Rapid Hydropower Assessment Model
Recent Upgrades and Applications

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ABSTRACT

The ability to identify renewable energy resources is of paramount importance in reducing fossil fuel dependency and addressing climate change. The Rapid Hydropower Assessment Model (RHAM) uses a Geographic Information System (GIS) to identify hydroelectric power opportunities. Using a Digital Elevation Model (DEM) and regional hydrologic data, RHAM calculates the amount of hydroelectric power available on all streams in a study area, screening out sites within parks and environmentally sensitive areas, and estimates project costs. RHAM can also assess the suitability of hydroelectric development in a given area, taking into account economic, environmental and social factors, and can assess storage hydro and clustered developments.

RHAM was first used in 2007 to assess run-of-river hydroelectric potential for the Province of British Columbia, Canada, an area of approximately 95 million hectares. Over 8,000 potential hydroelectric opportunities were identified. The Consulting Engineers of British Columbia recognized RHAM with an Award of Merit in 2008. RHAM has been applied in other parts of the world and the methodology recently revised to improve site optimization. This upgrade was applied to British Columbia in 2010, resulting in an updated inventory of the province's run-of-river hydroelectric potential.

INTRODUCTION

In 2007, BC Hydro and the BC Transmission Corporation (BCTC, now part of BC Hydro) retained Kerr Wood Leidal Associates Ltd. (KWL) to conduct an inventory of potential run-of-river hydroelectric sites in British Columbia, Canada. KWL completed the hydroelectric resource assessment in four months using the Rapid Hydropower Assessment Model (RHAM), a Geographic Information System (GIS) program developed by KWL; without RHAM, the assessment would have taken over a year.

Since 2007, RHAM has been applied in other parts of the world, from Mexico to Southeast Asia, for public and private clients including forestry and mining companies as well as First Nation communities.

In August 2010, BC Hydro engaged KWL to update the 2007 provincial study with a revised methodology, updated costing, and improved site optimization process. Over 7,200 potential run-of-river hydroelectric sites with a potential installed capacity of over 17,400 MW and annual energy of nearly 63,000 GWh per year were identified. Figure 1 shows the location of these sites with their associated size.

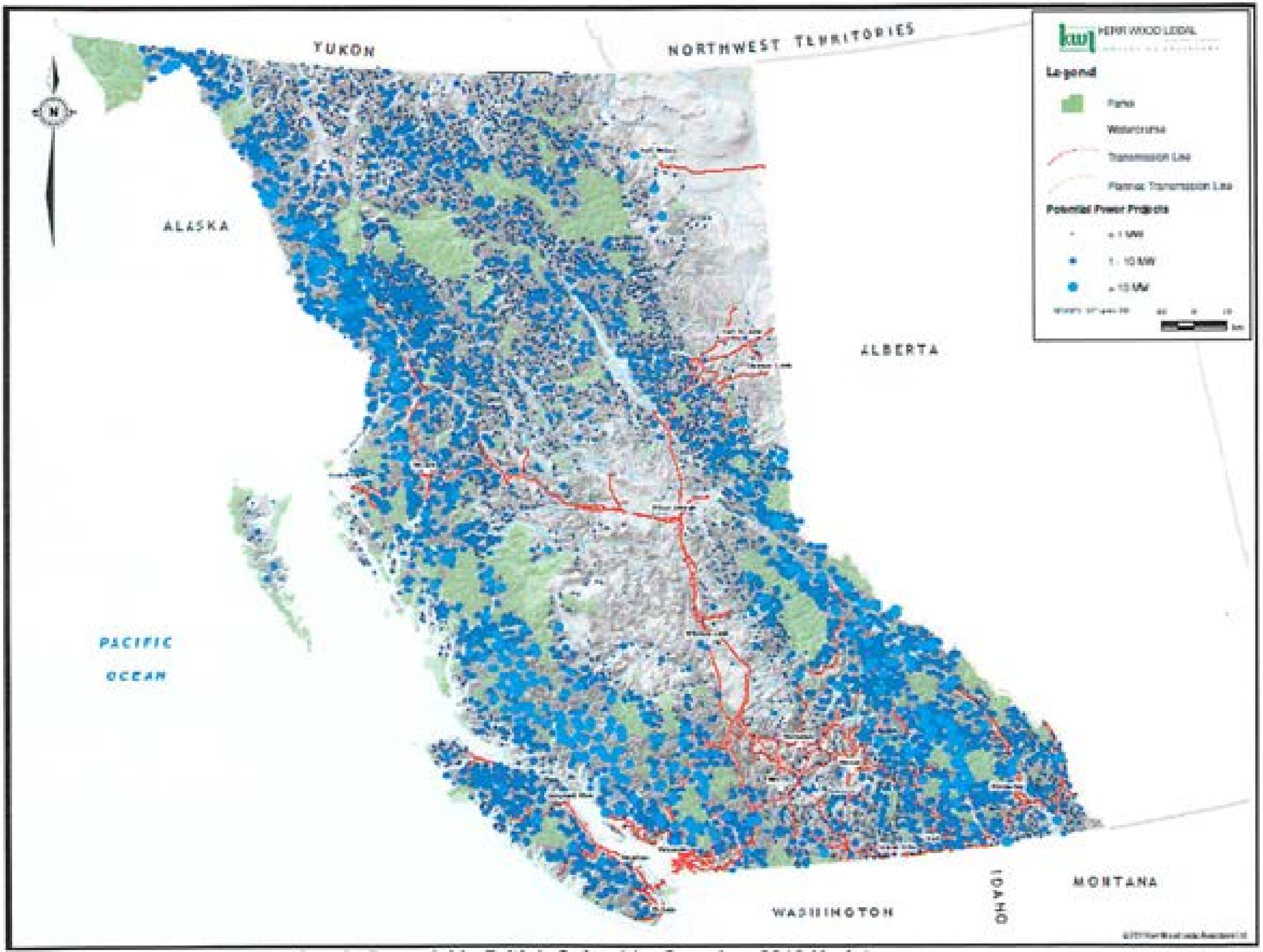

Figure 1: Run-of-River Hydroelectric Potential in British Columbia, Canada – 2010 Update

KWL estimated the cost for each project, which included access roads and power lines to connect to the BC Hydro and FortisBC power systems. Using capital cost and annual energy estimates, the unit energy cost was estimated for each project. The projects were then ranked to produce the supply curve of run-of-river hydroelectric potential for British Columbia presented as Figure 2.

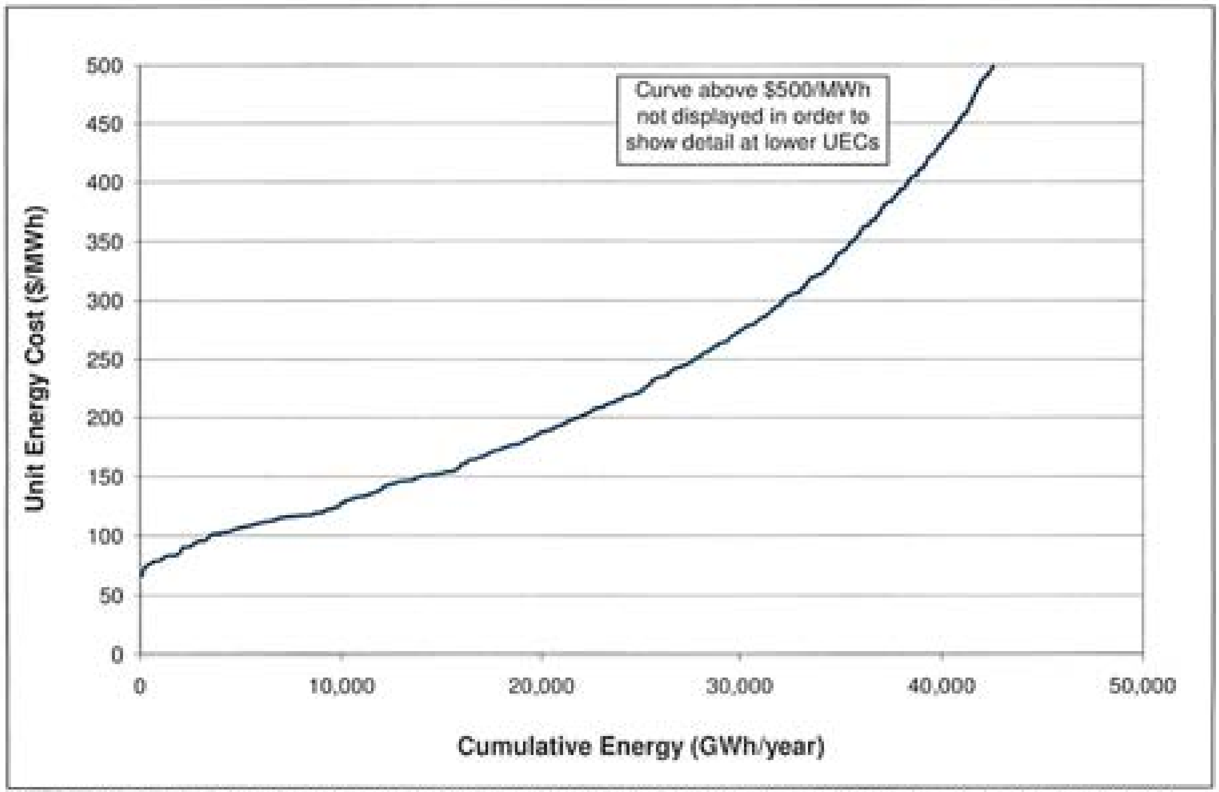

Figure 2: Run-of-River Hydroelectric Supply Curve for British Columbia, Canada – 2010 Update (2011 Canadian Dollars)

RHAM's GIS application provides several key capabilities for hydroelectric applications. Nearly all aspects of a hydroelectric project can be referenced to a geographic location, and the attributes of that project or location described using a database. RHAM links data to a geographic location and enables engineers to develop computational models that significantly increase the speed at which large volumes of data are processed into useful information.

Using RHAM, KWL analyzed every stream in 100 m sections, identifying potentially good locations for projects. This information was then used to estimate the size and cost of hydroelectric projects. Using RHAM's GIS capabilities, this information was compared with ecological mapping and land use information to determine site suitability.

For linear infrastructure such as roads, penstocks and power lines, RHAM can locate optimal alignments and estimate costs by analyzing slope, geology and land cover datasets

METHODOLOGY

Run-of-river hydroelectric facilities use the unregulated water flow and elevation drop (i.e. head) of streams to generate power. This type of hydroelectric project can be constructed with a small diversion dam (i.e. intake) to direct water from the stream channel into a penstock (i.e. pipeline) that conveys flow to a powerhouse. A turbine and generator in the powerhouse convert the potential energy into electricity, and the water is returned to the stream.

Several steps are involved in assessing hydroelectric projects. These include estimating flow, head and power; screening to identify feasible project locations; and estimating capital, operating and unit energy costs. The GIS-based tool developed by KWL is capable of determining these parameters on a widespread basis, while maintaining a relatively high level of detail.

The model was developed using ArcGIS 9.2 (and later ArcGIS 10) software with the Spatial Analyst extension, which is available from ESRI. This software is widely recognized as the industry standard for engineering GIS applications

FLOW

In RHAM, the mean annual discharge (MAD) at any given site is estimated using GIS tools, which are applied to a Digital Elevation Model (DEM) to calculate drainage area for any given stream location. The resulting area accumulation is then combined with a runoff surface to estimate MAD. The model results are then validated by comparing them to hydrological statistics. In the 2010 RHAM application to British Columbia, the model results were validated by comparing them to hydrological statistics from Water Survey of Canada (WSC) stream flow gauges.

The distribution of water flow, and hence power generation, was estimated from historical daily WSC records. The available WSC records were subdivided into the 29 hydrologic zones for British Columbia identified by Obedkoff[1]. Annual energy production for a normal year (annual energy), annual energy production for a low-flow year (firm energy), and the power that can be relied upon during high demand periods (dependable capacity) were estimated for potential project sites.

To develop an estimate of energy production, a regional hydrology analysis was carried out. This involved statistical analysis of WSC hydrologic data and use of GIS capabilities to distribute the resulting statistics to the potential project locations. Minimum flow releases to the diverted portion of the stream were assumed to be the lesser of actual flow or 15% of mean annual flow. Historical daily data to 2005 for all the WSC gauges in British Columbia were used, and the data was divided into zones of similar hydrologic characteristics as defined by Obedkoff to estimate regional stream flow characteristics.

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[1] British Columbia Streamflow Inventory, 1998, Coulson, C. H., Obedkoff, W., British Columbia Ministry of Environment, Lands and Parks, Resources Inventory Branch, Water Inventory Section, Victoria BC.

HEAD

Head is estimated by using the spatial statistics functions in ArcGIS. These functions perform a search around a given point and return the minimum elevation. The search was conducted in 500 m increments, from 500 m to 5,000 m. An algorithm was developed to prevent the search from identifying a minimum elevation in a neighboring watershed. Head was estimated by subtracting the minimum elevation identified from the elevation of the DEM cell at the intake. The search distance formed the basis for estimating the penstock length. ArcGIS was used to multiply the head and flow and to store information for each location, including head, flow and in-stream power. This resulted in approximately 10 million data points for British Columbia.

IN-STREAM POWER

In-stream power potential is the product of head (H), flow (Q) and fluid weight, as described by the following equation:

$$P_{\text{in-stream}} = \gamma_w Q H_s$$

where,

$P_{\text{in-stream}}$ = in-stream power (kW)
γ_w = 9.81 kN/m^3 (constant)
Q = mean annual flow (m^3/s)
H_s = static head from intake to powerhouse (m)

SCREENING

Given the large size of the initial power model output, the next step was to identify sites that are technically feasible for development. Table 1 describes the physical characteristics used as screening criteria..

Table 1: Screening of Projects Based on Flow, Head and Power

Parameter	Valid Range
Slope	> 4%
Mean Annual Discharge	0.1 – 200 m^3/s
Head	30 – 1,000 m
In-Stream Power	> 100 kW

In general, the minimum flow, head and power conditions represent economic limits to generating grid-connected power in British Columbia. The maximum flow condition establishes a limit for medium-sized hydroelectric facilities. The maximum head condition represents a maximum practicable pressure rating for penstocks and generating units.

Further screening was done to eliminate potential sites on glaciers, within parks, within stream reaches with salmon, and where hydroelectric projects have already been or are being developed.

POWER PROJECT IDENTIFICATION

After screening out locations in undevelopable areas, a large quantity of potentially developable sites remained. An optimization routine was developed to create a manageable inventory of projects that could be developed independently, and without encroachment upon each other. The 2010 update included the application of new optimization methodology developed by KWL that closely compares with hydroelectric projects that are being proposed and developed in British Columbia.

The site optimization and selection methodology of the 2007 study for British Columbia found the greatest power per unit length of penstock. This effectively finds the steepest drop for a given reach of stream. As an example, if there are two steep drops nearby, the larger of the two will generally be selected. In 2007 the mean annual discharge (MAD) was used as the design flow.

The 2007 methodology was a reasonable indicator for identifying potential sites, but developers often design a larger project to optimize the cost effectiveness of the project and extract as much capacity and energy as they can from a location since many capital costs are less sensitive to the size of the project and are a large portion of the total cost. This generally results in a project that extends beyond the steepest drop in a reach of the stream and a design flow that is greater than the MAD. The new optimization and site selection methodology used for the 2010 run-of-river update was designed to align more closely with what a developer might construct.

Both the 2007 and 2010 methodologies consider the steepest section of the stream, however the 2010 methodology generally selects larger projects with the steepest section encompassed by the larger potential project The 2010 optimization results in both a change to the project layout size (length of diverted stream and head) and a higher design flow. It selects the largest project on a given stream which is optimized to find the greatest change in gross power over the change in penstock length. This effectively finds the steepest drop of a stream reach and also includes nearby steep channel sections and nearby steep drops within the total length of the penstock. In addition to this, a larger design flow of 150% of MAD was used.

Conflicts between potential projects were resolved by creating buffers around projects using the optimized penstock distance. The smaller of the conflicting projects was removed from the project inventory. After completing the optimization process, a total of 7,282 potential sites were identified. This is a reduction of approximately 1,000 projects from 2007, some due to the new optimization method, some due to new parks and conservancies, and some due to better exclusion screening.

NET POWER & CAPITAL COSTS

To estimate penstock costs and power generation, the diameter, slope, length and wall thickness of the penstock for each project is determined. After sizing the penstock, the net power is calculated according to the following equation:

$P_{net} = \gamma_w Q(H_s - H_f)\eta$, where:

P_{net} = plant design capacity (kW)
γ_w = 9.81 kN/m^3 (constant)
Q = design flow = 1.5 mean annual flow (m^3/s)
H_s = static head from intake to powerhouse (m)
H_f = friction losses in penstock (m)
η = power plant efficiency, assume 0.85

Capital costs were developed for all projects. KWL staff have been involved in the development of hydro projects in British Columbia ranging from 1 to 50 MW in capacity. This experience was used to develop quantities and costs for individual project components (intake, powerhouse, penstock, generating equipment). This was accomplished by comparing component costs for projects that were either constructed or in an advanced stage of development where contractor and supplier quotes were available. This data was used to develop cost curves using regression. These comparisons showed that specific site conditions affect the cost of project components significantly.

The cost curves were also relevant for projects over 50 MW as the costs were developed on a component basis. There is greater uncertainty, however; with low head projects over 50 MW due to large water diversions that push the bounds of the cost curves. Of the projects identified in the study less than 0.2% have capacity over 50 MW.

Conventional means were used to estimate unit costs for construction of the power line, access roads, penstock, camps, and for equipment and crews. RHAM' was used to identify the least expensive route for access roads and power lines from a proposed hydroelectric project to an existing public or resource road and power line.

The main factors in estimating power line voltage are capacity and length. Power lines were sized based on serving each project independently, with the capacity of the power line set equal to or greater (based on voltage) than the capacity of the project. RHAM then identifies the least-cost route based on slope and land cover.

To account for site variations due to regional factors and remoteness (proximity to towns or city centers), costs for construction camps were developed and transportation of people and equipment were added to estimates. Four site categories were used to indicate remoteness of location (distance from a major town or city centre). It was assumed that all remote projects would include a camp.

The construction period required for a potential project varied depending on size. One year was used for project capacities of less than 1 MW, two years for 1 through 10 MW, and three years for greater than 10 MW.

Estimating project-specific costs, such as those for engineering or environmental management, require detailed site information. For inventory-level costing, typical allowances are expressed as a percentage of total capital cost.

Application to acquire tenure is required in British Columbia in the case of public land (land held by the Province of British Columbia). In cases where land is privately held, negotiations are necessary to potentially purchase or acquire permission to use the land.

OPERATING COSTS

Operations and maintenance costs were estimated to be 2% of total capital costs for power plants and access roads and 1.1% of total capital costs for power lines. Water rental fees were estimated in accordance with the British Columbia Ministry of Environment "Annual Water Licence Rental Rates Associated with Power Production" document revised on December 11, 2009. A land allowance cost in the form of an annual cost that was included in consideration of the cost to purchase, lease or obtain permission through negotiations to use the land for the construction and operation of hydropower projects. Finally, property taxes were estimated to be 3% of the assessed property value, which was assumed to be 80% of the capital cost of the civil infrastructure.

UNIT ENERGY COST

Unit energy costs were calculated by amortizing the total capital cost for each project at a 6% real discount rate over 40 years, adding the annual costs and dividing by the annual energy estimate for the site. A discount rate of 8% was also considered (results not shown in this paper). A rate higher than 8% would better reflect independent power producers' cost of capital.

JOB CREATION AND LAND AREA IMPACTED

A quantitative assessment included an estimate of the number of operations and construction jobs that could be created, and the amount of land area that would be affected. Construction jobs were estimated based on the capital cost, while operations jobs were based on the size of the project.

Impacted area calculations included the estimated rights-of-way for penstocks, access roads and power lines.

RESULTS

Results for the 2010 RHAM application to British Columbia are presented and discussed in the Introduction Section. There is large potential for future development of run-of-river hydroelectric projects in British Columbia. Future work for developers to proceed with potential project applications, licensing, electricity purchase agreements, and construction requires more comprehensive site investigation, First Nation discussions, environmental and social assessments, hydrologic data collection and analysis, and concept development.

OTHER RHAM APPLICATIONS

In 2010, KWL used RHAM to identify, evaluate and provide an assessment for pre-investment decisions for hydropower projects in the Piaxtla River basin of Mexico. This study was prepared for Mexico's Ministry of Energy with the financial support of the World Bank, Energy Sector Management Assistance Program. The Piaxtla River basin covers 6,954 km^2 in the Mexican States of Durango and Sinaloa. The study considered conventional hydropower projects with head greater than 2.5 m and in the range of small hydro, from 1 MW to 30 MW and mini hydro, from 100 kW to 1,000 kW. The hydropower potential was evaluated for every 30 m section of the streams in the Piaxtla River Basin. The results of the assessment are shown on Figure 3.

RHAM is currently being used to assess the run-of-river hydropower potential in a Southeast Asian country as part of a national alternative energy sources study. At the time of writing, the topography and hydrology analyses have been completed. Results from preliminary results will be screened and further analyzed to identify the most favorable project locations.

RHAM has also been used in studies for First Nation communities and private clients from the forestry and mining sectors in British Columbia and Yukon, who are interested in assessing and optimizing their resources or in investigating hydropower opportunities to supply power to their industrial activities.

STORAGE

KWL recently added the analysis of storage hydropower to RHAM. This module estimates in-stream storage. A GIS algorithm creates a 'virtual reservoir' by generating a line representing a dam crest at an evaluation point along a river and 'flooding' the DEM surface. This process essentially converts the DEM into a bathymetric surface, which is used to estimate storage volume of the reservoir. Dam volume is estimated based on the dam crest line, which is used to extract a cross-section profile from the DEM. The profile is converted to a volume that can be specified as either concrete or earth-fill and used for costing.

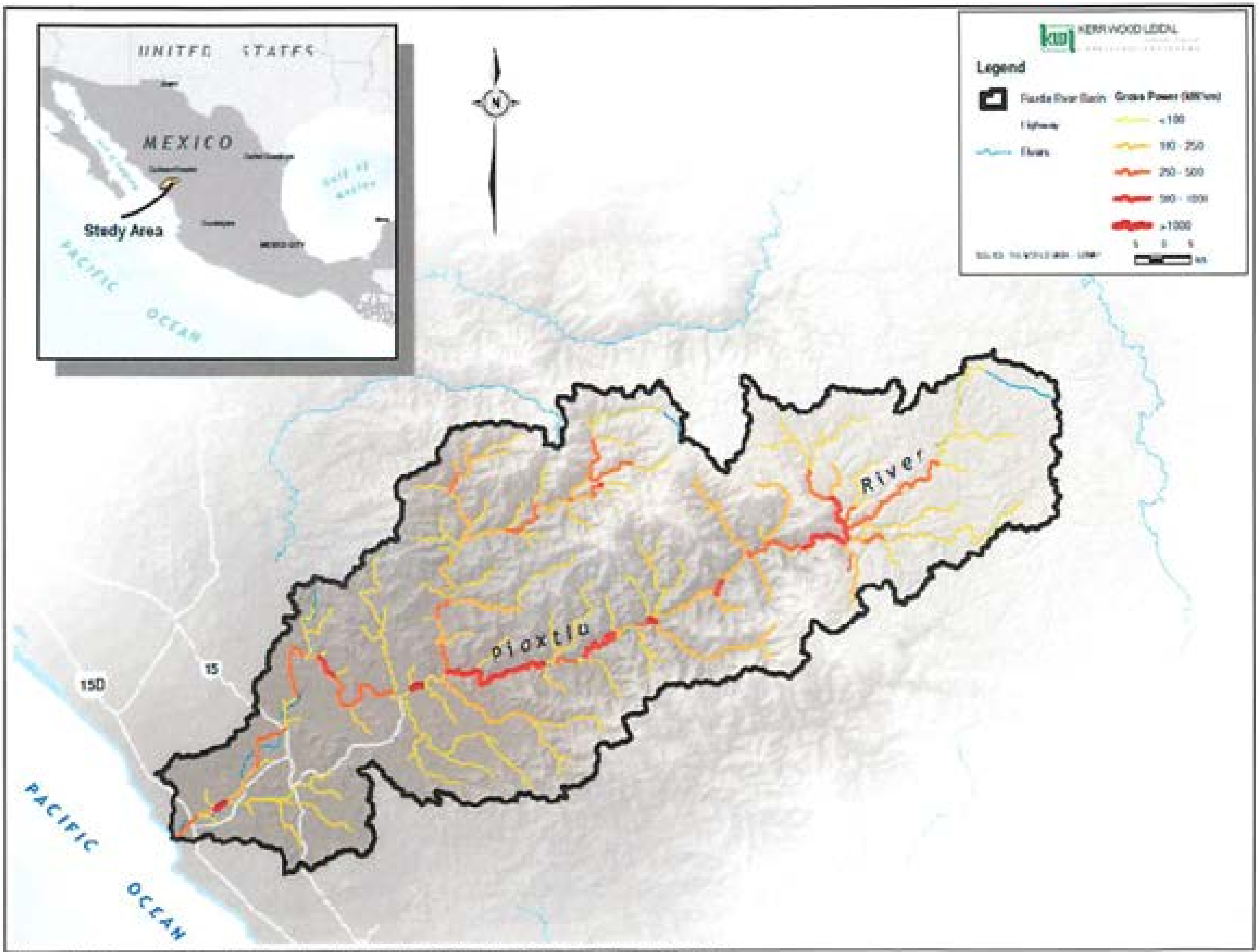

Figure 3: Run-of-River Hydroelectric Potential in the Piaxtla Basin, Mexico

The storage output from the model can be optimized using several parameters including the inundated area, stored volume, design flows and dam volume. This is useful for identifying locations that minimize land impacts and cost while achieving storage volume targets. The first storage hydro assessment with RHAM was conducted in early 2010 for BCTC on the Columbia Valley.

CONCLUSIONS

RHAM has assisted energy planners and power developers locate potential run-of-river hydropower projects sites in British Columbia and other parts of the world. The model can be applied to any region where GIS information is available or can be cost effectively developed. The quick, methodical evaluation of the hydroelectric power will help in the effort to reduce carbon fuel dependence and help ensure a sustainable energy future for the world.

The 2010 methodology upgrades result in an estimated project size (capacity & energy) that is expected to provide a closer representation of what a developer would construct. In general it results in more capacity and energy and often with lower unit electricity costs (UEC).

The authors would like to thank BC Hydro, the Mexican Federal Ministry of Energy, the World Bank, and private clients for the opportunity to develop, upgrade and apply RHAM to assess run-of-river hydropower potential. Their leadership, vision and cooperation throughout were essential to the success of this tool.

The authors would also like thank the other KWL staff that assisted in developing RHAM and completing this project. It would not have happened without their creativity, initiative and work ethic.

AUTHORS

Ron Monk leads Kerr Wood Leidal's Energy, Industrial and Mining Sector. Ron's expertise includes feasibility, design and construction of small hydroelectric projects. Projects include Kitasoo Hydro (1.7 MW), Tyson Creek Hydro (9.3 MW) and the assessment of run-of-river hydroelectric potential for BC Hydro and BCTC. Prior to returning to KWL in 2007, Ron worked at BC Hydro for 14 years where his key accomplishments included leading the 2004 Integrated Electricity Plan, co-initiating the hydrogen program and co-developing BC Hydro's sustainability vision.

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Stefan Joyce is a hydrotechnical engineer with over 10 years' experience in modeling, analysis, design, project management, construction and contract administration. His expertise includes creek and river hazard assessment and protection, hydrologic studies, hydroelectric feasibility and design, dam safety and decommissioning, storm water management, and the application of GIS tools for hydroelectric and water resources projects.

Mike Homenuke specializes in GIS-based infrastructure analysis and planning. He has developed several computer models, capital plans and feasibility studies for various clients. Mike is involved in the development of GIS applications for engineering services, including asset management, hydroelectric resource assessment and infrastructure planning.

Colleen O'Toole is a project engineer in Kerr Wood Leidal's Energy, Industrial and Mining Sector. Her project engineering experience includes GIS-based modeling, hydraulic modeling, detailed design, permitting and approvals with various agencies and specifications.