Turkey Lakes Watershed, Ontario, Canada: 40 years of interdisciplinary whole-ecosystem research

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Introduction

The Turkey Lakes Watershed (TLW) study (https://www.canada.ca/en/environment-climate-change/services/turkey-lakes-watershed-study.html) was established in 1979 and is one of the longest running watershed-based ecosystem studies in Canada (Foster, Beall & Kreutzweiser, 2005; Jeffries, Kelso & Morrison, 1988; Morrison, Cameron, Foster & Groot, 1999). The watershed drains 10.5 km^2 of Eastern Temperate Mixed Forest (Baldwin et al., 2018) or Great Lakes – St. Lawrence forest region (Rowe, 1972) within the Boreal Shield Ecozone (Wiken, 1986), and is located approximately 60 km north of Sault Ste. Marie, Ontario (47°03'N, 84°25'W) (Figure 1). Researchers from several federal government departments (Natural Resources Canada (NRCAN), Environment and Climate Change Canada (ECCC) and Fisheries and Oceans Canada (DFO) established this research watershed to evaluate the impacts of acid rain on terrestrial and aquatic ecosystems (e.g., Foster, Hazlett, Nicolson & Morrison, 1989; Hazlett, Curry & Weldon, 2011; Jeffries, Semkin, Beall & Franklyn, 2002; Kelso 1988). Since its inception, many studies have taken a multi-disciplinary, whole-ecosystem approach to investigate the processes governing terrestrial and aquatic responses to natural and anthropogenic disturbances. This holistic approach has allowed research to expand from its original acidification focus to address a range of other ongoing and emerging environmental issues (e.g. habitat alteration, organic contaminants, forest management, climate change) and to involve numerous academic, government and industrial collaborators.

Site description

The TLW has a total relief of 300 m from the highest point on Batchawana Mountain (626m) to the watershed outlet on Norberg Creek. The site is almost entirely underlain by Precambrian silicate greenstone (i.e. metamorphosed basalt) with some small outcrops of more felsic igneous rock (Semkin & Jeffries, 1983). A two-component glacial till, composed of ablation till superimposed on a compact basal till, overlies the bedrock. Till thickness varies from <1 m at high-elevation locations (with frequent surface exposure of bedrock) to 1-2 m at lower elevation, and with the occasional occurrence of extremely deep till sequences up to 70 m (Elliot, 1985; Buttle, Webster, Hazlett & Jeffries, 2018). Tills contain a small but measurable amount of $CaCO_3$ (0-2%) that increases with depth and is higher at lower elevation locations (Craig & Johnston, 1983).

TLW soils are predominantly podzols (spodosols) with well-developed L, F, H (O_i, O_e, O_a) horizons and accumulation of organic matter (10%), iron and aluminum in the B horizon (Hazlett, Semkin & Beall, 2001; Hazlett & Foster, 2002). The pH of the mineral soil is 4.0 at the surface, increasing to 5.5 at depth. Organic soils occupy wetlands and riparian areas of the watershed (Creed, Beall, Clair, Dillon & Hesslien et al., 2008; Wickware & Cowell, 1985).

The TLW forest is composed of uneven-aged tolerant hardwood forest dominated by mature to over-mature sugar maple (*Acer saccharum*) that are 150 - 200 years old. Minor components include yellow birch (*Betual alleghaniensis*), red maple (*Acer rubrum*), ironwood (*Ostrya virginiana*) white spruce (*Picea glauca*) and white pine (*Pinus strobus*). In riparian areas, eastern white cedar (*Thuja occidentalis*) balsam fir (*Abies balsamea*), tamarack (*Larix laricina*) and black ash (*Fraxinus nigra*) can be found (Morrison, 1990). Stands regenerate through gap dynamics and, due to natural tree mortality, are roughly in equilibrium in terms of aboveground net phytomass accumulation (Morrison, 1990). The watershed is relatively undisturbed. The most recent operational logging occurred in the 1950's when the area was selectively logged for high-quality yellow birch, sugar maple and likely white spruce and white pine (Jeffries et al., 1988). The biggest impact was a reduction in the overstory yellow birch component. There have been no significant natural disturbances (forest fires, insect outbreaks) across the watershed since the establishment of the study, with the exception of an experimental harvest in 1997 (see below).

The high relief and leeward position relative to Lake Superior influences the quantity of precipitation at the site. The mean annual precipitation for the period 1980 to 2017 was 1203 mm (unpublished data). Approximately a third of the precipitation falls as snow (Semkin et al., 2012), with snow cover developing typically in late October – November and melting during the March – April period. Average annual temperature over the 1980 to 2017 period was 4.5 °C (unpublished data). The TLW is showing evidence of climate change. While there have not been substantive changes in average annual precipitation, there have been other indicators of change. These include (Buttle et al., 2018; Hazlett, unpublished data): increasing annual air temperatures (0.3° C per decade, primarily driven by higher autumn temperatures), increasing potential evapotranspiration (PET), increasing growing degree days, lengthening of the growing season, more ice-free days on lakes (driven by later in the year dates of ice formation on), and less precipitation falling as snow (e.g., in December).

Observation network

The ECCC Algoma CAPMoN (Canadian Air and Precipitation Monitoring Network) site (47°02'01.2"N, 84°22'44.3"W), located about 600 m outside the watershed boundary (Figure 1), has measured atmospheric chemistry at the site since 1980. Constituents monitored include wet deposition (rain or snow) of major ions, (inferential) dry deposition and concentrations of acid-forming gases and particles. A meteorological station at the CAPMON site measures air temperature, wind speed and direction, relative humidity and vapour pressure, barometric pressure and solar radiation.

The TLW drainage system consists of first order streams and a cascading chain of 4 lakes. The Batchawana (separated into upper and lower basins), Wishart, Little Turkey and Big Turkey Lakes (surface areas of 6, 6, 19, 19 and 52 ha, respectively) are connected by Norberg Creek, which drains into Lake Superior via the Batchawana River (Figure 1). The lakes flush quite rapidly, with water renewal times ranging from 0.2 years at Wishart to 1.2 years at Upper Batchawana (Jeffries et al., 1988). Historically (1980 to 2019) lake temperature profile and chemistry, and lakeoutflow discharge and chemistry data were collected along the drainage network.

Stream flows and chemistry are monitored on an ongoing basis at v-notch weirs installed at 13 first order catchments within the watershed. These catchments vary in their topography from upland dominated with steep slopes to those having more moderate relief with swamps (Jeffries et al. 1988). Variation in stream hydrology and chemistry reflect these differences in basin topography and soils (Beall, Semkin & Jeffries, 2001; Creed, Sanford, Beall, Molot & Dillon, 2003; Leach, Buttle, Webster, Hazlett & Jeffries, 2020; Nicholson 1988). The catchments have a snowmelt-dominated hydrologic regime. The dominant anions in stream water are alkalinity (primarily HCO_3^-) and SO_4^{2-}, with NO_3^- and Cl^- as minor components. The dominant cation is Ca^{2+}, with lesser amounts of Mg^{2+}, Na^+, and K^+. Basins at lower elevation with presence of deep tills have higher average alkalinity and Ca^{2+}concentrations than bedrock dominated higher elevation catchments.

Hydrometeorology and surface water chemistry measurements make up the core monitoring at TLW; however, other ecosystem components, such as physical and chemical properties of throughfall, soil, soil pore water, groundwater, structure and composition of overstory and understory vegetation and abundance and composition of stream and lake aquatic biodiversity have been monitored at locations within the watershed (Table 1). Several experimental manipulations have been conducted at TLW, such as enhanced acidification experiments (Hogan, 1992; Thirukkumaran & Morrison, 1996) a comprehensive forest harvesting experiment (Buttle, Webster, Hazlett & Jeffries, 2018; Leach, Buttle, Webster, Hazlett & Jeffries, 2020; Kreutzweiser, Capell & Good, 2005; Morrison, Cameron, Foster & Groot, 1999; and a nearshore aquatic habitat manipulation experiment (Smokorowski, Pratt, Cole, McEachern & Mallory, 2006).

Data availability statement

TLW data are available primarily from federal agencies of NRCAN-CFS, ECCC (Atmospheric Science & Technology Directorate [ASTD] and Water Science & Technology Directorate [WSTD] and DFO. Other datasets from university partners must be requested through specific researchers. Table 1 provides an overview of some of the key datasets and contact/URL for the data. Some are available through in a public repository that does not issue DOIs, other data is available on request from the authors through collaborative projects.

Contributions to science and policy

The whole-ecosystem analysis of biogeochemical processes operating within the TLW has and continues to result in major advancements in water and ecosystem science, with important contributions to Canadian and international policy on air pollution and air quality issues, water resource management, sustainable forest management guidelines and practices, and climate change assessment and adaptation. TLW research results have contributed to the development of the Canada-U.S. Air Quality Agreement in 1991 and ongoing contributions to agreement progress reports and Canadian Acid Rain Assessments, Canada-Ontario Agreement on Water Quality and Canada-United States Great Lakes Water Quality Agreement, Forest Management Guidelines in Ontario and other jurisdictions, and a Blueprint for Forest Carbon Science in Canada. TLW science is also providing input to other high profile policy issues related to cumulative effects, drinking water treatability and ecosystem resilience to climate change. Since its establishment two hallmarks of the TLW study have been the focus on long-term research and collaboration with other research sites from across North America and the world. Numerous cross site comparison studies (e.g., Creed, Beall, Clair, Dillon & Hesslien, 2008; Hazlett et al., 2020; Kerr et al., 2012; Lawrence et al., 2015; Mitchell et al., 2010; Watmough et al., 2005) have placed the results from the TLW in context with other sites with different forest and soil types, climates and disturbance conditions. These comparisons facilitate a more comprehensive understanding of forest ecosystem processes and an ability to make broader science inferences and policy decisions from the interpretation of the research results.

Continuous long-term assessment of ecosystem function is necessary to track the effects of natural and anthropogenic disturbances on forests, and to assess mitigation or adaptation policies implemented by government and industry. As examples, research from the TLW has demonstrated that the re-measurement of ecosystem parameters over long time periods is required to evaluate the efficacy of pollution control policies, and that the initial effects of forest management can be maintained for a prolonged period after harvesting (e.g., Beall, Semkin & Jeffries, 2001; Buttle, Webster, Hazlett & Jeffries 2018; Hazlett et al., 2020). Only through long-term funding commitment by governments and other partners will we achieve a comprehensive understanding of how disturbances to forested landscapes impact ecosystems services; therefore, informing rigorous science-based sustainable management of these environments.

More than 400 scientific publications have resulted from the work at TLW, including many national, North American and international cross-site syntheses. This research has also led to the training of highly qualified future science professionals through MSc and PhD projects and theses. Public outreach is another important component of the TLW; every year tours and training are provided to high school, college, universities, researchers, managers and policy makers.

A full list of publications from the TLW can be found in at: https://www.canada.ca/en/environment-climate-change/services/turkey-lakes-watershed-study/publications.html, which covers publications in 12 different categories: Site Overview, Atmospheric/Meteorology, Forest/Understory, Soils, Soil Pore Water/Ground Water, Lakes, Water Birds, Fish and Aquatic Communities, Modelling and Remote Sensing, Internal Reports and Theses.

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TABLE 1: Description of data sets from Turkey Lakes Watershed, including agency responsible and contacts and/or links to data. Agency acronyms are Natural Resources Canada, Canadian Forest Service (NRCAN-CFS), Environment and Climate Change Canada (ECCC) Atmospheric Science & Technology Directorate (ECCC-ASTD) and Water Science & Technology Directorate (ECCC-WSTD), and Fisheries and Oceans Canada (DFO).

Data	Agency responsible	Description	Contact/Link
Air			
Atmospheric deposition	ECCC-ASTD	Concentration of major ions and nutrients in wet-only precipitation and air concentrations of various acidifying gases and particulates. Samples are collected at Algoma CAPMoN station located just outside the watershed. Daily to weekly from 1980.	https://open.canada.ca/data/en/datas a8aa-457a-af26-aa13e96ee2f4
Bulk deposition	ECCC-WSTD NRCAN-CFS	Concentrations of major ions, nutrients and some metals in atmospheric bulk deposition. Co-located on Algoma CAPMoN platform located just outside the watershed. Daily to monthly from 1980.	https://open.canada.ca/data/en/datas 3864-46b8-b367-8f19c0c86b6c

Data	Agency responsible	Description	Contact/Link
Meteorology measurements (at CAPMoN site)	ECCC-WSTD NRCAN-CFS	Air temperature, wind speed and direction, relative humidity and vapour pressure, barometric pressure and solar radiation. Co-located on Algoma CAPMoN platform located just outside the watershed. Daily from 1980.	Data available through collaborative projects. Contact Stephanie.Nelson@canada.ca.
Daily precipitation volumes and chemistry (at satellite sites within watershed)	NRCAN-CFS	Precipitation volume and measured chemistry from two sites within TLW (Headwater and Meadow locations). Weekly to biweekly 1980-present.	Data available through collaborative projects. Contact Stephanie.Nelson@canada.ca.
Snowpack chemistry and water equivalent	ECCC-WSTD	Snowpack has been sampled during both the accumulation and ablation stages at up to 13 sites. Snow depth and a physical description of the snowpack recorded at each station as well as snow density, water equivalent and chemistry (pH, major ions, and nutrients). Monthly for winters 1980/81-2016/17.	https://open.canada.ca/data/en/datas 3864-46b8-b367-8f19c0c86b6c
Water Throughfall	NRCAN-CFS	Bulk throughfall volume and concentration of major ions, nutrients and some metals in throughfall samples collected during the leaf-on period at one site. Monthly 1980-present.	Data is available through collaborative projects. Contact Stephanie.Nelson@canada.ca.

Data	Agency responsible	Description	Contact/Link
Forest floor percolate	NRCAN-CFS	Forest floor percolate volume and concentrations of major ions, nutrients and some metals in samples collected with zero-tension lysimeters below the F horizon at two slope positions (crest and middle slope) at one site. Monthly/more frequently during snowmelt.	Data is available through collaborative projects. Contact Stephanie.Nelson@canada.ca.
Mineral soil percolate	NRCAN-CFS	Mineral soil percolate concentrations of major ions, nutrients and some metals in samples collected with zero-tension lysimeters in the upper B horizon and at the ablation/basal till interface at two slope positions (crest and middle slope) at one site. Monthly/more frequently during snowmelt.	Data is available through collaborative projects. Contact Stephanie.Nelson@canada.ca.
Groundwater chemistry	ECCC-WSTD	Concentrations of major ions, nutrients and some metals in groundwater samples collected at 62, shallow and deep wells. Monthly 1980-2018.	https://open.canada.ca/data/en/datas 3864-46b8-b367-8f19c0c86b6c
Stream discharge from headwater catchments	NRCAN-CFS	Stream discharge (L/s) estimated from water level measurements made at weirs located on 13 forested headwater streams. Sub-daily to daily mean discharge 1981-present (intermittent data 2013-2019).	Annual discharge summaries (1980-2012) available from: https://open.canada.ca/en/open-maps. Additional data available through collaborative projects. Contact Stephanie.Nelson@canada.ca.

Data	Agency responsible	Description	Contact/Link
Stream chemistry from headwater catchments	NRCAN-CFS	Synoptic concentrations (mg/L) of major ions and nutrients collected from grab samples at 13 streams in the TLW. Daily, weekly or bi-weekly depending on season 1981-2019.	Synoptic stream chemistry available from: https://open.canada.ca/en/open-maps or Stephanie.Nelson@canada.ca.
Stream chemistry and discharge from lake outflows	ECCC-WSTD	Daily stream discharge and less frequent concentrations of major ions, nutrients and some metals in stream water samples collected at seven hydrological monitoring stations in the TLW. Six of the seven stations are located along the principal drainage channel (Norberg Creek) in the TLW. Four of the six are at or very near the outflow of the principal lakes in the TLW. The seventh station is located on the outflow stream of a small, unnamed lake draining into Turkey Lake. Bi-weekly to monthly 1980-2019.	Flow data is available at: https://wateroffice.ec.gc.ca/search/hist e.html Water chemistry data is available at: https://open.canada.ca/data/en/datas 3864-46b8-b367-8f19c0c86b6c

Data	Agency responsible	Description	Contact/Link
Lake chemistry	ECCC-WSTD	The thermal structure and dissolved O_2 profile of all 5 lakes and whole-lake, volume-weighted chemistry samples were collected at the same time. When a lake was thermally stratified, volume-weighted epilimnion, metalimnion and hypolimnion samples were collected in addition to the whole-lake sample. The samples were analyzed for pH, concentrations of major ions and nutrients, DOC and some metals. Sampling stations are situated at the deepest point in each lake and range from 4.5 m to 37 m in depth. Bi-weekly to monthly 1980-2019.	https://open.canada.ca/data/en/datas 3864-46b8-b367-8f19c0c86b6c
Aquatic biodiversity			
Stream macroinvertebrates	NRCAN-CFS	Aquatic macroinvertebrates were collected by modified Surber samplers in early October from 1995 to 2009 (pre- and post-harvest experiment) from streams draining the selection (C34) and shelter cut (C33) watersheds, as well as from C42 as a reference stream. In addition, invertebrate collection and decomposition rates were intermittently collected by standardized leaf packs between 2000 and 2009.	Data is available through collaborative projects. Contact Stephanie.Nelson@canada.ca.

Data	Agency responsible	Description	Contact/Link
Lake Zooplankton, Phytoplankton and Chlorophyll-a	DFO	Zooplankton data includes date, gear type, depth of sample, counts, and the density and diversity (Number/L) of zooplankton in each lake. Data collection years range from 1980-95 and 1998-2000. Phytoplankton data includes species counts and number of cells per milliliter of lake water for each lake in 1980. Chlorophyll-a data includes sample volume information, analytical data and concentration of chlorophyll-a (mg/m^3) in the epilimnion of the lakes. Data collection years range from 1983-85, 1987-88, 1991-95, and 1998-2000.	Data is available through collaborative projects. Contact Karen.Smokorowski@canada.ca.

Data	Agency responsible	Description	Contact/Link
Fish	DFO	Includes date, gear type, species, length-weight, age, clip, and tag information for each lake. This information is subsequently used for catch-per-unit-effort, abundance, as well as biomass and production calculations. Data collection years range from 1980, 1985-96 and 1998-2003, 2005, 2008. Fish species include Brook Trout (*Salvelinus fontinalis*), White Sucker (*Catostomus commersoni*), Lake Trout *S. namaycush*, Burbot (*Lota lota*), Northern Redbelly Dace (*Phoxinus eos*), Lake Chub (*Couesius plumbeus)*, Spottail Shiner (*Notropis hudsonius)*, Golden Shiner (*Notemigonus crysoleucas)*, Emerald Shiner (*N. atherinoides)*, Finescale Dace (*Chrosomus neogaeus)*, Fathead Minnow (*Pimephales promelas)*, and logperch (*Percina caprodes*).	Data is available through collaborative projects. Contact Karen.Smokorowski@canada.ca.
Land			

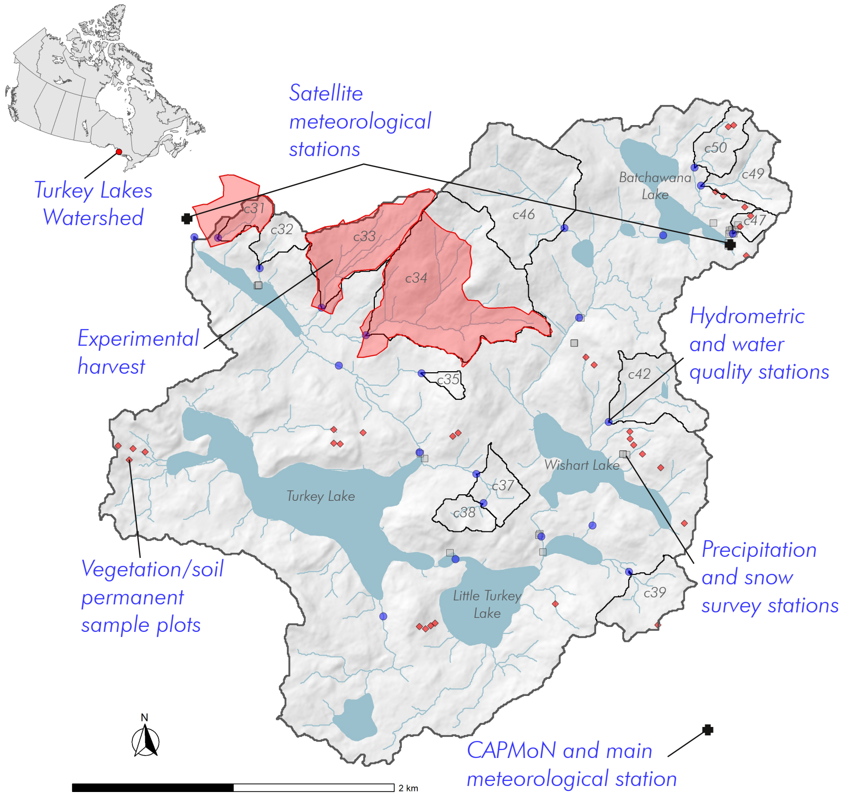
Data	Agency responsible	Description	Contact/Link
Overstory vegetation unharvested forest	NRCAN-CFS	Tree measurements in 31 unharvested PSPs (Permanent Sample Plots) established from 1980 to 1989 at different elevations across the watershed. They were established to study tree growth and species changes over time. Tree species, diameter at breast height (DBH), and height measurements are recorded within 0.10 ha circular plots at five-year intervals. 1980-present.	Data is available through collaborative projects. Contact Stephanie.Nelson@canada.ca.
Overstory vegetation harvest impacts study	NRCAN-CFS	Tree measurements for 32 PSPs associated with the harvest impacts study. Plots (0.10 ha circular) are located within different harvest treatment blocks representing clearcut, selection, shelterwood and uncut control harvest treatments. Harvesting was done in 1997 and DBH and height of the trees >5 cm DBH including ingrowth were measured in 1997, 2002, 2008, 2013 and 2018.	Data is available through collaborative projects. Contact Stephanie.Nelson@canada.ca.

Data	Agency responsible	Description	Contact/Link
Understory woody vegetation harvest impacts study	NRCAN-CFS	Understory woody vegetation was measured in approximately 200 5x5 m quadrats, associated with the harvest impacts study. Plots are located within different harvest treatment blocks and capture a variety of post-harvest canopy opening and soil disturbance combinations resulting from selection, shelterwood, and clearcut harvest operations. Data were collected in 2000, 2006, 2010, 2014 and 2019 and focused on the density and size of tree and shrub species $>$ 0.3 m tall. Additional assessments of the density and size of tree and shrubs $>$ 2 cm DBH were made in 36 adjacent 400 m^2 circular plots in 1999, 2004, 2010 and 2017.	Data is available through collaborative projects. Contact Stephanie.Nelson@canada.ca.

Data	Agency responsible	Description	Contact/Link
Soil	NRCAN-CFS	Soil properties from four intensive study sites including one clearcut harvested and three unharvested sites. Data includes profile morphology and physical (horizon depth, bulk density, coarse fragment content, texture) and chemical (pH, cations, CEC, C, N, P) properties determined to quantify soil nutrient pools, Sites have been resampled 3 or 4 times since the mid-1980s to determine long-term soil change.	Data is available through collaborative projects. Contact Stephanie.Nelson@canada.ca.

Figure Legends

FIGURE 1: Location of Turkey Lakes Watershed within Ontario, Canada (inset) and shaded relief map of watershed and some selected key infrastructure. The site of the experimental harvest area is outlined and shaded red. Refer to text and Table 1 for more information on the observation network and data access.


Turkey Lakes
Watershed
Satellite
meteorological
stations
Experimental
harvest
Hydrometric
and water
quality stations
Precipitation
and snow
survey stations
Vegetation/soil
permanent
sample plots
CAPMoN and main
meteorological station
Batchawana
Lake
Turkey Lake
Wishart Lake
Little Turkey
Lake
c31
c32
c33
c34
c35
c37
c38
c39
c42
c46
c47
c49
c50
N
2 km