Quantifying the Groundwater Component within the Water Balance of a Large Lake in a Glaciated Watershed: Lake Pyhäjärvi, SW Finland

by

Andrew James Wiebe

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Earth Sciences

Waterloo, Ontario, Canada, 2012

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Accurate estimates of the amount of groundwater entering a lake on a yearly basis may provide valuable information for assessing contaminant loadings such as nutrient mass fluxes and the subsequent contribution of groundwater to eutrophication. Groundwater exchange with lakes is often a critical component of a lake's water balance, yet its quantification has often proven problematic. Large component uncertainties preclude accurate estimation of the groundwater flux, upon which the assessment of contaminant loadings may depend.

In this study, water balance techniques for lake systems were assessed at Lake Pyhäjärvi (near Säkylä, SW Finland), a relatively large lake in a long established agricultural area. A water balance was conducted over 38 water years to estimate the net groundwater discharge into the lake. This was compared with groundwater flux estimates via Darcy's Law for the adjacent Honkala Aquifer in the Kuivalahti-Säkylä tributary esker (a potential conduit for groundwater impacted by agricultural practices). Direct runoff estimates were initially made using an average of river flow per unit area ratios from the two rivers that flow into the lake. Adjustments to these estimates were made using PART (Rutledge, 2007) hydrograph separation results from the larger river. The mean net groundwater discharge increased from -73 to +38mm per unit lake area (-4.8 to +2.5% of average total inflow) due to these adjustments, which yielded a better qualitative match with observations at the lake (e.g., Rautio, 2009; Rautio and Korkka-Niemi, 2011). Uncertainty analysis for the water balance indicated that relative uncertainty ranged from 40 to 2900% on the net groundwater flux, while the average absolute uncertainty was 118mm per unit lake area. Groundwater discharge estimates based on Darcy's Law were ≤ 22 mm per unit lake area (≤1.4% of average total inflow) with sizeable uncertainty (± one order of magnitude). Most of the uncertainty on the net groundwater discharge estimates was incurred from the evaporation, precipitation, and direct runoff components; esker flux uncertainty was essentially due to error on the hydraulic conductivity estimate. The resolution of the water balance method suggests that it is better suited to lakes with relatively large net groundwater contributions (>5% of average total inflow). Results highlight the following needs for large lake water balances: improvements in the accuracy of evaporation, precipitation, and direct runoff component estimates; and uncertainty analysis. Groundwater contributions to inflow rivers may be more important than direct discharge from highly permeable subsurface materials adjacent to lakes in the context of understanding nutrient loadings to large lakes.

Acknowledgements

This research was a collaborative effort between the University of Helsinki and Pyhäjärvi Institute, with funding provided by the Maa- ja Vesitekniikan Tuki RY Foundation, Pyhäjärven suojelurahasto, and the University of Waterloo (which provided funding through Research and Teaching Assistantships).

There are many professors, students, researchers, Pyhäjärvi area residents, and friends to thank for their assistance in my research. I would like to thank Dr. Dave Rudolph for initially connecting me with Dr. Kirsti Korkka-Niemi and providing the opportunity to travel to Finland to conduct research at Lake Pyhäjärvi that was a prelude to this thesis. I have appreciated Dave's "big picture" view of the scientific and societal implications of water research. Thank you to Dr. Korkka Niemi, who provided an interesting project and welcomed me to Finland during my two visits. Thanks to Dr. Brewster Conant, Jr., who visited the field site, provided valuable feedback, and was a member of my committee. Dave, Kirsti, and Brewster all provided valuable insight during our meetings. I'm also grateful to Dr. J.P. Jones for being on my committee.

Anne Rautio helped me to get oriented to the Turku and Helsinki campuses and answered my many questions. Henriikka Kivilä played a key role during field work, interviewing residents of the area around the lake, translating their knowledge and anecdotes into English for me, assisting with surveying, and chauffeuring me around the lake. Pyhäjärvi Institute researchers Marjo Tarvainen and Teija Kirkkala shared their knowledge of the lake. Officials and researchers at FMI, SYKE, Varsinais-Suomen Ympäristökeskus, and Säkylän kunnanvirasto provided helpful information and data. Residents around Lake Pyhäjärvi allowed us to measure water levels in their wells, shared their knowledge and stories, and offered hospitality. I would especially like to thank the Kivimäkis.

Thanks to all the donors who contributed to the 2010 R.N. Farvolden Scholarship.

Friends, colleagues, and family have been a great support via Crokinole challenges, sharing meals together, road hockey and soccer games, invitations to visit, and relaxing vacations from study. Thanks to Reynold Chow, Brent Lazenby, Nickie Unonius, Vahid Sohrabi, Marcelo Sousa, Steve Frey, and other colleagues for the many discussions and coffee breaks. Thanks to Inka Vesala, Vilhelm Lindholm, Rami Rekola, and Lihua Sun, who provided accommodation during the 2010 field season. Inka also assisted with some translations. Kiitos!

Dedication

To the Creator, who also walked along the lakeshore.

Table of Contents

List of Figures

List of Tables

Chapter 1 - Introduction

Within the context of global water supply challenges related to increasing demands for clean water from society and ecosystems, accurate water budgets based on the annual hydrologic cycle are needed for wise, sustainable management of this often limited natural resource. In order to achieve this, it is important to collect and analyze diverse sets of hydrological data. Developing a series of annual water budgets (e.g., over multiple year time scales) may allow for the identification of possible trends in precipitation, river baseflow, or changes in catchment storage, which are critical to the long-term management of regional water resources - especially in the face of changing climatic conditions.

Water budgeting/balance techniques have been routinely applied to lake systems, often as a necessary component in studies with chemical or biological concerns (Winter, 1995). However, although lake water budgets/mass balances have been a standard hydrological tool for some time, the amount of uncertainty related to some of the parameters (especially components such as evaporation, direct runoff, and net groundwater flux) may call into question the accuracy of the overall method or resulting estimated values of the individual components. This is especially a concern for large lakes and poses a challenge for water management. It is essential to quantify uncertainties to provide some idea of the confidence in the results.

Groundwater interactions and contributions to lake systems have been particularly problematic to accurately estimate. Groundwater exchange with a lake can take one of several forms (Rautio, 2009; cit. Woessner, 1998; Winter et al., 1998): i) Groundwater flow into the lake (groundwater discharge); ii) lake water flow into the subsurface (groundwater recharge); iii) flow both to and from the lake; and iv) no exchange. Historical hydrologic practice has generally neglected or insufficiently characterized possible groundwater-surface water exchange in hydrological studies of large lakes; however, the interaction between groundwater and surface water bodies is being realized to be increasingly important with respect to ecosystem health, in-stream flow aquatic species needs, and contaminant migration (e.g., Sophocleous, 2002; Hayashi and Rosenberry, 2002; Bruce et al., 2009).

In glaciated parts of the world such as North America, Europe, and Fennoscandia, glaciofluvial landforms such as eskers that are directly connected to lakes can enhance the groundwater exchange with the surface water system. Eskers are generally long, sinuous, sometimes discontinuous ridges with a core of coarse sediments that were deposited in tunnels in glacial ice by flowing meltwater. The coarse nature of esker sediments and their associated ability to readily transmit groundwater make them excellent source aquifers for water supplies, though they may be unconfined and vulnerable to surface contamination. Thus, eskers adjacent to lakes may be conducive to considerable groundwater – surface water exchange, with associated contamination risks for both aquifers and lakes. The role of these types of features in contributing to the groundwater component of a lake water budget is not well understood.

1.1 Objectives

The primary objective of this study was to estimate the amount of groundwater inflow/outflow to a particular lake in glaciated terrain (Lake Pyhäjärvi) via the water balance method, including an uncertainty analysis to ascertain the reliability of the estimates. This analysis also included the consideration of the relative contribution to the overall groundwater flux through a tributary esker that is connected to a large glaciofluvial complex and intersects the lake. Though the groundwater component of the lake's water budget has been assumed negligible in past studies (e.g., Kuusisto, 1975; Järvinen, 1978), recent research (Rautio, 2009; Korkka-Niemi et al., 2011; Rautio and Korkka-Niemi, 2011) has identified measureable amounts of groundwater discharge into the lake. Given eutrophication concerns, understanding the amount of groundwater discharge is important because groundwater provides a potential pathway for nutrients from catchment agriculture to enter the lake and threaten the fishing industry, recreational enjoyment, and ecological integrity of the lake.

The secondary objective of this study was to assess the accuracy and usefulness of estimating the groundwater component of the water budget for a large lake by applying a water balance approach. A water balance involves the solving of a conservation of mass equation accounting for all water entering and leaving a lake in a certain amount of time, along with any change in storage. Estimating the uncertainty related to the water balance components was crucial for this goal.

The current study will advance hydrologic understanding at Lake Pyhäjärvi in several ways. First, the updated lake-scale water balance will complement the recent, smaller scale, shallow shoreline, groundwater seepage studies of Rautio (2009), Korkka-Niemi et al. (2011), and Rautio and Korkka-Niemi (2011), as well as the Honkala Aquifer modelling by Artimo (2002). Second, the work re-visits the water balance theme of earlier researchers, adding a new dimension: a detailed focus on the groundwater component. This allows for the evaluation of the assumption that the net groundwater interaction with the lake is negligible. Third, this study seeks to quantify the uncertainty associated with the components of the water balance, including the net groundwater component. The water balances and uncertainty estimates for the period 1971 to 2008 extend the series of years assessed by Kuusisto (1975). Finally, the study includes a new method of estimating direct runoff into the lake, employing river hydrograph separation via the PART (Rutledge, 2007) program. This application of new and updated analyses may prove useful to the understanding of other large lakes as well as Lake Pyhäjärvi.

1.2 Thesis Organization

This thesis consists of seven chapters in total, including 1) introduction, 2) background, 3) methods, 4) results, 5) discussion, 6) conclusions, and 7) recommendations. The bibliography contains the references for all of the chapters and appendices. Ten appendices are included: Appendix A contains translations of Finnish words; Appendix B contains a map of PCE detection in wells in and around the Honkala Aquifer; Appendix C shows the locations of measured groundwater discharge; Appendix D depicts four cross-sections through the Honkala Aquifer; Appendix E provides a background map of data measurement stations; Appendix F shows a comparison of the fractional areas covered by various surficial geology materials in different parts of the watershed; Appendix G lists data for wells around the lake; Appendix H contains a mathematical assessment of the impact of lake area uncertainty on a water balance component's uncertainty; Appendix I contains raw data in tables and plots; and Appendix J contains tables of water balance results.

Chapter 2 - Background

2.1 Groundwater and Lakes

The patterns of groundwater recharge and discharge associated with lakes may be complex, varying spatially and temporally. Recharge to the groundwater system generally occurs over broad areas but can also occur more discretely (e.g., where surface water bodies lose water to aquifers). Discharge can also occur over broad areas but tends toward high fluxes in relatively discrete areas – springs and seeps, either on land or at the beds of surface water bodies. Seasonal and climatic trends can alter groundwater flow patterns. Local topography, geology, and hydrology influence how groundwater interacts with seas, lakes, streams, and wetlands. Summarizing the collective effects of these heterogeneities on the water balance can be challenging.

Groundwater interaction with lakes has been investigated in recent decades. The exchange between groundwater and lakes may be estimated in several ways, most of them indirect. One method is to divide the lakeshore into segments (and/or the entire lake into representative flux regions) and use differences between the hydraulic head in piezometers and the lake stage, hydraulic conductivity estimates (e.g., from slug tests), and Darcy's Law to estimate the groundwater flow through each segment or area (see Rosenberry and LaBaugh, 2008; Harvey et al., 2000). The main limitation of this method is the fact that head differences allow only estimation of the potential flux, and there are large uncertainties associated with hydraulic conductivity values. A second method involves the direct measurement of the amount of groundwater flux through the lakebed and into or out of a bottomless cylinder (Lee and Cherry, 1978). The open end of the cylinder ("seepage meter") is inserted a few centimeters into the lakebed sediments to enclose an area of the lakebed, and a collection bag is attached to a vent hole in the cylinder. The amount of water gained or lost from the bag divided by the collection time yields the flux at that specific location and time. Limitations to the seepage meter method include difficulties in extrapolating spatially (and temporally) variable point seepage flux measurements (Belanger and Montgomery, 1992), and sampling bias due to the types of sediment conducive to installation. A third method is thermal profiling (see Rosenberry and LaBaugh, 2008). While temperature-based methods have been used to quantify vertical groundwater velocity and flux without dependence on poorly constrained hydraulic conductivity estimates, studies tend to focus on rivers rather than lakes (e.g., Lapham, 1989; Conant, 2004). A fourth method employs chemical or isotope tracers to determine different sources of water and their relative contributions (e.g., Rosenberry and LaBaugh, 2008). Sacks et al. (1998) used sodium and chloride, Krabbenhoft et al. (1990) used stable isotopes, and Schmidt et al. (2009) used radioisotope Rn-222 in mass balances to estimate groundwater discharge into small lakes. While this method holds promise for verifying water balance results, the use of major ions may lead to invalid numerical solutions (Sacks et al., 1998). The parameter uncertainty, degree of mixing in the lake, and determination of the lake evaporate characteristics are further issues related to stable isotopes in large lakes (Rozanski et al., 2001). Another issue is that the radioactive decay of elements in underlying bedrock may possibly obscure the contribution of radioisotopes from groundwater discharge through sediments (J. Karhu, pers. comm., 2010). A fifth method is numerical modelling. Groundwater-lake exchange has been modelled by Winter (1978), Guyonnet (1991), Nield et al. (1994), Abbo et al. (2003), and Mylopoulos et al. (2007), among others. Numerical models can provide a regional description of the flow system around a lake, though to be accurate they need substantial amounts of geological and hydrological data for a large lake's watershed and extensive computational resources. Despite the value of the above methods, heterogeneity poses a challenge for determining representative groundwater flux estimates for a large lake. Understanding the amount of uncertainty related to a method's constituent measurements and calculations is therefore crucial in accurately quantifying groundwater – lake exchanges.

A sixth method is the water balance method. Trask (2007) notes that there are two main uses of water balances: First, the evaluation of all inputs, outputs, and changes in storage of the lake is frequently used to solve for an unknown component such as evaporation (e.g., Järvinen, 1978; Bennett, 1978) or net groundwater influx (e.g., Sacks et al., 1998; Zacharias et al., 2003; Tweed et al., 2009). Second, it is sometimes used to verify the balance of component magnitudes (i.e., the degree of closure of the water balance [e.g., Lenters, 2004]) when independent estimates exist for all (major) components. This particular study employs the former use and focuses on the estimation of the unknown net groundwater discharge component. A water balance is often a first step in many studies (cf. Winter, 1995) and is a necessary constituent of chemical tracer methods and numerical models. The water balance method is helpful because it attempts to quantify the magnitudes of the sources and sinks of water for a lake-atmosphere-groundwater system over a certain time period. The main limitation of the method is the amount of uncertainty associated with the components and calculated residual. Inaccuracies arise as a result of measurement, regionalization techniques, and the accumulation of errors in calculations (Winter, 1981). Evaporation, net groundwater flux, and direct runoff are typically the most uncertain components, though understanding the uncertainty of each component in association with its relative magnitude is essential. The water balance method and uncertainty are both discussed in greater detail below.

2.2 Eutrophication

Much of the study of groundwater – surface water interaction is motivated by concerns related to anthropogenic contamination of surface water bodies via groundwater migration from land use activities nearby. The transport of nutrients by groundwater into surface water is a significant concern. Eutrophication is a process whereby the presence of excess nutrients (mainly nitrogen and phosphorus, which are usually limiting macronutrients – Fruh, 1967; Mackenthun et al., 1964) can lead to runaway algal growth and formation of toxic cyanobacterial blooms (Scholten et al., 2005), decreased water transparency and alteration of faunal communities (e.g., Savage et al., 2010; Bonsdorff et al., 1997; Rönnberg and Bonsdorff, 2004), undesirable water quality changes (e.g., Smith et al., 2006; Carpenter et al., 1998; Howarth et al., 2000), and depletion of dissolved oxygen in deeper parts of stratified surface water (e.g., Fruh, 1967; Smith et al., 2006; Rodhe, 1969). A major implication of the eutrophication process is that it can render regions of surface water uninhabitable to fish (e.g., Fruh, 1967). Increased growth of rooted shoreline plants can negatively impact boating and fishing, and algal mats blown against shore ruin aesthetics (Fruh, 1967). Eutrophication is of global concern and one of the greatest threats to coastal environments (Savage et al., 2010; Nixon, 1995). For example, the presence of excess nutrients threatens the Baltic Sea basin with reduced water quality and ecosystem damage (Savage et al., 2010; Nixon, 1995; Rabalais, 2002), and eutrophication is the most pressing issue facing Finnish inland waters (Frisk and Bilaletdin, 2001). Quantification of the groundwater flux component of a lake's water budget is necessary for understanding nutrient transport into a lake and could play an important role in protecting water quality.

2.3 Water Balance

A water balance (or water budget) is an accounting of all inputs and outputs of water from a specified region, along with any changes of water storage in that region, over a certain amount of time. It must be noted that each "known" (i.e., measured or estimated) term in a water balance equation has an associated uncertainty due to the impossibility of measuring or spatially interpolating each flux with exact accuracy. Thus the residual term, often the net groundwater contribution, also encompasses all uncertainties from the other parameters. The confidence in the residual groundwater component decreases as it decreases in size, due to the increase of the relative magnitude of the uncertainty accumulated from all other terms in the equation. Some researchers (e.g., Trask, 2007) have employed statistical techniques in attempts to reduce the amount of uncertainty in water balance estimates of groundwater discharge. Lake water balance components' uncertainty values have been discussed in detail by Winter (1981). Since local hydrological influences of precipitation, evaporation, and snowmelt are highly dynamic, varying from year to year, a water budget should extend over multiple years (e.g., Wetzel, 1975). Extended datasets are needed in order to estimate the amount of uncertainty on the various measured components and to calculate a reasonable water budget residual. However, caution must be applied when dealing with long-term data; the average value for a component may not accurately reflect the component during a particular year.

A water budget may be calculated over the course of a calendar year or a water year. The American Meteorological Society (2000) defines a water year (or hydrologic year) as the period between the beginning of the season of infiltration into the soil and the end of the season of maximum evapotranspiration; generally regarded as October to September in the Northern Hemisphere. The advantage of conducting a water balance over the course of a water year is that this avoids issues related to the storage of water in snow: water stored in snow during the autumn of a year (Oct - Dec) would add to the precipitation total of the former calendar year but only be mobile and actively contributing to the soil and/or lake system in the next.

2.4 Field Study Site

2.4.1 Lake Pyhäjärvi, SW Finland

Lake Pyhäjärvi (i.e., Säkylän Pyhäjärvi, 60° 54´-61° 06´N, 22°09´-22°25´E – Rautio and Korkka-Niemi, 2011) is a picturesque, large lake nestled between the forests, fields, and rocks of southwestern Finland (Figure 2.1). Surrounded by summer cottages and a few small communities, it is valuable for its fishing industry, recreational enjoyment, industrial use, and ecosystem-sustaining habitat. Pyhäjärvi is the largest lake in southwestern Finland and has increased value as one of few lakes in its region (Ventelä et al., 2007; cit. Ventelä et al., 2005). The lake is notably quite shallow (5.5m on average), contains few islands, and makes up a large percentage (25%) of its watershed. Lake Pyhäjärvi's watershed (616 km^2) is predominately an agricultural region and is one of the oldest and most important such areas in Finland; the lake itself has been a source of drinking water and fish for centuries (Luoto, 2000; cit. Häkkinen, 1996; Ventelä et al., 2007). Two rivers (Yläneenjoki and

Pyhäjoki) drain the agricultural lands to the south and east into the lake, while one river (Eurajoki) conveys water from Kauttua Falls at the northern extent of the lake northwest to the Baltic Sea (Figure 2.2). The most prominent urban area is the community of Säkylä, located on an esker ridge along the northeastern shoreline of the lake. Table 2.1 contains data on the lake and watershed.

The landscape around Lake Pyhäjärvi has been sculpted by glacial erosion and deposition. The Kuivalahti-Säkylä tributary esker lies along the northeastern shoreline of the lake. It contains several aquifers, including the Honkala Aquifer near Säkylä. The Kuivalahti-Säkylä esker is a tributary of the large Virttaankangas Glaciofluvial Complex.

Local residents of the Säkylä area are aware of the presence and importance of groundwater. They talk about the "cold sands" of some of the beaches during the summer, note which wells are "spring wells" (lähdenkaivo – wells that were originally and may continue to be at least seasonally flowing artesian wells), remember how their household wells were deemed unusable by the municipality due to a PCE plume in their aquifer, lament which shallow bedrock wells run dry in the summer, and are concerned about water companies planning artificial groundwater recharge schemes in their area.

2.4.2 Water in the Watershed

Mannio et al. (2005) mention that it was common in Fennoscandia in the past to drain arable land, wetlands, and lakes in order to bring additional land into agricultural production, and that this led to increased nitrogen loading to surface waters, especially with the intensification of agriculture. Similarly, the water level of Lake Pyhäjärvi was lowered about two metres in the 1850's to increase pasture land (Räsänen et al., 1992; cit. Veira, 1974). Regulation of the water levels in Lake Pyhäjärvi began in the 1940's for hydroelectricity production (Räsänen et al., 1992), and the level currently varies within a narrow vertical range of less than one metre. The regulation of Lake Pyhäjärvi's water level via the dam at the lake's outflow to the Eurajoki River implies that the lake is a forced hydrological system, unable to respond in a completely natural manner based on seasonal and annual variations in precipitation, evaporation, streamflow, and groundwater recharge or discharge.

Groundwater extraction in the Lake Pyhäjärvi catchment is currently minimal. Uses include rural household withdrawals from private wells, and some non-drinking use by local residents. There is one pumping station (Lohiluoma) for artificial groundwater recharge immediately north of the lake (permit of 5000m^3/day), which withdraws about 1700m^3/day directly from lake and about 3000m^3/day from the ground (J. Reko, pers. comm., 2010). Isotope results suggest that almost all of the “groundwater” withdrawn is actually lake water that has migrated through the sediments to the screen (K. Korkka-Niemi, pers. comm., 2011). The municipalities pipe potable water into the basin from outside for use by most residents in the larger communities and also pipe their wastewater from the basin (J. Reko, pers. comm., 2010). The municipal systems are being expanded to offer water and wastewater services to an increasing number of rural residents. PCE contamination of the Honkala Aquifer forced the closure of the municipal supply well in Säkylä (cf. Artimo, 2002). This production well was located on the Kuivalahti-Säkylä esker and near the lake; it formerly supplied water to residents until the 1990's.

The lake received municipal and industrial waste water prior to the 1960's (Ventelä et al., 2007). The lake now only receives wastewater from rural residents' summer cottages that have individual septic systems with seepage beds that discharge into the groundwater. There are currently only a few industries operating near the lake. Two with water permits include a food processing plant (permit ca. 1100 m^3/yr) and a sugar plant (permit ca. 160,000 m^3/year) (OIVA – Environment and Spatial Information Services, 1 May 2011), while a paper mill draws water from the Eurajoki River downstream from the lake, thus neither affecting the lake nor the lake water level measurements. Agriculture is a primary user of water in the catchment. An unknown amount of water (mainly lake water, but some groundwater) is used for irrigation (K. Korkka-Niemi, pers. comm.., 2011). Drainage of the fields is very important at certain times of the year, and many drainage ditches convey excess water into the rivers and lake.

2.4.3 Climate

Though at a relatively high northern latitude, southern Finland is warmed along with Sweden and Norway by the Gulf Stream (warm air circulation resulting from the northward flow of water from the Gulf of Mexico through the Atlantic Ocean), and its coastal areas are certainly moderated by the Baltic Sea. Southwestern Finland has a mean annual air temperature of about 5°C, mean annual precipitation around 600mm, four distinct seasons, and a winter season about four months long (Tikkanen, 2005).

Changes in the climate of northern Europe could make water management more complicated. The amount of precipitation at global middle and high latitudes is expected to increase (Okkonen et al., 2010; Christensen et al., 2007), and climate change may lead to earlier melting of lake ice, longer growing seasons, and increased internal eutrophication (Alcamo et al., 2007; Straile et al., 2003;

Eisenreich, 2005). The potential for more extreme seasons (hotter, drier summers and milder winters) may increase the variability in the hydrological systems of lakes. Though average temperatures in northern Europe are expected to increase to a lesser extent than those in other parts of the continent (Alcamo et al., 2007), holistic tools are needed for understanding and managing complex watershed systems.

2.4.4 Bedrock Geology

The bedrock of Finland consists mostly of metamorphic and igneous rocks of Paleoproterozoic age, the crystalline basement of which makes up the Precambrian Fennoscandian Shield that stretches from southern Norway and Sweden to the White Sea in Russia (Anttila et al., 1999; Donner, 1995). The metamorphic rock of the southwestern Svecofennian part of the shield was crosscut by rapakivi granite (Laitila batholith, ca. 1.65 – 1.54 Ga), and then overlain by the (unmetamorphosed, Mesoproterozoic) Satakunta/Jotnian sandstone (ca. 1.6 – 1.2 Ga); following this, all older rocks were cut by diabase intrusions (ca. 1.46 – 1.22 Ga) (Kohonen and Rämö, 2005). There is essentially no sedimentary bedrock younger than the Precambrian (Anttila et al., 1999; Platt, 1955).

Lake Pyhäjärvi is bounded by five main types of bedrock (Figure 2.3): rapakivi (“crumbly” – Platt, 1955) granite to the west, mica gneisses and schists to the south, granodiorite and other intrusive rocks to the east, sandstone to the north and under most of the lake, and olivine diabase dykes in the northwest. A normal fault runs near the southeast facing shoreline of the lake (south of Säkylä) and then continues north (leaving the shoreline), following the contact between the Jotnian sandstone and granodiorite/mica gneiss (Korsman et al., 1997; Anttila et al., 1999; Kohonen and Rämö, 2005). The contact between the sandstone and the granodiorite intersects the Kuivalahti-Säkylä esker between monitoring wells HP1 and HP2 (see Figure 3.1), near a change in gradient of the water table (cf. Kaitanen and Ström, 1978, Appendix I). Figure 2.3 also shows the triangular wedge shape of the sandstone underlying the lake, between the rapakivi granite and the Svecofennidic basement (e.g., Tikkanen, 1981). This wedge is a depression (graben), a fact that has preserved this low-resistance rock from erosion (Eronen et al., 1982; Donner, 1995). The sandstone is fairly flat-lying, influencing the bathymetry of the lake and its general lack of islands (Eronen et al., 1982), and dips toward the northeast (Lindroos et al., 1983). The thickness of the sandstone between Lake Pyhäjärvi and Lake Köyliönjärvi to the northeast is about 200m (Paulamäki et al., 2002; cit. Elo et al., 1993). The contact between the western edge of the sandstone and the rapakivi granite occurs in the deepest part of the lake (Eronen et al., 1982). The highly resistant olivine diabase dykes (Post-Jotnian) that cut across the sandstone at the north end of lake currently form a boundary for the lake (e.g., noted by Eronen et al., 1982; Anttila et al., 1999), and also for the watershed.

The bedrock near the lake may be fractured near ground surface. The rapakivi granite tends to be somewhat fractured at shallow depths (< 100m) and less fractured below that (Lipponen, 2006; cit. Rönkä, 1983; Karro, 1999). A report by A. Artimo (unpublished, 1998) shows that the fracturing of the (sandstone, gabbro, and granodiorite) bedrock beneath the Honkala Aquifer (roughly between wells K1 and K7 – see Figure 3.1) yields an uneven surface with “valleys” of fractured material (in longitudinal cross-section along the esker), though this may be a localized scenario.

The bedrock topography in the watershed is variable. For example, borehole logs from the Säkylä area indicate bedrock at depths varying between 4 and 20m below ground surface (Municipality of Säkylä, unpublished maps and borehole logs, 1979-2005), while Artimo (2002) summarized the thickness of the Honkala Aquifer in his model as varying between 0 and 55m (though this may have included fractured bedrock zones). Bedrock relief in Fennoscandia was largely determined in Precambrian times (Donner, 1995; Anttila et al., 1999) due to weathering and mostly non-marine conditions during the Phanerozoic Eon (Platt, 1955).

2.4.5 Quaternary Geology

There were likely many glaciations in Fennoscandia during the Quaternary period that originated from the Caledonian mountains between Norway and Sweden, though only three or four episodes are evident in the stratigraphy of the region (John, 1984). During the most recent glaciation, the Weichselian (ca. 115ka – 10ka BP), sea level was about 110m below the present level (Donner, 1995; John, 1984). The maximum extent of the Weichselian glaciation reached into northern Germany in the south and perhaps 500km east of the current Finland-Russia border (Donner, 1995). Central Finland was likely glaciated continuously through the Middle and Late Weichselian, and glacial abrasion constitutes the most significant form of erosion during the Quaternary (Donner, 1995). The maximum thickness of the ice sheet in the vicinity of Lake Pyhäjärvi is estimated to have been slightly more than 2500m (Donner, 1995), and isostatic rebound resulting from depression of the crust due to this weight of ice is currently about 5mm/year near Lake Pyhäjärvi (cf. Eronen et al., 2001). Deglaciation led to the predominantly glaciofluvial formation of the Salpausselkä end moraines/ridges (I and II – more extensive; III – only in the west) in southern Finland (Donner, 1995).

Ice flow in the region has been identified in both east-southeast and south-southeast directions from analyses of till fabric, striae, and drumlin axis orientation (cf. Donner, 1995; Mäkinen, 2003; Tikkanen, 1981). Analysis of the striae, till fabric, and the dispersal of Satakunta Jotnian sandstone and rapakivi granite indicates earlier transport by ice to the south-southeast (parallel to the long axis of the lake) followed by more easterly transport (only evident west of Eura) (Tikkanen, 1981; Donner, 1995). The formation of the large Säkylänharju-Virttaankangas Glaciofluvial Complex east of the lake (Figure 2.4) has been suggested to have occurred between two sub-lobes of the Baltic Sea ice lobe during the Late Weichselian deglaciation; the two lobes may have advanced at different rates and may be a reflection of differing bedrock surface elevations (Kujansuu et al., 1995; Kaakinen et al., 2010; Mäkinen, 2003; Punkari, 1980; Salonen, 1991). The Kuivalahti-Säkylä esker is a tributary esker of this complex (Figure 2.5), and part of an esker chain that extends southeast from Säkylä to Mellilä, terminating at the Salpausselkä III ridge (Kaitanen and Ström, 1978).

A series of giant glacial meltwater lakes (Baltic Ice Lake, Yolida Sea, Ancylus Lake, Littorina Sea) existed in the Baltic basin during the past 11ka prior to the present Baltic Sea and Gulf of Bothnia, under the influences of melting ice, isostatic rebound, and connection to the North Sea (John, 1984). The region of Southwestern Finland around Lake Pyhäjärvi was submerged beneath these seas until at least the start of the Littorina stage (about 7500 radiocarbon years BP), when elevated locations east of the lake began to emerge (Eronen et al., 1982).

The question of the location of the Eura-Säkylä tributary esker has been addressed by Lindroos et al. (1983), who comment that the larger Harjavalta-Köyliö-Säkylänharju esker follows the Jotnian sandstone-Svecofennian basement contact (at the eastern edge of the sandstone wedge), and that the Kuivalahti – Irjanne – Eura – Säkylä esker (beside Lake Pyhäjärvi) follows the rapakivi granite-sandstone contact (at the western edge of the sandstone zone) (Figures 2.3 and 2.4). The esker does not seem to follow the contact along the northwestern shoreline of Lake Pyhäjärvi, however. The location of the Eura – Irjanne portion of the esker is controlled by bedrock contacts between the rapakivi granite and the Jotnian Sandstone to some extent, though it favours the sandstone (Tikkanen, 1981) – perhaps because the sandstone dips northwest (cf. Lindroos et al., 1983).

The Kuivalahti-Säkylä tributary esker is about 60 km in length between Säkylä on the lake's shore and Kuivalahti on the Baltic Sea, and it consists mostly of sandstone near the lake (Tikkanen, 1981). It is submerged beneath the lake near Kauttua, is sometimes buried beneath clay, and is sometimes discontinuous (Tikkanen, 1981), disappearing from the surface until it re-emerges in a more east-west direction near the town of Eurajoki and runs toward Kuivalahti (cf. Lindroos et al., 1983). There is evidence of subglacial formation at Irjanne – i.e., no till between bedrock and the esker (Tikkanen, 1981).

The thickness of Quaternary sediments varies substantially along with the bedrock topography (Artimo, 2002; Lindroos et al., 1983). The extent of the overburden is patchy and bedrock is close to ground surface throughout most of the catchment, as suggested by the many outcrops evident on the surficial geology map (described below).

2.4.6 Eskers

Eskers form in the complex, evolving environments associated with glaciers and their meltwater. They may be unconfined ridges composed mostly of a core of coarse sand and gravel, or may have a mantle of finer material deposited by glaciomarine environments and littoral biota (cf. Brennand, 2000). For instance, the Honkala Aquifer is mostly unconfined (Artimo, 2002). Due to the pressure regime at the base of a glacier, these ridges can exhibit topographic control as well as counter-topographic gradient, pressure-controlled flow, which is exemplified by an esker being submerged beneath sediments or water bodies at some locations and at ground surface at others, changing its elevation. The Kuivalahti-Säkylä esker follows this pattern (as noted above). Studies in northern Canada suggest that eskers may radiate outward from an ice divide or end in an arcuate moraine, and that esker density tends to be high over crystalline bedrock (Brennand, 2000). The Fennoscandian basement rocks would thus be expected to be overlain by many eskers.

Eskers tend to invite human settlement and infrastructure since they provide valuable building materials and stability for building foundations and roads; thus urban, aggregate, or industrial development and the use of esker groundwater often compete against one another. This is unfortunate, given that eskers and other glaciofluvial deposits form the best aquifers in Finland (cf. Karro, 1999). The City of Rauma (northwest of Lake Pyhäjärvi) cannot use its esker aquifer due to sand and gravel extraction, urban development, and the presence of a cemetery (Lindroos et al., 1983). These land uses pose risks in terms of contamination of groundwater, and may also threaten surface water if there are connections between the two because of the coarse grained nature of glaciofluvial deposits and the potential for rapid migration of contaminants. The Kuivalahti-Säkylä tributary esker composes a significant length (about 9km) of the shoreline of Lake Pyhäjärvi, thus combining the potential land use risks of rapid groundwater transport within coarse-grained, unconfined aquifers with those associated with groundwater discharge into a large surface water receptor.

Eskers are also important for the filtration of water and the artificial storage of groundwater. The percolation of water through sediments of the unsaturated and saturated zones allows for physical (e.g., advection, dispersion, diffusion) and biological (e.g., growth and decay, active adhesion/detachment, survival) processes to attenuate microbes and pathogens (Sen, 2011). Treated surface water may be pumped into aquifers and stored there until needed in the future; this is known as artificial recharge. The Kauttua peninsula in the north of Lake Pyhäjärvi has a small artificial recharge operation, whereas the nearby Virttaankangas Glaciofluvial Complex is the site for Turku Region Water Ltd.'s construction of a large artificial recharge operation with a pipeline to conduct the water south to the city of Turku (Artimo et al., 2008).

2.4.7 Surficial Geology

Quaternary landforms often compose the microrelief in Fennoscandia (Donner, 1995), and eskers are accordingly a prominent feature of the landscape of southwest Finland. Mäkinen (2003) portrays the landscape of the area between Tampere, Pori, Turku, and the Salpausselkä III end moraine as littered with glaciofluvial deposits and various moraines. The esker chain that borders on the lake is a small tributary of a larger, 70km-long landform that connects with the large Virttaankangas complex, the entire (somewhat discontinuous) glaciofluvial sequence stretching from the Salpausselkä III end moraine/ridge to the Gulf of Bothnia near Pori (Figure 2.5; Tikkanen, 1981; Mäkinen, 2003). Mäkinen (2003) calls the esker beside Lake Pyhäjärvi the *Kuivalahti-Säkylä tributary esker* (see Figure 2.4).

Figure 2.6 shows the surficial geology of the Lake Pyhäjärvi catchment. The western shore of the lake is dominated by thin soils (mostly till) over bedrock (rapakivi granite), though there are a couple of small agricultural areas. One of these areas is the former Lake Kiperijärvi basin, which was drained to prepare land for agriculture by cutting a channel through the intervening ridge to Lake Pyhäjärvi. The channel still drains the area, including the drainage ditches fed by groundwater springs. The northwestern shoreline of the lake is similarly mostly glacial till and bedrock. The shoreline near the mouth of the Yläneenjoki in the south is fine-grained with some peat, though sand and till dominate progressing counterclockwise around the lake toward Säkylä. The terrain of the Yläneenjoki River's subcatchment is less permeable than that of Pyhäjoki's catchment; Figure 2.6 shows that the larger river is surrounded by more bedrock outcrops and clay (cf. Eronen et al., 1982). The entrance of the Pyhäjoki River into the lake is marked by silty soil, and it collects water from a catchment with considerable amounts of sand and coarse-grained glaciofluvial material from the Virttaankangas complex. The northeastern shore of the lake is mostly contained by the Kuivalahti-Säkylä esker ridge with its beaches of sands, gravels, and red sandstone cobbles. The extreme northeast of the basin is dominated by till.

2.4.8 Watershed Topography

Figure 2.7 shows the topography in and around the basin. The ground surface topography in the basin ranges in elevation (N60 datum) from 40m (catchment outflow) to 145m (Virttaankangas complex) while the bathymetry of Lake Pyhäjärvi varies from about 19m (deepest part of the lake, rapakivi granite – sandstone contact) to an average lake level elevation around 44.9m (Figure 2.8). The Yläneenjoki River is incised more deeply into the terrain than the Pyhäjoki, though its river valley is only about 2 to 3m deep on average and always less than 5m deep (Luoto, 2000). The Pyhäjoki has a greater sinuosity.

2.4.9 Hydrogeology

The Quaternary sedimentary cover is usually thin in Finland and the southern part of the country exhibits scoured bedrock surfaces, where sediments are mostly related to the most recent glaciation (Saarnisto and Salonen, 1995). This is much different from the sedimentary formations present in southern Europe (Platt, 1955), or those in southern North America, where aquifers can span large areas. Groundwater is nonetheless important in Finland and schemes such as artificial recharge are being applied to maximize water supplies.

The largest and most economic aquifers in Finland are eskers, deltas, and ice-marginal formations of glaciofluvial origin, though these are unevenly distributed and constitute only 3 – 4% of the country's area (Karro, 1999; Lipponen, 2006; cit. Kujansuu and Niemelä, 1984). Figure 2.9 shows the (overburden) aquifers in the vicinity of the Lake Pyhäjärvi watershed. Though morphologically connected to the Säkylänharju-Virttaankangas Glaciofluvial Complex, the aquifers of the Kuivalahti-Säkylä esker have been interpreted to be isolated from the aquifer systems of the complex. Artimo et al. (2003) comment that though Finnish eskers make good aquifers in terms of the available quantity of water, their coarse nature implies susceptibility to contamination.

The groundwater of the Honkala Aquifer system seems to be disconnected from Pyhäjoki River. The detection of PCE from a spill at a dry cleaning facility on the esker in wells on the south side of the river near the lake provides evidence for this (Appendix B). Many of the networks that drain the land around the lake are not natural channels but rather constructed with straight line segments and sharp junctions (e.g., Peruskartta maps). It is unknown how well the local groundwater systems relate to these drainage ditches. The large number of drainage ditches in the middle of the fields suggests poor natural drainage and a high water table.

The properties of the soils in the catchment are not well known. Hydraulic conductivity values in the Quaternary sediment types of the catchment range over many orders of magnitude. Artimo et al. (2003) state ranges for till (10^{-8} – 10^{-6}m/s), coarse glaciofluvial material (10^{-4} – 10^{0}m/s), fine glaciofluvial sediment (10^{-7} – 10^{-4}m/s), and clay (10^{-11} – 10^{-7}m/s) in the nearby Virttaankangas complex, though these are a mixture of literature and measured values. Residence times for groundwater in most parts of the catchment are unknown. The residence time of the groundwater in the Honkala aquifer before it reaches Lake Pyhäjärvi is likely on the order of decades, estimating from PCE transport from a dry cleaning facility in Huovinrinne to wells near the lake (cf. Artimo, 2002). Järvinen (1978) comments that some hydraulic head gradients between (unspecified) water table elevations near the shore and the lake stage indicated groundwater discharge and that no reverse gradients were observed. This has also been observed during this current study.

About 50% of precipitation is roughly estimated to recharge the groundwater system through the coarse esker sediments (K. Korkka-Niemi, pers. comm.., 2010). Recharge rates in the nearby Virttaankangas Glaciofluvial Complex (dependent on soil properties) are estimated to range between 260 and 400mm per year (Kaakinen et al., 2010). The amount of recharge in other parts of the catchment is likely lower than in the esker, and may be minimal where bedrock is close to surface.

Bedrock wells in Finland tend to be viable only for individual households, while community-scale groundwater extraction is only viable in special cases and requires knowledge of fracture zones (Karro, 1999; Lipponen, 2006; cit. Rönkä, 1993; cit. Leveinen et al., 2000). In support of this, household wells near the western shore of Lake Pyhäjärvi have been drilled to depths greater than 100m through bedrock in order to intercept enough fracture zones for a viable water supply. This information suggests limited groundwater flow through fractures from west of the lake and consequently, a low probability that deep rapakivi granite groundwater discharges into the lake in large quantities. The choice by Finnish Energy Industries to locate a nuclear waste repository in the crystalline bedrock (granite, mica gneiss, and tonalite-granodiorite) of Olkiluoto (e.g., Anttila et al., 1999), an island just off the western coast of Finland in the Gulf of Bothnia (about 60km northwest of the lake), suggests that researchers consider groundwater flow in this bedrock to be minimal.

Lindroos et al. (1983) discuss groundwater north of the lake and state the following: bedrock and overburden wells give similar yields, with an average bedrock well producing 36 m^3/d; the groundwater there tends to be bicarbonate in nature with high TDS, though this decreases moving away from the Baltic coast; eskers contain the least dissolved constituents, compared to glacial till overlain by clay; the rapakivi wells have associated fluoride; and iron is often in the water. Bedrock wells north of the lake tend to be drilled deeper than 40m on average (Lindroos et al., 1983).

In summary, glaciofluvial aquifers are important water sources in Finland, though they tend to be small and discontinuous due to glacial erosion and deposition patterns, and bedrock aquifers generally yield only enough water for individual households.

2.4.10 Hydrology

2.4.10.1 Precipitation

As noted above, southwestern Finland receives a reasonable amount of precipitation each year. Roughly 30% of this falls as snow (Platt, 1955). Platt (1955) estimated annual precipitation to be around 600mm/year while contouring the entire country's precipitation. This agrees well with Kuusisto's (1975) calculation (via the Thiessen polygon method) of Lake Pyhäjärvi's annual precipitation average between 1938 and 1973 as 633mm, with a standard deviation of 122mm. Precipitation has been measured daily at eight precipitation stations within 70km of the lake for varying amounts of time: six since 1970, one since 1975, and one for five years in the early 1990s. In Finland, snowfall precipitation amounts were calculated manually for Wild precipitation gauges (with Nipher wind shields) twice per month until 1982; Tretyakov gauges have since been used to measure both rain and snow (Seuna and Linjama, 2004).

2.4.10.2 Evaporation

Several researchers have estimated evaporation from Lake Pyhäjärvi. Järvinen (1978) estimated evaporation via a water balance to be 407mm and 443mm per unit surface area of the lake for June through October, in 1972 and 1973, respectively. Evaporation pan coefficients varied between 0.76 and 1.25 for three evaporation stations near the lake for June through September, 1971 – 1973. However, Järvinen likely did not rigorously assess the net groundwater flux; it was assumed to be negligible. Kuusisto (1975) calculated a slightly higher average lake evaporation (491 mm / year) for the period 1938 to 1973 via the Shuliakovski (1969) aerodynamic method. The amount of evaporation from December to April was estimated to be a constant 40mm per unit lake area for each year of this period. Kuusisto also developed mathematical relationships relating Jokioinen meteorological station Class A evaporation pan measurements to estimates from the Shuliakovski (1969) aerodynamic method for May through September. The Kuusisto estimates are mostly based on indirect observations. The derivation of mathematical equations relating wind speed and vapour pressure at Lake Pyhäjärvi to observations elsewhere employed data from three years of direct observations at the lake. For comparison with the above estimates, the (average) potential evapotranspiration in the vicinity of the lake has been estimated by Platt (1955) to be between 480 and 500mm/year via the Thornthwaite (1948) equation.

2.4.10.3 River Runoff

River runoff in the region near the lake has been generally estimated at between 200mm and 300mm (per unit catchment area) per year by Hyvärinen and Kajander (2005). However, Kuusisto's (1975) data for the period 1938 – 1973 suggest a higher annual mean runoff of at least 378mm per unit area of the combined Yläneenjoki and Pyhäjoki subcatchments (i.e., 766mm per unit area of the lake). Kuusisto’s (1975) river flow estimates are mostly based on indirect observations from a nearby river (Aurajoki) catchment and relationships derived from three years of direct observations from the Yläneenjoki and Pyhäjoki Rivers.

Flow in each of the three rivers is calculated based on daily river stage measurements at weirs and associated ratings curves. The ratings curves are recalculated from time to time (OIVA – Environment and Spatial Information Services, 29 Dec 2011).

2.4.10.4 Direct Runoff

Direct runoff (the combination of overland runoff and interflow) to the lake was estimated by J. Järvinen for the ungauged parts of the catchment using the runoff per unit area values obtained from the flow volumes based on measurements at the weirs on the Yläneenjoki and Pyhäjoki Rivers (J. Järvinen, pers. comm., 2011). In general, true overland runoff is seldom measured in any catchment, though overland flow, interflow, and subsurface storm flow have been researched; error estimates are lacking for the direct runoff component and further research is needed (Winter, 1981).

2.4.10.5 Changes in Lake Storage

The lake stage water levels of Lake Pyhäjärvi are measured daily at Kauttua, i.e., at the north of the lake (near the outflow to the Eurajoki River). Hyvärinen et al. (1973) comment that reasonably strong seiche oscillations (up to 5cm) can occur in Lake Pyhäjärvi due to its large exposed surface, that the influence of this is only minor for water budgets over extended periods of time, and that the uncertainty on each of the four water level recorders they used was ± 2mm.

2.4.11 Local Environmental/Governmental Agencies

Several organizations collaborate to manage the water in the watershed. Research (related to food systems, water quality, and restoration) in the watershed is conducted by Pyhäjärvi Institute. The municipalities of Säkylä, Yläne, and Eura provide water and wastewater services to residents and deal with groundwater contamination in their respective areas (Säkylä east of the lake, Yläne to the south, and Eura to the west and north). Varsinais-Suomen ELY (i.e., Southwestern Finland's regional economic development, transportation and environmental organization) governs the region around Lake Pyhäjärvi, and the Finnish Environment Institute (SYKE) oversees environmental issues for the entire country. Water resources management in Finland falls under the European Union Water Framework Directive (European Commission, 2000). The Directive is an innovative, legally-binding set of environmental guidelines for EU member states that implements integrated, catchment-based, water resources management over a time scale of more than 25 years (Sigel et al., 2010; Holzwarth, 2002). Finland is obligated to assess, monitor, and remediate the water quality of surface water and groundwater resources.

2.4.12 Restoration of Lake Pyhäjärvi

Similar to the situation of the Baltic Sea (e.g., Savage et al., 2010), impacts of eutrophication on Lake Pyhäjärvi increased in the second half of the 20th Century due to intensified agricultural production coupled with the use of industrial fertilizers (Räsänen et al., 1992; Rautio, 2009). For example, Lepistö et al. (2008) noted the increasing incidence of cyanobacterial blooms since the late 1980's. Agricultural practices regarding fertilizers, pesticides, and herbicides are governed by the EU agri-environment programme to protect water quality (Ventelä et al., 2007). Local environmental organizations have been active in addressing eutrophication concerns by initiating measures to reduce the amount of phosphorous in Pyhäjärvi catchment waters: filtration ditches have been constructed, municipal wastewater treatment systems have been expanded, and reduction of the lake's internal load has been achieved by selective fishing (Ventelä et al., 2007; cit. Kirkkala, 2001). Analysis of groundwater exchange with Lake Pyhäjärvi is needed because some of the rural wastewater and agricultural runoff likely travel via groundwater pathways into the lake. The nutrient load borne by groundwater has previously been calculated indirectly. Estimating the net groundwater discharge component of the lake's water budget may allow for better estimates for this loading source.

2.4.13 Previous Studies at Lake Pyhäjärvi

Several studies on the hydrology and hydrogeology of Lake Pyhäjärvi have been published in recent decades. A preliminary study by Hyvärinen et al. (1973) calculated evaporation for the lake using a water balance equation for 1971 and 1972, compared these results to evaporation estimates via Shuliakovski's (1969) method, and noted how the shallow nature of Lake Pyhäjärvi led to an earlier increase in evaporation in spring and an earlier decrease in fall, compared to a deeper, nearby lake. As noted above, Kuusisto (1975) followed this study with a series of water balances for the years 1938 to 1973, calculated monthly pan relationships from about half of this period for the Jokioinen station Class A pan, and estimated the evaporation from the lake from December to April to be 40mm via the Shuliakovski (1969) formula. Many of Kuusisto's (1975) water balance estimates were based on indirect component (evaporation, river runoff, and direct runoff) estimates for the first thirty-three years of the study; only one of nine precipitation stations was operational for the entire study period. Monthly standard deviations and their sum were used by Kuusisto as a measure of variability for the components of the water balance. Kuusisto's work also assessed the water level regulation and Eurajoki flow rates needed for industry (Eronen et al., 1982). Järvinen (1978) added two years and two lakes to the Hyvärinen et al. (1973) comparison and calculated Class A evaporation pan coefficients relative to the Shuliakovski (1969) method evaporation for three stations near Pyhäjärvi, commenting generally that the water balance method was the least reliable (compared with the Shuliakovski and floating evaporimeter methods), and that data from a floating evaporimeter at

Pyhäjärvi were unavailable (spoiled by waves). Eronen et al. (1982) reviewed the above studies in a discussion of the hydrology of the lake in their article on the post-deglaciation history of the lake. Attention to groundwater in the above studies is limited to the comment by Hyvärinen et al. (1973) that bank storage was of "minor importance" due to consistent lake water levels, and comments by Järvinen (1978) that hydraulic gradients indicated discharge in some locations but never recharge conditions. Artimo (2002) used MODFLOW, MODFLOWP, and MT3D to model the transport of PCE in the Honkala Aquifer adjacent to the lake, including the simulation of groundwater flowpaths terminating in the lake and prediction of future concentrations in the aquifer. Ventelä et al. (2007) discussed restoration efforts to combat the eutrophication of Lake Pyhäjärvi (which is associated with high external nutrient loads) and calculated phosphorus budgets. Rautio (2009) and Rautio and Korkka-Niemi (2011) recently located shoreline groundwater seeps (using temperature and geochemical anomalies) and measured fluxes using seepage meters, and Rautio (2009), Korkka-Niemi et al. (2011), and Rautio and Korkka-Niemi (2011) verified groundwater discharge using chemical and isotopic analyses. An attempt at quantification of the amount of groundwater exchange via the inclusion of a groundwater component in the Lake Pyhäjärvi water budget builds on the work of these scientists and is necessary to refine phosphorus budgets. Assessment of the magnitude of the groundwater contributions to Lake Pyhäjärvi will likely assist water managers.

Table 2.1: An introduction to Lake Pyhäjärvi and its watershed.

Lake Pyhäjärvi	
Lat./Long. Extent[*] (Finland KKJ Zone 1 Extent)[†]	60°54' – 61°06' N; 22° 09' – 22° 25' E (6755058 – 6777624m N; 1562420 – 1576411m E)
Lake Area[‡]	155 km^2
Coastline Length[**]	88 km
Volume[*]	8.49 x 10^8 m^3
Mean Depth[*]	5.5 m
Maximum Depth[*]	26 m
Length[††]	25.5 km
Width[††]	9 km
Water Level Regulation (1960 - 2010)[‡]	44.47 m – 45.39 m
Mean Water Level[‡]	44.9 m
Watershed Area[*]	616 km^2
Yläneenjoki River	
Length[‡‡]	36 km
Catchment Area[***]	234 km^2
Pyhäjoki River	
Length[†††]	15 km
Catchment Area[***]	78 km^2

[*] Ventelä et al. (2007).

[†] Employed Viestikallio Tools (Aarnio, S.A.) to transform coordinates.

[‡] OIVA – Environment and Spatial Information Services (29 Jul 2011, 8 Sep 2010); N60 datum.

[**] Rautio and Korkka-Niemi (2011).

[††] Järvinen (1978).

[‡‡] Koivunen (2004).

[***] Tarvainen and Ventelä (2007).

[†††] Koivunen et al. (2006).

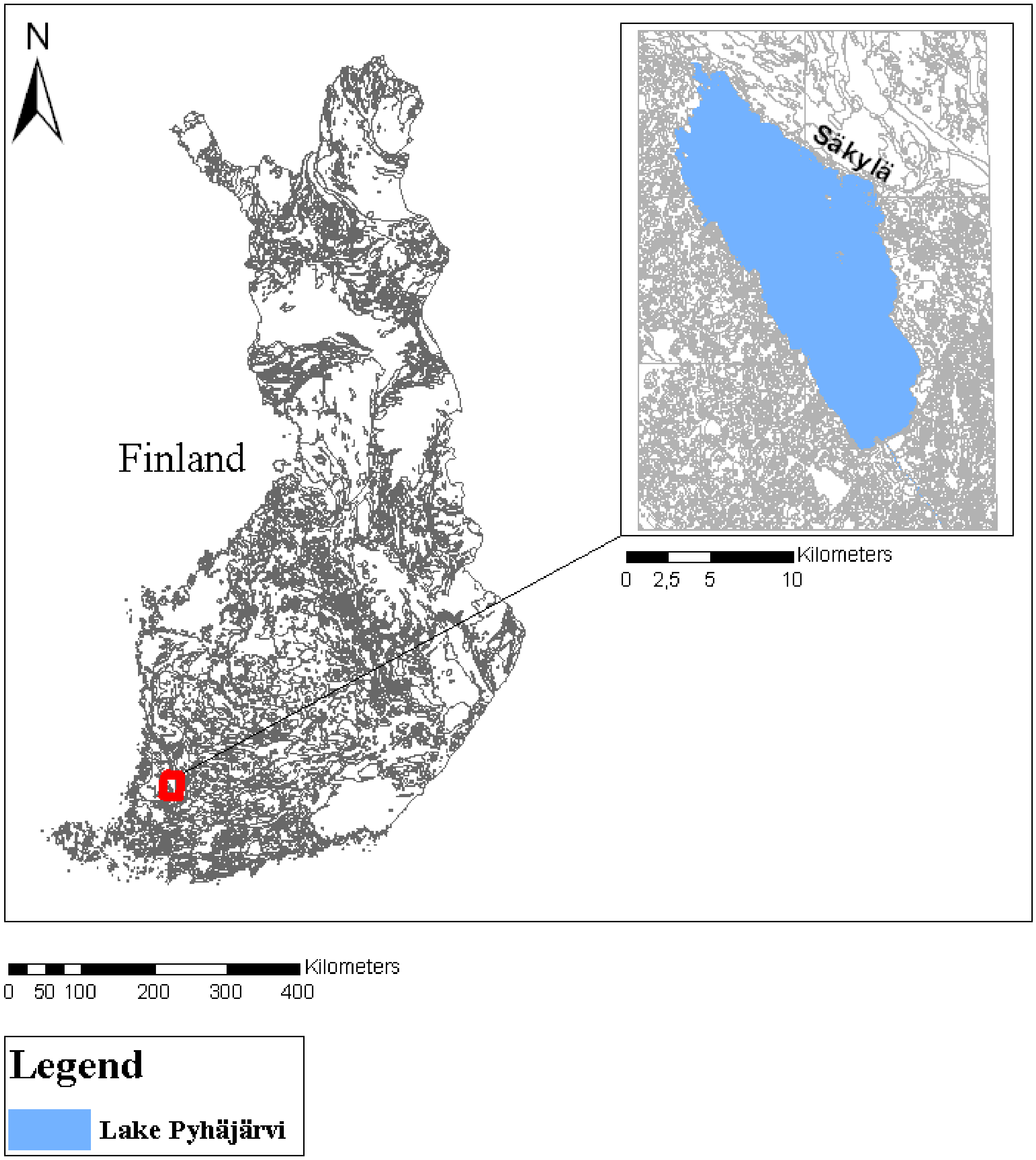


Figure 2.1: Index map of the location of Lake Pyhäjärvi (©GTK, 2008a; ©GTK, 2008b).

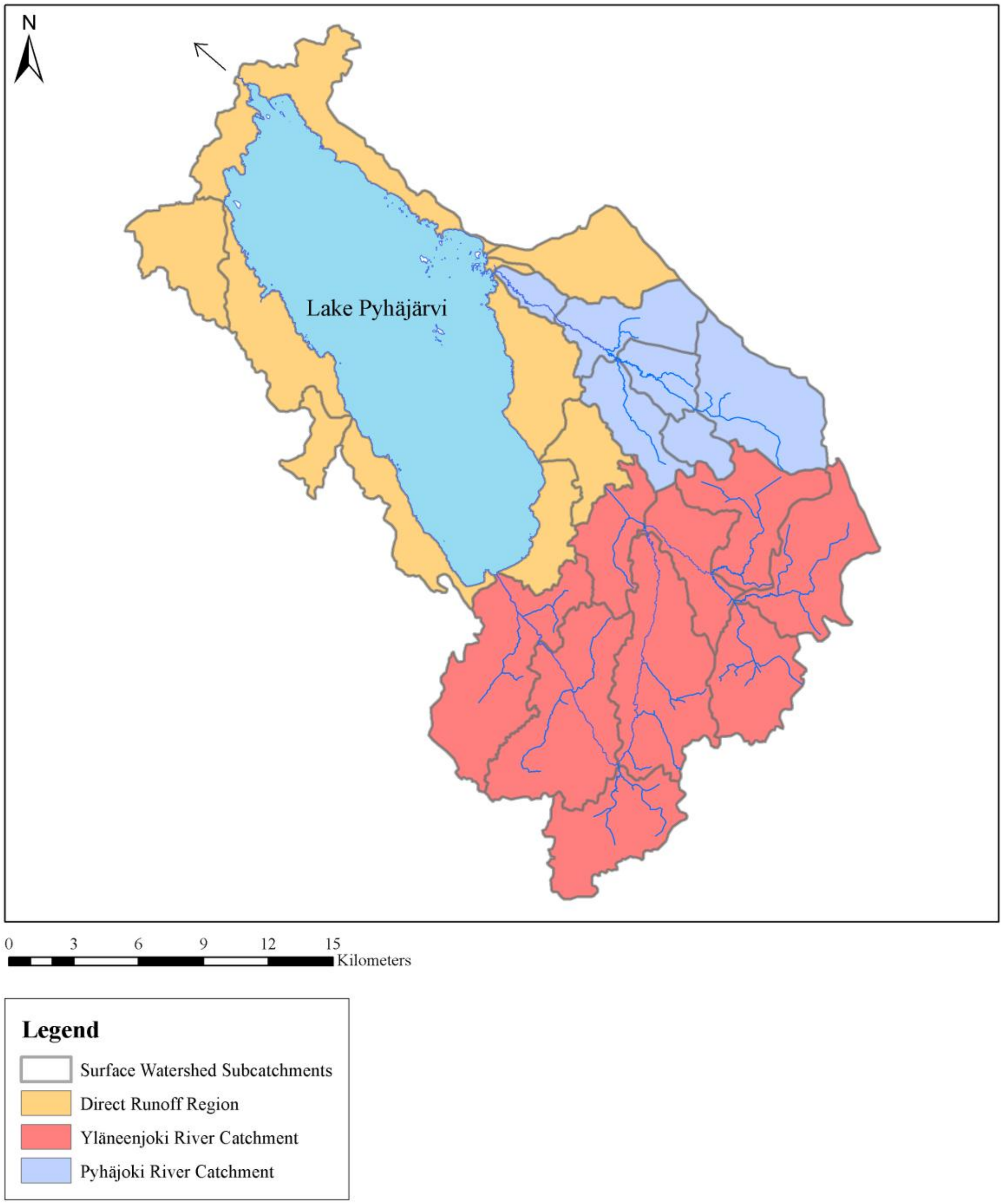


Figure 2.2: The Lake Pyhäjärvi watershed (©MML, 2009a; ©SYKE, 2010).

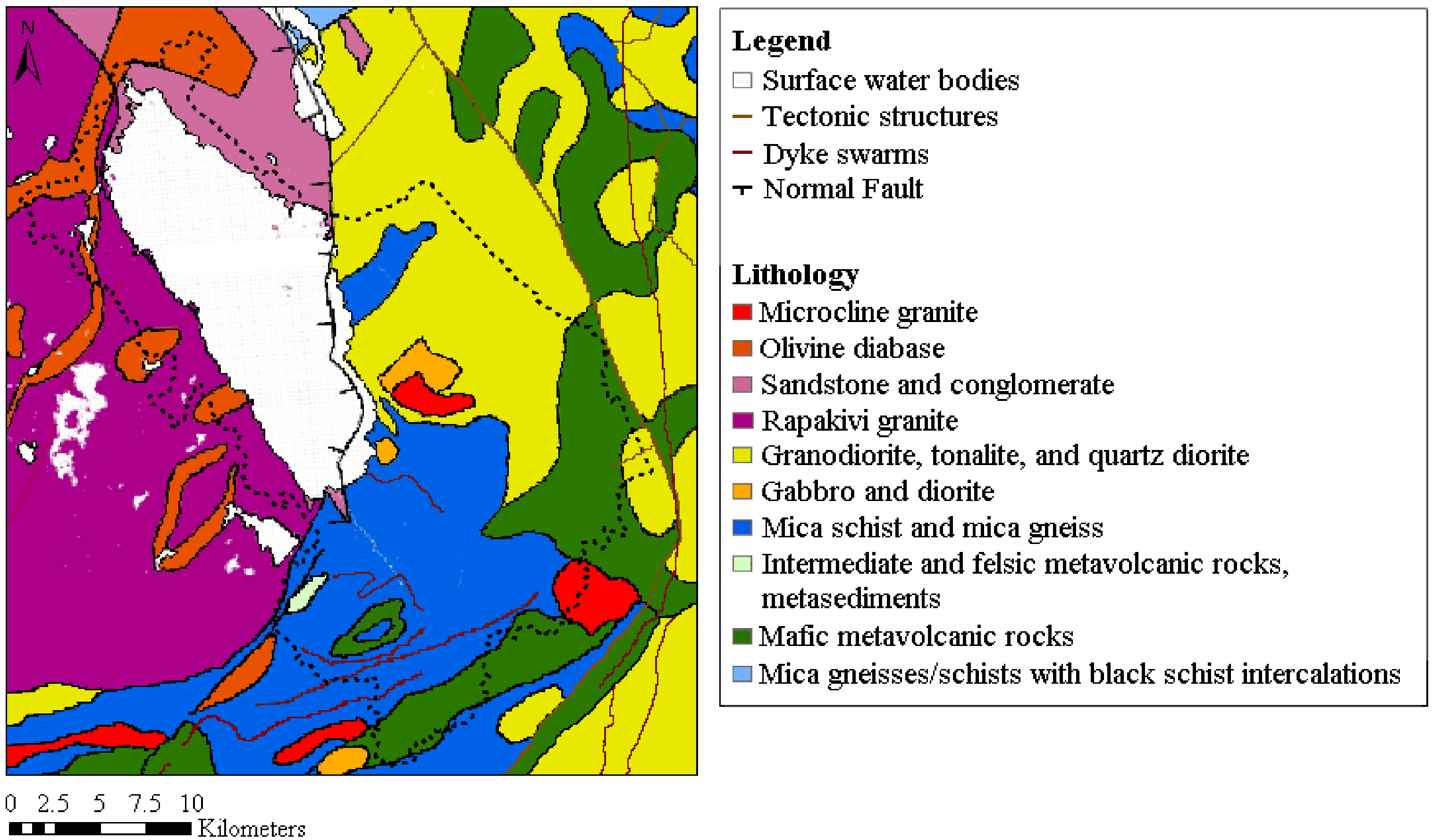


Figure 2.3: Bedrock geology of the Lake Pyhäjärvi watershed (after Korsman et al., 1997; ©GTK, 2008a; ©SYKE, 2010).

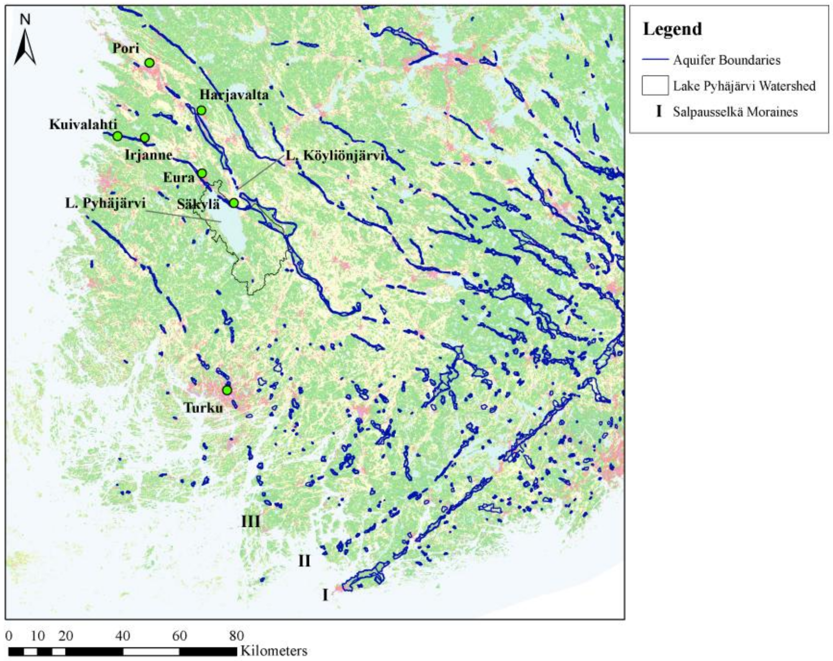


Figure 2.4: Naming conventions for the eskers near Lake Pyhäjärvi (©SYKE, 2004; ©SYKE, 2009). The conventions are after Lindroos et al. (1983).

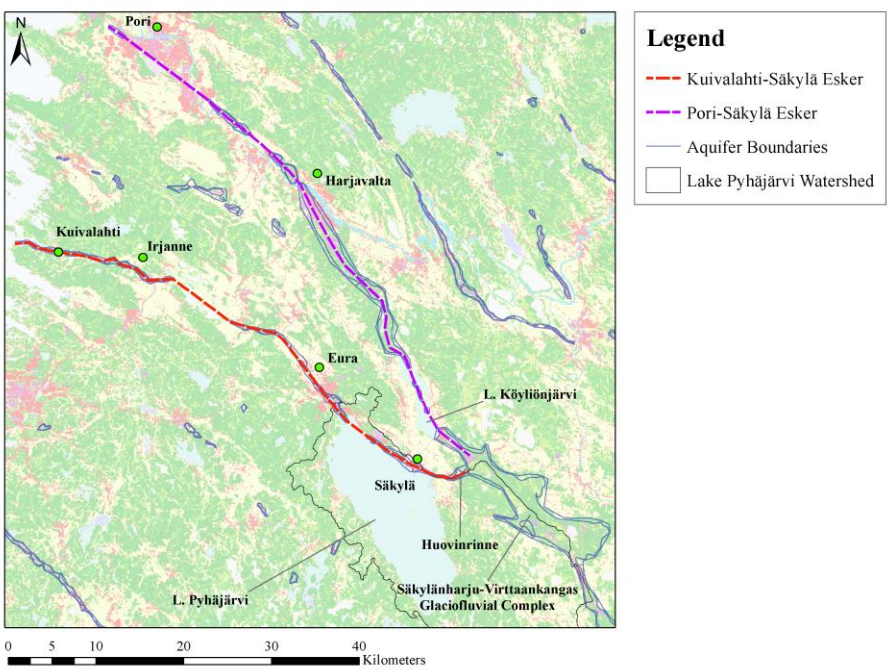


Figure 2.5: Aquifers and glaciofluvial deposits in SW Finland (©SYKE, 2004; ©SYKE, 2009).

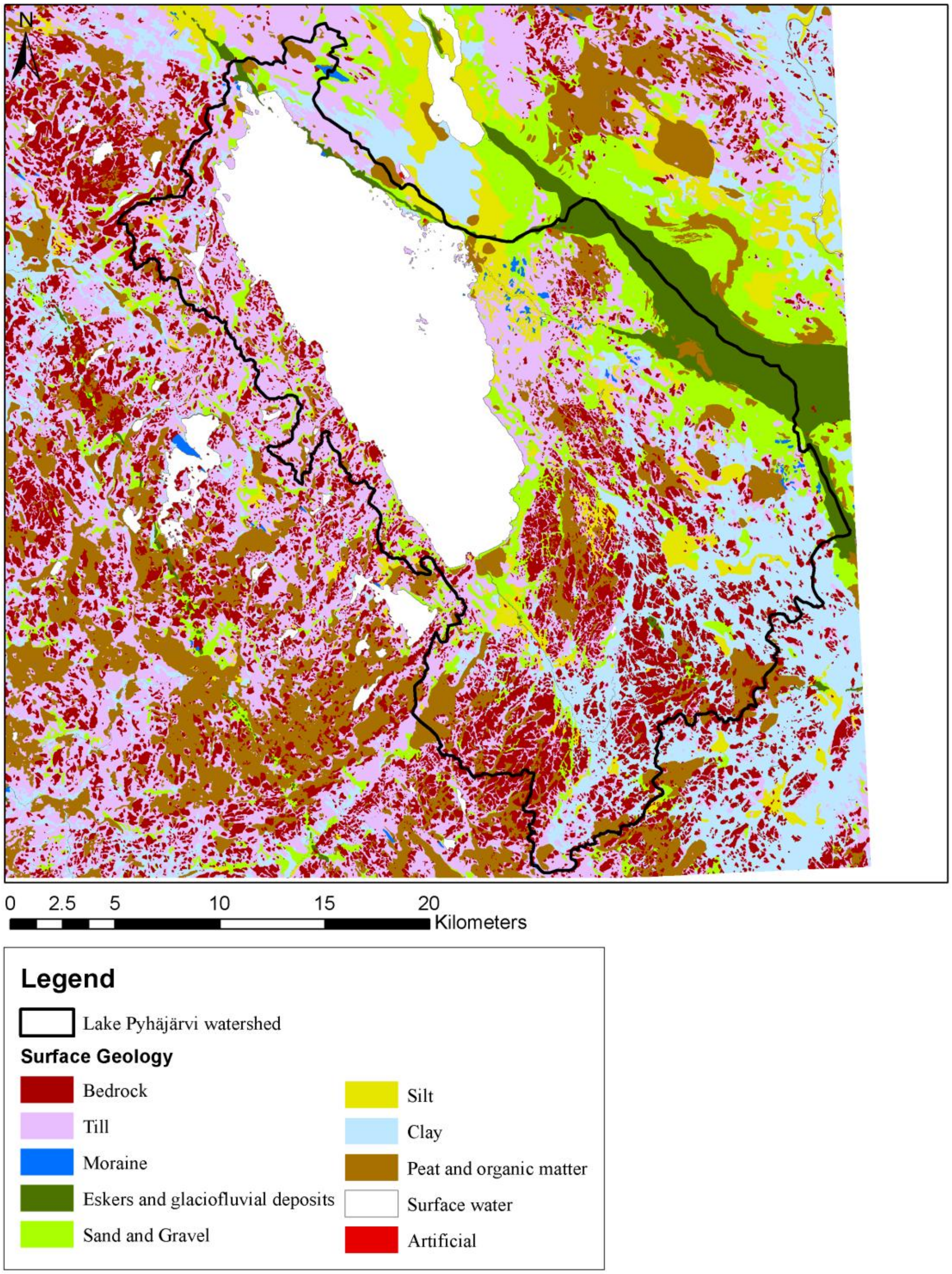


Figure 2.6: Surficial geology of the Lake Pyhäjärvi watershed (©GTK, 2008b; ©SYKE, 2010).

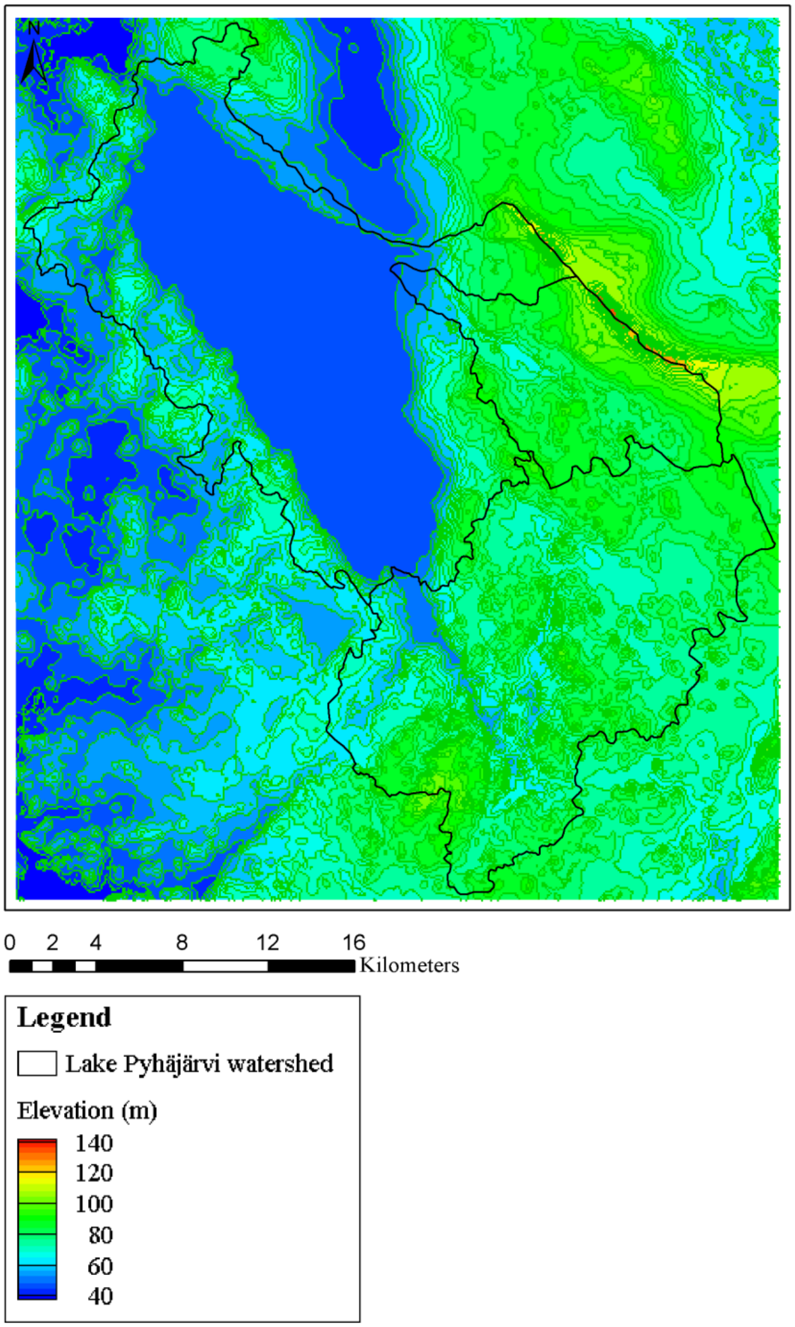


Figure 2.7: Topography of the Lake Pyhäjärvi watershed (©MML, 2009c). The elevations are relative to the N60 datum.

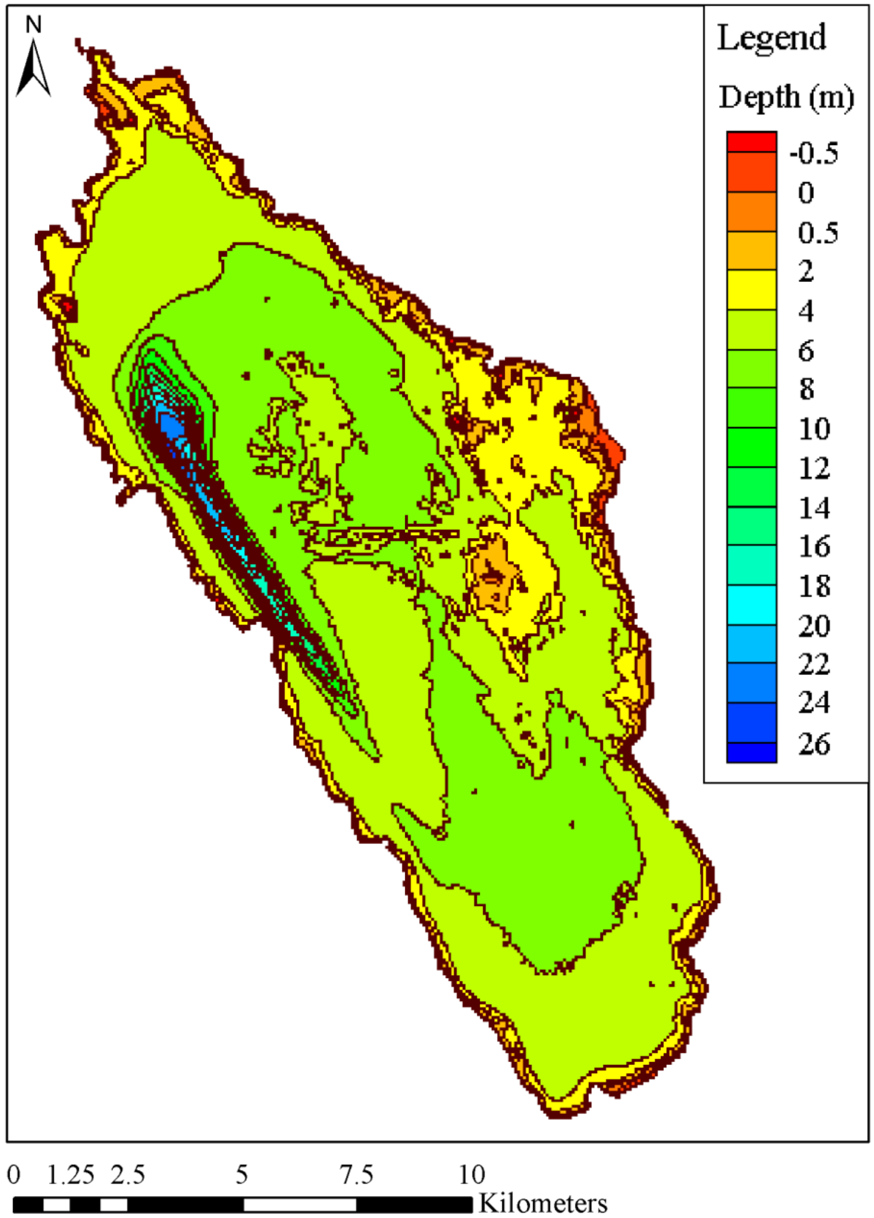


Figure 2.8: Bathymetry of Lake Pyhäjärvi (©MML, 2009b). The depths are relative to the average lake surface elevation (44.9m, relative to N60 datum).

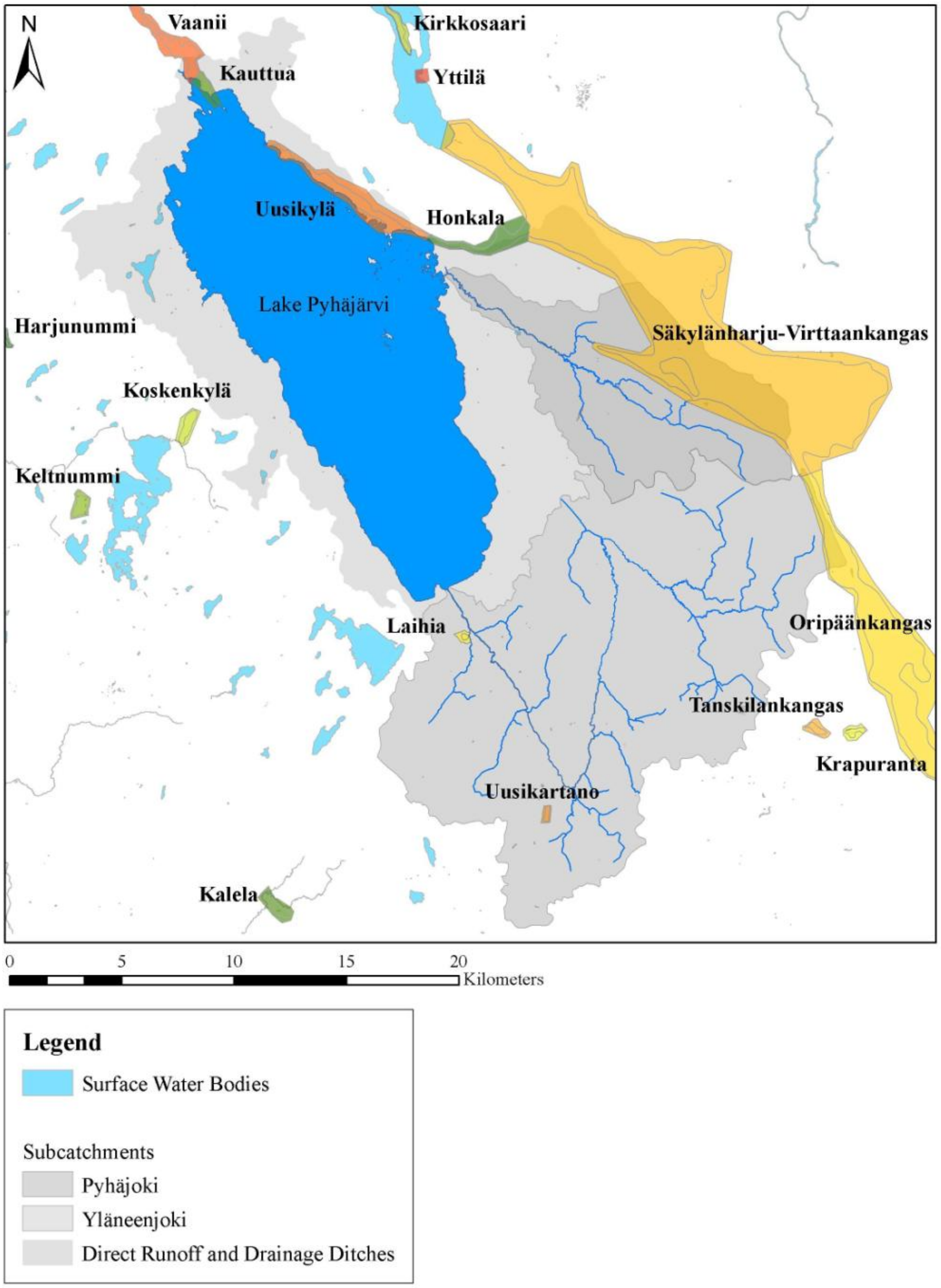


Figure 2.9: Overburden aquifers in the vicinity of Lake Pyhäjärvi (©GTK, 2008b; ©SYKE, 2009; ©SYKE, 2010). The rivers were drawn using Peruskartta maps (©MML, 2009a).

Chapter 3 - Methods

3.1 Introduction

This study was composed of two main parts: i) field work, and ii) computer mapping and data analysis. Field work at Lake Pyhäjärvi began in autumn 2008 and ended after the summer of 2010, for the purposes of this study. The initial reconnaissance work to locate groundwater discharge into the lake, and the installation of seepage meters and mini-piezometers, is described by Rautio (2009). Field work during the summer of 2010 included a well survey (measuring water levels and GPS coordinates of 86 wells), topographic elevation surveying of 35 well casing tops, and shoreline reconnaissance of nearshore lakebed soil types and shoreline water electrical conductivity between Säkylä and Kauttua. Computer and analytical work included the following: correcting the GPS positions of wells; estimating topographic elevations for some wells; contouring topographic maps to estimate lake area fluctuations; calculating the Darcy flux of groundwater through the Honkala Aquifer of the Kuivalahti-Säkylä tributary esker into the lake, determining its uncertainty, and drawing an associated flownet; and calculating several versions of a water balance. Two water balances were conducted to estimate the net groundwater discharge into the lake based on two different direct runoff estimation methods. An alternative water balance (which calculated the evaporation component) was also developed to show the impact of neglecting the groundwater component. Finally, uncertainty estimates were made for all of the water balance components.

3.2 Field Methods

3.2.1 Well Water Levels and Elevations Survey

A well survey was conducted during the summer of 2010. The survey consisted of measuring water levels (Solinst water level tape) and global positioning system (GPS) coordinates (Garmin eTrex GPS) during three phases: i) Locating wells in the Säkylä area that were on a list from the Varsinais-Suomen Ympäristökeskus and used during sampling for PCE contamination in the Honkala Aquifer (28 of the 92 listed), ii) finding unlisted wells by inquiring among home and cottage residents, and locating unused public wells (59 wells in total), and iii) measuring water levels in Amcor Plastics Oy (two wells) and Huovinrinne military area wells (11 wells – measurements were made by K. Korkka-

Niemi and A. Rautio, 8 Jul 2010). Some information was gained through interviewing local residents about well yields and bedrock depth.

The top elevations of 35 wells from phases i) and ii) were surveyed in late July / early August 2010, mostly in the Säkylä area. Eight of these were wells on the Varsinais-Suomen Ympäristökeskus list pertaining to PCE concentrations that were lacking a recorded elevation. University of Helsinki survey equipment (Nikon AX-2S auto level, ±2.5mm) was employed along with benchmarks identified on the Peruskartta maps, and survey circuit errors were calculated as described in Singh et al. (2000).

3.2.2 Shoreline Analyses

Groundwater discharge into the lake has been suggested by previous researchers based on measurements of hydraulic head gradients between shallow shoreline groundwater in mini-piezometers and the lake, and has been verified by anomalies in the water's electrical conductivity, pH, and temperature in addition to seepage flux measurements and geochemical (isotopic and PCE concentration) analyses (e.g., Rautio, 2009; Korkka-Niemi et al., 2011; Rautio and Korkka-Niemi, 2011). Field work during the autumn of 2008 identified three possible near-shore locations of significant groundwater discharge from the esker into the lake near Säkylä, and winter mapping (early 2009) of open water at the shoreline indicated additional locations, four of which were later instrumented (Rautio, 2009). Appendix C shows the four sites farthest to the east, which all exhibited groundwater discharge (Rautio, 2009).

Field work in 2009 and 2010 included direct measurement of seepage at known groundwater discharge locations and a survey of suspected locations. Seepage meters and mini-piezometers were constructed similar to those described by Lee and Cherry (1978) and installations followed their procedures (Rautio, 2009). Groundwater discharge into the seepage meters' collection bags was verified by measuring the electrical conductivity of the water using a YSI 600XLM-V2-M multiparameter probe. Reconnaissance of shallow near-shore sediment at several locations between Säkylä and Kauttua along the northwestern shoreline of the lake was conducted during the summer of 2010 with a hand auger and a Russian peat corer. Samples were inspected for their general sediment type, mainly at locations of known or suspected groundwater discharge (e.g., areas discovered to be ice-free in winter). Electrical conductivity measurements were made *in situ* at the shoreline with a

YSI 600XLM-V2-M multiparameter probe near Kauttua and several other sites of suspected groundwater discharge.

3.3 Computational Methods

3.3.1 GPS Locations

The GPS locations of wells were adjusted with respect to format and accuracy. Transformation of GPS coordinates from Finland KKJ Zone 3 (YKJ) to Finland KKJ Zone 1 was achieved by using the Online FGI Coordinate Transform Service of the National Land Survey of Finland (Finnish Geodetic Institute, 2008). Due to the inaccuracy (±6m to ±31m, depending on the number of satellites in view) of the Garmin eTrex GPS device employed in the field to record well locations, some GPS positions required manual correction using Peruskartta maps in ArcMap 10 (ESRI, 2010) GIS software.

3.3.2 Well Top Elevation Estimates

A MATLAB 7.11 (MathWorks, 2010) script was written to interpolate a ground surface elevation for 38 wells (from phase (ii) in section 3.2.1, above) for which this information was lacking. The program interpolated the value at the coordinates of each well from topographic elevation points (MML, 2009c) within a 400 by 400m square with the well at the centre. The interpolated elevation values (approximately ±1m) were compared to manual estimates made by rough interpolations on Peruskartta topographic maps in ArcMap, and the manual estimate was chosen if the interpolated value seemed unreasonable.

3.3.3 Assessing Variation of the Honkala Aquifer Water Levels

The available water levels at 17 wells in the Honkala Aquifer were analyzed in order to verify their consistency, especially in the years since Artimo's (2002) assessment. Data were obtained from OIVA – Environment and Spatial Information Services (3 Dec 2010) for the time period from 1 Sep 1996 to 1 May 2010 and supplemented with measurements made on 29 Jun 2010 and 8 Jul 2010. Data for 10 wells were available from 1 Sep 1996 to 8 Jul 2010 at a general interval of one to two months (excluding winter), while seven wells had shorter time series. The average water level and standard deviation were calculated for each well. Outlier measurements were considered to be those that differed from the average by over 2m, as well as those that differed from the average by over 0.5m on two dates (1 May 2000 and 1 Jan 2007) that exhibited supposed anomalous readings in multiple wells simultaneously. Variations of water level within each calendar year were calculated for each well as the difference between the maximum and minimum recorded water levels, excluding supposed outliers. The maximum variation and the average variation within one calendar year were then calculated from this set of differences. This was done in order to compare the results to those of Artimo (2002).

3.3.4 Assessing Variation in Lake Area

Variation in the area of the lake due to changes in lake stage was assessed in order to ascertain whether the uncertainty on the lake area value used to normalize some components of the water balance was significant with respect to their error estimates (i.e., influenced the average relative uncertainty percentages for those components by more than 1%) or could be neglected. The lake areas for the regulated range of lake stages were calculated using ArcMap 10, and the interpolation of elevation data was verified by comparing the results with those from Tecplot 10 (Amtec Engineering, Inc., 2003). The elevation points (from the topographic [MML, 2009c] and bathymetric [MML, 2009b] datasets) along the shoreline of the lake within the 40 and 50m range (relative to the N60 datum) were selected in ArcMap and then kriged (ordinary kriging, exponential semivariogram, 5m cell size, variable search radius, 20 points). The 40 to 50m range was merely a buffer around the regulated range of lake stage elevations. The resulting file was then contoured within the 1m range of regulated lake stage elevations, allowing the areas between contours and the cumulative areas to be calculated. A similar procedure was undertaken using Tecplot in order to verify the ArcMap results: A set of points consisting of all bathymetric points and one in five topographic points within about 500 m of the shoreline was kriged using the default settings (range of 0.3, linear drift, octant point selection, 8 points) for a domain of 500 by 500 cells covering a region 16.2km E-W by 24.6km N-S and then contoured over the regulated range of lake stages. The Tecplot contour map was georeferenced in ArcMap and then compared with the ArcMap contouring results. The lake area stated in the OIVA – Environment and Spatial Information Services (10 Aug 2010) database was compared to the maximum and minimum estimates from the ArcMap contours. The absolute value of the maximum of the differences between these two estimates and the area employed was used to calculate the magnitude of the relative error on a water balance component at which the lake area uncertainty would influence the component's relative error by more than 1%.

3.4 Darcy's Law Calculations

Four cross-sections (Appendix D) oriented roughly perpendicular to the long axis of the Kuivalahti-Säkylä tributary esker that were developed by A. Artimo (unpublished report, 1998) were used to calculate possible fluxes of groundwater through the Honkala Aquifer into Lake Pyhäjärvi (Figure 3.1). It was assumed that groundwater flow was essentially in the direction of the long-axis of the esker. The Darcy flux was calculated via

$$q = -K\frac{dh}{dl}, \tag{3.1}$$

where q is the Darcy flux (m/s), K is the hydraulic conductivity (m/s), and *dh/dl* is the hydraulic gradient, i.e., the difference in head between two points divided by the distance between them. The volumetric flow rate through the esker between each cross-section pair was calculated as:

$$Q = |q \times A_{avg}|, \tag{3.2}$$

i.e., the absolute value of the product of the Darcy flux (q) and the average of the areas of saturated thickness on the two cross-sections (A_{avg}). The normalized contribution of the groundwater discharge from the esker, i.e., the flow per unit area of the lake, was estimated by dividing the Q estimates by the (presumed static) area of the lake (A = 155.18932km^2; OIVA – Environment and Spatial Information Services, 10 Aug 2010).

The hydraulic conductivity value was selected based on values used in groundwater models of sites near Lake Pyhäjärvi and their supporting measurements or literature values. A hydraulic conductivity value of $K = 1 \times 10^{-3}$m/s was chosen as a maximum of the range (5.8×10^{-10}m/s – 1.2×10^{-3}m/s) employed by Artimo (2002) during his modelling of the Honkala Aquifer and its surroundings, and it compares with the range (10^{-4} – 10^{0} m/s) used by Artimo et al. (2003) for modelling coarse glaciofluvial sediments in the geomorphologically connected Virttaankangas complex, and with literature estimates for clean sand and gravel (e.g., Freeze and Cherry, 1979). The range given by Artimo (2002) encompasses all sediment types present in a model domain that extends north and south of the esker: the larger hydraulic conductivity values correspond to “gravel” and “sand / gravel” units at the core of the esker while the smaller values correspond to “clay / silt” deposits beside it. Artimo (2002) and Artimo et al. (2003) estimated hydraulic conductivity based on samples from boreholes, sedimentological trends, and literature values. The coarse-grained esker core of the

Honkala Aquifer is likely to be quite permeable, as indicated by the available borehole data and cross-sections (which show that the aquifer is composed of gravel, gravelly sand, and sand - A. Artimo, unpublished report, 1998), and well-sorted into coarse sediment fractions if it was formed by glaciofluvial meltwater. Thus, the choice of a hydraulic conductivity value of 1×10^{-3}m/s seems reasonable.

The hydraulic gradients were estimated based on the difference between the average water levels of each pair of wells in the centre of the cross-sections and the horizontal distance between them. The exception to this is the Honkalan Ottamo (Honkala production) well, for which only a single water level measurement was available. Ten water levels over the period 10 Oct 1999 – 25 Sep 2007 were obtained for the wells HP1, HP2, and HP4 (see Figure 3.1) (OIVA – Environment and Spatial Information Services, 6 Dec 2010).

The estimates of the cross-section area of the esker were obtained by scanning the cross-section figures into PDF files and then using Adobe Acrobat 8 Professional to calculate the area. The actual areas of reference rectangles on the cross-sections were determined and combined with the area of the reference rectangle from Adobe Acrobat to produce a ratio of actual square metres to digital square millimetres. The areas of the esker cross-sections were outlined below the water table in Adobe Acrobat, and the esker was extrapolated in terms of width since the cross-sections do not show the entire esker. The contact between the gravel and the moraine could only be roughly interpreted because of the quality of the figures. The Area tool in Adobe Acrobat was used to calculate the area of the coarse sediments of the esker, and then the ratio was applied to estimate the actual area. Despite cross-sections 1 through 3 not being entirely perpendicular to the long-axis of the esker, the areas were assumed to be the same for truly perpendicular cross-sections at the same location.

A plan view flow net for the Honkala Aquifer was also drawn to portray the flow estimated by the Darcy's Law calculations. An attempt was made to follow the general principles for graphical construction (e.g., Freeze and Cherry, 1979): for instance, that equipotential lines are perpendicular to impermeable walls, that flowlines are generally parallel to each other and to impermeable walls, and that flow lines converge when flow per unit width (in this case thickness) increases. The esker was assumed to be homogeneous and anisotropic, with dominant flow along its long axis. The flow rate per unit width was calculated via (Freeze and Cherry, 1979):

$$Q_w = \frac{m}{n} KH, \tag{3.3}$$

where Q_w is the flow rate per unit width, m is the number of streamtubes, n is the number of equipotential intervals, K is the hydraulic conductivity, and H is the total head drop. Finally,

$$Q_{norm} = \frac{Q_w w}{A}(3.1536 \times 10^7 s/yr)(1000mm/m), \tag{3.4}$$

where Q_{norm} is the groundwater discharge through the esker in mm per unit area of the lake, w is the average thickness of the esker, and A is the area of the lake. The average thickness of the esker was estimated via

$$w_i = \frac{A_i}{l_i}, \text{ and} \tag{3.5}$$

$$w = \frac{1}{n}\sum_{i=1}^{n} w_i, \tag{3.6}$$

where w_i, A_i, and l_i are the average thickness, the area, and the lateral length of cross-section i, and n is the number of cross-sections (i.e., 4). Thus, the arithmetic mean was employed to estimate the average esker thickness.

3.5 Water Balance

The basic idea behind a water balance is to determine an unknown component (input, output, or stored amount) by solving an equation for a defined region in which all the other variables are known. The conservation of mass equation regarding the rates of water mass transfer into and out of a particular region is as follows:

$$\left(\frac{\Delta S}{\Delta t}\right) = \sum_{i=1}^{n} Q_{in,i} - \sum_{j=1}^{m} Q_{out,j}, \tag{3.7}$$

where ΔS is the change in lake storage volume, Δt is the change in time, $Q_{in,i}$ is the volumetric mass flux of component i water into the region during time Δt, and $Q_{out,j}$ is the volumetric flux out via component j during time Δt. If the change in time (Δt) is multiplied by both sides of the equation, the equation becomes:

$$\Delta S|_t = \left(\sum_{i=1}^{n} V_{in,i} - \sum_{j=1}^{m} V_{out,j}\right)_t, \tag{3.8}$$

thus considering the volumes (V) accumulated within time period t for all components i and j. Expanding the sums and applying the equation to a lake on a yearly basis,

$$\Delta S = \left(V_{R,in} + V_{GW,in} + V_{DR} + V_P\right) - \left(V_{R,out} + V_E + V_{GW,out} + V_{WITH}\right), \tag{3.9}$$

where $V_{R,in}$ is the total annual volume of river influx, $V_{GW,in}$ is the total annual volume of groundwater discharge into the lake, V_{DR} is the total annual volume of direct runoff (overland runoff and interflow) received by the lake, V_P is the total annual volume of direct precipitation, $V_{R,out}$ is the total annual volume lost to outgoing rivers, V_E is the total volume lost from the lake surface to evaporation, $V_{GW,out}$ is the total annual groundwater recharge lost from the lake to adjacent aquifers, and V_{WITH} is the total annual volume withdrawn from the lake by pumping. Dividing by the (presumed static) area of the lake, combining the three river fluxes into a net flux, and rearranging to solve for the difference between $V_{GW,in}$ and $V_{GW,out}$, the above equation becomes:

$$\frac{1}{A}(\Delta V_{GW}) = \frac{1}{A}(\Delta S + V_E + V_{WITH} - V_P - V_R - V_{DR}), \tag{3.10}$$

where A is the area of the lake, ΔV_{GW} is the net annual volume of groundwater received by the lake, and V_R is the annual net volume gained from river flows. Simplifying further:

$$G = h_S + E + W - P - R - DR, \tag{3.11}$$

where all quantities have units of length per unit area of the lake per year, with G representing the net groundwater input, h_S the vertical change in lake stage (higher being positive), E the sum of evaporative losses, W the amount withdrawn by pumping at the Lohiluoma artificial recharge station, P the direct precipitation amount, R the normalized net river flow into the lake, and DR the normalized direct runoff contribution. The equation could be expanded to account for the water possibly drawn from the lake by one vegetable processing plant, a few shoreline residents' pump intakes, water imported into the watershed (e.g., in the form of beverages) that is not exported by the municipal wastewater systems, and the amount lost due to the removal of fish from the lake, if these quantities were not considered negligible. The equation might be enhanced by inclusion of the amount of irrigation water withdrawn from the lake, but this quantity is unknown (K. Korkka-Niemi, pers. comm., 2011).

For the purpose of displaying the water balance components, plots related to a rearranged form of Equation 3.11, i.e.,

$$G + R + DR + P - E - W - h_S = 0, \tag{3.12}$$

were produced. With the exception of the change in storage, these plots display components contributing water to the lake above zero, while components removing water from the lake are shown below zero. Thus the net groundwater discharge component may be seen to provide the balance of the inflows and outflows of the lake for each water year.

The water balance was conducted for each water year between October 1971 and September 2009, as described below. GNU Octave 3.2.4 (Eaton et al., 2008) programs were written to calculate four of the components (storage change, pumping withdrawals, river discharge, and direct runoff) and also the sums of the raw data for the evaporation and precipitation components for each water year. Further calculations were made using spreadsheets. Data used during the water budget were collected at several meteorological and hydrological stations in the vicinity of the lake. Appendix E shows the locations of the stations at which precipitation, evaporation, lake stage, and river discharges were measured. The following describes the estimation of each component of the water budget in greater detail.

3.5.1 Water Levels and Storage

As mentioned above, lake stage water levels are measured in the north of the lake, near the outflow to the Eurajoki River at Kauttua. Daily measurements were retrieved from OIVA – Environment and Spatial Information Services (8 Sep 2010). The difference,

$$h_S = WL_{1\ Oct\ y+1} - WL_{1\ Oct\ y}, \tag{3.13}$$

was calculated between the start of the next water year (y + 1) and the first day of the current water year (y) because 365 (or 366 for a leap year) differences were needed in order to avoid skipping a day's water level between water years. The difference between 1 October and 1 October is equivalent to the sum of the differences between all days of the water year. Storage changes based on lake area variation were assumed negligible. Also, since the water balance was conducted on a per unit lake area basis, changes in storage volume were never calculated explicitly.

3.5.2 Evaporation

Daily Class A evaporation pan measurements were obtained from OIVA – Environment and Spatial Information Services (5 Jun 2010) for the Jokioinen (WY 1957 – 2008) station (location shown in Appendix E). Pan evaporation data were generally available for the months May through September each calendar year, and all available data were summed. A pan coefficient was applied to these Class

A pan data, and then an estimate for the remaining months of the year was added. Thus, the lake evaporation for the water year starting in year y ($E_{lake,y}$) was estimated via:

$$E_{lake,y} = c \times E_{Jok,y} + E_{Dec\ to\ Apr}, \tag{3.14}$$

where $E_{Jok,y}$ is the sum of all daily evaporation pan measurements made during the period of observation of the water year, c is the pan coefficient (0.8), and $E_{Dec\ to\ Apr}$ is Kuusisto's (1975) estimate for the evaporation from December to April. The Jokioinen station was chosen, following Kuusisto's (1975) work. The Mietoinen station could alternatively been selected since both have complete datasets over the time period of interest for the water balance. The mathematical equations derived by Kuusisto (1975) to relate the Shuliakovski (1969) aerodynamic method results for lake evaporation to the Jokioinen pan data were not used because they were considered to be based on too few direct data (measurements over only three years), and the aerodynamic evaporation estimates by no means provide the "true" evaporation. A pan coefficient of 0.8 was supposed to be a reasonable estimate, given the lack of long-term data. This value was chosen based on studies in the United States, where coefficients near the east and west coasts have been found to be of this magnitude (Hounam, 1973; cit. Kohler et al., 1959). The common coefficient of 0.7, which comes from the annual U.S. average (Dingman, 1994), was not chosen due to Lake Pyhäjärvi's proximity to the coast of the Baltic Sea. Its shallow depth may also influence the amount of evaporation. As noted above, pan coefficients (Järvinen, 1978) were only available for three stations for three years each. The "annual" coefficients (i.e., May – Sep) for these three years were all greater than 0.70.

3.5.3 Pumping Withdrawals

The Lohiluma pumping station has a permit to withdraw 5000 m^3/d of water from the lake and the esker sediments at Kauttua to the north of the lake (J. Reko, pers. comm., 2010). Withdrawing nearly the maximum amount daily, the station pumps 1700 m^3 directly from the lake and 3000 m^3 with a production well. Isotope data suggest that the amount withdrawn from the ground nearly all originates from the lake (K. Korkka-Niemi, pers. comm., 2011.). This current withdrawal scheme was applied to all years of the water balance since the OIVA – Environment and Spatial Information Services (15 Jun 2011) database suggests that it has been in operation since 1965. The volume of water pumped from the lake for the irrigation of agricultural fields or non-potable use by individual residents (e.g., for sauna or washing or garden use) is unknown and was not estimated.

3.5.4 Precipitation

The isohyetal method (e.g., Dingman, 1994) was employed for estimates of spatial precipitation volumes and involved contouring point precipitation values and calculating a representative precipitation amount per unit lake area from the percentages of the lake covered by the various contour bands. Daily point measurements were obtained from the Finnish Meteorological Institute (FMI; 24 May 2011) for seven stations (WYs 1971 – 2008; one dataset incomplete) and from OIVA – Environment and Spatial Information Services (13 Oct 2010) for one station (WYs 1990 - 1994). The yearly point precipitation sums from the six or seven stations with available data were contoured in Tecplot 10 using a kriging routine (range of 0.3, linear drift, octant point selection, eight points) for a domain of 500 by 500 cells covering a region 160km E-W by 200km N-S. Each contour map was imported into ArcMap, georeferenced based on the point precipitation station locations, and manually traced over the surface of the lake. A polygon file was generated for each year with the traced contour bands, manually entered contour interval values, and ArcMap toolbox-calculated areas between the intervals (Figure 3.2). The yearly precipitation was calculated (for year *y*) as follows:

$$PA_{i,y} = \left(\frac{LB_{i,y}+UB_{i,y}}{2}\right)\left(A_{i,y}\right), \text{ and} \tag{3.15}$$

$$P_{lake,y} = \left(\frac{\sum_{i=1}^{n} PA_{i,y}}{\sum_{i=1}^{n} A_{i,y}}\right), \tag{3.16}$$

where $PA_{i,y}$ is the product of the average precipitation value in contour interval i (LB and UB denoting lower and upper bounds, respectively) with $A_{i,y}$, the area of the overlap for the interval and the lake; $P_{lake,y}$ is the representative yearly precipitation sum. The sum of the areas of overlap was marginally larger (0.35km^2) than the lake area used elsewhere (see below) due to the inclusion of islands and differences between the calculation methods.

An Online coordinate conversion program, Viestikallio Tools KKY/WGS84/Maidenhead (10mm setting) (Aarnio, S.A.), was used to calculate the Finland KKJ Zone 1 coordinates of the point precipitation stations from the latitude-longitude format obtained from SYKE (H. Sirviö, pers. comm., 2011).

3.5.5 River Discharge

The discharge data for all three rivers connected to the lake were found in the OIVA – Environment and Spatial Information Services (23 Sep 2010) database. The flow rates are listed as daily single measurements (m^3/s). Adjustments were made both to account for several months of missing data and to account for additional drainage to the inflow rivers from ungauged regions of their catchments. There were five months in the 38 years of the water balance that were missing river flow data (two for Pyhäjoki River in WY 1971 – 1972; three for Eurajoki: two in WY 1985 – 1986, one in WY 1998 – 1999). The flow rates for these five months were estimated as follows: First, the average value for the each particular missing month was calculated for the particular river from the set of available amounts for that given month from all 38 water years. Second, the sum of river flow rates from all months except the missing month(s) was calculated for each water year with a complete dataset for the particular river. Since there were three water years with missing data, three lists of sums were calculated (one for the Pyhäjoki River and two for the Eurajoki River). Third, an index for each of these three years was calculated as the ratio of the sum for that year from the particular river to the average from the relevant list. Finally, the estimate for each missing month was obtained by multiplying the index for the particular year (for the particular river) by the monthly average for the particular river.

The river discharge amounts for the Yläneenjoki and Pyhäjoki Rivers for all water years were adjusted to correct for the ungauged parts of the river subcatchments between each weir and the lake. The set of daily flow rates for each year were converted to have units of m^3/d, and the relative yearly flow volume per unit area of the gauged part of the catchment was calculated (for year y):

$$fraction_{r,y} = \left(\frac{\sum_{i=1}^{n} D_{i,r,y}}{A_{r,g}}\right), \quad (3.17)$$

where $D_{i,r,y}$ is the daily discharge (m^3/d) for the i^{th} of n days of the water year for river r, and $A_{r,g}$ is the area of the gauged part of the subcatchment of river r. The yearly discharge was then corrected via:

$$R_{r,adj,u\ y} = \sum_{i=1}^{n}(D_{i,r,y} + [fraction_{r,y}][A_{r,t} - A_{r,g}]), \text{ and} \quad (3.18)$$

$$R_{r,adj,y} = \frac{R_{r,adj,u,y}\left(\frac{1000mm}{m}\right)}{A}, \quad (3.19)$$

where $R_{r,adj,u,y}$ is the adjusted but not yet normalized sum of river flow volumes for river r in m^3 per year, $A_{r,t}$ is the total area of the catchment of river r, A is the area of Lake Pyhäjärvi, and $R_{r,adj,y}$ is the normalized, adjusted inflow from river *r* during the water year starting in year *y*. The adjusted sum for each river was then incorporated into the net river discharge equation,

$$R_{net,adj,y} = R_{Yl,adj,y} + R_{Py,adj,y} - \frac{\sum_{i=1}^{n} D_{Eu,i,y}}{A}(1000mm/m), \tag{3.20}$$

where $R_{net,adj,y}$ is the adjusted net river influx component of the water balance (mm per unit lake area), $R_{Yl,adj,y}$ and $R_{Py,adj,y}$ are the adjusted contributions of the Yläneenjoki and Pyhäjoki Rivers, and $D_{Eu,i,y}$ is the daily discharge (converted to m^3/d) measured on the Eurajoki River on the i^{th} of *n* days of the water year starting in year *y*.

3.5.6 Direct Runoff (Overland Runoff and Interflow)

3.5.6.1 Average Runoff Method

The method used to estimate the amount of direct runoff into the lake (referred to below as the "average runoff method" or "average direct runoff method") was adapted from Eronen et al. (1982), who made a generalized estimate of runoff in the watershed based on river flow in units of volume per unit time per unit area. It is also essentially a rearrangement of the rational method (e.g., Gray et al., 1970) for estimating the peak runoff rate in a watershed for a precipitation event as a product of a runoff coefficient, the rainfall intensity, and the watershed area, though the runoff was calculated for the entire water year in this case. River flow rates were used to develop the direct runoff estimate here because no measurements related to overland runoff or interflow were available. It was assumed that river runoff in the two river catchments would be at least somewhat representative of the runoff regime of the (ungauged) subcatchment areas adjacent to the lake (e.g., in terms of sharing similar rainfall intensities, geology, topographic slopes, and vegetation).

Estimation of the direct runoff was conducted by first calculating the amount of river flow per unit area of river catchment for the two rivers and then applying their average to the areas adjacent to the lake that do not drain into rivers but rather drain directly into the lake. The normalized fraction (for river *r* during the water year starting in year *y*, in mm per unit area of the lake) of river flow per unit (gauged) area of catchment was calculated for each river via:

$$fraction_{r,y} = \left(\frac{1000mm/m}{A}\right)\left(\frac{\sum_{i=1}^{n} D_{i,r,y}}{A_{r,g}}\right), \tag{3.21}$$

where A is the area of the lake in m^2, $D_{i,r,y}$ is the daily discharge (m^3/d) for the i^{th} day of the water year for river r, there are n days in the water year, and $A_{r,g}$ is the area of the gauged part of the catchment of river r. Then

$$DR_{adj,y} = \left(\frac{fraction_{Yl,y} + fraction_{Py,y}}{2}\right)\left(A_{adj}\right), \tag{3.22}$$

where Yl and Py denote the Yläneenjoki and Pyhäjoki Rivers, A_{adj} is the sum of subcatchment areas around the lake (excluding the two river catchments), and $DR_{adj,y}$ is the average direct runoff estimate for those adjacent areas in the water year starting in year y. This represents the height of water (per unit area of the lake) estimated to be contributed by the areas adjacent to the lake that do not drain into the two inflow rivers.

3.5.6.2 PART-Adjusted Runoff Method

While groundwater recharge from a lake has been estimated via river hydrograph separation in at least one study (Demlie et al., 2007), the author is unaware of any studies employing such a technique to estimate direct runoff to a lake. Hydrograph separation results from the Yläneenjoki River were used to calculate an alternative to the average runoff estimate described above. While the average runoff method considered the total river flow from both the Yläneenjoki and the Pyhäjoki Rivers, the alternative method described below considered only the surface water fraction of the Yläneenjoki River discharge. This was because total river flow is composed of overland flow, interflow, and groundwater baseflow, while the direct runoff component of the lake's water balance should strictly represent only overland flow and interflow from subcatchment areas adjacent to the lake. Thus, hydrograph separation provided a way to estimate the direct runoff into the lake by assuming that the gauged Yläneenjoki subcatchment area is a suitably representative analog to the direct runoff regions. The choice of the Yläneenjoki River over the Pyhäjoki River is discussed below. While hydrograph separation was also conducted for the Pyhäjoki River, these results were only used for comparison with those from the larger river and were not used in direct runoff calculations.

The United States Geological Survey (USGS) program PART (Rutledge, 2007) was used to perform hydrograph separation for the Yläneenjoki and Pyhäjoki Rivers (1972 – 2009) using river discharge data from OIVA – Environment and Spatial Information Services (23 Sep 2010). Figure 3.3 provides a hydrograph separation example for the Yläneenjoki River over a short time period. The following summarizes Rutledge's (1998) description of how PART works: The program partitions streamflow into surface flow and groundwater discharge by setting discharge equal to streamflow on days that are at least a certain number of days (*N*) after a precipitation event and where the slope on the graph of the logarithm of stream flow rate vs. time is below a threshold for interflow and surface flow (0.1 log cycles), and then conducts linear interpolation to calculate groundwater discharge between these days. The value for *N* signifies the number of days after a precipitation event during which the stream would be receiving surface/event water (i.e., the length of the recession limb on the hydrograph) and is estimated by Linsley et al.'s (1958) empirical equation,

$$N = A^{0.2}, \tag{3.23}$$

where *N* is the number of days of influence of direct runoff following a hydrograph peak, and *A* is the drainage area above the gauge (in mi^2; Gray, 1970). The PART program checks to make sure that the interpolation does not estimate groundwater discharge to be greater than the measured streamflow.

The inputs to the program include the name of the stream, its catchment area in square miles, and daily mean streamflow measurements (date and volumetric flow rate in ft^3/s). The program assumes diffuse groundwater recharge, negligible regulation and diversion of streamflow, groundwater discharge is occurring only into the stream, and measurement of discharge at a single outflow at the downstream end of the basin; the results are recommended to be used at a scale of at least one year (Rutledge, 1998).

The input files for the two Finnish rivers were created by copying the format from example files included with the program and replacing the date and flow rate columns with the date and flow rates from each. The dates were converted to the required format, and the flow rates were converted to cubic feet per second in the input files; the river catchment areas were also converted to mi^2 and added to the station.txt file. The results from the PART program were manually converted into metric units.

In this revised direct runoff analysis, the subcatchment areas adjacent to the lake were first divided into two types: those discharging through a single (natural or constructed) channel into the lake and those bordering on the lake over broader areas more conducive to transmitting both direct runoff flow and possibly groundwater flow. Figure 3.4 shows the locations of the subcatchments around the lake that are not part of the Yläneenjoki or Pyhäjoki River catchments, and their revised types. The direct runoff for the subcatchments with a single drainage channel was calculated in the same manner as the ungauged parts of the river catchments (cf. Equations 3.17 to 3.19), i.e.,

$$fraction_{Yl,y} = \left(\frac{1000mm/m}{A_{lake}}\right)\frac{\sum_{i=1}^{n} D_{i,Yl,y}}{A_{Yl,g}}, \text{ and} \tag{3.24}$$

$$DR_{single\ drain,y} = (fraction_{Yl,y})(A_{single\ drain}), \tag{3.25}$$

where $fraction_{Yl,y}$ is the relative fraction of Yläneenjoki river flow per unit area of the gauged part of the Yläneenjoki catchment (in mm per unit lake area) during the water year starting in year y, $A_{single\ drain}$ is the sum of the areas of the subcatchments with single drains, and $DR_{single\ drain,y}$ is the total estimated direct runoff estimate for those areas. To this was added:

$$DR_{adj\ area,y} = (fraction_{Yl,PART,y})(fraction_{Yl,y})(A_{adj\ area}), \tag{3.26}$$

such that

$$DR_{total,y} = DR_{single\ drain,y} + DR_{adj\ area,y}, \tag{3.27}$$

where $fraction_{Yl,PART,y}$ is the difference between 1 and the baseflow index (i.e., the estimated percentage of the total flow constituted by overland flow and interflow into the river) from PART for the river Yläneenjoki during the water year starting in year y; $A_{adj\ area}$ is the combined area of the subcatchments bordering the lake to a greater extent than those with single drains; and $DR_{total,y}$ is the total direct runoff estimate for the water year for runoff areas outside of the two river catchments (where direct runoff in the ungauged regions of the river catchments was assumed to enter the rivers rather than the lake). The fractional flow and PART results for the Yläneenjoki River were chosen due to the surficial geology of most the subcatchments adjacent to the lake seeming to be finer grained; the larger river's finer sediments were supposed to be more representative than the coarser nature of the Pyhäjoki catchment. Appendix F shows that the Pyhäjoki subcatchment has twice the percent area of sand and gravel of the direct runoff and single drainage channel regions. The appendix also shows that the Yläneenjoki subcatchment has more clay and bedrock than the direct runoff and single drainage channel regions, while the latter subcatchments have considerably more till. The Yläneenjoki subcatchment may be considered reasonably representative of the direct runoff and single drainage channel subcatchments if the till is assumed to exhibit low permeability. This method is referred to below as the “PART-adjusted runoff method” or “PART-adjusted direct runoff method.”

3.5.7 Lake Area

The area of Lake Pyhäjärvi was used to normalize the river discharge measurements and the direct runoff estimates. The area used was the one listed in the information for the lake in the OIVA – Environment and Spatial Information Services (10 Aug 2010) database, i.e., $A = 155.18932\text{km}^2$. A slightly different value was used in the isohyetal precipitation calculations, as noted above. Variation in the area of the lake due to changes in lake stage was assumed negligible. This assumption was assessed as indicated above.

3.5.8 Average Total Inflow and Outflow

The magnitude of the net groundwater discharge component of the water balance was assessed relative to other inputs to the lake by comparing it to the average total inflow to the lake. The average total inflow (neglecting any groundwater contributions) was calculated via:

$$TI_{AVG} = \frac{\sum_{y=1971}^{2008} TI_y}{n}, \text{ and} \tag{3.28}$$

$$TI_y = R_{Y,y} + R_{P,y} + P_{isohyet,y} + DR_y, \tag{3.29}$$

where TI_{AVG} is the average from all n water years of the water balance, and TI_y, $R_{Y,y}$, $R_{P,y}$, $P_{isohyet,y}$, and DR_y are (respectively) the total inflow to the lake, the adjusted Yläneenjoki River discharge, the adjusted Pyhäjoki River discharge, the isohyetal precipitation estimate, and the direct runoff estimate based on the average runoff for the water year beginning in year y. Similarly, the average total outflow (neglecting groundwater flow) was calculated via:

$$TO_{AVG} = \frac{\sum_{y=1971}^{2008} TO_y}{n}, \text{ and} \tag{3.30}$$

$$TO_y = R_{E,y} + E_y + W_y, \tag{3.31}$$

where TO_{AVG} is the average from all n water years of the water balance, and TO_y, $R_{E,y}$, E_y, and W_y are respectively the total outflow, the Eurajoki River discharge, the evaporation estimate from the pan coefficient method, and the Lohiluoma pumping withdrawal estimate for the water year beginning in year y. The average total outflow was calculated merely to compare to the average total inflow.

3.6 Alternative Water Balance

One way to assess the appropriateness of neglecting the groundwater component of the water budget is to conduct the water balance with a constant net groundwater discharge of 0mm per unit area per year and calculate evaporation as the residual:

$$E = P + R + DR - h_S - W, \tag{3.32}$$

where E is the sum of evaporative losses, P the direct precipitation amount (isohyetal method), R the normalized net river flow into the lake, DR the normalized direct runoff contribution (via the average runoff method), h_S the vertical change in lake stage (higher being positive), and W the amount withdrawn by pumping at the Lohiluoma artificial recharge station (all quantities in mm per unit lake area during the same water year). This approach allows for the following: a comparison with the results from a water balance that includes the groundwater component; a search for evidence of the missing net groundwater flux component; and an assessment of the impact of neglecting the groundwater component.

3.7 Uncertainty Estimates

The following definitions of absolute and relative uncertainty and methods of combining them (e.g., Taylor, 1997; Lee and Swancar, 1997) were used to assess the uncertainty related to the calculations based on Darcy's Law, and to develop uncertainty estimates for components of the water balance equation. Absolute uncertainty is defined as:

$$\mathrm{R} = \mathrm{x} + \delta\mathrm{x}, \tag{3.33}$$

where R is the measured quantity, x is the best estimate, and δx is the absolute uncertainty (an estimate of the error associated with x). The operations of addition and subtraction involve combining the absolute uncertainties on all of the parameters as follows:

$$\mathrm{S} = (\mathrm{x} + \delta\mathrm{x}) + (\mathrm{y} + \delta\mathrm{y}), \tag{3.34}$$

entails

$$\delta\mathrm{S} = (\ (\delta\mathrm{x})^2 + (\delta\mathrm{y})^2)^{1/2}, \tag{3.35}$$

where S is, in this case, the sum of best estimates x and y, and δS is the uncertainty on that result.

The relative (or fractional) uncertainty on measured quantity *R* (above) is (δx / x). Relative uncertainty is often stated as a percentage. Multiplication and division require the relative uncertainties on the parameters involved to be combined. For example,

$$\mathrm{P} = (\mathrm{x} + \delta\mathrm{x})(\mathrm{y} + \delta\mathrm{y}), \tag{3.36}$$

where *P* is in this case the product of *x* and *y*. The relative uncertainty on *P* is:

$$\frac{\delta P}{P} = \left(\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2\right)^{1/2}. \tag{3.37}$$

The absolute uncertainty on *P* is then the product of *P* and its relative uncertainty.

The relative uncertainty related to calculations involving quantities raised to powers other than *1* must also be introduced for the uncertainty analysis related to the calculations based on Darcy's Law. In general (e.g., Tyler, 1977), if

$$D = Z^n, \text{ then} \tag{3.38}$$

$$\frac{\delta D}{D} = n\frac{\delta Z}{Z}, \tag{3.39}$$

where *Z* is some number or expression associated with absolute uncertainty δZ, *n* is a positive integer or fraction, *D* is the result of raising *Z* to the power of *n*, and δD is the absolute uncertainty on *D*. Thus, the relative error on the result is the product of the exponent and the relative error on the base (Tyler, 1977).

3.7.1 Uncertainty Estimates for Calculations Based on Darcy's Law

3.7.1.1 Hydraulic Gradient Uncertainty

The uncertainty on the hydraulic gradient was calculated in several steps. First, the amount of uncertainty on the hydraulic head difference between each pair of wells at the centre of adjacent cross-sections was estimated. This estimate was made by combining the uncertainty estimates on the difference between the individual well water levels with an uncertainty estimate pertaining to the use of the average hydraulic head difference. The error on each single change in head was calculated via

$$\delta(h_2 - h_1)_i = \sqrt{\left(\delta h_{1,i}\right)^2 + \left(\delta h_{2,i}\right)^2}\,, \tag{3.40}$$

where h_2 and h_1 are water levels at two centre wells in adjacent cross-sections on date i, and $\delta(h_2 - h_1)$ is the absolute uncertainty on the difference in water levels due to the measurement of the water levels and the surveying of the well top elevations. A combined uncertainty of ±0.02m was assumed for the survey elevations and water levels in wells HP1, HP2, and HP4, while a combined uncertainty of ±1m was assumed for the Honkalan Ottamo well (due to uncertainty regarding its casing top elevation). The error regarding the use of the average water levels was estimated by calculating the difference in water levels for each of the ten measurement dates and then setting the absolute uncertainty to be the absolute value of the maximum difference between the average and each of the ten head differences. The water level at the Honkalan Ottamo well was assumed to be equivalent to its single measurement for all ten dates due to the lack of data. Thus, the total relative uncertainty on the head change was

$$\frac{\delta(dh)}{dh} = \frac{\max_i\{(h_2 - h_1)_i - dh_{avg}\}}{dh_{avg}} + \frac{\sqrt{(n)\ \delta(h_2 - h_1)_i^2}}{n}, \tag{3.41}$$

where dh_{avg} is the average difference in water levels, n is the number of measurement dates (10), and $\frac{\delta(dh)}{dh}$ is the relative uncertainty related to the change in head. The second term in Equation 3.41 is the relative error on the average hydraulic head difference from all measurement dates.

Second, an error estimate for the distance between each pair of centre wells in adjacent cross-sections was developed. The amount of error on each well coordinate was assumed to be ±8m (a typical uncertainty for a Garmin eTrex GPS device in the area, though the position may have been recorded with greater accuracy). Since (for each pair of wells 1 and 2)

$$dl = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}, \tag{3.42}$$

it follows that

$$\delta(y_2 - y_1) = \delta(x_2 - x_1) = \sqrt{(\delta x_2)^2 + (\delta x_1)^2}, \tag{3.43}$$

$$\delta((x_2 - x_1)^2) = ((x_2 - x_1)^2)(2)\frac{\delta(x_2 - x_1)}{(x_2 - x_1)}, \tag{3.44}$$

$$\delta((y_2 - y_1)^2) = ((y_2 - y_1)^2)(2)\frac{\delta(y_2-y_1)}{(y_2-y_1)}, \text{ and} \tag{3.45}$$

$$\delta((x_2 - x_1)^2 + (y_2 - y_1)^2) = \sqrt{\delta((x_2 - x_1)^2) + \delta((y_2 - y_1)^2)}, \tag{3.46}$$

the uncertainty on the distance could be estimated as

$$\frac{\delta(dl)}{dl} = \left(\frac{1}{2}\right)\frac{\delta\left((x_2-x_1)^2 + (y_2-y_1)^2\right)}{(x_2-x_1)^2 + (y_2-y_1)^2}. \tag{3.47}$$

In the above equations, *dl* is the distance between two wells that is calculated from their Finland KKJ Zone 1 (x, y) coordinates, δx and δy are the absolute error values for the x and y coordinates, respectively, and the absolute uncertainties on the various expressions are denoted $\delta(Z)$, where Z is the expression of interest; $\frac{\delta(dl)}{dl}$ is the relative uncertainty on distance *dl*, accounting for the square root. Finally, the relative uncertainty on the hydraulic gradient could be calculated as

$$\frac{\delta\left(\frac{dh}{dl}\right)}{\frac{dh}{dl}} = \sqrt{\left(\frac{\delta(dh)}{dh}\right)^2 + \left(\frac{\delta(dl)}{dl}\right)^2}. \tag{3.48}$$

This procedure was followed for all three pairs of adjacent centre wells.

3.7.1.2 Hydraulic Conductivity Uncertainty

The uncertainty on the hydraulic conductivity value was assumed to be ±one order of magnitude. Since the shifts to the larger and smaller orders of magnitude constitute different percentages of the selected hydraulic conductivity value, the upper and lower error bars were calculated separately. Upper and lower absolute uncertainty bounds were estimated via

$$\delta K_{upper} = |K_{max} - K_{sel}|, \text{ and} \tag{3.49}$$

$$\delta K_{lower} = |K_{min} - K_{sel}|, \tag{3.50}$$

where K_{max} is 1×10^{-2}m/s, K_{sel} is the hydraulic conductivity value that was selected as representative (i.e., 1×10^{-3}m/s), and K_{min} is 1×10^{-4}m/s. The associated upper and lower relative uncertainty components were obtained by dividing by K_{sel}.

3.7.1.3 Normalized Groundwater Discharge Estimate Uncertainty

Given the relative uncertainty values for the hydraulic gradient and hydraulic conductivity estimates, the relative uncertainty on the Darcy flux was calculated (for the upper and lower directions) for each of the three cross-section pairs via

$$\left[\frac{\delta q}{q}\right]_{upper} = \sqrt{\left(\frac{\delta K_{upper}}{K_{upper}}\right)^2 + \left(\frac{\delta\left(\frac{dh}{dl}\right)}{\frac{dh}{dl}}\right)^2}\text{, and} \tag{3.51}$$

$$\left[\frac{\delta q}{q}\right]_{lower} = \sqrt{\left(\frac{\delta K_{lower}}{K_{lower}}\right)^2 + \left(\frac{\delta\left(\frac{dh}{dl}\right)}{\frac{dh}{dl}}\right)^2}. \tag{3.52}$$

Assuming an error of 10% on the average of the areas between cross-sections (A_{avg}),

$$\left[\frac{\delta Q}{Q}\right]_{upper} = \sqrt{\left(\left[\frac{\delta q}{q}\right]_{upper}\right)^2 + \left(\frac{\delta A_{avg}}{A_{avg}}\right)^2}\text{, and} \tag{3.53}$$

$$\left[\frac{\delta Q}{Q}\right]_{lower} = \sqrt{\left(\left[\frac{\delta q}{q}\right]_{lower}\right)^2 + \left(\frac{\delta A_{avg}}{A_{avg}}\right)^2}, \tag{3.54}$$

where $\left[\frac{\delta Q}{Q}\right]_{upper}$ is the relative uncertainty estimate for the extension of error above the calculated volumetric groundwater flux estimate (Q), and $\left[\frac{\delta Q}{Q}\right]_{lower}$ is the relative uncertainty for the extension of error below the calculated estimate. Assuming that the uncertainty related to lake area variation is negligible with respect to the large amounts of uncertainty on the other variables, the relative uncertainties in the upper and lower directions for the normalized flux estimates are the same as for the upper and lower volumetric flux estimates, respectively. The absolute uncertainties for these two directions were obtained by multiplying these relative uncertainties by the *Qnorm* estimates for each of the three pairs of cross-sections.

3.7.1.4 Uncertainty on the Flownet Groundwater Discharge Estimate

The uncertainty on the amount of groundwater discharge estimated to migrate through the Honkala Aquifer during the flownet analysis was not calculated. The flownet approach may be considered to have uncertainty at least as great as the calculations based on Darcy’s Law since it is a graphical method involving similar variables (e.g., hydraulic conductivity and hydraulic head differences) in its equations.

3.7.2 Water Balance Water Year-Specific Uncertainty Estimates

An uncertainty estimate was derived for the groundwater component of the water balance employing average direct runoff based on all of the other components' values for each year. The following explains how the uncertainty on each component was estimated, and how all of the component estimates were combined to provide the uncertainty on the net groundwater component.

3.7.2.1 Storage Change

The uncertainty on the storage change was developed by assuming that the uncertainty on a water level reading is about half of the value observed by Hyvärinen et al. (1973) in terms of water level variation due to seiches (i.e., a result of 25mm). Then (neglecting any impacts of uneven land uplift),

$$\delta h_S = \left((\delta WL_{1\ \mathrm{Oct}\ y+1})^2 + (\delta WL_{1\ \mathrm{Oct}\ y})^2 \right)^{1/2}, \tag{3.55}$$

where δh_S is the absolute uncertainty on the change in storage for the water year of interest, and y is the calendar year at the start of the water year. The impacts of variations in the area of the lake due to lake stage changes were assumed to be negligible with respect to the uncertainty related to seiches. This assumption was assessed as indicated above (see Section 3.3.4).

3.7.2.2 Evaporation

For calculation purposes, it was assumed that the amount of uncertainty on the evaporation estimate for each water year was 15%. Then (for the water year starting in year y):

$$\delta \mathrm{E}_{\mathrm{abs,y}} = (0.15)(E_{Lake,y}), \tag{3.56}$$

where $\delta E_{abs,y}$ is the absolute error estimate, $E_{Lake,y}$ is the evaporation estimate from Equation 3.14. The relative error of 15% is meant to address uncertainty due to the lack of a long-term pan coefficient related to an accurate evaporation method at the lake, as well as uncertainty on the amount of evaporation during the months when evaporation is not measured. The actual pan coefficient could be greater or less than the value employed (0.8), leading to either an increase or decrease in actual evaporation from the lake. Similarly, the amount of evaporation from November through April could be slightly greater or less than the 40mm per unit lake area estimated by Kuusisto (1975). The amount of error should theoretically be greater than that estimated for the fairly accurate energy budget method (i.e., 10% - Winter, 1981). A lake evaporation estimate based on a pan coefficient accounting for lake depth and climatic regime has been suggested to be accurate to within 10 to 15% (Dingman, 1994; Harbeck et al., 1954).

3.7.2.3 Pumping Withdrawals

Despite the fact that the exact pumping schedule at the Lohiluoma artificial recharge station is unknown, the amount of uncertainty on the pumping withdrawals component of the water balance is likely negligible (i.e., probably less than 1mm per unit lake area per year). Thus, the amount of uncertainty associated with the component, δW, was estimated at 0mm per unit lake area per water year. The amount of uncertainty on the unknown volume withdrawn from the lake for agricultural irrigation was also neglected.

3.7.2.4 Precipitation

The uncertainty on the precipitation component was estimated by considering both the uncertainty on measurements at the individual gauges and the uncertainty related to the interpolation of the point data to produce an estimate for the lake. The contribution from the interpolation was estimated via comparison of the isohyetal method with an alternative spatial interpolation method. Lacking a way to estimate the true amount of precipitation that falls on the lake, a comparison of two different spatial interpolation methods provides a way to estimate the possible uncertainty of the precipitation estimate for each water year. The individual yearly differences between the isohyetal method result and the areal estimate for Kauttuankoski (OIVA – Environment and Spatial Information Services, 6 Oct 2010) were used as interpolation error estimates for their respective years. Mathematically:

$$\delta P_{abs.y} = U_{gauge,y} + |P_{isohyetal,y} - P_{K\ areal,y}|, \tag{3.57}$$

where (for the water year beginning in year y) $\delta P_{abs,y}$ is the absolute error estimate, U_{gauge} is the uncertainty related to the measurement of precipitation at the individual gauges, $P_{isohyetal,y}$ is the isohyetal method result, and $P_{K\ areal,y}$ is the areal precipitation calculated for Kauttuankoski at the base of the watershed. Six or seven individual point precipitation stations were used in the calculation for the Kauttuankoski station (H. Sirviö, pers. comm., 2011). The value chosen for U_{gauge} was 5% of the isohyetal precipitation estimate for the water year. This value was selected based on Winter's (1981) comment that instrument errors can range up to 5%.

3.7.2.5 River Runoff

Since the volumetric discharge in the Yläneenjoki, Pyhäjoki, and Eurajoki Rivers is estimated using permanent weirs and associated ratings curves, the amount of error on the estimates should be relatively low. Though stream discharge measurements may be accurate to within five percent (for continuous monitoring of river stage, Winter [1981]; Herschy [1973]), an accuracy of 10% on each daily discharge estimate was assumed for each river. This larger amount was meant to account for the fact that only one flow rate was listed per day, as well as for uncertainties related to changing channel conditions. Thus,

$$\delta R_{r,y} = \sqrt{\sum_{i=1}^{n} (\delta R_{r,i})^2}, \tag{3.58}$$

where $\delta R_{r,y}$ is the absolute error for the gauged part of the catchment of river r during the water year starting in year y, and $\delta R_{r,i}$ is the absolute error for the i^{th} day of n days in the water year (i.e., 10% of the daily flow rate in m^3/d). These calculations (made using GNU Octave) incorporated the estimated flow amounts for the five months lacking data, as described above. The relative uncertainty estimates for the Yläneenjoki and Pyhäjoki Rivers were assumed to be the same for their gauged and total catchment areas. Normalizing by the lake area and correcting for the ungauged areas of these two rivers entailed:

$$\frac{\delta R_{r,y,final}}{R_{r,y,final}} = \sqrt{\left(\frac{\delta R_{r,y}}{R_{r,y}}\right)^2 + \left(\frac{\delta A_{r,g}}{A_{r,g}}\right)^2 + \left(\frac{\delta A_{r,t}}{A_{r,t}}\right)^2 + \left(\frac{\delta A_{lake}}{A_{lake}}\right)^2}, \tag{3.59}$$

where $\frac{\delta R_{r,y,final}}{R_{r,y,final}}$ is the relative error for the entire flow estimate for river r during the water year starting in year y, $\delta A_{r,g}$ is the absolute error estimate ($\pm$ 1km^2) for the area of the gauged part of the catchment of river r ($A_{r,g}$), $\delta A_{r,t}$ is the absolute error estimate ($\pm$ 1km^2) for the total catchment area of river r ($A_{r,t}$), and δA_{lake} is the absolute error estimate ($\pm$ 2.5km^2) for the lake area (A_{lake}). Similarly,

$$\frac{\delta R_{Eu,y,final}}{R_{Eu,y,final}} = \sqrt{\left(\frac{\delta R_{r,y}}{R_{r,y}}\right)^2 + \left(\frac{\delta A_{lake}}{A_{lake}}\right)^2}, \qquad (3.60)$$

where $\frac{\delta R_{Eu,y,final}}{R_{Eu,y,final}}$ is the relative error for the normalized estimate for discharge through the Eurajoki River during the water year starting in year *y*. Finally, the absolute uncertainty on the net river discharge estimate for each water year was calculated via:

$$\delta R_{net,y} = \sqrt{\left(\delta R_{Yl,y,final}\right)^2 + \left(\delta R_{Py,y,final}\right)^2 + \left(\delta R_{Eu,y,final}\right)^2}, \qquad (3.61)$$

where $\delta R_{Yl,y,final}$, $\delta R_{Py,y,final}$, and $\delta R_{Eu,y,final}$, are (respectively) the absolute errors on the total Yläneenjoki, Pyhäjoki, and Eurajoki River discharge estimates for the water year starting in year *y*.

3.7.2.6 Direct Runoff

The uncertainty on the direct runoff estimate is quite large since there are no measurements of overland flow or interflow in the catchment. An analog for direct runoff may be the regionalization of streamflow. Scheider et al. (1978) found that the extrapolation of long-term average unit stream discharge (i.e., streamflow per unit area) to ungauged parts of a small catchment ($5.3 km^2$) incurred errors with a mean of 18% during a one-year study of seven streams (cf. Winter, 1981). Since the average precipitation during the year of that study was quite close (96%) to the mean precipitation, the average direct runoff method described above could be comparable. As noted above, the average direct runoff method considered river flow per unit area during each water year, thus accounting for variation in the amount of precipitation. Despite the fact that the Scheider et al. (1978) study was for channelized flow while at a much smaller scale than that of the Pyhäjärvi watershed and potentially might sample less variability, a relative error similar to their mean was chosen here. Suppose the relative error on the yearly direct runoff estimates is 20%. Then

$$\delta DR_y = (0.2)\left(DR_y\right), \qquad (3.62)$$

where δDR_y, is the absolute uncertainty on the average direct runoff estimate (DR_y) for the water year beginning in year *y*. This proposed method of estimating direct runoff uncertainty from the runoff per unit area of river subcatchment is only a rough estimate. The actual amount of uncertainty is related to the amount and intensity of precipitation, changes in soil and vegetation, types of land use, and variations in topography and slopes in subcatchments around the lake. The amount of uncertainty could be larger: Scheider et al. (1978) found the range in uncertainty to be -2 to 68% (Winter, 1981).

3.7.2.7 Net Groundwater Discharge

The water year-specific uncertainty estimate for the net groundwater discharge component of the water balance equation was calculated via (for the water year beginning in year *y*; cf. Lee and Swancar, 1997; Sacks et al., 1998):

$$\delta G_y = \left((\delta h_S)^2 + (\delta E_{abs,y})^2 + (\delta W)^2 + (\delta P_{abs,y})^2 + (\delta R_{net,y})^2 + (\delta DR_y)^2 \right)^{1/2} , \quad (3.63)$$

where δG_y is the uncertainty estimate for net groundwater discharge into the lake, δh_S is the uncertainty with respect to the change in storage, $\delta E_{abs,y}$ is the uncertainty for the evaporation component, δW is the uncertainty related to the pumping withdrawals at Lohiluoma, $\delta P_{abs,y}$ is the uncertainty related to the precipitation component, $\delta R_{net,y}$ is the uncertainty for the net river influx, and δDR_y is the uncertainty associated with the direct runoff estimate. Since the uncertainty related to water extraction was neglected, the equation simplifies to:

$$\delta G_y = \left((\delta h_S)^2 + (\delta E_{abs,\,y})^2 + (\delta P_{abs,\,y})^2 + (\delta R_{net,\,y})^2 + (\delta DR_y)^2 \right)^{1/2} . \quad (3.64)$$

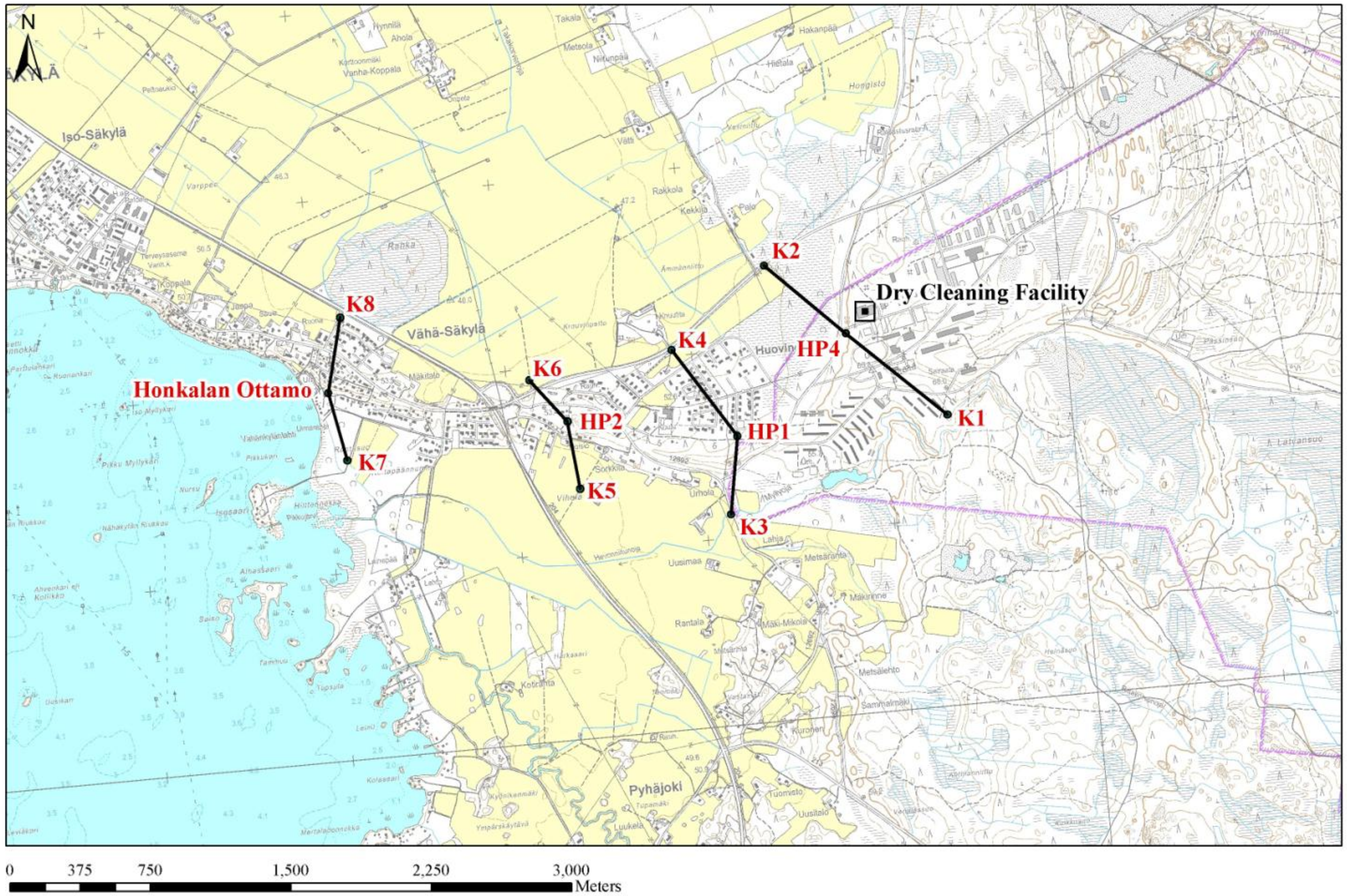
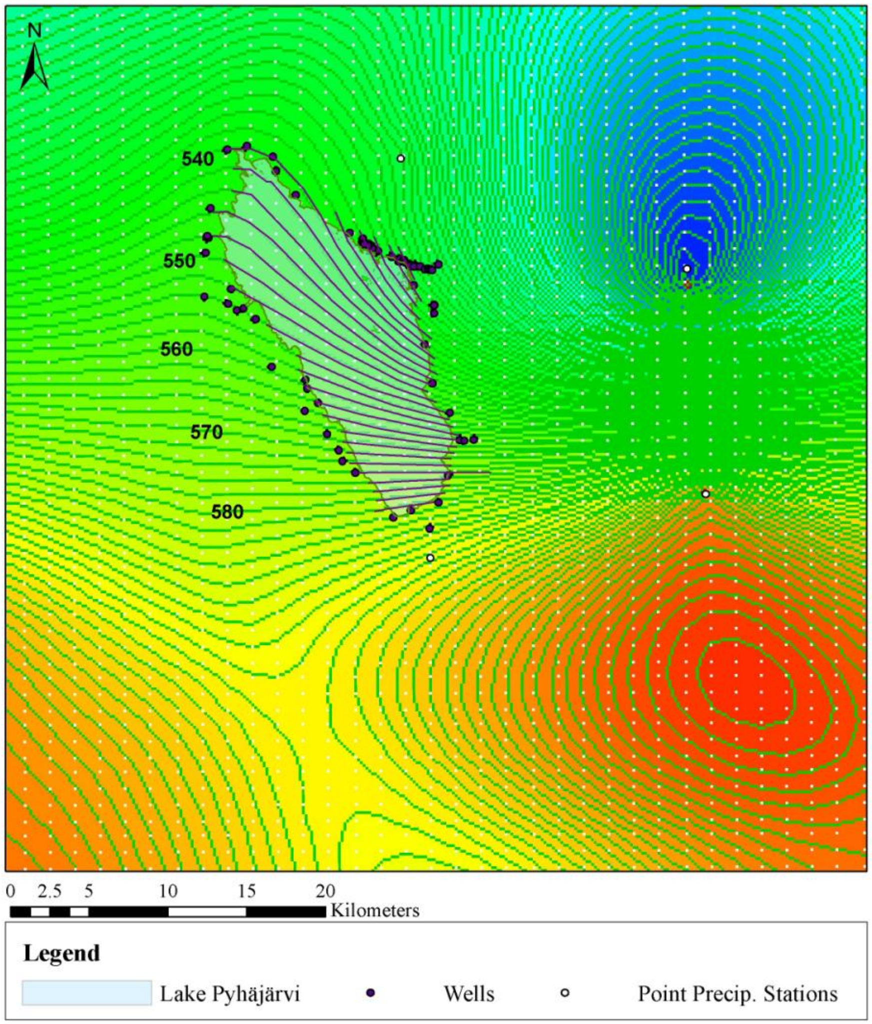


Figure 3.1: Cross-sections through the Honkala Aquifer (after A. Artimo [unpublished report, 1998]; ©MML, 2009a). The cross-sections are numbered 1 through 4, progressing east to west.



Precip. Interval Avg. (mm)	Interval Area (km^2)
531	0.47
533	1.87
535	2.09
537	3.97
539	5.67
541	11.6
543	15.25
545	14.10
547	15.01
549	13.44
551	10.73
553	8.57
555	6.65
557	5.41
559	5.30
561	5.18
563	4.77
565	3.81
567	3.4
569	3.18
571	3.02
573	2.94
575	2.75
577	2.05
579	2.01
581	1.65
583	0.65

Figure 3.2: Isohyetal precipitation method example for WY 1971-1972 (©GTK, 2008b). The wells and precipitation stations were used for georeferencing the contour map from Tecplot into ArcMap.

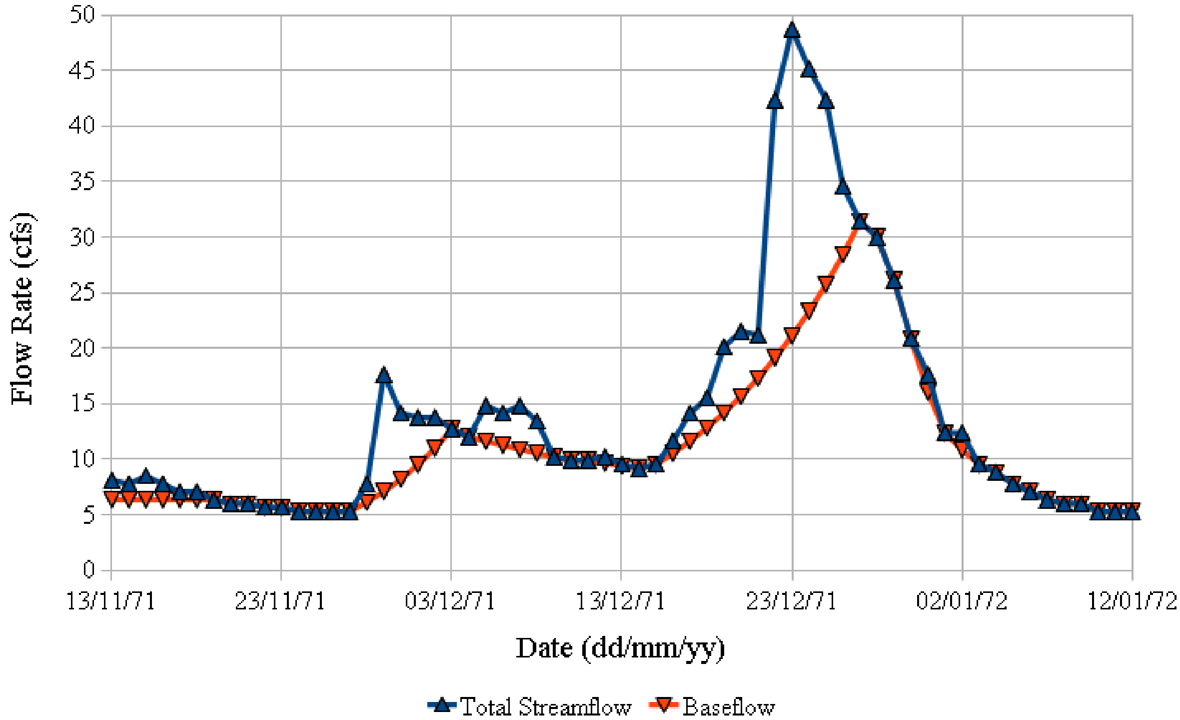


Figure 3.3: Yläneenjoki River hydrograph example (OIVA – Environment and Spatial Information Services, 23 Sep 2010). The streamflow data were analyzed using the PART program (Rutledge, 2007).

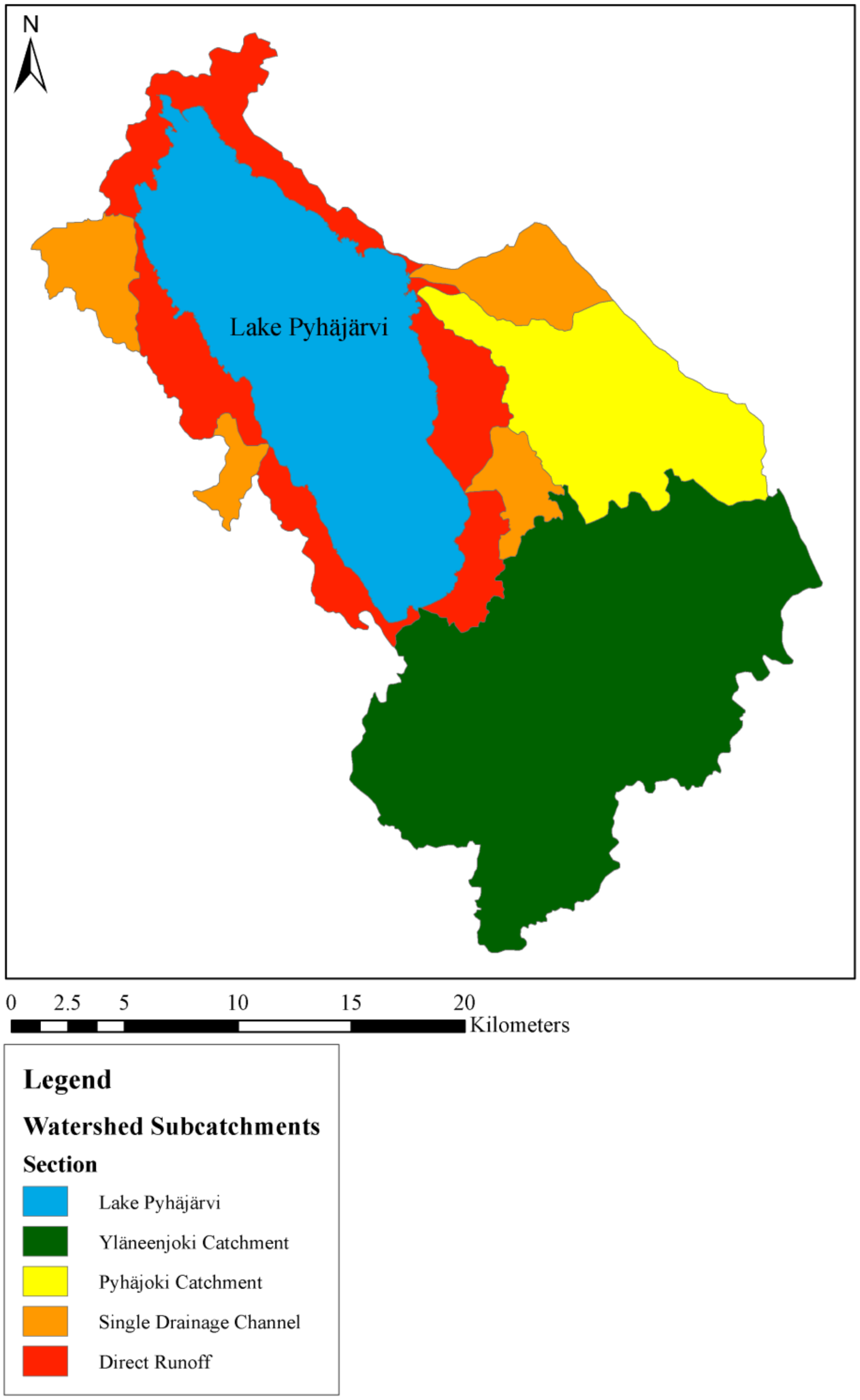


Figure 3.4: Types of subcatchments in the Lake Pyhäjärvi watershed (©SYKE, 2010). The areas of the five regions are listed in Appendix I.

Chapter 4 - Results

4.1 Introduction

The following results have been organized roughly in order of increasing complexity. First, water levels and near shore analysis are presented; next, the groundwater flux estimates based on Darcy's Law for the Honkala Aquifer; and finally, three water balance methods (based on average runoff, PART-adjusted runoff, and negligible net groundwater exchange, respectively) and their uncertainty analyses.

4.2 Measurement of Water levels in the Honkala Aquifer

Figure 4.1 shows the water level variations in wells with multiple recorded water levels from 1 Sep 1996 to 8 Jul 2010. There are some anomalous values that do not follow the trends. The statistics for the dataset are found in Table 4.1, showing the range of standard deviations to be 0.10m (HP3) to 0.69m (K8). The maximum water table fluctuations (assuming accurately measured levels) occur at well K8 at the northern edge of the esker. The maximum variation within one calendar year (ignoring outliers) was 1.18m, while the average was 0.40m. The water levels seem stable and no clear trends of increasing or decreasing water table elevation are present. The flow system in the Honkala aquifer seems quite consistent from year to year.

4.3 Near Shore Analysis - Seepage Meters, Mini-Piezometers, Shallow Sediment Cores

Calculations using data from seepage meters and mini-piezometers (2008 – 2009) yielded groundwater discharge fluxes ranging from 10^{-7} to 10^{-5} m/s at four shoreline sites at the edge of the esker (Rautio, 2009). The fluxes were highest at the Kivimäki and Row House sites and lower at the Heinonen and Boat House sites (see locations in the map in Appendix C). The range of fluxes reported by Rautio (2009) represents moderate to high seepage rates with respect to values reported in the literature (10^{-9} – 10^{-4}m/s – Rautio, 2009; Rosenberry and LaBaugh, 2008).

The shoreline reconnaissance conducted during the summer of 2010 found grey clay near the shore and close to the lakebed surface along the northeastern shoreline where the ice-free areas had been found in winter. The clay was generally found about 3m from the shoreline south of the Boat House site at a shallow depth (about 10cm). The trend seemed to be that coarse sand and cobbles would be present at the shoreline, but the thickness of the coarser sediments appeared to be minimal after progressing into the lake a few metres. The winter mapping (Rautio, 2009) and shallow sediment core results suggest that high rates of seepage of groundwater from the Kuivalahti-Säkylä tributary esker into the lake are likely restricted to narrow regions of certain sections of the shoreline of the lake.

4.4 Honkala Aquifer Groundwater Flux and Uncertainty Based on Darcy's Law

Table 4.2 presents estimates of groundwater discharge into the lake from the Honkala Aquifer near Säkylä based on Darcy’s Law calculations using a likely representative average hydraulic conductivity. The average hydraulic gradient between pairs of adjacent cross-sections varied over one order of magnitude, with the higher gradient observed farther from the lake, to the east where the topographic slope of the terrain is greater. The cross-sectional area of the esker also declines from east to west as it approaches the lake near Säkylä. The magnitude of the hydraulic conductivity in the esker has the most influence on the order of magnitude of the groundwater discharge from the Honkala Aquifer into the lake. If the hydraulic conductivity in the coarse sand and gravel of the aquifer is near the 1×10^{-3}m/s estimate, then the discharge volume per unit lake area could be as much as 22mm per year (about 1.4% of the average total water balance inflow – see below). This largest estimate may be the most reasonable since it represents the entire flux of groundwater though the esker prior to the possible divergence of flowpaths out of the esker. Particle tracking conducted by Artimo (2002) and PCE detection in wells south of the esker near the lake suggest that some of the groundwater flow escapes the Honkala Aquifer about half-way between the PCE spill location and the boundary with the Uusikylä Aquifer to the northwest. This suggests that the flux estimate for the region between Cross-Sections 1 and 2 is a better representation of the flow through the esker than the estimates for the following two pairs of cross-sections. However, if the hydraulic conductivity is one order of magnitude greater or less, the discharge through the esker would similarly vary by one order of magnitude. Despite this sensitivity to the hydraulic conductivity, the calculated Darcy fluxes (-6.97×10^{-7} to -6.81×10^{-6} m/s) are mostly of the same order of magnitude as those observed by Rautio (2009) in seepage meters at selected shoreline sites (Appendix C). Some of the fluxes in the seepage meters were one order of magnitude greater than the maximum flux estimated for the pairs of cross-sections.

Table 4.3 shows that although the uncertainty on the hydraulic gradient varies from 7.6 to 58% over the three cross-section pairs, an overwhelming amount of error is located in the estimate for the hydraulic conductivity (± one order of magnitude). Most of the uncertainty on the hydraulic gradient comes from the minor variation in head levels rather than the distance calculation. The amount of error on the hydraulic gradient and the estimated 10% error on the average area between the cross-sections have negligible impacts on the uncertainty of the final groundwater flux estimate when compared with the error on the hydraulic conductivity. Despite the potentially large amount of uncertainty on the results of these calculations (± one order of magnitude, or +900%, -90%), the match of the Darcy flux (q) with the seepage fluxes observed by Rautio (2009) is encouraging. This weighting of the error toward a larger value is likely reasonable since groundwater flux may be expected to occur predominately through the most permeable sediments.

Suspected flow patterns in the Honkala Aquifer are drawn as a flownet in Figure 4.2. The related calculations suggest the same order of magnitude as the result for the calculations based on Darcy's Law, though contouring may contribute uncertainty as well. The groundwater discharge estimate was 80mm per unit lake area per year (5.2% of average total inflow – see below), based on an average esker thickness of about 8m. This estimate has at least as much uncertainty as the estimates in Table 4.3, i.e., about ± one order of magnitude, based on the contribution from the hydraulic conductivity. Appendix G contains a list of water levels in wells in the Honkala Aquifer and elsewhere around the lake.

The calculations based on Darcy's Law for the Honkala Aquifer with a hydraulic conductivity estimate of 1×10^{-3}m/s indicate a groundwater discharge flux estimate that is a small component of the overall water budget for the lake. The calculations of flux through the cross-sections and the flownet analysis both provide estimates (22mm and 80mm per year, respectively) of groundwater flux within the average uncertainty of the net groundwater discharge component of the average runoff water balance (discussed below). Both of these estimates also constitute at least a reasonably large ($\geq$ 30%) proportion of the average net groundwater discharge component of the average runoff and PART-adjusted runoff water balances (discussed below).

4.5 Water Balance and Uncertainty Analysis

4.5.1 Water Balance Based on Average Runoff

The water balance associated with the average runoff method is presented in Figure 4.3 (see Appendix J). There seems to be either near-equilibrium or net groundwater recharge during the 1970's, approximately equilibrium net groundwater discharge and recharge or a small amount of net discharge during the 1980's, and net groundwater recharge from the 1990's to the end of the study period. Twelve of the 38 water years in the water balance have net discharge estimates. The magnitude of the net groundwater discharge ranges from -293 to 128 mm per unit lake area, while the mean and standard deviation are -73 and 109 mm, respectively. The two-sided error bars corresponding to the uncertainty encompass equilibrium between net discharge and recharge for 25 of the water years, so the magnitude of the groundwater component was larger than the uncertainty in 13 water years.

The total inflow sum exceeded the outflow sum in 26 of the water years of the water balance. The average total inflow from all water balance parameters (excluding the groundwater component) was 1530 mm per unit lake area, while the average total outflow was 1414 mm per unit lake area. An average net groundwater flux magnitude of 73 mm per unit lake area constitutes about 4.8% of the average total inflow. As mentioned above, the groundwater flux estimate for the Honkala Aquifer was 1.4% of average total inflow (22mm per unit lake area), thus constituting a considerable proportion of the magnitude of the average net groundwater discharge for the water balance based on average runoff.

4.5.2 Water Balance Uncertainty

According to the method of calculating the year-specific uncertainty, the bulk of the uncertainty (both in terms of the maximum and the average, compared with those of other components) on the groundwater component comes from the evaporation, precipitation, and direct runoff components. Year-specific uncertainty estimates for the various components of the water balance are reported in Table 4.4. The precipitation and direct runoff components had the largest ranges in estimated absolute year-specific uncertainty (23 to 113mm and 21 to 100mm, respectively). The absolute uncertainty of the net groundwater discharge component ranged from 80 to 148mm per unit lake area. Relative precipitation uncertainty ranged from 5 to 20%, while the magnitude of the net river inflow uncertainty ranged from 3 to 22%, and the magnitude of the year-specific groundwater uncertainty ranged from 40 to 2900%; the relative evaporation and direct runoff uncertainties were respectively fixed at 15% and 20% as described above. The water level variation absolute uncertainty (35mm/unit lake area) was constant by design, ranging from 9 to 350% in terms of relative uncertainty. The estimated uncertainty on the pumping withdrawals at Lohiluoma was considered negligible. The variation in lake area was found to be small: the lake area was estimated to vary between 153.4 km^2 (at a water level of 44.40m) and 157.7km^2 (at 45.40m), thus its uncertainty is at most 2.5km^2 (a percentage difference of 1.6% with respect to the area employed, i.e., 155.18932km^2). The impact of this uncertainty (< 0.5% for uncertainty estimates ≥ 5%) may be neglected without a variation in the averages of the relative uncertainties estimated for the water balance components (see Appendix H). Though the minimum net river inflow uncertainty was less than 5%, the uncertainty calculations for this component explicitly accounted for the lake area uncertainty. Both the ArcMap and Tecplot kriging yielded similar contour line placement for lake stage variation.

The magnitude of the net groundwater discharge component and its uncertainty are compared in Figure 4.4. The amount of uncertainty is larger than the magnitude of the groundwater flux in 25 of the 38 years of the water balance. The net groundwater discharge is quite variable; its standard deviation from Table 4.4 (shown on the plot) was 109 mm per unit lake area. The amount of uncertainty was less variable, and it exhibited a standard deviation of 14mm per unit lake area (not shown).

The year-specific uncertainty estimates in Table 4.5 facilitate evaluation of the combined effect of the (average) magnitudes of the components and their relative error estimates. These typical absolute uncertainty amounts suggest that the bulk of the uncertainty comes from the evaporation (68mm), precipitation (61mm), and direct runoff (59mm) components, while lake stage ranks fourth (35mm), net river discharge contributes the least (20mm), and pumping withdrawals were ignored. For reference, the average uncertainty on the net groundwater discharge component was 118 mm per unit lake area.

4.5.3 Water Balance Revisions Based on Hydrograph Separation

Table 4.6 lists the PART hydrograph separation results for WYs 1971 – 2008 (the Pyhäjoki River dataset was incomplete for WY 1971-1972). The mean baseflow index for the Yläneenjoki River was 65% and the mean index for the Pyhäjoki River was 78%, while the standard deviations of the two were 6.3% and 4.7%, respectively. Figures 4.5 and 4.6 display the results. The baseflow indices of the two rivers vary in concert over about half of the time period (see Figure 4.6), though the difference between the smaller and larger rivers' indices ranges from -0.7% to 27% overall, with an average difference of 13%.

Adjusting the direct runoff in an attempt to incorporate the baseflow estimate from PART into the direct runoff calculations for subcatchments where not all direct flow into the lake may be channelized yields a larger estimate of net groundwater discharge. Figure 4.7 shows the revised water balance (see Appendix J). The average net groundwater discharge component increased to +38 mm per unit lake area per year (about 2.5% of the average total inflow) with these direct runoff adjustments. This constitutes an increase in the mean net groundwater discharge of 111 mm per unit lake area, essentially equivalent to the magnitude of the average uncertainty on the groundwater component. The net groundwater discharge estimates follow the same trend for the water balance employing the PART-adjusted runoff as for the method using the average runoff, though they are shifted to the positive. Again the decade of the 1980's stands out as exhibiting above average net groundwater discharge, while the others show equilibrium or below average estimates. The standard deviation of the net groundwater flux component was slightly higher than it was for the water balance using the average runoff (118mm/unit lake area - see Table 4.5), indicating slightly greater variability.

4.5.4 Alternative Water Balance Based on Negligible Groundwater Component

Employing the alternative water balance to estimate evaporation while assuming equilibrium groundwater recharge and discharge leads to evaporation estimates with greater variability (a standard deviation of 102mm vs. 45mm for the pan coefficient method) and a larger mean (523mm vs. 450mm; Figure 4.8; Table 4.5; Appendix J). It is evident that the evaporation estimates are more extreme (i.e., deviate more from the mean) during years when the water balance based on PART-adjusted runoff estimated the net groundwater component to be large in magnitude.

While the evaporation from the method assuming a negligible net groundwater component seems reasonable for most water years (though perhaps too low or too high for water years exhibiting net groundwater flux estimates of large magnitude in the other balances), the pan coefficient evaporation method estimated a tighter range and lower mean for the evaporation component. However, the evidence from the (average runoff and PART-adjusted runoff) water balances and from the calculations for the Honkala Aquifer suggests that the groundwater component of the water budget for Lake Pyhäjärvi is small on average. This is a puzzle that cannot be solved given the resolution afforded by these water balances, and there is a current lack of accurate evaporation estimates for the lake. The net groundwater flux may in fact be variable depending on the water year, but the associated, relatively large amount of uncertainty on the estimates for the 38 water years of the water balance questions the reality of its variability. Revisions to the direct runoff estimate based on PART hydrograph separation led to an increase in the mean of the net groundwater discharge component of about the same magnitude as the average of its uncertainty estimates (about 7.2% of average total inflow). The positive average of the net groundwater discharge component of the PART-adjusted runoff water balance is a better qualitative match with the observations of groundwater discharge. Though the overall net amount of groundwater exchange may be low, the water level analysis and calculations based on Darcy's Law for the Honkala Aquifer, and the fact that the lake level is regulated within a narrow range, suggest that a certain amount of the net groundwater flux consistently enters the lake through that aquifer each year. This amount is likely on the order of tens of millimetres per unit lake area per year, and it likely enters the lake as seepage in the immediate vicinity of the shoreline at several distinct locations.

Table 4.1: Statistics for available historical water levels in the Honkala Aquifer from 01 Sep 1996 to 08 Jul 2010 (OIVA – Environment and Spatial Information Services, 3 Dec 2010).

Well Name	No. of Water Levels	Average Water Level* (m)	No. of Outliers	Maximum Water Level (m)*	Minimum Water Level (m)*	|Max - Min| (m)*	Standard Deviation*	|Outlier – Avg| (m)	Outlier Dates
K20	24	45.61	1	45.87	45.28	0.59	0.13	5.01	01/01/2007
K8	61	46.55	0	47.42	45.18	2.24	0.69	-	-
K30	77	46.24	0	46.56	45.79	0.77	0.16	-	-
HP 3	10	45.91	0	46.04	45.78	0.26	0.10	-	-
HP 2	10	46.48	0	46.66	46.29	0.37	0.13	-	-
K35	29	47.15	0	47.56	46.62	0.94	0.24	-	-
HP 1	10	48.55	0	49.03	48.12	0.91	0.23	-	-
K3	18	47.06	2	47.32	46.75	0.57	0.15	3.64	01/01/07; 08/07/2010
HpI	100	49.03	1	49.65	48.45	1.20	0.28	1.49	01/01/2007
Hp 51	100	49.39	1	50.00	48.79	1.21	0.30	4.01	01/01/2007
HpII	100	49.14	1	49.77	48.54	1.23	0.29	1.44	01/01/2007
124	100	50.44	1	51.36	49.73	1.63	0.36	2.79	01/01/2007
HP 4	10	54.00	0	54.75	53.26	1.49	0.40	-	-
K33	76	46.63	0	47.05	46.22	0.83	0.17	-	-
131	99	55.08	0	55.63	54.23	1.40	0.41	0.60	01/05/2000
HPIII	99	58.74	0	59.09	58.4	1.11	0.69	0.76	01/05/2000
127	101	69.64	1	70.28	68.72	1.56	0.37	4.30	01/01/2007

* Rejecting outliers

Table 4.2: Results of Darcy's Law calculations for the Honkala Aquifer near Säkylä.

Cross-Section*	Well	Average Water Level (m) †	Distance to previous cross-section (m)	K (m/s)‡	dh/dl	q (m/s)	Area of Cross-Section (m^2)	Q = $\lvert(q)(A_{avg})\rvert$ (m^3/s)**	Q per unit lake area per year (mm)
1	HP4	54.00	-	-	-	-	19208	-	-
2	HP1	48.55	799	1.0×10^{-3}	6.81×10^{-3}	-6.81×10^{-6}	12118	0.1067	22
3	HP2	46.48	914	1.0×10^{-3}	2.26×10^{-3}	-2.26×10^{-6}	10280	0.0254	5.2
4	Honkalan Ottamo	45.59	1287	1.0×10^{-3}	6.97×10^{-4}	-6.97×10^{-7}	4634	0.00520	1.1

* The four cross-sections are depicted in Figure 3.1 and were drawn by A. Artimo (unpublished report, 1998).
† The average water levels were calculated from data in OIVA - Environment and Spatial Information Services (3 Dec 2010) and are stated relative to the N60 datum.
‡ The hydraulic conductivity value ($K = 1\times10^{-3}$m/s) was chosen as a maximum of the range employed by Artimo (2002) during his modelling of the Honkala Aquifer, and it compares with literature estimates for clean sand and gravel (e.g., Freeze and Cherry, 1979).
** A_{avg} is the average of the previous and current cross-section areas.

Table 4.3: Uncertainty estimates for calculations based on Darcy's Law.

Cross-Section Pair		Distance (m)	Average Head Difference (m)	Hydraulic Gradient	Hydraulic Conductivity (m/s)	Average of Cross-Section Areas (m^2)	Groundwater Flux Estimate (mm/unit lake area)
1 – 2 (HP4 - HP1)	Estimate	799	5.45	6.81×10^{-3}	1.0×10^{-3}	15663	22
	Absolute Uncertainty	11	0.41	5.2×10^{-4}	$+9\ x\times10^{-3}$ -9×10^{-4}	1566	+ 200 - 20
	Relative Uncertainty	1.4%	7.5%	7.6%	+900% -90%	10%	+ 900% - 90.9%
2 – 3 (HP1 - HP2)	Estimate	914	2.07	2.26×10^{-3}	1.0×10^{-3}	11199	5.2
	Absolute Uncertainty	13	0.61	6.7×10^{-4}	$+9\ x\times10^{-3}$ -9×10^{-4}	1120	+ 46.4 - 4.9
	Relative Uncertainty	1.4%	29%	29%	+900% -90%	10%	+ 901% - 95.1%
3 – 4 (HP2 - Honkalan Ottamo)	Estimate	1287	0.90	6.97×10^{-4}	1.0×10^{-3}	7457	1.1
	Absolute Uncertainty	18	0.52	4.4×10^{-4}	$+9\ x\times10^{-3}$ -9×10^{-4}	746	+ 9.5 - 1.0
	Relative Uncertainty	1.4%	58%	58%	+900% -90%	10%	+ 900% - 93.3%

Table 4.4: Year-specific uncertainty analysis for the average runoff water balance (units: mm per unit lake area).

WY Start	δh_S	δE	δW	δP	δR	δDR	δG
1971	35.4	75.18	0	65.56	8.96	40.62	113.73
1972	35.4	75.74	0	70.23	15.74	49.43	120.88
1973	35.4	62.82	0	81.64	24.94	77.12	135.77
1974	35.4	71.88	0	70.99	28.99	77.27	135.17
1975	35.4	74.18	0	77.83	8.39	28.00	116.91
1976	35.4	62.21	0	93.44	15.08	51.88	129.51
1977	35.4	67.38	0	57.26	17.46	58.50	113.13
1978	35.4	65.67	0	67.93	19.49	59.68	118.84
1979	35.4	67.52	0	80.10	16.38	43.53	119.96
1980	35.4	62.02	0	74.21	36.55	100.27	148.31
1981	35.4	72.18	0	86.63	24.64	64.20	136.73
1982	35.4	70.49	0	77.86	19.20	53.95	124.75
1983	35.4	62.08	0	97.83	25.80	76.10	145.38
1984	35.4	62.98	0	34.96	25.05	61.75	104.32
1985	35.4	69.09	0	87.01	24.27	50.77	129.48
1986	35.4	57.60	0	64.70	25.19	68.05	118.41
1987	35.4	72.33	0	69.56	26.39	63.56	126.73
1988	35.4	79.88	0	36.74	27.45	61.80	116.43
1989	35.4	71.57	0	39.11	18.82	56.49	107.01
1990	35.4	57.37	0	54.62	13.27	45.82	99.01
1991	35.4	74.47	0	71.46	22.71	63.36	128.20
1992	35.4	62.80	0	112.77	16.63	57.10	146.46
1993	35.4	69.17	0	61.25	16.90	48.00	111.26
1994	35.4	66.02	0	54.52	26.99	74.29	121.79
1995	35.4	63.72	0	74.32	11.46	34.08	110.13
1996	35.4	71.33	0	55.52	18.74	60.81	116.07
1997	35.4	49.84	0	34.67	21.98	68.00	100.23
1998	35.4	75.34	0	30.31	24.39	55.21	107.20
1999	35.4	63.98	0	49.95	24.56	83.82	124.38
2000	35.4	64.64	0	51.03	21.90	62.54	111.47
2001	35.4	70.12	0	29.93	21.95	63.11	107.38
2002	35.4	63.76	0	23.41	5.44	21.30	79.68
2003	35.4	57.40	0	59.33	9.85	41.90	99.60
2004	35.4	63.99	0	50.88	21.03	55.06	106.82
2005	35.4	85.15	0	41.96	14.67	45.76	112.13
2006	35.4	70.21	0	46.30	22.31	65.90	114.75
2007	35.4	64.61	0	64.13	26.61	79.95	129.00
2008	35.4	68.94	0	34.90	21.69	54.89	103.48

Table 4.5: Summary of water balance results for water years from 1971 to 2008 (units: mm per unit lake area).

Water Balance Method	Component						
	Storage Change	Evaporation	Pumping Withdrawals	Isohyetal Precipitation	Adjusted Net River Discharge	Direct Runoff	Net Ground-water Discharge
Component Average							
Average Runoff	3.16	450.12	11.06	607.38	-362.54	292.62	-73.11
PART-Adjusted Runoff	3.16	450.12	11.06	607.38	-362.54	181.84	37.66
No Net Groundwater	3.16	523.23	11.06	607.38	-362.54	292.62	0.00
Component Standard Deviation							
Average Runoff	171.10	45.38 (11%)	0.00	91.02 (15%)	227.45 (63%)	77.54 (26%)	108.82 (149%)
PART-Adjusted Runoff	171.10	45.38	0.00	91.02	227.45	58.24 (32%)	117.85 (313%)
Negligible Net Groundwater	171.10	102.27 (20%)	0.00	91.02	227.45	77.54	0.00
Year-Specific Uncertainty Average							
Average Runoff	35.40	67.52 (15%)	0.00	61.44 (10%)	20.31 (6%)	58.55 (20%)	118.17 (162%)

Note: The absolute value of the percentage of the component average is listed in parentheses for some cases.

Table 4.6: PART results for the Yläneenjoki and Pyhäjoki Rivers.

WY Start	Yläneenjoki Total Flow* (mm/unit gauged area)	Yläneenjoki Baseflow Index	Pyhäjoki Total Flow* (mm/unit gauged area)	Pyhäjoki Baseflow Index
1971	181.81	0.644	-	-
1972	274.34	0.650	243.96	0.821
1973	402.77	0.650	405.88	0.812
1974	443.60	0.665	366.67	0.749
1975	131.06	0.612	162.57	0.783
1976	304.30	0.649	239.72	0.790
1977	339.76	0.781	273.65	0.814
1978	353.03	0.652	272.75	0.736
1979	231.44	0.743	225.00	0.834
1980	532.07	0.558	519.34	0.684
1981	345.43	0.700	327.74	0.825
1982	288.95	0.680	276.79	0.814
1983	396.27	0.559	401.68	0.785
1984	327.38	0.737	320.14	0.799
1985	260.63	0.743	271.70	0.859
1986	372.90	0.696	340.62	0.740
1987	363.07	0.682	303.37	0.705
1988	327.03	0.735	320.95	0.775
1989	300.56	0.706	291.81	0.700
1990	257.45	0.724	223.05	0.797
1991	359.17	0.733	305.17	0.764
1992	321.85	0.649	276.89	0.754
1993	280.38	0.519	222.96	0.660
1994	442.98	0.666	335.98	0.795
1995	186.80	0.651	170.53	0.792
1996	359.85	0.611	277.77	0.743
1997	401.22	0.576	311.76	0.724
1998	319.55	0.647	259.37	0.776
1999	506.66	0.676	372.28	0.738
2000	334.55	0.616	321.27	0.784
2001	319.74	0.632	342.04	0.807
2002	74.31	0.636	149.05	0.867
2003	218.39	0.613	221.01	0.821
2004	276.84	0.590	300.54	0.825
2005	239.97	0.691	239.85	0.812
2006	362.00	0.547	329.03	0.785
2007	457.53	0.536	380.82	0.800
2008	267.87	0.608	307.68	0.819

* Data were obtained from OIVA – Environment and Spatial Information Services (23 Sep 2010).

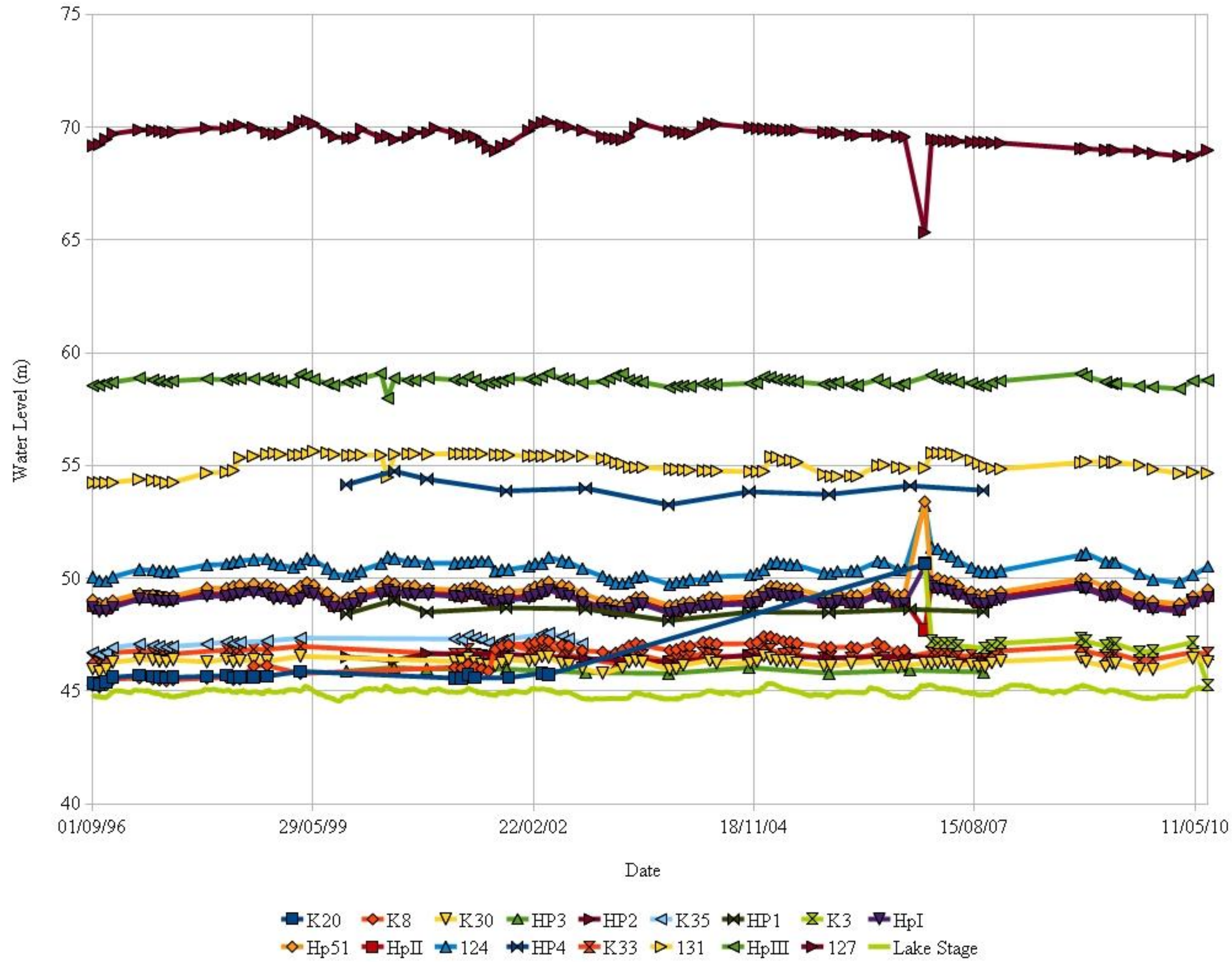


Figure 4.1: Available historical water levels in the Honkala Aquifer (OIVA – Environment and Spatial Information Services, 3 Dec 2010). Some wells seem to have anomalous water levels (HPIII and 131 on 1 May 2000; 127, 124, HP51, K20, HPI, HPII, K3 on 1 Jan 2007; K3 on 8 Jul 2010).

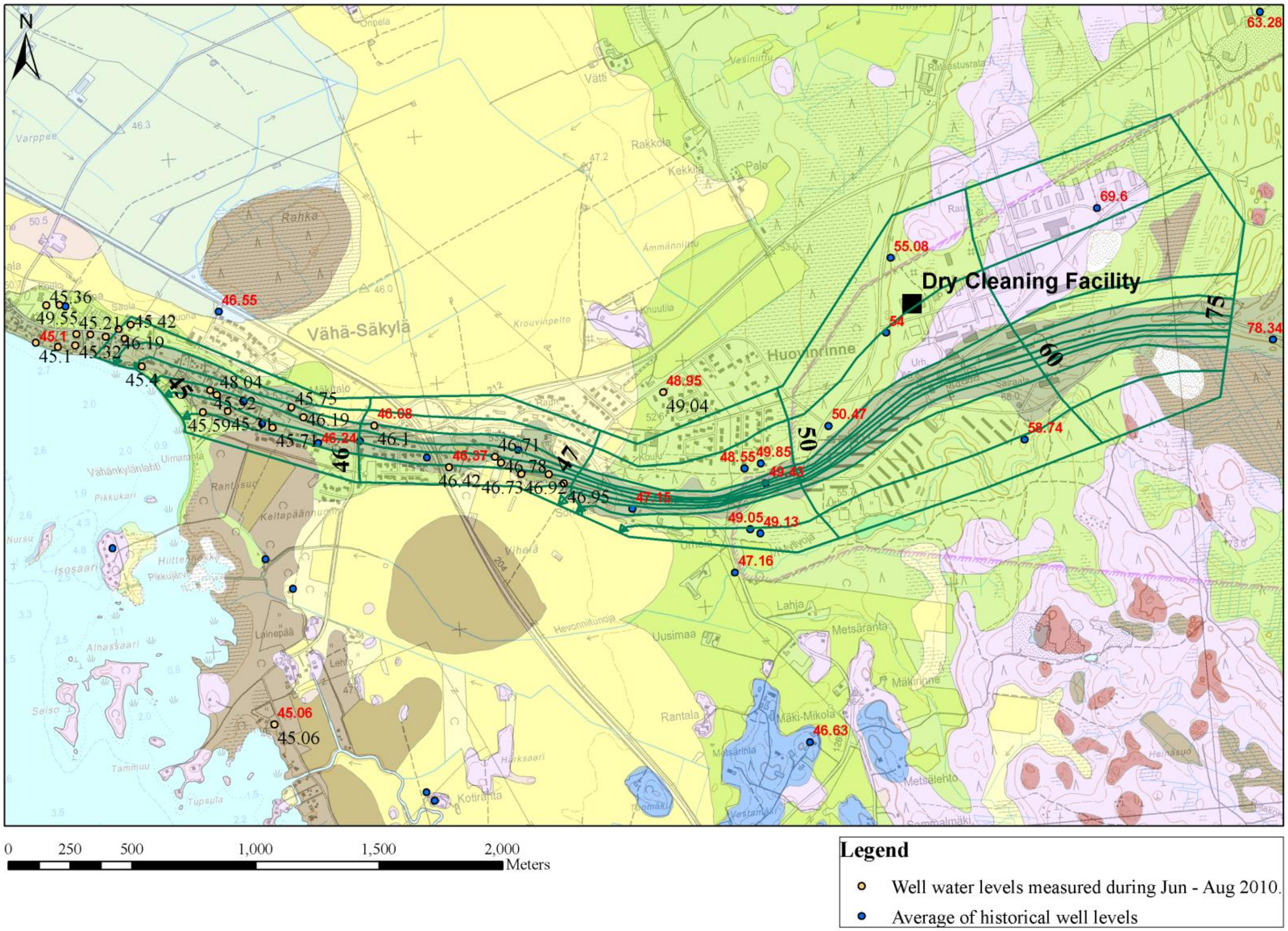


Figure 4.2: Flownet for the Honkala Aquifer (©GTK, 2008b; ©MML, 2009a; ©SYKE, 2009 [modified]).

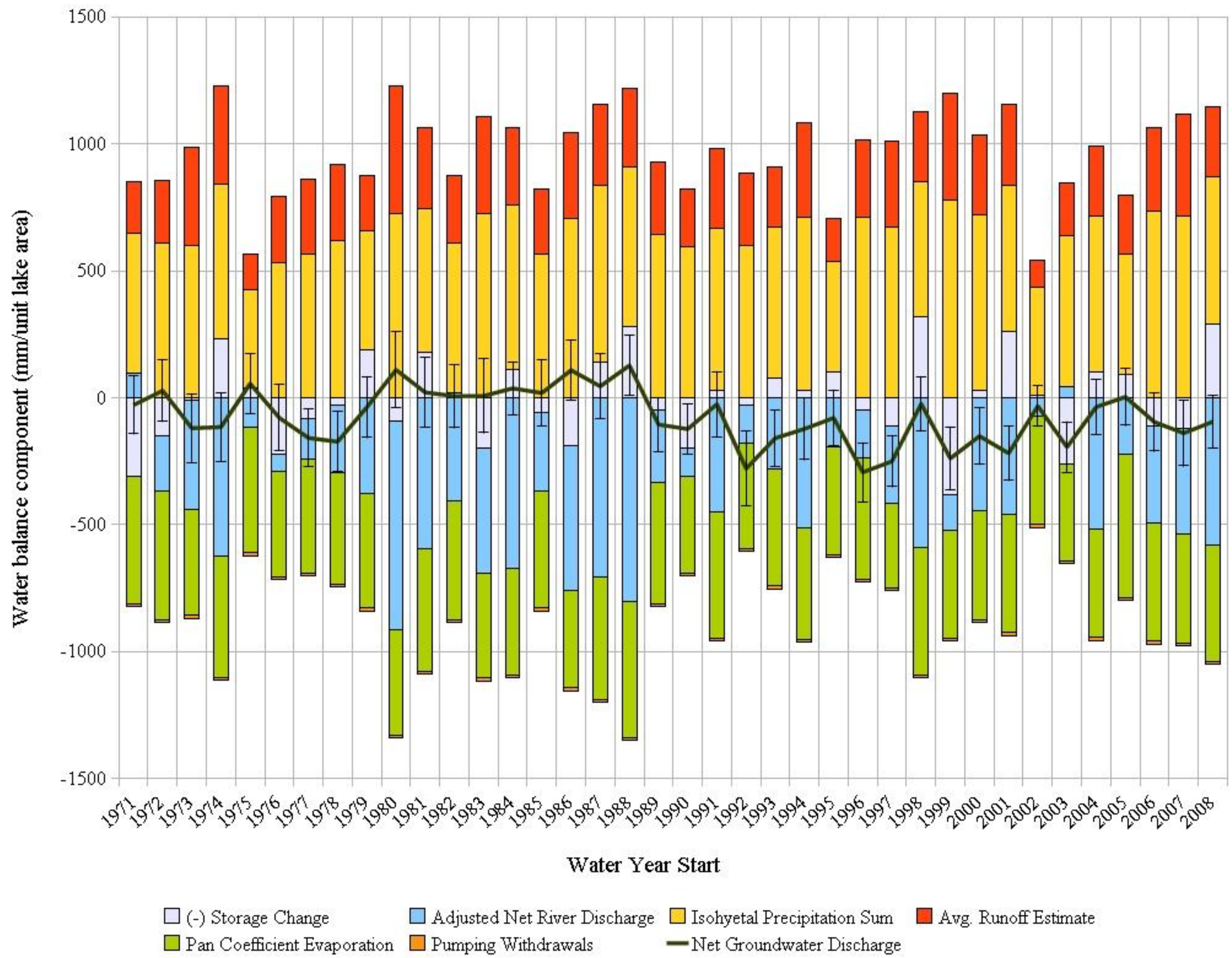


Figure 4.3: Water balance employing the average direct runoff estimate (WYs 1971-2008). With the exception of storage change, components contributing a net gain to the lake are shown above zero; those exhibiting net removal are below. The error bars are the water year-specific uncertainty values. The mean net groundwater discharge was -73mm/unit lake area.

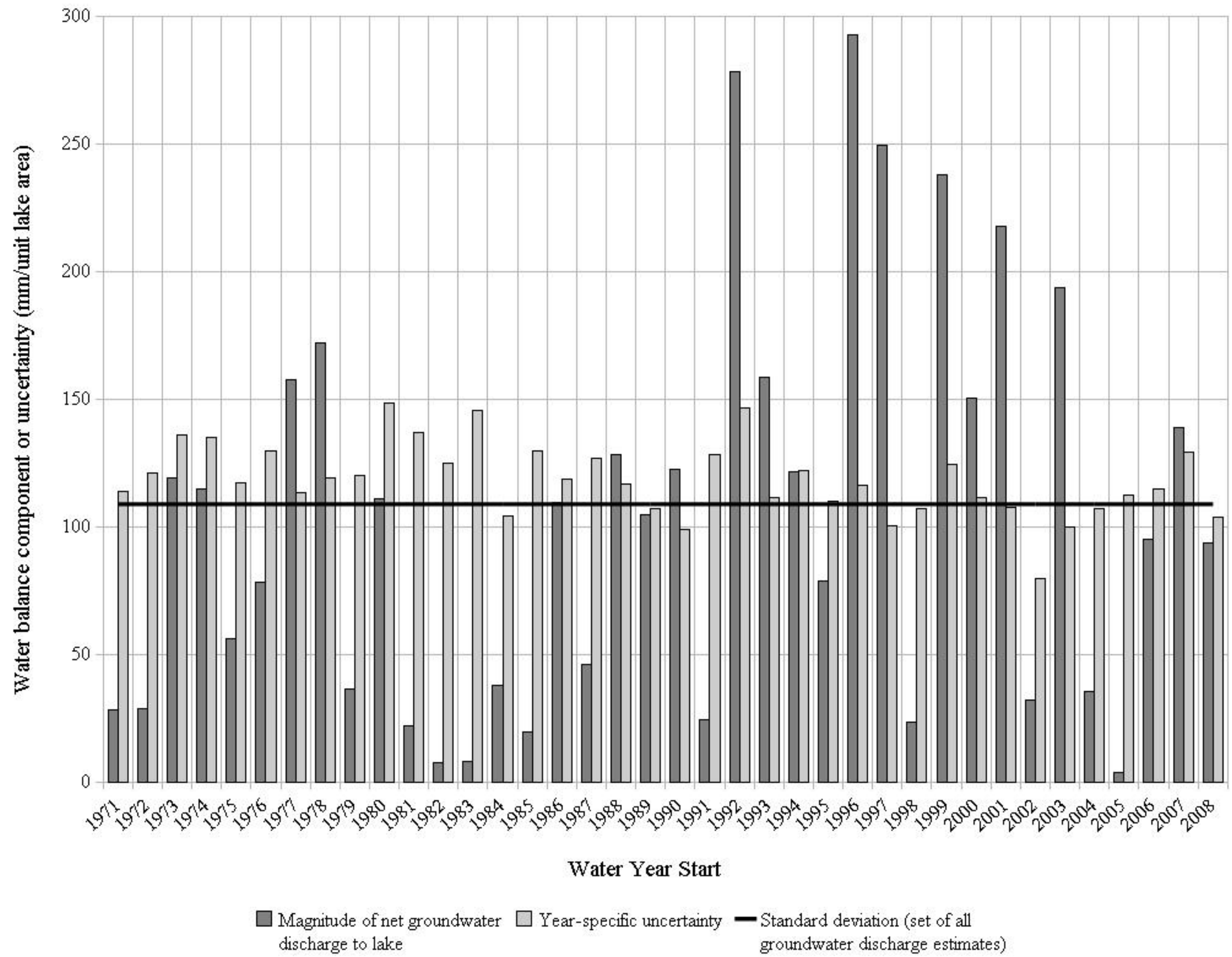


Figure 4.4: Comparison of net groundwater flux magnitude and uncertainty. The net groundwater flux component is from the water balance employing the average runoff estimates.

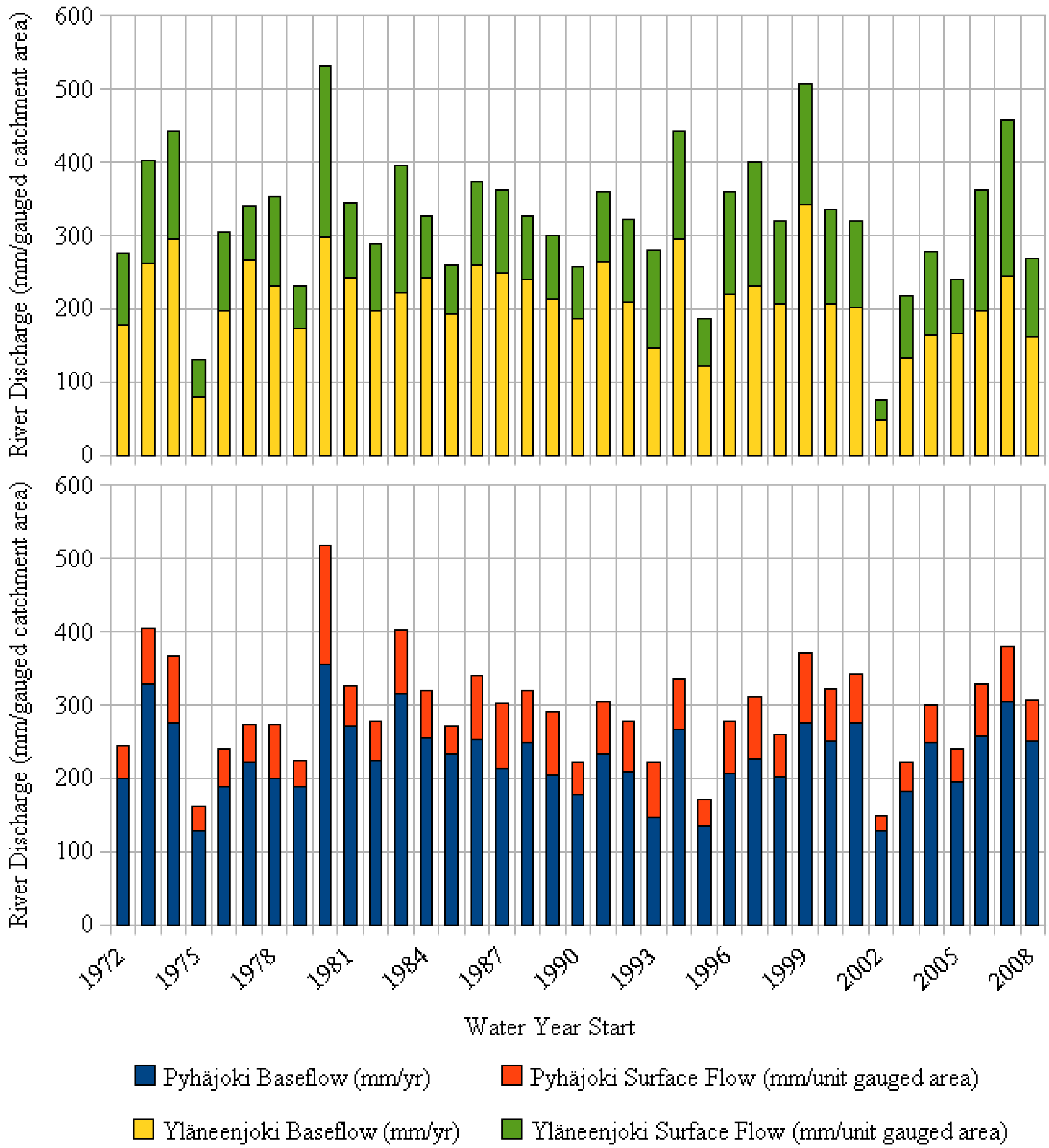


Figure 4.5: PART hydrograph separation results for the Yläneenjoki and Pyhäjoki Rivers. The river flow rates were obtained from OIVA – Environment and Spatial Information Services (23 Sep 2010).

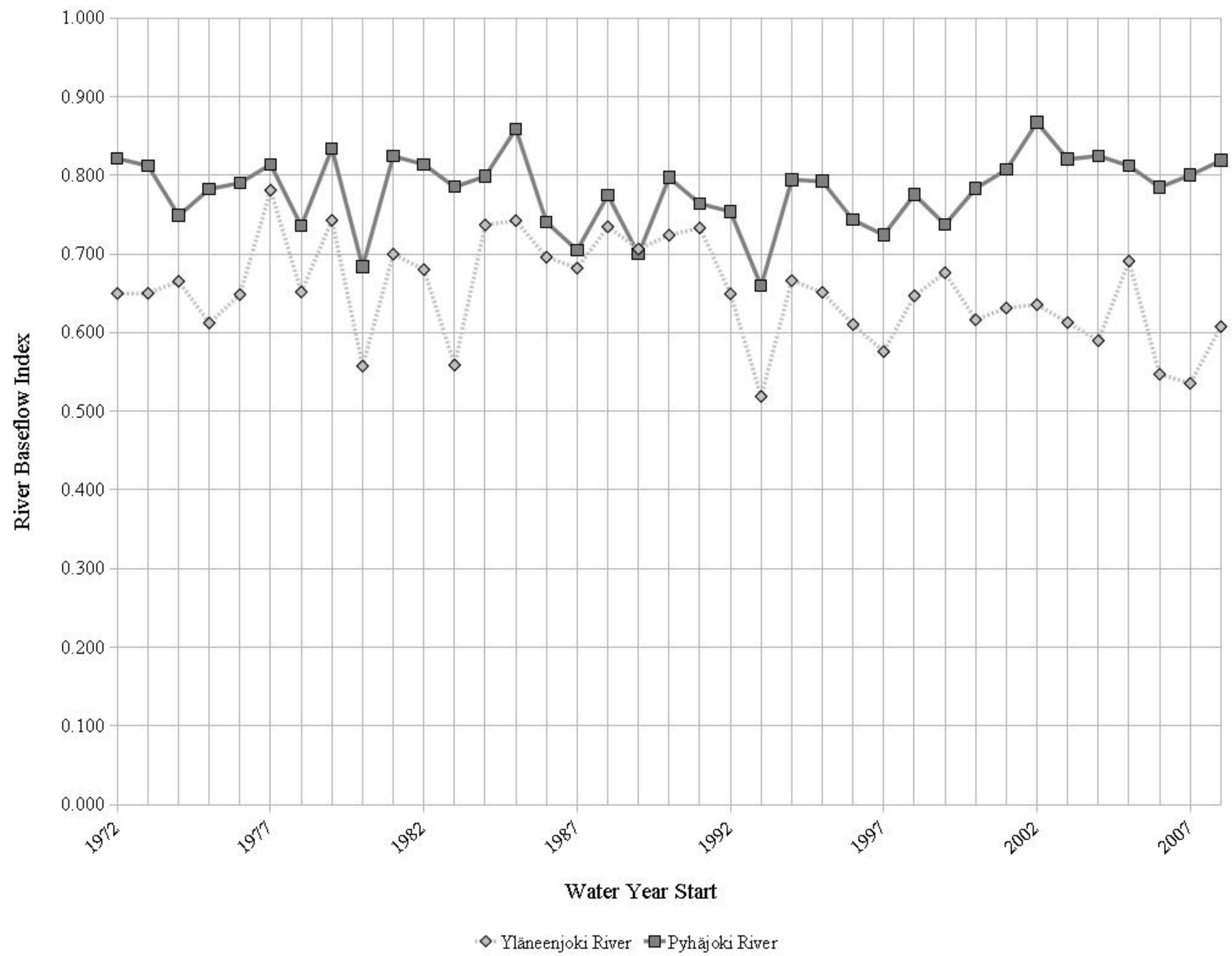


Figure 4.6: Baseflow indices from PART for the Yläneenjoki and Pyhäjoki Rivers. The river flow rates were obtained from OIVA – Environment and Spatial Information Services (23 Sep 2010).

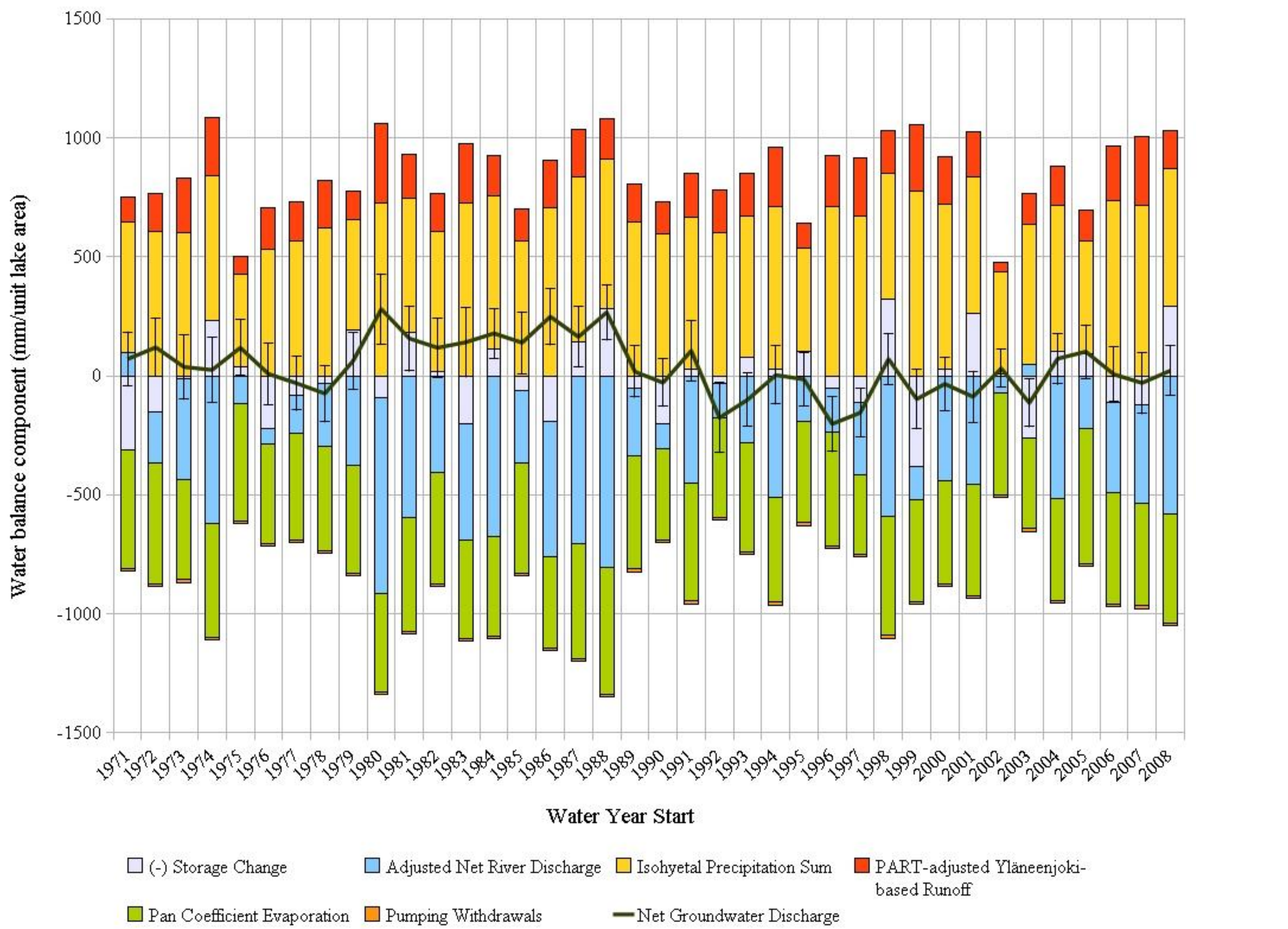


Figure 4.7: Water balance employing PART-adjusted direct runoff (WYs 1971-2008). With the exception of storage change, components contributing a net gain to the lake are shown above zero; those exhibiting net removal are below. The error bars are the water year-specific uncertainty values from the average runoff water balance. The mean net groundwater discharge was 38mm/unit lake area.

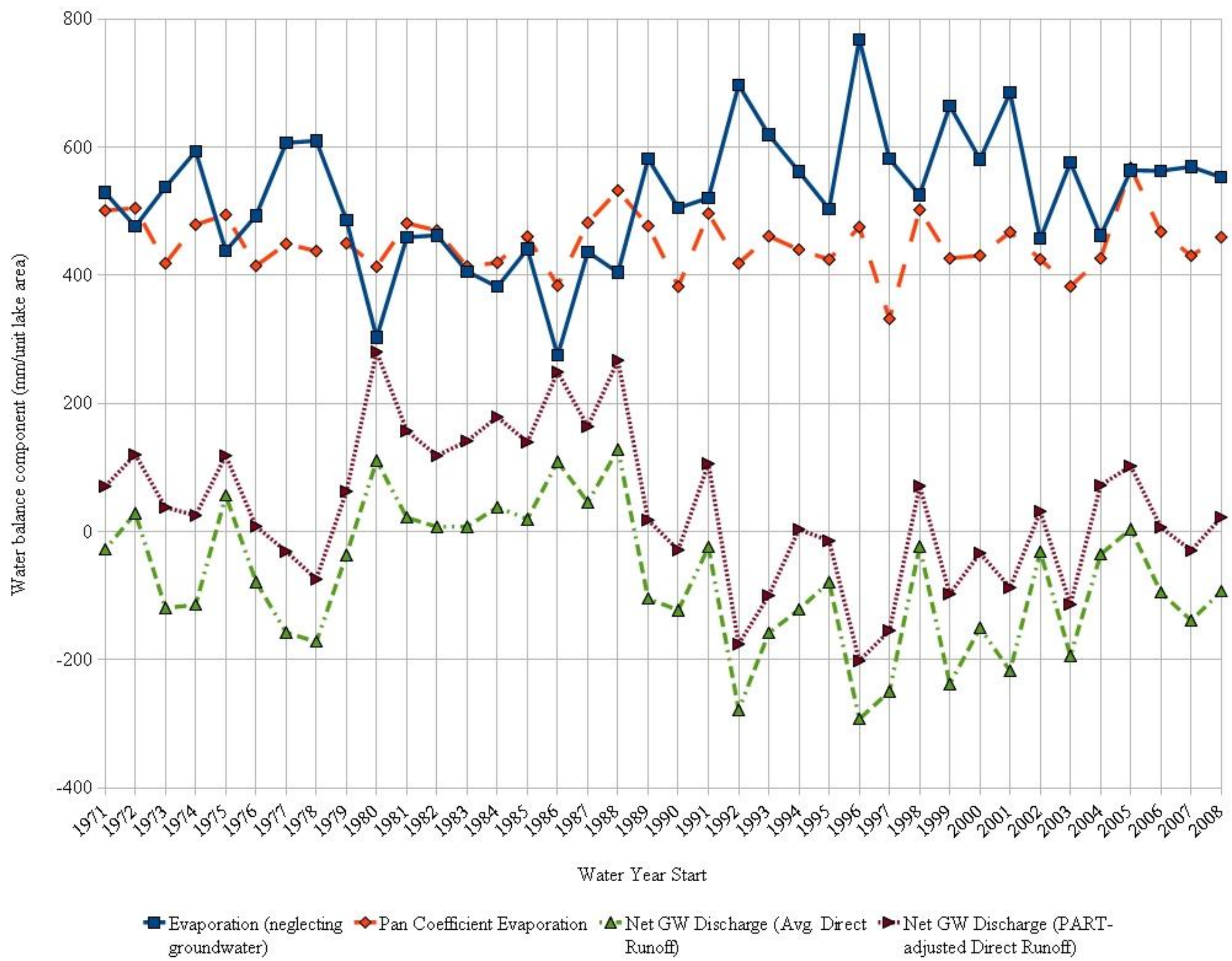


Figure 4.8: Alternative water balance with evaporation as the residual and negligible groundwater exchange. The net groundwater discharge estimates associated with the average runoff and the PART-adjusted runoff water balances are included for reference.

Chapter 5 - Discussion

In the past (e.g., Kuusisto, 1975; Järvinen, 1978), the groundwater component of a lake's water budget may often have been neglected. The net groundwater flux is a hidden component of the water balance that may be difficult to quantify due to uncertainties on measured components. A flow-through lake may exchange approximately equal amounts of groundwater discharge and recharge with adjacent aquifers such that the net flux may easily be lost within the residual term of the equation. Research at Lake Pyhäjärvi combines the important issue of water balance component uncertainty with the theme of discerning how to evaluate groundwater flow and groundwater-surface water exchange in complex glacial terrain with discontinuous aquifers, where nutrient loadings are a concern.

5.1 Water levels

There seem to be several anomalous data points in the OIVA – Environment and Spatial Information Services (3 Dec 2010) data (e.g., 4m increases in water level in a three month period – see Table 4.1). Otherwise, the average variation in calendar year data are in good agreement with Artimo (2002), who stated that the average variability at a single well was about 0.5m. It seems that the steady state assumption for the Honkala Aquifer is reasonable on a yearly scale. While the small variability displayed by the water levels in the wells of the Honkala Aquifer cannot improve the reliability of the Darcy's Law estimates due to the overwhelming uncertainty related to the hydraulic conductivity, the data do suggest consistency. Thus, we may conclude that the groundwater flow system is not very transient at over a period of at least several years, and the use of Darcy’s Law with the assumption of steady state conditions seems reasonable.

The water level measurements in the Honkala Aquifer during summer 2010 generally describe flow down the esker to the lake and are mostly reasonable. There are a couple of levels that seem too high with respect to the surrounding wells, and some supposedly upgradient wells have slightly lower water levels that those nearby. Small differences on the order of 10 or 20 cm may be explained by survey error or domestic well pumping. The levels that seem too high by several metres may possibly be due to human measurement or transcription error.

The water levels in the Honkala Aquifer of the Kuivalahti-Säkylä tributary esker seem consistent over time and generally indicate flow through the esker into Lake Pyhäjärvi. The associated hydraulic gradients are likely to be fairly well estimated in a system that is close to steady state.

5.2 Near Shore Analysis

The seepage meter results (Rautio, 2009; Korkka-Niemi et al., 2011; Rautio and Korkka-Niemi, 2011) prove that groundwater discharge is occurring, but they are limited in terms of spatial extent. The seepage meters and mini-piezometers could not be installed into particularly stony parts of the lakebed. Further, their installation (by hand and without diving equipment) was restricted to a water depth of less than about 1m. This precludes any measurement of groundwater discharge through the lakebed further from shore in potential "geological windows" (cf. Conant, 2004). The vertical hydraulic gradients suggested by mini-piezometers ranged from 10^{-2} to 10^{-1} close to the shoreline at several specific sites (Rautio, 2009), though gradients may be different between sites and fluxes may likely be lower at locations farther than about 3m from shore due to the presence of low permeability clay layers. The seepage meters suggest moderate to fairly high seepage flux, but only at several specific locations. Slow groundwater migration through the lakebed may be the case in general.

5.3 Darcy's Law

Observed contaminant (PCE) transport and subsequent modelling by Artimo (2002) suggest that a hydraulic conductivity value of 1×10^{-3}m/s is reasonable for the Honkala Aquifer. The hydraulic conductivity of the coarse-grained, glaciofluvial esker core is more likely to be high than low, given its genesis in fast-flowing meltwater and the sizes of the cobbles on the beaches adjacent to the esker ridge. Malkki and Wihuri (1982) interpreted a range of 10^{-3} – 10^{-1} m/s for the hydraulic conductivity in four Finnish eskers via the tracer dilution method. However, a simple, steady state recharge calculation to estimate the amount of water that infiltrates and is available in the Honkala Aquifer suggests that less water than the estimated 22mm per unit lake area per year might be supplied by precipitation. Using the maximum recharge estimate from Kaakinen et al. (2010) for the nearby Virttaankangas Glaciofluvial Complex (400mm/yr), the Honkala Aquifer recharge area stated in the OIVA – Environment and Spatial Information Services (9 Jun 2010) database (1.73km^2), and the lake area (155km^2) allows an equivalent of only 4 mm per unit lake area per year. This is also much lower than the estimate offered by the flownet analysis. If a bulk hydraulic conductivity value of 1×10^{-3}m/s or larger is representative of the Honkala Aquifer, it may be the case that the recharge area for the aquifer is larger than $1.73 km^2$. Alternatively, if the representative hydraulic conductivity is slightly lower, i.e., 1×10^{-4}m/s, the Darcy's Law and areal recharge calculations would be roughly the same. However, this would entail a travel time for PCE on the scale of centuries, which does not match the observations. The hydraulic conductivity may in fact be larger than 1×10^{-3}m/s because the modelling by Artimo (2002) did not account for retardation or biodegradation of the solvent.

The Darcy flux (*q*) estimates through the three pairs of cross-sections are of an order of magnitude similar to the seepage meter fluxes reported by Rautio (2009); however, this is not conclusive evidence that the chosen hydraulic conductivity value (1×10^{-3}m/s) is accurate. The issues of the spatial variability of seepage flux, the preferential installation of seepage meters in sandy areas, and the possibility for flux to concentrate at permeable regions of the lakebed preclude precise proof.

Recharge of precipitation water infiltrating through the unsaturated zone in the esker was not considered in the Darcy's Law analysis. This is not likely to significantly alter the elevation of the water table at the cross-section wells if the Honkala Aquifer system is close to steady state, as is suggested by the minimal yearly changes in hydraulic head. Further, the uncertainty related to the average well levels is likely less than the uncertainty on the hydraulic conductivity estimate.

As mentioned above, the largest groundwater flux estimate from the calculations based on Darcy's Law (for the flow between Cross-Sections 1 and 2) may be the most reasonable due to Artimo's (2002) particle tracking and the detection of PCE wells south of the esker near the lake. The decrease in the hydraulic gradient between the first pair of cross-sections and the next may reflect this leakage of groundwater. Interestingly, though perhaps unrelated, a bedrock fault line at the contact between the Satakunta sandstone (under the lake) and the crystalline basement rocks to the east intersects the esker somewhere in this vicinity. This fault zone may potentially also allow groundwater to leak out of the esker.

The areas used in the calculations for the Darcy flux through the cross-sections of the esker were chosen to include the entire area (approximately) transverse to the esker between the water table and the supposed bottom of the gravel or sand unit. This assumed that groundwater in the entire esker drained into the lake, rather than supposing that the flowpaths diverge away from a vertical plane through the centre of the long axis of the esker (as surface water would at a topographic basin divide). This suggests that the estimate of 22mm per unit lake area is a possible maximum for the flux through the esker, given the hydraulic conductivity and hydraulic gradient estimates of 1×10^{-3}m/s and 6.81×10^{-3}, respectively. Artimo's (2002) model was built on the prior assumption of groundwater from the entire esker migrating into the lake. A further assumption that was made was that the average water level at the well in the centre of the cross-section is representative of the water level for the entire cross-section. This latter assumption seems reasonable from the relatively flat water tables drawn on cross-sections from A. Artimo (unpublished report, 1998; Appendix D).

5.4 Hydrograph Separation

The PART hydrograph separation results are qualitatively consistent with Eronen et al. (1982) comments and the soil types observed on the surficial geology map. Both suggest that the Yläneenjoki subcatchment is finer-grained than the Pyhäjoki subcatchment. The average baseflow index for the Yläneenjoki River is 13% lower than the average Pyhäjoki index, suggesting soils of lower permeability. Despite seeming qualitatively reasonable, there is a lack of quantitative results for comparison. Current isotope results are not useful because of the similarity of the isotopic signatures in precipitation and groundwater in the river subcatchments (A. Rautio, pers. comm., 2011).

Figure 4.6 suggests that direct runoff estimates based on the hydrograph separation method developed above will be impacted by both the relative magnitude and the variation in baseflow of the river chosen as an anolog. The baseflow indices of the two rivers do not always vary in the same direction from water year to water year, nor do they vary to the same extent (e.g., WY 2005-2006). The differences in variation may be related to precipitation amounts or intensities in different geographical areas around the lake. However, this suggests that though a river may be selected as analygous to a direct runoff region adjacent to a lake based on soil types, other factors may be present that influence the runoff regime from subcatchment to subcatchment.

Another issue related to the hydrograph separation is the role of the ditches that drain the agricultural fields of the catchment. These would capture precipitation that could otherwise remain ponded on the land and either eventually infiltrate into the subsurface or evaporate. The degree to which the catchment has been anthropogenically modified likely influences the runoff regime in each subcatchment; however, the PART hydrograph separation technique has been employed by the USGS in populated catchments (e.g., the Great Lakes Basin – c.f. Neff et al., 2005) that would face the same issues. The Lake Pyhäjärvi watershed is certainly very rural and is less densely populated than parts of the Great Lakes Basin.

5.5 Water Balance and Uncertainty Analysis

One question that arose during the uncertainty analysis was: How much should the uncertainty vary from water year to water year? For instance, perhaps precipitation is more uniformly distributed during one year with respect to another and thus has relatively less uncertainty. Similarly, for other components with uncertainty estimates based on their total magnitudes (e.g., evaporation and direct runoff, in this current study), a smaller total magnitude will produce a smaller uncertainty estimate. The minimum absolute uncertainty value for the net groundwater discharge component is associated with the water year for which the direct runoff estimate is at its minimum value. Apart from that year, the uncertainty on the groundwater component is always greater than 99mm per unit lake area. The amount of uncertainty on the groundwater component is thus expected to be somewhat variable, but this variability is generally within the range of 99 to 148mm per unit lake area.

The year-specific uncertainty analysis supposed that inter-method variability was representative of the the amount of uncertainty associated with contouring the precipitation values. The percent difference between the two methods (i.e., the isohyetal and Kauttuankoski areal estimate methods), with respect to the isohyetal values, varied between 0.2 and 15% (in addition to the 5% baseline value for uncertainty related to the precipitation gauges). Since Winter (1981) states that mathematical methods may differ by up to 18%, this seems to be a reasonable range for uncertainty values related to the interpolation of precipitation estimates. Precipitation via the isohyetal method is likely more representative than the areal precipitation estimate from Kauttuankoski, though it involves some assumptions (e.g., that the contours are roughly representative of the actual distribution of precipitation, that the precipitation over the lake is related to that experienced at the nearby stations – i.e., that the precipitation at the stations does not largely come from moisture evaporated from the lake). The contouring method was chosen over the Thiessen polygon method for estimating precipitation inputs to the lake due to its slightly more accurate representation of the geometry of the spatially distributed data. The process of georeferencing the contour map, tracing the contour lines, and calculating the average amount for a contour interval's intersection with the lake likely contributes very little uncertainty, compared with the kriging process itself. However, the kriging method of interpolation has been evaluated to provide the best estimates of regional precipitation in comparative studies (Dingman, 1994).

Obtaining accurate lake evaporation estimates is a challenge. Estimates accurate to within 10 to 15% are possible using the pan coefficient method, while the accuracy may be 15 to 20% at best when using mass transfer methods (Winter, 1981). For this current study, few evaporation data were available from locations directly adjacent to the lake. A Class A pan located close to Lake Pyhäjärvi at Säkylä was only in operation for four of the 38 water years of the study period, for example. The Jokioinen pan evaporation records that were used ignore the six to seven months of the year when no evaporation data were collected at the stations. Accounting for sublimation from snow and ice during winter and the small amount of evaporation during spring and autumn increased the total evaporation estimate by 40mm per year, borrowing the aerodynamic estimates of Kuusisto (1975) for December – April. This additional evaporation constitutes nearly 10% of the mean evaporation estimate (450mm). The accuracy of these Shuliakovski (1969) aerodynamic estimates made by Kuusisto (1975) is unknown. Further, blowing snow may add or remove amounts of water from storage above the lake that are difficult to quantify. Unfortunately, there were not enough data to conduct the more accurate energy budget method (uncertainty < 10% – Winter [1981]) to estimate the lake evaporation.

The total lake area likely varies less than the estimated 4.3km^2 range since the contour maps estimated lake shorelines at some places above what seems reasonable with respect to the Peruskartta maps' contours. The envelope from lowest to highest contour spanned an unreasonably large distance adjacent to the shoreline (e.g., 60m) at some locations. Still, the lake area uncertainty was negligible with respect to other sources of error.

One concern to researchers at Pyhäjärvi Institute is the impact of dry summers on water quality. Can groundwater discharge explain water quality that is better than expected? A brief look at the net groundwater discharge estimates for years with precipitation at the low end of the range suggests not. While WY 1975-1976 has slightly positive estimates of net groundwater discharge, WY 1995-1996 and WY 2002-2003 have slight negative estimates (see Figure 4.3). All three of these water years are followed by a decrease in the amount of net groundwater of over 100 mm per unit lake area, however. The water quality in the lake may be controlled mostly by river inflows and associated nutrient loads. These three water years with minimal precipitation are associated with the lowest volumetric river inflow sums. The fact that the lake volume is essentially constant entails more dilution of the river nutrient load during a water year with relatively little precipitation.

Adjustment of direct runoff estimates using hydrograph separation results brings up questions of representation. Adjusting the river runoff per unit area (in the direct drainage areas that do not have single drainage channels) to a surface runoff fraction of the extrapolated value may make sense despite the number of ditches because many fields in the river catchments have their own ditches as well. The adjustment of the direct runoff estimates based on the Yläneenjoki hydrograph separation results produced estimates at approximately the upper end of the error bars from the uncertainty on the net groundwater component. This suggests that the magnitudes of the adjustments are reasonable. Further, the water balance employing a direct runoff component adjusted via the PART results exhibits a better match with the observations of groundwater discharge into the lake and the lack of observations of groundwater recharge out of the lake (Hyvärinen et al., 1973; Järvinen, 1978; Rautio, 2009; Korkka-Niemi et al., 2011; Rautio and Korkka-Niemi, 2011).

The assessment of which components of the water balance contribute the most uncertainty is important. Evaporation, precipitation, and direct runoff seem to contribute the most error. The contribution from the evaporation component may be expected to be substantial since the component is quite large and its estimation method (via pan coefficient) has at least as much error as the more accurate energy balance method (10% - Winter, 1981). The precipitation component is also large in magnitude and variable across the precipitation gauge network. Though the relative uncertainty at each particular gauge may be low (perhaps 5%), interpolation may add up to nearly three times as much error (cf. Winter, 1981). Precipitation interpolation methods have been compared in several studies (e.g., Dingman, 1994). However, the uncertainty on the direct runoff component, composed of overland and interflow, is not typically assessed (Winter, 1981). In a watershed dominated by soils with low permeability and many bedrock outcrops, where the ungauged region contributing direct runoff to the lake is sizeable (i.e., approximately equivalent to the surface area of the lake, see Figure 2.2), and where the amount of precipitation is not negligible, the amount of direct runoff is likely to be a significant part of the water balance. The percent error estimated for the direct runoff component (20%) is not likely to be unreasonably large, given the complete lack of measurement data. Water budgets of greater reliability could be achieved especially by improvements in the methods for estimating evaporation and direct runoff, though the relative magnitude of the net groundwater flux may often be small such that minor reductions in its absolute uncertainty may still leave it overwhelmed.

5.6 Large Lakes and the Water Balance Method

Though groundwater exchange with lakes has the potential to be significant in terms of lake water quality and/or the volume of water transferred between a lake and its adjacent aquifers (especially in semi-arid contexts – Shapley et al., 2005), uncertainty estimates for the groundwater component of the water balance of a lake may be greater than 100% (e.g., Winter, 1981; cf. Thodal, 1997). Studies of lakes with surface areas of tens of square kilometres or more have sometimes generally classified lakes as exhibiting negligible groundwater exchange (e.g., Lenters, 2004) or being dominated by groundwater (Schwalb et al., 1999; Valero-Garcés et al., 2003); others have used water balance methods to quantify estimates of net groundwater flux up to around 30% of total inflow (e.g., net discharge of 33% – Lake Trichonis [Zacharias et al., 2003]; net recharge of 31% – Lake Awassa [Ayenew and Gebreegziabher, 2006]; net recharge of 16% – Lake Ardibo [Demlie et al., 2007]; net discharge of 8% – Lake Hayq [Demlie et al., 2007]; net recharge of 7% – Lake Koronia [Mylopoulos et al., 2007]). Many water balance studies do not include the uncertainty analysis that is crucial to assessing the reliability of the results. This is particularly important for large lakes: water volumes from water balance components may be large, and small relative errors could entail error quantities of substantial absolute magnitude. The current study shows that a water balance method employing typical meteorological (point precipitation and pan evaporation) and hydrological (river flow and lake stage) data is unable to satisfactorily estimate the net groundwater component for a large, shallow lake (> 150km^2) with a mean net groundwater flux of less than 5% of average total inflow. The estimation of the net groundwater flux might be simplified in a setting where geological evidence suggested that either the potential for recharge or discharge was limited when the other was not. Similarly, a rough general estimate might also be plausible for a lake water balance suggesting either consistent recharge or discharge that matched observations. The average runoff water balance for Lake Pyhäjärvi suggests that groundwater recharge is predominant, but this does not match the observations (e.g., Järvinen, 1978) of some groundwater discharge and no recharge. The average runoff water balance over the water years 1971 to 2008 exhibits variability between equilibrium groundwater exchange and net recharge with uncertainty estimates often of magnitude similar to the net groundwater flux estimates themselves.

The typical uncertainty estimates developed in the current study may aid in the development of improvements to the water balance method for lakes. If it is the case that evaporation, precipitation, and direct runoff generally contribute the largest amounts of error in a water balance equation, then improvements to the method could involve the following: i) the use of evaporation estimation methods having greater accuracy (e.g., multiple evaporimeters in the lake of interest, the energy budget method, and comparison of pan evaporation to either of these), ii) an increase in the precipitation gauge density, especially north and west of the lake, iii) addressing the possibility for precipitation stations to capture less than the total amount of precipitation, and iv) the development of new methods to measure or constrain the amount of direct runoff into lakes. An increase in instrumentation could be a start for direct runoff: runoff flux in drainage ditches could be measured, and perhaps generalized graphs could be produced for lakes in order to model rainfall rates, antecedent moisture conditions, and runoff volumes for certain regions. Also, methods that estimate direct runoff to lakes based on river hydrograph separation (e.g., the PART-adjustment method described above) or knowledge of groundwater infiltration rates during rainfall events rather than general river flow per unit area averages could be tested to ascertain their accuracy. The use of the PART-adjustment direct runoff method in the water balance in the current study seemed to provide estimates of groundwater discharge that were a better match with observations.

In addition to pursuing better estimates of the water balance components with the largest amounts of error, geological and hydrogeological surveys conducted around the lake of interest may inform net groundwater estimates from a water balance equation. The current study lacked sufficient stratigraphic information in the vicinity of the shoreline around most of the lake, though stratigraphic data and water levels suggest that a consistent amount of groundwater enters the lake through the Honkala Aquifer. More of these local estimates of groundwater flux are needed. Hydraulic conductivity estimates are typically prone to uncertainty, but pumping tests should be conducted to determine representative bulk aquifer estimates for this parameter. Interviewing local residents or well drillers may also provide valuable information about local flow systems or bedrock depth.

5.7 The Potential Importance of Groundwater Discharge

It is entirely possible that the net groundwater exchange with the lake is nearly non-existent during some years. It may even be the case that on average the net amount of groundwater discharge is very small with respect to other parameters in the water balance. However, this does not necessarily imply that the groundwater – lake exchange is insignificant. On the contrary, the esker could potentially be pouring hundreds of thousands of cubic metres (4mm per unit lake area corresponds to 6×10^5 m^3) of PCE- and phosphorous-laden groundwater – at a constant temperature of 6°C – through relatively small permeable regions in shallow areas of the lake (while a roughly equivalent amount of lake water enters aquifers elsewhere). The fact that the net groundwater discharge component is small (or sometimes small) compared with the other components of the water balance may be misleading (cf. Harvey et al., 2000). Also, groundwater is important to the lake even if the amount of direct groundwater exchange is minimal because a large percentage of river water (65% of the Yläneenjoki River and 78% of the Pyhäjoki River, on average) is likely groundwater. Since the average inflow totals from the two rivers are 483 and 148mm per unit lake area for the Yläneenjoki and Pyhäjoki

Rivers (respectively), the groundwater in the river inflow to the lake may constitute over 400mm per unit lake area each year.

The resolution of the water balance with respect to the residual net groundwater discharge component, impacted by the large amount of uncertainty on the evaporation and direct runoff terms especially, is not suitable to provide definite answers of how much groundwater is entering the lake each year. Calculations based on Darcy's Law, however, suggest that the Honkala Aquifer consistently contributes a certain amount.

Chapter 6 - Conclusions

Two water balances were conducted to estimate groundwater discharge into Lake Pyhäjärvi over the 38 water years between October 1971 and September 2009. The mean net groundwater discharge estimate for the PART-adjusted direct runoff water balance was 38mm per unit lake area per water year (2.5% of average total inflow). This exhibits a better match with the observations of groundwater discharge into the lake and the lack of observations of groundwater recharge out of the lake than the water balance based on the average direct runoff. The adjustment of the direct runoff component based on the Yläneenjoki River hydrograph separation results increased the mean net groundwater discharge component from the average direct runoff water balance by 111mm per unit lake area. The mean net groundwater discharge estimate from the water balance using average runoff fractions from the two inflow rivers was -73mm per unit lake area per water year (-4.8% of average total inflow).

The resolution of the water balance method is not sufficient to accurately estimate the yearly net groundwater discharge into Lake Pyhäjärvi on a consistent basis. The net groundwater discharge seems quite variable in magnitude and fluctuates between net discharge and net recharge, especially in the PART-adjusted direct runoff water balance. The water years of the 1980's stand out as a decade with a relatively larger amount of groundwater discharge (in both the average runoff and PART-adjusted runoff water balances). The groundwater component surpassed the year-specific uncertainty estimate in 13 out of 38 water years. Its relative uncertainty ranged from 40 to 2900%, while the average absolute uncertainty was 118mm per unit lake area. The year-specific uncertainty was most strongly influenced by the error on the evaporation, precipitation, and direct runoff terms of the water balance equation.

The baseflow indices for the Yläneenjoki and Pyhäjoki Rivers from hydrograph separation using the USGS program PART (65% and 78% of streamflow, respectively) for water years between October 1971 (Yläneenjoki) or October 1972 (Pyhäjoki) and September 2009 are qualitatively reasonable but cannot currently be compared to other quantitative estimates of baseflow. Results suggest that adjustments to direct runoff estimates based on hydrograph separation will be impacted by both the relative magnitude and the variation of baseflow in the river chosen as an anolog. The baseflow indices of the two rivers sometimes varied in different directions in addition to varying by different amounts from water year to water year. The Yläneenjoki River catchment was identified as being more representative of the surface soil conditions in the direct runoff regions around Lake Pyhäjärvi.

Calculations based on Darcy's Law suggest that groundwater discharge from the Honkala Aquifer into Lake Pyhäjärvi ranges from 1 to 22mm per unit lake area per year, depending on the esker segment selected. The maximum in this range may be the most representative (due to the leakage of water out of the esker and into the lake via another aquifer) and corresponds to about 1.4% of the average total inflow of the (average runoff) water budget. Uncertainty analysis suggests that the hydraulic gradient contributes minimal error while the hydraulic conductivity is less well known and conveys its uncertainty (± one order of magnitude) to the flux estimates. The water levels in the esker aquifer seem to be reasonably consistent, varying 0.43m on average within a calendar year from 1996 to 2010. Though a small component of the overall water budget for the lake, the esker's highly permeable sediments may consistently contribute on the order of 10^5 m^3 of potentially contaminated groundwater per year (based on the Honkala Aquifer recharge area) through several relatively small regions of the lakebed near the shore.

Thus, the net groundwater flux is a relatively small component of the lake's water balance (<5% of average total inflow), with groundwater discharge from the Honkala Aquifer possibly constituting a considerable portion of this flux. Rigorous uncertainty analysis tempers acceptance of the yearly groundwater flux estimates as the true values with the understanding that the estimated magnitude could be 60% of its size or smaller, or that the direction of the net flux estimate could actually be the opposite. The results suggest that the common water balance method is better suited to lake water budgets with net groundwater contributions greater than those estimated for Lake Pyhäjärvi.

The impact of ignoring the groundwater component in the lake's water budget was also assessed. A water balance with an assumed groundwater component of 0mm per unit lake area per water year produced estimates of evaporation with a higher mean and greater variability than the pan coefficient method estimated. These evaporation estimates were more extreme during years when the water balance based on the PART-adjusted runoff estimated the net groundwater component to be large in magnitude. Thus, caution should be applied when dealing with evaporation estimates from water balances ignoring groundwater, especially those differing greatly from the mean.

For other large lakes similar to Lake Pyhäjärvi, improvements in accuracy are especially needed for the evaporation, precipitation, and direct runoff components. In the current study, these three components contributed the most uncertainty to the net groundwater flux estimates on average. The use of existing methods, such as an *in situ* evaporimeter or intensive energy budget, may increase the accuracy of evaporation estimates. Testing of the accuracy of direct runoff methods employing river hydrograph separation (e.g., the PART-adjustment method developed in this study) or infiltration rates during rainfall events may lead to the development of new methods for this poorly understood (cf. Winter, 1981) component. Smaller-scale analyses of aquifers around a lake that estimate groundwater flux via stratigraphic and water level data, hydraulic conductivity estimates from pumping tests, and calculations based on Darcy's Law, may inform water balance estimates of this potentially significant component. However, groundwater contributions to inflow rivers may be a more significant concern in terms of nutrient loadings to large lakes.

Chapter 7 - Recommendations

The following describes recommendations pertaining to: i) the hydrograph separation method for adjusting direct runoff estimates, ii) lake evaporation estimates, iii) isotopes, iv) watershed modelling, v) eutrophication concerns, and vi) water balance uncertainty analysis.

7.1 Improving the Hydrograph Separation Method for Adjusting Direct Runoff

The technique of adjusting direct runoff estimates from river flow per unit area ratios using hydrograph separation requires further development. One issue is that of how to choose which river or stream catchment is sufficiently analygous to a direct runoff region adjacent to a lake. Factors in addition to proportional areas of surface soil types may be considered. It may be possible to account for differences in precipitation amounts and intensity between the river catchment and the direct runoff subcatchment. Studies could also be made to compare multiple direct runoff estimation methods for a given lake and its watershed. For instance, the average runoff and PART-adjustment methods described above could be compared with the runoff coefficient map method of Barazzuoli et al. (1989), which is based on the method of Kennessey (1930). This runoff coefficient map method involves the selection of coefficients based on the slope of the terrrain, the permeability of the soil, and the types of vegetation (Barazzuoli et al., 1989). Field studies are also necessary to verify the accuracy of these techniques. The study of flow rates in ungauged ditches and of infiltration rates in different types of soils may provide comparative runoff data at a small scale. Numerical modelling may be helpful in assessing the range of direct runoff estimates at a larger scale.

The accuracy of the PART hydrograph separation results for the Yläneenjoki and Pyhäjoki Rivers should be assessed. Since hydrogen and oxygen isotopes are not useful for differentiating groundwater and precipitation (hence river water) in the river subcatchments (A. Rautio, pers. comm., 2011), geochemical analyses could be conducted for verification of the baseflow estimates.

7.2 Improving Lake Evaporation Estimates

Evaporation estimates for Lake Pyhäjärvi have been forced to rely on indirect wind speed and vapour pressure data or on Class A pan evaporation data from tens of kilometres away from the lake (e.g., Kuusisto, 1975). It would be beneficial to obtain long-term evaporation estimates from within the lake itself or from the immediate area around the lake. Evaporimeters could be installed in the lake, and perhaps a strategy to mitigate the impacts of waves could be developed. Estimating evaporation using an energy budget is another alternative. Energy budgets may provide the most accurate estimates of evaporation, but they involve the measurement of multiple parameters (Winter, 1981).

7.3 Constraining the Water Balance using Isotopes

Isotope mass balances may provide a tool to constrain the water balance estimates of net groundwater discharge into Lake Pyhäjärvi. Water samples from various sources such as lake water, river water, overburden groundwater, and bedrock groundwater could be collected and analyzed for the isotope Rn-222 in order to discern its usefulness as a tracer. The use of this particular isotope may be complicated by the presence of uranium and its daughter products in the rapakivi granite west of the lake (J. Karhu, pers. comm., 2010).

7.4 Numerical Modelling

A numerical model of the lake and its direct runoff regions may be a helpful tool. A model such as HydroGeoSphere (Therrien et al., 2010) could be used to model surface water and groundwater flow in an integrated manner. Various direct runoff estimation methods could be compared with such a model. Uncertainty related to the evaporation, precipitation, and direct runoff methods could also be assessed via stochastic or other methods. More research on the geology and hydrogeology of catchment regions to be modelled (especially on the stratigraphy and thicknesses of units) would be required for accurate analysis of the groundwater flow systems.

7.5 Addressing Eutrophication Concerns

Nutrient loadings should be addressed primarily in the river subcatchments. The hydrograph separation results from PART (Rutledge, 2007) suggest that groundwater baseflow constitutes a large proportion of the river flow volumes entering the lake (65% for the Yläneenjoki and 78% for the Pyhäjoki, on average). Thus, groundwater in the river inflow to the lake may constitute over 400mm per unit lake area per year. The amount of groundwater discharging to the lake directly is likely less than this, though the calculation of the net amount via the water balance precludes estimation of the total amount of groundwater entering the lake directly.

7.6 Water Balance Uncertainty Analysis

Uncertainty analysis for a water balance requires several pieces of information in addition to the component measurement data themselves. Knowledge of the accuracies of instruments (e.g., particular precipitation gauges), of measurement methods (e.g., calculating stream flow using a weir), and of mathematical interpolation techniques (e.g., Kriging) are all necessary. Instrument types and their uncertainty estimates could easily be posted in online databases (such as the Finnish database, OIVA – Environment and Spatial Information Services) where this information is not available. Attention to error analysis is important early in an investigation since each step in the data analysis process has an associated uncertainty expression to update the uncertainty. The method used in the current study to calculate the uncertainty on the groundwater component (e.g., Lee and Swancar, 1997; Sacks et al., 1998) was mostly suitable. However, it lacks a way to deal with error bars that extend predominantly in one direction. For example, certain types of precipitation gauges tend to catch less than the total precipitation (Dingman, 1994; Winter, 1981). Further, it was difficult to estimate the uncertainty on the direct runoff component due to the lack of published material on this topic (cf. Winter, 1981). More research on the direct runoff component of lakes in different settings and its associated uncertainty is needed.

Bibliography

Aarnio, M. (Sine anno). Viestikallio Tools: KKJ/WGS84/Maidenhead. http://www.viestikallio.fi/tools/kkj-wgs84.php. Accessed 26 May 2011.

Abbo, H., Shavit, U., Markel, D., and Rimmer, A., 2003. A numerical study on the influence of fractured regions on lake/groundwater interaction; the Lake Kinneret (Sea of Galilee) case. J. Hydrol. 283, 225-243.

Alcamo, J., Moreno, J.M., Nováky, B., Bindi, M., Corobov, R., Devoy, R.J.N., Giannakopoulos, C., Martin, E., Olesen, J.E., and Shvidenko, A., 2007. Europe, in: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K. pp.541-580. http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter12.pdf. Accessed 13 Jul 2011.

American Meteorological Society, 2000. “water year”. Glossary of Meteorology. http://amsglossary.allenpress.com/glossary/search?p=1&query=water+year&submit=Search. Accessed 11 May 2011.

Amtec Engineering, Inc., 2003. Tecplot Reference Manual, Version 10. Bellavue, WA.

Anttila, P., Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M., Wikström, L., and Öhberg, A., 1999. Final disposal of spent nuclear fuel in Finnish bedrock: Olkiluoto site report. POSIVA 99-10. Helsinki, Finl.

Aquifers [pohjavesialueet], PvesiAlue.shp and PvesiRaja.shp. SYKE, 2009. GIS digital mapping data (shapefiles).

Artimo, A., 2002. Application of flow and transport models to the polluted Honkala aquifer, Säkylä, Finland. Boreal Env. Res. 7, 161–172.

Artimo, A., Mäkinen, J., Berg, R.C., Abert, C.C., and Salonen, V.-P., 2003. Three-dimensional geologic modeling and visualization of the Virttaankangas aquifer, southwestern Finland. Hydrogeol. J. 11, 378-386.

Artimo, A., Saraperä, S., Ylander, I., 2008. Methods for Integrating an Extensive Geodatabase with 3D Modeling and Data Management Tools for the Virttaankangas Artificial Recharge Project, Southwestern Finland. Water Resour. Manag. 22, 1723-1739.

Ayenew, T., and Gebreegziabher, Y., 2006. Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Awassa, Ethiopia. Hydrolog. Sci. J. 51 (3), 418-431.

Barazzouli, P., Izzo, S., Menicori, P., Micheluccini, M., Salleolini, M., 1989. A New Practical Aid to Regional Hydrogeologic Planning: The Runoff Coefficient Map. Environ. Manage. 13 (5), 613-622.

Base maps [peruskartta], UL3424L_RK1_1.tif, UL3424R_RK1_1.tif, UL3442L_RK1_1.tif, UM3313L_RK1_1.tif, UM3313R_RK1_1.tif, UM3331L_RK1_1.tif, UM3312R_RK1_1.tif, UM3314L_RK1_1.tif, UM3314R_RK1_1.tif, and UM3323L_RK1_1.tif. MML, 2009a. GIS digital mapping data.

Bathymetric elevations, skunta_syvpiste.shp. MML, 2009b. N60. GIS digital mapping data.

Bedrock Map 1:1 000 000, [CD-ROM], Finland. GTK, 2008a. Available: University of Turku Laboratory of Computer Cartography, controlled access, CD 114. GIS digital mapping data. Accessed 21 Jan 2009.

Belanger, T.V., and Montgomery, M.T., 1992. Seepage meter errors. Limnol. Oceanogr. 37 (8), 1787-1795.

Bennett, E.B., 1978. Water budgets for Lake Superior and Whitefish Bay. J. Great Lakes Res. 4(3-4), 331-342.

Bonsdorff, E., Blomqvist, E.M., Mattila, J., and Norkko, A., 1997. Long-term changes and coastal eutrophication. Examples from the Åland Islands and the Archipelago Sea, northern Baltic Sea. Oceanol. Acta 20, 319-329.

Brennand, T.A., 2000. Deglacial meltwater drainage and glaciodynamics: inferences from Laurentide eskers, Canada. Geomorphology 32, 263-293.

Bruce, J.P., Cunningham, W., Freeze, A., Gillham, R., Gordon, S., Holysh, S., et al., 2009. The Sustainable Management of Groundwater in Canada. The Canadian Council of Canadian Academies, Ottawa, Canada.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. Ecol. Appl. 8 (3), 559-568.

Catchment areas [valuma-alueet], Jako3.shp. SYKE, 2010. GIS digital mapping data (shapefile).

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., and Whetton, P., 2007. Regional Climate Projections, in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA. pp. 847-940. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch11.html. Accessed 17 Jun 2011.

Conant, Jr., B., 2004. Delineating and quantifying ground-water discharge zones using streambed temperatures. Ground Water 42 (2), 243-257.

CORINE LAND COVER 2000, Pixel size 25m x 25m, clc_fi25m.tif. SYKE, 2004. GIS digital mapping data.

Demlie, M., Ayenew, T., and Wohnlich, S., 2007. Comprehensive hydrological and hydrogeological study of topographically closed lakes in highland Ethiopia: The case of Hayq and Ardibo. J. Hydrol. 339, 145-158.

Dingman, S.L., 1994. Physical Hydrology. Prentice Hall, Englewood Cliffs, NJ.

Donner, J., 1995. The Quaternary History of Scandinavia: World and Regional Geology 7. Cambridge University Press, New York, NY.

Eaton, J.W., Bateman, D., and Hauberg, S., 2008. GNU Octave Manual Version 3. Network Theory Limited. http://www.octave.org.

Eisenreich, S.J. (Ed.), 2005. Climate change and the European water dimension. EU Report 21553. European Commission: Rome, Italy. 253pp.

Elo, S., Kuivamäki, A., Kurimo, M., 1993. The additional geophysical investigations of the Kauttua-Virttaankangas tunnel route in 1992. Espoo: Geological Survey of Finland. Unpublished report. [In Finnish].

Eronen, M., Heikkinen, O., and Tikkanen, M., 1982. Holocene development and present hydrology of Lake Pyhäjärvi in Satakunta, southwestern Finland. Fennia 160 (2), 195-223.

Eronen, M., Glückert, G., Hatakka, L., van de Plassche, O., van der Plicht, J., and Rantala, P., 2001. Rates of Holocene isostatic uplift and relative sea-level lowering of the Baltic in SW Finland based on studies of isolation contacts. Boreas 30, 17-30.

ESRI, 2010. ArcMap 10.0. http://www.esri.com/.

European Commission, 22 Dec 2000. European Water Framework Directive. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities L327, 1-72. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0060:20090625:EN:PDF. Accessed 27 Jul 2011.

Finnish Geodetic Institute, 2008. FGI Coordinate Transform Service. http://coordtrans.fgi.fi/transform.jsp. Maanmittauslaitos [National Land Survey of Finland].

Freeze, R.A., and Cherry, J.A., 1979. Groundwater. Prentice Hall, Englewood Cliffs, NJ.

Frisk, T., and Bilaletdin, Ä., 2001. An integrated model system for the management of lakes and their catchments: case study of Lake Längelmävesi, Finland. Integrated Water Resources Management. Proceedings of a symposium held at Davis, CA. April 2000. IAHS Publ. 272, 99–105. http://iahs.info/redbooks/a272/iahs_272_099.pdf.

Fruh, E.G., 1967. The overall picture of eutrophication. J. Water Pollution Control Fed. 39 (9), 1449-1463.

Gray, D.M., 1970. Handbook on the principles of hydrology. Secretariat, Canadian National Committee for the International Hydrological Decade. Ottawa, Canada.

Guyonnet, D.A., 1991. Numerical modeling of effects of small-scale sedimentary variations on groundwater discharge into lakes. Limnol. Oceanogr. 36 (4), 787-796.

Harbeck, G. E., Jr., Kennon, F. W., Kohler, M. A., et al., 1954. Water Loss Investigations: Lake Hefner Studies, Technical Report. U.S. Geological Survey Prof. Paper 269.

Harvey, F.E., Rudolph, D.L., and Frape, S.K., 2000. Estimating ground water flux into large lakes: Application in Hamilton Harbour, western Lake Ontario. Ground Water 38 (4), 550-565.

Hayashi, M., and Rosenberry, D.O., 2002. Effects of Ground Water Exchange on the Hydrology and Ecology of Surface Water. Ground Water 40 (3), 309-316.

Herschy, R.W., 1973. The magnitude of errors at flow measurement stations. Proceedings of the Koblenz Symposium on Hydrometry (1970). IAHS Publ. 99, 109-131.

Holzwarth, F., 2002. The EU Water Framework Directive – a key to catchment-based governance. Water Sci. Technol. 45 (8), 105-112.

Hounam, C.E., 1973. Comparison between Pan and Lake Evaporation. World Meteorological Organization, Technical Note No. 126, 52p.

Howarth, R., Anderson, D., Cloern, J., Elfring, C., Hopkinson, C., Lapointe, B., Malone, T., Marcus, N., McGlaterhy, K., Sharpley, A., and Walker, D., 2000. Nutrient Pollution of Coastal Rivers, Bays, and Seas. Issues Ecol. 7, 1-15.

Hyvärinen, V. and Kajander, J., 2005. Rivers and Lakes of Fennoscandia, in: Seppälä, M. (Ed.), The Physical Geography of Fennoscandia. 2005. Oxford University Press, New York, NY, pp.135-157.

Hyvärinen, V., Järvinen, J., and Tuominen, T., 1973. Water balance of Lakes Pyhäjärvi and Pääjärvi. Proceedings of the Helsinki Symposium. IAHS Publ. 109, 276-283.

Häkkinen, K., 1996. Suomalaisten esihistoria kielitieteen valossa. Suomalaisen Kirjallisuuden Seura, Helsinki. 224p. [In Finnish].

John, B., 1984. Scandinavia: a new geography. Longman Group Ltd., New York, NY. 365p.

Järvinen, J., 1978. Estimating Lake Evaporation with Floating Evaporimeters and with Water Budget. Nord. Hydrol. 9, 121-130.

Kaakinen, A., Salonen, V.-P., Artimo, A., and Saraperä, S., 2010. Holocene groundwater table fluctuations in a small perched aquifer inferred from sediment record of Kankaanjärvi, SW Finland. Boreal Environ. Res. 15, 58-68.

Kaitanen, V., and Ström, O., 1978. Shape development of sandstone cobbles associated with the Säkylä-Mellilä esker, southwest Finland. Fennia 155, 23-67.

Karro, E., 1999. Hydrogeochemical studies of the bedrock and glaciofluvial aquifers in Finland. Ph.D. Dissertation, University of Helsinki, Helsinki, Finl.

Kennessey, B., 1930. Lefolyasi téniezok és retenciok. Vizugy, Koziemények.

Kirkkala, T., 2001. Lake Pyhäjärvi Restoration Project – Tool Development. LIFE96/ENV/FIN/68. Final Report. Southwest Finland Regional Environment Centre.

Kohler, M.A., Nordenson, T.J., and Baker, D.R., 1959. Evaporation maps for the United States. U.S. Weather Bureau. Tech. Paper No. 37.

Kohonen, J., and Rämö, O.T., 2005. Sedimentary rocks, diabases, and late cratonic evolution, in: Lehtinen, M., Nurmi, P.A., and Rämö, O.T. (Eds.), Precambrian Geology of Finland – Key to the Evolution of the Fennoscandian Shield. Elsevier B.V., Amsterdam, pp.563-604.

Koivunen, S. (Ed.), 2004. Yläneenjoki – vesiensuojelu ja virkistyskäyttö. Pyhäjärvi-instituutti. Sarja B nro 11. Eura, Finl. [In Finnish].

Koivunen, S., Nukki, H., and Salokangas, S., 2006. Satakunnan vesistöt, käyttö ja kunnostustarpeet. Pyhäjärvi-instituutti. Sarja B nro 12 [Viitattu 6.4.2009]. [In Finnish]. http://www.ymparisto.fi/download.asp?contentid=49454. Accessed 30 Jun 2011.

Korkka-Niemi, K., Rautio, A., Niemistö, P., and Karhu, J.A., 2011. Hydrogeochemical and isotopic indications of groundwater - surface water interactions at Lake Pyhäjärvi, SW Finland. GQ10: Groundwater Quality Management in a Rapidly Changing World. Proceedings of the 7th International Groundwater Quality Conference, Zurich, Switzerland, 13-18 Jun 2010. IAHS Publ. 342, 423-426.

Korsman, K., Koistinen, T., Kohonen, J., Wennerström, M., Ekdahl, E., Honkamo, M., Idman, H., and Pekkala, Y. (Eds.), 1997. Bedrock Map of Finland 1:1 000 000. Geological Survey of Finland, Espoo, Finl.

Krabbenhoft, D.P., Anderson, M.P., Bowser, C.J., and Valley, J., 1990. Estimating groundwater exchange with Sparkling Lake, Wisconsin, 1: Use of the stable isotope mass-balance method. Water Resour. Res. 26, 2445-2453.

Kujansuu, R., and Niemelä, J., 1984. Map of Quaternary deposits of Finland 1:1 000 000. Geological Survey of Finland, Espoo, Finl.

Kujansuu, R., Kurkinen, I., and Niemelä, J., 1995. Glaciofluvial deposits in Finland, in: Ehlers, J., Kozarski, S., and Gibbard, P. (Eds.), Glacial deposits in North-East Europe. A.A. Balkema, Rotterdam, Netherlands, pp.67-75.

Kuusisto, E., 1975. Säkylän Pyhäjärven vesitase ja säännöstely (English summary: The water balance and regulation of Lake Pyhäjärvi). Vesihallitus – National Board of Waters, Finland. Publications of the Water Research Institute 11. 86pp. [In Finnish with English summary.]

Lapham, W.W., 1989. Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity. U.S. Geological Survey Wat. Sup. Paper 2337.

Lee, D.R., and Cherry, J.A., 1978. A field exercise on groundwater flow using seepage meters and mini-piezometers. J. Geol. Educ. 27, 6-10.

Lee, T.M., and Swancar, A., 1997. The influence of evaporation, groundwater, and uncertainty in the hydrologic budget of Lake Lucerne, a seepage lake in Polk County, Florida. U.S. Geological Survey Wat. Sup. Paper 2439.

Lenters, J.D., 2004. Trends in the Lake Superior water budget since 1948: A weakening seasonal cycle. J. Great Lakes Res. 30 (Supplement 1), 20-40.

Lepistö, A., Huttula, T., Bärlund, I., Granlund, K., Härmä, P., Kallio, K., Kiirikki, M., Kirkkala, T., Koponen, S., Koskiaho, J., Kotamäki, N., Lindfors, A., Malve, O., Pyhälahti, T., Tattari, S., and Törmä, M., 2008. New measurement technology, modelling, and remote sensing in the Säkylän Pyhäjärvi area – CatchLake. Reports of the Finnish Environment Institute 15. Helsinki, Finl.

Leveinen, J., Rönkä, E., and Karro, E., 2000. Groundwater quality – a constraint of groundwater exploration in hard rock areas. Proceedings of the workshop on Hard Rock Hydrogeology, Äspö, Sweden. Nordic Association for Hydrology, NHP Report 45, pp.79-90.

Lindroos, P., Hyyppä, J., Stén, C.-G., and Tuittila, H., 1983. Rauman — Kokemäen seudun maaperä. Suomen geologinen kartta 1:100 000. Maaperäkartan selit-ykset, 1132 Rauma ja 1134 Kokemäki. Geologinen Tutkimuslaitos, Espoo, 71 pp. [In Finnish with English summary.]

Linsley, R.K., Kohler, M.A., and Paulhus, J.L.H., 1958. Hydrology for engineers. McGraw-Hill Book Co., Inc., New York, NY.

Lipponen, A., 2006. Topographical, structural and geophysical characterization of fracture zones: implications for groundwater flow and vulnerability. Ph.D. Dissertation, University of Helsinki, 58pp.

Luoto, M., 2000. Spatial analysis of landscape ecological characteristics of five agricultural areas in Finland by GIS. Fennia 178 (1), 15-54.

Mackenthun, K.M., Ingram, W.M., and Porges, R., 1964. Limnological aspects of recreational lakes. Pub. Health Service Publ. No. 1167, U.S. Govt. Printing Office, Washington, D.C.

Malkki, E., and Wihuri, H., 1982. Measurement of hydraulic conductivity by the tracer dilution method. B. Eng. Geol. Environ. 26 – 27 (1), 473–476.

Mannio, J., Skjelkvåle, B.-L., Wilander, A., Fjeld, E., Rekolainen, S., 2005. Lake – Water Pollution, in: Seppälä, M. (Ed.), The Physical Geography of Fennoscandia. Oxford University Press, New York, NY. pp.391-404.

MathWorks, 2010. MATLAB. http://www.mathworks.com/help/techdoc/.

Mylopoulos, N., Mylopoulos, Y., Veranis, N., and Tolikas, D., 2007. Groundwater modeling and management in a complex lake-aquifer system. Water Resour. Manag. 21, 469-494.

Mäkinen, J., 2003. Time-transgressive deposits of repeated depositional sequences within interlobate glaciofluvial (esker) sediments in Köyliö, SW Finland. Sedimentology 50, 327-360.

Neff, B.P., Piggott, A.R., and Sheets, R.A., 2005. Estimation of Shallow Ground-Water Recharge in the Great Lakes Basin. U.S. Geological Survey Sci. Inv. Rep. 2005-5284, 20p.

Nield, S.P., Townley, L.R., and Barr, A.D., 1994. A framework for quantitative analysis of surface water-groundwater interaction: Flow geometry in a vertical section. Water Resour. Res. 30 (8), 2461-2475.

Nixon, S.W., 1995. Coastal Marine Eutrophication: A definition, social causes, and future concerns. Ophelia 41, 199-219.

Okkonen, J., Jyrkama, M., and Kløve, B., 2010. A conceptual approach for assessing the impact of climate change on groundwater and related surface waters in cold regions (Finland). Hydrogeol. J. 18, 429-439.

Paulamäki, S., Paananen, M., and Elo, S., 2002. Structure and geological evolution of the bedrock of southern Satakunta, SW Finland. Posiva 2002-04.

Platt, R.R. (Ed.), 1955. Finland and its Geography. American Geographical Society Handbook Series. Duell, Sloan, and Pearce, New York, NY, 510pp.

Punkari, M., 1980. The ice lobes of the Scandinavian ice sheet during the deglaciation of Finland. Boreas 9, 307–310.

Rabalais, N.N. 2002. Nitrogen in aquatic ecosystems. Ambio 31 (2), 102-112.

Rautio, A., 2009. Characterization of Groundwater-Lake Interactions at Lake Pyhäjärvi, SW Finland. M.Sc.Thesis, University of Turku, Turku, Finl., 92pp.

Rautio, A., and Korkka-Niemi, K., 2011. Characterization of groundwater–lake water interactions at Pyhäjärvi, a lake in SW Finland. Boreal Environ. Res. 16, 363-380.

Rodhe, W., 1969. Crystallization of Eutrophication Concepts in Northern Europe, in: Eutrophication: Causes, Consequences, Correctives. Proceedings of the International Symposium on Eutrophication, University of Wisconsin, Madison, 1967. National Academy of Sciences-Natural Research Council, USA. Washington, D.C. pp. 50-64.

Rosenberry, D.O., and LaBaugh, J.W., 2008. Field techniques for estimating water fluxes between surface water and ground water. U.S. Geological Survey Techniques and Methods 4-D2, 128 p.

Rozanski, K., Froehlich, K., and Mook, W.G., 2001. Surface Water, Vol. III, in: Mook, W.G. (Ed.), Environmental isotopes in the hydrological cycle: Principles and applications, IHP-V, Technical Documents in Hydrology No. 39, UNESCO, Paris, 117pp. http://www-naweb.iaea.org/napc/ih/IHS_resources_publication_hydroCycle_en.html. Accessed 6 Aug 2011.

Rutledge, A.T., 1998. Computer Programs for Describing the Recession of Ground-Water Discharge and for Estimating Mean Ground-Water Recharge and Discharge from Streamflow Records–Update. U.S. Geological Survey Water-Resour. Inv. Rep. 98-4148. Reston, VA. http://pubs.usgs.gov/wri/wri984148/. Last Updated: 1 Sep 2005. Accessed 17 Nov 2010.

Rutledge, A.T., 2007. Program User Guide for PART. U.S. Geological Survey. http://water.usgs.gov/ogw/part/UserManualPART.pdf. Jan 2007. Accessed 17 Nov 2010.

Räsänen, M., Salonen, V.-P., Salo, J., Walls, M., and Sarvala, J., 1992. Recent history of sedimentation and biotic communities in Lake Pyhäjärvi, SW Finland. J. Paleolimnol. 7, 107-126.

Rönkä, E., 1983. Drilled wells and groundwater in the Precambrian crystalline bedrock of Finland. Finnish National Board of Waters. Publications of the Water Research Institute, Report 52. 57p.

Rönkä, E., 1993. Increased depth of drilled wells – advantage or drawback? In: Banks, S. and Banks, D. (Eds.), I.A.H. Memoirs XXIV, Part 2, pp.772-779.

Rönnberg, C., and Bonsdorff, E., 2004. Baltic Sea eutrophication: area-specific ecological consequences. Hydrobiologia 514, 227-241.

Saarnisto, M., and Salonen, V.-P., 1995. Glacial History of Finland, in: Ehlers, J., Kozarski, S., Gibbard, P.L. (Eds.), Glacial Deposits in North-East Europe. A.A. Balkema, Rotterdam, Netherlands, pp. 3-10.

Sacks, L.A., Swancar, A., and Lee, T.M., 1998. Estimating groundwater exchange with lakes using water-budget and chemical mass-balance approaches for ten lakes in ridge areas of Polk and Highlands Counties, Florida. U.S. Geological Survey Water-Resour. Inv. Rep. 98-4133.

Salonen, V.-P., 1991. Glacial dispersal of Jotnian sandstone fragments in southwestern Finland, in: Autio, S. (Ed.), Current Research 1989-90. Geol. Surv. Finl. Spec. Paper 12, pp.127-130.

Savage, C., Leavitt, P.R., and Elmgren, R., 2010. Effects of land use, urbanization, and climate variability on coastal eutrophication in the Baltic Sea. Limnol. Oceanogr. 55 (3), 1033-1046.

Scheider, W.A., Moss, J.J., and Dillon, P.J., 1978. Measurement and uses of hydraulic and nutrient budgets. Proceedings of the National Conference on Lake Restoration, Minneapolis, Minnesota, August 22-24, 1978. U.S. Envrionmental Protection Agency, EPA 440/5-79-001, pp.77-83.

Schmidt, A., Gibson, J.J., Santos, I.R., Schubert, M., and Tattrie, K., 2009. The contribution of groundwater discharge to the overall water budget of Boreal lakes in Alberta/Canada estimated from a radon mass balance. Hydrol. Earth Syst. Sci. Discuss. 6, 4989-5018.

Scholten, M.C.Th., Foekema, E.M., Van Dokkum, H.P., Kaag, N.H.B.M., and Jak, R.G., 2005. Eutrophication Management and Ecotoxicology. Springer-Verlag, Berlin, Germany.

Schwalb, A., Burns, S.J., and Kelts, K., 1999. Holocene environments from stable isotope stratigraphy of ostracods and authigenic carbonate in Chilean Altiplano Lakes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 148, 153-168.

Sen, T.K., 2011. Processes in Pathogentic Biocolloidal Contaminants Transport in Saturated and Unsaturated Porous Media: A Review. Water, Air, Soil Poll. 216, 239–256.

Seuna, P., and Linjama, J., 2004. Water balances of the northern catchments of Finland, in: Kane, D.L., and Yang, D. (Eds.), Northern Research Basins Water Balance. Proceedings of a workshop held at Victoria, Canada, Mar 2004. IAHS Publ. 290, 111-119.

Shapley, M.D., Ito, E., and Donovan, J.J., 2005. Authigenic calcium carbonate flux in groundwater-controlled lakes: Implications for lacustrine paleoclimate records. Geochim. Cosmochim. Acta 69 (10), 2517-2533.

Shuliakovski, L.G., 1969. Formula for computing evaporation with allowance for the temperature of the free water surface. Soviet Hydrology, Selected Papers Issue 6.

Sigel, K., Klauer, B., Pahl-Wostl, C., 2010. Conceptualising uncertainty in environmental decision-making: The example of the EU water framework directive. Ecol. Econ. 69 (3), 502-510.

Singh, R., Artman, D., Taylor, D., Brinton, D., 2000. Basic Surveying – Theory and Practice. Seminar. Oregon Department of Transportation Geometronics Unit. 15 – 17 Feb 2000. Bend, OR. http://www.oregon.gov/ODOT/HWY/GEOMETRONICS/docs/BasicManual2000_02.pdf?ga=t. Accessed 15 July 2010.

Smith, V.H., Joye, S.B., and Howarth, R.W., 2006. Eutrophication of freshwater and marine ecosystems. Limnol. Oeanogr. 51 (1), Part 2, 351-355.

Sophocleous, M., 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeol J. 10, 52-67.

Straile, D., Livingstone, D.M., Weyhenmeyer, G.A., and George, D.G., 2003. The response of freshwater ecosystems to climate variability associated with the North Atlantic Oscillation, in: Hurrell, J.W., Kushnir, Y., Ottersen, G., and Visbeck, M. (Eds), The North Atlantic Oscillation: climatic significance and environmental impact. Geophysical Monograph Series 134. American Geophysical Union, Washington, D.C., pp.263-279.

Surface soil geology [maaperä] 1:20 000, Kaista 1 (Sheets 1133 and 1134) and 2 (Sheets 2111 and 2212). GTK, 2008b. GIS digital mapping data (shapefiles). Online distribution.

Tarvainen, M., and Ventelä, A.-M., 2007. Pyhäjärven suojelutyö 2000 - 2006. Pyhäjärvi Instituutin julkaisuja. Sarja B nro 14. Eura. 84pp. [In Finnish.]

Taylor, J.R., 1997. An Introduction to Error Analysis: the study of uncertainties in physical measurements, second ed. University Science Books, Sausalito, CA.

Therrien, R., McLaren, R.G., Sudicky, E.A., and Panday, S.M., 2010. HydroGeoSphere: A Three-dimensional Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport. Code Documentation and User's Guide. Groundwater Simulations Group, Univ. of Waterloo, Canada.

Thodal, C.E., 1997. Hydrogeology of Lake Tahoe Basin, California and Nevada, and Results of a Ground-Water Quality Monitoring Network, Water Years 1990-92. U.S. Geological Survey Water-Resour. Inv. Rep. 97-4072.

Thornthwaite, C.W., 1948. An Approach toward a Rational Classification of Climate. Geogr. Rev. 38, 55-94.

Tikkanen, M., 1981. Georelief, its origin and development in the coastal area between Pori and Uusikaupunki, south-western Finland. Fennia 159 (2), 253-333.

Tikkanen, M., 2005. Climate, in: Seppälä, M. (Ed.), The Physical Geography of Fennoscandia. Oxford University Press, New York, NY. pp. 97-112.

Topographic elevations [korkeusmalli], 25m point spacing, 20n_dem2.xyz and 20m_dem2.xyz. MML, 2009c. N60. GIS digital mapping data ([x, y, z] coordinates).

Trask, J.C., 2007. Resolving hydrologic water balances through novel error analysis, with focus on inter-annual and long-term variability in the Tahoe Basin. Ph.D. Dissertation, University of California, Davis, 378pp.

Tweed, S., Leblanc, M., and Cartwright, I., 2009. Groundwater-surface water interaction and the impact of a multi-year drought on lakes conditions in South-East Australia. J. Hydrol. 379, 41-53.

Tyler, F., 1977. A Laboratory Manual of Physics, fifth ed. Edward Arnold, London, U.K. 264pp.

Valero-Garcés, B.L., Delgado-Huertas, A., Navas, A., Edwards, L., Schwalb, A., and Ratto, N., 2003. Patterns of regional hydrological variability in central-southern Altiplano (18°-26°S) lakes during the last 500 years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 194, 319-338.

Veira, M., 1974. Pyhäjärven rannat Yläneellä (The shores of Lake Pyhäjärvi at Yläne). Unpublished M.Sc. Thesis, University of Turku, Turku, 89pp. [In Finnish].

Ventelä, A.-M., Arvola, L., Helminen, H., and Sarvala, J., 2005. Sense of place – meaning of a lake for Finnish mental environment. Vesitalous 46 (4), 27-31. [In Finnish].

Ventelä, A.-M., Tarvainen, M., Helminen, H., and Sarvala, J., 2007. Long-term management of Pyhäjärvi (southwest Finland): eutrophication, restoration – recovery? Lake Reserv. Manage. 23, 428-438.

Wetzel, R.G., 1975. Limnology. W.B. Saunders Co., Philadelphia, PA.

Winter, T.C., 1978. Numerical simulation of steady-state three-dimensional groundwater flow near lakes. Water Resour. Res. 14 (2), 245-254.

Winter, T.C., 1981. Uncertainties in estimating the water balance of lakes. Water Resour. Bull. 17 (1), 82-115.

Winter, T.C., 1995. Hydrological Processes and the Water Budget of Lakes, in: Lerman, A., Imboden, D.M., and Gat, J.R. (Eds.), Physics and Chemistry of Lakes, second ed. Springer-Verlag, Berlin, Germany, pp. 37-62.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998. Ground Water and Surface Water: A Single Resource. U.S. Geological Survey Circular 1139. Denver, CO. http://pubs.usgs.gov/circ/circ1139/. Accessed 14 Jul 2011.

Woessner, W.W., 1998. Changing views of stream-groundwater interaction, in: Van Brahana, J., Eckstein, Y., Ongley, L.K., Schneider, R., and Moore, J.E. (Eds.), Gambling with groundwater – Physical, chemical, and biological aspects of aquifer-stream relations: Las Vegas, Nevada. Proceedings of the Joint Meeting of the XXVIII Congress of the International Association of Hydrogeologists and the annual meeting of the American Institute of Hydrologists, Las Vegas, NV, 28 Sep - 2 Oct 1998, pp. 1-6.

Zacharias, I., Dimitriou, E., and Koussouris, T., 2003. Estimating groundwater discharge into a lake through underwater springs by using GIS technologies. Environ. Geol. 44, 843-851.

Appendix A

Finnish Terminology and Organizations

Table A.1: Finnish words, places, and organizations.	
Finnish Word	**Translation/Description**
Eura	Town at the north end of Lake Pyhäjärvi, on the Eurajoki River.
Eurajoki	The single outflow river of Lake Pyhäjärvi
GTK (Geologian Tutkimus Laitos)	Finnish Geological Survey
Harju	Esker
Honkala	Aquifer in the Kuivalahti – Säkylä tributary esker that extends from Lake Pyhäjärvi at Säkylä to the Virttaankangas glaciofluvial complex to the northeast.
Huovinrinne	Finnish military area located on the esker on the outskirts of Säkylä.
Järvi	Lake
Joki	River
Kauttua	Region at the north end of Lake Pyhäjärvi; location of the Lohiluoma pumping well and artificial groundwater recharge operation
Köyliönjärvi	The lake to the northeast of Lake Pyhäjärvi
Lähdet	Groundwater spring
MML (Maanmittauslaitos)	National Land Survey of Finland
OIVA – Environment and Spatial Information Services	Online Finnish environmental database including hydrological and hydrogeological data.
Olkiluoto	Nuclear waste repository on the western coast of the Gulf of Bothnia, northwest of Lake Pyhäjärvi
PaITuli	Online Finnish archive including a variety of spatial data.
Peruskartta	General base maps covering areas of Finland at a scale of 1:25,000.
Pohjavesi	Groundwater
Pyhäjoki	The smaller of the two rivers draining into Lake Pyhäjärvi
Rapakivi granite	Weathered granite located to the west of Lake Pyhäjärvi
Säkylä	Town beside Lake Pyhäjärvi
Säkylänharju-Virttaankangas	Large glaciofluvial complex located east of Lake Pyhäjärvi and extending from Lake Köyliönjärvi to south of Highway 41.
Salpausselkä I, II, and III	Extensive end moraines / ridges in southern Finland.
Satakunta sandstone	Sandstone unit under the lake and in the region of Satakunta (north of the lake) that extends NW to the Baltic Sea.
SYKE (Suomen Ympäristökeskus)	Finnish Environment Institute
Uusikylä	Aquifer in the Kuivalahti – Säkylä esker that borders on Lake Pyhäjärvi's NE shoreline; NW of the Honkala Aquifer.
Varsinais-Suomen ELY	Southwest Finland Regional Economic Development, Transportation and Environmental Agency
Yläneenjoki	The larger of the two rivers draining into Lake Pyhäjärvi
Ympäristökeskus	Environment Centre

Appendix B

PCE Detection in Monitors near the Honkala Aquifer

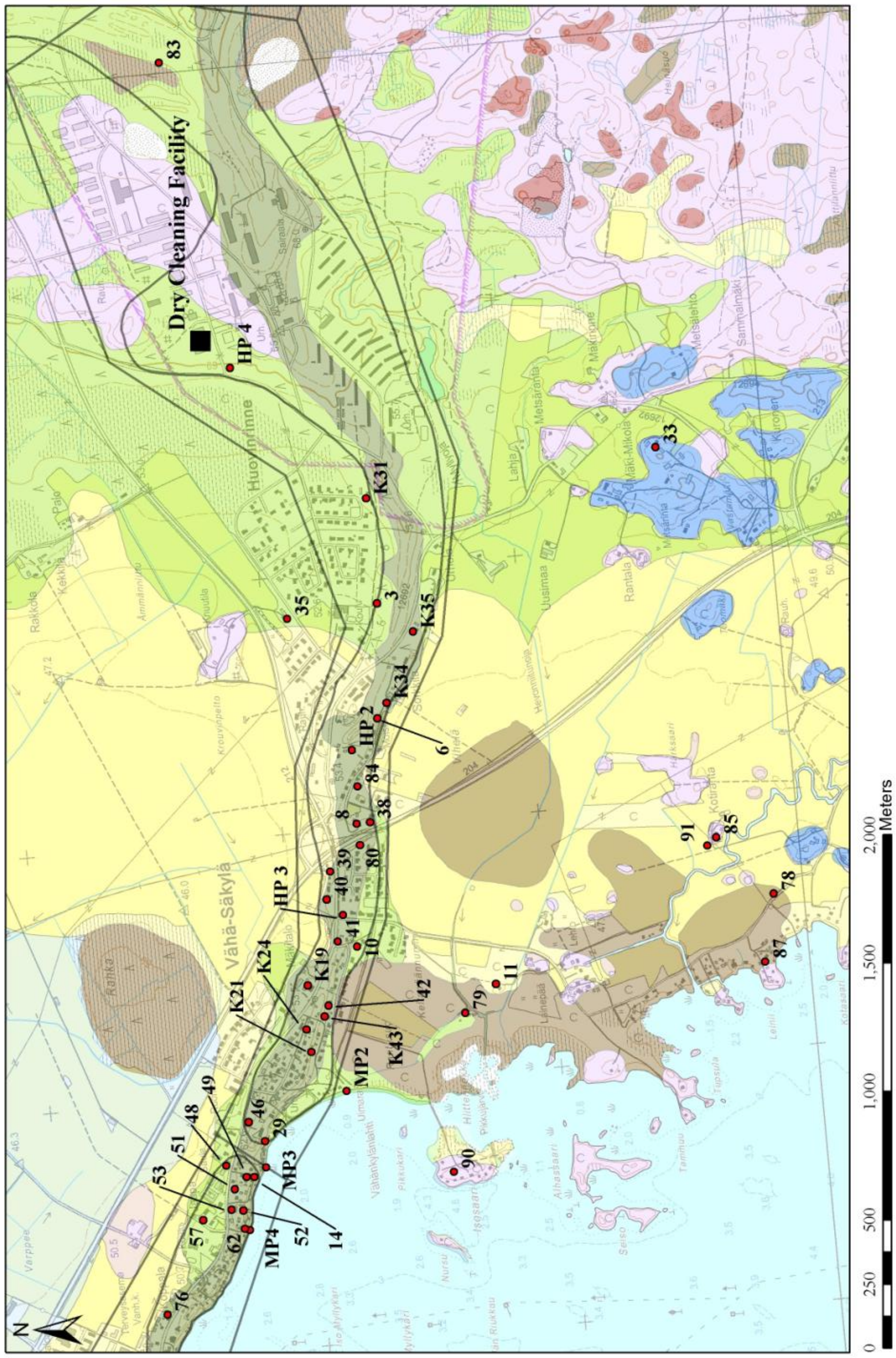


Figure B.1: Wells and monitors exhibiting PCE detection following Huovinrinne spill (©GTK, 2008b; ©SYKE, 2009; Varsinais-Suomen Ympäristökeskus, unpublished table and map, 1998; OIVA - Environment and Spatial Information Services, 22 Dec 2010; Rautio, 2009). The surficial soil map is an overlay over the Peruskartta maps.

Appendix C

Shoreline Sites of Seepage Meter and Mini-Piezometer Installations

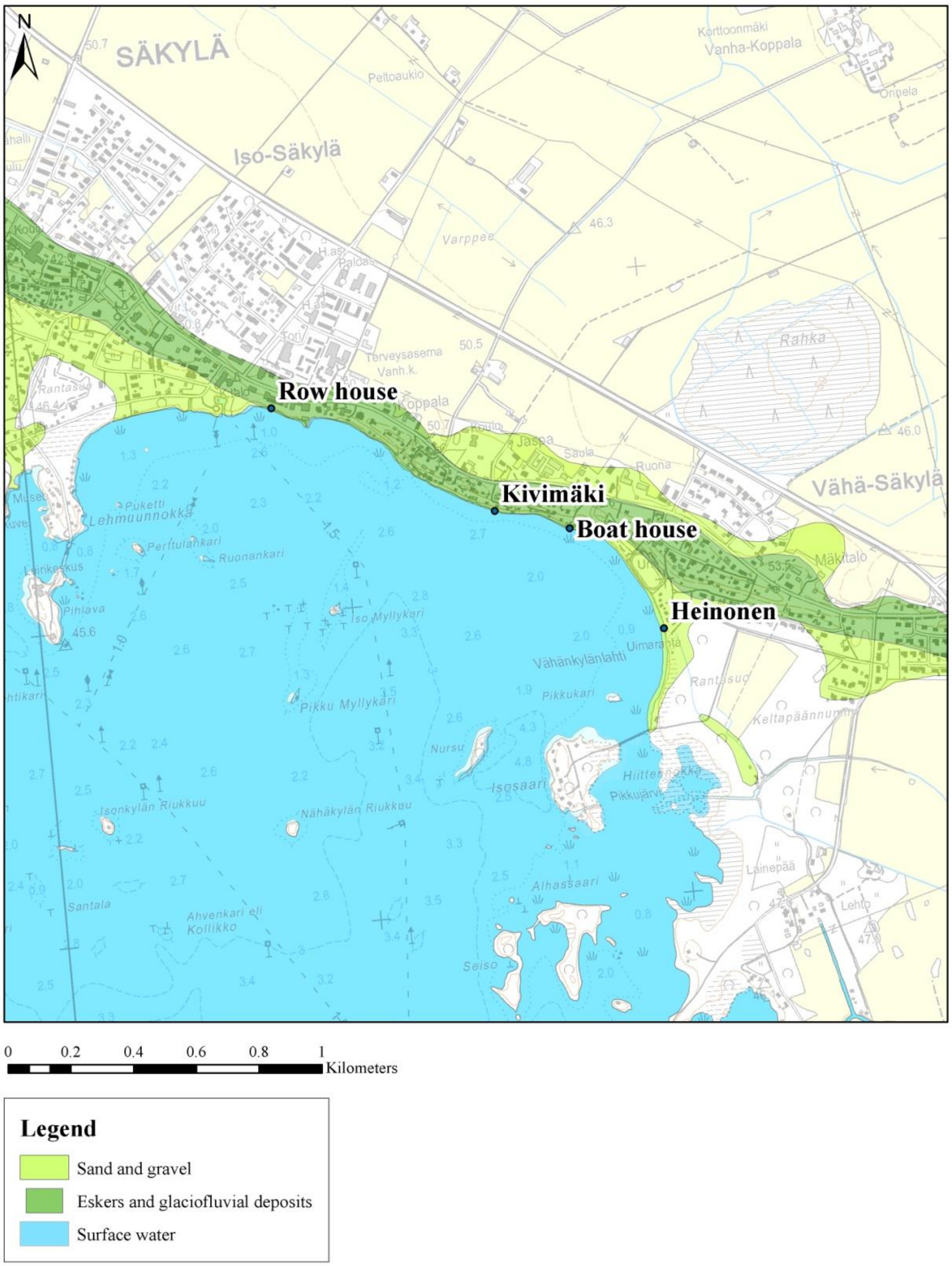


Figure C.1: Groundwater discharge locations (after Rautio, 2009; ©GTK, 2008b; ©MML, 2009a).

Appendix D

Esker Cross-Sections used in Darcy's Law Calculations

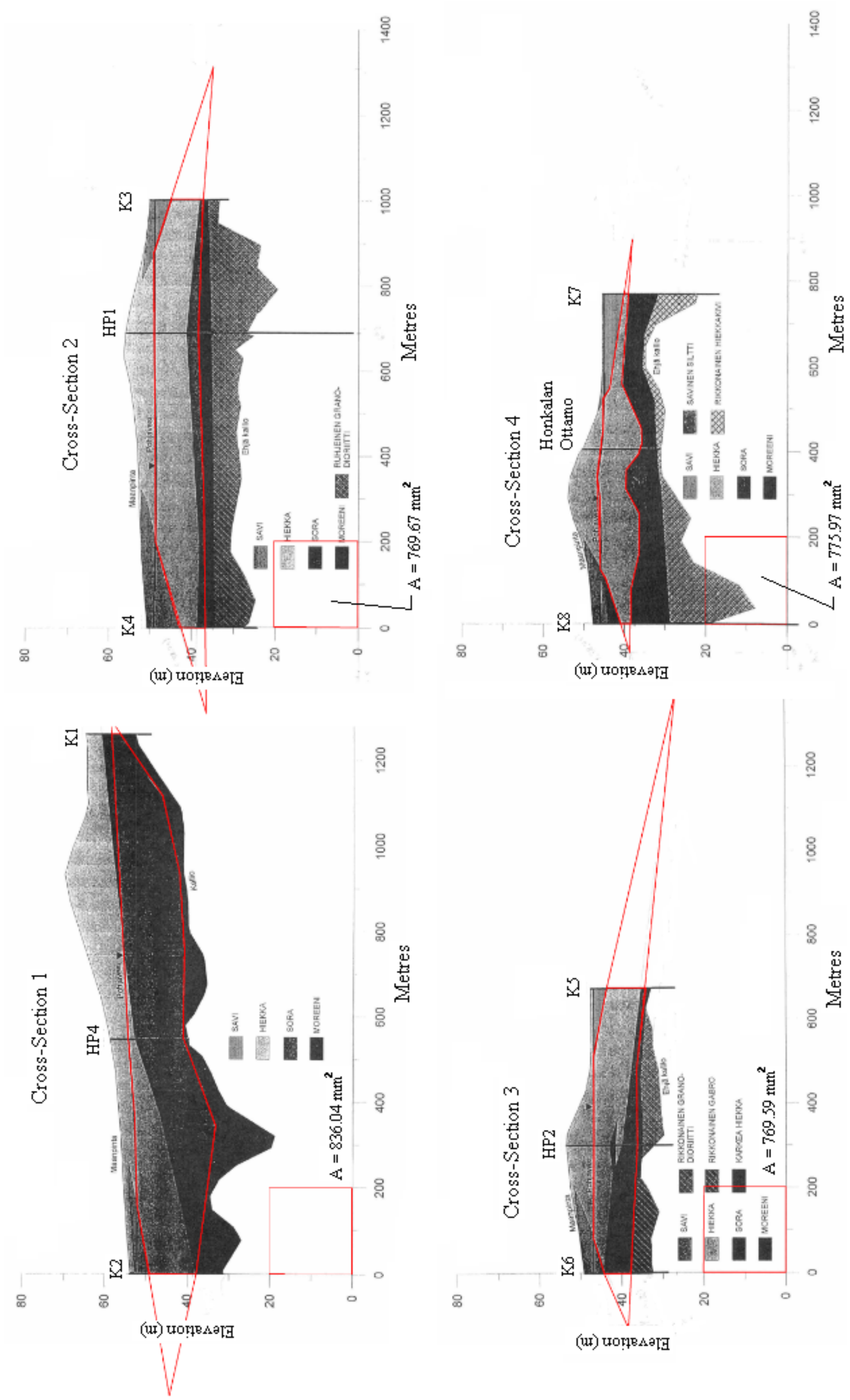


Figure D.1: Cross-sectional areas used in calculations based on Darcy's Law (after A. Artimo, unpublished report, 1998).

Appendix E
Observation Stations

Table E.1: Locations of data stations and periods of observation.

Station Name	Data Type	Finland KKJ Zone 1 Coordinates		Observation Period Start Date	Observation Period End Date
		x	y		
Lake Pyhäjärvi[1]	Lake water levels	1563837	6777531	01/01/14	11/01/11
Yläneenjoki River[2]	River Discharge	1576794	6752246	15/05/70	03/01/11
Pyhäjoki River[2]	River Discharge	1577559	6767305	01/06/71	03/01/11
Eurajoki River[2]	River Discharge	1562557	6778650	01/01/65	03/01/11
Jokioinen[3]	Evaporation	1636105.17	6747540.99	30/06/57	09/10/10
Kokemäki[3]	Evaporation	1567203	6796573	12/05/98	07/10/09
Mietoinen[3]	Evaporation	1546729.56	6723230.63	01/05/60	25/10/09
Säkylä[3]	Evaporation	1575004	6767820	04/06/71	27/09/76
Laitila Haukka[4]	Point Precipitation	1541353.87	6747290.47	01/01/70	23/05/11
Köyliö Yttilä[4]	Point Precipitation	1573714.29	6777567.13	01/01/70	23/05/11
Oripää Teinikivi[4]	Point Precipitation	1593071.11	6756192.2	01/01/70	23/05/11
Pöytyä Yläne / Yläne KK[4]	Point Precipitation	1575588.62	6752124.22	01/07/75	23/05/11
Jokioinen Observatorio[4]	Point Precipitation	1636088.92	6747508.66	01/01/70	23/05/11
Lieto Tammentaka[4]	Point Precipitation	1579489.65	6719017.23	01/01/70	23/05/11
Huittinen Sallila / Vampula[4]	Point Precipitation	1591883.77	6770561.14	01/01/70	23/05/11
Eura Haveri[5]	Point Precipitation	1576794	6752246	01/01/90	31/12/95
Kauttuankoski[6]	Areal Precipitation	1562790	6778427	01/01/65	26/12/09

[1] OIVA – Environment and Spatial Information Services (8 Sep 2010).
[2] OIVA – Environment and Spatial Information Services (23 Sep 2010).
[3] OIVA – Environment and Spatial Information Services (5 Jun 2010). Only data from the Jokioinen evaporation pan was used in the water balance calculations.
[4] H. Sirviö, pers. comm., 2010. Coordinate transforms were made using an Online coordinate conversion program (Viestikallio Tools KKY/WGS84/Maidenhead [10mm setting] [Aarnio, S.A.]) to convert the point precipitation station coordinates from the lat-long format to Finland KKJ Zone 1.
[5] OIVA – Environment and Spatial Information Services (13 Oct 2010).
[6] OIVA – Environment and Spatial Information Services (6 Oct 2010).

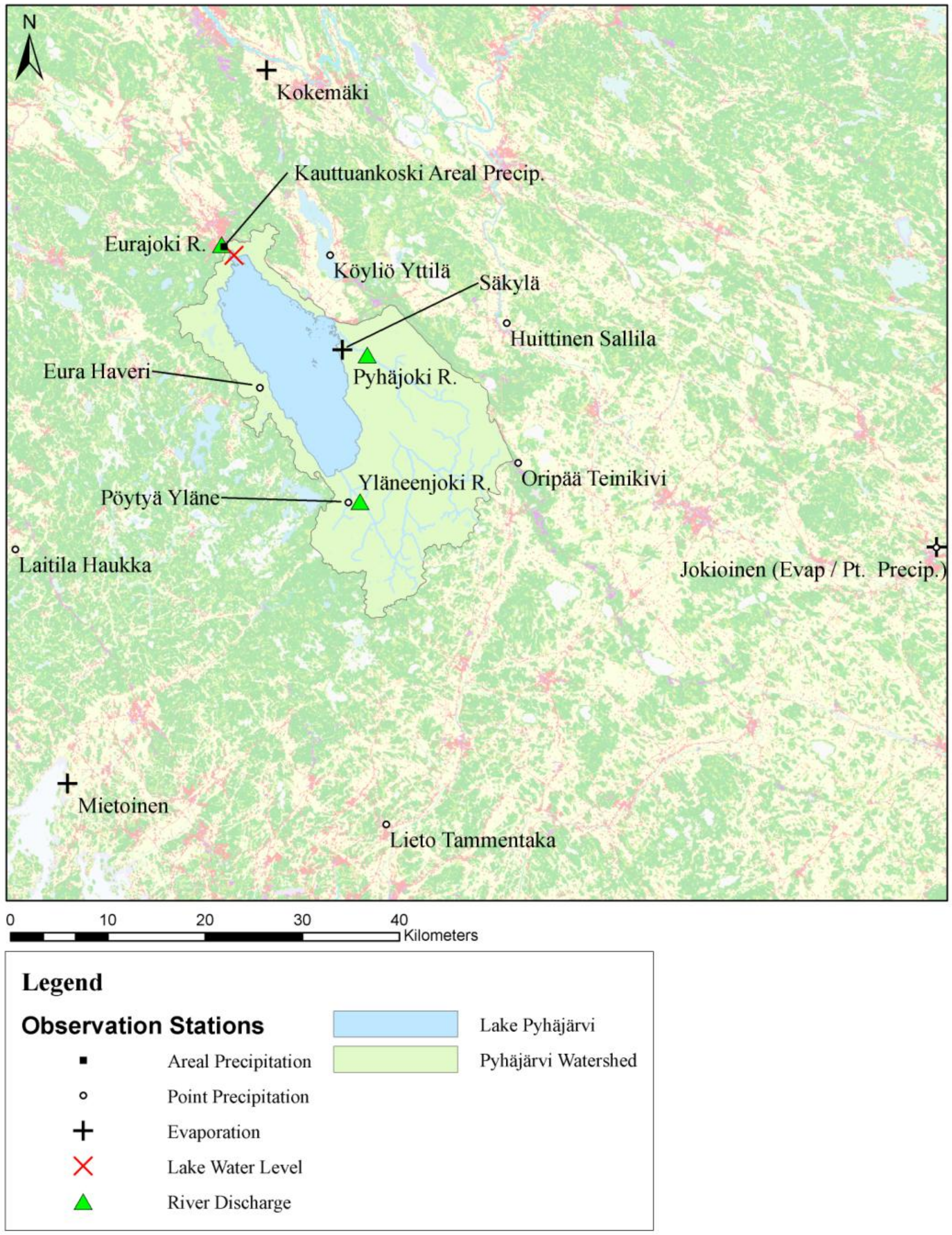


Figure E.1: Observation stations for water balance parameters (©SYKE, 2004; ©GTK, 2008b; ©MML, 2009a; OIVA – Environment and Spatial Information Services [4 Jan 2011]; H. Sirviö, pers. comm., 2011).

Appendix F

Comparison of Amounts of Surficial Geology Materials in Subcatchments

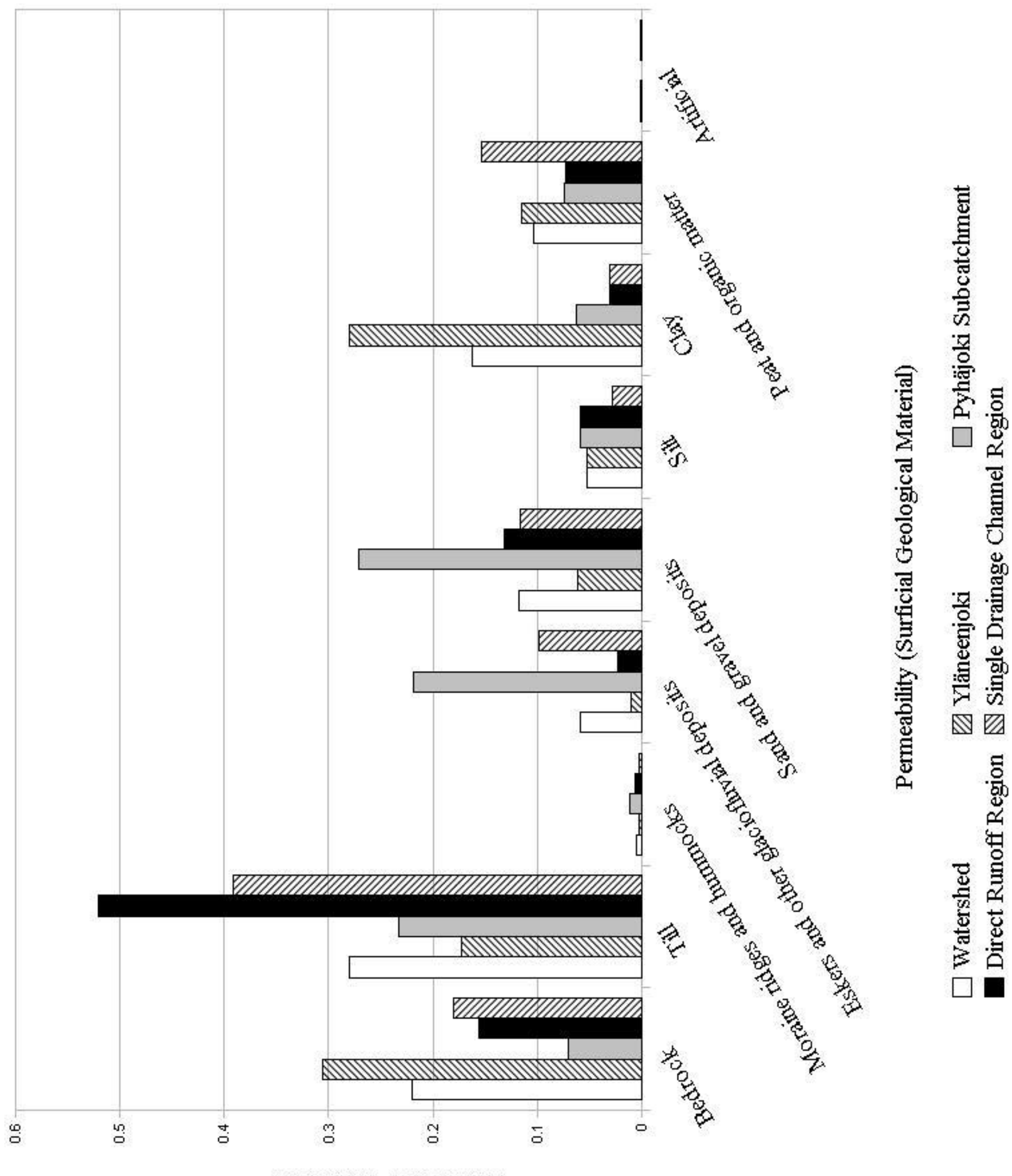


Figure F.1: Fractional areas of subcatchments covered by various geological materials at ground surface (GTK, 2008b; SYKE, 2010). The area fractions were calculated from raster files (25m x 25m cell size) generated using ArcMap 10.

Appendix G

Well Data – Water Levels and Elevations

Table G.1: Data from the 2010 well survey (after Varsinais-Suomen Ympäristökeskus, unpublished table and map, 1998).

Name*	**x†**	**y†**	**Top Elevation (m)‡**	**Water Table Elevation (m)‡**	**Bottom Elevation (m)‡**	**Bedrock Elevation (m) ‡,****	**Date**
Wpt 5	*1573123*	*6771316*	*48.52*	*45.17*	-	-	*28/06/2010*
Wpt 6	*1573555*	*6771040*	*46.18*	*45.10*	-	-	*28/06/2010*
Wpt 7	1573644	6771024	48.12	45.878	44.07	-	28/06/2010
Wpt 8	1573718	6771075	52.49	45.51	43.35	-	28/06/2010
Wpt 9	1573776	6771073	51.05	45.315	43.95	-	28/06/2010
Wpt 10	1573714	6771030	52.12	44.849	44.57	-	28/06/2010
Wpt 11	1573597	6771192	49.97	45.355	44.48	-	28/06/2010
Wpt 12	*1573650*	*6771194*	*50.25*	*49.55*	-	-	*28/06/2010*
Wpt 13	1573837	6771064	51.97	45.205	43.75	-	28/06/2010
Wpt 14	1573915	6771056.87	51.36	45.315	43.83	-	28/06/2010
Wpt 15	1573938	6771114	48.67	45.42	44.17	-	28/06/2010
Wpt 16	1573890	6771095	49.29	46.19	43.53	-	28/06/2010
Wpt 17	*1573985*	*6770945*	*47.56*	*45.40*	*43.76*	-	*28/06/2010*
Wpt 18	1574287	6770829	54.4	48.035	44.34	-	29/06/2010
Wpt 19	1574261	6770848	54.46	45.515	43.65	-	29/06/2010
Wpt 20	*1574232*	*6770760*	*48.54*	*45.59*	-	-	*29/06/2010*
Wpt 21	1574332	6770764.66	52.91	45.305	44.55	-	29/06/2010
Wpt 22	1574590	6770780	53.09	45.745	44.06	-	29/06/2010
Wpt 23	*1574639*	*6770739.7*	*51.14*	*46.19*	-	-	*29/06/2010*
Wpt 24	1574513	6770698	50.15	45.71	45.04	-	29/06/2010
Wpt 25	1574926	6770705.78	50.82	46.1	44.79	-	29/06/2010
Wpt 26	*1575413*	*6770579*	*49.41*	*46.71*	-	-	*29/06/2010*
Wpt 27	1575229	6770537	49.22	46.415	44.88	-	29/06/2010
Wpt 28	*1575439*	*6770556.1*	*49.58*	*46.78*	-	-	*29/06/2010*
Wpt 29	1575521	6770510	49.4	46.73	46.33	-	29/06/2010
Wpt 30	1575632	6770508.94	50.65	46.92	45.27	-	29/06/2010
Wpt 31	1575694	6770472	50.56	46.95	45.01	-	29/06/2010
Wpt 32	1576095	6770840	52.09	49.04	46.04	-	29/06/2010
Wpt 33	*1572205*	*6771646.1*	*49.50*	*45.57*	-	-	*29/06/2010*
Wpt 34	*1572259*	*6771663.5*	*50.69*	*45.58*	*44.37*	-	*29/06/2010*

Table G.1 (Continued): Data from the 2010 well survey (after Varsinais-Suomen Ympäristökeskus, unpublished table and map, 1998).

Name[*]	**x**[†]	**y**[†]	**Top Elevation (m)**[‡]	**Water Table Elevation (m)**[‡]	**Bottom Elevation (m)**[‡]	**Bedrock Elevation (m)** [‡,**]	**Date**
Wpt 35	*1572034*	*6771784*	*52.07*	*45.61*	*44.66*	-	*29/06/2010*
Wpt 36	*1572178*	*6771681.9*	*50.25*	*45.56*	*44.13*	-	*29/06/2010*
Wpt 37	*1572182*	*6771724*	*51.49*	*45.63*	*45.56*	-	*29/06/2010*
Wpt 38	*1571837*	*6772030.7*	*55.52*	*45.54*	*44.82*	-	*29/06/2010*
Wpt 39	*1571891*	*6771795*	*47.55*	*45.40*	-	*29.55*	*29/06/2010*
Wpt 40	*1571914*	*6771813*	*50.23*	*45.49*	-	-	*29/06/2010*
Wpt 41	*1571260*	*6772256*	*55.67*	*45.57*	*44.67*	-	*30/06/2010*
Wpt 42	1571676	6772155	**54.04**	**50.81**	-	-	30/06/2010
Wpt 43	*1571664*	*6772020*	*52.85*	*45.51*	*44.38*	-	*30/06/2010*
Wpt 44	*1571336*	*6772483*	*54.59*	*52.70*	*51.94*	-	*30/06/2010*
Wpt 45	*1571309*	*6772448*	*54.36*	*45.49*	*7.56*	*24.36*	*30/06/2010*
Wpt 46	*1571360*	*6772170*	*54.52*	*45.65*	*44.18*	-	*30/06/2010*
Wpt 47	*1571387*	*6772103*	*53.17*	*45.51*	*44.13*	-	*30/06/2010*
Wpt 48	*1570468*	*6772846*	*51.93*	*45.34*	*44.27*	-	*30/06/2010*
Wpt 49	*1567043*	*6775241*	*49.58*	*45.43*	*44.11*	-	*01/07/2010*
Wpt 50	*1565779*	*6776805*	*51.27*	*45.01*	*43.13*	-	*01/07/2010*
Wpt 51	*1565750*	*6776758*	*52.21*	*45.22*	*43.95*	-	*01/07/2010*
Wpt 52	*1565571*	*6777694*	*52.72*	*50.64*	*47.16*	-	*01/07/2010*
Wpt 53	1563938	6778369	**54.92**	**49.87**	**46.85**	-	01/07/2010
Wpt 54	1562677	6778150	**51.36**	**47.81**	**44.55**	-	01/07/2010
Wpt 55	1561449	6772498	**57.46**	**56.03**	**53.82**	**57.46**	01/07/2010
Wpt 56	1561493	6772495	**58.14**	**56.87**	**55.48**	-	01/07/2010
Wpt 57	1561409	6772628.57	**60.32**	**60.32**	**-39.68**	**60.32**	01/07/2010
Wpt 58	1561305	6771555	**54.10**	**51.81**	**47.72**	-	01/07/2010
Wpt 61	1562925	6769243	**59.18**	**57.07**	**55.28**	-	01/07/2010
Wpt 64	1562730	6768325.9	**64.90**	**62.62**	**59.48**	**64.90**	01/07/2010
Wpt 65	*1575831*	*6768259*	*49.83*	*46.59*	*45.20*	-	*02/07/2010*
Wpt 66	*1575815*	*6768213*	*50.08*	*48.25*	*46.43*	-	*02/07/2010*
Wpt 67	*1574520*	*6769497*	*45.73*	*45.06*	*44.36*	-	*02/07/2010*
Wpt 68	*1575814*	*6767707.4*	*52.54*	*49.67*	*47.90*	-	*02/07/2010*
Wpt 70	1575230	6765759	**45.96**	**44.96**	**43.75**	-	02/07/2010
Wpt 71	1575722	6763260	**50.62**	**49.00**	**46.46**	-	02/07/2010

Table G.1 (Continued): Data from the 2010 well survey (after Varsinais-Suomen Ympäristökeskus, unpublished table and map, 1998).							
Name*	**x†**	**y†**	**Top Elevation (m)‡**	**Water Table Elevation (m)‡**	**Bottom Elevation (m)‡**	**Bedrock Elevation (m) ‡,****	**Date**
Wpt 72	1575721	6763254.58	**50.59**	**48.90**	**46.46**	-	02/07/2010
Wpt 73	1576847	6761387.17	54.20	53.83	18.20	51.20	07/07/2010
Wpt 74	1577436	6759630	**52.68**	**51.24**	**50.17**	-	07/07/2010
Wpt 75	1577742	6759600	**56.09**	**54.88**	**54.01**	**48.79**	07/07/2010
Wpt 76	1578341	6759665.14	**70.00**	**68.69**	**67.28**	**67.28**	07/07/2010
Wpt 77	1576702	6757385.42	**46.08**	**43.42**	**42.37**	-	07/07/2010
Wpt 78	1576091	6755655	**50.00**	**49.27**	**47.45**	-	07/07/2010
Wpt 79	1575533	6754017	**46.5**	**45.57**	**43.33**	-	07/07/2010
Wpt 80	1574360	6755172	**50.53**	**48.93**	**45.87**	-	07/07/2010
Wpt 81	1573241	6754716	**49.34**	**48.35**	**46.49**	-	07/07/2010
Wpt 82	1570814	6757567	**59.60**	**55.99**	**32.60**	**59.60**	07/07/2010
Wpt 83	*1570010*	*6758316.2*	*65.72*	*64.00*	*59.82*	-	*08/07/2010*
Wpt 84	*1569770*	*6758987*	*70.98*	*69.65*	*66.18*	-	*08/07/2010*
Wpt 85	*1569769*	*6758999*	*70.52*	*68.93*	*65.66*	-	*08/07/2010*
Wpt 86	1569044	6760015.71	**68.07**	**66.82**	**64.34**	-	08/07/2010
Wpt 87	1568454	6762007	**44.91**	**43.25**	**41.43**	-	08/07/2010
Wpt 88	1567620	6761505	**64.82**	**61.84**	**59.51**	-	08/07/2010
Wpt 90	1567770	6762922	**47.15**	**45.60**	**41.16**	-	08/07/2010
Wpt 92	1567673	6763495	**47.18**	**44.85**	**44.15**	-	08/07/2010
Wpt 93	1565500	6764310	**56.35**	**53.77**	**52.14**	-	08/07/2010
Wpt 95	1563307	6767919	**54.96**	**52.61**	**49.96**	**49.96**	09/07/2010
Wpt 96	1561611	6774403.54	**51.36**	**49.87**	**47.73**	-	09/07/2010
Wpt 98	1563719	6768036	**50.42**	**48.51**	**46.22**	**37.42**	09/07/2010
Wpt 99	1564500	6767339.98	**64.60**	**63.00**	**62.13**	-	09/07/2010
Wpt 100	1561236	6768775	**49.86**	**46.86**	**45.86**	-	09/07/2010

* "Wpt" stands for "waypoint."

† The coordinates (Garmin eTrex GPS; Finland KKJ Zone 1) are approximate; most eastings and northings are accurate to about ± 8m.

‡ Elevations are listed relative to the N60 datum. Those in bold were interpolated from topographic points; associated elevations are also in bold. Italicized wells' top elevations were surveyed during July and August 2010.

** Bedrock elevations are listed where well owners knew the approximate depth to bedrock.

Table G.2: Well top elevation survey results. *,†					
Name	**Survey Elevation (cm)**	**Adjustment (cm)**	**Final Elevation (cm)**	**Survey Circuit Error (cm)**	**Notes**
Wpt 5	4852.2	0	4852.2	-3.3	
Wpt 6	4618.2	0	4618.2	-0.7	
Wpt 12	5024.5	0	5024.5	-0.7	At ground surface.
Wpt 17	4755.5	0	4755.5	3.2	
Wpt 20	4827.1	26.5	4853.6	3.2	Elevation of ground surface; adjust for casing height, 26.5cm.
Wpt 23	5114.1	0	5114.1	1.4	Measured to ground surface; no casing height above ground.
Wpt 26	4940.7	0	4940.7	-2.1	
Wpt 28	4957.7	0	4957.7	-2.1	
Wpt 33	4956.4	-6	4950.4	10.4	
Wpt 34	5068.9	0	5068.9	10.4	
Wpt 35	5206.9	0	5206.9	10.4	
Wpt 36	5025.4	0	5025.4	10.4	
Wpt 37	5148.8	0	5148.8	10.4	
Wpt 38	5519.2	33	5552.2	-6.8	Elevation is for ground surface. Adjust for casing height (33cm).
Wpt 39	4754.8	0	4754.8	10.4	
Wpt 40	5028	-5.5	5022.5	10.4	Adjust for lid thickness (5.5cm).
Wpt 41	5567.2	0	5567.2	0.7	
Wpt 43	5285.2	0	5285.2	-6.8	
Wpt 44	5458.7	0	5458.7	-1.8	
Wpt 45	5435.7	0	5435.7	-1.8	
Wpt 46	5451.5	0	5451.5	-6.8	
Wpt 47	5317	0	5317	-6.8	
Wpt 48	5192.8	0	5192.8	0.8	
Wpt 49	4957.8	0	4957.8	3.7	
Wpt 50	5127	0	5127	-0.2	
Wpt 51	5221.2	0	5221.2	-0.2	
Wpt 52	5272.2	0	5272.2	1	
Wpt 65	4982.6	0	4982.6	0.3	
Wpt 66	5007.7	0	5007.7	0.3	
Wpt 67	4581.1	-8	4573.1	-0.1	Adjust for lid thickness (8cm).
Wpt 68	5254.4	0	5254.4	2	
Wpt 73	5419.5	0	5419.5	4.5	
Wpt 83	6551	20.5	6571.5	-2.3	Elevation of ground surface. Add 20.5cm to obtain measuring point (hole in casing).
Wpt 84	7097.6	0	7097.6	0.4	
Wpt 85	7051.8	0	7051.8	0.4	

* Wells were surveyed between 21 Jul 2010 and 03 Aug 2010.

† All elevations are listed in centmetres relative to the N60 datum. University of Helsinki survey equipment (Nikon AX-2S auto level) was used.

Appendix H
Assessment of the Impact of Lake Area Uncertainty

Definitions:

Given

$$\frac{1}{A}(\Delta V_{GW}) = \frac{1}{A}(\Delta S + V_E + V_{WITH} - V_P - V_R - V_{DR}),\text{ and} \tag{H.1}$$

$$G = h_S + E + W - P - R - DR, \tag{H.2}$$

where Equation H.1 is a volumetric water balance equation and Equation H.2 is the normalized version in which all components are normalized by the lake area, define the following:

Let e_A be the relative (percentage) error on the area of the lake (A). Therefore, $e_A = 0.016$.

Let x be a component estimate of the lake's normalized water balance (H.2) in units of L/L^2/year.

Let e_x be the relative (percentage) error on the component x.

Solution:

Determine the size of e_x such that the lake area uncertainty would change its magnitude by more than an arbitrary threshold of 1%:

$$\sqrt{e_x^2 + e_A^2} - e_x > threshold. \tag{H.3}$$

$$\sqrt{e_x^2 + e_A^2} - e_x > 0.01. \tag{H.4}$$

Rearranging and squaring both sides,

$$e_x^2 + e_A^2 > 0.0001 + 0.02e_x + e_x^2. \tag{H.5}$$

Thus,

$$e_x < \frac{e_{A-0.0001}^2}{0.02}. \tag{H.6}$$

Substituting for e_A:

$$e_x < 0.008. \tag{H.7}$$

Therefore the magnitude of the percent error on a normalized component of the water balance will only be affected to a degree greater than a change of 1% if the error on the component is itself less than 0.8%. It follows that any reasonable estimate of a water balance component (likely > 1%) will be relatively unaffected by the inclusion of the lake area uncertainty in the calculation of its associated uncertainty.

For reference, if the relative error on component *x* is 5%, and Equation H.3 is used to solve for *threshold*, the amount of change on the relative error is 0.25%. Since relative error estimates are merely estimates of the amount of uncertainty that can be expected, and in this case are rounded to the nearest percentage, this is acceptable. Further, the amount of change to a component's relative error decreases as the relative error increases.

Appendix I

Raw Data Used in Water Balance

Table I.1: Water levels on the first day of the water years between 1971 and 2009 (OIVA – Environment and Spatial Information Services, 8 Sep 2010).

Date	Water Level (cm)*
1 Oct 1971	4455
1 Oct 1972	4486
1 Oct 1973	4501
1 Oct 1974	4502
1 Oct 1975	4479
1 Oct 1976	4475
1 Oct 1977	4497
1 Oct 1978	4505
1 Oct 1979	4508
1 Oct 1980	4489
1 Oct 1981	4498
1 Oct 1982	4480
1 Oct 1983	4478
1 Oct 1984	4498
1 Oct 1985	4487
1 Oct 1986	4493
1 Oct 1987	4512
1 Oct 1988	4498
1 Oct 1989	4470
1 Oct 1990	4475
1 Oct 1991	4495
1 Oct 1992	4492
1 Oct 1993	4495
1 Oct 1994	4487
1 Oct 1995	4484
1 Oct 1996	4474
1 Oct 1997	4479
1 Oct 1998	4490
1 Oct 1999	4458
1 Oct 2000	4496
1 Oct 2001	4493
1 Oct 2002	4467
1 Oct 2003	4466
1 Oct 2004	4492
1 Oct 2005	4482
1 Oct 2006	4473
1 Oct 2007	4484
1 Oct 2008	4496
1 Oct 2009	4467

* Relative to the N60 datum.

Table I.2: Jokioinen Class A evaporation pan data.*								
Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
1971	0	140.78	160.82	156.51	116.41	51.76	17.38	0
1972	0	116.34	159.02	149.66	90.95	43.19	13.95	0
1973	6.78	95.96	168.35	174.71	88.6	32.82	9.01	0
1974	0	119.89	145.49	84.52	75.29	39.3	14.27	0
1975	0	106.73	120.58	149.31	106.38	51.77	12.45	0
1976	0	142.75	132.23	122.91	113.9	43.93	0	0
1977	0	108.7	142.41	94.03	83.19	40.12	12.99	3.15
1978	0	144.96	158.62	94.23	71.8	25.77	10.79	0
1979	0	131.77	164.94	67.63	89.82	32.29	9.71	0
1980	3.56	106.07	156.79	123.19	78.84	34.49	10.86	0
1981	0	140.79	107.47	107.4	67.82	32.47	16.86	0
1982	0	94.3	134.33	159.15	107.44	39.46	8.52	0
1983	0	95.68	116.87	149.39	118.76	48.16	14.29	0
1984	0	140.64	114.42	94.81	78.45	24.69	8.75	0
1985	0	112.05	122.08	114.89	79.53	37.57	8.86	0
1986	0	108.88	175.52	127.41	74.12	30.97	12.75	0
1987	0	93.17	84.97	143.43	65.69	29.95	19.37	0.15
1988	0	132.87	145.96	150.15	63.43	40.85	9.24	0
1989	47.02	133.48	154.3	151.63	72.33	47.67	11.73	0
1990	31.4	113.97	159.36	112.19	85.26	32.5	10.32	0
1991	0	87.7	85.39	123.38	80.74	40.57	9.56	0
1992	0	141.13	178.08	145.55	71.77	24.48	4.28	0
1993	0	154.92	98.64	121.79	58.94	34.78	0	0
1994	0	107.74	103.93	185.64	92.71	36.42	2.65	0
1995	0	86.21	128.16	135.73	109.28	38.17	16.02	0
1996	0	104.62	110.55	91.57	106.27	51.93	8.7	0
1997	0	104.15	151.28	118.5	114.18	47.6	2.27	0
1998	0	98.29	82.72	86.97	53.81	41.27	7.11	0
1999	0	110.79	153.92	149.14	94.55	62.34	9.58	0
2000	0	141.42	124.79	95.69	71.41	40.29	19.16	0
2001	0	102.11	105.6	134.33	89.73	37.76	0	0
2002	0	123.04	121.77	116.93	112.56	60.02	0	0
2003	0	94.57	116.18	134.19	87.11	49.26	7.24	0
2004	0	106.9	111.24	87.72	82.23	32.98	0	0
2005	0	110.47	114.03	135.21	81.96	41.6	0	0
2006	0	120.9	159.22	188.9	133.27	57.26	7.06	0
2007	0	107.14	163.29	111.74	103.18	42.67	0	0
2008	0	133.9	119.75	133.61	68.76	32.37	11.41	0
2009	0	134.41	115.66	116.38	97.69	48.91	6.2	0

* All data are in mm. The monthly sums were calculated using data from OIVA – Environment and Spatial Information Services (5 Jun 2010).

Table I.3: Point precipitation values from the Eura Haveri gauge.[*,†]												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1990	79.5	77.2	58.1	51.6	16.3	31.9	106.4	63.5	56.8	48.3	35.9	54.8
1991	77.1	19.1	34.0	11.8	38.1	72.0	14.7	106.4	100.9	49.6	88.8	52.5
1992	38.2	47.3	51.0	60.2	10.2	30.7	81.8	86.4	74.9	61.7	77.4	39.4
1993	84.5	13.9	27.4	34.1	9.3	52.4	79.5	151.7	10.5	70.7	6.2	93.4
1994	59.4	1.7	67.4	42.2	28.8	70.2	0.0	78.6	109.8	90.4	28.2	58.2
1995	44.4	78.7	55.2	41.9	72.3	83.5	51.2	58.2	28.0	75.2	42.8	23.5

[*] All data are in mm. The monthly sums were calculated using daily data from OIVA – Environment and Spatial Information Services (13 Oct 2010).

[†] Daily data from the other point precipitation gauge stations (Laitila Haukka, Lieto Tammentaka, Huittinen Sallila, Köyliö Yttilä, Oripää Teinikivi, Pöytyä Yläne, and Jokioinen Observatorio) were obtained from the Finnish Meteorological Institute (24 May 2011), and are available upon request: http://en.ilmatieteenlaitos.fi/.

Table I.4: Kauttuankoski areal precipitation estimates for the Lake Pyhäjärvi watershed.[*]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1971	53	35	37	19	15	20	32	52	36	50	34	51
1972	8	31	15	71	18	53	87	141	31	35	57	36
1973	23	32	21	65	40	97	114	57	71	47	46	50
1974	55	56	35	10	27	57	124	56	90	81	64	89
1975	69	17	27	35	55	39	30	47	97	26	27	36
1976	37	37	33	23	12	57	75	19	62	18	52	39
1977	40	24	21	81	64	43	107	50	61	60	89	21
1978	23	8	59	30	15	79	37	77	97	30	60	10
1979	50	11	29	39	32	22	188	110	75	20	99	41
1980	8	12	9	28	20	60	44	109	75	137	107	59
1981	47	34	51	7	18	125	87	76	17	98	99	61
1982	28	14	14	44	65	13	33	93	60	33	95	76
1983	80	5	22	39	37	80	52	30	87	81	47	96
1984	88	32	35	18	57	89	123	49	73	105	65	40
1985	40	24	35	45	40	58	67	91	40	31	59	62
1986	56	7	34	42	42	17	52	124	99	60	104	60
1987	18	32	21	4	34	97	76	130	98	46	36	30
1988	58	42	38	53	56	105	113	80	74	76	18	63
1989	44	76	68	36	30	55	65	87	18	47	57	42
1990	82	84	52	46	17	18	80	71	56	52	38	53
1991	77	20	35	10	38	77	21	100	99	56	89	49
1992	42	47	55	65	10	29	63	107	63	80	80	46
1993	84	19	29	34	12	52	93	139	14	78	6	92
1994	60	2	65	40	32	63	2	80	102	83	27	58
1995	48	76	54	42	84	86	47	67	31	72	45	23
1996	8	32	31	25	64	42	98	22	27	48	137	48
1997	35	60	35	44	13	66	92	41	114	55	55	41
1998	69	39	29	16	45	109	84	102	27	82	13	49
1999	61	71	34	37	11	31	42	56	47	138	45	100
2000	48	53	38	37	28	53	136	94	19	66	89	55
2001	29	39	29	53	26	28	87	74	134	86	37	27
2002	81	52	37	3	35	88	96	25	12	26	41	7
2003	47	10	7	21	103	40	46	69	6	61	42	78
2004	35	34	25	11	27	83	83	55	88	31	51	95
2005	79	23	7	14	32	49	60	159	35	42	92	32
2006	28	20	28	52	39	37	19	54	52	159	68	85
2007	76	6	34	29	38	53	102	33	62	57	57	82
2008	76	55	42	38	9	102	34	157	36	127	81	53
2009	24	21	35	7	26	58	65	51	38	53	58	43

[*] All data are in mm. The monthly sums were calculated using data from OIVA – Environment and Spatial Information Services (6 Oct 2010).

Table I.5: Point precipitation sums for eight precipitation gauges in the vicinity of Lake Pyhäjärvi.*								
Water Year Start	Laitila Haukka	Lieto Tammentaka	Huittinen Sallila	Köyliö Yttilä	Oripää Teinikivi	Pöytyä Yläne	Jokioinen Observatorio	Eura Haveri
1971	623.3	580.8	431.6	527.5	621.2	-	638.8	-
1972	643.8	591.2	433.6	580.4	729.1	-	557.7	-
1973	623.4	585.5	533.3	590.7	638.6	-	535.7	-
1974	641.4	703.7	564.7	578.6	668.8	-	542.2	-
1975	450.2	446.6	296	332	452.8	455.8	360	-
1976	587.7	736.9	499.3	61.1	590.1	611.3	543.5	-
1977	641.2	659.9	489.2	539.8	599.6	598.7	573.6	-
1978	609.3	623.2	542.6	605	633.9	649	594	-
1979	570.6	598.9	406.6	453.2	518.7	482	520.2	-
1980	768.6	833.6	668.4	706	793.4	759.4	746.9	-
1981	692.6	648.3	548	526.8	647.4	601.4	704.8	-
1982	617.5	709.2	617.5	558.8	685.3	622.9	625.6	-
1983	817.8	832.9	716.7	670.6	848.7	789.1	754.9	-
1984	681	669	580.9	636.2	667.2	663.8	627.6	-
1985	629.6	743	554.3	495	616	660.1	599.5	-
1986	750.8	740	753.1	684.9	609.1	711.3	671.5	-
1987	739.5	732.3	776.8	635	696.2	756.7	656.6	-
1988	627.5	622.7	593.7	612	608.2	662.8	635.9	-
1989	700.6	766.1	712.5	610.5	-	678.2	670.2	-
1990	610.7	677	613.5	557.8	-	650.9	617.1	613.1
1991	671	628.2	656	623.7	-	626.4	580.5	671.6
1992	648.5	665.5	590.8	577.4	-	616	603.1	641.8
1993	654.3	581.7	584.9	559.8	-	605.7	516.2	628.4
1994	702.1	709.3	731.6	674.5	-	686.5	716.7	690.2
1995	437.4	525.3	490.4	480.2	-	379.4	513.9	-
1996	680.1	731	795.4	712.8	-	715.5	765.7	-
1997	661.4	700.1	705.8	698.2	703.7	623	605	-
1998	478.3	524.1	534.5	503	540.4	575.6	500.2	-
1999	737.8	693.4	903.3	750.6	879.2	795.2	676.1	-
2000	720.7	753.8	672.9	692.5	724.8	693	717.9	-
2001	555.2	555.2	603.1	603.7	607.7	536.9	503.9	-
2002	419.5	425	435.1	450.4	451.5	395	472.2	-
2003	634.4	547.4	639.3	570.8	682.8	621.9	774.1	-
2004	660.1	693.8	654.7	551.2	630.9	689.5	625	-
2005	467.8	556.3	482.8	485.6	572.8	468.7	475.3	-
2006	817.5	851.3	707.8	692.6	764.3	781.6	731.2	-
2007	722.4	796.1	728.5	675.8	819.8	770.6	697.4	-
2008	625	669	570.7	584.4	600.9	569.5	599.8	-
1971	623.3	580.8	431.6	527.5	621.2	-	638.8	-

* All amounts are in mm. The sums for seven of the point precipitation gauge stations (Laitila Haukka, Lieto Tammentaka, Huittinen Sallila, Köyliö Yttilä, Oripää Teinikivi, Pöytyä Yläne, and Jokioinen Observatorio) were calculated from daily data obtained from the Finnish Meteorological Institute (24 May 2011), which are available upon request: http://en.ilmatieteenlaitos.fi/. The daily data for the Eura Haveri station sums were obtained from OIVA – Environment and Spatial Information Services (13 Oct 2010).

Table I.6: Monthly Yläneenjoki River flow volumes per unit lake area.*												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1971	0	0	0	0	0	2.96	1	1.4	1.66	2.33	3.58	9.8
1972	2.52	0.81	3.27	127.69	40.89	3.98	12.4	18.35	5.19	11.91	43.29	57.07
1973	6.43	4.39	24.58	87.8	30.62	12.68	49.42	7.75	12.32	43.65	40.09	13.73
1974	31.12	60.02	26.5	152.88	35.46	4.05	26.91	35.32	41.56	100.44	101.38	122.48
1975	111.24	12.72	18.22	64.03	14.83	11.21	2.02	1.38	3.18	3.05	3.75	12.62
1976	2.61	0.86	1.22	80.35	41.6	13.51	2.09	2.12	2.6	2.56	9.43	32.95
1977	3.2	2.46	35.85	140.13	84.32	4.31	31.91	22.16	17.01	55.45	80.84	28.84
1978	5.87	2.21	6.5	123.26	41.17	7.43	9.64	10.19	59.91	28.51	64.8	4.98
1979	1.64	1.34	2.08	93.81	77.86	3.1	57.39	47.99	64.64	30.68	96.68	44.22
1980	7.41	0.92	0.77	40.19	20.54	11.07	2.52	10.64	28.17	124.65	137.51	22.25
1981	17.31	14.24	13.29	148.93	70.9	32.08	38.88	30.45	24.91	70.71	103.39	31.38
1982	5.24	3.23	22.2	123.43	63.46	3.75	1.02	1.36	9.35	10.99	74.27	73.99
1983	69.97	4.62	3.03	82.4	25.56	9.87	3.9	0.71	7.49	39.21	30.75	15.88
1984	27.58	10.16	6.19	223.89	51.65	12.13	43.24	10.53	31.82	86.29	69.43	60.02
1985	4.58	0.77	0.94	64.01	101.49	17.8	1.71	3.57	4.97	10.63	37.75	13.81
1986	9.06	2.27	6.69	126.55	45.1	4.79	0.94	15.29	57.98	52.75	78.95	38.43
1987	1	0.37	0.34	62.02	55.37	43.24	8.58	71.99	60.34	51.89	32.57	15.53
1988	41.89	34.13	7.64	120.59	55.06	12.13	14.78	47.57	27.11	63.16	32.07	3.27
1989	40.29	78.89	129.33	38.78	14.34	7.16	2.69	3.79	1.38	5.12	29.69	20.91
1990	32.65	146.31	88.35	48.58	3.06	1.08	1.2	1.12	3.47	16.29	31.99	34.57
1991	39.33	9.98	64.52	79.47	20.68	11.55	6.39	4.03	8.02	60.43	95.45	34.64
1992	33.99	16.13	101.88	79.61	21.18	1.04	0.56	2.15	8.87	29.47	63.74	79.34
1993	47.45	9.63	29.12	64.86	13.85	2.41	8.64	54.67	5.38	35.96	5.32	41.81
1994	35.55	2.84	12.32	160.95	22.77	19.37	1.33	1.37	16.32	60.49	34.68	57.25
1995	39.12	52.5	66.42	124.79	77.69	43.37	2.77	1.24	2	13.25	21.75	7.54
1996	1.8	0.66	0.69	88.4	61.83	11.2	28.41	1.05	0.55	2.05	111.84	47.84
1997	6.51	28.27	77.12	58.12	42.02	8.99	14.84	9.95	49.24	40.27	42.87	39.15
1998	79.98	45.96	19.32	57.91	32.57	26.86	38.52	60.32	25.58	57.27	22.37	25.81
1999	53.7	12	21.32	190.91	17.4	2.37	0.81	0.78	0.91	79.34	21.8	88.35
2000	82.82	38.28	59.18	176.1	9.44	1.94	30.7	48.27	6.95	12.7	97.65	68.99
2001	13.82	17.8	13.75	102.05	25.21	2.64	6.65	1.31	62.12	34.46	69.87	18.53
2002	19.26	102.55	70.47	55.26	9.77	3.11	20.22	2.04	0.35	0.47	0.8	0.55
2003	0.41	0.06	13.73	15.26	55.56	4.65	0.52	1.49	0.82	3.02	18.27	48.14
2004	19.01	15.07	44.59	77.25	5.12	1.22	26.03	1.12	18.38	16.45	24.82	78.34
2005	115.38	25.23	2.52	35.35	10.05	2.25	1.59	33.6	5.85	10.41	64.58	26.46
2006	21.5	1.94	0.57	136.74	32.5	8.38	0.43	0.35	0.76	43.71	106.67	110.1
2007	76.82	3.75	60.77	34.43	8.21	6.59	1.35	3.84	3.28	10.73	63.8	104.56
2008	109.54	79.47	65.92	60.4	3.15	4.97	4.04	45.25	28.97	83.59	94.01	78.29
2009	6.61	1.53	1.5	61.95	7.62	3.79	0.32	0.22	0.61	9.08	33.87	16.36

* All amounts are in mm per unit lake area. The daily flow values (m^3/s) were obtained from OIVA – Environment and Spatial Information Services (23 Sep 2010).

Table I.7: Monthly Pyhäjoki River flow volumes per unit lake area.*												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1971	0	0	0	0	0	2.41	1.2	1.15	1.02	1.44	0	0
1972	6.83	5.59	6.91	42.79	13.03	1.92	3.87	5.03	2.59	4.26	11.65	14.26
1973	4.11	4.32	12.32	23.73	11.17	6.47	11.16	4.36	6.93	12.98	13.82	17.01
1974	18.2	22.46	11.58	48.66	14	2.88	7.09	8.18	14.06	25.87	27.28	36.04
1975	30.25	6.84	8.78	17.25	7.45	6.17	2.01	1.76	2.77	3.05	3.46	6
1976	3.52	1.64	1.62	33.1	12.24	5.73	1.88	2.08	2.16	2	4.48	9.02
1977	4.07	2.9	15.54	33.4	23.71	2.99	4.52	5.29	4.83	13.45	22.79	8.95
1978	2.36	1.63	7.76	32.66	13.94	6.23	4.32	2.54	12.1	7.72	15.12	4.29
1979	1.71	1.41	2.74	29.39	21.8	2.66	12.02	15.82	13.63	9.1	23.13	17.63
1980	4.84	1.7	1.75	17.59	8.03	5.27	3.61	4.58	8.62	35.07	43.75	14.77
1981	8.46	5.68	13.08	45.53	23.15	15.67	17.03	14.24	7.86	20.53	30.33	13.87
1982	4.15	3.12	11.07	34.16	21.57	4.02	3.08	3.07	5.19	5.38	21.26	21.16
1983	21.78	4.98	3.5	26.53	10.25	5.47	3.28	2.56	4.05	11.16	10.44	11.06
1984	13.27	4.31	3.69	73.99	23.51	10.59	13.63	4.72	8.58	22.83	19.64	21.45
1985	3.73	2.08	1.81	24.88	35.3	8.69	3.56	3.29	3.33	5.32	10.18	7.58
1986	5.36	2.89	8.19	31.51	14.5	4.07	2.31	5.13	30.77	20.08	23.96	21.45
1987	4.91	1.66	1.62	14.06	13.45	11.94	3.63	28.29	15.18	11.08	7.28	4.64
1988	13.37	8.9	4.31	40.24	21.2	8.84	4.04	10.33	8.46	17.18	10.9	3.33
1989	12.1	27.22	43.43	15.41	6.13	4.85	5.19	3.18	2.05	3.84	8.57	7.84
1990	8.6	50.59	28.99	16.42	3.46	2.07	2.38	1.98	2.52	4.55	7.15	8.59
1991	13.66	4.97	17.98	27.35	8	4.54	2.78	2.61	2.74	16.1	21.52	10.64
1992	10.87	5.5	33.35	24.65	8.53	1.79	1.7	2.67	6.21	11.36	17.04	25.23
1993	12.58	5.75	10.11	17.8	5.85	2.23	2.44	15.59	4.27	12.16	3.45	11.34
1994	9.66	2.19	3.75	36.58	9.23	8.96	1.71	1.43	4.43	13.91	9.94	13.61
1995	8.82	13.5	16.94	38.56	20.97	14.35	3.36	1.77	2.32	5.76	6.66	3.62
1996	2.24	1.5	1.78	22.2	19.27	5.22	8.78	1.71	1.48	2.1	20.97	12.57
1997	3.56	11.2	26.56	16.52	14.98	4.97	4.15	2.44	10.63	13.01	11.84	10.3
1998	19.24	15.39	7.73	18.72	12.5	10.41	7.78	12.63	7.12	14.44	6.61	6.95
1999	11.5	4.38	7.62	55.74	7.96	2.27	1.69	1.4	1.45	16.78	6.95	21.03
2000	19.52	9.03	13.11	49.56	5.52	2.94	9.2	16.94	4.53	7.23	28.36	19.93
2001	8.29	7.41	8.74	30.25	12.99	4.36	4.88	3.02	15.66	13.91	22.75	10.84
2002	8.37	28.65	21.04	23.47	11.16	5.06	9.85	3.06	2.74	2.71	2.9	2.78
2003	2.4	2.06	7.48	9.44	26.93	5.81	2.48	2.76	2.37	3.38	5.53	11.95
2004	8.91	6.31	15.35	21.52	4.95	3.05	9.28	2.83	10.88	12.48	11.77	22.88
2005	34.59	10.82	3.96	15.49	8.2	3.91	2.37	8.81	6.09	7.37	20.12	11.44
2006	7.98	2.57	2.39	32.68	14.98	5.55	1.97	2.65	3.15	15.73	28.73	29.96
2007	21.8	3.74	17.64	15.51	6.25	4.21	3.27	3.55	4.36	6.99	18.58	25.64
2008	24.93	21.59	20.08	20.02	4.72	4.55	3.21	16.1	12.73	25.34	31.08	28.15
2009	7.87	5.29	4.64	23.57	6.84	4.8	2.54	2.28	2.31	4.08	9.14	6.15

* All amounts are in mm per unit lake area. The daily flow values (m^3/s) were obtained from OIVA – Environment and Spatial Information Services (23 Sep 2010).

Table I.8: Monthly Eurajoki River flow volumes per unit lake area.*												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1971	0	0	0	0	0	68.03	60.74	50.77	51.72	37.13	24.66	26.89
1972	25.67	23.94	23.16	21.55	22.1	21.77	23.22	25.44	26.17	27.39	29.28	69.98
1973	66.98	44.54	34.07	114.86	162.79	72.15	40.42	47.38	44.43	43.87	84.46	106.23
1974	126.66	147.42	226.93	182.94	76.22	41.87	43.59	58.68	100.55	145.48	164.96	216.35
1975	228.99	221.86	152.6	85.18	83.07	62.08	39.53	41.37	32.62	34.85	31.79	34.13
1976	31.4	33.35	34.52	34.13	33.79	27.28	35.52	34.13	30.4	29.34	29.12	34.74
1977	33.91	31.07	35.46	61.02	199.59	65.97	38.36	39.08	50.11	43.37	131.95	144.47
1978	100.44	77.05	62.8	52.56	45.37	36.52	35.13	36.13	44.76	65.97	71.54	102.61
1979	85.79	55.51	60.13	48.32	38.58	33.01	53.78	147.81	172.7	141.8	104.95	144.97
1980	141.69	48.27	36.24	35.02	35.13	38.36	41.14	36.97	36.08	132.17	182.67	205.99
1981	171.98	230.04	200.2	142.3	108.34	93.87	182.5	136.79	101.16	109.01	158.17	170.81
1982	171.48	155.55	117.86	52.5	124.93	78.05	50.05	44.82	46.38	42.81	42.81	103
1983	133.84	131.33	112.74	110.46	94.81	57.01	54.67	49.94	45.15	42.92	49.55	53.45
1984	95.15	138.24	158.34	141.75	170.92	141.97	95.2	110.57	91.31	100.16	185.12	184
1985	128.5	89.25	87.91	81.62	147.76	104.17	63.08	79.78	76.33	56.06	48.21	50
1986	0	0	96.87	73.04	111.79	82.68	56.73	36.8	49.72	94.48	122.2	158.23
1987	139.85	99.16	101.83	85.01	50.38	68.42	74.21	137.51	171.14	173.87	139.57	90.19
1988	91.58	117.69	133.39	131.17	135.79	133.62	87.63	97.26	74.6	100.71	79.95	51.44
1989	100.71	175.93	237.89	274.47	254.04	78.28	32.68	36.41	36.13	34.3	27.73	22.1
1990	17.76	97.87	262.28	255.99	49.49	28.95	25.11	28	34.85	42.53	34.57	35.69
1991	40.59	36.58	50.11	103.39	96.65	47.6	46.93	39.47	34.3	45.76	88.3	134.84
1992	139.52	126.83	99.82	231.88	129.11	38.53	36.91	35.85	37.75	41.42	64.19	115.13
1993	102.94	120.92	87.74	43.48	54.06	38.19	38.08	31.57	33.24	35.13	37.91	37.52
1994	67.48	113.02	134.95	156	91.19	37.91	34.41	36.08	33.01	49.61	50.05	62.19
1995	115.86	175.21	230.49	227.21	139.74	154.55	51.94	48.21	42.87	48.32	43.59	40.75
1996	38.92	32.29	34.52	61.63	90.58	48.83	42.03	42.65	35.58	38.58	41.31	68.14
1997	89.75	86.52	132.06	135.34	131.61	47.94	35.19	33.29	30.4	32.18	37.52	58.74
1998	104.05	105.5	119.42	116.53	118.2	90.58	110.18	89.19	86.63	57.01	81.56	70.15
1999	82.29	87.13	147.15	224.09	225.65	109.45	33.4	16.81	0	27.78	30.29	45.99
2000	87.41	115.75	159.62	192.63	166.58	55.4	38.75	79.28	92.98	73.27	149.82	194.25
2001	148.65	89.19	65.58	91.86	110.12	59.4	30.01	27.56	69.26	92.25	94.48	97.15
2002	77.67	122.32	179.72	186.45	94.87	33.85	44.59	53.28	34.8	23.94	15.92	17.26
2003	18.87	18.71	20.32	19.99	19.65	29.62	23.27	24.94	28.23	26.17	29.34	36.8
2004	33.18	32.24	34.96	34.96	32.96	38.53	35.3	31.57	28.62	31.85	30.9	88.74
2005	171.87	177.88	157.11	163.63	76.61	59.01	48.21	43.7	35.85	31.51	47.1	73.38
2006	78.72	55.56	44.26	90.8	107.4	84.01	38.92	30.23	21.32	24.33	79.17	186.45
2007	175.37	143.64	158.56	111.51	63.08	42.37	41.37	35.19	30.9	36.97	41.2	96.71
2008	168.25	194.52	231.77	210.28	91.23	40.47	43.44	49.56	92.8	103.74	195.61	203.18
2009	142.63	127.82	109.18	56.45	46	41.15	43.23	41.87	28.11	21.31	20.38	37.47

* All amounts are in mm per unit lake area. The daily flow values (m^3/s) were obtained from OIVA – Environment and Spatial Information Services (23 Sep 2010).

Table I.9: Areas of watershed subcatchment regions.		
Region	Area (km^2)	Data Source
Lake Pyhäjärvi	155.18932	OIVA – Environment and Spatial Information Services (10 Aug 2010)
Yläneenjoki River, gauged region above weir	197	OIVA – Environment and Spatial Information Services (17 Nov 2010)
Yläneenjoki River, entire catchment	234	Tarvainen and Ventelä (2007)
Pyhäjoki River, gauged region above weir	73	OIVA – Environment and Spatial Information Services (17 Nov 2010)
Pyhäjoki River, entire catchment	78	Tarvainen and Ventelä (2007)
Direct runoff, single drain area (used for PART-adjustments)	54.88	ArcMap 10, using catchment shapefiles (©SYKE, 2010)
Direct runoff, broad runoff regions (used for PART-adjustments)	95.03	ArcMap 10, using catchment shapefiles (©SYKE, 2010)
Entire direct runoff region used for average direct runoff calculations*	148	Calculated from a watershed area of 615km^2 (Räsänen et al., 1992), and the above data for the lake and the entire river catchments

* Differs slightly from the sum of the two direct runoff areas from the PART-adjustments due to the use of different data sources and rounding.

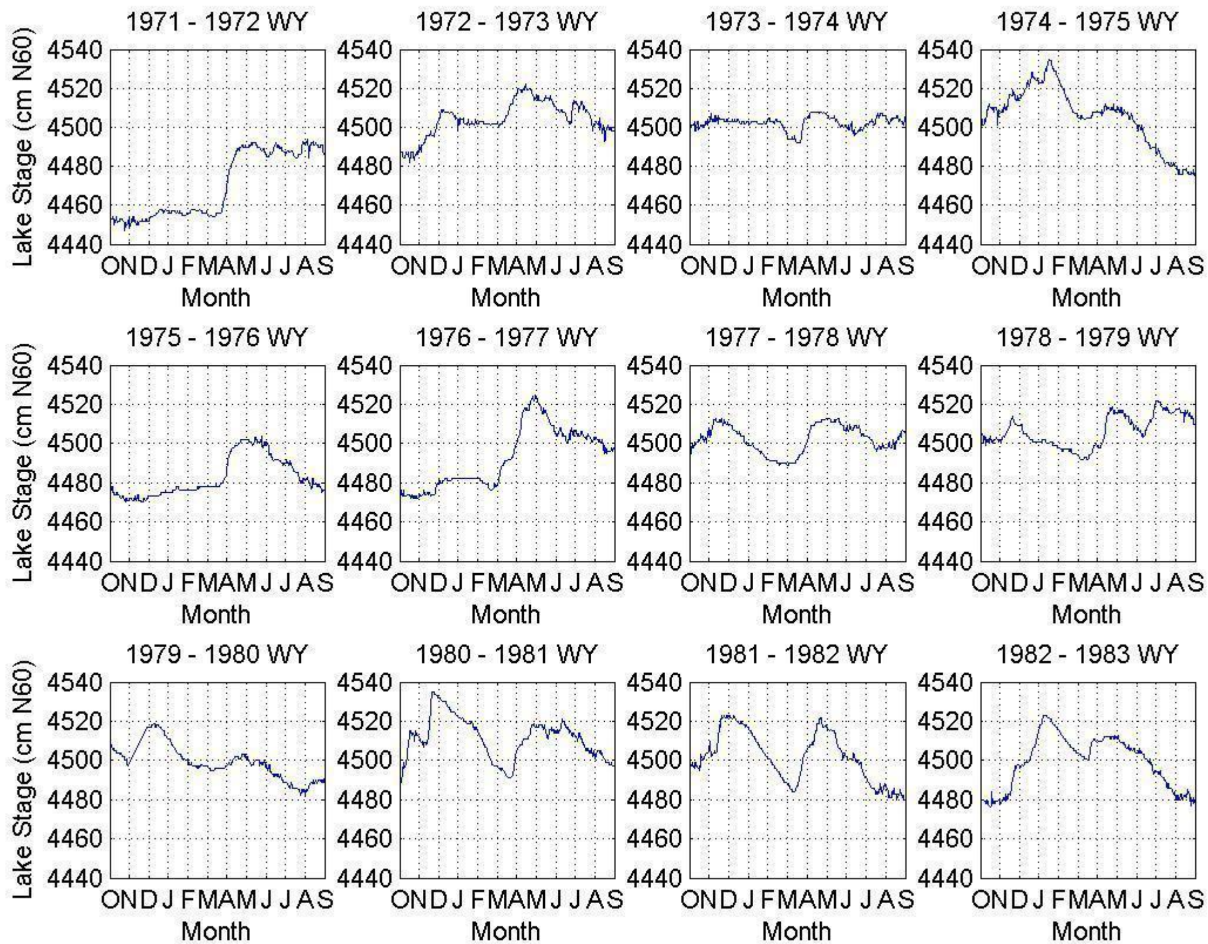


Figure I.1: Lake Pyhäjärvi water levels at Kauttua for the water years 1971 - 1982 (OIVA - Environment and Spatial Information Services, 8 Sep 2010).

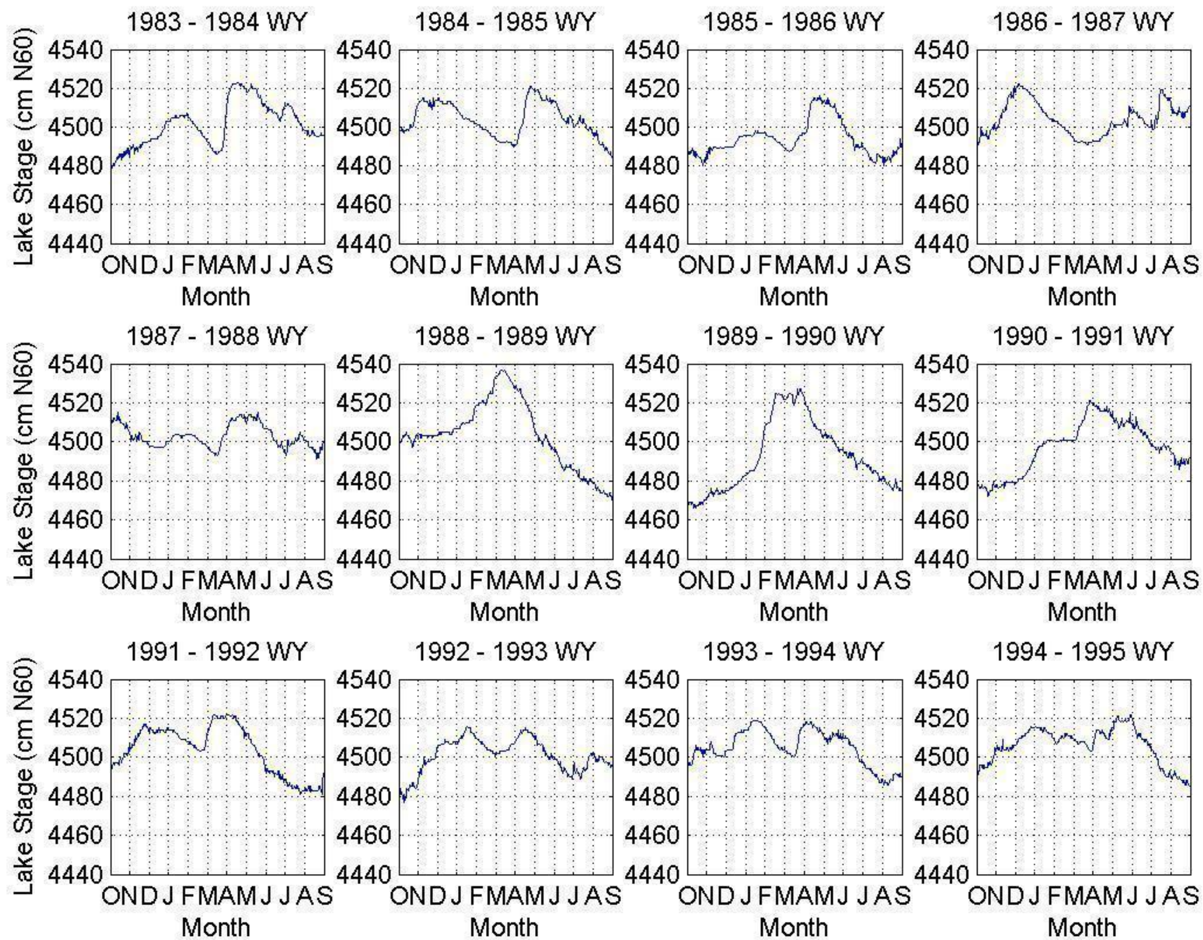


Figure I.2: Lake Pyhäjärvi water levels at Kauttua for the water years 1983 - 1994 (OIVA - Environment and Spatial Information Services, 8 Sep 2010).

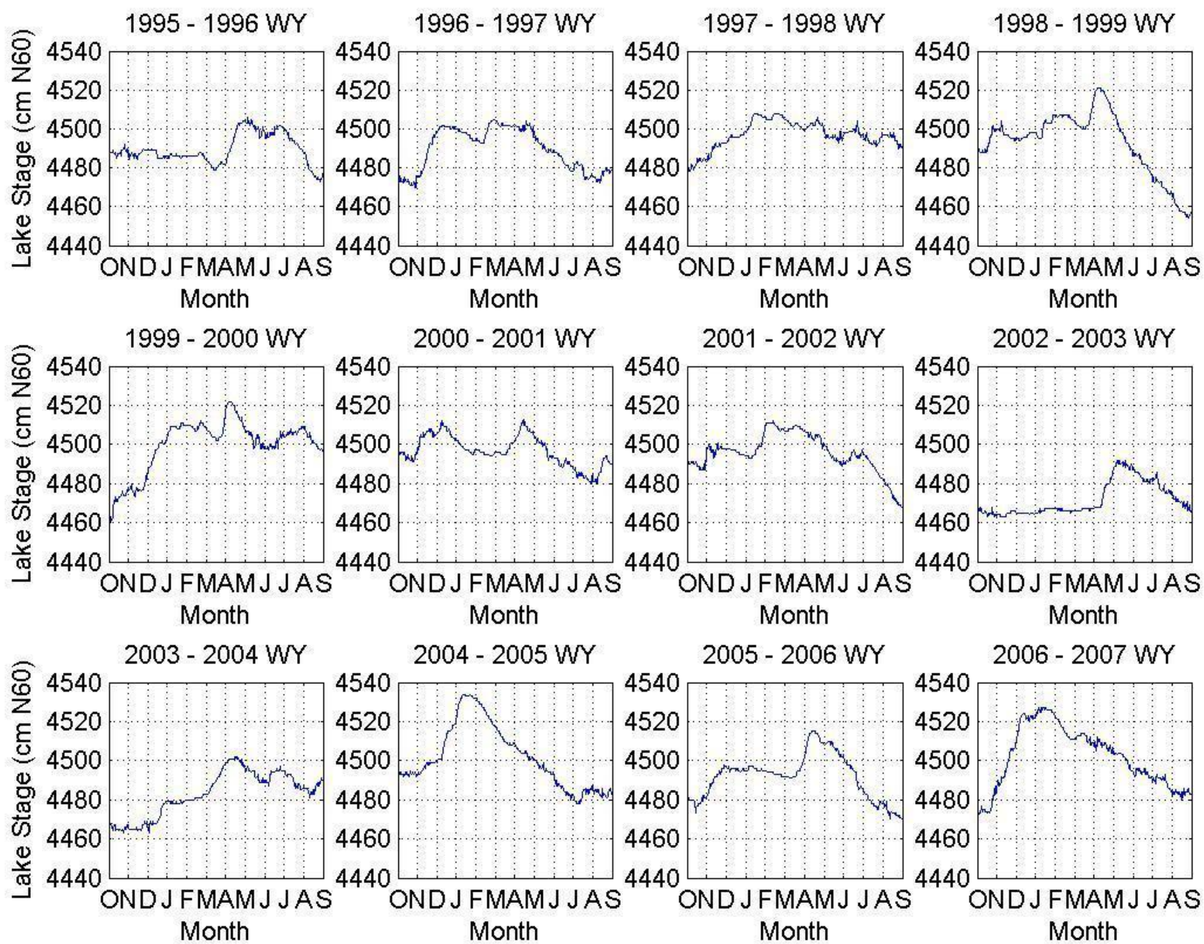


Figure I.3: Lake Pyhäjärvi water levels at Kauttua for the water years 1995 - 2006 (OIVA - Environment and Spatial Information Services, 8 Sep 2010).

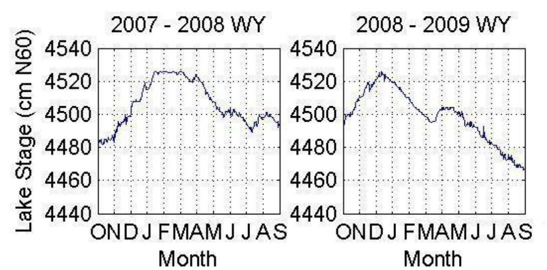


Figure I.4: Lake Pyhäjärvi water levels at Kauttua for the water years 2007 - 2008 (OIVA - Environment and Spatial Information Services, 8 Sep 2010).

Appendix J
Water Balance Results

Table J.1: Water balance results employing the average fraction of river runoff per unit catchment area from the Yläneenjoki and Pyhäjoki Rivers in the direct runoff estimate (OIVA – Environment and Spatial Information Services, 5 Jun 2010, 10 Aug 2010, 8 Sep 2010, 23 Sep 2010, 13 Oct 2010, 4 Jan 2011, 19 May 2011; FMI, 24 May 2010; J. Reko, pers. comm., 2010; K. Korkka-Niemi, pers. comm., 2011).*

Year	Storage Change	Pan Coeff. Method Evap.	Pumping Withdrawals	Adjusted Net River Discharge†	Isohyetal Precip.	Avg. Runoff	Net GW Discharge to Lake
1971	310	461.23	11.08	**100.47**	552.04	**208.15**	-78.34
1972	150	464.94	11.05	-217.99	608.18	247.14	-11.35
1973	10	378.80	11.05	-428.10	601.43	385.59	-159.07
1974	-230	439.23	11.05	-620.91	609.48	386.37	-154.65
1975	-40	454.54	11.08	-115.95	385.44	140.02	16.11
1976	220	374.76	11.05	-68.44	533.22	259.41	-118.38
1977	80	409.22	11.05	-160.71	566.04	292.50	-197.56
1978	30	397.79	11.05	-266.38	619.02	298.39	-212.19
1979	-190	410.12	11.08	-378.56	468.32	217.65	-76.20
1980	90	373.45	11.05	-824.71	727.15	501.35	70.71
1981	-180	441.23	11.05	-594.03	563.55	320.99	-18.23
1982	-20	429.90	11.05	-403.77	587.52	269.77	-32.56
1983	200	373.84	11.08	-489.96	726.49	380.49	-32.10
1984	-110	379.90	11.05	-673.11	647.41	308.76	-2.11
1985	60	420.61	11.05	**-339.29**	566.30	253.83	10.82
1986	190	343.97	11.05	-568.97	704.53	340.23	69.23
1987	-140	442.22	11.08	-706.45	696.25	317.78	5.72
1988	-280	492.54	11.05	-804.23	630.80	308.98	88.04
1989	50	437.13	11.05	-284.57	645.15	282.46	-144.86
1990	200	342.48	11.05	-108.10	595.14	229.12	-162.64
1991	-30	456.46	11.08	-450.14	635.31	316.78	-64.41
1992	30	378.68	11.05	-146.50	599.19	285.50	-318.45
1993	-80	421.15	11.05	-279.79	590.26	240.01	-198.28
1994	-30	400.16	11.05	-511.12	682.61	371.43	-161.71

Table J.1 (Continued): Water balance results employing the average fraction of river runoff per unit catchment area from the Yläneenjoki and Pyhäjoki Rivers in the direct runoff estimate (OIVA – Environment and Spatial Information Services, 5 Jun 2010, 10 Aug 2010, 8 Sep 2010, 23 Sep 2010, 13 Oct 2010, 4 Jan 2011, 19 May 2011; FMI, 24 May 2010; J. Reko, pers. comm., 2010; K. Korkka-Niemi, pers. comm., 2011).*

Year	Storage Change	Pan Coeff. Method Evap.	Pumping Withdrawals	Adjusted Net River Discharge†	Isohyetal Precip.	Avg. Runoff	Net GW Discharge to Lake
1995	-100	384.77	11.08	-192.31	436.51	170.39	-118.73
1996	50	435.53	11.05	-187.92	713.14	304.04	-332.68
1997	110	292.26	11.05	-307.04	669.82	339.98	-289.44
1998	-320	462.28	11.05	**-578.10**	530.20	276.05	-74.82
1999	380	386.54	11.08	-141.36	777.95	419.11	-278.08
2000	-30	390.95	11.05	-443.05	692.60	312.72	-190.27
2001	-260	427.46	11.05	-457.39	577.97	315.56	-257.63
2002	-10	385.05	11.05	-73.76	425.15	106.50	-71.79
2003	260	342.65	11.08	45.75	592.28	209.52	-233.82
2004	-100	386.62	11.05	-516.89	614.86	275.31	-75.62
2005	-90	527.64	11.05	-220.83	476.88	228.80	-36.15
2006	110	428.06	11.05	-380.72	735.47	329.51	-135.13
2007	120	390.71	11.08	-415.91	716.71	399.76	-178.76
2008	-290	419.57	11.05	-580.42	580.10	274.44	-133.50

* All components are listed in mm per unit lake area.
† The components in bold were corrected for missing river discharge data.

Table J.2: Water balance results employing PART-adjusted direct runoff for subcatchment areas adjacent to the lake with considerable shoreline distances (OIVA – Environment and Spatial Information Services, 5 Jun 2010, 10 Aug 2010, 8 Sep 2010, 23 Sep 2010, 13 Oct 2010, 4 Jan 2011, 19 May 2011; FMI, 24 May 2010; J. Reko, pers. comm., 2010; K. Korkka-Niemi, pers. comm., 2011).*							
Year	Storage Change	Pan Coeff. Method Evap.	Pumping Withdrawals	Adjusted Net River Discharge†	Isohyetal Precip.	PART-adjusted Yläneenjoki-based Runoff	Net GW Discharge to Lake
1971	310	461.23	11.08	**100.47**	552.04	104.37	25.44
1972	150	464.94	11.05	-217.99	608.18	155.81	79.99
1973	10	378.80	11.05	-428.10	601.43	228.74	-2.22
1974	-230	439.23	11.05	-620.91	609.48	246.50	-14.79
1975	-40	454.54	11.08	-115.95	385.44	77.65	78.49
1976	220	374.76	11.05	-68.44	533.22	172.82	-31.79
1977	80	409.22	11.05	-160.71	566.04	165.91	-70.98
1978	30	397.79	11.05	-266.38	619.02	200.49	-114.29
1979	-190	410.12	11.08	-378.56	468.32	118.69	22.76
1980	90	373.45	11.05	-824.71	727.15	331.50	240.56
1981	-180	441.23	11.05	-594.03	563.55	185.60	117.16
1982	-20	429.90	11.05	-403.77	587.52	158.80	78.41
1983	200	373.84	11.08	-489.96	726.49	246.89	101.51
1984	-110	379.90	11.05	-673.11	647.41	167.89	138.77
1985	60	420.61	11.05	**-339.29**	566.30	133.65	131.00
1986	190	343.97	11.05	-568.97	704.53	200.36	209.10
1987	-140	442.22	11.08	-706.45	696.25	199.53	123.98
1988	-280	492.54	11.05	-804.23	630.80	169.71	227.31
1989	50	437.13	11.05	-284.57	645.15	159.65	-22.05
1990	200	342.48	11.05	-108.10	595.14	135.18	-68.69
1991	-30	456.46	11.08	-450.14	635.31	186.39	65.99
1992	30	378.68	11.05	-146.50	599.19	182.79	-215.74
1993	-80	421.15	11.05	-279.79	590.26	181.56	-139.82
1994	-30	400.16	11.05	-511.12	682.61	246.15	-36.43

Table J.2 (Continued): Water balance results employing PART-adjusted direct runoff for subcatchment areas adjacent to the lake with considerable shoreline distances. (OIVA – Environment and Spatial Information Services, 5 Jun 2010, 10 Aug 2010, 8 Sep 2010, 23 Sep 2010, 13 Oct 2010, 4 Jan 2011, 19 May 2011; FMI, 24 May 2010; J. Reko, pers. comm., 2010; K. Korkka-Niemi, pers. comm., 2011).*

Year	Storage Change	Pan Coeff. Method Evap.	Pumping Withdrawals	Adjusted Net River Discharge†	Isohyetal Precip.	PART-adjusted Yläneenjoki-based Runoff	Net GW Discharge to Lake
1995	-100	384.77	11.08	-192.31	436.51	106.09	-54.44
1996	50	435.53	11.05	-187.92	713.14	213.18	-241.82
1997	110	292.26	11.05	-307.04	669.82	245.06	-194.52
1998	-320	462.28	11.05	**-578.10**	530.20	181.48	19.75
1999	380	386.54	11.08	-141.36	777.95	278.44	-137.41
2000	-30	390.95	11.05	-443.05	692.60	196.15	-73.70
2001	-260	427.46	11.05	-457.39	577.97	185.50	-127.57
2002	-10	385.05	11.05	-73.76	425.15	43.11	-8.40
2003	260	342.65	11.08	45.75	592.28	129.38	-153.67
2004	-100	386.62	11.05	-516.89	614.86	167.39	32.30
2005	-90	527.64	11.05	-220.83	476.88	130.41	62.23
2006	110	428.06	11.05	-380.72	735.47	227.75	-33.38
2007	120	390.71	11.08	-415.91	716.71	290.66	-69.66
2008	-290	419.57	11.05	-580.42	580.10	158.69	-17.74

* All components are listed in mm per unit lake area.

† The components in bold were corrected for missing river discharge data.

Table J.3: Alternative water balance results for equation with evaporation as the residual and a constant groundwater component of zero (OIVA – Environment and Spatial Information Services, 10 Aug 2010, 8 Sep 2010, 23 Sep 2010, 13 Oct 2010; FMI, 24 May 2010; J. Reko, pers. comm., 2010; K. Korkka-Niemi, pers. comm., 2011).*						
Year	Storage Change	Pumping Withdrawals	Adjusted Net River Discharge†	Isohyetal Precipitation Sum	Avg. Runoff Estimate	Evaporation (neglecting groundwater)
1971	310	11.08	**100.47**	552.04	**208.15**	539.57
1972	150	11.05	-217.99	608.18	247.14	476.28
1973	10	11.05	-428.10	601.43	385.59	537.87
1974	-230	11.05	-620.91	609.48	386.37	593.88
1975	-40	11.08	-115.95	385.44	140.02	438.42
1976	220	11.05	-68.44	533.22	259.41	493.14
1977	80	11.05	-160.71	566.04	292.50	606.78
1978	30	11.05	-266.38	619.02	298.39	609.98
1979	-190	11.08	-378.56	468.32	217.65	486.32
1980	90	11.05	-824.71	727.15	501.35	302.74
1981	-180	11.05	-594.03	563.55	320.99	459.46
1982	-20	11.05	-403.77	587.52	269.77	462.46
1983	200	11.08	-489.96	726.49	380.49	405.94
1984	-110	11.05	-673.11	647.41	308.76	382.01
1985	60	11.05	**-339.29**	566.30	253.83	409.79
1986	190	11.05	-568.97	704.53	340.23	274.74
1987	-140	11.08	-706.45	696.25	317.78	436.50
1988	-280	11.05	-804.23	630.80	308.98	404.50
1989	50	11.05	-284.57	645.15	282.46	581.99
1990	200	11.05	-108.10	595.14	229.12	505.12
1991	-30	11.08	-450.14	635.31	316.78	520.86
1992	30	11.05	-146.50	599.19	285.50	697.13
1993	-80	11.05	-279.79	590.26	240.01	619.43
1994	-30	11.05	-511.12	682.61	371.43	561.87

Table J.3 (Continued): Alternative water balance results for equation with evaporation as the residual and a constant groundwater component of zero (OIVA – Environment and Spatial Information Services, 10 Aug 2010, 8 Sep 2010, 23 Sep 2010, 13 Oct 2010; FMI, 24 May 2010; J. Reko, pers. comm., 2010; K. Korkka-Niemi, pers. comm., 2011).*						
Year	Storage Change	Pumping Withdrawals	Adjusted Net River Discharge†	Isohyetal Precipitation Sum	Avg. Runoff Estimate	Evaporation (neglecting groundwater)
1995	-100	11.08	-192.31	436.51	170.39	503.50
1996	50	11.05	-187.92	713.14	304.04	768.21
1997	110	11.05	-307.04	669.82	339.98	581.70
1998	-320	11.05	**-578.10**	530.20	276.05	537.10
1999	380	11.08	-141.36	777.95	419.11	664.62
2000	-30	11.05	-443.05	692.60	312.72	581.22
2001	-260	11.05	-457.39	577.97	315.56	685.09
2002	-10	11.05	-73.76	425.15	106.50	456.84
2003	260	11.08	45.75	592.28	209.52	576.47
2004	-100	11.05	-516.89	614.86	275.31	462.24
2005	-90	11.05	-220.83	476.88	228.80	563.79
2006	110	11.05	-380.72	735.47	329.51	563.20
2007	120	11.08	-415.91	716.71	399.76	569.47
2008	-290	11.05	-580.42	580.10	274.44	553.07

* All components are listed in mm per unit lake area.
† The components in bold were corrected for missing river discharge data.