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MODELLING SEDIMENT MOVEMENT FOR A MULTI-OPTION LARGE-SCALE HYDROELECTRIC DAM REMOVAL PROJECT

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Abstract: The Mactaquac Generating Station (MGS), a 672 MW run-of-the-river hydroelectric facility on the main stem of the Saint John River, New Brunswick, Canada was built in 1968 by New Brunswick Power. Since 2013, the Canadian Rivers Institute has been undertaking the Mactaquac Aquatic Ecosystem Study (MAES), a planned, whole-river multidisciplinary ecosystem study and manipulation of the MGS, in support of a decision-making process regarding the future of the aging facility. Future options under consideration range from in-situ refurbishment to full removal and river restoration. Prediction of the potential transport and fate (or long-term retention) of post-inundation sediment is a crucial aspect for decision-makers. Extensive bathymetric surveys, sediment surveys, core sampling, and laboratory studies were conducted to estimate the volume of sediment upstream, sediment bed composition, thickness, particle size diameter, erosion rate and threshold shear stress. These results were integrated into the hydrodynamic model Delft3d that was calibrated and validated using water level and flow data. The model results predicted the downstream fate of the sediments under various hydrodynamic regimes, including the case of complete removal of the hydraulic structure. Given drawdown scenarios were simulated, and sediment movement was quantified. The sediment transport studies have helped to identify areas of interest for future research focus, and have furthered the field and laboratory techniques undertaken by the team. The results of the MAES project will help to advance the science of dam renewal decision-making processes using a holistic, multidisciplinary approach.

1 INTRODUCTION

The Mactaquac Generating Station (MGS), a 672 MW run-of-the-river hydroelectric facility on the main stem of the Saint John River, New Brunswick, Canada was built in 1968 by New Brunswick Power (the "power company"). The Canadian Rivers Institute is undertaking the Mactaquac Aquatic Ecosystem Study (MAES), a planned, whole-river multidisciplinary ecosystem study and manipulation of the MGS, in support of a decision-making process (the "Mactaquac Project") regarding the future of the aging facility. Future options under consideration range from in-situ refurbishment to full removal and river restoration. The Mactaquac Project is the largest dam removal ever taken under consideration and the MAES is the largest coordinated study of its type ever undertaken in support of a potential dam removal project.

The MAES is a multi-year assessment of the structure and function of a large river ecosystem and the predictive analyses of the proposed manipulations, i.e., what are the environmental challenges and opportunities for either replacing or removing the dam? The highly-integrated research establishes baseline environmental conditions, appropriate metrics for biomonitoring, and predicts the water, sediment, thermal regimes, and future habitats for a dam removal scenario. In the dam refurbishment scenario, the research examines the consequences for species at risk and fish passage, and models future management options for environmental flows.

The MAES is an investment by the power company in the research and development required to sustain its hydropower business model in a changing world of new green economies. The premature ageing of the MGS and the pressing consideration of future options for the dam and the river's ecosystem goods and services is a precedent setting case for Canada. The MAES was intended to create a template of approaches and methods that facilitate the incorporation of aquatic ecosystem science into informed decision making and management for this and many future hydropower projects and additionally, the science of river restoration. As a consequence, the MAES will also set new standards for the future of Environmental Impact Assessments in Canada. This paper focuses on one of the keystone objectives of the MAES: understanding the current and future sediment environment under the dam removal scenario.

1.1 Study Area

With a catchment area of 55,000 km^2 and overall length of 618 km, the Saint John River (Figure 1) is one of the largest river systems on the eastern seaboard of North America. At the MGS, the river discharge averages ~1000 m^3/s with river widths and depths averaging 750m and 2m, respectively (Kidd et al. 2011). Average annual air temperature is 5^oC and there is an average of 1,100mm of precipitation annually. The river supports the greatest diversity of aquatic plants and animals in eastern Canada, including 15 species at risk (McAlpine and Smith 2010). Human development began in the watershed in the 1600s (logging, fisheries, and later heavy industries), but the watershed remains 80% forested with a human population of ~500,000. There are >200 dams across the river network with 11 hydroelectric generation stations (first built in 1890) and of these, the MGS (Figure 2) located approximately 20km upriver from the City of Fredericton, New Brunswick, is the largest with a nameplate hydroelectric generating capacity of 672MW (6 Kaplan-type 112 MW units). The earthen and concrete structures of the dam span ~1,100m and it is 55m high. The MGS headpond covers an area of 84km^2 and extends 100km upstream to just above the Town of Woodstock, New Brunswick.

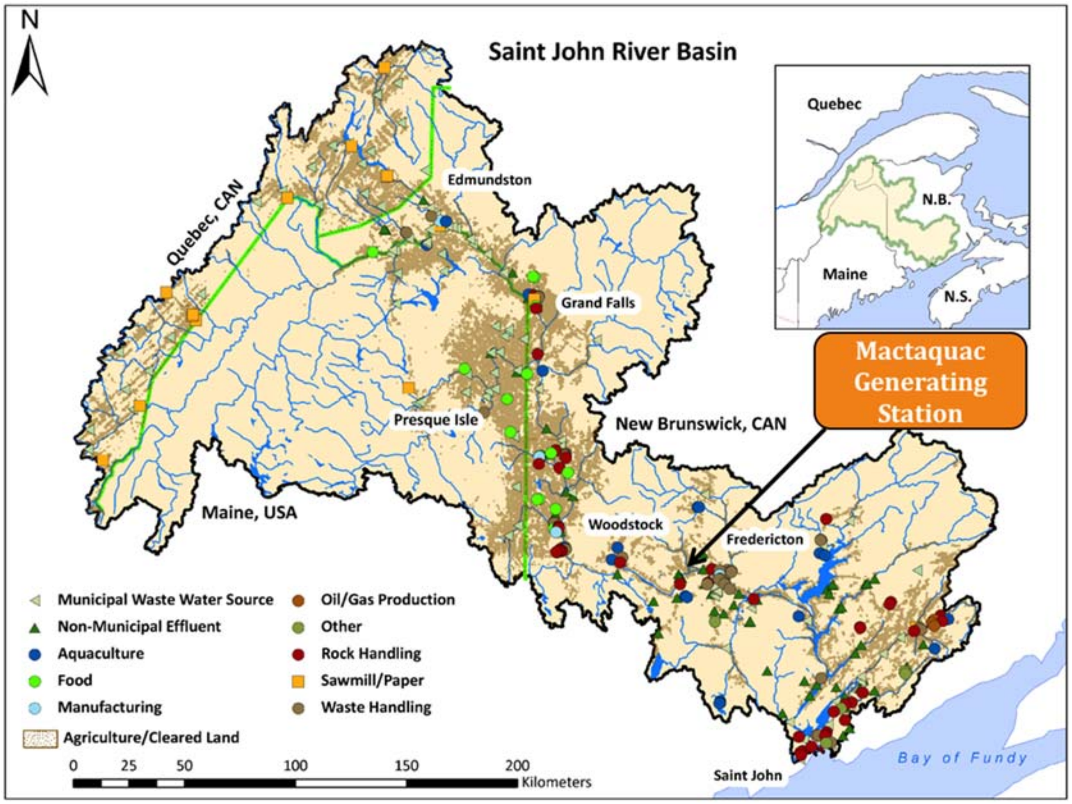

Figure 1: Saint John River Watershed and MAES Study Area

Figure 2: The Mactaquac Generating Station, Fredericton, NB

1.2 Objective

There are two levels of analysis for a drawdown programme associated with a large dam removal: the actual drawdown and the physical and biological conditions that will remain post-drawdown. During the drawdown phase, the key environmental challenges to be modeled are 1) sediment re-suspension in the headpond and in the water being discharged downstream, and 2) subsequently understanding the potential environmental impacts associated with this activated sediment. To do this required first answering a series of questions, including: what is the current state of the river morphology and sediment environment (i.e., prior to the headpond drawdown); how will the sediment relocate during and after drawdown; and how does the post-drawdown equilibrium-state river morphology and sediment environment differ from the current conditions?

The broad objective of this sediment component of the MAES can be defined as: collecting field and historical data to establish the baseline sediment and other necessary conditions in the environment to develop a computer-based mathematical model to simulate various drawdown scenarios that could be used to estimate the changes to the sediment environment caused by potential Mactaquac Project options. There are similar questions and objectives relating to flow dynamics, water quality, and other abiotic and biotic factors that were also incorporated into and/or addressed via the model outputs that are not included within the scope of this paper. These questions included, but were not limited to: what is the resulting morphology of the restored river within the headpond area; what are the effects of sediment relocation on downstream infrastructure and aquifer recharge zones; and how are fish habitat and fish passage conditions changed under the various options? It should also be noted that this paper does not contain the specific results of the model or any subsequent studies as these are not publically available at this time. The primary purpose of this paper is to present the methods applied (and created) to develop the sediment transport model to the point at which these questions could be answered.

2 METHODS

Working on such a large, actively regulated river system that includes substantial seasonal flow differences, a tidal range that exceeds 7m in the estuary, a limited fieldwork sampling window because of the Canadian winter, and with varied water depths from very shallow island habitat to a deep and lake-like headpond has presented challenges in data collection. It is fair to say that our ‘lessons learned’ list is ponderous in length. Developing a 2D/3D hydrodynamic and sediment transport model of this magnitude is an exercise in collecting, organizing and manipulating many types of big data. Relatively recent technologies (e.g., Acoustic Doppler Current Profiler (ADCP), Light Detection and Ranging (LiDAR)) allow for the collection of big data in short increments of time while modern computers allow for computational models with greater refinement then previously possible. Deciding on the metrics and the appropriate means of data acquisition required consideration of environmental properties, availability of tools, cost of data acquisition and/or processing, and working within the Mactaquac Project schedule. To this end, the MAES team – comprised of nine professors of varying engineering and biological disciplines, multiple Post-Docs and Research Assistants, and many graduate-level students – combined their expertise, along with that of other experts consulted around the world to arrive at a set of metrics necessary to meet the objective.

2.1 Morphology

2.1.1 Geomorphological Conditions

The first step in establishing the current state of the river morphology and sediment environment was to review existing information and assess the headpond geomorphology and estimate sediment distribution processes (O’Sullivan et al., 2016). The geomorphological assessment concluded that sediment deposited within the headpond may not be significant in relation to other large dam removals (e.g. Elwha, Glines Canyon, and processes based experiments such as the Cougar Reservoir drawdown). This was based on the observation that the relief surrounding the Model Study Area (Figure 3) is gently sloping with gradients ranging from 1-10^{o} (with anomalous occurrence of slopes ≥10^{o} also present) with the proximal surficial geology comprising of shallow morainal deposits constituting various till deposits and sands and gravels. Thus, the Model Study Area lies in a low energy environment and the sediment yield supplied to the headpond is likely to have been relatively low even when erosion from weathering and anthropogenic forcing are considered (soil erosion is a function of relief, surficial geology/soil erodibility, rainfall intensity, and land use). It is predicted that a high energy event, e.g., heavy rainfall, snow melt runoff, etc., would be required to entrain coarser grained sediments in addition to relief alone. It was further hypothesized that the presence of the Beechwood Dam (located approximately 140km upstream of MGS) and its associated headpond acts to trap most of the bedload sediment travelling downstream from the majority of the Saint John River basin above MGS.

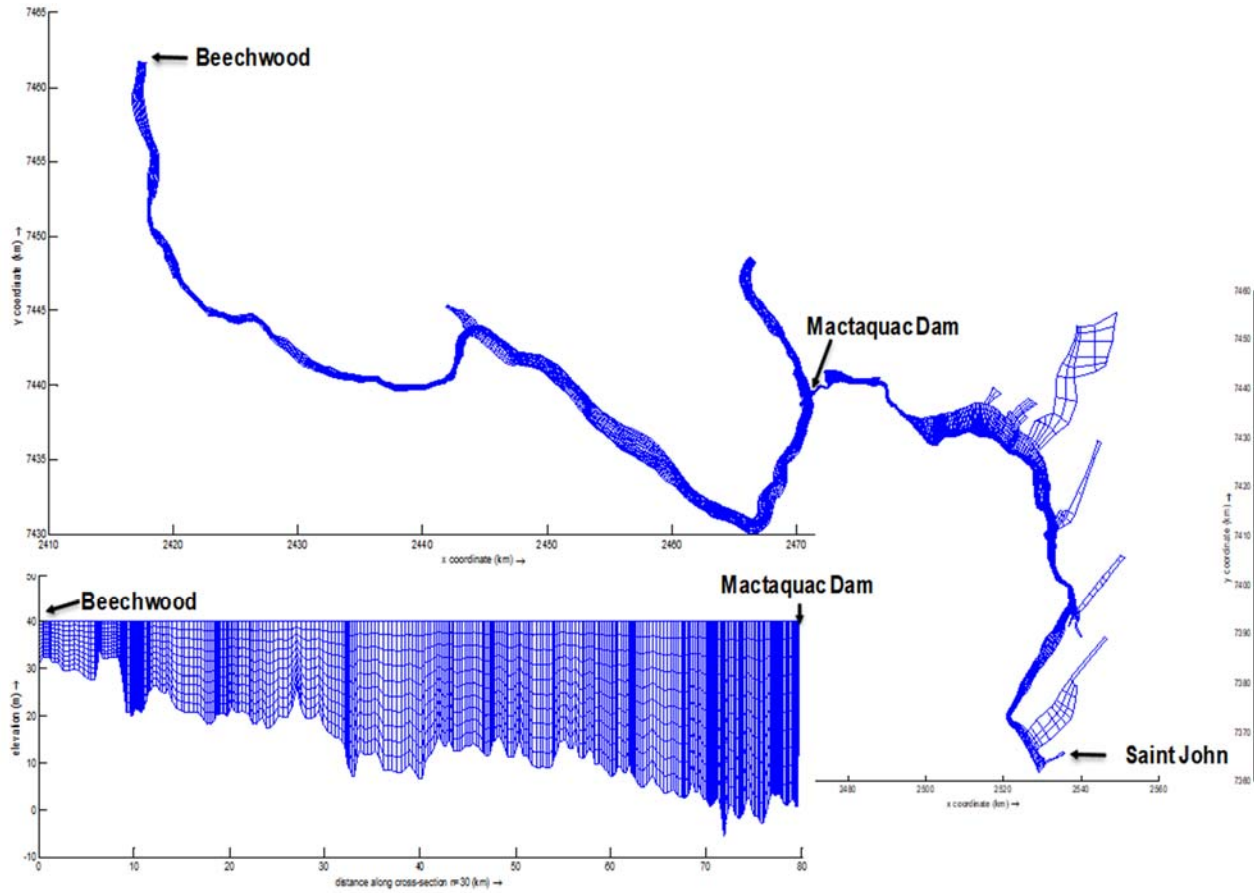

Figure 3: Model Study Area with Model Curvilinear Grid

2.1.2 Bathymetry

Previously-derived bathymetry, recorded in the first few years after the MGS was commissioned, was available for the headpond and for the river downstream of the City of Fredericton. However, these data were nearly 45 years old at the start of the study and were based on soundings taken at 100m intervals. It was determined that a new and reliable bathymetry for all areas incorporated into the model was required. Reliable updated bathymetric data for the headpond allows for water/sediment volumes to be calculated for use in hydrodynamic, sediment transport, and water quality models.

To obtain maximum coverage of the Mactaquac Headpond, the bathymetric survey (Bremner et al., 2016) used a multibeam system in water depths greater than approximately 5 m following prescribed methods to meet or exceed the CHS Order 1a standard (based on International Hydrographic Service standards). The power company provided a vessel (the 'Sea Truck'; Figure 4) for use as the platform for all multibeam work. In shallower depths (<5m), such as occur in near-shore areas of the headpond and throughout the fluvial portions of the Model Study Area, single-beam bathymetry was collected using Lowrance HDS-series sonar units deployed from small flat-bottom boats (Wallace and Gautrea, 2016). This relatively inexpensive set of tools allowed for a small fleet operated by students to collect large quantities of reliable bathymetric data in difficult-to-access locations over a single season. Logged single-beam sonar data were converted to a GIS-compatible format using CIBioBase software (www.cibiobase.com).

Figure 4: The Sea Truck Survey Vessel

The bottom elevation of some areas, particularly marginal island habitats and riparian flood zones that emerge in low-water conditions, were not accessible using sonar-based methods. For these areas, the surficial elevations were obtained from LiDAR images and corrected using standard GPS-based survey methods then merged with the sonar-based bathymetry into a single layer.

2.2 Hydrodynamic Conditions

Water level data were obtained from existing gauges maintained by Environment Canada and the power company within the Saint John River. The power company was also able to provide discharge data from the MGS (since 1969) and the upstream Beechwood Generation Station (since 1957) for the duration of their operation.

Flow data in the island reach between MGS and the City of Fredericton were obtained via an Acoustic Doppler Current Profiler (ADCP) mounted to a remote controlled boat. The ADCP used was a nine-beam system and the raw data were processed using the Velocity Mapping Toolbox software from the US Geological Survey to extract the streamwise, transverse, and vertical velocities, and velocity magnitude by taking account the secondary flow vector. Transect measurements were taken at 14 stations including within the main channel and at major channel bifurcations. Discharge at MGS was regulated during three ADCP events to represent late spring fish migration, summer low, and fall storm flow conditions. ADCP data were also collected in the headpond at three transect locations during summer low flow.

2.3 Sediment Quantity

2.3.1 Post-inundation Sediment Layer Thickness

In order to understand the distribution of sediment that has accumulated in the headpond since the emplacement of the MGS in 1968, a four-tiered approach was applied which included: acoustic sub-bottom profiling, coring, bathymetry comparison, and suspended sediment mass calculations.

Acoustic sub-bottom profiling surveys were undertaken over a two-year period (Grace and Butler, 2016). Initial attempts using a 28 / 3.5 kHz chirp sonar survey proved ineffective for imaging the relatively thin layer of sediment that has accumulated in the headpond. Subsequent attempts using a higher resolution Seistec system was successful for the lower one-third portion of the headpond where the sediment layer is relatively thin (average thickness of approximately 26cm) and comprised entirely of sediment deposited from suspension. In the middle one-third of the headpond, gas was present in the sediments at the sediment/water interface which interfered with the acoustic penetration such that reliable sediment thickness estimates were not obtained. A small-scale ground penetrating radar survey was undertaken to test this method for estimating thickness in gas-charged sediments and the results were encouraging. The gas is likely the result of organic waste from a nearby pulp mill buried within a post-inundation deposited sandy bedload. The portion of the headpond upstream of the Village of Nackawic remains relatively fluvial and the sub-bottom profiles do not reveal any soft sediment in excess of the minimum resolvable 12 cm. This conclusion is also supported by the multibeam bathymetry in which boulders and rocks are clearly visible, indicating the bottom composition is much larger grain size, and the thin silty sediments accumulated downstream in the headpond have only sparsely accumulated in this reach of river.

A coring program was undertaken to truth and support the sub-bottom profiling program. A weighted and powered vibracore was deployed from an A-frame crane fitted to the Sea Truck. The vibracore was determined to be ineffective at extracting clean cores from the relatively thin sediment layer in the lower one-third of the headpond and in the fluvial reach above Nackawic. It is believed that the vibration was not needed to penetrate in these areas and that it inadvertently caused disturbance to the loosely compacted semi-cohesive sediments. Deploying the vibracore with the vibrator not engaged, thus using it as a gravity corer, produced much more useable cores. Additional cores were obtained through the winter ice using a hand-deployed weighted corer. Results from the coring program appear to coincide well with the mapped thicknesses based on the sub-bottom profiles.

Deriving the sediment thickness layer by comparing the historical bathymetry (1969) with the current reservoir bathymetry may be possible. This has been done for individual cross sections; the method for doing this is as whole GIS layers is currently being worked out. Back calculating the sediment deposition in the headpond may also be possible using recently collected total suspended solids (TSS) data fitted to a flow curve and matching this to historical flow conditions from 1969-present. The TSS data have been collected (Section 2.3.2) but the process for doing the calculations is still in progress.

2.3.2 Total Suspended Solids (TSS)

To establish baseline conditions, a combined approach of historical data review and field data collection was applied (Yamazaki et al., 2017). MAES requested water quality data for stations along the Saint John River (SJR) and its tributaries from the New Brunswick Department of Environment and Local Government (NBDELG) to identify typical values and understand how suspended sediment moves through the River in time and space. Two historical data sets were provided: SJR Stations 1994-1998 and SJR and Tributary Stations 2003-2014. To understand typical turbidity and suspended sediment values at stations located on or near the Saint John River, the data were organized to demonstrate spring freshet averages, spring freshet peaks, fall storm peaks as well as summer, fall, and spring averages. Additional recent TSS data were collected by MAES under various flow and precipitation conditions throughout the Model Study Area.

2.4 Sediment Quality

For the purpose of this paper, ‘sediment quality’ is limited to the information required to model its transport, specifically grain size and shear stress. Other metrics like sediment chemistry were also collected but are not discussed herein. Material for determining grain size was taken from within the cores which were sliced in 1cm intervals. Grain size distributions for the samples were determined (Yamazaki et al., 2016) using a laser diffraction particle size analyzer.

Laboratory experiments were conducted in an erosion flume to determine the resuspension and transport properties of the sediment, including the shear stress needed to initiate movement. Using an adjustable vertical gate at the downstream end of the flume, and a variable speed pump, a constant water level can be achieved for an increasing pump setting. A core can be inserted into the floor of the flume so that only the top is exposed to the moving water. Once the top layer has eroded away, the core is pushed upwards to expose a new layer to the flow. As the volume flow rate was increased, velocity profiles were recorded for each setting. The velocity follows a logarithmic curve near the sediment/water interface, and by plotting the velocity as a function of the log(depth) in the water column, a relationship was derived to calculate the shear stress present. The variation of critical shear stress and erosion rate with depth were observed and recorded for the length of each core.

2.5 Hydrodynamic and Sediment Transport Model

The selection of the model platform was accomplished in a similar manner to that described for the model metrics presented above. Delft3D was selected for its demonstrated successes in similar (though smaller) undertakings, for its modular flexibility to address the stated and other objectives, and because it is open source. As described by the developer (Delft3D-FLOW, 2013), the FLOW module is a multi-dimensional (2D or 3D) hydrodynamic and sediment transport simulation programme which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid. In 3D simulations, the vertical grid is defined following the Z-layer approach. The MOR module computes sediment transport (both suspended and bedload) and morphological changes for an arbitrary number of cohesive and non-cohesive fractions. For the suspended load this module connects to the advection-diffusion solver of the FLOW module and density effects may be taken into account. An essential feature of the MOR module is the dynamic feedback between modules, which allows for simulations on any time scale from days (e.g., drawdown stages) to centuries (e.g., long-term effects of sediment entrainment).

Early consultations with the software developer resulted in dividing the Model Study Area into two reaches: A) from the Beechwood Generating Station to the MGS; and B) from the MGS to just above the Port of Saint John where the river enters the Bay of Fundy. This dual-model approach allows for the discharge data from Beechwood, located at the furthest upstream extent of the Model Study Area, to be used as the input to the upstream portion of the model while the MGS discharge serves as the input to the downstream portion. One of the primary benefits of having and using discharge data from these facilities is that the contribution from upstream tributaries at both points is inherently included. Another benefit is that the data sources are longstanding (from dam commissioning to the present) and reasonably accurate. The approach also breaks the Model Study Area up into two approximately 100km river reaches which results in reduced computation time with improved accuracy.

Prior to working in the Delft3D platform, a 1D, steady-state model of the Saint John River between the Town of Woodstock and the City of Saint John was developed (NATECH, 2015) to calculate average current speeds at eleven locations (four sections in the headpond, and seven downstream of the MGS). The purpose of the 1D model was to establish predictions and a working understanding of general flow conditions in the Model Study Area to guide and check the development of the 2D model. The Delft3D model was first established in 2D (depth averaged) using rectangular grid elements. Sensitivity tests were carried out with two physical parameters (i.e., roughness and eddy viscosity) and calibration was accomplished using water level data from a year with a large spring freshet (2008). The hydrodynamic model output was then compared to that of a more normal spring freshet (2014) for verification. Predicted depth-averaged water surface elevations and velocities, as well as associated sediment dynamics, were then simulated under various hydroclimatic and seasonal flow conditions, in addition to given drawdown scenarios. TSS and historic/present bathymetric data were used to assess the sediment transport predictions. A second calibration was later undertaken using the ADCP-generated flow data to improve the model accuracy in the island-rich reach between MGS and the City of Fredericton. The final step was to advance the model to 3D.

3 DISCUSSION

It is important to note that from start to finish, the development of a fully functioning and reasonably accurate 3D hydrodynamic and sediment transport model for the approximately 200km-long Model Study Area took nearly four years to accomplish. Throughout this time, at various steps, the model in its various forms was useful for answering questions posed by the power company and their engineering consultants in support of the Mactaquac Project decision making process. Similarly, early model outputs were used by the MAES graduate students in support of their research. By the time that the model reached its full functionality (March 2018), the decision to refurbish rather than remove the MGS had been made. Thus, the sediment transport component of the model, though useful during the decision making process, may not be the most useful aspect of the model going forward. That said, sediment transport simulations will continue to be used to predict the long-term effects of fine sediment retention in the headpond on downstream sediment-dependent wetlands and of bedload sediment retention on the morphology of downstream islands and bars.

What were once considered as secondary objectives are now considered as primary and the flexibility and robustness of the model is proving worthy of the transition. For example, the hydrodynamic component of the model is already in use to understand flows in near proximity to MGS to meet the power company's objective of improving existing fish passage facilities. Simulations will be run to complement the fish passage studies, giving estimates of velocity distributions and water levels to support the engineering of new fish pass structures and approaches. Similarly, the 2D model is also being used to support ecosystem studies linking biotic and abiotic components in an ecohydraulics context in critical inter-island habitats via the development of a fuzzy-logic based habitat simulation software.

Finally, with the completion of this model, the power company is already getting returns on its investment in the research and development required to sustain its hydropower business model in a changing world of new green economies by using ecosystem-based science to support its decision making process, and through its investment in the local training of students to ensure that the professionals of tomorrow are ready to enact the decisions of today. For the MAES, the model development process has succeeded at creating a template of approaches and methods for this and many future hydropower projects and additionally, the science of river restoration, that are applicable around the world.

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