as discussed, did lead to water tables higher than the controls. In general, harvesting had the greatest effect on water tables at IL. This is expected, because conifer removal normally results in increased water yields (Bosch and Hewlett 1982).
- The second GL control (GL-C2) had higher cumulative water-table differences than the first control (GL-C1). The levels on the second control (GL-C2) may have been influenced by the water table of the adjacent SO and WT harvested catchments. This is possible because the GL-C2 catchment is very narrow, and is placed between the SO and WT catchments (Figs. 3.7 and 3.8).
- The general drop in the cumulative water-table differences for the controls and most of the harvested areas could have been due to slight mechanical- or temperature-induced alterations, which increased the overall substrate permeability of the general recharge area of all the catchments, thereby allowing a little more water to leak towards deeper running aquifers. If so, then the difference between GL and IL could be related to the fact that the bedrock outcrops are common at IL, but absent at GL. Also, the bedrock at IL (rhyolite) was found to shatter easily following road construction across the treatment watersheds. These roads were constructed parallel to the ridgeline for the WT and ES treatments, and towards the ridge of the SO treatment (Figs. 3.9 and 3.10). The control was the upper-most sub-catchment above the treatment catchments. At

GL, bedrock shales only came close to the surface at ridge tops. Here, pre-existing roads were used for access and transport.

Ranking the Responses

The cumulative water level differences increased on all harvested catchments relative to the control levels. In general, harvesting appeared to have the greatest effect on the water table fluctuations at IL. Differences between the harvested catchments themselves, however, were subtle. At IL, water levels increases were in the following order from low to high

- Control
- Stem-only
- Whole-tree
- Extra-slash

At GL, this order is given by

- Control 1
- Control 2
- Whole-tree
- Stem-only
- Extra-slash

This ranking order was compared with the ranking order of the following catchment attributes (Table 5.1):

Table 5.1. Catchment rankings (1 = least, 2 = Intermediate, 3 = most), at the a) Gounamitz Lake and b) Island Lake study sites, for several factors that may influence shallow groundwater levels following harvesting.

a)

Catchment	Water Table Increase	Slash Load ^a	Vegetative Recovery ^b	Catchment Area
GL-ES	3	3	1	2

- 1) Area harvested - the greater the catchment size harvested, the lesser the evapotranspirational losses on an area-wide basis. As a result, more of the incoming water can be expected to percolate towards the wells at the bottom of the larger catchments.
- 2) Vegetative recovery - areas where the post-harvest vegetation recovers faster should have a smaller cumulative water table increase over the controls because pre-harvest conditions are restored sooner and more effectively (Martin *et al.* 2000; Sun *et al.* 2001).
- 3) Slash left on site - the method of harvesting may modify the hydrological response: slash acts as an insulator, and keeps wind and solar radiation from the soil surface. As a result, slash deposits have been found to reduce soil moisture losses (Smethurst and Nambiar 1990). However, slash also provides

a surface on which precipitation could be caught and evaporated back into the atmosphere.

The differences in water table responses to harvest among treated catchments cannot be explained by any *one* of the causal factors just described. It is probable that differences in water table responses could be due to a combination of various factors. For example, at GL, the order of water table response between catchments matched the order of slash loading on the study areas, and the order of vegetative recovery (Table 5.1). However, at IL, the order of water table response did not correspond with either of these influences (Table 5.1). These results suggest it would be difficult to predict inter-catchment differences in shallow groundwater table response to harvesting without knowing all the contributing factors, and the strength of each of their influence.

Increased post-harvest water table levels over the pre-harvest predicted levels generally occurred in early spring, during the summer, and lasted into the late fall (Figs. 5.4 and 5.5). The early spring increases were likely due to a general post-harvest advance in snowmelt timing. Such advances have been reported in previous studies (Hornbeck *et al.* 1986; Hornbeck *et al.* 1997). Early spring rises, however, were only recorded at IL. Here, the coniferous forest cover prior to harvesting would have produced the most spring shade. At GL, ground shading at this time is generally low underneath the dominant hardwood cover

The increases in post-harvest, summer water levels are also consistent with other studies pertaining to post-harvest groundwater and streamwater levels (Holstener-Jorgensen 1967; Aubertin and Patric 1974; Williams and Lipscomb 1981; Hornbeck *et al.*

1986). However, the increased summer water levels observed in this study often extended into mid-November (Figs. 5.4 and 5.5).

CONCLUSIONS

Harvesting affected the water table fluctuations within all the catchment wells as follows:

- There were notable post-harvesting increases relative to the controls in all SO, ES, and WT treatments, from early spring to late fall, but not in winter.
- Each well had its own pattern of water table fluctuations in terms of timing, and flashiness. To allow for detailed well-to-well comparisons, these differences were removed through data synchronization and smoothing.
- Water levels dropped across all catchments. The reason for these decreases cannot be determined based on the analyses presented in this Chapter. Possible explanations suggested here are: 1) year-to-year changes in the weather patterns; 2) increased wind exposure in and around the harvested catchments, or; 3) substrate disturbance, which could have altered groundwater flow regimes.

CHAPTER 6

SHALLOW WELL TEMPERATURES

INTRODUCTION

The objective of the Chapter is to present a detailed pre- and post-harvest analysis of the well-temperature data from both study areas, by catchment, and by treatment versus control. This analysis followed a number of steps, as outlined in Fig. 6.1.

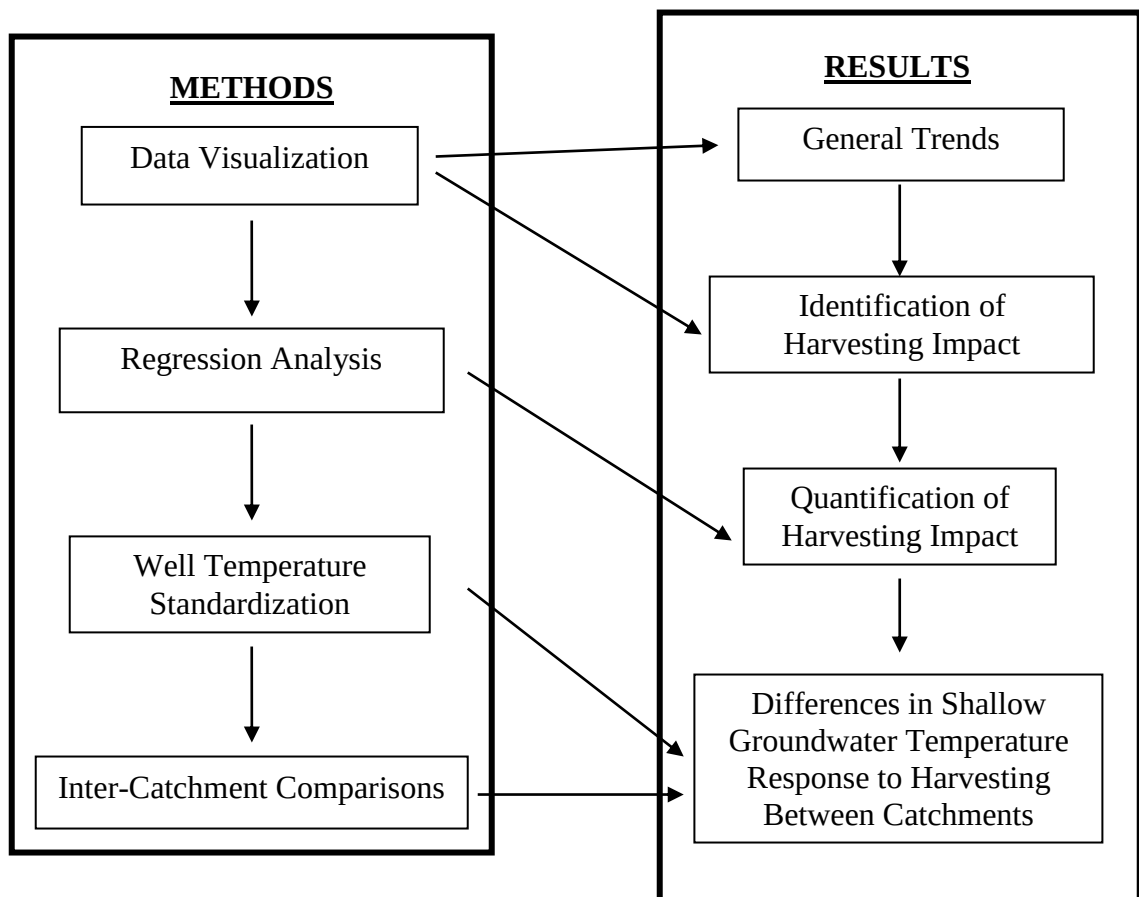


Fig. 6.1. Flowchart of the shallow-well temperature analysis.

METHODS

The completed and finalized spreadsheet for the well temperatures, obtained as described in Chapter 3, served as the template for the visualization and analysis of the well temperatures.

Data Visualization

For each study area, the temperature data for all catchments were graphed together as a time series across the entire recording period of four-plus years, using Microsoft Excel (Microsoft Corporation 1999). This allowed for a general overview and comparison of trends and variations among the pre- and post-harvest temperature records, by catchment. The second way of visualizing the data involved overlaying the pre- or post-harvest data points for each year, by catchment and study area. Displaying the data in this way readily illustrated whether pre- and post-harvest, year-to-year changes in well temperature had occurred. The third visualization method involved plotting the well temperatures of the treated catchments against the controls, by study area, to visualize changes in slope between the pre- and post-harvest data.

Regression Analysis

The following multiple regression equation was used to quantitatively relate the pre-harvest well temperatures of the treated basins (y) to the well temperature of the control basin (x), by year fraction, per study area:

$$y = A + B x + C \sin[2*3.14*(t-D)] \quad (\text{Equation 6.1})$$

where:

A = value of intercept with the y-axis

B = linear regression coefficient for control well

C = regression coefficient for sine function, to account for differences in temperature amplitude between the treatments and the control

D = a parameter to account for the lag between the treatment and control temperatures.

t = time of year as a fraction of the whole year

Equation 6.1 was then used to predict the well temperatures of the treated catchments, had harvesting not occurred, to allow for the quantification of each treatment response, by catchment and by study area. For this prediction, the temperature of the control well (x) and year fraction (t) are the predictor variables. Analytical details are described in Appendix II.

Well Temperature Standardization

Since each well had its own pre-harvest temperature level and amplitude, it was decided to standardize the temperature records of all the wells to the same level and amplitude. This was done by forcing the 1999 maximum and 2000 minimum temperatures of all the wells to become the same, using the GL-SO well as the reference. The numerical process that enabled this is based on the following formula:

$$T_{a,new} = T_{b,min} + (T_{a,old} - T_{a,min}) \frac{\Delta T_b}{\Delta T_a}$$

where:

$T_{a,old}$ = unadjusted temperature record of a particular well

$T_{a,new}$ = adjusted temperature record

$T_{a,min}$ = minimum unadjusted temperature of the well for a given reference year
(e.g., 2000)

$T_{b,min}$ = minimum temperature of the reference well for the same reference year

ΔT_a = difference between unadjusted maximum and minimum temperature of a particular well for the same reference year

ΔT_b = difference between maximum and minimum temperature of the reference well for the same reference year.

Inter-catchment Comparisons

Each harvested catchment was ranked by standardized post-harvest well temperature increase, and by catchment-specific vegetative recovery, slash load, well location in relation to catchment geometry, and potential incoming solar radiation.

These ranking activities were intended to reveal whether the ranking order any of these factors would be consistent with the ranking of the standardized treatment-induced temperature responses across the two study areas.

RESULTS AND DISCUSSION

General Trends in Shallow Well Temperatures, Across the Years

Plotting the temperatures over time (Fig. 6.2) revealed that the well temperatures followed a seasonal pattern that is common for groundwater in temperate regions (Messina *et al.* 1997). For example, the well temperatures in all catchments consistently lagged behind the air temperature, and peaked between the first of October and the middle of December, with the lowest temperatures occurring between mid-April and the

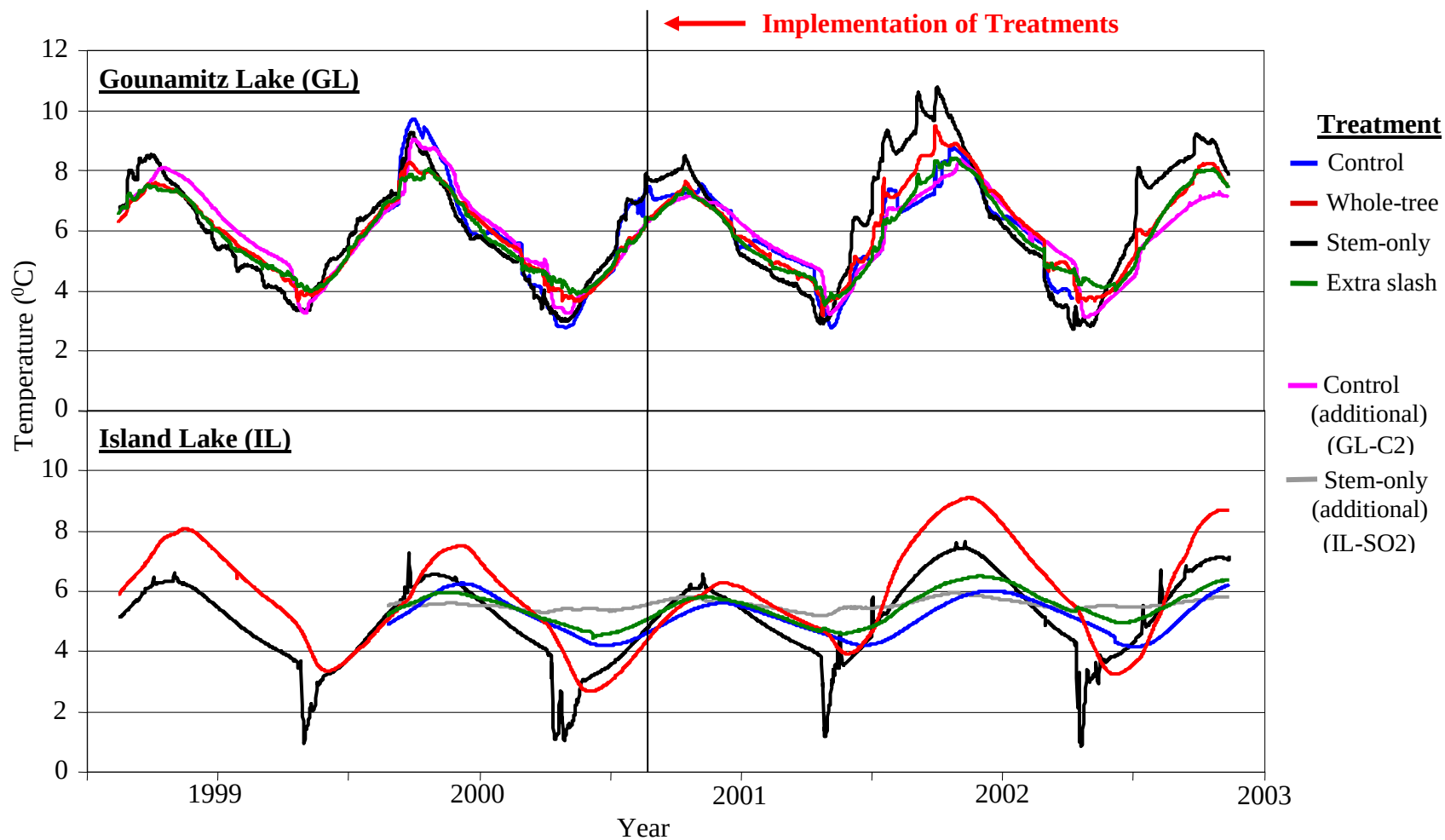


Fig. 6.2. Temperature over time as recorded by measuring probes at the bottom of monitoring wells on study catchments at Gounamitz Lake and Island Lake.

first part of July. This 2-3 month lag between the timing of maximum and minimum solar radiation, and maximum and minimum groundwater temperature is most likely due to the time it takes for heat to be transferred from the soil surface to the depth through which the groundwater flows.

In contrast, some of the wells showed immediate temperature dips during the snowmelt season, when large volumes of cold water can be expected to enter the groundwater pool from the recharge zone of each catchment. At GL, GL-C2 showed this dip most clearly and consistently. The other wells also displayed this dip in at least one year, but GL- SO was least affected. At IL, the snowmelt-induced temperature dips were pronounced in the upper IL-SO1 and IL-WT wells, and quite drastic for the former. That particular well dried up during periods of low flow, but responded quickly during periods of high flow. These dips were less noticeable for the other IL wells, presumably because these wells are deep, and were therefore less influenced by seasonal fluctuations (Wu and Nofziger 1999). The flatter year-round temperature curves measured for IL-C, ES, and lower SO (IL-SO2) wells demonstrated this effect (Fig. 6.2).

Apart from this, there were other significant differences in the amount of details expressed in the temperatures of the GL and IL wells:

- At GL, well temperatures generally followed a more weather-dependent pattern than at IL (Fig. 6.2). Here, the greater permeability of the GL substrate likely allowed for quick infiltration during precipitation events. Consequently, the shallow groundwater temperatures responded readily as the incoming water quickly carried its temperature to the wells. At IL, water infiltrated and seeped

through the ground more slowly, and – therefore – its temperature had a longer time to equilibrate with the substrate before the water reached the wells.

- the temperature of the upper SO well was somewhat more sensitive than the other IL wells, because it periodically dried up.
- At GL, the well temperatures were more synchronized with each other (Fig. 6.2).

There was much more synchronization variability at IL, where the temperatures in the upper SO catchment peaked and troughed earlier than all the other catchments, except possibly the deep IL-SO2 well.

Since the temperature of water passing from catchments is a reflection of the temperature of soils and substrates (Beschta *et al.* 1987), the variable timing of temperature peaks and troughs between catchments at IL suggested that the water that arrived at each well traveled through a different subsoil environment. This variability demonstrated that the processes governing shallow groundwater water flow varied noticeably, even between the small and adjacent catchments. At IL, the variability may be further accentuated by small water reservoirs that were evident as standing surface water, and saturated surface soils, dispersed throughout the catchments. The high heat capacity of these water reservoirs may have further contributed to the delayed temperature responses of the wells.

Pre- and Post-Harvest Differences: each Year, by Year-Fraction

The well temperatures plotted in Fig. 6.2 suggest that post-harvest well temperatures increased in general, but the actual signal of this increase was somewhat

confounded by the inherent well-to-well differences related to differences in well depth, and was possibly also related to differences in the overall, under-ground flow regime.

The year-by-year plots in Figs. 6.3 and 6.4 were designed to ascertain the extent to which the post-harvest temperatures would differ from the pre-harvest temperatures, by year, and by treatment, with no pre- and post-harvest differences to be expected for the control wells. As shown, the post-harvest year-to year variations for the control wells remained more consistent with each other than the post-harvest well temperatures of the treated catchments. For the latter, the plots in Figs 6.3 and 6.4 confirmed that there was a general increase in temperature.

At GL in particular, the temperatures in the control wells were fairly consistent between years, except during the fall season when they diverged (Fig. 6.3). This divergence was likely due to yearly differences in weather: the two years prior to harvesting, and the first summer following harvest, were hottest and driest. On the other GL catchments, temperatures also diverged in the fall seasons, but here, the post-harvest well temperatures were almost always as high, or higher, during the fall than during the pre-harvest years. Since all the GL catchments were subject to the same weather conditions, it can be assumed that the differences between the controls and the treatment temperatures in the post-harvest seasons were almost always as high, or higher, than the plots were due to treatment. Thus, harvesting – as shown - caused fall temperatures to rise above pre-harvest conditions.

At IL, the temperature of the control well showed very little year-to-year change, demonstrating that year-to-year changes in weather had little influence on the well temperatures here (Fig. 6.4). The well temperatures in the control well were, again,

Fig. 6.3. Seasonal comparison of temperatures between each year pre- and post-harvest at the (a) first control (G1-C1); (b) second control (GL-C2); (c) stem-only; (d) whole-tree; and (e) extra-slash catchments at Gounamitz Lake.

Fig. 6.4. Seasonal comparison of temperatures between each year pre- and post-harvest at the (a) control ; (b) upper stem-only (IL-SO1); (c) lower stem-only (IL-SO2); (d) whole-tree; and (e) extra-slash catchments at Island Lake.

generally highest in the pre-harvest years. Among the wells of the treated catchments, the lower SO well (IL-SO2) showed the least year-to-year temperature changes.

Pre- and Post-Harvest Differences: Treatments versus Control

The temperature plots of the treatment wells versus the control wells are shown in Figs. 6.5 and 6.6, to explore the general association pattern among the wells with time of year, pre- and post harvest. In these plots, the temperatures of each well formed a loop, with its lower part beginning May/June and increasing in slope until October/December, when the temperatures looped back on the upper portion of the graph for the remainder of the year. For a given well, these loops were essentially re-traced for each pre-harvest year, but a minor to major change occurred in the slope of the loop after harvesting, thereby signaling a post-harvest response.

At GL, all but one of the scatter plots displayed a visible change in slope in the post-harvest years (Fig. 6.5). The exception occurred when the temperatures of the two controls were plotted against each other. In having two controls, GL thereby offered an extra test for the treatment impact evaluation: had the slope changed here also, it would have suggested that there could be a cause other than harvesting. At IL, the slopes of these plots also increased following treatment on all catchments, thus confirming a harvest impact (Fig. 4.6).

Pre- and Post-Harvest Differences: Within-Catchment Quantification

Figures 6.7. and 6.8 show two temperature tracks for the wells of each catchment: actual and simulated versus time. These simulations are those that were generated from the control wells for the pre-harvest period, by way of Equation 1. This

Fig. 6.5. Temperature at the bottom of wells on the (a) first control (GL-C1); (b) stem-only; (c) whole-tree; and (d) extra-slash catchments at Gounamitz Lake plotted against the temperature at the bottom of the well on the second control catchment (Gl-C2) over the four-plus years of the study. Temperature measurements are separated by year pre- or post-harvest for comparison.

Fig. 6.6. Temperature at the bottom of wells on the (a) upper stem-only (IL-SO1); (b) lower stem-only (IL-SO2); (c) whole-tree; and (d) extra-slash catchments at Island Lake plotted against the temperature at the bottom of the well on the control catchment over the four-plus years of the study. Temperature measurements are separated by year pre- or post-harvest for comparison.

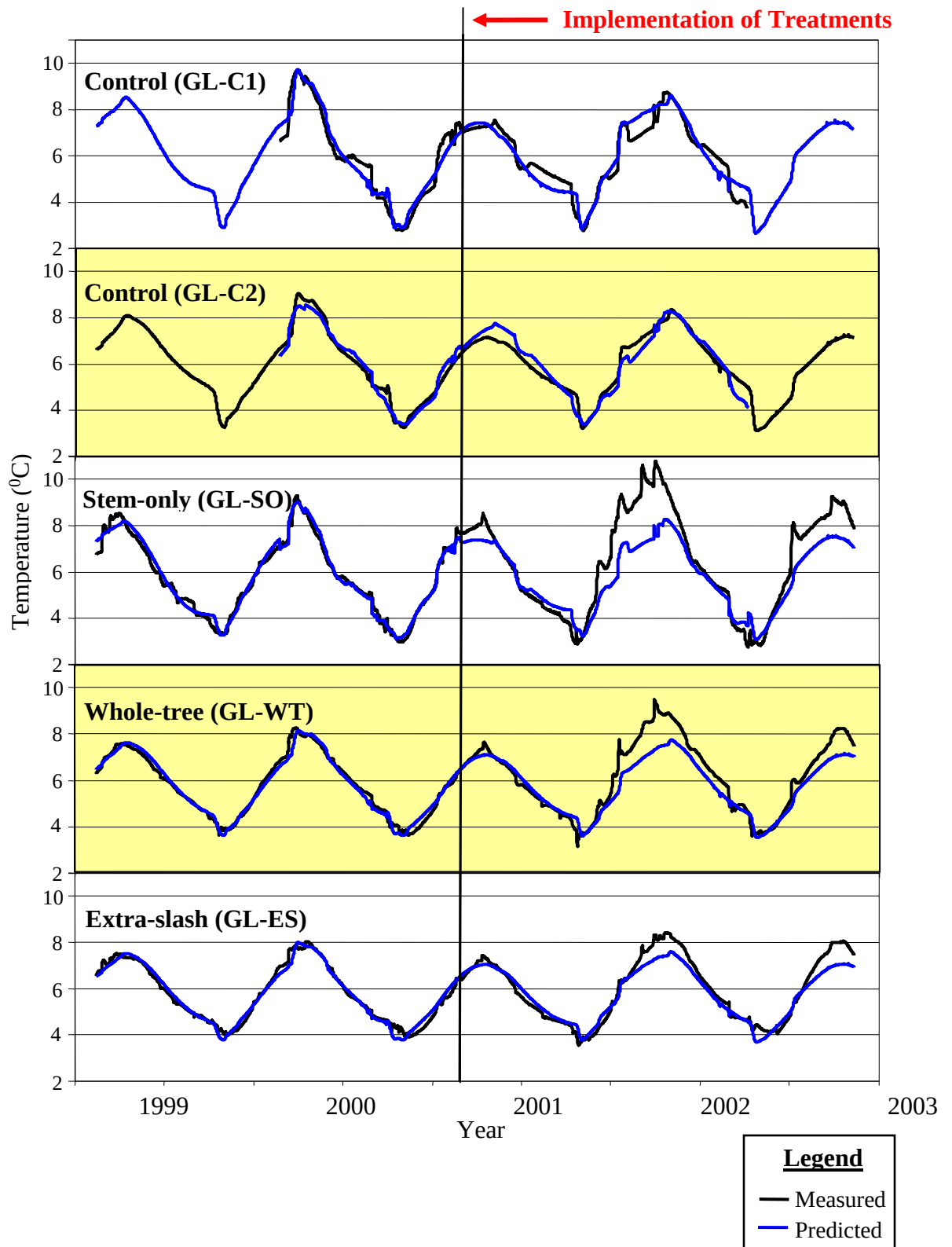


Fig. 6.7. Comparison of measured temperatures at Gounamitz Lake with predictions of a no-harvest condition, based on regressions with the control catchments.

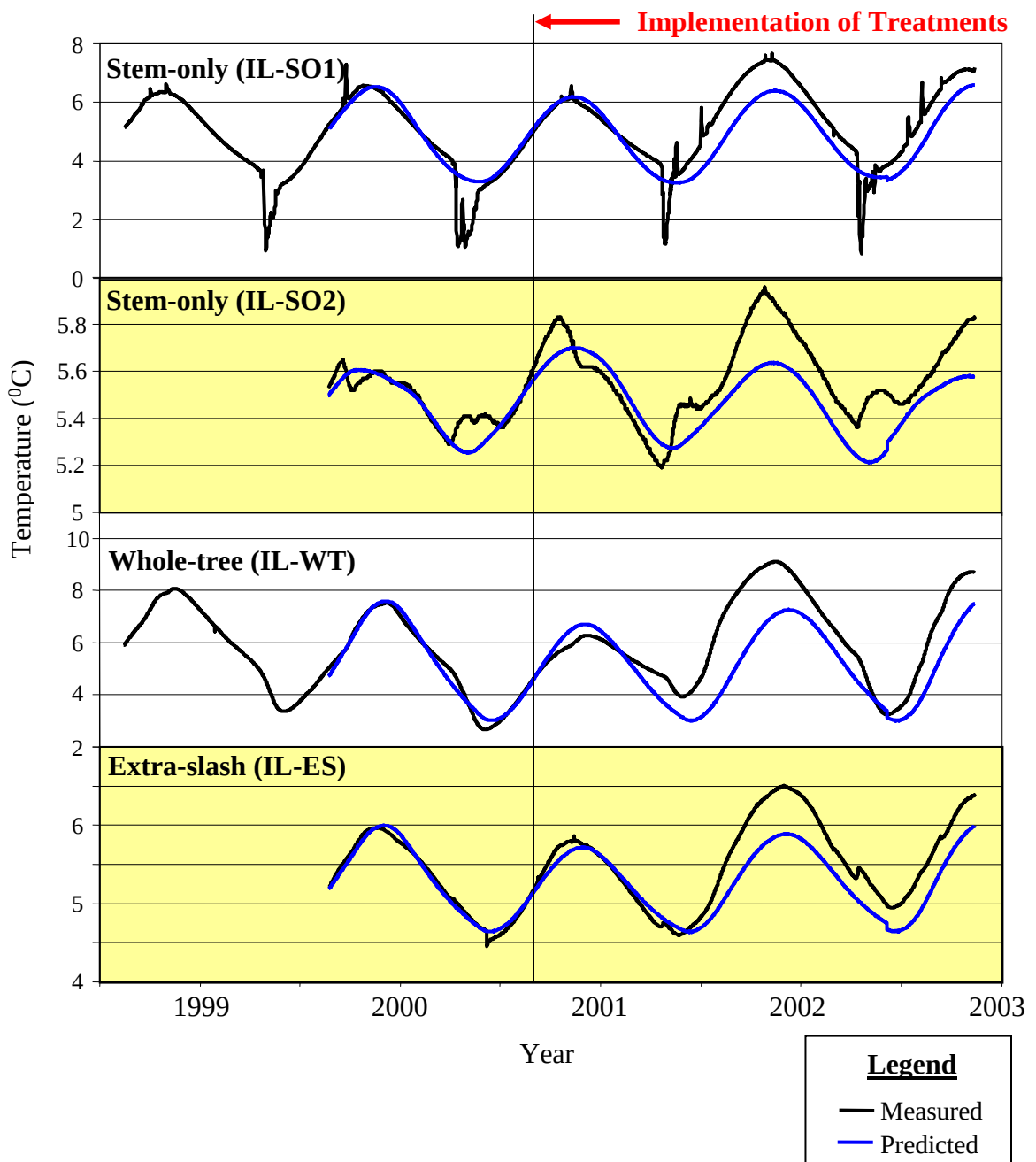


Fig. 6.8. Comparison of measured temperatures at Island Lake with predictions of a no-harvest condition, based on regressions with the control catchments.

served as the best-possible estimation of pre-harvest temperature pattern in each well for the entire study period. As can be observed, actual and simulated well temperatures

remained in close agreement with each other, even for the post-harvest period for the control wells, but diverged in the wells on the treated catchments.

At GL, pre-treatment measured and predicted temperatures were very close (Fig. 6.7). Here, the temperatures from the two control wells closely matched the predicted values for the entire duration of the study. All treatment wells showed increased temperatures following harvest. Among them, the SO catchment showed the greatest increase due to harvesting, with a 1.0°C change in the fall season immediately following harvesting, a 2.5°C increase in the second fall, and a 1.7°C increase in the third fall season. The WT catchment showed the second largest effect, with a 1.8°C increase in the second fall season following treatment implementation, and a 1.1°C increase in the third fall. Among the treatment catchments at GL, the ES catchment showed the least effect, with a 0.8°C increase in the second fall season, and a 1.0°C increase in the third. Minimum temperatures in the springtime did not change noticeably following treatment.

At IL, pre-treatment measured and predicted temperatures matched very closely, with only a couple of exceptions occurring for the two SO wells (Fig. 6.8). In these wells, there were anomalies of short duration, which were likely caused by sporadic influxes of surface water at times when the soil received much water, such as rainy periods and spring thaw. Following harvest, temperatures increased in all wells. The greatest increase was observed for the WT catchment, with increases of 1.8 and 1.2°C in the second and third post-harvest fall seasons, respectively. The groundwater in the upper SO well showed the next greatest change, with increases of 1.2°C in the second season, and 0.6°C in the third. Increases for the ES well were 0.6°C in the second season and 0.4°C in the third. For the lower SO catchment, the measured temperature of this water is very

irregular with the scale magnified as it is in Fig. 6.8. If there is a harvesting induced temperature increase in this well, it is likely 0.5 °C or less.

Pre- and Post-Harvest Differences: Standardizing the Quantification

The above pre- to post-harvest differences in well temperatures were likely influenced by several well- and basin-specific characteristics, as mentioned above. Therefore, the actual and simulated pre-treatment temperature records - as standardized for the GL-SO well - were also used to standardize the maximum post-harvest effects. The results of so doing are summarized in Table 6.1. As shown, this process revealed only subtle differences between treatments, and there were no substantive differences between the two study areas.

Table 6.1. Standardized temperature increases in degrees celcius following harvesting for the a) Gounamitz Lake and b) Island Lake sites.

a)

Catchment	Fall Season, Post-Harvest			
	1 st	2 nd	3 rd	3-Year Average
GL-SO	1.1	2.5	1.7	1.8
GL-WT	0.7	2.4	1.5	1.5
GL-ES	0.6	1.2	1.5	1.1
Average	0.8	2	1.6	---

b)

Catchment	Fall Season, Post-Harvest			
	1 st	2 nd	3 rd	3-Year Average
IL-SO1	0	2.4	1.1	1.2
IL-SO2	2.2	5.3	4.2	3.9
IL-WT	-0.6	2.4	1.6	1.1
IL-ES	0.6	2.8	1.8	1.7
Average ^a	0	2.5	1.5	---

At GL the SO treatment produced the greatest standardized temperature increase, with an average peak increase of 1.8 °C. The WT and ES catchments had average

increases of 1.5 °C and 1.1 °C, respectively. At IL, the IL- SO2 well was not considered because of its stable yearly temperature regime, and its position in the landscape suggests that its water flow also originates from surrounding catchments. Among the remaining IL catchments, the ES well had the greatest post-treatment temperature increase of 1.7 °C, followed by the upper SO well at 1.2 °C, and the WT well at 1.1 °C.

Indexing and Ranking Post-Harvest Well-Temperature Responses in Relation to Catchment Characteristics

Catchment-specific attributes that could possibly influence the temperature of the groundwater can, in principle, be captured by deriving attribute-specific indices for:

- slash load
- vegetative recovery
- potential incoming solar radiation
- well location in relation to catchment geometry

In this, a general slash load index is implied by experimental design. An index for the post-harvest recovery was derived from the post-harvest vegetative recovery description in Chapter 4. A generalized index for the well locations in reference to the catchment geometry can be referred to as “Soil-Water Contact Time Index”. This Index, as well as a “Solar Radiation Index”, was derived in Chapter 3.

All the catchment attribute indices, and standardized post-harvest well temperature responses are ranked in Table 6.2. Examining this Table reveals no obvious cause/effect relationship between the water temperature increases in the context of

Table 6.2. Catchment rankings (1 = least, 2 = Intermediate, 3 = most), at the a) Gounamitz Lake and b) Island Lake study sites, for several factors that may influence shallow groundwater temperatures following harvesting.

a)	Temperature	Slash	Potential Incoming	Vegetative	Soil/Water
----	-------------	-------	--------------------	------------	------------

potential solar radiation received, vegetative recovery, and soil contact time. The difference in post-harvesting temperature increases between catchments, are likely due to a combination of various causal factors. It is, therefore, difficult to predict the observed inter-catchment differences in shallow groundwater temperature based on specific treatment and basin differences. For example, it was predicted at the commencement of this study that the WT harvest would cause the greatest shallow groundwater temperature increases, because the absence of slash should have resulted in the greatest soil temperature increases (Mahendrappa and Kingston 1994; McInnis and Roberts 1995). This was not the case for either study area, even though the WT catchment at GL was calculated to have the highest potential incoming solar radiation. Here, the order of

temperature increase *did* coincide with the order of water-soil contact times among the catchments (Table. 6.2). However, this relationship was weak, and this was not the case at IL. At IL, the observed post-harvest temperature increases correlated with slash loading only, but the order is opposite to what one would expect, i.e., the catchment with the extra slash should have had the lowest soil temperature increases, and therefore, the lowest well temperature increase.

At GL, the harvest-induced groundwater temperature increases were about the same as at IL (only 10% greater, on average, see Table 6.1). This also differed from what was expected at the outcome of the study, because the impermeable soils at IL should have translated into longer residence times for water in the soil, compared with GL and its permeable soils. Longer residence times should have caused the water to respond the most to increases in soil temperatures. In addition, vegetative recovery was better at GL (Chapter 4), which should therefore have registered somewhat lower post-harvest temperature increases.

The general post-harvest temperature increase should naturally relate to the increased amount of solar radiation received by the exposed ground. Not only would GL receive more potential radiation than IL based on its position in the landscape (Table 3.3), but the pre-harvest forest at GL would also have a greater albedo. Chaplin *et al.* (2000) concluded that deciduous forests should reflect twice as much incident radiation as coniferous forests in the summertime. Therefore, it is possible that greater post-harvesting, ground-level increases in solar radiation at GL were more important than differences in vegetative recovery and soil/water contact times in governing shallow groundwater temperatures.

The general post-harvest well-temperature increases, as reported above, are consistent with those for streamwater reported by Harr and Fredriksen (1988). These authors found that maximum post-harvest stream temperatures increased by 2-3 °C. Although temperatures in the Harr and Fredriksen (1988) study returned to normal three years following harvest, this groundwater study was not long enough to conclude when temperatures will return to normal. A decrease, however, was noted for the third fall following harvest (Figs. 6.7 and 6.8). Other studies on streamwater have found that it takes as long as 15 years for streamwater temperatures to return to normal (Johnson and Jones 2000).

At GL, only maximum well temperatures appeared to be affected by harvesting, which is consistent with the streamwater study by Rishel *et al.* (1982). However, at IL, the findings are more consistent with the streamwater study by Holtby (1988), because minimum temperatures also increased, albeit to a much lesser extent than the maximum summer increases. These differences between the two areas of this study may be due to differences in hydrogeology. For example, there are many pockets at IL of soils that remain saturated throughout the summer. The heat retained by water pockets may help maintain the harvest-induced temperature increases of the wells throughout the year.

It is difficult to say whether the harvest-induced temperature increases found in this study are damaging to ecosystem processes. As noted by Macdonald *et al.* (2003), modest temperature changes could have impacts on many components of stream ecosystems. However, impacts are not well enough understood to predict whether the changes measured here would be beneficial or detrimental, and to what degree. The US Department of the Interior (1968) recommends keeping temperature increases at, or

below, 2.8 °C (5 °F). The temperature increases seen here are below this threshold, with the GL SO catchment closest, increasing 2.5°C in the second fall following harvesting (Fig. 6.7). However, according to Barton *et al.* (1985), temperature increases between 2-4 °C may affect the distribution of coldwater species.

Perhaps more important than increases in maximum temperatures is the *timing* of the temperature increases (Johnson and Jones 2000). Many aquatic species have intimate relationships with their surroundings, and slight changes in water temperature patterns may interfere with their life cycles (US Department of the Interior 1968). In addition to the increased maximum shallow water temperatures recorded in this study, the water reaches certain degrees of warmth earlier in the year. For example, in the second fall following harvest, shallow groundwater draining the SO catchment at GL reached an 8 °C temperature 2.5 months earlier in the year than expected had harvesting not taken place (Fig. 6.7). The change was more extreme at IL, where temperatures in the second post-harvest year reached 7 °C three months earlier than expected had harvesting not occurred (Fig. 6.8). Such changes in temperature patterns may expose species, whose life cycles are altered by such changes, to unexpected environmental conditions, such as cooler or warmer stream temperatures, or the food source of the species may not yet be available (US Department of the Interior 1968, Curry *et al.* 2002).

CONCLUSIONS

Through visual assessment and data analysis, it was discovered that harvesting increased shallow well temperatures into at least the third post-harvest year. In almost all cases, these increases appeared to be the greatest in the second fall season following harvesting, with increases of as much as 2.5 °C. Harvesting also affected the timing of the

increases, with seasonal temperatures advanced as much as three months ahead of predictions in a no-harvest scenario.

Despite considerable differences in geology, terrain, and stand conditions between the two study areas, there were only minor differences between study areas in terms of the post-harvest well-temperature responses. These results imply that the harvesting-induced temperature increases measured here may be found over much of New Brunswick, or at least northern New Brunswick.

The difference in the magnitude of temperature increases between catchments following harvesting cannot be attributed to the type of harvesting alone, or any other single factor, including solar radiation inputs, early vegetative recovery, or catchment shape, size or slope. Rather, the amount of increase is likely dependant on a compensating combination of various post-harvest factors.

CHAPTER 7

INTRODUCTION TO THE HYDROLOGY MODEL (FORHYM)

INTRODUCTION

The specific objectives of this Chapter are:

- To introduce the ForHyM model in terms of its general outline and functions.
- To present special features developed to deal with modeling groundwater table fluctuations.
- To apply the model to simulate forest growth, pre- and post-harvest soil moisture, snow pack accumulation, solar radiation received at the soil surface, and soil temperature for the general study areas, by forest cover type (softwood, hardwood). The simulation lasted for a period of 20 years (1980-2000), with forest harvesting occurring five years into the simulation.

Model Overview

This Chapter focuses on modeling all aspects of hydrological and thermal flows and storage components in small forest catchments. The computer model used is ForHym (Forest Hydrology Model), which was first developed at UNB in the early 1990's 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 in 2000 (Bhatti *et al.* 2000). Since then, the model has gone through further revisions designed to make the model more portable,

for direct application for a variety of stand, soil, and climatic conditions (Balland 2002).

Specifically, the newest version includes the following revisions:

- Soil parameters such as porosity, saturated hydraulic conductivity, field capacity, and permanent wilting point, heat capacities and thermal conductivities of soil layers have been re-programmed to reflect their inter-dependencies among each other, and their fundamental dependencies on soil texture (sand, silt and clay contents), soil organic matter (OM) content, soil coarse fragment (CF) content and soil depth (from Balland and Arp 2004).
- Calculations for solar radiation input, water flow, and ice formation in soil and snow have been reformulated, to improve the overall placement of the calculations within the wider climate, landscape or watershed context, i.e., as such, the modified model output responds – explicitly – to changes in watershed aspect and slope, and location, as defined by latitude and elevation (from Balland and Arp 2004).
- The revised version includes the simulation of snowpack density, as it changes over the course of the winter, in response to daily weather (from Balland and Arp 2004).
- The revised version also includes an improved formulation for interdependency of heat retention and water flow, especially when the soil freezes and thaws. As such, the revisions also address (*inter alia*) the formation of permafrost, and the dependency of permafrost on weather and climate change (from Balland and Arp 2004).
- A new, seasonal growth function is introduced, as opposed to the original continuous growth function. The new growth function is dependent on growing

degree days, with forest growth beginning at approximately the time of bud-swell, and ending around the period of hardening-off.

- Also included, is a seasonal growth function for forest growth, based on the original post-harvest growth function (Jewett 1995). The new growth function is dependent on growing degree days, with forest growth beginning at approximately the time of bud-swell, and ending around the period of hardening-off.
- A new component was added to allow for calculation of shallow groundwater level fluctuations (see Chapter 8).

For a more detailed overview of the ForHyM model, including the growth function, see Appendix IV.

General Subsurface Water Flow Patterns at Gounamitz Lake and Island Lake

In pursuing the objectives of this Chapter, it is important to realize that the water that runs through the wells is not necessarily the sum of the water that percolates through the soil. The water that runs through the wells has, in principle, a specific recharge area within the immediate catchment, and that water may also mix with aquifer water derived from other catchments at higher elevations. As such, the water, as it flows toward the wells, follows specific pathways. These pathways depend, in principle, on topography, surface, season, and bedrock geology of each catchment. Based on general field observations, specifically through the process of well drilling, it is now suggested that the water flows as described in Fig. 7.1. The suggested flow model proposes that there is an underground network of constricted flow channels, all mostly located underneath the glacially derived over-burden (regolith). These channels are recharged during wet

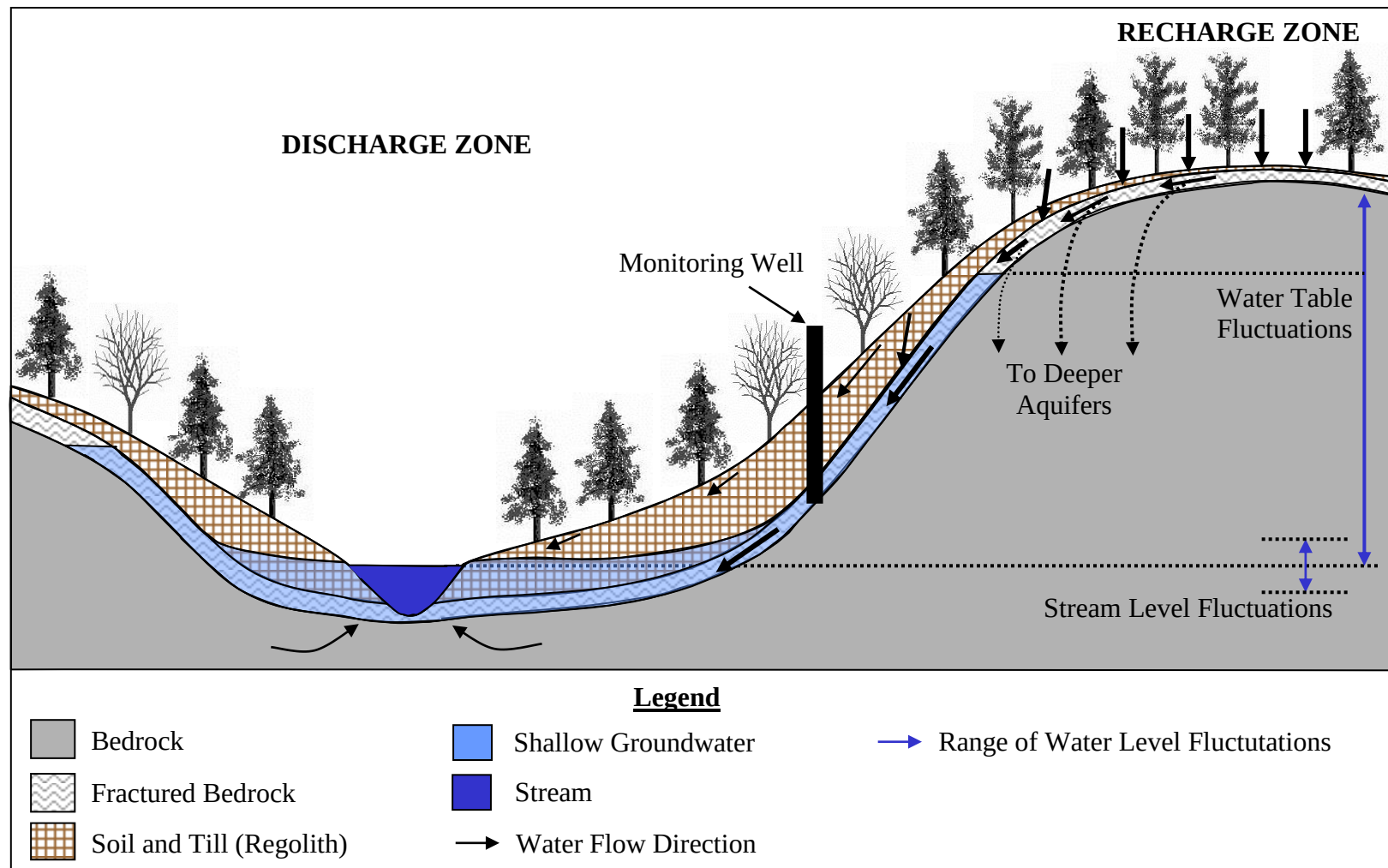


Fig. 7.1. Model of groundwater flow at the Gounamitz Lake and Island Lake study areas, based on site observations, including well drilling.

weather, and gradually empty during dry weather. Specifically, the main shallow groundwater flow path is confined to the mostly-shattered top layer of the underlying bedrock, just underneath the glacial till that fills most of the catchments of these study areas. This till is generally shallow on and along the ridge-lines, which therefore allows for ready groundwater recharge, especially in areas containing soils of high slope and low permeability. Much of the precipitation and snowmelt water received outside of that area would likely exit the catchment as run-off, or interflow, on top of the fairly impervious regolith.

The water entering the recharge areas would maintain some of its original temperature signal all the way to the wells, especially when there is rapid flow through the sub-terrain. If the water flows slowly, then the water should adopt the temperature of the substrate through which it flows. If the flow is restricted, water levels and temperatures at the wells may lag with respect to each rain and snowmelt event, by as much as several days (Chapter 5). Also, if the water table rises, the water would adopt the temperature of the substrate closer to the surface. This means that the water would be warm during high water flow in the summer, and cool during high water flow in the winter, especially during snowmelt.

Temperature Simulations

The ForHyM model does not simulate shallow groundwater temperatures directly, but is capable of simulating soil temperatures at various depths (Yin and Arp 1993; Bhatti *et al.* 2000; Houle *et al.* 2002). Since groundwater temperature is expected to equilibrate with the temperature of the soil layer in which this water resides, it is therefore suggested that the soil temperature profiles of the surrounding uplands can be

used to predict the general temperature of the well water. Therefore, the ForHyM model was used to explore the soil temperatures of the upland areas, and to compare these with the water temperatures in the shallow wells. Conversely, having the temperature of the well water provides an estimate of the depth through which the groundwater flows before it arrives at the wells.

METHODS

The deciduous Gounamitz Lake study area was chosen as the site to be used in this Chapter to demonstrate the abilities of ForHyM to simulate water and heat retention in soils, and in the substrate below. Two main steps were involved in preparing the ForHyM model to simulate the thermal and hydrological flows of interest for this particular study area, namely:

- entering model input that is appropriate for GL.
- customizing the model to predict shallow groundwater levels at GL.

ForHyM Model Inputs

There are two main types of inputs required for the ForHyM model: weather and catchment characteristics. Entry of the required inputs into the ForHyM model was facilitated by a model-user interface developed in Excel (Fig. 7.2; Microsoft Corporation 1999; Balland, personal communication, 2003).

Weather Inputs

- Most of the weather data that was used in the model run for this Chapter was obtained from Environment Canada weather stations in Edmundston, NB, located

Microsoft Excel - Data

File Edit View Insert Format Tools Data Window Help

y-axis

V54

MODEL INPUTS

Latitude	47.669
Altitude in m	325
Watershed area in ha	11
Aspect	130.8
Coniferous fraction	0
Deciduous fraction	0.7
Root depth code	5
Slope angle in degrees	4.5
Slope in percent	0.078459096

Temperature code	0
Fog code	0
Distance to coast in km	200
Climate factor	0
Subsoil layers moisture code	0
Bedrock moisture code	1
Quartz fraction in CF	0.1
Mean yearly snowdepth	22

Description of soil layers	Thickness	Texture	OM content	CF content
Forest floor	3.89	13	0.763614	0
Soil - A	32	13	0.121755679	0.476372646
Soil - B	19	13	0.072316	0.6567
Soil - C	100	13	0	0.6567
Subsoil - Sub 1	10	13	0	0.6567
Subsoil - Sub 2	100	13	0	0.6567
Subsoil - Sub 3	100	13	0	0.6567
Subsoil - Sub 4	100	13	0	0.6567
Subsoil - Sub 5	100	13	0	0.6567
Subsoil - Sub 6	100	13	0	1
Subsoil - Sub 7	100	13	0	1
Subsoil - Sub 8	100	13	0	1
Subsoil - Sub 9	100	13	0	1
Subsoil - Sub 10	100	13	0	1
Subsoil - Sub 11	100	13	0	1
Bedrock	100	13	0	1

Sand	Clay
0.4128	0.1025
0.56000883	0.0855609
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077
0.6389	0.1077

Calculate energy input

STELLA

Prepare data sheets

MODELMAKER

Prepare data files

Cutting time	2100
Mean growing season	185

Input parameters Data Calibration Energy Temperature Rain Snow C1 C2 C3 C4 C5 C6 C7 C8

Draw AutoShapes

Fig. 7.2. Model-user interface in Excel (Microsoft Corporation 1999) used for ForHyM inputs.

approximately 50 km south-west of the Gounamitz Lake study area. Missing precipitation and air temperature values within the 20-year data set from the Edmundston stations were filled using the corresponding values from the Environment Canada weather station at Nictau, NB, located approximately 60 km south-east of the Gounamitz Lake study area.

The required weather inputs were:

- mean daily air temperature
- total daily snowfall
- total daily rainfall

Catchment Characteristic Inputs

The required inputs related to catchment characteristics were (Figs. 7.2 and 7.3):

- Geographical position – Latitude (degrees) and altitude (m).
- Slope – Two slope inputs were required: 1) in degrees, for calculation of solar radiation fluxes; and 2) as a percent, for calculation of lateral water flows.
- Aspect - Aspects were entered in degrees, with a south aspect equal to zero.

Degrees increase positively from south toward the east, with a north aspect equal to +180. Degrees increase negatively to the west of south, up to a value of -180 at the north.

- Catchment area (ha).
- Stand-type – The coniferous/deciduous fraction (fraction of the expected LAI given a typical fully-stocked stand) must be specified, along with associated estimated root depths, from shallow (1) to very deep (6).
- Geology – Geology-related inputs included:

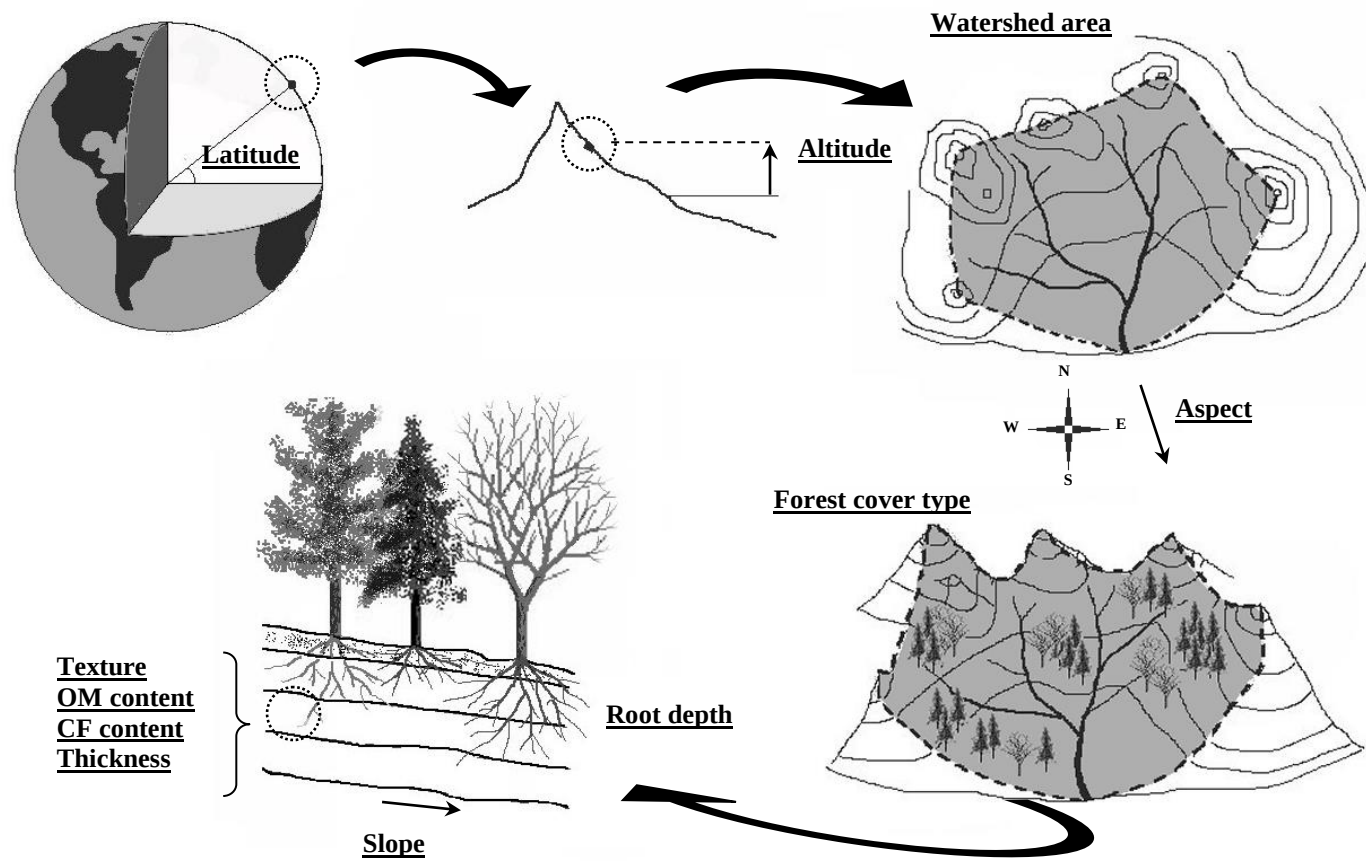


Fig. 7.3. Critical Inputs for ForHym related to catchment characteristics (Balland and Arp 2004).

- subsoil layers moisture code: field capacity (0), or saturation point (1);
 - bedrock moisture code: field capacity (0), or saturation point (1);
 - quartz fraction in coarse fragments.
- Climate – Climate-related inputs included:
 - climate factor: maritime (0), or continental climate (1);
 - temperature code: air temperatures measured under canopy (1), or otherwise (0);
 - fog code: no fog (0), or fog function activated (1).;

distance to coast (km);

 - mean snowpack depth (cm).
- Soil description – a catchment's sub-surface is divided into 16 layers:
 - forest floor;
 - upper ("A") soil layer;
 - middle ("B") layer;
 - lower ("C") layer;
 - 11 subsoil layers;
 - a bedrock layer

For each layer, the following had to be specified:

- thickness (as fraction);
- texture – Texture can be entered as a texture type code (ex: 5 = sandy loam), or as specific sand/clay content (texture type code = 13);
- organic matter content (as fraction);
- coarse fragment content (as fraction).

The input values for these catchment characteristics were those used for the first control catchment at GL (GL-C1), as presented in Appendix V.

RESULTS AND DISCUSSION

Canopy Growth

As modeled, harvesting of the hardwood stems at GL reduced the summer Leaf Area Index (LAI) from slightly over $8 \text{ m}^2/\text{m}^2$, to $1 \text{ m}^2/\text{m}^2$ or less, with canopy recovery calculated to be mostly complete within 15 years following harvest (Fig. 7.4). On tolerant hardwood stands such as this, the LAI is expected to recover fairly quickly because of stump sprouting (MacDonald and Powell 1983). With a more severe harvest disturbance, a slower canopy recovery rate would have been expected.

Solar Radiation Inputs Received by the Soil

Net Solar Radiation, as modeled, is the combined direct and diffuse solar radiation. Shown in Fig. 7.5 is the part of the radiation that is received by the ground. This radiation varies greatly within each year: during portions of the winter when the soil is covered by snow, radiation inputs are modeled to be zero. Thereafter, modeled inputs increase abruptly following snowmelt, and prior to leaf-out. With leaf-out, radiation inputs are calculated to decrease again until leaf fall, when ground-level radiation inputs would be elevated once more until resumption of snowfall.

For several years following harvesting, the yearly ground-level radiation patterns change (Fig. 7.5). Net Solar Radiation, as received by the ground immediately following snowmelt, increases by more than 30% over the previous year. In the absence of

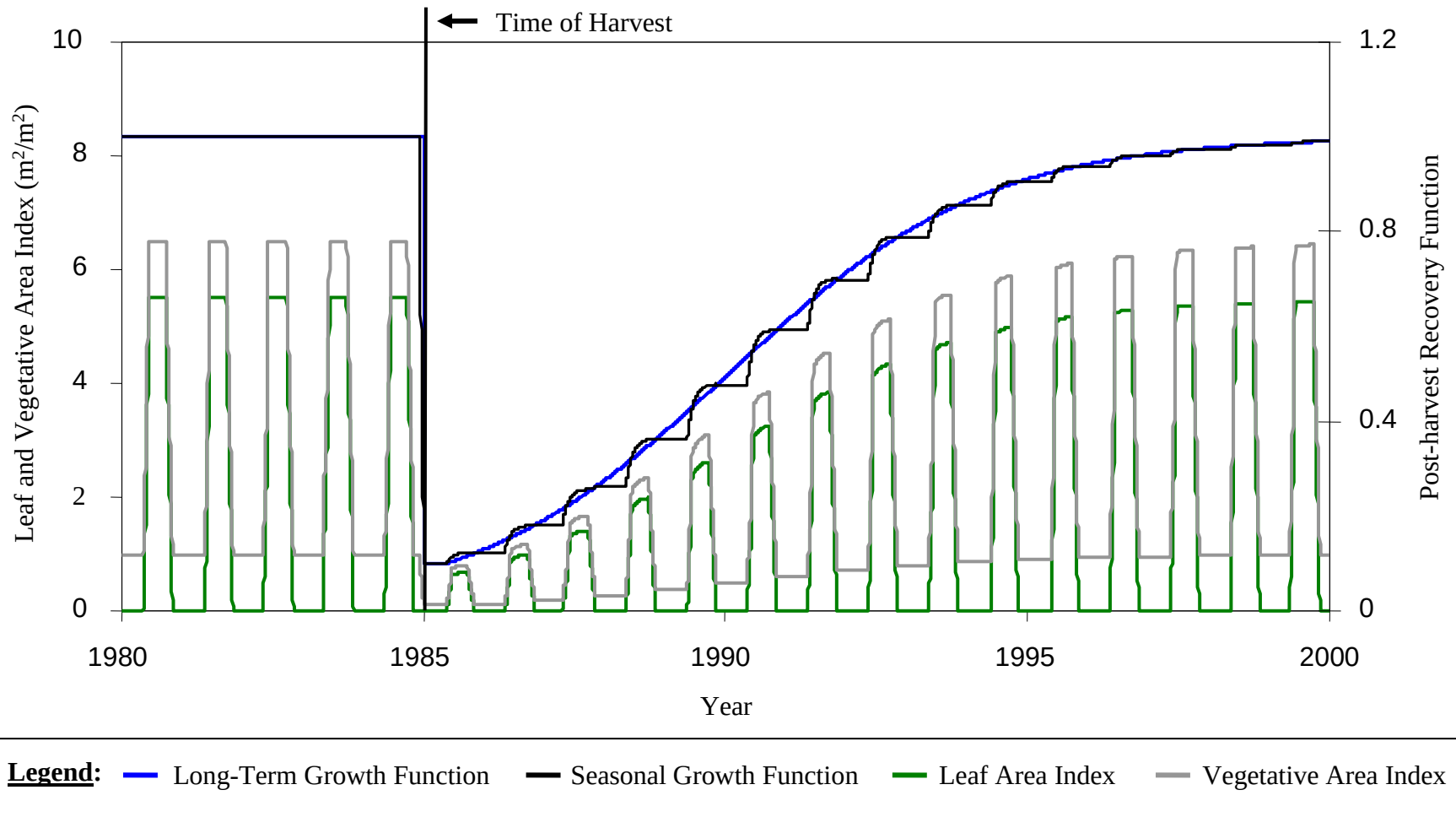


Fig. 7.4. ForHyM simulation of canopy growth on the first control catchment at Gounamitz Lake (GL-C1) over a 20 year period, including the predicted response to harvesting.

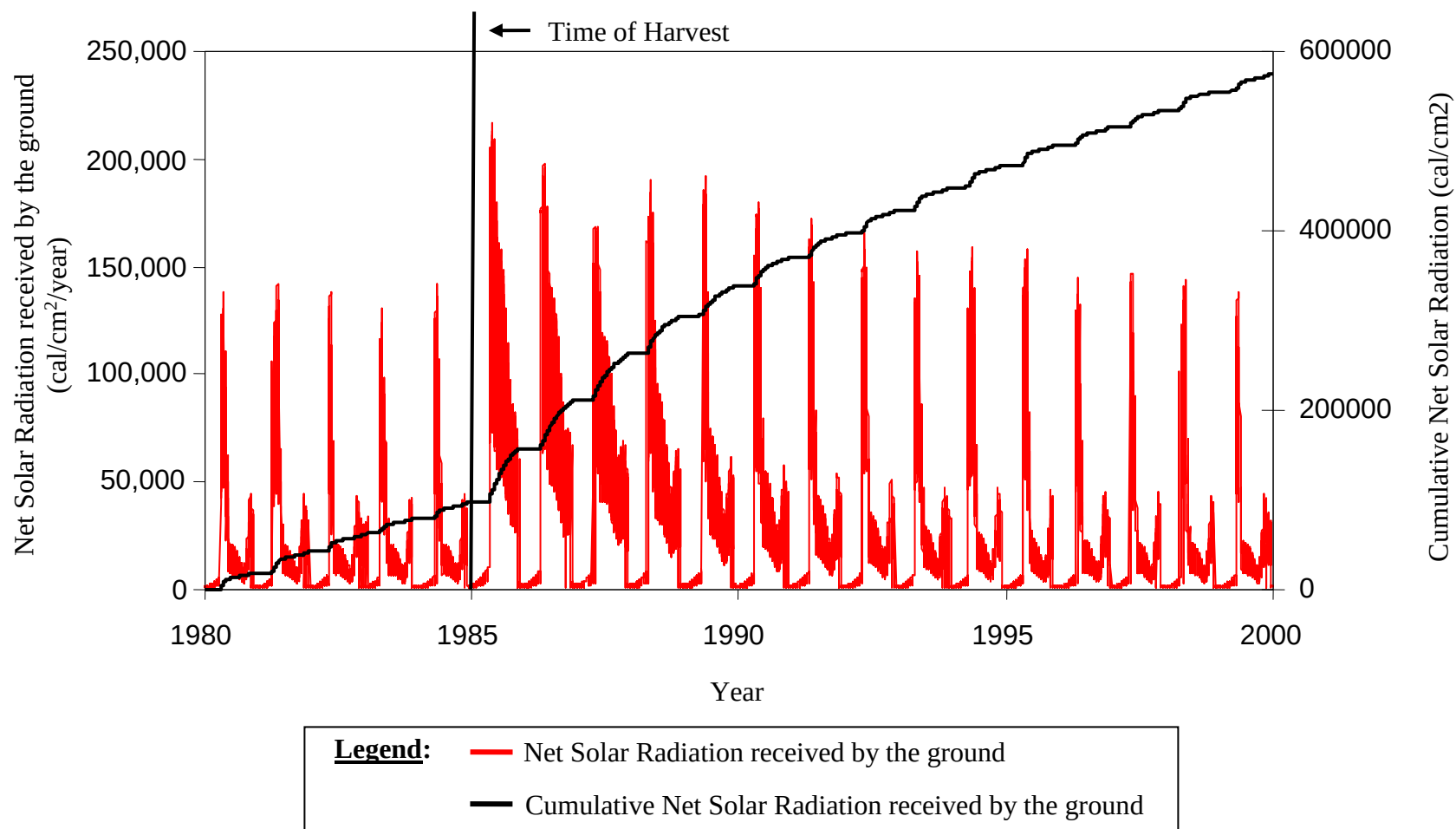


Fig. 7.5. ForHyM simulation of net solar radiation received by the soil surface of the first control catchment at Gounamitz Lake (GL-C1) over a 20 year period, including the predicted effects of harvesting.

significant post-harvest vegetation, radiation levels decrease only gradually throughout the remainder of the summer as day length shortens. The cumulative radiation levels, as calculated, change accordingly.

Soil Temperature

Following harvesting, soil temperatures are calculated to increase. This increase is most pronounced at the soil surface, in the first summer following harvesting, where temperatures are approximately 2 °C warmer than what is calculated without harvesting (Fig. 7.6). Little change, however, is expected in the minimum temperatures as the soil is normally insulated under snowpack during the coldest time of the year.

In general, the amplitudes of the seasonal fluctuations in the simulated soil temperatures decrease with increasing depth below the soil surface (Fig. 7.7), as also demonstrated by Wu and Nofziger (1999). The temperature curves also lag, and become smoother with increasing depth, as daily changes in the local weather patterns are buffered with increasing soil depth. In the winter, temperatures near the soil surface are calculated to remain at a nearly constant temperature of zero degrees Celsius, while water in the soil layer changes phase between liquid and ice (Fig. 7.7).

Snow Depth

The weather records obtained from the Environment Canada weather stations include partial records of snow depth accumulations. These records provide an additional means by which the model accuracy can be gauged. As shown, there is generally a close match between the records and the calculated snow depth where actual measurements exist, with the exception of the winters of 1980-81 and 1981-82 (Fig. 7.8). During these

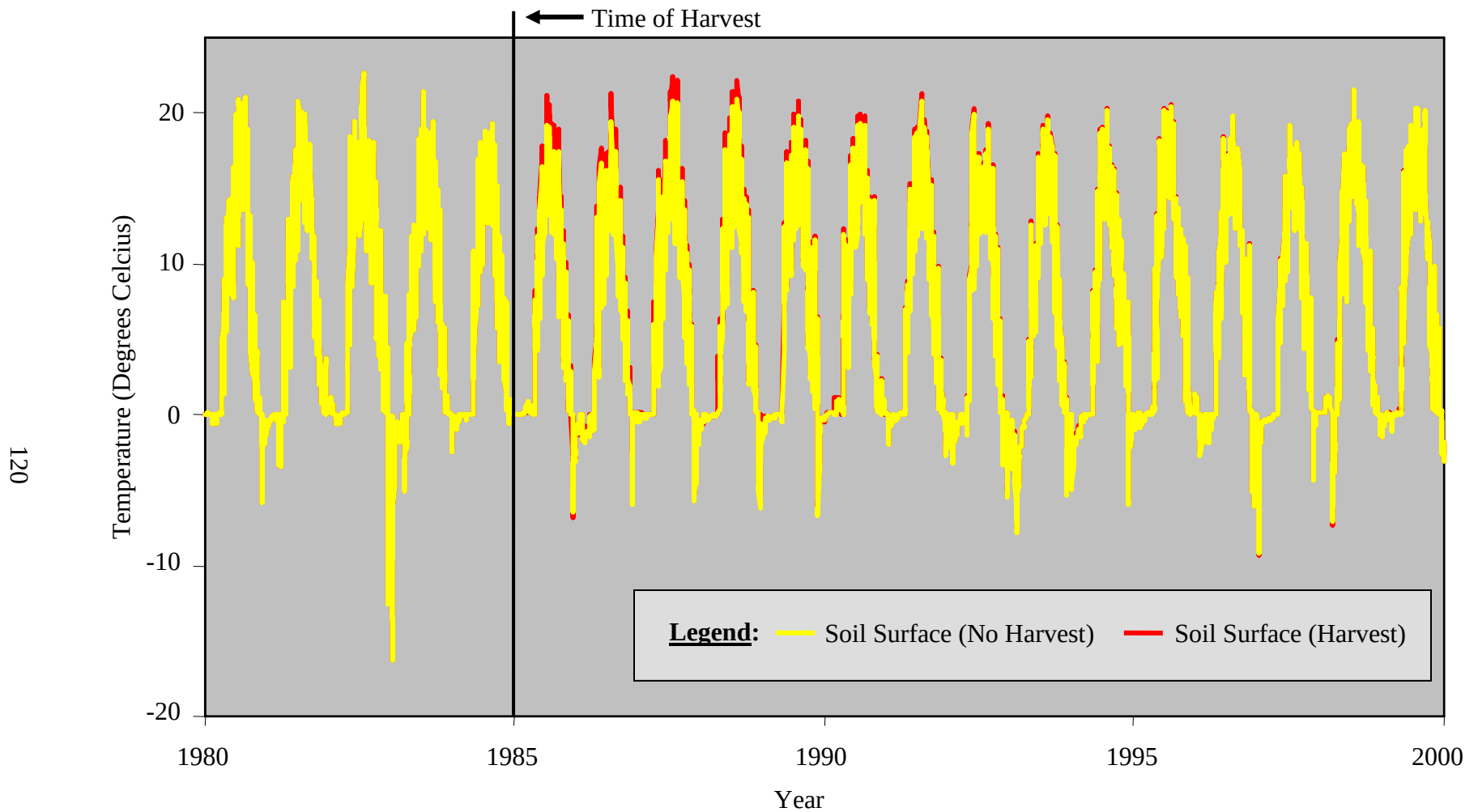


Fig. 7.6. ForHyM simulations (with harvesting, and without harvesting) of temperature at the soil surface of the first control catchment at Gounamitz Lake (GL-C1) over a 20 year period.

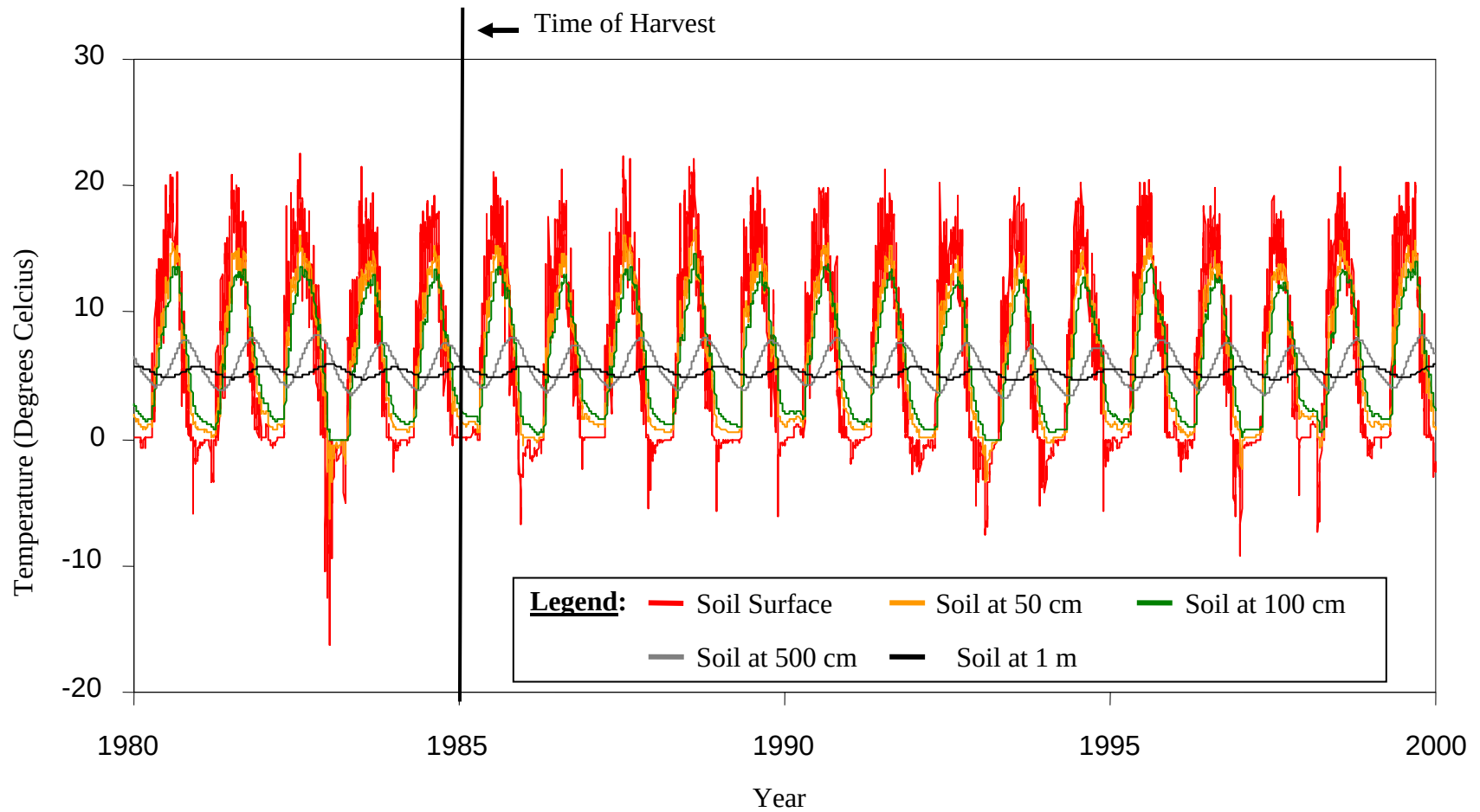


Fig. 7.7. ForHyM simulation of soil temperatures at various depths on the first control catchment at Gounamitz Lake (GL-C1) over a 20 year period, including the predicted effects of harvesting.

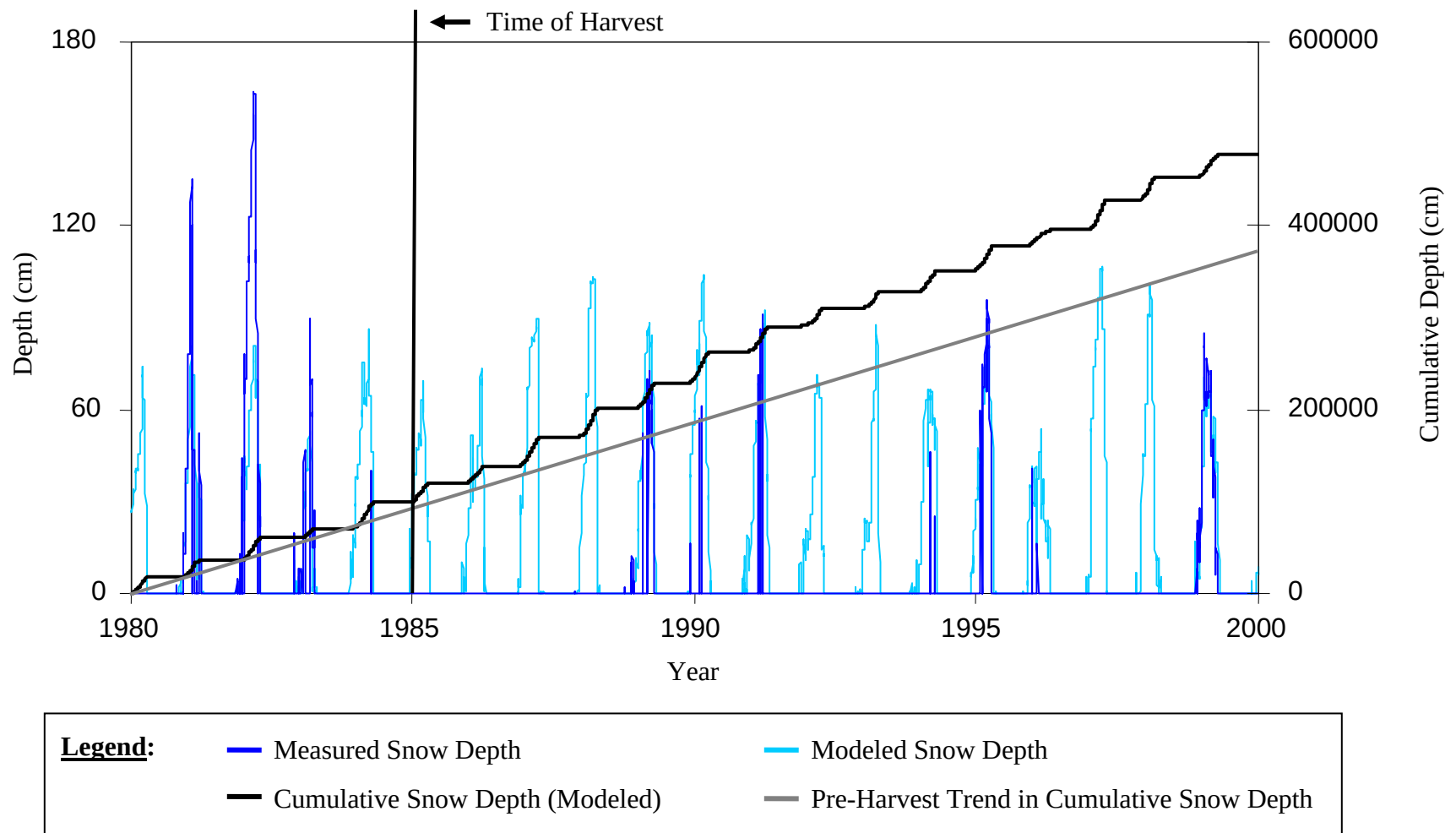


Fig. 7.8. ForHym predictions of snow depths on the first control catchment at Gounamitz Lake (GL-C1) over a 20 year period, including the predicted effects of harvesting, compared with actual snow depth measurements from a nearby weather station.

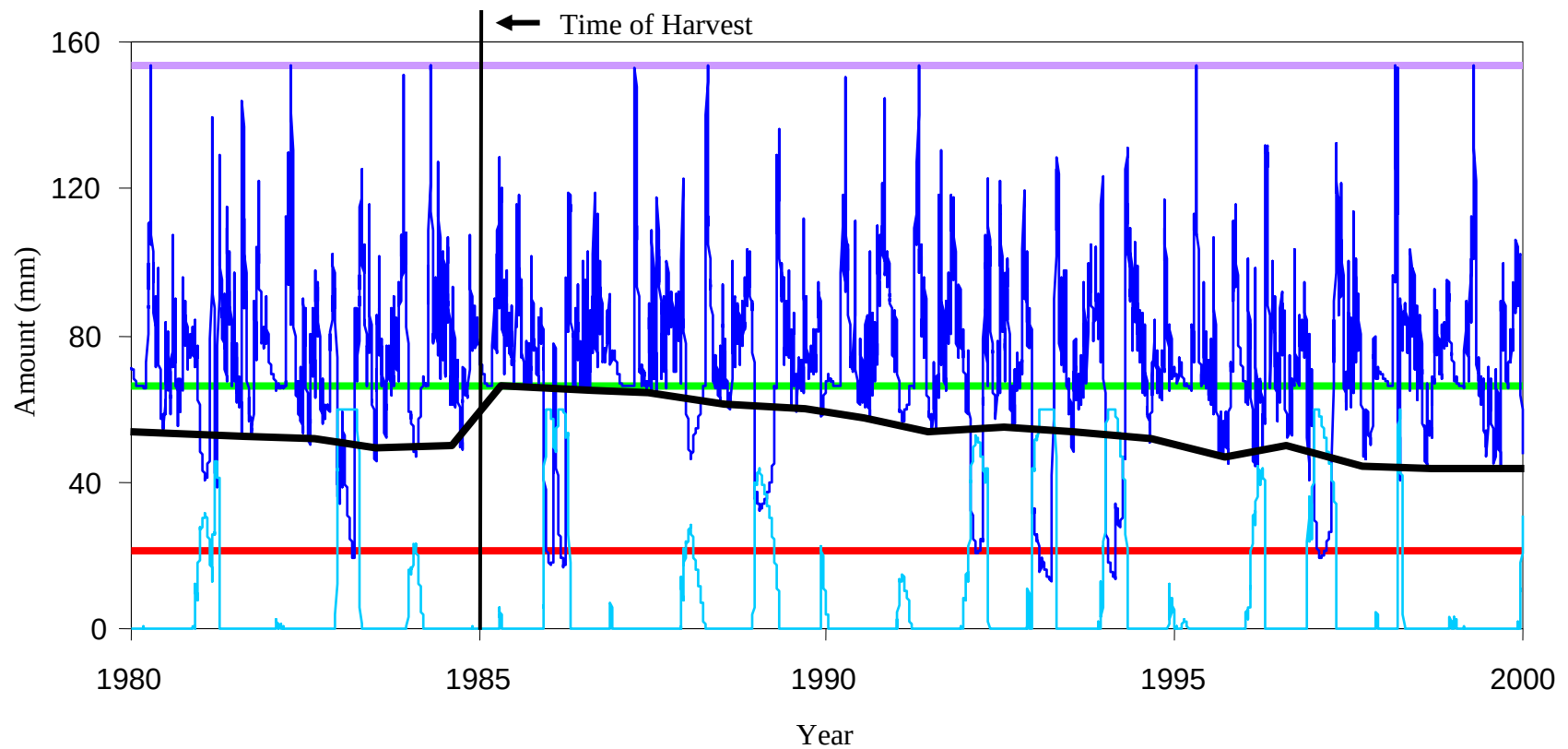
winters, modeled depths are much less than measured depths. Possible explanations for these discrepancies are: 1) the model is predicting snow depth under a forest canopy, while the measurements from the weather station are taken in the open (W. Richards, personal communication, April 14, 2004); 2) snow densities of one or several snow falls that year are less than the model predicted, 3) wind accompanying snow in those years prevent the snow collection devices at the weather stations from catching and recording all the snowfall.

Following a simulated harvest, modeled snow depths increase for several years, as evident by a change in slope of the cumulative snow depth in Fig. 7.8. Snow depths are also expected to increase following harvesting, as canopy interception is temporarily reduced.

Soil Water/Ice Content

There is a noticeable change in simulated soil moisture levels following harvesting: for at least five years following harvesting, minimum summer moisture expectations increase, and rarely drop below field capacity (Fig. 7.9). These increases in soil moisture following harvesting would be due to reduced evapotranspiration following tree removal.

Overall, water levels in the upper mineral soil layers are simulated to remain between the soil Field Capacity and the Saturation Point for most of the simulations (Fig. 7.9). Occasionally, soil moisture is calculated to drop below the field capacity. This occurs during dry periods, but also during very cold winters when soil temperatures are calculated to drop below 0 °C for prolonged periods of time, such as the winter of

**Legend:**

Volume of Pores in Soil

Field Capacity of Soil

Permanent Wilting Point of Soil

Water in Soil

Ice in Soil

Soil Water Summer Baseline

Fig. 7.9. ForHyM simulation of water and ice content in the combined upper two soil layers (‘A’ and ‘B’ layers) on the first control catchment at Gounamitz Lake (GL-C1) over a 20 year period, including the predicted effects of harvesting.

1982/1983 (Figs. 7.7 and 7.9). During these cold periods, much of the soil water converts to ice.

CONCLUSIONS

The ForHyM model is capable of producing expected hydrological and thermal patterns within the soil, both in the absence of harvesting, and following harvesting. The model is generally in agreement with measured snow depths.

Following harvesting, the following changes are simulated by the model:

- soil moisture increases, especially during the summer.
- snow depth above the soil increases.
- net solar radiation received by the ground (Forest Floor or snow) increases.

CHAPTER 8

USE OF A HYDROLOGY MODEL (FORHYM) TO PREDICT THE TIMING AND MAGNITUDE OF SHALLOW GROUNDWATER LEVEL FLUCTUATIONS

INTRODUCTION

This Chapter evaluates the ability of ForHyM to predict fluctuations in shallow groundwater levels at the two study areas. Specifically, the objectives are:

- to modify ForHyM so that shallow groundwater levels can be modeled;
- to compare ForHyM simulated shallow groundwater level fluctuations given a no-harvest scenario, with measured pre-harvest levels;
- to evaluate the ability of ForHyM to accurately simulate the effect of harvest on shallow groundwater levels;
- to compare measured inter-catchment differences in shallow groundwater response to harvesting with simulated inter-catchment differences.

METHODS

Modeling Groundwater Levels

The original version of ForHyM was not designed to model shallow groundwater fluctuations. Therefore, the following equation was built into the model to estimate well levels (y) based on soil gravitational water (x):

$$y = a + bx \quad \text{(Equation 7.1)}$$

where:

y = well level (m);

a = a reference water level;

b = adjustable coefficient to deal with substrate-specific porosity.

x = gravitational water (m), as calculated with ForHyM.

As illustrated in Equation 7.1, the water levels in the wells are represented by the amount of gravitational water in the soil layers. The magnitude of the water table fluctuations are largely dependent on the porosity of the catchment substrate in the vicinity of the wells, i.e., water table fluctuations increase with decreasing pore space in the sub-terrain, but also increase as the groundwater backs up towards the surrounding ridges during wet weather.

Model Inputs

The model inputs for this Chapter are essentially the same as for Chapter 7, with the following exceptions:

- Weather data records for the study areas were interpolated from weather records obtained from multiple weather stations near the study areas (Appendix I).
- Inputs were entered into the model to allow for the modeling of hydrological and thermal processes of all 10 catchments within the two study areas (see Appendix V for specifics).

- The measured shallow groundwater levels and temperatures obtained from all 10 wells were added to the model to enable direct comparisons. Measured groundwater temperatures were used to estimate the depth of flow (see Chapter 9).

Model Calibration

Model calibrations consisted of adjustments made to both the groundwater levels and designated water flow calibration parameters. Calibration adjustments were made to obtain the best fit between measured and modeled pre-harvest water levels.

Groundwater Levels

The equation used for calculating shallow groundwater levels in ForHyM (Equation 7.1) involves two methods for calibration: 1) initial water levels, and 2) pore space coefficient. The initial water level differed for each well, because the probes were all placed into the wells at different depths, depending on the depth of the well. Once the initial reference water level was chosen, the magnitude of subsequent water level fluctuations modeled for each well were adjusted by changing the coefficient for pore space.

Water Flow Calibration Parameters

The model-user interface that was developed for the ForHyM model (described in Chapter 7) contains a section for model calibration (Fig. 8.1). This section allows for model fine-tuning. Only the “water flow” calibration parameters needed to be adjusted for these study areas, because these adjustments are very site specific: they depend on

CALIBRATION PARAMETERS	
Snowmelt	
Air temperature adjustor	0.1
Water flows	
Surface runoff adjustor	1
Infiltration in FF adjustor	1
Interflow in FF adjusor	1
Infiltration in soil adjustor	1
Interflow in soil adjustor	1
Infiltration in C adjustor	1
Interflow C adjustor	1

Fig. 8.1. Calibration section of the ForHyM model-user interface (Balland, personal communication, 2004).

soil characteristics, and for these study areas, only one general soil description was available for each area. The water flow parameters are:

- Surface Runoff Adjustor – This adjuster is only used when there is snow on the ground, and adjusts the rate at which water moves laterally through the snow and ice above the soil.
- Infiltration in FF Adjustor – Adjusts the rate at which water moves vertically into the Forest Floor.
- Interflow in FF Adjustor – Adjusts the rate at which water moves laterally within the Forest Floor.

- Infiltration in Soil Adjustor - Adjusts the rate at which water moves vertically into the upper soil layers (“A” and “B” layers).
- Interflow in Soil Adjustor - Adjusts the rate at which water moves laterally within the upper soil layers (“A” and “B” layers).
- Infiltration in “C” Adjustor - Adjusts the rate at which water moves vertically into the lower (“C”) soil layer.
- Interflow in “C” Adjustor - Adjusts the rate at which water moves laterally within the lower (“C”) soil layer.

Calibrating the model using these parameters is an iterative process, which can be shortened with careful outcome evaluations at each step. The first step in the calibration was to compare the measured water levels with modeled levels. If water levels were too slow to increase in response to precipitation or snowmelt events, or too fast to decrease following precipitation or snowmelt events, either the infiltration rates were too low, or the interflow rates were too high. Conversely, if water levels were too fast to increase in response to precipitation or snowmelt events, or too slow to decrease following precipitation or snowmelt events, either the infiltration rates were too high, or the interflow rates were too low. Soil layers most in need of adjustment were determined by observing the modeled water content in each of the various soil layers, as graphed by ForHyM. For example:

- If shallow groundwater levels increased too abruptly following a precipitation event, the entire soil moisture profile is examined. If the water content in the upper soil layer was increasing abruptly at a rate

similar to the shallow groundwater level, it was best to start calibration with this soil layer, by either increasing interflow in the layer above it (Forest Floor layer in this case), or decreasing the infiltration rate into the upper soil layers.

- If summer or winter base-flow shallow groundwater levels were decreasing too fast, the same procedure was used to identify the most likely sources of the differences. However, at time of base-flow, it was usually the lower soil layers that needed adjustment, as the water, as calculated, had drained from the upper soil layers by that time. This problem was usually resolved by reducing interflow through the lower (“C”) layer.

It should be noted that adjusting a calibration parameter to improve the fit between modeled and measured water levels at one point in the simulation would alter the water flow throughout the whole simulation, and could therefore decrease the overall fit of the modeled data in other portions of the simulation. This would necessitate another calibration step, until the best possible fit is obtained for the pre-harvest period.

Accumulation of Shallow Groundwater Levels

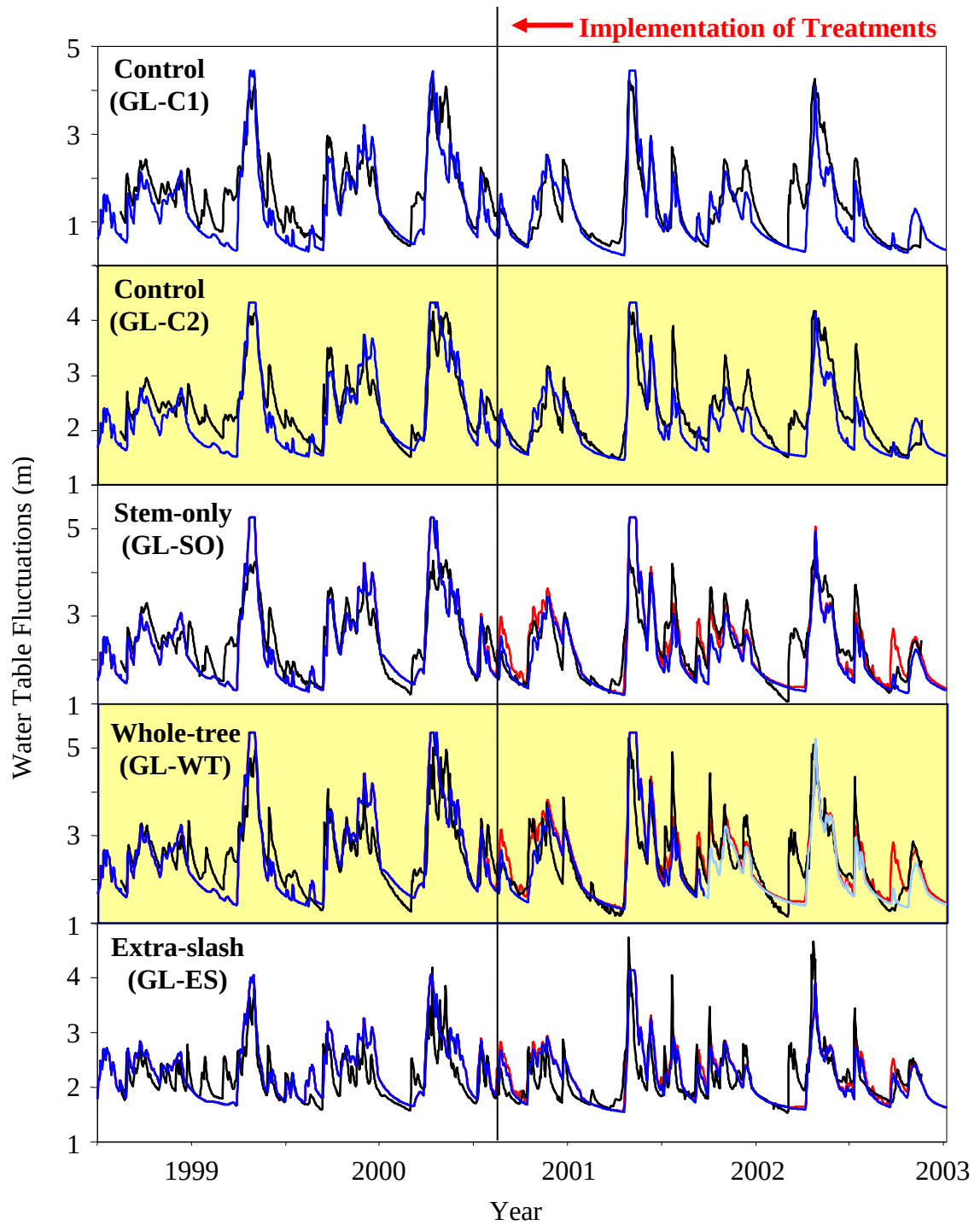
Modeled shallow groundwater levels were accumulated and graphed horizontally using the same procedures used for the measured shallow groundwater levels in Chapter 5. Modeled water levels were presented this way to check whether ForHyM was able to reproduce the measured effects of harvesting, including differences in response between the catchments.

RESULTS AND DISCUSSION

ForHyM Shallow Groundwater Level Simulations

Overall, a good fit could be achieved between measured and simulated water table fluctuations for all 10 catchments at the GL and IL study areas (Figs. 8.2 and 8.3). In general, the fit is best for the GL catchments. Here, fairly uniform, permeable soils, and the smooth, gently rolling slopes make the overall substrate hydrology more predictable than at IL, where terrain is hummocky, and soil conditions are quite variable. Among the 10 catchments, the fit between measured and modeled water levels was poorest for the upper IL-SO1 well. This is because the incomplete data set from this well (this well dries up for portions of each summer and winter) made model calibration difficult (Fig. 8.3).

As expected, on harvested catchments, the model output that included a harvesting simulation produced the best fit with the measured data (Figs. 8.2 and 8.3). When simulating the effects of harvesting, predicted water levels were higher during the summer than modeled levels under a no-harvest scenario. Thus, the model was able to predict the water table's response to a reduction in evapotranspiration. However, the model did not simulate the early spring snowmelts that appeared to have occurred in the spring of 2002 following harvest, but these particular increases were not necessarily related to harvesting, as they also appeared for the GL controls. It is possible that the early snowmelt event in 2002 was caused by an early spring rain, or an early thaw that was not accurately simulated by the model. In general, the model's accuracy was somewhat reduced during the wintertime. For example, there are several instances during



Legend: — Measured — Model Simulation — Model Simulation with Harvesting

Fig. 8.2. Comparison of measured shallow groundwater level fluctuations, with simulations produced by ForHyM for catchments at Gounamitz Lake.

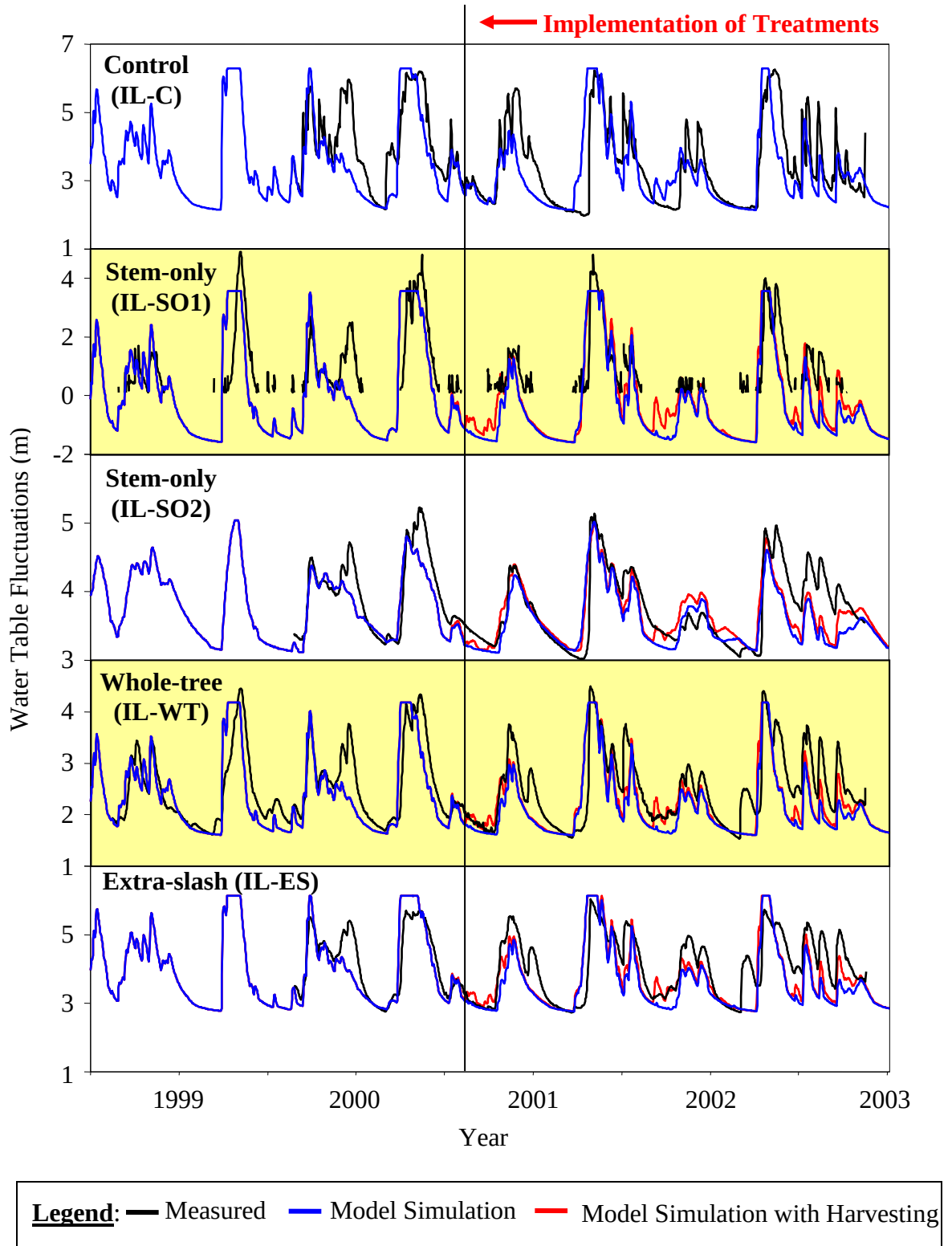


Fig. 8.3. Comparison of measured shallow groundwater level fluctuations, with simulations produced by ForHyM for catchments at Island Lake.

the simulation when modeled groundwater levels during spring thaws and rains did not exactly match the timing and magnitude of the measurements (Figs. 8.2 and 8.3).

For GL, the simulated harvesting effect on groundwater levels was much smaller for the GL-ES catchment than it was for the other catchments (Fig. 8.2). This was the opposite of what was determined from the measured data in Chapter 5, where the GL-WT catchment showed the smallest harvest-induced increase, and the GL-ES catchment had the largest. The reason why the GL-ES catchment showed the smallest modeled increase in response to harvesting was related to the total deciduous/coniferous fraction, which was set at 0.7 for this basin, compared to a fraction of 1.0 for the other catchments at GL (see Chapter 7 and Appendix V). A lower fraction was necessary to obtain the best possible fit between measured and modeled pre-harvest water levels. The removal of scattered softwood trees from the eastern end of the study area at some point in the past (as evident by decomposing stumps) caused the reduction in LAI assignment.

During the spring snowmelt periods, the modeled water levels of many catchments reached a maximum level, and then remained constant for a period of up to one month before decreasing again (Figs. 8.2 and 8.3). The simulated water levels responded in this way because all the soil layers in the model were saturated. In general, the soil layers at IL were expected to remain saturated longer because of the relatively impermeable soil conditions compared with GL.

There were only small differences in the “water flow” calibration parameter values between the catchments (Table 8.1). The differences were particularly small between catchments within each study area, especially at GL, suggesting similarities in the subsurface flow regimes. However, differences in the groundwater level calibration

Table 8.1. Calibration settings for "water flow" required to produce the best fit between measured groundwater level data and ForHym model outputs.

Adjustor	Catchment									
	GL-C1	GL-C2	GL-SO	GL-WT	GL-ES	IL-C	IL-SO1	IL-SO2	IL-WT	IL-ES
Surface runoff	1	1	1	1	1	1	1	1	1	1
Infiltration in FF	1	1	1	1	1	1	1	1	1	1
Interflow in FF	0.008	0.008	0.008	0.008	0.008	0.02	0.02	0.02	0.02	0.02
Infiltration in soil	0.3	0.3	0.3	0.3	0.3	1	1	0.1	1	0.75
Interflow in soil	0.0008	0.0002	0.0005	0.0005	0.0008	0.0001	0.0001	0.0005	0.0001	0.0001
Infiltration in C	1	1	1	1	1.5	1	1	0.1	1	0.5
Interflow C	0.4	0.4	0.4	0.4	0.6	1.5	1.5	0.9	0.9	0.75

values were more substantial (Table 8.2). Large differences in the Initial Reference Water Levels were expected because the measuring probes were placed in the well water at variable depths. Differences in the coefficient values for the subsoil pore space were, however, somewhat of a surprise, especially for the GL catchments. Here, the soils were understood to be fairly uniform across the site, with little interference from the surrounding catchments. These calibration values suggest that either there were significant differences between the catchments in substrate bulk density in the areas surrounding the wells, or small differences in substrate bulk density may translate into significant differences in water level response. The large differences in the coefficient values for pore space between the catchments at IL were to be expected because of a large amount of variability in substrate conditions throughout the study area, as well as the high likelihood of additional groundwater flow originating from areas of higher elevation surrounding the catchments.

Table 8.2. Groundwater level calibration values for the 10 catchments at Gounamitz Lake and Island Lake.

Catchment	Initial Reference Water Level (m)	Gravitational Water Coefficient
GL-C1	0.9	45
GL-C2	1.3	30
GL-SO	0.9	43
GL-WT	1	43
GL-ES	1.4	27
IL-C	2	40
IL-SO1	-1.8	50
IL-SO2	3	19
IL-WT	1.5	25
IL-ES	2.6	33

Cumulative Groundwater Levels

When the cumulative modeled water levels were graphed horizontally, the patterns that resulted were similar to those of the cumulative measured water tables in Chapter 5 (Figs. 5.6 and 8.4). In both cases, water levels decreased following harvesting, with levels at IL decreasing the most. Since the model reproduced this pattern based only on inputs of air temperature and rain/snowfall, this suggests that the combination of these factors were, in fact, responsible for the measured post-harvest water level drops, although this was not apparent from the analysis in Chapter 5. That is, the post-harvest years were – coincidentally - drier and/or hotter than the pre-harvest years. This cause/effect implication would have gone unnoticed without ForHyM, thereby highlighting the usefulness of this model as an analytical hydrology investigation tool.

As expected, all of the modeled cumulative water levels of the harvested catchments increased relative to the control catchments (Fig. 8.4). However, the current model design would not be able to reproduce all the measured differences in the harvesting responses among the treated catchments that was observed in Chapter 5.

At GL, the modeled response to harvesting was the similar for the SO and WT catchments, with summer water tables on both showing the greatest increases due to harvesting. The model response of the GL-ES catchment was notably different from the other harvested catchments because the coniferous/deciduous fraction model input was set lower than the other catchments, and therefore this catchment had a smaller modeled response to harvesting.

At IL, the model predicted the SO catchment to have the greatest response to harvesting, with the WT and ES catchments having a similar response. Here, the modeled

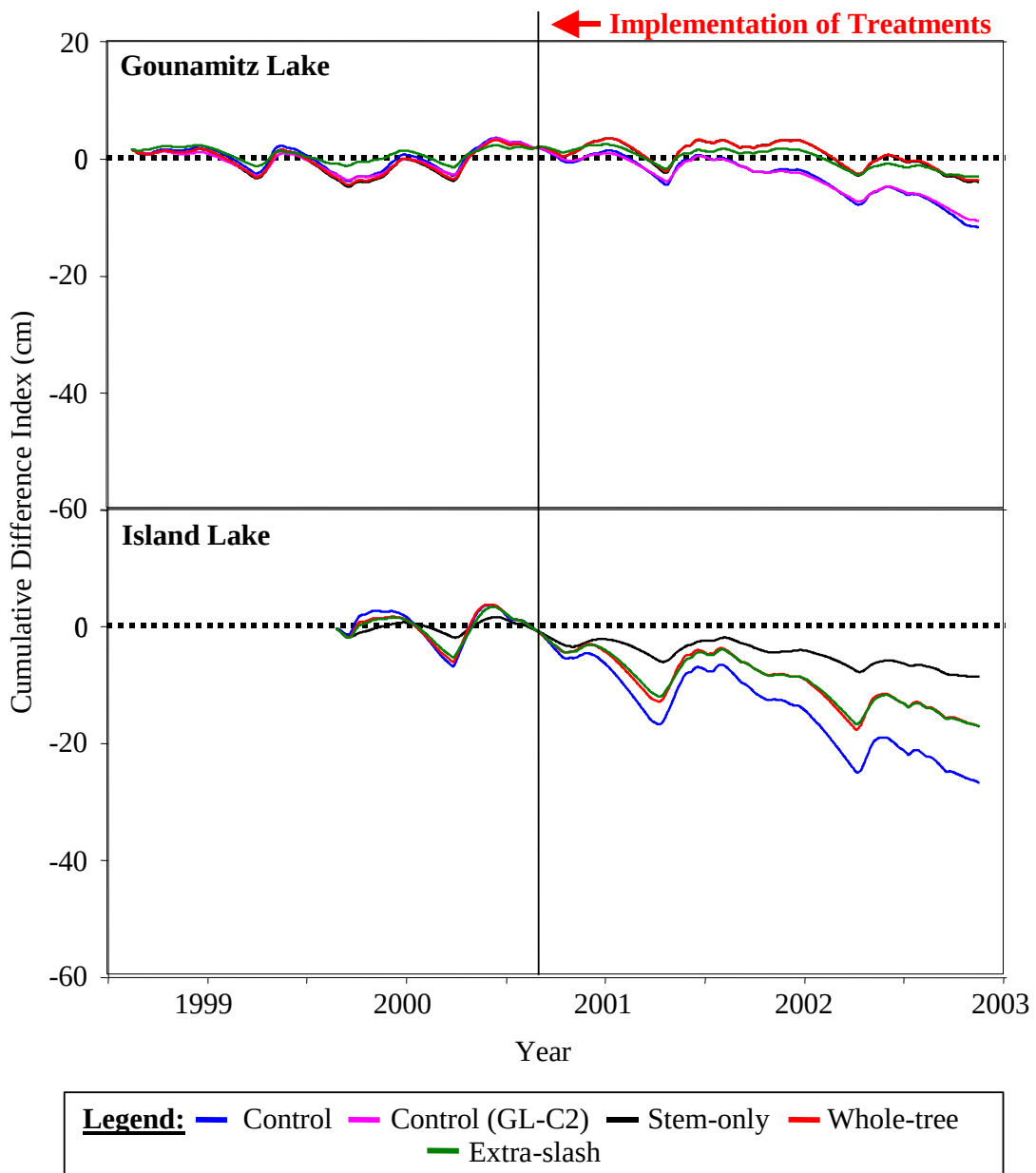


Fig. 8.4. Change in cumulative water table levels simulated by ForHyM for the two study areas given a scenario of harvesting in August 2000. The slopes of the cumulative water levels were adjusted so that the pre-harvest slopes equalled zero for all sites.

differences between treated catchment responses to harvesting were due to calibration differences. As calibrated, the modeled water level fluctuations on the WT and ES catchments were spikier than those of the SO catchment. Had the calibrated water levels for the WT and ES catchments been less flashy, these catchments would likely have had a similar predicted response to harvesting as the SO catchment.

CONCLUSIONS

The hydrology model, ForHyM was able to reproduce the measured well water fluctuations at both study areas with a reasonable degree of accuracy. This was done with only air temperature and precipitation (rainfall/snowfall) as model input, and adjusting several calibration parameters to the local basin and soil conditions. The ability of the model to closely reproduce the water level fluctuations for all catchments reflects its general portability. Once calibrated, the model should then be able to predict water levels under a similar stand, substrate, and terrain conditions in different parts of the province, with reasonable accuracy.

The modeled results confirm that observed post-harvest decreases in well water levels across all the catchments were actually the result of pre- and post-harvest differences in weather pattern. The model was also able to simulate an increase in water levels in response to harvesting, relative to the control catchment. However, although the general model response to harvesting was similar to the measured response, the model, as designed, was not able to reproduce the measured differences in harvest response between the treated catchments. To make the model sensitive to particular harvest treatments, it is recommended:

- to specifically design the post-harvest interception and evaporation equations to account for differences in interception and evaporation based on amount of slash cover, and on the extent of ground disturbance,
- to calculate the impact on slash and soil disturbance on post-harvest albedo, and
- to observe the pattern of post-harvest vegetative recovery more closely.

CHAPTER 9

USE OF A HYDROLOGY MODEL (FORHYM) FOR SHALLOW GROUNDWATER TEMPERATURE INVESTIGATIONS

INTRODUCTION

This Chapter explains whether the ForHyM soil temperature calculations can be used to interpret the observed pre- and post-harvest well temperatures at the base of each treatment and control basin at GL and IL. Well water temperatures at both sites displayed similar seasonal trends, but there were also differences, especially in response to daily weather patterns (Chapter 6).

METHODS

ForHyM was run as described in Chapter 8 for the pre- and post-harvest period from mid-1998 to 2003, with harvest occurring late in the summer of 2000. For the purpose of this Chapter, the following ForHyM outputs were generated:

- daily soil temperatures at various depths
- daily soil moisture
- daily snowpack accumulations

These outputs were used in the following specific ways:

- For estimating the depth at which the shallow groundwater flows; this was done by overlaying the temperatures from each well on the predicted soil

temperatures. From this, the most likely depth of flow was identified the closest match by amplitude, and the timing of maximum temperatures.

- For estimating expected soil temperature increases resulting from harvest: to improve the visual display of the harvesting effect, the calculated daily temperature output over time was smoothed using SPSS (SPSS Inc. 2002) Central Moving Average function. For this analysis, the control catchments from each study area were chosen as representative examples of their respective study areas.
- Interpreting well temperature patterns in relation to calculated snow depth, soil moisture, and soil temperatures at various depths, using select catchments from each study area as examples. This was done by overlaying the soil temperatures on plots with measured well temperature, calculated snowpack depths, and soil moisture content in the upper (“A” and “B”) mineral soil layers.

RESULTS AND DISCUSSION

Estimated Depth of Shallow Groundwater Flow

For many catchments, the depth at which calculated soil temperatures matched the observed well temperatures depended on the criteria used for matching (Table. 9.1). For example, for many catchments, a deeper depth was required for temperatures to have similar amplitudes, and a shallower depth was required to match the calculated and observed temperature peaks. In general, the differences between amplitude and peak temperature matching were larger at IL, where the geospatial flow pattern is likely more

Table 9.1. Soil depths at which modelled soil temperature patterns resemble well water temperature patterns for each catchment at Gounamitz Lake and Island Lake.

Catchment	Well Depth (m)	Modeled Soil Depth (m) Required For:	
		Similar Soil And Well Temperature Amplitudes	Similar Soil And Well Temperature Peak Timing
GL-C1	6.1	3.5	3.5
GL-C2	5.8	5.5	5.0
GL-SO	6.1	4.0	3.5
GL-WT	5.2	5.5	4.2
GL-ES	6.1	5.5	4.2
IL-C	7.6	6.5	7.3
IL-SO1	4.4	5.0	5.0
IL-SO2	5.6	11.3	6.5
IL-WT	6.1	4.5	6.8
IL-ES	6.2	8.5	6.7

complex, and in part, restricted by fairly impermeable soils. The greatest differences in soil depth between the two criteria occurred for the lower SO well (IL-SO2), where the amplitude of the well temperatures suggested that the flow was almost twice the depth required for matching the timing of peak temperatures. Here, it is possible that well temperatures during the winter, and wet portions of the year, were mostly influenced by flushes of water from deep groundwater sources, but during summer low-flow periods, well temperatures were more influenced by the surrounding soil temperatures.

In general, the estimated depths of groundwater flow, based on the comparison of soil temperatures and well temperatures, were similar to the well depths (Table 9.1). Since the wells were drilled into the fractured bedrock to the top of the solid bedrock, these findings further support the shallow groundwater flow model proposed in Chapter 7 (Fig. 7.1), i.e., much of the shallow groundwater flow would be confined to the fractured bedrock layer. The lower SO well (IL-SO2), and the ES well (IL-ES) at IL were

exceptions. These two wells appeared to have been influenced by deep groundwater sources originating outside of the local catchment boundaries (Table 9.1).

Modeled Soil Temperature Responses to Harvesting

Calculated temperatures at the soil surface of the control catchments at GL and IL were similar to each other, both with, and without harvest simulation (Figs. 9.1 and 9.2). The calculated increases in soil surface temperatures in the second fall following harvesting would have been approximately 1.6 °C for the GL control (GL-C1), and approximately 1.5 °C for the IL control (IL-C).

At the estimated depth of shallow groundwater flow, calculated soil temperatures following simulated harvest differed between GL and IL. At GL, temperatures in the second fall following simulated harvest increased approximately 0.6 °C (Fig. 9.1). At IL, temperatures in the second fall following simulated harvest increased approximately 0.3 °C (Fig. 9.2). Therefore, the observed increases in well temperatures following harvest were generally greater than calculated increases in the soil temperatures at the estimated flow depth. For example, shallow groundwater at the GL SO catchment has the same estimated flow depth (350 cm) as the first control at GL (GL-C1). Therefore, soil temperature increases at this depth following harvesting would be similar (0.6 °C), but from Chapter 6, it was shown that well temperatures actually increased 2.5 °C.

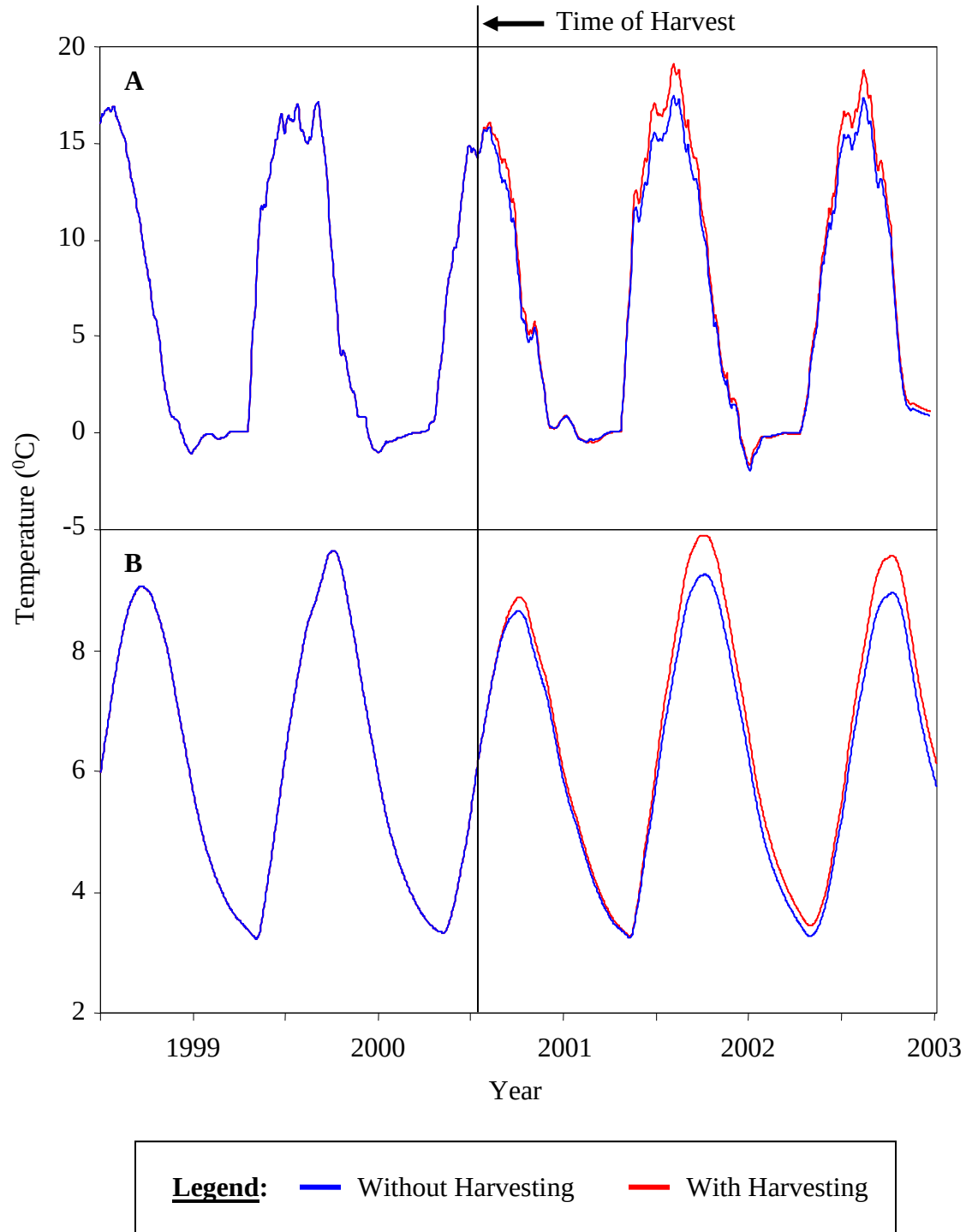


Fig. 9.1. Soil temperatures at A) the soil surface (smoothed with a Centered Moving Average of 25), and B) at the depth of estimated shallow groundwater flow (350 cm), as simulated by ForHyM for the first control catchment (GL-C1) at Gounamitz Lake, with and without harvesting.

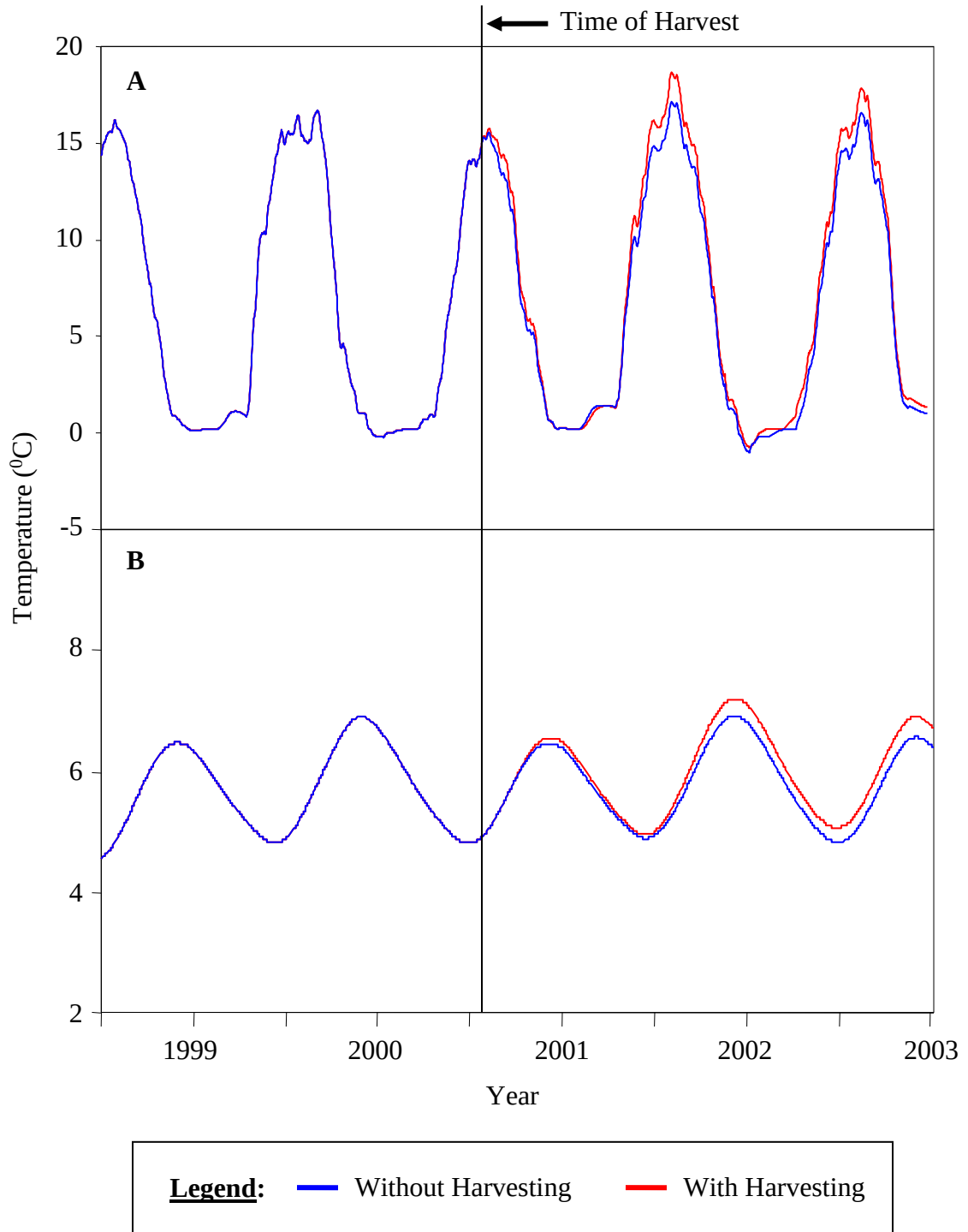


Fig. 9.2. Soil temperatures at A) the soil surface (smoothed with a Centered Moving Average of 25), and B) at the depth of estimated shallow groundwater flow (730 cm), as simulated by ForHyM for the control catchment (IL-C) at Island Lake, with and without harvesting.

Relating Observed Well Temperatures to Modeled Soil Temperature, Soil Moisture, and Snowpack

In general, well temperatures at GL were strongly influenced by soil moisture and snowpack levels, while well temperatures at IL were not (Figs. 9.3 and 9.4). At GL, large increases in soil moisture, indicating specific rain or snowmelt events, caused abrupt increases in the well temperatures during the warmest periods of the year, and abrupt decreases in the coldest periods of the year. During periods where large snowpacks were calculated to exist, well temperatures were most stable (Fig. 9.3). Even during winter thaws, water would likely be trapped within the snowpack, and would therefore not enter the soil (Balland 2002).

The changes in well temperatures that occur during periods of high soil moisture could be caused, in part, by elevated water tables: as water tables rise, water – as it flows towards, and through, the wells – will experience warmer or cooler substrates depending on the time of year and height of water table. For example, at GL-C1, well temperatures during periods of high soil moisture closely resembled the general pattern of soil temperatures at a substrate depth of 3.5 m, while the well temperatures during periods of low soil moisture closely resemble soil temperature patterns at a depth of 5 m (Fig. 9.3). Consequently, a decrease in soil substrate depth of 1.5 m would correspond to a calculated change in maximum soil temperature of 1 to 2 °C (Fig. 9.3). Similar increases in well temperatures were observed on many of the catchments in response to harvesting, when post-harvest water levels were raised by similar amounts, especially during summer and fall (Chapters 5 and 6). Therefore, it is likely that elevated water tables following

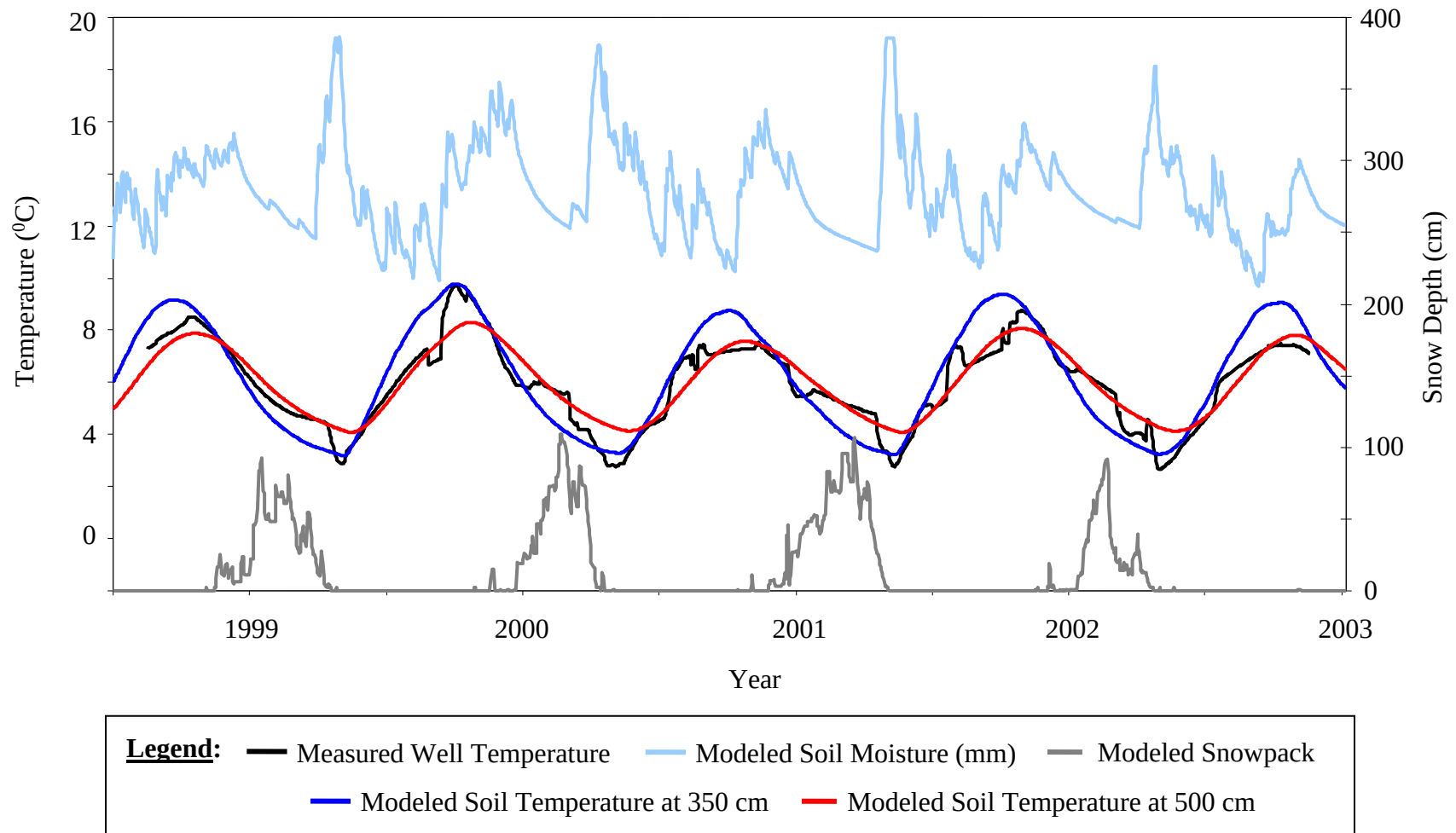


Fig. 9.3. Relationships between measured well temperatures and soil moisture in upper soil layers (“A” and “B”), snowpack, and soil temperature at two different depths, as calculated using ForHyM for the first control catchment (GL-C1) at Gounamitz Lake.

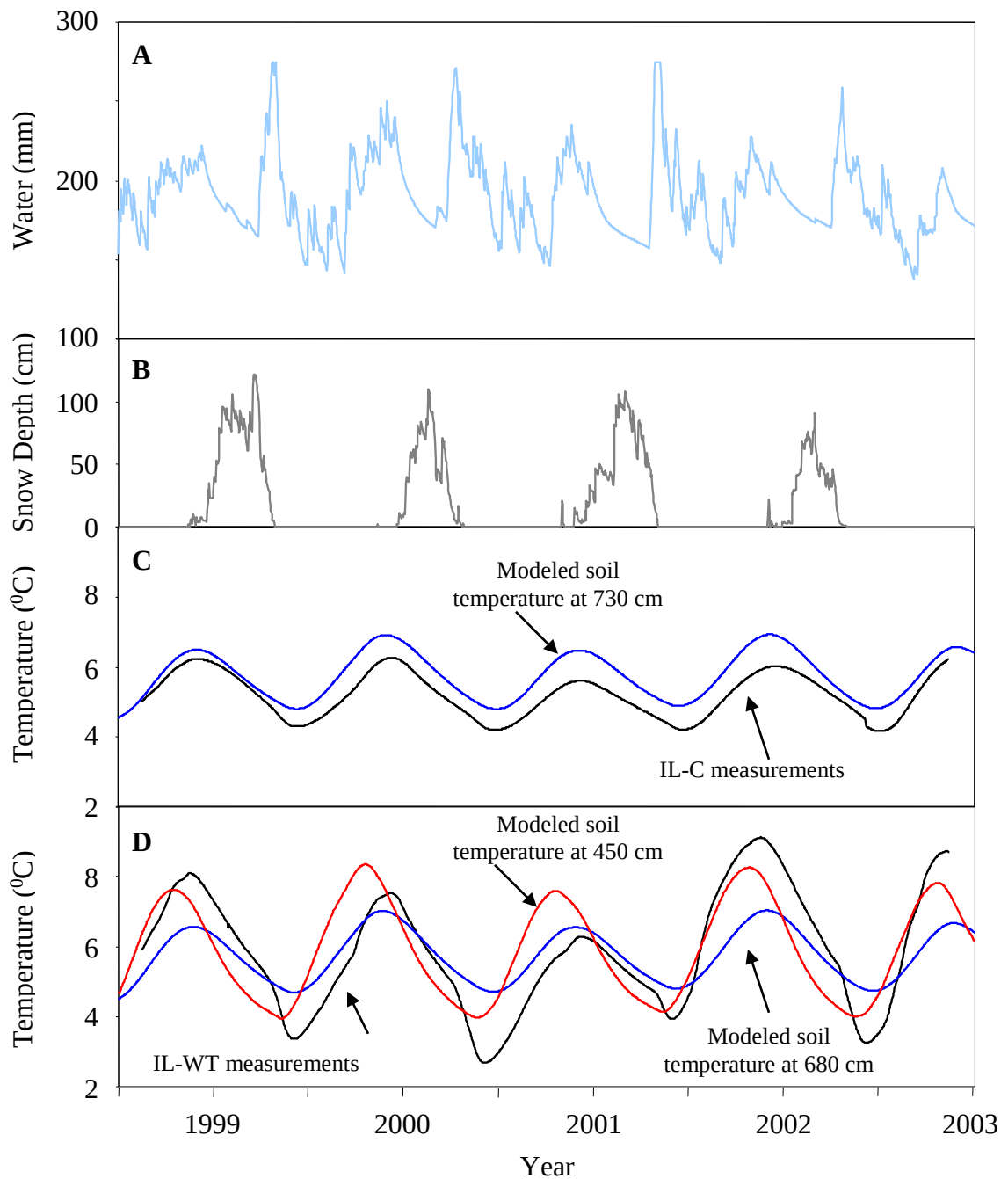


Fig. 9.4. ForHyM calculations for: soil moisture in the upper soil layers (**A**), snow depths (**B**), soil temperatures at 730 cm (**C**), and 450 and 680 cm (**D**), in comparison with IL-C (**C**) and IL-WT (**D**) well measurements at Island Lake.

harvesting would also— at least in part - be responsible for increasing or decreasing post-harvest well temperatures.

At IL, the observed patterns among the well temperatures were more variable between catchments, and also more variable over time for some catchments such as IL-WT (Fig. 9.4). These patterns are a reflection of the complexity of the terrain and the underlying substrate conditions at IL. Detailed comparisons of observed well temperatures and modeled soil temperature, soil moisture, and snowpacks for all GL and IL catchments are included in Appendix VI.

CONCLUSIONS

Shallow groundwater temperatures are influenced by rain and snowmelt events. This relationship is much stronger at GL, where the soil substrate is relatively permeable, and flow is more predictable. The influence of rain and snowmelt on groundwater temperatures appears to be, at least in part, related to their impact on water table levels; as water rises in the soil substrate, it comes in contact with warmer, or colder, substrate temperatures, depending on the season. As such, observed increases in well temperatures following harvesting are probably related to a combination of increased soil temperatures at the surface and throughout, and elevated water tables.

Estimated depths of shallow groundwater flow, based on ForHyM simulations, generally support the suggestion introduced in Chapter 7, that shallow groundwater flow would be restricted to the fractured bedrock layer above the solid bedrock.

Flow depths were calculated to be more variable at IL. Here, flows measured in the IL-SO2 and IL-ES wells were likely influenced by deep groundwater flows that would likely originate from other catchments.

CHAPTER 10

CONCLUDING REMARKS

CONCLUSIONS

To date, most research on the impacts of forest harvesting operations on watershed hydrology focused on high-order streams. This Thesis focused on impacts of harvesting on shallow groundwater temperature and levels at the base of small forest catchments (< 30 ha). The main conclusions from this Thesis are as follows:

1. In general, fluctuations in shallow groundwater levels, and seasonal changes in well temperatures, are closely synchronized in the adjacent or closely spaced catchments at GL and IL. However, the timing and magnitude of seasonal temperature changes among the wells at IL differ somewhat as a result of differences in flow depths and pathways.
2. Shallow groundwater levels increased in all treated catchments following harvesting. These increases were as much as two meters (GL-WT), and mainly occurred in the summer and fall.
3. Harvesting caused well temperatures to increase for all catchments (relative to the control) regardless of the clearcutting method used. The temperatures increased by as much as 2.5 °C in the second fall following harvesting, and the timing of temperature increases were advanced by as much as 3 months.

4. Well temperatures and water levels increased after harvesting. These increases varied among the treated catchments, but there were no relationships to the specific clearcutting treatments examined. Therefore, it was concluded that if the method of clearcutting were to influence the magnitude of well temperature and water level increases, this effect would be small if not insignificant overall.
5. ForHyM was able to reproduce observed shallow groundwater fluctuations of all 10 catchments with a reasonable degree of accuracy, following adjustment of six “water flow” calibration parameters, and an adjustment of the initial water level.
6. Soil and soil substrate permeability affected the observed well temperature patterns. Well temperatures at GL, where soils are fairly permeable, were much more sensitive to rainfall and snowmelt events than well temperatures at IL, where soils and substrate were much less permeable.
7. ForHym is an effective hydrological investigation tool: the model simulations suggest that unexplained decreases in water levels across all catchments following harvesting were due to changes in weather, and not related to harvest method. The model was also able to help interpret the well temperatures, demonstrating the influence of snowpack, soil moisture, and groundwater levels on these temperatures.
8. In general, flow depths estimated from soil temperature calculations by ForHyM matched the well depths. Since the wells were drilled to, and into, the top of the fractured bedrock layer (top of the solid bedrock), these results support the shallow groundwater flow model proposed in Chapter 7.

9. Post-harvest vegetative recovery surveys of the study areas three years following harvesting revealed that there were significant differences between catchments, and between study areas, in the early vegetative response to harvesting. GL had much more vegetative cover than IL, largely as a result of profuse raspberry regeneration, and GL also had a larger number of tree seedlings. Among the catchments, the ones harvested using the WT method had the fastest vegetative recovery. These findings suggest that the hydrology at GL may recover to the pre-harvest state faster than at IL, and the WT harvested catchments may recover faster than catchments harvested with the SO method.

ORIGINAL CONTRIBUTIONS

1. The effect of harvesting on water temperatures was examined as it relates to increases in soil temperatures following canopy removal. No previous studies on the effect of harvesting on groundwater temperatures could be found. For this study, shallow groundwater temperatures were monitored using the strategic placement of wells: monitoring changes in water temperatures near the base of the flow accumulation of upland catchments allowed for an accurate evaluation of the effects of harvest in most catchments, where the water would not be mixed by seepage from other catchments at higher elevations.
2. No previous studies examining the influences of different clearcut harvesting methods on groundwater temperatures or levels could be found. In this Thesis, a multiple paired catchment approach is used to determine what effect, if any, type of clearcutting has on shallow groundwater temperatures and levels. The harvesting treatments used were: 1) whole-tree, 2) stem-only, and 3) stem-only

with extra slash added. Despite this investigation, differences in catchment responses to harvesting could not be attributed to the harvest method and various catchment attributes (such as catchment area, vegetative recovery, potential incoming solar radiation, and soil/water contact time), thereby suggesting that the generally small differences in catchment responses remain unexplained.

3. This Thesis provided the first scientific, well-documented test to determine the ability of ForHyM to model shallow groundwater levels. The model was successfully calibrated to closely reproduce shallow groundwater level fluctuations observed on 10 catchments in northern New Brunswick.
4. Interactions between groundwater temperatures, soil substrate, and water levels were previously unexplained, or unreported. The results presented here suggest that substrate permeability, and depth of shallow groundwater flow, dictate the general pattern of well temperature response: substrate permeability determines the sharpness of the response, and the change in quantities of incoming water dictates the magnitude of change.
5. While the process of completing weather records by replacing missing data with predictions based on regressions with other nearby weather stations has been done before (Dunne and Leopold 1978), the approach used here is somewhat unique. The scattered nature of precipitation events made it difficult to predict the amount and timing of precipitation at the study areas based on regressions with surrounding weather stations. To circumvent this problem, missing precipitation values were predicted based on regressions of accumulated precipitation.

6. This Thesis is the first known case where a series of systematic, and fully justified shifting, stretching, and smoothing of the data was used to increase the fit between shallow groundwater levels and well temperatures among neighboring catchments.

SUGGESTIONS FOR FURTHER WORK

Monitoring Shallow Groundwater Temperatures and Levels

In terms of monitoring shallow groundwater temperatures and levels, the following is suggested as future work:

1. Continue monitoring of the wells at these study areas: water tables are predicted, and expected, to be elevated for many more years as a result of the harvest, even though the impacts of harvesting on shallow groundwater temperatures start to decrease on most catchments in the third fall following harvest.
2. Track vegetative recovery: If monitoring of these experimental wells continues, monitoring the progression of vegetative recovery on each catchment could assist in the interpretation of future well data, as the forest vegetation returns to pre-harvest conditions.
3. Study the ecological significance of the small increases in shallow groundwater temperatures that were measured here: shallow groundwater temperatures increased up to 2.5 °C in response to harvesting, and seasonal temperatures were advanced as much as 3 months. Without further studies, it is hard to know what impact, if any, these changes will have on aquatic stream life below these wells.

4. Further study the impacts of harvesting on shallow groundwater temperatures and levels: since the sample size for this project was small, additional studies would add to the sample pool, and increase confidence in the overall conclusions. Also, future studies may help to examine more pre- and post-harvest factors (cover types, post-harvest treatments, etc.) to determine the influence of each on shallow groundwater temperatures and levels.

Hydrology Modeling with ForHyM

The following future work is suggested with ForHyM:

1. Introduce modifications that will allow for direct modeling of shallow groundwater temperatures. Such modifications should account for differences in substrate permeability, and changes in temperature that occur as a result of the fluctuating water table levels.
2. Further test the model: the model should be tested on other sites to further test the portability of the model, including the extent to which calibration parameters must be adjusted for the model outputs to conform with hydrological measurements for snowpack, stream discharge, and well temperatures and levels.
3. Interpret the differences in calibration settings: there were small differences in the calibration settings between the study areas, and among the catchments within each study area. A closer examination may reveal the cause of these differences and help determine those factors that might limit the model's portability.
4. Improve the energy balance: imperfections in the winter energy balance limit the overall ability of the model to accurately reproduce the observed shallow groundwater level fluctuations during winter. Several winter thaws at each study

area showed increases in the observed shallow groundwater levels, but these were not simulated by the model. This suggests that too much water may be retained in the calculation for water retention, by way of ice formation in the snowpack or in the underlying soils.

5. Investigate the inability of the model to reproduce the different water level responses to harvesting among the catchments. As recommended in Chapter 8, one important modification would be to program the model to account for the effects of different slash loadings following harvest, in terms of, e.g.: increased water retention, enhanced or reduced rate of evapotranspiration, reduced albedo, and changes in surface temperature due to wind and surface roughness.

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APPENDIX I

CONSTRUCTION OF COMPLETE WEATHER DATA SETS FOR GOUNAMITZ LAKE AND ISLAND LAKE

Complete weather data sets for the two study areas were constructed from four Environment Canada (EC), and four New Brunswick Department of Natural Resources and Energy (NBDNRE) weather stations, located near the study areas (Fig. 3.13.). For each study area, the two closest EC and NBDNRE stations were used. The EC stations in Edmundston (ED) and St. Leonard (SL), New Brunswick, and NBDNRE stations at Boston Brook (BB) and Petit Ouest (PO), New Brunswick were used to calculate weather conditions at GL. The EC stations at Charlo (CH) and Upsalquitch Lake (UL), New Brunswick and NBDNRE stations at McRae Lake (ML) and Mulligan Gulch (MG), New Brunswick were used to calculate weather conditions at IL (Fig. 3.13. and Table I A). Of these eight stations, only two – SL and CH - had complete data sets. The other stations had data missing for the periods listed in Table I B.

The weather conditions experienced at the study areas are most likely best represented by the weather records at the NBDNRE stations, because in the case of both study areas, these stations are closer in proximity and altitude than the respective EC stations (Fig. 3.13. and Table I A). However, the NBDNRE stations have the more incomplete data sets (Table I B). Therefore, the missing data sets within the NBDNRE files were filled-in with predictions from the other weather stations. Once the NBDNRE

Table I A. coordinates and elevations for study sites and weather stations.

Site/Station	Latitude	Longitude	Altitude (m)
Gounamitz Lake	47° 34' 12"	67° 38' 29"	325
Edmundston	47° 20'	68° 11'	152
St. Leonard	47° 9'	67° 50'	243
Boston Brook	47° 27' 6"	67° 37' 42"	329
Petit Ouest	47° 38' 18"	67° 26' 6"	258
Island Lake	47° 40' 53"	66° 28' 7"	325
Charlo	47° 59'	66° 20'	40
Upsalquitch Lake	47° 27'	66° 25'	625
Mulligan Gulch	47° 35' 9"	66° 38' 18"	432
McRae Lake	47° 41' 6"	66° 14' 36"	404

weather files were constructed for each of the NBDNRE stations, the two closest stations to each study area were averaged to produce the required model inputs for FORHYM.

CONSTRUCTING AIR TEMPERATURE INPUTS

Multiple regression was used to determine missing values within both the EC and NBDNRE weather files. This was done with the statistical software program called StatView (SAS Institute Inc. 1998). Only other weather stations with p-values < 0.05 were used as independent variables. These prediction equations all had r^2 values > 0.920 (Table I C), and produced daily average temperature values for days in which they were missing. Maximum and minimum temperatures from nearby stations were used to predict the maximum and minimum temperatures in question. The differences between the maximum and minimum temperatures were then divided by two, and this value was added and subtracted from the predicted average to give a predicted maximum and minimum temperature.

Table I B. Dates for which a) temperature and b) precipitation data was missing from official weather station data between January 1, 1997 and October 31, 2002.

a)	Edmundston	Upsalquitch Lake	McRae Lake	Mulligan Gulch	Boston Brook	Petit Ouest
	06/01/97 - 06/30/97	03/01/01 - 03/04/01	01/01/97 - 05/20/98	01/01/97 - 05/20/98	01/01/97 - 05/27/98	01/01/97 - 05/27/98
	08/01/97 - 08/11/97	03/08/01 - 03/09/01	12/14/99 - 03/18/00	05/05/99 - 05/31/99	10/06/98 - 05/26/99	10/06/98 - 05/26/99
	08/01/98 - 08/31/98	06/30/02	12/03/00 - 02/14/01	10/28/99 - 11/29/99	09/29/99 - 05/24/00	09/30/99 - 05/24/00
	03/01/00 - 03/30/00		04/27/01	12/15/99 - 03/24/00	09/21/00 - 05/08/01	12/03/00 - 02/19/01
	01/01/01 - 02/28/01		09/26/01 - 05/15/02	12/03/00 - 04/05/01	09/27/01 - 05/15/02	03/02/01 - 04/25/01
	10/01/01 - 10/31/01			06/26/01	10/20/02 - 10/31/02	09/26/01 - 05/28/02
	08/31/02			08/24/01 - 05/15/02		
b)	Edmundston	Upsalquitch Lake	McRae Lake	Mulligan Gulch	Boston Brook	Petit Ouest
	06/01/97 - 06/30/97	02/12/98	01/01/97 - 05/21/98	01/01/97 - 05/22/98	01/01/97 - 05/26/98	01/01/97 - 05/26/98
	08/01/98 - 08/31/98	02/24/98 - 02/27/98	10/06/98 - 05/01/99	10/06/98 - 05/30/99	10/06/98 - 05/24/99	10/06/98 - 05/24/99
	10/01/98	02/01/00 - 02/02/00	10/01/99 - 05/26/00	10/01/99 - 05/04/00	09/30/99 - 05/24/00	09/29/99 - 05/24/00
	10/30/98	02/10/00 - 02/11/00	10/01/00 - 05/28/01	10/01/00 - 05/28/01	10/01/00 - 05/28/01	09/24/00 - 05/09/01
	03/01/00 - 03/30/00	02/14/00	09/24/01 - 05/02/02	08/23/01 - 05/02/02	09/24/01 - 05/02/02	09/24/01 - 05/02/02
	01/01/01 - 02/28/01	02/16/00	05/07/02 - 05/08/02	05/07/02 - 05/08/02	05/07/02 - 05/08/02	05/07/02 - 05/09/02
	10/01/01 - 10/31/01	01/14/02	05/14/02	05/14/02	05/14/02 - 05/27/02	05/14/02
	8/31/02	01/19/02	10/23/02 - 10/31/02	10/23/02 - 10/31/02	10/29/02 - 10/31/02	10/03/02 - 10/31/02
		01/23/02				
		01/27/02				
		02/03/02				
		03/12/02				

Table I C. Values calculated by StatView (SAS Institute Inc. 1998) for regression equation variables used to predict average daily temperatures for weather stations that were missing measurements. Also included are the respective r^2 values.

Dependent Variable	Order Used	Independent Variable																		r2
		Intercept		CH		ED		SL		UL		BB		MG		ML		PO		
		Value	SE (+-)b	Cc	SE (+-)b	Cc	SE (+-)b	Cc	SE (+-)b	Cc	SE (+-)b	Cc	SE (+-)b	Cc	SE (+-)b	Cc	SE (+-)b	Cc	SE (+-)b	
ED	1	0.46	0.058	0.275	0.021			0.617	0.024	0.113	0.022									0.972
UL	1	-1.589	0.048	0.284	0.021	0.116	0.023	0.563	0.025											0.969
BB	1	0.262	0.156			0.196	0.023	0.216	0.026				0.568	0.02						0.954
BB	2	0.627	0.216	0.107	0.029	0.257	0.03	0.246	0.034	0.389	0.029									0.923
MG	1	0.295	0.04							0.193	0.015					0.817	0.015			0.993
MG	2	0.901	0.08	0.179	0.025	0.126	0.023			0.719	0.024									0.976
ML	1	0.857	0.072	0.323	0.021					0.699	0.021									0.973
PO	1	0.097	0.108			0.191	0.024	0.222	0.028				0.572	0.021						0.97
PO	2	0.533	0.154	0.154	0.029	0.227	0.03	0.263	0.035	0.355	0.029									0.953

^a Where more than one equation exists for a dependent variable, the equation labeled #1 was used first to fill in as many missing values as possible, then the remainder of the missing values were filled with equation #2.

^b SE = Standard Error

^c C = Coefficient

Missing data within the EC records were filled first, because the data files for these stations were most complete. The EC records were then used to predict the missing data in within the NBDNRE files. The NBDNRE stations often had closer relationships among themselves for daily average temperatures than they had with the EC stations (Table I C). Therefore, any missing data points in the NBDNRE files that could be filled with regressions using other NBDNRE stations as predictors, where filled first. The remaining missing data points were predicted from the EC stations.

Finally, the completed temperature data sets for the two NBDNRE weather stations nearest each study area were averaged together to produce one data set for each area. All regression equations and relevant information used for filling missing air temperature data at selected weather stations are presented in Table I C.

CONSTRUCTING PRECIPITATION INPUTS FOR HYDROLOGICAL MODELING WITH FORHYM

The missing precipitation data was filled in the same order as was done for missing air temperatures. However, obtaining complete precipitation input files was more difficult. Missing precipitation data could not be estimated from simple regression equations. This is because precipitation amounts and timing are quite variable between locations, especially when far apart from each other. Sometimes events are highly localized, occurring at one location but not at another. To address this problem, cumulative precipitation records were regressed. Daily total precipitation records from the CH and SL stations were cumulated over the duration of the study, and the temperature data from the UL and ED stations were cumulated only to a point where data was missing. The cumulated data were regressed against each other, and the resulting

regression equation was used to predict the values that were needed to fill the data gap (Table I D). The resulting data set was then re-accumulated up to the next set of missing data, at which point the same process was repeated. This procedure was continued until all missing precipitation values were filled.

A similar procedure was used for the NBDNRE weather stations, which had large data gaps, because precipitation values were missing for each winter (Table I B). So, instead of filling gaps with regressions based on cumulative data up to the point of missing data, each of the summer data sets were cumulated individually for all eight weather stations for the period for which they all contained data. Regression equations were then established for each summer based on the accumulated values. Then, the summer-based regression equations were used to predict the missing cumulative values half way into the winter seasons to each side of the summer. For example, the regression equations based on the Summer 2000 data would be used to predict data into the latter portion of the 1999/2000 winter and into the early portion of the 2000/2001 winter. As was the case for missing air temperature data, accumulations from the other NBDNRE stations were used to fill in missing data points where possible, with the remainder of the missing points filled using the completed EC data sets as predictors (Table I E).

Following completion of cumulative data sets, the cumulative values were converted to daily precipitation. This was done for each day by simply obtaining the difference between that day and the previous day. Because the regression equations were not perfect, a few negative values for precipitation occurred in the seams of the data set where the predicted accumulated data sets came together in the middle of winter, or

Table I D. Values calculated by StatView (SAS Institute Inc. 1998) for regression equation variables used to predict cumulative daily total precipitation for Environment Canada weather stations that were missing measurements. Also included are the respective r^2 values.

Dependent		Independent Variable										r ²
		Intercept		CH		ED		SL		UL		
				C ^c	SE (+-) ^b	C ^c	SE (+-) ^b	C ^c	SE (+-) ^b	C ^c	SE (+-) ^b	
Variable	Dates ^a	Value	SE (+-) ^b	C ^c	SE (+-) ^b	C ^c	SE (+-) ^b	C ^c	SE (+-) ^b	C ^c	SE (+-) ^b	
ED	01/01/97 - 07/01/97	20.316	1.331	0.992	0.006							0.995
ED	07/01/97 - 08/01/98	-25.552	2.786	0.226	0.026			0.291	0.052	0.451	0.039	0.997
ED	08/01/98 - 03/01/00	-57.481	3.684	-0.272	0.013			1.18	0.014			0.998
ED	03/01/00 - 01/01/01	22.309	5.309	-0.155	0.02			1.021	0.02			0.997
ED	01/01/01 - 10/01/01	33.219	4.591					1.27	0.023	-0.359	0.019	0.997
ED	10/01/01 - 08/31/02	68.425	4.965					1.265	0.025	-0.372	0.021	0.997
UL	01/01/97 - 02/12/98	-35.266	1.849					1.087	0.003			0.998
UL	02/12/98 - 02/01/00	14.876	4.653	0.685	0.017			0.478	0.018			0.998
UL	02/01/00 - 01/14/02	-3.462	4.891	0.606	0.018	-0.307	0.018	0.834	0.026			0.999

^a regression equation used to fill missing data between these dates.

^b SE = Standard Error

^c C = Coefficient

Table I E. Values calculated by StatView (SAS Institute Inc. 1998) for regression equation variables used to predict cumulative daily total precipitation for New Brunswick Department of Natural Resources weather stations that were missing measurements. Also included are the respective r^2 values.

Dependent Variable	Order	Summer ^b	Independent Variable																	r ²
			Intercept		CH		ED		SL		UL		BB		ML		PO			
			Value	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c		
BB	1	1998	-8.807	1.642					0.536	0.041	0.295	0.034								0.995
MG	1	1998	-30.85	2.546	0.714	0.072					0.577	0.055								0.996
ML	1	1998	-6.95	3.177	1.866	0.121			-0.8	0.113										0.991
PO	1	1998	-28.362	2.952							0.767	0.008								0.986
BB	1	1999	-43.508	5.553	0.675	0.03			0.288	0.032										0.993
MG	1	1999	138.267	8.526	0.269	0.043					0.65	0.043								0.994
ML	1	1999	75.882	8.554			0.418	0.093			0.4	0.058								0.989
PO	1	1999	-100.441	6.927			1.248	0.011												0.99
BB	1	2000	-217.379	15.33					0.184	0.036	0.824	0.039								0.991
MG	1	2000	-197.644	33.106	0.981	0.095					0.311	0.058								0.996
ML	1	2000	41.042	18.59	0.417	0.053					0.347	0.033								0.997
PO	1	2000	22.702	13.323			-0.654	0.119	0.252	0.057	0.955	0.049								0.988
BB	1	2001	117.658	18.096			0.292	0.038			-0.087	0.017			0.335	0.03	0.54	0.029		0.999
BB	2	2001	-340.222	24.801					0.431	0.042	0.679	0.05								0.996
MG	1	2001	658.096	110.934			0.624	0.098			-0.918	0.158			0.63	0.079	0.816	0.115		0.999
MG	2	2001	-297.603	46.202					0.816	0.078	0.454	0.093								0.989
ML	1	2001	-396.72	32.978	0.215	0.035							1.437	0.139			-0.58	0.132		0.994
ML	2	2001	-843.64	42.417					0.466	0.072	0.83	0.085								0.99
PO	1	2001	-558.6	45.777							0.532	0.071	0.936	0.074	-0.33	0.053				0.997
PO	2	2001	-717.765	20.229							1.187	0.012								0.992

Table I E. (continued)

Dependent Variable	Order Used ^a	Summer ^b	Independent Variable																	r ²
			Intercept		CH		ED		SL		UL		BB		ML		PO			
			Value	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c	C ^d	SE (+-) ^c		
BB	1	2002	156.311	12.992	-0.39	0.039	0.523	0.074	0.359	0.068	0.461	0.023								0.998
MG	1	2002	316.791	14.101	0.207	0.026					0.664	0.018								0.998
ML	1	2002	-346.112	15.623					0.309	0.038	0.691	0.027								0.997
PO	1	2002	274.404	19.509			0.391	0.049							0.471	0.033				0.996
PO	2	2002	121.155	14.906					0.358	0.036	0.41	0.026								0.995

^a Where more than one equation exists for a dependent variable, the equation labeled #1 was used first to fill in as many missing values as possible, then the remainder of the missing values were filled with equation #2.

^b Regression equations are based on relationships between cumulative data during the summer of this year. Each summer equation was used to predict missing values half way into the previous and following winter (see Appendix III for further explanation).

^c SE = Standard Error.

^d C = Coefficient.

where predicted accumulated values met actual values. In these cases, the negative values were replaced with zeros.

Next was the problem of determining the proportion of precipitation that arrived in the form of snow, and the amount that arrived in the form of rain. The snow and rain amounts were calculated from the total precipitation amounts using a snow/rain fraction calculated as follows:

$$\begin{aligned} &\text{if } \text{mintemp} > 0 \text{ then rain else if } \text{mintemp} \leq 0 \text{ and } \text{maxtemp} > 0 \\ &\quad \text{then } \text{maxtemp} / (\text{maxtemp} - \text{mintemp}) \\ &\quad \text{else if } \text{maxtemp} \leq 0 \text{ then snow} \end{aligned}$$

where:

Mintemp = minimum daily air temperature

Maxtemp = maximum daily air temperature

When the daily maximum air temperatures do not climb above 0 °C, all precipitation is assumed to be snow. Likewise, when daily minimum temperatures do not drop below 0 °C, all precipitation is assumed to be rain. In cases where daily temperatures cross the freezing mark, the estimated percentage of the day that the temperature is above 0 °C is the estimated percentage of the total daily precipitation that is assumed to fall as rain. The remainder of the daily precipitation is assumed to fall as snow.

All regression equations and relevant information used for filling missing precipitation data at selected weather stations are presented in Table I D and Table I E.

FINAL ADJUSTMENTS TO THE WEATHER DATA

When weather records for a location are interpolated from weather stations of surrounding areas, a certain amount of inaccuracy is to be expected due to the scattered nature of weather patterns.

After interpolated weather records were added as inputs to the hydrology model, ForHyM, and the model was calibrated (Chapter 8), there were a few instances where modeled predictions did not match the actual data. During these times, fluctuations in the well water levels suggested the occurrence of precipitation or snowmelt events that the model did not simulate, or vice-versa. The weather records for these periods were closely examined. If the weather records of any one of the four observed weather stations surrounding each study area recorded weather conditions that were better reflected by the well water fluctuations, the weather record from that weather station replaced the interpolated record. In several cases, these adjustments to the model's weather inputs resulted in more accurate model outputs. All changes that were made to the interpolated weather records are presented in Tables I F and I G.

Table I F. Adjustments made to the interpolated weather record at Gounamitz Lake based on the comparison of measured water levels and those simulated by ForHyM.

Date	Interpolated Air Temperature (°C)	Adjusted Air Temperature (°C)	Interpolated Rainfall (mm)	Adjusted Rainfall (mm)	Interpolated Snowfall (cm)	Adjusted Snowfall (cm)
10/28/98			5	3		
10/29/98			11.8	5.8		
10/30/98			22	10		
11/11/98			3.1	0	5	20
11/12/98			0.4	0	0.2	0
11/14/98					1	0
11/15/98			1.6	0	4.4	15
11/23/98	2.2	0				
11/24/98	3	0				
11/26/98			0.6	0	4	20
11/27/98			2.3	0	2.8	0
11/30/98			1	0	5.2	15
12/01/98	4.2	2	0.2	0		
12/02/98			0.2	0	0.9	0
05/26/99			4.9	13		
05/27/99			4.3	13		
05/28/99			1.6	4		
09/07/99			0.5	0		
09/08/99			27.8	20.5		
09/09/99			28.2	11		
09/10/99			13	2		
09/11/99			52.3	33.4		
09/21/99			2.3	4.6		
09/22/99			13.8	9		
09/23/99			11	6.2		
09/24/99			0.1	0		
12/17/00	1.1	4				
12/18/00			0.6	4		
05/13/00			8.9	3.6		
05/14/00			25	0.2		
05/15/00			18.8	27		
05/16/00			1.2	0		
11/06/01			14.9	0		
05/08/02			2	2.4		
05/09/02			0.6	7.8		

Table I G. Adjustments made to the interpolated weather record at Gounamitz Lake based on the comparison of measured water levels and those simulated by ForHyM.

Date	Interpolated Rainfall	Adjusted Rainfall	Interpolated Snowfall	Adjusted Snowfall
11/22/99	0.78	1	0.25	0
11/24/99	2.2	3.1	0.97	0
11/26/99	5.49	9.9	4.4	0
02/29/00	0.93	8	0.75	0
12/17/00	8.38	16	7.85	0
12/18/00	0.16	0.7	0.53	0
09/25/01	28.74	13		
09/26/01	15.64	7		
09/27/01	9.49	5		
09/28/01	3.21	0		
11/09/01	3.76	7	3.16	0
11/30/01	3.72	9	5.9	0
12/03/01	0.95	2	0.97	0

APPENDIX II

INTER-WELL TEMPERATURE REGRESSION EQUATIONS

Inter-well relationships for temperature during the pre-harvest years were established by way of multiple regression analysis. The basic structure of this analysis was introduced in Chapter 6. The resulting regression equations were used to predict: 1) missing data values, and 2) well temperatures for the post-harvest period had harvesting not occurred.

The first regression equation that was constructed was the predictor equation for the GL-C1 catchment. This equation used the other GL control catchment as the independent variable (Table II). This equation was first used to fill in the missing data points on the GL-C1 catchment. Doing so resulted in a complete data set for GL-C1, which was then used to predict the well temperatures of the other catchments during the post-harvest period.

At GL, there were two control catchments, so water temperatures at each of the treated catchments were predicted using each of the controls. For each treated catchment, the particular control catchment that was chosen for prediction purposes was the one that produced the best r^2 for the pre-harvest well-to-well calibrations (Table II). However, in cases where the r^2 values were similar, the GL-C2 well temperatures were used as the predictor variable, because this data set was completely comprised of actual

Table II. Values for regression parameters (A=y-intercept, B=coefficient for comparison well, C=coefficient for sine function, D= horizontal shift in data curve.) used to predict post-harvesting shallow groundwater temperatures in the absence of treatments, and respective r^2 values. Bold, italicized numbers indicate those used in the data analysis described in Chapter 4.

Dependent Temperature	Independent Temperature	A		B		C		D		r^2
		Value	SE (+/-) ^a	Value	SE (+/-) ^a	Value	SE (+/-) ^a	Value	SE (+/-) ^a	
<i>GL-C2</i>	<i>GL-C1</i>	<i>2.973</i>	<i>0.093</i>	<i>0.503</i>	<i>0.016</i>	<i>1.033</i>	<i>0.037</i>	<i>0.64</i>	<i>0.004</i>	<i>0.968</i>
<i>GL-SO</i>	<i>GL-C1</i>	<i>1.951</i>	<i>0.063</i>	<i>0.651</i>	<i>0.011</i>	<i>0.757</i>	<i>0.025</i>	<i>0.462</i>	<i>0.004</i>	<i>0.987</i>
GL-WT	GL-C1	3.743	0.066	0.348	0.011	1.072	0.029	0.604	0.002	0.978
GL-ES	GL-C1	4.36	0.081	0.237	0.014	1.178	0.037	0.581	0.002	0.962
<i>GL-C1</i>	<i>GL-C2</i>	<i>-0.838</i>	<i>0.211</i>	<i>1.134</i>	<i>0.035</i>	<i>0.637</i>	<i>0.022</i>	<i>0.328</i>	<i>0.02</i>	<i>0.949</i>
GL-SO	GL-C2	1.649	0.124	0.692	0.021	1.114	0.025	0.425	0.005	0.96
<i>GL-WT</i>	<i>GL-C2</i>	<i>2.436</i>	<i>0.076</i>	<i>0.561</i>	<i>0.013</i>	<i>0.659</i>	<i>0.026</i>	<i>0.534</i>	<i>0.003</i>	<i>0.976</i>
<i>GL-ES</i>	<i>GL-C2</i>	<i>2.8</i>	<i>0.076</i>	<i>0.497</i>	<i>0.013</i>	<i>0.7</i>	<i>0.025</i>	<i>0.517</i>	<i>0.003</i>	<i>0.973</i>
<i>IL-SO1</i>	<i>IL-C</i>	<i>1.788</i>	<i>0.515</i>	<i>0.588</i>	<i>0.1</i>	<i>1.157</i>	<i>0.075</i>	<i>0.584</i>	<i>0.009</i>	<i>0.96</i>
<i>IL-SO2</i>	<i>IL-C</i>	<i>6.37</i>	<i>0.099</i>	<i>-0.177</i>	<i>0.019</i>	<i>0.316</i>	<i>0.02</i>	<i>0.648</i>	<i>0.003</i>	<i>0.869</i>
<i>IL-WT</i>	<i>IL-C</i>	<i>-1.891</i>	<i>0.38</i>	<i>1.373</i>	<i>0.073</i>	<i>0.896</i>	<i>0.069</i>	<i>0.664</i>	<i>0.004</i>	<i>0.979</i>
<i>IL-ES</i>	<i>IL-C</i>	<i>3.013</i>	<i>0.102</i>	<i>0.439</i>	<i>0.02</i>	<i>0.249</i>	<i>0.017</i>	<i>0.626</i>	<i>0.006</i>	<i>0.983</i>

^a SE = Standard Error

measurements. At IL, there was only one control catchment. So the well temperatures from this control were used as the predictor variable for all the IL well-to-well regression equations. Table II contains the variable values and other notable information from the regression equations, as calculated by SPSS (SPSS Inc. 2002), for the two study areas.

APPENDIX III

SHALLOW GROUNDWATER TABLE DATA PROCESSING

Multiple regression equations were constructed to fill missing data points in the raw data, and to predict water table levels in the post-harvesting period for a no-harvesting scenario. Pre-harvest relationships between the water table levels of the various catchments were used to construct the regression equations. When predicting post-harvest water table levels for a no-harvest scenario, only variables related to the control catchments were used as independent variables, as these catchments remained untouched over the duration of the study. The general form of these equations was as follows, with the particulars presented in Table III:

$$Y = A + BX_1 + CX_2 + \dots$$

where:

Y = shallow groundwater level to be predicted.

A = value of intercept with y-axis.

B, C, ... = Coefficients.

X₁, X₂, ... = levels of predictor wells (synchronized and standardized data).

To construct these equations, the water table data had to be processed according to the following steps:

- raw data synchronization (several steps)
- predicting values of missing data to complete the raw data sets

DATA SYNCHRONIZATION

The water table data sets were synchronized so that they could be used in regression equations to predict each other as closely as possible. The first tactic used was to lead or lag the timing of complete data sets to address the problem of timing differences in water table responses between catchments. Data for the IL-WT well had to be shifted one half week earlier, and data from the IL-ES well had to be shifted one full week earlier (see Chapter 5 for more discussion).

Secondly, some of the data sets were smoothed using SPSS' (SPSS Inc. 2002) "Centered Moving Average" function. With this smoothing function, peaks and troughs in the data sets of flashy catchments were subdued to more closely fit trends on the other catchments that had less flashy water table responses (see Fig. III for an example). The "Centered Moving Average", is the average of all values a fixed number of points to each side of the averaged value. The disadvantage of using this method of data transformation is that it reduces the size of the data set, because an average value can only be produced if there are the necessary number of data points to either side for use in the average. For example, if the number of data points to be used in the average is 10 points in either direction of the average, the resulting "averaged" data set will be 20 points shorter than the original data set. For this reason, the maximum number of data points that was used in this data analysis for averaging was 25, or 6 days to either side of the averaged value, given that there were two measurements per day. By doing this, the data sets were still

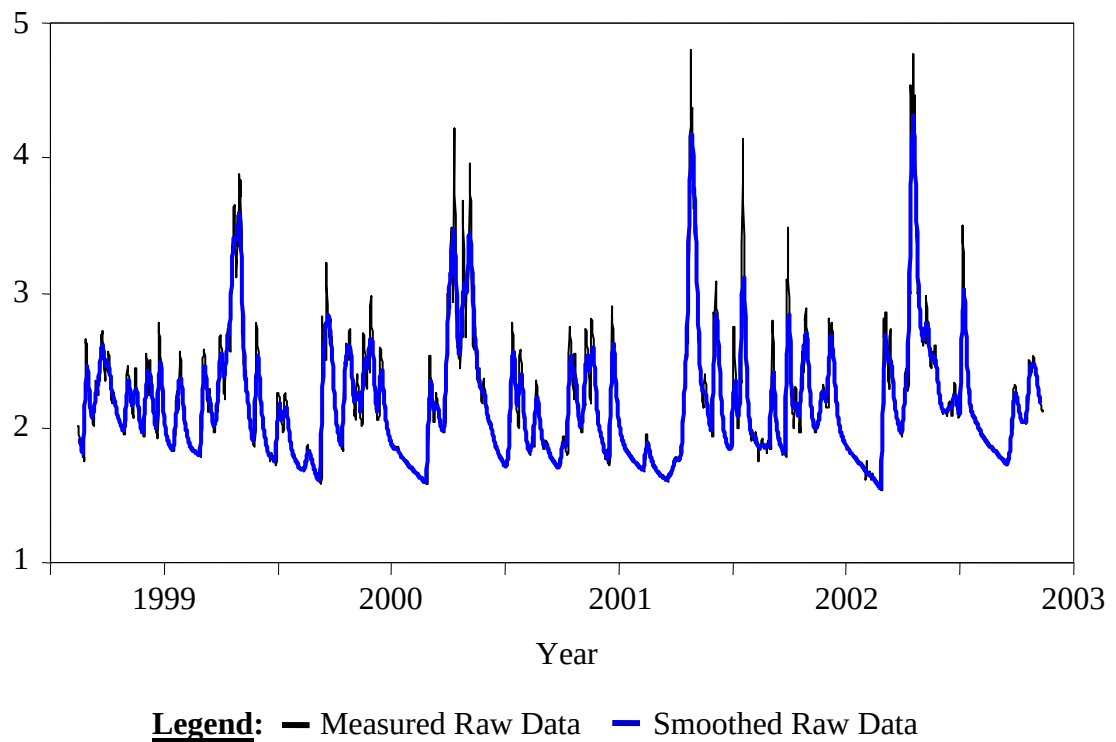


Fig. III. Raw data for water table levels in the Gounamitz Lake Extra-slash well before and after smoothing with SPSS's (SPSS Inc. 2002) "Centered Moving Average" smoothing function. A "Centered Moving Average" of 15 is shown.

smoothed enough to improve the fit between catchments, without greatly reducing the size of the data set.

Lastly, because the relationships between some of the wells were non-linear, some of the data sets had to be squared for the regressions to optimize the fit.

RAW DATA COMPLETION

At GL, the only catchment that did not have a complete data set for water table fluctuations was the first control catchment (GL-C1), which was missing data for the first full year of the study. Before this catchment was used as an independent variable in the

regression equations, these missing data points were filled using regression equation #1 from Table II A, which uses three other GL wells as predictors. The completed data sets from the two control catchments were then used as independent variables for the prediction of post-harvesting levels had harvesting not occurred (Table III A). The statistical computer program, StatView (SAS Institute Inc. 1998) was used to construct all the GL regressions except the equation to predict values for GL-ES. The “Centered Moving Average” function in SPSS (SPSS Inc. 2002) had to be used to construct this equation.

At IL, only one catchment had a complete data set for water table levels in the first year of the study, so only the last full year before treatment implementation was used to formulate regression equations to predict post-harvesting water table levels. All regressions for IL were constructed using SPSS (SPSS Inc. 2002) and are presented, with their relevant information, in Table III B.

Table III A. Values calculated by SPSS (SPSS Inc. 2002) and StatView (SAS Institute Inc. 1998) for regression equation variables used to fill missing data points and predict post-harvesting shallow groundwater temperatures in the absence of treatments on the Gounamitz Lake site. Also included are the respective r^2 values.

Dependent Variable	Equation Number	Independent Variable																
		Intercept		GL-C1		GL-C1 squared		GL-C3		GL-C3 squared		GL-SO		GL-SO squared		GL-ES		r ²
		Value	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	
GL-C1 ^c	1	0.661	0.102					-1.443	0.149	0.308	0.03	1.496	0.114	-0.166	0.024	0.479	0.025	0.979
GL-C1 ^c	2	0.032	0.132					0.902	0.1	0.066	0.018							0.925
GL-C2	3	0.755	0.044	0.577	0.03	0.022	0.005											0.928
GL-SO	4	-1.041	0.026	1.532	0.018	-0.164	0.003			0.099	0.003							0.984
GL-WT	5	-0.565	0.075	0.337	0.064	0.055	0.011	1.05	0.113	-0.127	0.022							0.967
GL-ES ^d	6	0.989	0.049			0.107	0.002	0.505	0.037	-0.139	0.008							0.921

^a SE = Standard Error.

^b C = Coefficient.

^c Equation #1 was used to fill missing data in the first year of the study. Equation #2 was used to predict post-harvest water table levels.

^d the GL-ES values used as dependent variables were "Centered Moving Averages" of 15 (see Chapter 5).

Table III B. Values calculated by SPSS (SPSS Inc. 2002) for regression equation variables used to predict post-harvesting shallow groundwater temperatures in the absence of treatments on the Island Lake site, and respective r^2 values.

Dependent Variable	Independent Variable										r ²
	Intercept		IL-C		IL-C squared		IL-C (20) ^c		IL-C (25) ^d		
	Value	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	C ^b	SE (+-) ^a	
IL-SO1 ^e	-0.973	0.121	-0.235	0.081					1.487	0.089	0.836
IL-SO2 ^f	2.662	0.093	-0.268	0.056	0.032	0.005	-0.936	0.158	1.404	0.146	0.886
IL-WT ^e	2.513	0.105	0.666	0.06	0.075	0.006			0.678	0.033	0.922
IL-ES ^e	0.551	0.088			-0.018	0.004			0.971	0.04	0.904

^a SE = Standard Error.

^b C = Coefficient.

^c The IL-C values used were "Centered Moving Averages" of 20 (see Chapter 5).

^d The IL-C values used were "Centered Moving Averages" of 25 (see Chapter 5).

^e Dependent variables were shifted 0.5 of a week ahead of actual measurement date in order to achieve best predictions with the regression (see Chapter 5).

^f Dependent variables were shifted 1 week ahead of actual measurement date in order to achieve best predictions with the regression (see Chapter 5).

APPENDIX IV

GENERAL OVERVIEW OF THE FORHYM MODEL

GENERAL SOFTWARE DESCRIPTION (adapted from Balland and Arp 2004)

The modified ForHym model remains programmed in the Stella modeling software (High Performance Systems 1998). This software enables the programming of hydrologic and energetic processes by way of three object types (Fig. IV A):

- Basic variables (shown as circles): these can take on constant values, or can be defined in terms of other variables and/or constants.
- “Flow” variables (shown as circles attached to broad arrows): these can be used to calculate the flow of water or heat; invariably, these flows are associated with stock variables; they are programmed in the same way as the basic variables.
- “Stock” variables (shown as boxes): these can be used to accumulate quantities of water or energy over time in any compartment, e.g., any soil layer, the forest canopy, the snowpack; stock variables strictly follow the principle of energy and matter conservation; stock variables need to be initialized.

The values taken by each of these three variable types can all be tabulated or plotted on a graph. Tabulation can be done for each time step, or can be done for set time intervals. Calculations proceed by checking values within all circles and boxes, and by upgrading these according to the programmer specifications, one step at a time. The time

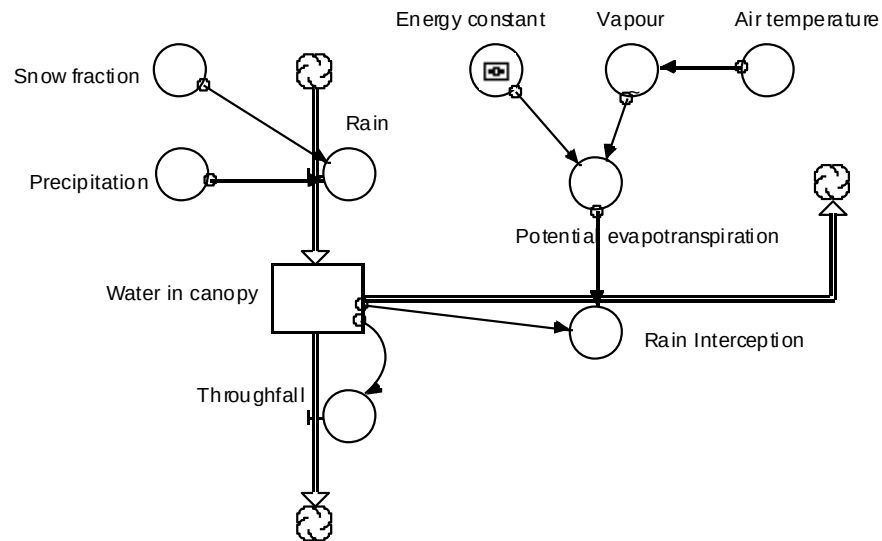


Fig. IV A. Sample of Stella program display. Shown are basic variables (circles), flow variables (attached to broad arrows) and stock variables (boxes). Thin arrows show how variables are connected with one another. Cloud-like symbols mean output into or input from the “environment”. Circles containing parameters that are used for model calibration are flagged with a small box inside (from Balland and Arp 2004).

step is determined by the user, with a shorter time step producing more precision, but longer processing times.

MODEL OVERVIEW (adapted from Balland and Arp 2004)

ForHyM is basically a one-dimensional trickle-down model, but with overflows (Fig. IV B). These overflows can be used to assess lateral flows (surface runoff, interflows and base flow) as well. The sum of these flows determines the discharge rate of the river draining the catchment considered. Flow rate calculations are based on Darcy’s Law. For lateral flows, average slope at the watershed scale determines the flow gradient. When soil is saturated, flow rates are determined from estimated values for the

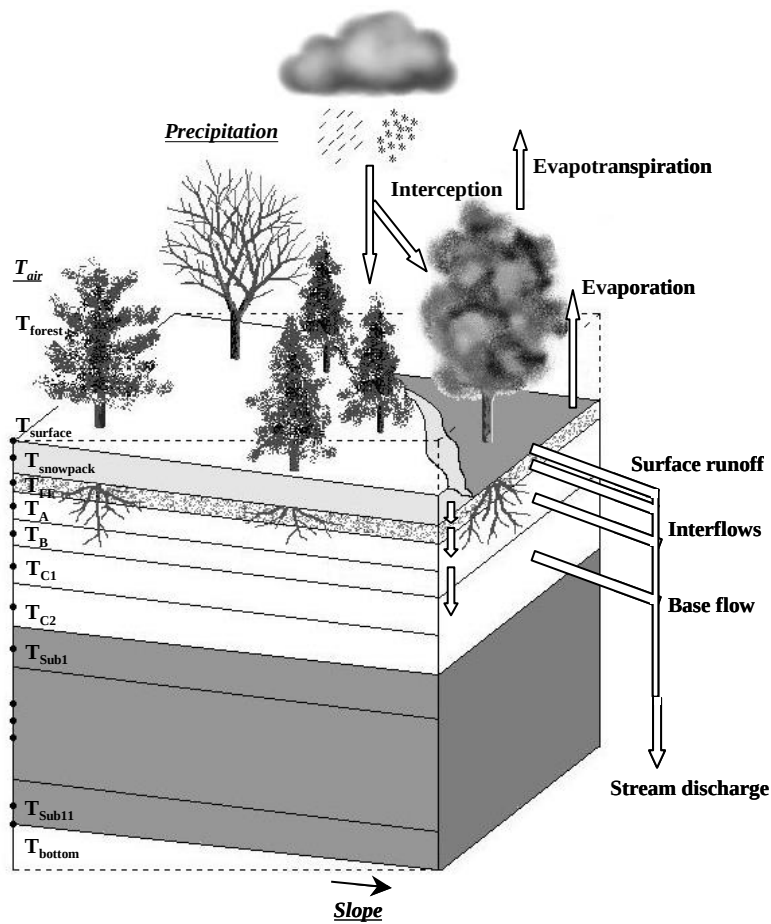


Fig. IV B. Hydrologic calculations in ForHyM (from Balland and Arp 2004).

saturated hydraulic conductivity. When the soil water content is between saturation and field capacity, a similar equation is used, but with a soil- moisture dependent adjustment for the hydraulic conductivity. Below field capacity, there is no gravitational flow of water.

The model recognizes the following forest stand compartments: canopy, snowpack, forest floor (FF), soil (layers A, B and C), and twelve subsoil layers (Fig. IV C). The moisture content of each layer is determined by adding all flow inputs (positive)

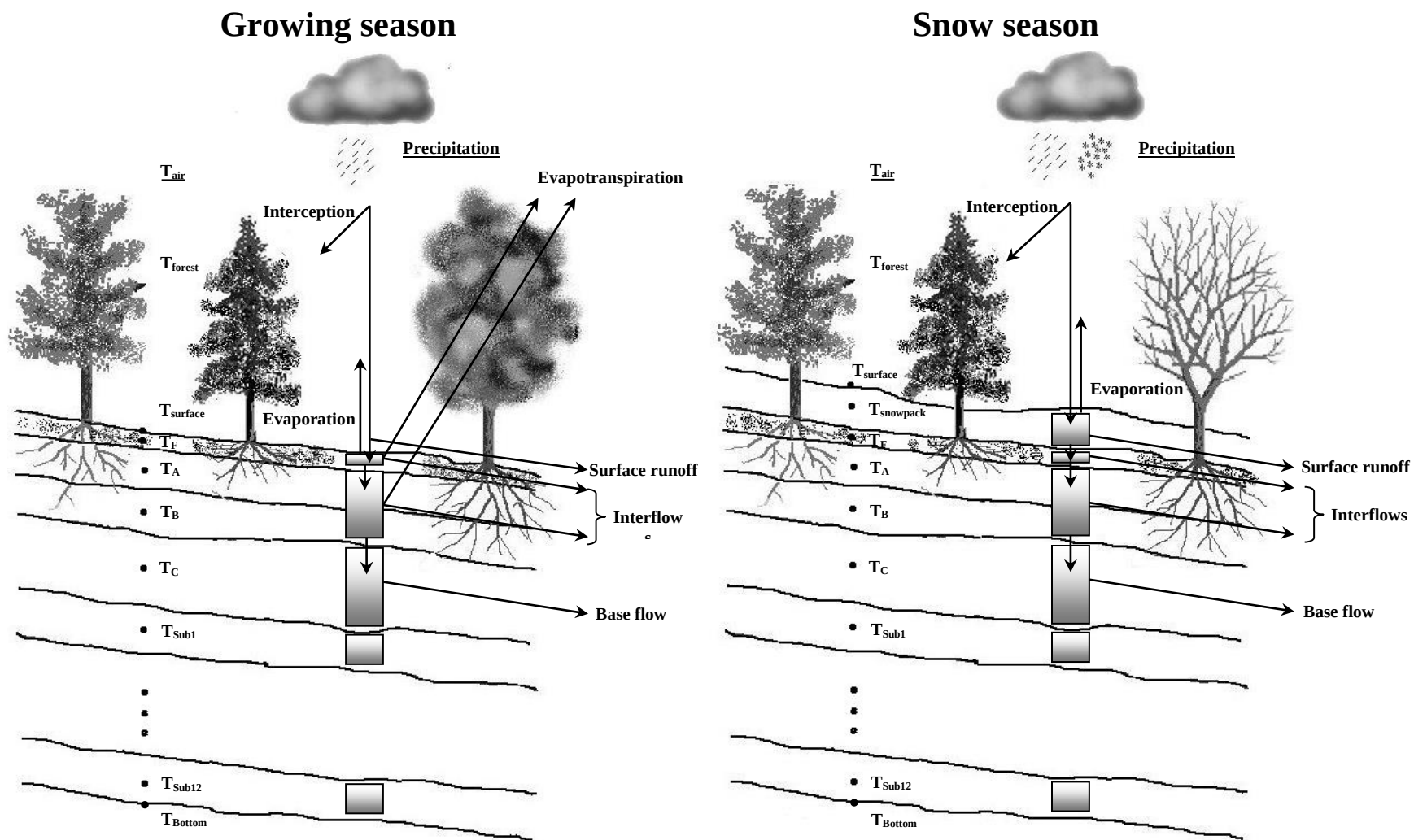


Fig. IV C. Overview of ForHyM (from Balland and Arp 2004).

and outputs (negative) on top of the moisture content in each layer at the preceding time step (antecedent condition).

Some water, as simulated, is removed from the two A and B soil layers, and from the forest floor through evapotranspiration, based on a generalized vegetation-area index, and on air temperature. Water lost by through evapotranspiration is removed from the soil by the roots, and evaporates at the level of the leaves. Soil moisture content, as formulated, cannot drop below the permanent wilting point. The hydrology module of the ForHyM model is summarized in Fig. IV D.

Temperatures are calculated for top and middle of the snowpack and of each soil and subsoil layer (Fig. IV C). The temperature at a depth of more than 12 m (T_{bottom}), and the temperature at the surface (T_{surface}) define the boundary conditions for the algorithm. T_{bottom} is assumed to be constant year-round, and is calculated from the mean yearly air temperature and air temperature range, and the mean annual snow depth (Yin and Arp 1993). T_{surface} is obtained through an energy balance at the surface of the snow (during snow season), or the forest floor, or of the exposed soil mineral surface, as detailed below. This energy balance takes into account direct solar radiation, long wave radiation, surface-air heat transfer, and heat conduction from or to the snowpack or the forest floor. T_{forest} is the air temperature inside the forest canopy, which is adjusted from daily air temperature data based on forest cover and the presence/absence of a snowpack, because colder air usually lies above the snowpack inside the forest.

There is a constant flow of information between the hydrology and energy modules of ForHyM: for each time step, the energy module is set to calculate how much

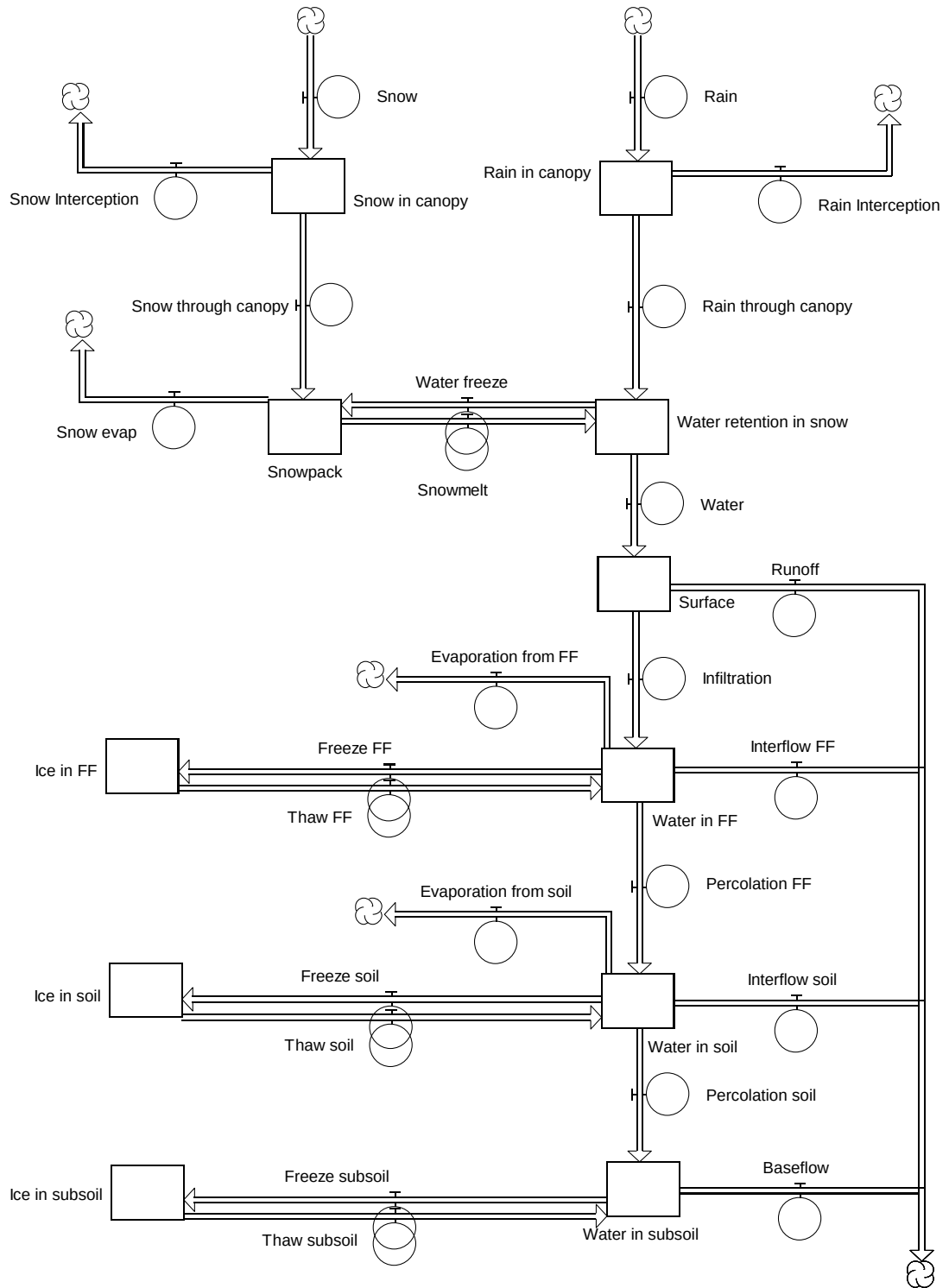


Fig. IV D. Hydrology module in ForHyM (from Balland and Arp 2004).

energy is available to freeze water or melt ice in each layer, including the snowpack. In the hydrology module, the energy released to change water into ice is used to calculate the amount of water that is diverted from percolation and runoff at that time. In turn, the amount of ice and water in each layer is used to re-calculate heat capacities and thermal conductivities of these layers. Moreover, when the temperature of a moist layer becomes negative, the mean temperature of that layer is reset to 0°C until all the liquid water present in this layer is converted to ice. Once all the moisture is frozen, temperatures are allowed to drop further. The reverse is also true: once cold ice reaches 0° C, ice begins to melt in proportion with the incoming heat.

MODELING FOREST GROWTH

Forest growth is modeled in terms of canopy spread, as post-harvest hydrology and energy flows are likely most dependent on this than any other measure of forest growth. Specifically, evapotranspiration, as modeled, is dependant on the Leaf Area Index (LAI), which is the measure of the total leaf surface area per unit area of soil surface. Rain, snow, and solar radiation interception are dependant on the Vegetative Area Index (VAI), which is the measure of total leaf and branch surface area per unit area of soil surface.

Canopy growth simulations in ForHym are based on a Post-Harvest Vegetational Recovery Effects Function, which is, in-turn, based on measured pre- and post-harvest mid-summer mid-day albedo changes, as described by Bourque *et al.* (1995):

$$\text{Post-harvest Recovery Function} = \left[\frac{a_r}{[(1 - a_r)] \exp(-k_{\text{recovery}} * t) + a_r} \right]$$

Here, the “ a_r ” parameter can be used to accelerate or delay post-harvest vegetative recovery on account of tree planting and/or other silvicultural interventions that promote tree growth, soil compaction, soil rutting, raised water-tables, loss of advanced regeneration, and/or general lack of stump sprouting; k_{recovery} is a parameter that reflects inherent site quality: low for poorly drained and excessively well drained sites, and higher for moist and nutrient-rich sites (Balland and Arp 2004).

Leaf-out in the model occurs after a specific threshold for cumulative degree days, and the timing of leaf abscission depends on a threshold for day-length. Leaf growth is expected to reach a saturation level within a month following leaf-out. As modeled, when leaves are out on the trees, the rate of leaf and branch expansion (LAI and VAI, or canopy closure) is dependent on the seasonal growth function.

APPENDIX V

CATCHMENT CHARACTERISTICS USED AS FORHYM INPUTS

Table V A. Values used for ForHyM model inputs related to climate and geology, for all catchments at Gounamitz Lake and Island Lake.

Geological/Climatic Factor	Value
Temperature Code	0
Fog Code	0
Distance to Coast (km)	200
Climate Factor	0
Subsoil Layers Moisture Code	0
Bedrock Moisture Code	1
Quartz Fraction in Coarse Fragments	0.1
Mean Yearly Snowdepth (cm)	22

Table V B. General catchment characteristics used as inputs for the hydrology model, ForHyM.

Characteristic	Catchment									
	GL-C1	GL-C2	GL-SO	GL-WT	GL-ES	IL-C	IL-SO1	IL-SO2	IL-WT	IL-ES
Latitude (degrees)	47.669	47.669	47.669	47.669	47.669	47.681	47.681	47.681	47.681	47.681
Altitude (m)	325	325	325	325	325	325	325	325	325	325
Watershed area (ha)	9.1	6	9.8	12.5	11	7.4	14.4	15.2	11.5	20.1
Aspect (degrees)	116.2	138.9	74.7	112.6	130.8	11.3	-34	-33.2	-47.6	-37.7
Conifer fraction	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5
Deciduous fraction	1	1	1	1	0.7	0	0.3	0.3	0.3	0.3
Root depth code	5	5	5	5	5	3	3	3	3	3
Slope angle (degrees)	4.1	6.4	4.8	4.4	4.5	3.9	3.2	3.2	5.8	5.4
Slope (%)	0.0715	0.1115	0.0837	0.0767	0.0785	0.0680	0.0558	0.0558	0.1011	0.0941

Table V C. Soil inputs for the Gounamitz Lake study site used when running the FORHYM model.

Soil Layer	Catchment					All			
	GL-C1	GL-C2	GL-SO	GL-WT	GL-ES	Organic Matter Content (Fraction)	Coarse Fragment Content (Fraction)	Sand Fraction	Clay Fraction
	Thickness ^a (cm)	Thickness ^a (cm)	Thickness ^a (cm)	Thickness ^a (cm)	Thickness ^a (cm)				
Forest Floor	3.89	3.89	3.89	3.89	3.89	0.764	0.000	0.413	0.103
Upper Soil Layers	32	32	32	32	32	0.122	0.476	0.560	0.086
Middle Soil Layers	19	19	19	19	19	0.072	0.657	0.639	0.108
Lower Soil Layers	100	100	100	100	100	0.000	0.657	0.639	0.108
Subsoil Layer # 1	10	80	10	20	10	0.000	0.657	0.639	0.108
Subsoil Layer # 2	100	100	100	100	100	0.000	0.657	0.639	0.108
Subsoil Layer # 3	100	100	100	100	100	0.000	0.657	0.639	0.108
Subsoil Layer # 4	100	100	100	100	100	0.000	0.657	0.639	0.108
Subsoil Layer # 5	100	100	100	100	100	0.000	0.657	0.639	0.108
Subsoil Layer # 6	100	100	100	100	100	0.000	1.000	0.639	0.108
Subsoil Layer # 7	100	100	100	100	100	0.000	1.000	0.639	0.108
Subsoil Layer # 8	100	100	100	100	100	0.000	1.000	0.639	0.108
Subsoil Layer # 9	100	100	100	100	100	0.000	1.000	0.639	0.108
Subsoil Layer # 10	100	100	100	100	100	0.000	1.000	0.639	0.108
Subsoil Layer # 11	100	100	100	100	100	0.000	1.000	0.639	0.108
Bedrock	100	100	100	100	100	0.000	1.000	0.639	0.108

^a Thickness to the bedrock reflects the well depths, which were drilled to the bedrock surface.

Table V.D. Soil inputs for the Island Lake study site used when running the FORHYM model.

Soil Layer	Catchment					All			
	GL-C1	GL-C2	GL-SO	GL-WT	GL-ES	Organic Matter Content (Fraction)	Coarse Fragment Content (Fraction)	Sand Fraction	Clay Fraction
	Thickness ^a (cm)	Thickness ^a (cm)	Thickness ^a (cm)	Thickness ^a (cm)	Thickness ^a (cm)				
Forest Floor	9.85	9.85	9.85	9.85	9.85	0.776	0.000	0.468	0.172
Upper Soil Layers	31	31	31	31	31	0.083	0.472	0.468	0.172
Middle Soil Layers	17.2	17.2	17.2	17.2	17.2	0.035	0.536	0.557	0.152
Lower Soil Layers	100	100	100	100	100	0.000	0.536	0.655	0.139
Subsoil Layer # 1	92	12	22	63	72	0.000	0.536	0.655	0.139
Subsoil Layer # 2	100	100	100	100	100	0.000	0.536	0.655	0.139
Subsoil Layer # 3	100	100	100	100	100	0.000	0.536	0.655	0.139
Subsoil Layer # 4	100	100	100	100	100	0.000	1.000	0.655	0.139
Subsoil Layer # 5	100	100	100	100	100	0.000	1.000	0.655	0.139
Subsoil Layer # 6	100	100	100	100	100	0.000	1.000	0.655	0.139
Subsoil Layer # 7	100	100	100	100	100	0.000	1.000	0.655	0.139
Subsoil Layer # 8	100	100	100	100	100	0.000	1.000	0.655	0.139
Subsoil Layer # 9	100	100	100	100	100	0.000	1.000	0.655	0.139
Subsoil Layer # 10	100	100	100	100	100	0.000	1.000	0.655	0.139
Subsoil Layer # 11	100	100	100	100	100	0.000	1.000	0.655	0.139
Bedrock		100	100	100	100	0.000	1.000	0.655	0.139

^a Thickness to the bedrock reflects the well depths, which were drilled to the bedrock surface.

APPENDIX VI

RELATIONSHIPS BETWEEN MEASURED WELL TEMPERATURES, AND SOIL
MOISTURE IN UPPER SOIL LAYERS (“A” AND “B”), SNOWPACK, AND SOIL
TEMPERATURE AT ESTIMATED DEPTH OF FLOW, AS CALCULATED USING
FORHYM FOR THE 10 CATCHMENTS AT THE GOUNAMITZ LAKE AND
ISLAND LAKE STUDY AREAS

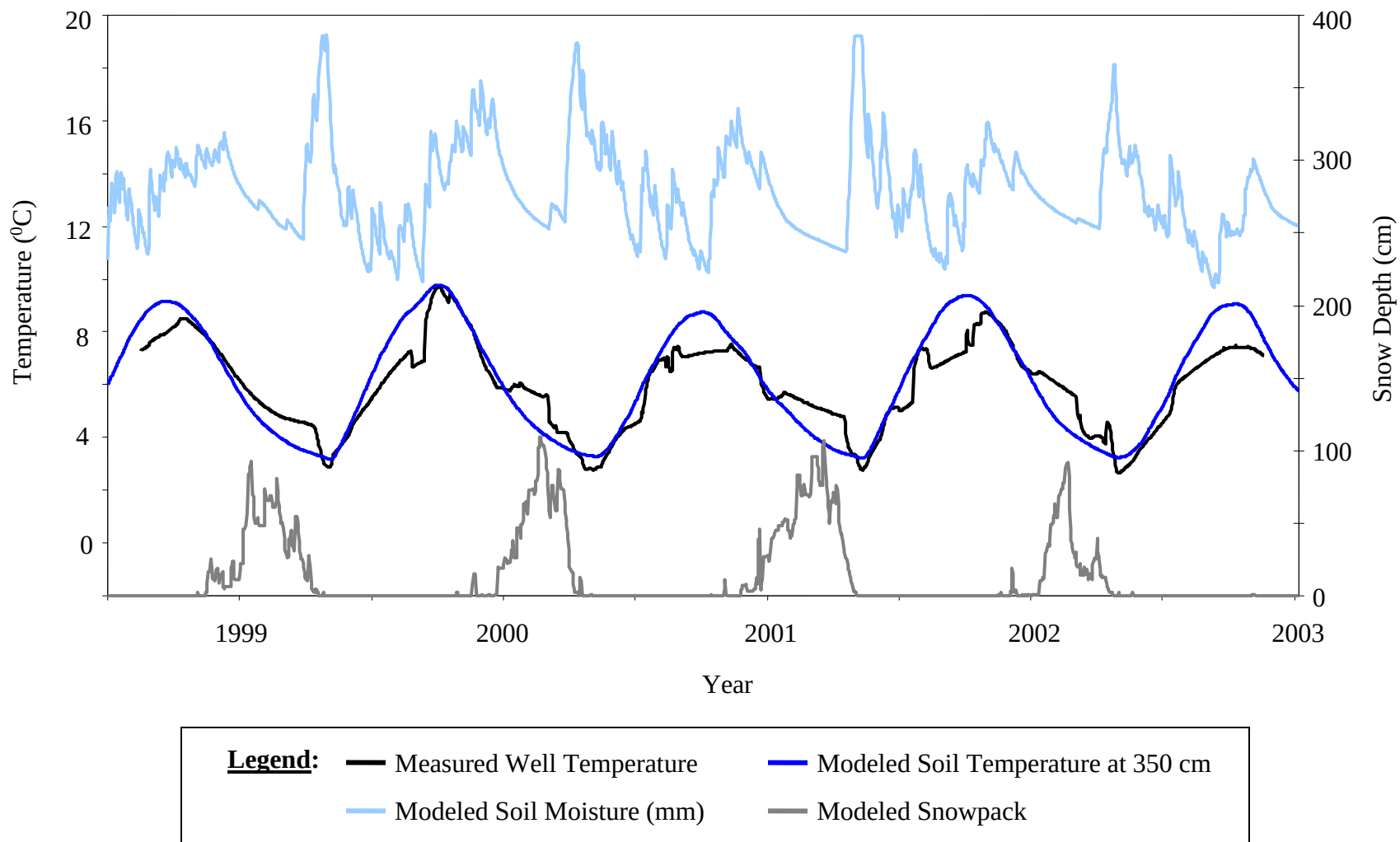


Fig. VI A. Gounamitz Lake first control catchment (GL-C1). Note: Soil moisture values (in mm) are multiplied by 0.07, and are graphed on the temperature axis for display purposes.

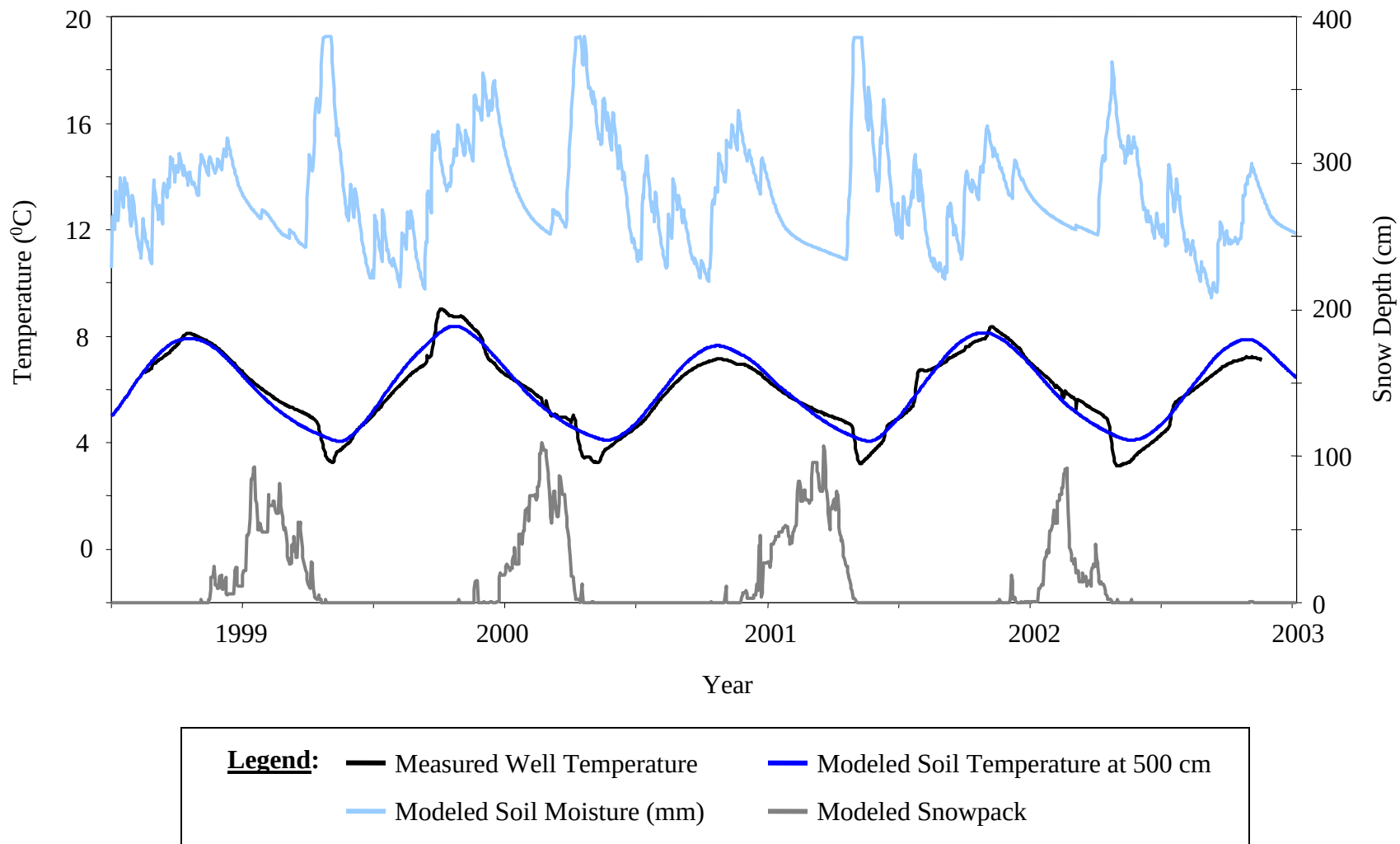


Fig. VI B. Gounamitz Lake second control catchment (GL-C2). Note: Soil moisture values (in mm) are multiplied by 0.07, and are graphed on the temperature axis for display purposes.

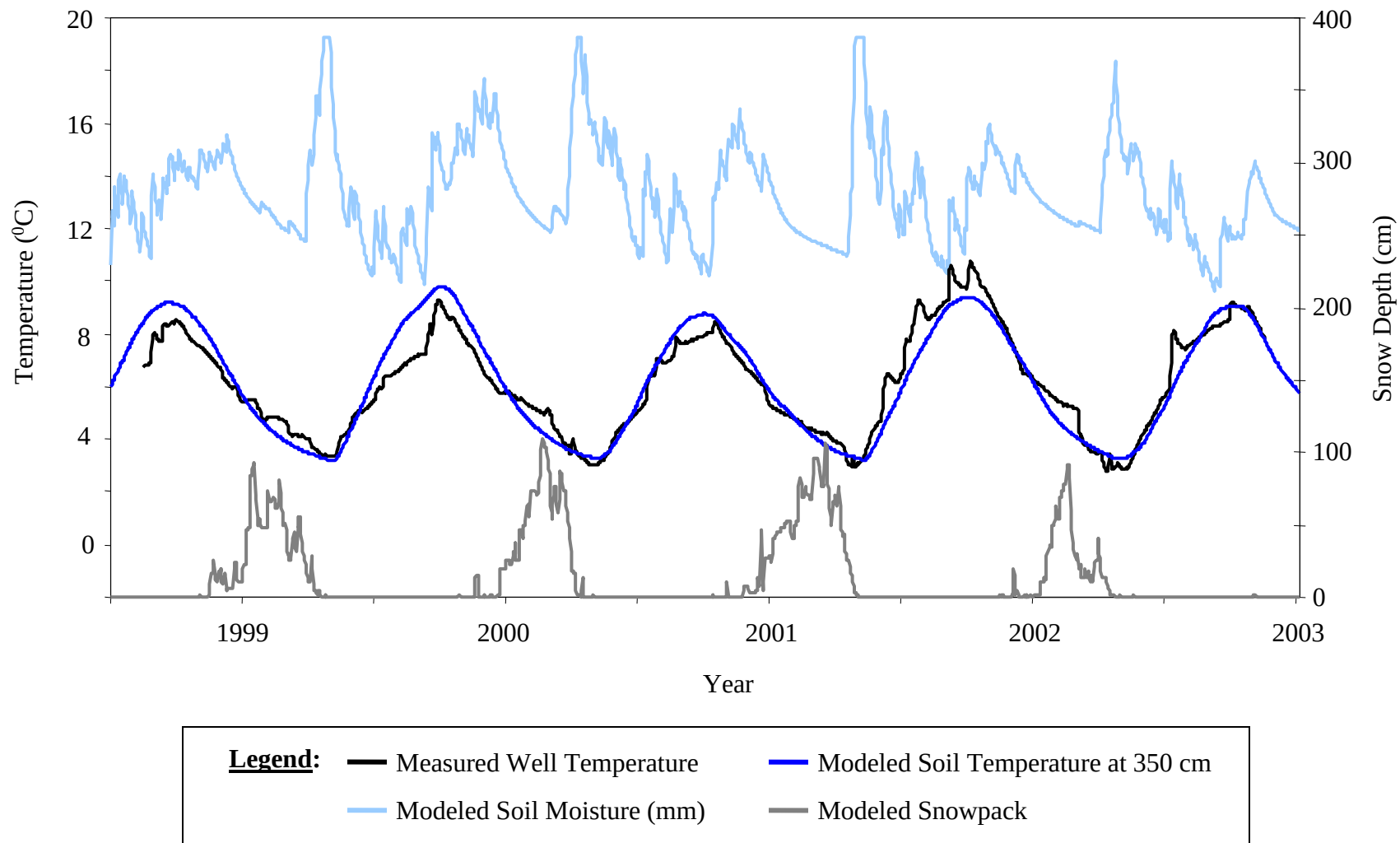


Fig. VI C. Gounamitz Lake stem-only catchment (GL-SO). Note: Soil moisture values (in mm) are multiplied by 0.07, and are graphed on the temperature axis for display purposes.

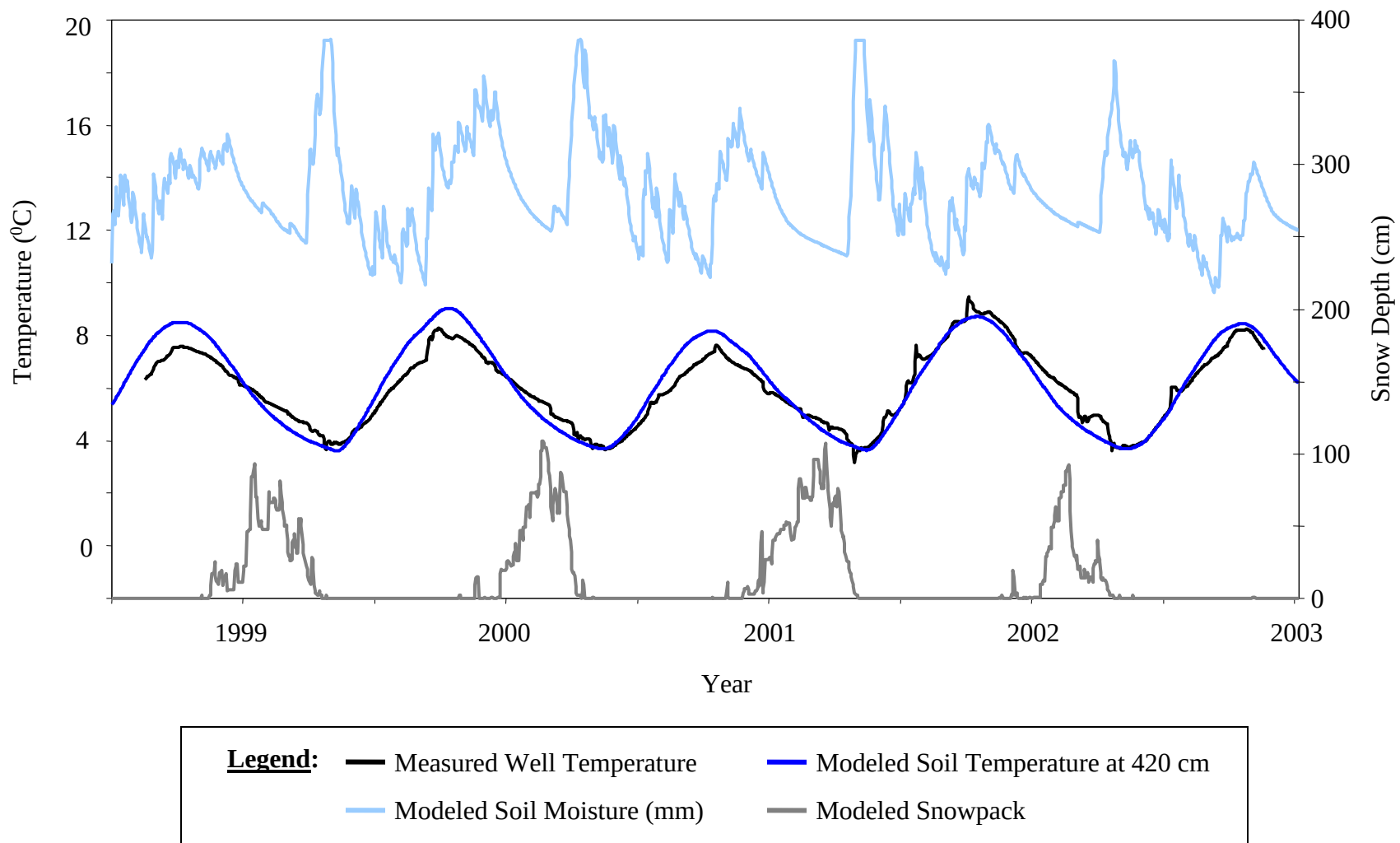


Fig. VI D. Gounamitz Lake whole-tree catchment (GL-WT). Note: Soil moisture values (in mm) are multiplied by 0.07, and are graphed on the temperature axis for display purposes.

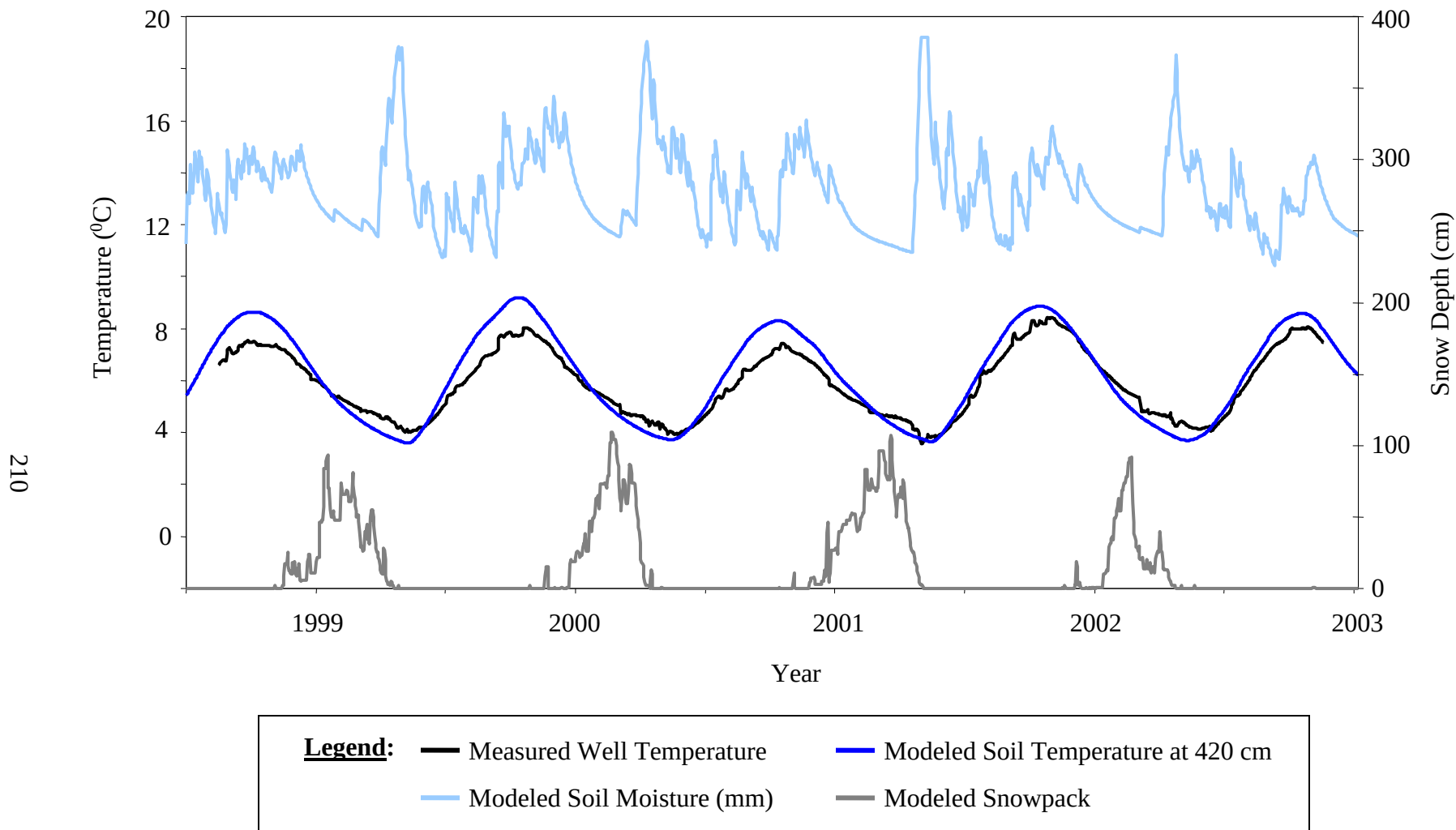


Fig. VI E. Gounamitz Lake extra-slash catchment (GL-ES). Note: Soil moisture values (in mm) are multiplied by 0.07, and are graphed on the temperature axis for display purposes.

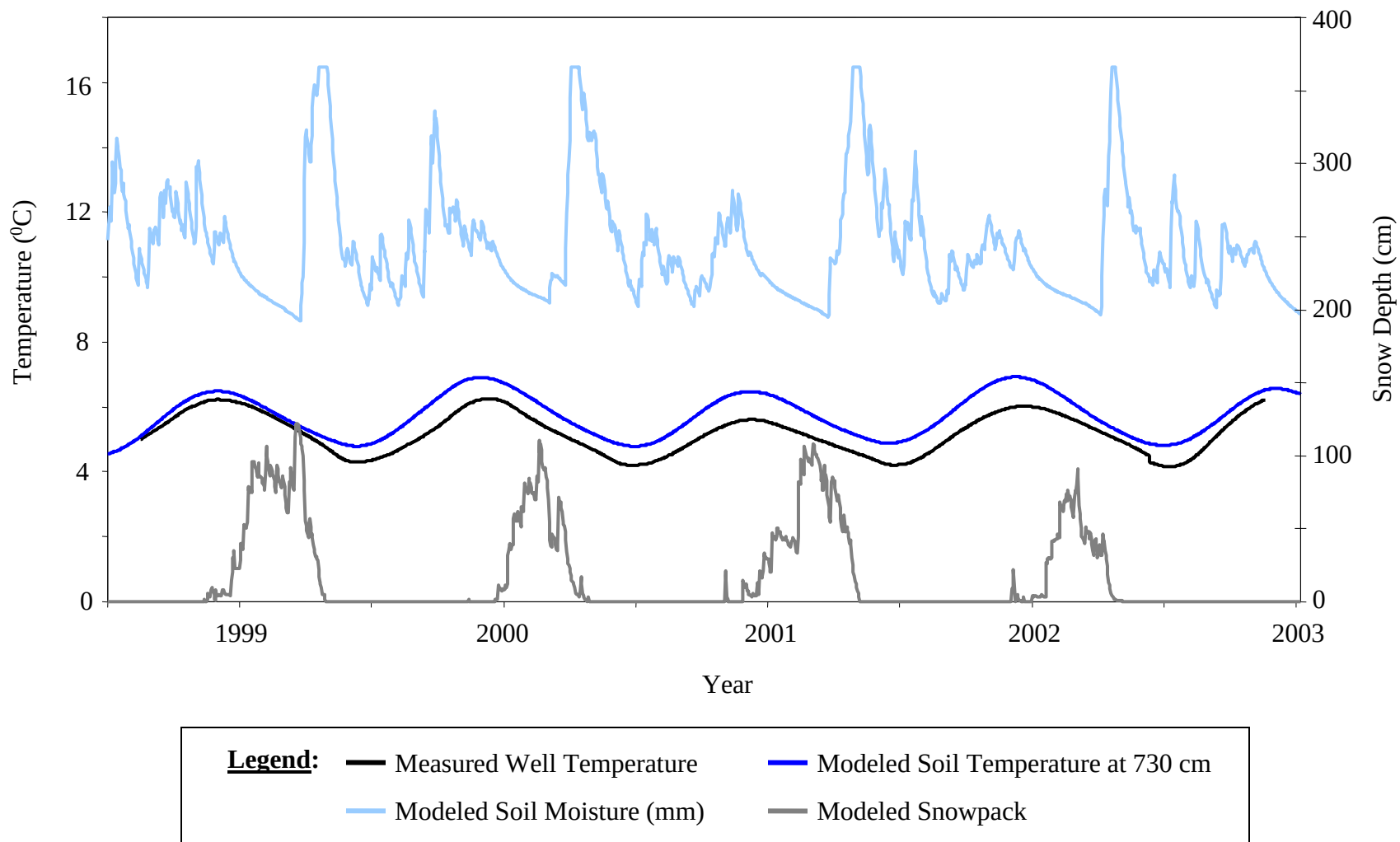


Fig. VI F. Island Lake control catchment (IL-C). Note: Soil moisture values (in mm) are multiplied by 0.045, and are graphed on the temperature axis for display purposes.

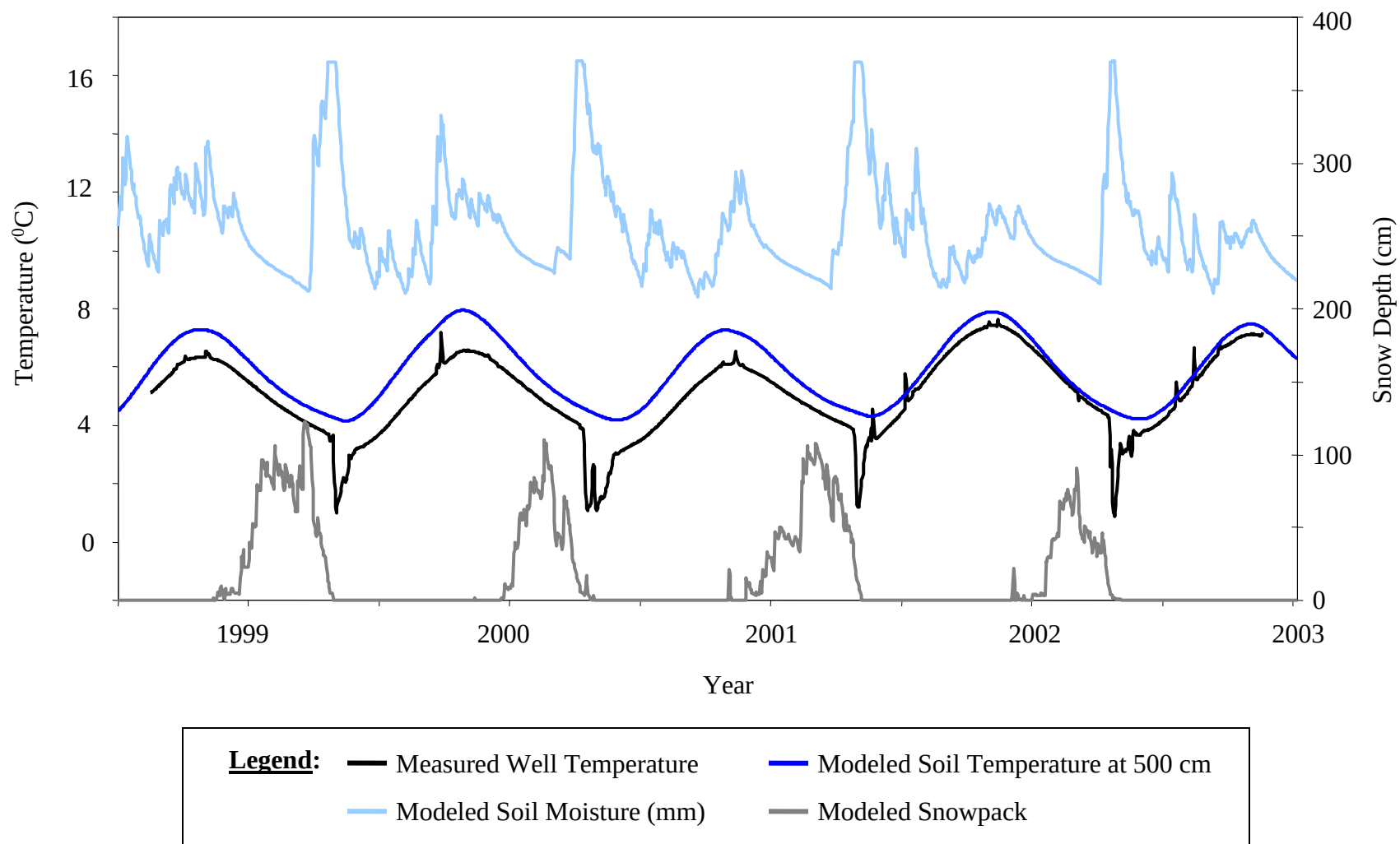


Fig. VI G. Island Lake stem-only catchment (upper well, IL-SO1). Note: Soil moisture values (in mm) are multiplied by 0.045 for display purposes.

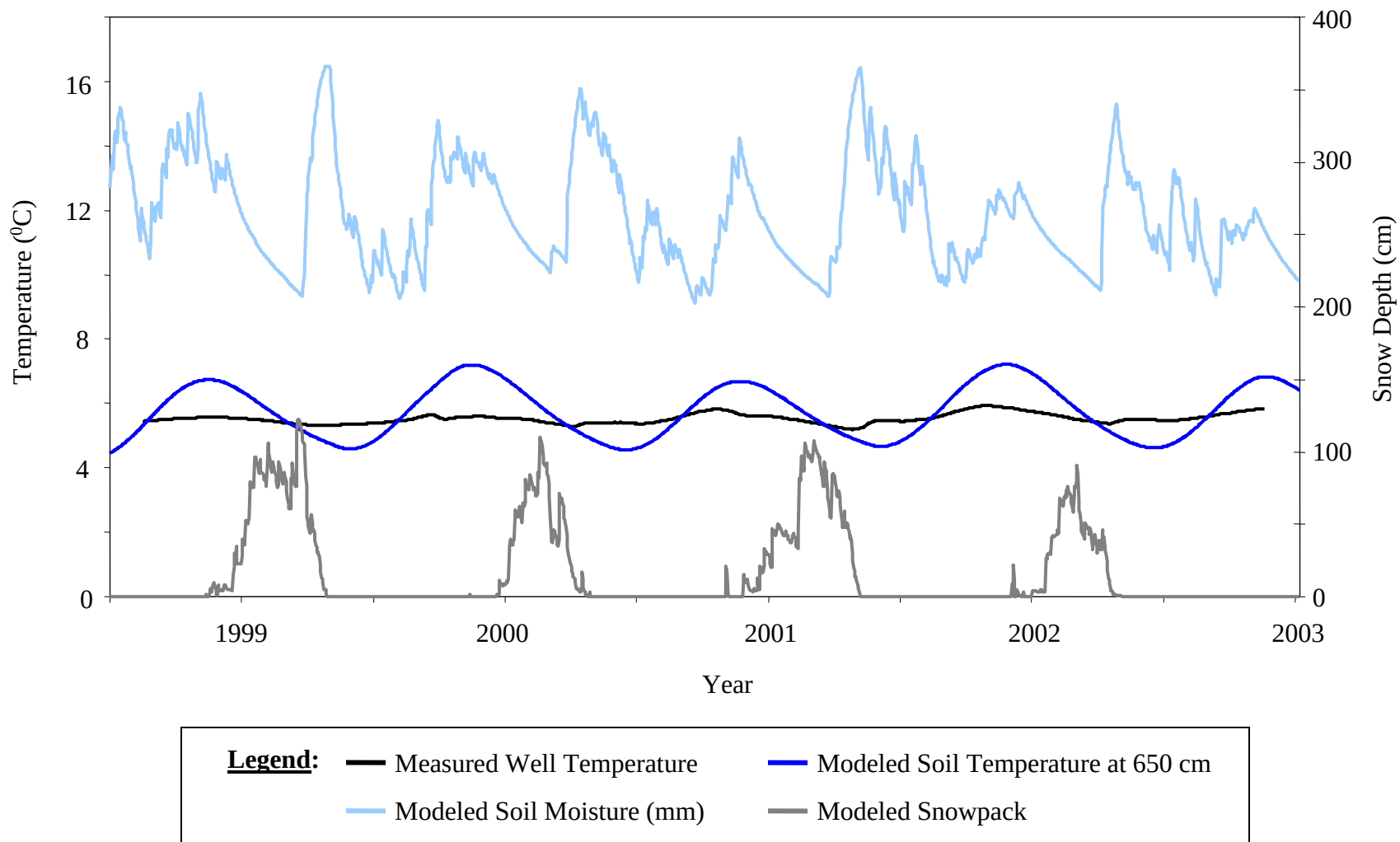


Fig. VI H. Island Lake stem-only catchment (lower well, IL-SO2). Note: Soil moisture values (in mm) are multiplied by 0.045, and are graphed on the temperature axis for display purposes.

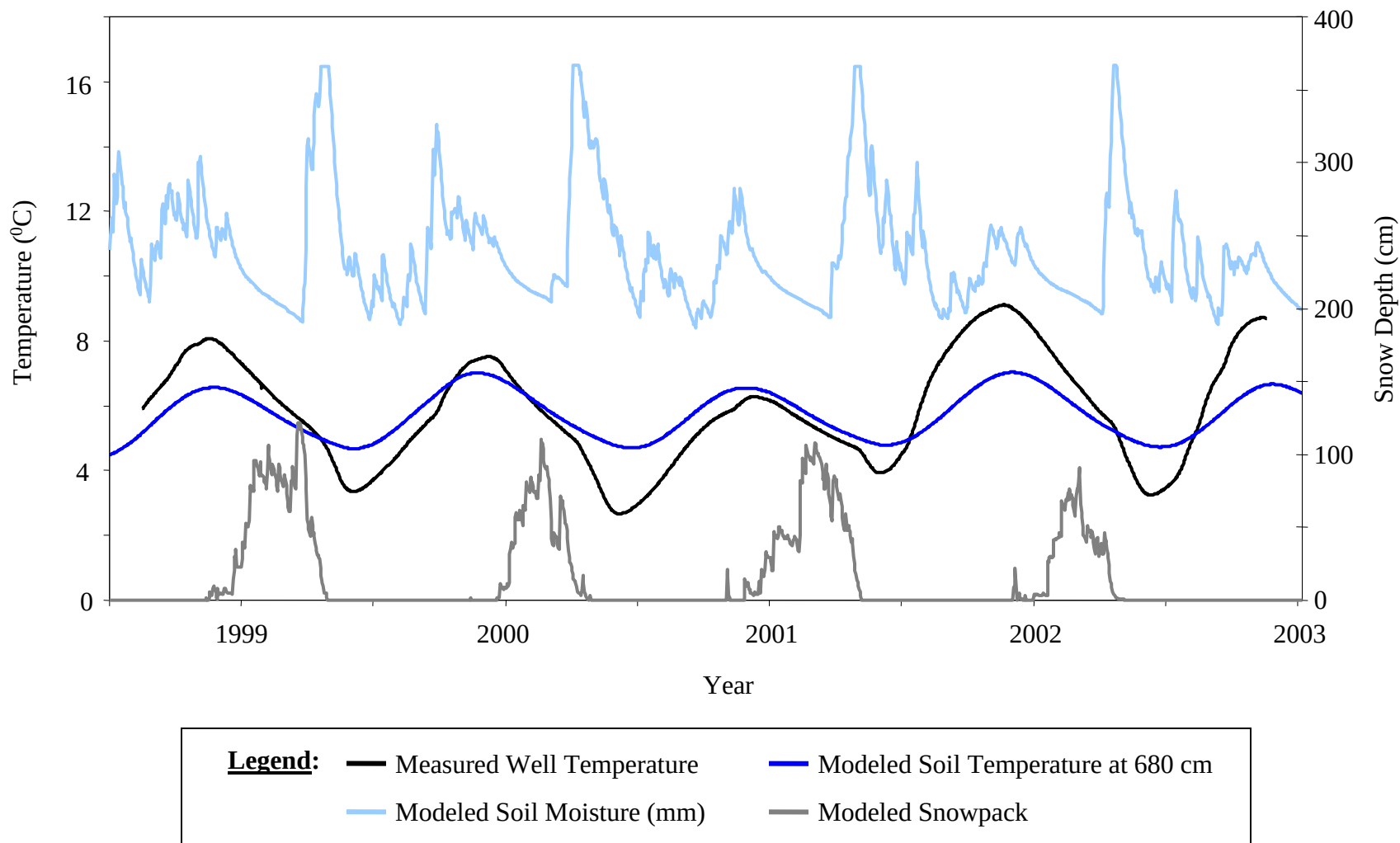


Fig. VI I. Island Lake whole-tree catchment (IL-WT). Note: Soil moisture values (in mm) are multiplied by 0.045, and are graphed on the temperature axis for display purposes.

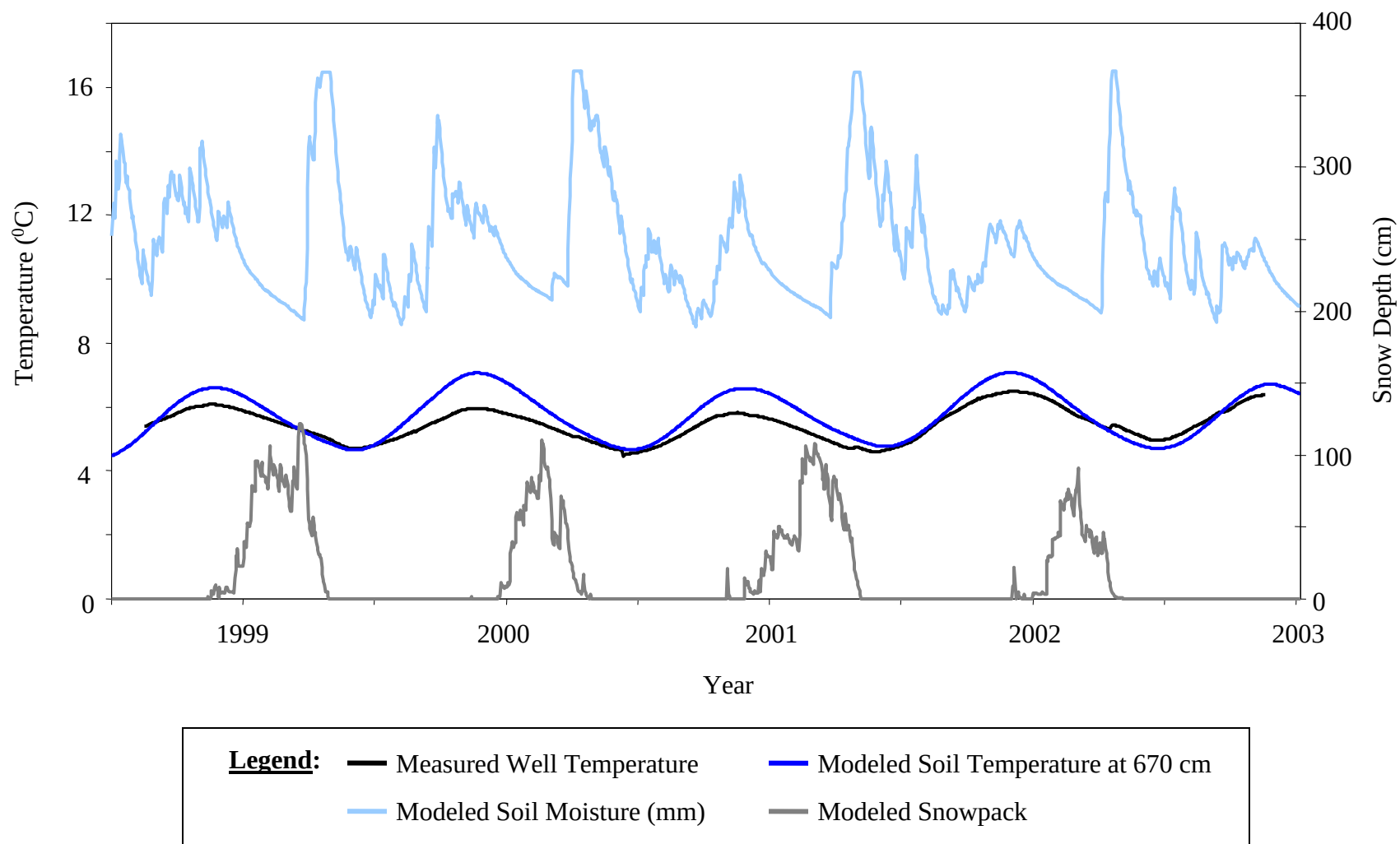


Fig. VI J. Island Lake extra-slash catchment (IL-ES). Note: Soil moisture values (in mm) are multiplied by 0.045, and are graphed on the temperature axis for display purposes.

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- Steeves, M. T. 2001. Water Quality: Comparing Water in Wells, Streams and Ponds Downslope From Forested Subcatchments. B.Sc. Thesis, University of New Brunswick, Fredericton, NB.
- Conference Presentations:** None