The Kwakshua Watersheds Observatory, central coast of British Columbia, Canada

Ian J. W. Giesbrecht1,2 | William C. Floyd3,4 | Suzanne E. Tank1,5
Ken P. Lertzman1,2 | Brian P. V. Hunt1,6 | Maartje C. Korver1,7
Allison A. Oliver1,5,8 | Ray Brunsting1 | Paul Sanborn1,9
Santiago G. Gonzalez Arriola1 | Gordon W. Frazer1,10 | Kyra A. St. Pierre1,6
Shawn Hateley1 | James McPhail1,11 | Colby Owen1,11 | Stewart Butler3
Bryn Fedje1 | Emma Myers1 | Lucy Quayle1 | Emily Haughton1
Isabelle Desmarais1 | Rob White1 | David J. Levy-Booth1,12
Colleen T. E. Kellogg1 | Jennifer M. Jackson1 | William W. Mohn12
Steven J. Hallam12 | Justin Del Bel Belluz1

Abstract

The Kwakshua Watersheds Observatory (KWO) is an integrative watersheds observatory on the coastal margin of a rain-dominated bog-forest landscape in British Columbia (BC), Canada. Established in 2013, the goal of the KWO is to understand and model the flux of terrestrial materials from land to sea – the origins, pathways, processes and ecosystem consequences – in the context of long-term environmental change. The KWO consists of seven gauged watersheds and a network of observation sites spanning from land to sea and along drainage gradients within catchments. Time-series datasets include year-round measurements of weather, soil hydrology, streamflow, aquatic biogeochemistry, microbial ecology and nearshore oceanographic conditions. Sensor measurements are recorded every 5 min and water samples are collected approximately monthly. Additional observations are made during high-flow conditions. We used remote sensing to map watershed terrain, drainage networks, soils and terrestrial ecosystems. The watersheds range in size from 3.2 to 12.8 km², with varying catchment characteristics that influence hydrological and biogeochemical responses. Despite local variation, the overall study area is a global hotspot for yields of dissolved organic carbon, dissolved organic nitrogen and dissolved iron at the coastal margin. This observatory helps fill an important gap in the global network of observatories, in terms of spatial location (central coast of BC), climate (temperate...
Located along the outer coast of BC (Figure 1; 51.655, –128.049), the KWO consists of Kwakshua Channel, Meay Inlet and the surrounding watersheds (Figure 2), which span a range of catchment characteristics (Table 1). Historical (1981–2010) average catchment precipitation ranges from 2988 mm to 3939 mm, primarily in the form of rain (3.6%–9.8% snow) (Figure 1, Table 1) due to mild (ocean moderated) winter temperatures (Giesbrecht et al., 2017). Historical mean annual temperatures vary from 7.2°C to 8.5°C, depending on catchment elevation (Table 1). Bedrock lithology is predominantly quartz diorite (Roddick, 1996), with limited areas of quaternary sediments (Eamer & Shugar, 2015). Soils are predominantly shallow Spodosols and Folists over bedrock, with deep peat accumulations (Hemists) in depressional wetlands (Eamer & Shugar, 2015). Soil organic carbon stocks are large (>273 ± 46 Mg C ha⁻¹; calculated from McNicol et al., 2018), exceeding the average of this carbon-dense rainforest region (228 ± 111 Mg C ha⁻¹; McNicol et al., 2019). Open and forested bog wetlands are extensive and exposed bedrock is common (Green, 2014; Thompson et al., 2016a). Trees are predominantly short (Frazer, 2015a; dataset 6; Hoffman et al., in press) compared to the iconic stands common to the coastal rainforest (Simard et al., 2011) – although stands of tall trees occur where soils are deep and well drained. Mainstream channels are generally bedrock controlled and relatively stable, despite reaches with steep gradients and highly turbulent flow. After an initial 5–6-year period of observing the seven largest watersheds, in 2020 we selected four watersheds for ongoing measurement, which span the range of catchment characteristics, streamflow and freshwater biogeochemistry (Figure 2, Table 1).

There has been a continuous Indigenous presence on this part of the BC coast for at least 13 000 years (McLaren et al., 2018) with abundant archaeological evidence of habitations (McLaren et al., 2015) and extensive, diverse resource gathering and resource management activities (Jackley et al., 2016). Indigenous communities today retain rich oral traditions, environmental knowledge and place names throughout the region (e.g., www.hauyat.ca). While the contemporary forest landscape contains ecological legacies of past Indigenous activities such as cultural fire (Hoffman et al., 2017) and intertidal resource use (Trant et al., 2016), the KWO watersheds remain unimpacted by industrial logging, road building, point-source pollution, dams, or water extraction. The CIFS serves as the hub for this observatory. The station is accessed by sea-plane or boat and provides accommodations, labs, supplies and fabrication shops for field teams who then access the observatory by boat or helicopter and on foot. The KWO is located within, and operated in close coordination with, the Hakai Lúxvbílís
Conservancy (protected area). Research permits were obtained from BC Parks, the Heiltsuk Nation and the Wuikinuxv Nation. The Heiltsuk and Wuikinuxv Nations should be contacted regarding additional expectations for researchers in their unceded territories.

4 | OBSERVATORY DATA TYPES AND INFRASTRUCTURE

4.1 | Geospatial data layers

As a foundation for catchment science, we developed key geospatial data layers from combinations of remote sensing and field observations (Table 2). A LiDAR-derived elevation model was used to delineate and characterize watersheds and stream networks (Gonzalez Arriola, Frazer, & Giesbrecht, 2015; dataset 1; Gonzalez Arriola, Frazer, Giesbrecht, Floyd, & Holmes, 2015; dataset 2). Forest and wetland ecosystems were classified and mapped using airborne LiDAR and satellite imagery (Thompson et al., 2016b; dataset 3). Predictive soil maps were developed by combining LiDAR with >300 field observations of soil properties (Sanborn et al., unpublished data; see also Supplementary Information in Oliver et al., 2017a). Field surveys were used to map the bathymetry of the six largest lakes (Gonzalez Arriola et al., 2016; dataset 4).

4.2 | Sensor network

Continuous (5 min intervals), near real time environmental monitoring is made possible by a telemetry network that uses radio (900 MHz...
### Table 1: Key characteristics of the seven catchments of the Kwakshua Watersheds Observatory.

| ID   | Area (km²) | Slope (%) | Elev. (m) | Lake cover (%) | Wetland cover (%) | MAP (mm) | PAS (%) | MAT (°C) | Runoff (mm) | DOC yield (Mg C km⁻²) |
|------|------------|-----------|-----------|---------------|-------------------|----------|--------|---------|------------|------------------------|
| 703d | 12.79      | 40.3      | 1012      | 1.9           | 24.3              | 3939     | 9.8    | 7.17    | 3628       | 37.0                   |
| 693  | 9.28       | 30.2      | 680       | 4.4           | 42.8              | 3775     | 6.5    | 7.77    | 3422       | 29.7                   |
| 708  | 7.79       | 28.5      | 385       | 7.5           | 46.3              | 3228     | 3.9    | 8.45    | 2158       | 24.1                   |
| 844d | 5.71       | 32.5      | 495       | 0.3           | 35.2              | 3793     | 5.2    | 8.03    | 2471       | 43.6                   |
| 819  | 4.81       | 30.1      | 465       | 0.3           | 50.2              | 3811     | 5.5    | 7.85    | 1689       | 35.7                   |
| 1015 | 3.33       | 34.2      | 432       | 9.1           | 23.8              | 3450     | 4.4    | 8.31    | 1791       | 24.7                   |
| 626d | 3.17       | 21.7      | 160       | 4.7           | 48.0              | 2988     | 3.6    | 8.52    | 2174       | 37.7                   |

Note: Catchment size, topography, landcover, climate, runoff and dissolved organic carbon (DOC) yield vary across the catchments.
Abbreviations: MAP, mean annual precipitation; MAT, mean annual temperature; PAS, precipitation as snow.

- From Gonzalez Arriola, Frazer, and Giesbrecht (2015). Mean catchment slope and maximum catchment elevation (elev.) were measured from the LiDAR derived digital elevation model.
- From Oliver et al. (2017a). “Wetland” refers to all sites that are as wet as- or wetter than- Bog Woodland (Banner et al., 1993) in the mapping by Green (2014). Runoff and DOC yield calculated for Water Year 2015 (1 October 2014 – 30 September 2015).
- Catchment scale mean climate normals (1981–2010) were calculated from ClimateBC spatial data (Wang et al., 2012).
- Watersheds in operation as of 2020.

**Figure 2** Map of the Kwakshua Watersheds Observatory, showing study watershed boundaries, sensor network nodes and links, sampling sites and the surface drainage network draped over a LiDAR derived bare-earth hillshade. The Calvert Island Field Station is located at the west end of Kwakshua Channel, as shown in the inset map. All seven watersheds were operated from 2013–2019. Four watersheds were selected for ongoing operation as of 2020: 703, 844, 1015 and 626.
## Table 2
A summary of key data packages and ongoing data streams from the Kwakshua Watersheds Observatory, organized by theme.

| Data package | Description | Dates | Citation and DOI |
|--------------|-------------|-------|------------------|
| **Geospatial data layers** | | | |
| 1. Watershed boundaries and properties | LiDAR derived watershed boundaries and terrain metrics | 2012/2014 | Gonzalez Arriola, Frazer, & Giesbrecht, 2015 (10.21966/1.15311) |
| 2. Stream networks | LiDAR derived stream networks | 2012/2014 | Gonzalez Arriola, Frazer, Giesbrecht, Floyd, & Holmes, 2015 (10.21966/0r2c-5a62) |
| 3. Ecosystem classification | 18 classes of forest and wetland cover derived from LiDAR and RapidEye | 2012/2014 | Thompson et al., 2016b (10.21966/1.135248) |
| 4. Lake bathymetry | High resolution bathymetry and volume estimates for the 6 largest lakes | 2016 | Gonzalez Arriola et al., 2016 (10.21966/fcwf-p919) |
| 5. Digital Elevation Model (DEM) | 3 m LiDAR derived DEM | 2012/2014 | Gonzalez Arriola & Frazer, 2015 (10.21966/rzwv-4a72) |
| 6. Forest structure | 72 LiDAR derived forest structure metrics for 20 m pixels | 2012/2014 | Frazer, 2015a (10.21966/mq9t-bw79) |
| 7. Canopy Height Model (CHM) | 2 m LiDAR derived CHM | 2012/2014 | Frazer, 2015b (10.21966/581b-5q35) |
| **Weather and stream discharge** | | | |
| 8. Precipitation | Sensor measurements from 18 sites (5 min) | 2013–2019<sup>a</sup> | Haughton, Floyd, et al., 2020a (10.21966/xnh1-tp28) |
| 9. Air temperature and relative humidity | Sensor measurements from 18 sites (5 min) | 2013–2019<sup>a</sup> | Haughton, Floyd, et al., 2020b (10.21966/z0pt-xm42) |
| 10. Freshwater discharge | Stream stage and discharge measurements from seven streams (5 min) | 2013–2019<sup>a</sup> | Korver et al., 2020 (10.21966/fh63-w427) |
| **Aquatic ecosystems and biogeochemistry** | | | |
| 11. Dissolved Organic Carbon (DOC) flux data | DOC loads (daily) and DOM quality (approx. monthly) from seven streams | 2013–2016 | Oliver et al., 2017b (10.21966/1.321324) |
| 12. Freshwater biogeochemistry | Suite of biogeochemical measurements sampled approx. monthly from seven streams | 2013–2019<sup>a</sup> | Tank et al., 2020 (10.21966/7qnv-6y88) |
| 13. Event-based stream sampling | Select biogeochemical measurements across storm hydrographs | 2015–2018 | Korver et al., 2019 (10.21966/mn5a-7534) |
| 14. Stream temperature | Sensor measurements from seven streams (5 min) | 2013–2018<sup>a</sup> | Haughton, Giesbrecht, et al., 2020 (10.21966/7nb6-zk37) |
| 15. Limnology of major lakes | Suite of biogeochemical measurements at varying frequencies | 2016–2019 | Desmarais et al., 2020 (10.21966/rqtr-2n80) |
| 16. Organic carbon across land-ocean interface | Suite of biogeochemical measurements sampled approx. monthly from seven streams | 2014–2016 | Oliver et al., 2020 (10.21966/66x5-a210) |
| 17. Nutrient stoichiometry across land-ocean interface | Suite of biogeochemical measurements sampled approx. monthly from seven streams | 2014–2018 | St. Pierre, Hunt, Tank, Giesbrecht, Floyd, et al., 2020 (10.21966/n0h9-cq15) |
| **Landscape ecology and hillslope hydrology** | | | |
| 18. Ecosystem plot network across a landscape gradient | Forest plots established across a gradient of soil drainage and forest productivity | 2012–2015 | Giesbrecht et al., 2015 (10.21966/1.56481) |
| 19. Ground water sampling | Select biogeochemical measurements sampled approx. monthly for up to 11 sites | 2016–2019 | Giesbrecht et al., 2020 (10.21966/mnwn-gw16) |
| 20. Soil microbial processes | Environmental observations across seasons, soil depths and two landscape positions | 2015–2016 | Levy-Booth et al., 2018b (10.21966/1.715630) |

<sup>a</sup>Date column denotes data types with ongoing observations.

Note: Hyperlinks in the references provide direct access to published data packages.
UHF links between sensors nodes, 2.4 and 5 GHz at high-elevation communication nodes) and fibre-optic links to feed data to a satellite internet connection (Figure 2). The complex terrain required innovative solutions for communication and power, including the design of compact, self-powered portable radio repeaters and a combination of solar and micro-hydro power to maintain battery banks.

4.3 Weather and stream discharge

Spatially distributed weather stations (Figure 2) measure air temperature, relative humidity, rain and snow depth – at mid and high-elevation stations and windspeed and direction at all sites with exposure (Table 2; see Haughton, Floyd, et al., 2020a, 2020b; datasets 8 and 9). Solar radiation and total precipitation are also measured at a reference station on Tsunami Hill near the CIFS and a high elevation weather station at 738 m.

Stream height (stage) is measured at 5-min intervals at each gauging station and periodic discharge measurements are taken along the range of potential stages to develop stage-discharge rating curves. Stream discharge is measured manually at low flows using the velocity-area method (ISO, 2007). Moderate to high flows are measured using salt dilution (Moore, 2005) via a custom-designed automated salt dilution system that allows for 20–50 streamflow measurements between visits (Oliver et al., 2017a). The automated system utilizes up to 1000 L of salt in solution (1000 g NaCl to 5000 mL of water) stored at each location that can deliver a specific volume (5 L–60 L) to a pre-set target river stage, where a minimum of two downstream electrical conductivity sensors measure the resulting salt wave. Discharge measurements from the automated salt dilution had less than 5% error for the majority of points used in rating curves, except for extreme flows, where between 10% and 15% error was acceptable depending on the watershed. Data generated from the salt dilution measurements are delivered in near real-time via the telemetry network to a database where discharge is calculated. The telemetry network also allows for on-demand salt dilution discharge measurements outside of the pre-set targeted stages. Between 2014 and 2020, over 500 streamflow measurements were made, including near peak flows in many watersheds, reducing uncertainty in high flow estimates. Less than 2.5 days or 0.12% of the discharge data from the 5 year dataset were extrapolated beyond the highest measured discharge in the rating curves. Despite this, complex stream channel geometry and highly turbulent flows led to a collective discharge uncertainty between –24% and +43% (Korver et al., 2020; dataset 10) based on 95% confidence intervals calculated using methods in Coxon et al. (2015). Four of the seven watersheds have had at least one shift in the rating curve following high flows; however, rating curves were quickly rebuilt using the automated salt dilution systems.

4.4 Aquatic ecosystems and biogeochemistry

To quantify biogeochemical exports to the ocean and to trace water sources and flowpaths, water samples were collected from all seven stream outlets (Figure 2, Table 2). On an ongoing basis, freshwater samples are collected approximately monthly for measurement of dissolved organic carbon (DOC) concentration and stable isotopes ($\delta^{13}$C), particulate organic carbon and nitrogen (POC and PON) concentration and isotopes ($\delta^{15}$N), dissolved organic matter (DOM) composition (via metrics of absorbance and fluorescence; e.g., Weishaar et al., 2003; Helms et al., 2008; Murphy et al., 2013), total and dissolved (organic and inorganic) nutrients, metals and major ions and water stable isotopes ($\delta^{18}$O, $\delta^{2}H$) (Oliver et al., 2017b; dataset 11; Tank et al., 2020; dataset 12; St. Pierre, Oliver, Tank, Hunt, Giesbrecht, et al., 2020; dataset 16; St. Pierre, Hunt, Tank, Giesbrecht, Floyd, et al., 2020; dataset 17). Conductivity, temperature and pH are measured at each stream outlet in situ. To estimate combined sampling and analytical precision, we collected triplicate samples from randomly selected sites. We found generally good precision for constituents such as DOC (1.2% coefficient of variation [CV]; mean = 12.08 mg L$^{-1}$; n = 40 replicates) and lower precision for low concentration constituents such as total phosphorus (CV = 29.5%; mean = 12.86 µg L$^{-1}$; n = 67; see Tank et al., 2020; dataset 12). All replicate measurements are retained in the dataset for user assessment and error calculation. In addition to these monthly data, we characterized storm events using two kinds of automated and stage-specific water sampling devices; one site had an ISCO pump sampler and several sites had single-stage samplers (Edwards & Glysson, 1999) installed at vertical increments above the stream at low flow (Korver et al., 2019; datasets 13). Sensors were used to capture higher frequency in-stream observations of turbidity (5 min), fluorescent dissolved organic matter (fDOM) (5 min) and CO$_2$ (60 min) from 2014–15 through 2019. Stream temperature is measured at 5-min intervals, on an ongoing basis (Haughton, Giesbrecht, et al., 2020; dataset 14). Limnological properties of key lakes were characterized from 2016 to 2019, including lake bathymetry, water temperature and electrical conductivity profiles, water transparency (Secchi depth) and water chemistry (e.g., DOC, DOM composition, nutrients, metals and water stable isotopes) at surface, bottom, inlet and outlet sites (Desmarais et al., 2020; dataset 15).

To understand land-ocean coupling in the KWO region, water properties were measured approximately monthly at nearshore estuarine stations (Figure 2, Table 2). This includes conductivity-temperature-depth profiles from 2014 onwards. From about 2014 through to 2016–17, we also measured DOC concentration and $\delta^{13}$C-DOC, DOM absorbance, POC and PON concentration and stable isotopes, inorganic nutrients and chlorophyll-a (as a proxy for phytoplankton biomass) (see Oliver et al., 2020; dataset 16; St. Pierre, Hunt, Tank, Giesbrecht, Floyd, et al., 2020; dataset 17). For a subset of 22 time points between 2013 and 2016, we also estimated prokaryotic abundance and examined microbial community composition in both estuarine and freshwater samples. At the easternmost oceanographic station (Figure 2), a complimentary mooring has more recently (2018) been established to collect high-frequency measurements of surface seawater and marine boundary layer CO$_2$, salinity and temperature (Evans et al., 2020).
4.5 | Landscape ecology and hillslope hydrology

To better understand how variable landscape mosaics influence hillslope and watershed function, in 2012–2015 we established and described a network of 20 × 20 m forest plots distributed across a gradient of soil drainage and forest productivity (Giesbrecht et al., 2015; dataset 18). A subset of sites contains shallow wells used to monitor water table dynamics (2013 to present) and subsurface biogeochemistry (2016–2019; Giesbrecht et al., 2020; dataset 19). Two contrasting sites (an open peat bog and a bog forest) located on Tsunami Hill, a short walk from the field station (Figure 2), were additionally instrumented at multiple depths with soil water sampling devices, soil temperature sensors and redox probes, as well as gas flux collars at the surface (Levy-Booth et al., 2018b; dataset 20) (Table 2).

5 | EMERGING RESULTS AND FUTURE DIRECTIONS

The rainforest climate and the geology of this area interact with topography to produce spatial mosaics of vegetation (Thompson et al., 2016a) and soils (Heger et al., 2018; Oliver et al., 2017a) and to create a cascade of dynamic connections from Pacific weather to soil hydrology (Levy-Booth et al., 2018a), streamflow and stream temperature (Giesbrecht et al., 2017), carbon exports (Oliver et al., 2017a) and the nearshore ocean ecosystem (St. Pierre, Oliver, Tank, Hunt, Giesbrecht, et al., 2020).

Rainstorms dominate the hydrology of these watersheds. All seven watersheds respond rapidly to rain inputs, owing to shallow and permeable soils and fall–winter storms contribute a high proportion of annual flow while each summer sees a notably drier period (Giesbrecht et al., 2016). Storm hydrographs lag behind rain events in the catchments with substantial lakes (Oliver et al., 2017a). The main lakes are small (0.051 km²–0.298 km²), shallow (3.3 m–12.1 m mean depth) (Gonzalez Arriola et al., 2016) and thermally stratified from about April through November (Desmarais et al., 2020).

The KWO site stands out globally for high yields of water and DOC, yet we observe substantial variation among closely located catchments (Table 1), with topography, lakes and soils modifying DOC yields and DOM composition (Oliver et al., 2017a). The Kwakshua watersheds also stand out globally for high yields of dissolved organic nitrogen and dissolved iron, which enhance the concentrations of these organic matter associated nutrients in nearshore marine waters (St. Pierre, Hunt, Tank, Giesbrecht, Korver, et al., 2020). By contrast, yields of dissolved inorganic nutrients (nitrogen, phosphorous and silica) are low in global context and dilute nearshore waters, reflecting a lack of significant anthropogenic or geologic sources (St. Pierre, Hunt, Tank, Giesbrecht, Korver, et al., 2020).

In the near term, ongoing observations will be used to further elucidate land-sea linkages and landscape controls on hydrological and ecological processes, in the context of regional gradients (Figure 1; Bidlack et al., 2021) and collaboration networks (Bidlack et al., 2017; Sullivan et al., 2017). Over the longer term, the KWO aims to support a broad range of local-level and network-level studies that capitalize on the unique opportunities of this observatory to study the changing coastal margin ecosystem.

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DATA AVAILABILITY STATEMENT

Data products from the KWO are listed (Table 2), with hyperlinks in the references for direct access. This includes fixed and quality-controlled data packages which are published to an open access data repository hosted by the Hakai Institute. In the future, new KWO datasets can be
discovered by searching the overarching data repository for the Hakai Institute at https://data.hakai.org. To make the most of the KWO data, we encourage direct communication and collaboration with researchers responsible for particular data streams, which can be facilitated by emailing data@hakai.org.

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