A HYDROLOGIC AND MORPHOLOGIC ANALYSIS OF THE BLACK LAKE, ALASKA

Submitted to:

Chignik Regional Aquaculture Association
2731 Meridian Street, Suite B
Bellingham, WA 98225

Submitted by:

Prof. A. Papanicolaou, Dr. M. Elhakeem and JT. Sanford

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College of Engineering
The University of Iowa
Iowa City, Iowa 52242-1585

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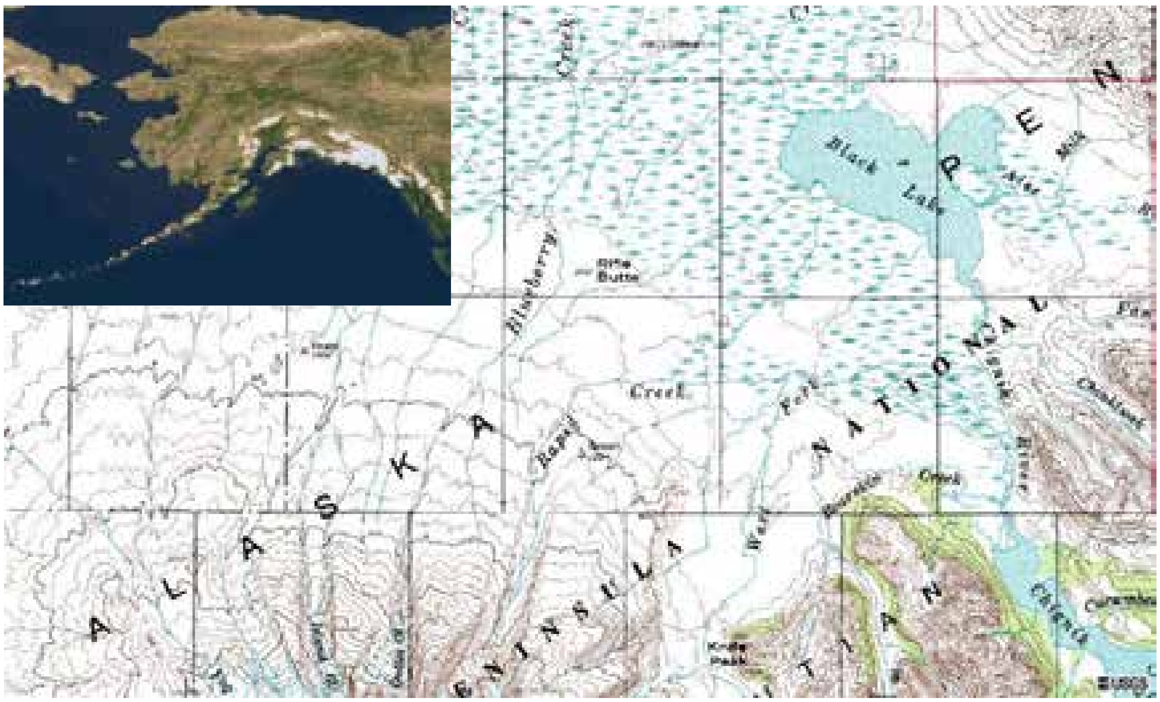

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Brandon Hobbs helped in the earlier phase of modeling. Brandon Billing helped in reviewing the manuscript of the final report. Their efforts are acknowledged here.

Iowa City, February 2006

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ABSTRACT

The Chignik Regional Aquaculture Association (CRAA) is concerned that Black Lake, located on the south side of the Alaska Peninsula, is naturally degrading as a juvenile sockeye salmon nursery habitat. CRAA considers the low-water storage capacity in the Black Lake system to be a major threat to Chignik sockeye salmon production.

A unique methodological design was developed to address the water capacity reduction in the lake. This included the use of hydrodynamic/sediment transport numerical models in order to enhance our understanding of the physical/hydrological changes occurring in the lake. Finally, predictions of the changes that may occur in the lake's water capacity within 22, 57 and 100 years are provided.

There are three possible causes for the low-water storage capacity found in the Black Lake, namely, sedimentation, low water influx and changes at the outlet geometry of the Black lake. This study examined all three causes.

With respect to the sedimentation issue, it was found that the deposition of the incoming sediment, originated from Alec (Sqaw) River, into the lake over the past 50 years has not substantially affected the lake storage capacity. It reduced the lake storage capacity by only about 1.0 % for the period of 1950-2005.

With respect to the lake water influx, results suggest that the lake receives sufficient water influx to be able to fill to its 1950s storage capacity.

It was concluded that the reduction in the lake water storage is mainly attributed to changes in the lake outlet geometry. The lake outlet base-level has been dropped by at least 1.0 m compared to the 1950s base-level. This drop can be attributed to the high differential found in sediment transport rates between the lake exit or the entrance of the Black River and the confluence of the West Fork with the Black River. Prior studies have recorded that the sediment influx from the West Fork has been significantly high and has affected the longitudinal gradient of the Black River downstream of the confluence point due to the occurrence of significant sediment deposition. Because the sediment rates entering the Black River are low comparatively to the rates from the West

Fork, the river tends to degrade its bed upstream from the confluence in order to reach to the same level of longitudinal slope with the downstream section. In a nut-cell, the drop at the lake's outlet describes the response of the Black River to significant sediment influx from the West Fork.

To increase the water storage capacity in the Black Lake system, the researchers' recommendation is the raising of the lake outlet base-level by 1.0 m and the placement of a temporal sill (e.g. inflatable sill, or a broad crested weir) at the outlet of the lake. The temporal sill would allow an increase in the storage of the lake. This increase is quantitatively described for the first time in this report. The sill should be installed during low flow conditions and removed during high flows. The placement of the sill will help the lake to temporarily regain its storage capacity. To get a complete answer to the Black Lake problem, the authors suggest carrying out an experimental study by building a physical model for the lake and its inlets and outlet to evaluate the performance of the outlet structure under various flow conditions. The physical model study also will explore ways to control excess sedimentation from the West Fork.

Our long-term predictions pinpoint that a complete destruction to the ecosystem of the lake can happen within a century if the problem is not immediately addressed. The lake may lose 79 % of its 1950s storage capacity within a 100 year period.

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1. INTRODUCTION

Over the past 55 years, the Black Lake, located in the Alaska Peninsula, Alaska (Figure1) has experienced an unrecovered reduction in its water capacity, about 23 % reduction of its volume since 1950; high fluctuations on its water volume as low as 44 % and up to 77% of its original volume in 1950 and weak water circulation. The variations in the lake's flow and geomorphologic characteristics can be attributed to the following reasons: 1) hydro-meteorological changes such as freezing or thawing of the surface-water in the lake due to significant temperature variations; 2) hydrologic changes in the lake system such as reduction or increase in the flow entering to or leaving from the lake; 3) geomorphologic changes due to variations in the amount of the incoming and exiting sediments, which in turn have affected the lake size and its inlet and outlet geometry. These variations have also affected the habitat of the aquatic biota system in the lake. Based on information provided by the Chignik local community of Native Americans and the Chignik Regional Aquaculture Association, a significant reduction has been recorded in the sockeye salmon and the overall salmon population in the region. For example, by comparing the observations made in 1990 with the 1950s, it has been shown that sockeye salmon are no longer consistently over wintering in Black Lake (Ruggerone 2003). This reduction in winter use is attributed to an oxygen deficiency caused by lesser lake volume.

The questions that this research has aimed to address here are, "what type of action would be required for the Black Lake system to regain its original state of water availability and ecosystem?" and "what are the forecasted changes based on established methods that are expected in the drainage basin of the Black Lake within a 100-year time window if no action is taken?" To answer such complex questions, a multifaceted approach was required that involved a general understanding of the hydrologic and geomorphologic processes in the lake, analysis of historic and current data and employment of established numerical models to examine different scenarios for increasing the useful volume of the lake.

This undertaking had many challenges. Modeling the wind, water and sediment influxes into the Blake Lake was challenging as the lake is a complex system experiencing the effects of non-linear interactions between the Black River at the lake outlet and the Alec River (Scow River) entering the lake via a fork-shaped exit as shown in Figure2. Another complexity added to this undertaking was lack of continuous flow and sediment data records. Black Lake is located in a remote place and access to the site can only be provided via a small air plane. Performing field work at the site remains a challenge and other means must be mastered to circumvent these limitations. However, the data provided by prior research has been proven a valuable resource.

2. OBJECTIVES

The main objective of this study is to simulate a wide range of flow conditions and test different hypothetical scenarios via established hydrodynamic and sediment numerical models. For this purpose, existing historic and current hydrologic and sediment data found in the Black Lake system were employed towards the calibration and application of the models. The models, once calibrated, can be used to simulate flow and geomorphologic changes in the Black Lake system for current conditions as well as to predict changes that may occur in the system over a period of 100 years. The team used historic and current information to interpret the causes of the above-mentioned variations and has developed a unique methodological design to address water capacity reduction in the lake that is applicable to other systems experiencing similar hydro-meteorological and morphological changes. Finally, the researchers provide a practical solution to the problem by suggesting either the raising of the outlet-base level of the Black Lake or the construction of a flow control structure at the lake's outlet. The role of the West Fork in affecting the geometry of the Black Lake outlet is discussed.

3. SITE DESCRIPTION

The Black Lake is located on the Alaska Peninsula (Figure1). The Lake drains into the Pacific Ocean through a series of lagoons and rivers. The Alec River feeds the northern end of the Black Lake and has pool-riffle morphology with a meandering gravel-bed channel (Figure3). At the exit of the Alec River into the Black Lake, a delta exists, which is comprised of multiple channels and vegetated islands (Figure2). The surface area of Black Lake is approximately 21 km^2, with an average shallow water depth of about 1.9 m. An important feature of the lake is the formation and development of a sand-spit (Figure4) which extends from the north and southwest boundaries of the lake near the Alec River delta. According to Ruggerone (2003), the length of the sand-spit has increased 30% over the past 20 years and extends across nearly 80% of the lake. Formation of the sand spit reduces the circulation inside the lake.

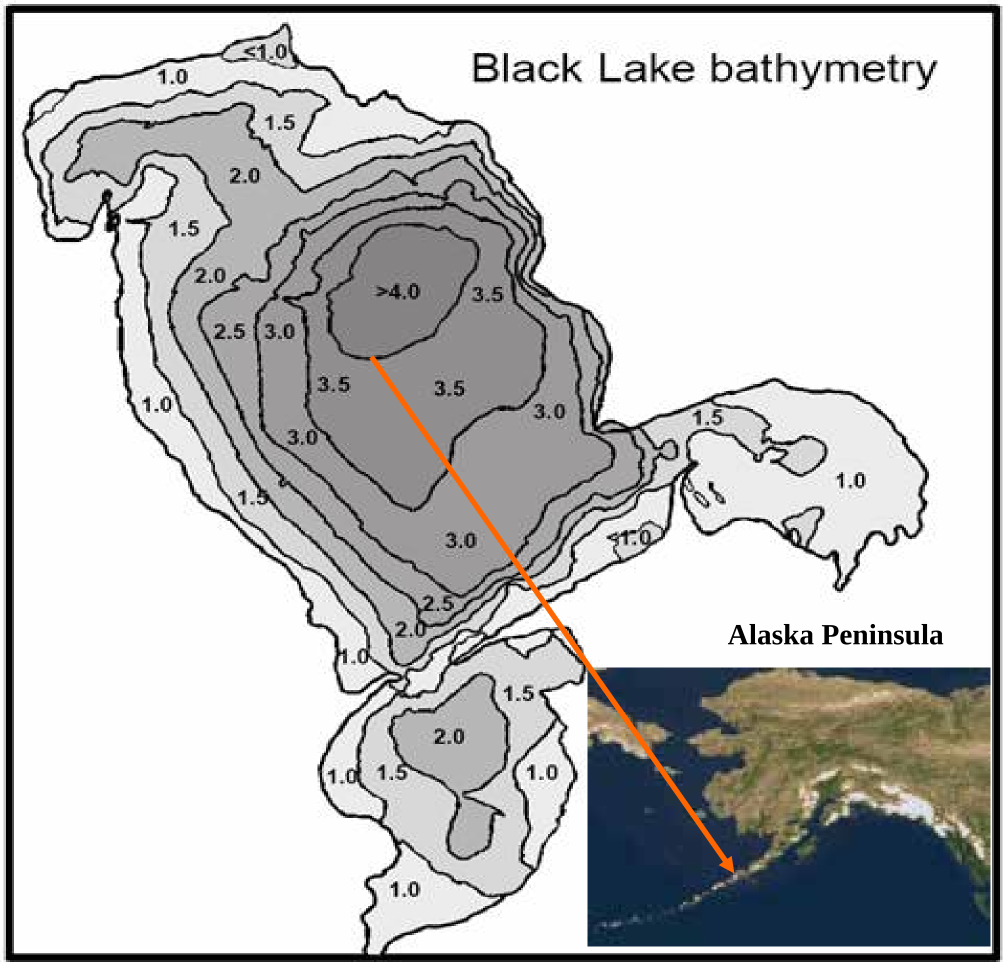


Figure 1. Study site location and topography of the Black Lake. Depth contours taken every 0.5 meters (after Chasco et al. 2003).

Figure 2. Alec River delta; flow splits to north and south channels prior to the entrance to the lake (Sept. 2001).

Figure 3. Meandering pattern in the Alec River.

a. Ground view. b. Aerial view.

Figure 4. The sand-spit emanating from the Alec River delta to the Black Lake (Sept. 2001).

The Black Lake is drained at its south end by the Black River, which has two major tributaries: The Red Salmon which consists of a meandering gravel pool-riffle channel (Figure5) and the West Fork River which consists of a complex drainage system of multiple-branch braided channels, showing evidence of channel avulsion and instability (Figure6). In turn, Black River drains into Chignik Lake, creating a large, braided, sand and gravel delta at the head of the lake (Figure7). A detailed description of the physical characteristics of the Black Lake drainage system can be found in Buffington (2002) and Ruggerone (2003).

Figure 5. Confluence of the Red Salmon River with the Black River below the outlet of Black Lake (Sept. 2001). Flow in Black River is toward the bottom of the photograph.

Figure 6. A single branch of the West Fork River, showing the typical braided morphology (Sept. 2001).

Figure 7. Confluence of the West Fork and Black Rivers above Chignik Lake (seen at the top right) (Sept. 2001).

4. METHODOLOGY

Different hydrodynamic and sediment transport models were used in the analysis of this problem. Following is a description of these models as well as the methods used for implementing these models based on the available information and data, developed relationships, and assumptions. The key components of the methodology are:

1. Acquisition of historic and current information about flow and sediment in the Alec River; including sediment bed composition and cross-sections.
2. Obtaining of detailed bathymetry, storage - elevation, wind magnitude and direction, and sediment bed composition for the lake.
3. Identification of the hydrodynamic and sediment transport model that is suitable to use within the Alec River.

4. Choice of a suitable hydrologic model to route the available inflow and sediment data through the lake and examine the lake behavior under various flow/sediment conditions.
5. Choice of a suitable two-dimensional model (2-D) hydrodynamic/sediment model to simulate the inflow and sediment in the lake.
6. Evaluation of the performance of each model for different flow events including a range of hypothetical flow events.
7. Prediction of the expected possible variations in the lake water surface area and storage that may occur in the system over a period of 100 years.

The 1-D hydrodynamic/sediment transport model: The flow and sediment transported from the Alec River into the Black Lake was simulated using a one-dimensional numerical model applied to flow and sediment transport in steep mountain streams. The one-dimensional numerical model, 3ST1D, which stands for Steep Stream Sediment Transport 1-D model, is applicable to unsteady flow conditions that occur over transcritical flow stream reaches such as flows over step-pool sequences or flow in pool-riffle sequences. These conditions match those of the Upper Alec River. The 3ST1D consists of two coupled components: hydrodynamics and sediment transport. The hydrodynamic component is addressed here by solving the unsteady form of the Saint-Venant equations. The Total Variation Diminishing Dissipation (TVD)-MacCormack scheme, which is a shock-capturing scheme capable of rendering the solution oscillation free, is employed here to approximate the hydrodynamic solution over transcritical flow stream reaches. The sediment transport component of the model accounts for multi-fractional sediment transport and incorporates a series of various incipient motion criteria and frictional formulas applicable to mountain streams. In addition, sediment entrainment is estimated based on a state-of-the art formula that accounts for the bed porosity, turbulent bursting frequency, probability of occurrence of strong episodic turbulent events, and sediment availability in the unit bed area (Papanicolaou et al. 2004).

For this study, 3ST1D was modified for the use in the Alec River. A dimensionless shear value of 0.06 was considered as the sediment incipient criterion value, and the Ackers-White formula for determining sediment transport rates. The

Ackers-White formula is applicable for sand with a diameter less than 2 mm, and predicts the total sediment load viz., bed load and suspended load (Chang 1992). The 3ST1D, being a 1-D model was deemed sufficient for this work because of the lack of available data in the Alec River. Data provided consist of cross sectional measurements at various locations in the Upper Alec River and the northern and southern channels. Table 1 shows the input hydraulic and sediment parameters for the Alec River used in running the 3ST1D model. The results obtained from 3ST1D are the transport rates of each size fraction of sediment flowing out of the northern and southern channels of the Alec River. The model was calibrated using flow, sediment load measurements (fluxes) obtained by Ruggerone (1993) and the sediment samples taken by Papanicolaou in August 2003. These samples obtained by Papanicolaou in August 2003 were analyzed and the size distribution of the material was obtained. Cross sectional geometries were supplied by CH2MHill in 2004.

Table 1. Hydraulic and sediment parameters for 3ST1D.

River section	**Flow Q (m^3/s) (Jun 5th, 1992)**	**Modeled reach length (m)**	**Bed slope (S_o)**	**Bottom width (m)**	**Manning's roughness *n***	**Median diameter d_{50} (mm)**	**Distribution of the surface bed material (mm)**
Upper Alec River	68.16	3555	0.00038	40.0	0.013	0.374	3% with d = 2mm 11% with d = 0.85mm 27% with d = 0.43mm 28% with d = 0.25mm 23% with d = 0.15mm 5% with d = 0.106mm 2% with d = 0.075mm
North Channel	37.73 (55%)	1305	0.00019	18.6	0.010	0.196	0.1% with d = 0.85mm 2% with d = 0.43mm 15% with d = 0.25mm 50% with d = 0.15mm 17% with d = 0.106mm 9% with d = 0.075mm
South Channel	30.43 (45%)	2436	0.00020	21.42	0.010	0.196	0.1% with d = 0.85mm 2% with d = 0.43mm 15% with d = 0.25mm 50% with d = 0.15mm 17% with d = 0.106mm 9% with d = 0.075mm

The hydrologic model: A hydrologic model was developed to route the available inflow and sediment data and to examine the lake behavior under various flow and sediment conditions. The model is based on the storage equation which can be expressed as:

$$\frac{dS}{dt} = Q + P - O - L \qquad (1)$$

in which *S* is the storage, *t* is time, *Q* is the inflow rate to the lake, *P* is the direct precipitation in the lake, *O* is the outflow from the lake and *L* is the losses due to seepage and evaporation. To provide a form that is more suitable for hydrologic routing, the storage *S* at time *n*+1 were calculated as follows:

$$S_{n+1} = S_n + Q_n + P_n - O_n - L_n \qquad \text{for } n = 1, 2, \ldots, N \qquad (2)$$

where, all the variables at the right hand side of Eq. (2) have been estimated at the previous instant *n*.

For the site under consideration, the direct precipitation in the lake was insignificant compared to the inflow and was neglected. Losses due seepage and evaporation are also considered negligible due to the geology of the site (no fractured rocks are present) and the existing climatic conditions favor minimal evaporation. Therefore, Eq. 2 can be simplified to:

$$S_{n+1} = S_n + Q_n - O_n \qquad \text{for } n = 1, 2, \ldots, N \qquad (3)$$

The above-mentioned equation has been also used to route the transported rate of sediment through the lake.

To apply Eq. (3) the following information and relationships were considered:

1. The records of the daily inflows of the Alec River for 6/1/2004 - 5/31/2005. Figure8 shows the typical annual cycle in the Alec River for this period. The mean daily inflow within the year for the recorded data was 18.9 m^3/s with daily discharges varying from 8.75 m^3/s up to 103.84 m^3/s. The mean daily inflow was

used here as a reference flow Q_R = 18.9 m^3/s. To study the response of the lake for different hypothetical inflow events, the reference flow Q_R was multiplied by factors ranging from 0.25 to 3.0 to account for historic low or high flow events. Figure 9 shows the range of the generated time series with respect to the reference flow.

2. For the purpose of comparison, the 1950s water storage of lake was considered as a reference volume (S_R = 112.78 millions m^3). This condition represents the maximum storage capacity. It was found that the ratio of the annual inflow entering the lake to its maximum capacity Q_R / S_R is larger than 5, which means that the lake response would be very sensitive to the inflow. Therefore, the routing of the lake was carried out based on the daily discharge to consider the sub-monthly fluctuation in both inflow and outflow.

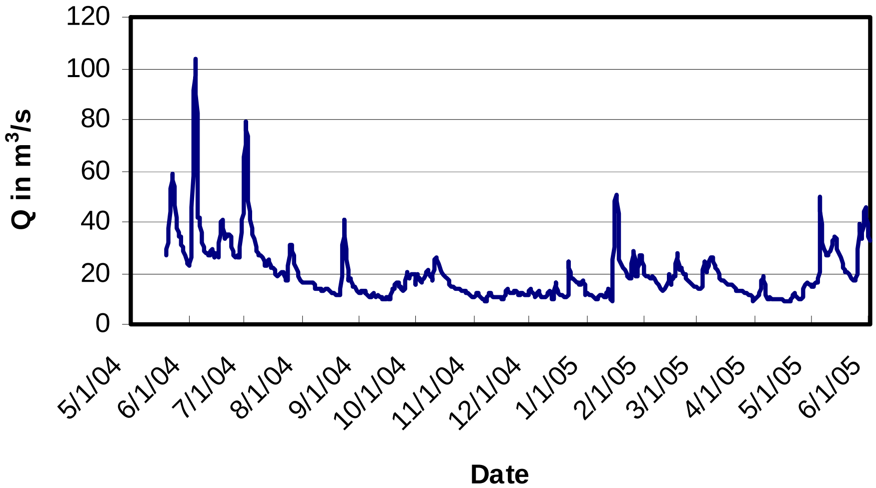


Figure 8. The typical annual cycle in the Alec River (June 1st, 2004 – May 31st, 2005), the mean daily inflow within the year was 18.9 m^3/s.

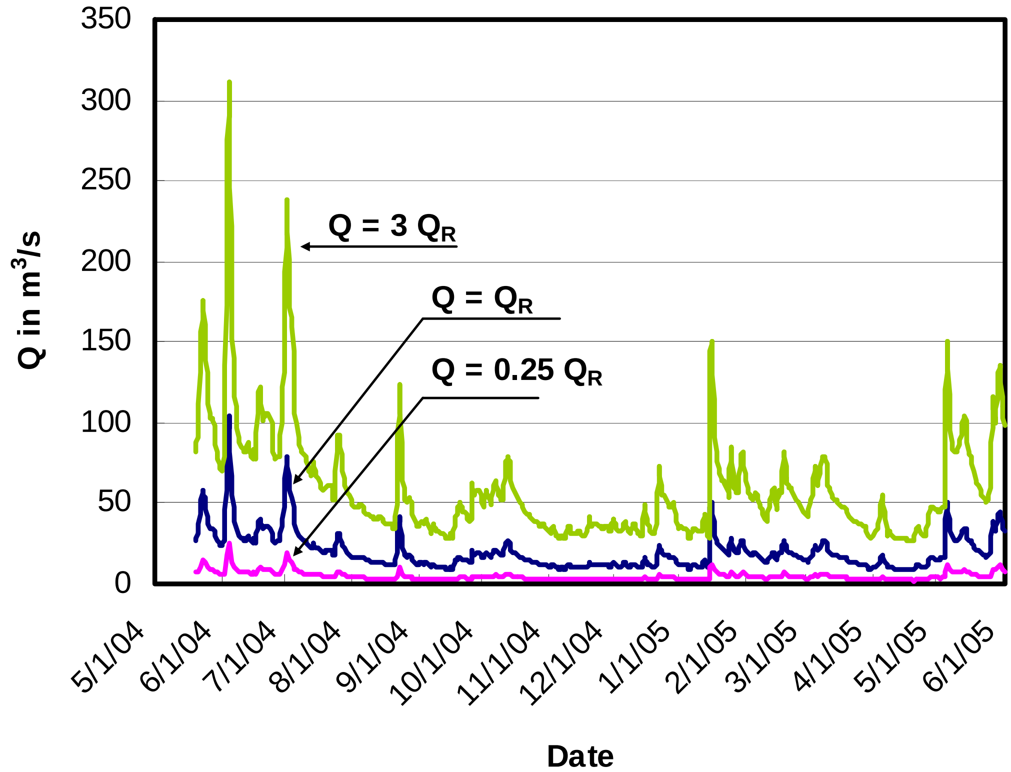


Figure 9. Range of the generated time series with respect to the reference discharge, $Q_R = 18.9$ m^3/s.

3. Elevation (stage)-Storage relationship: An elevation (stage)-storage relationship (Figure10) was developed based on the USGS survey data and bathymetry of the lake (Figure1). In developing the relationship, it was assumed that the elevation (stage) is equal to the USGS recorded bench mark + 1000m. The relationship can be expressed mathematically as follows:

$$E = 995 + 0.127956 \times \left[-1.8183 + \left(1.8183^2 + 15.63 \times (6.6808 + S) \right)^{1/2} \right] \qquad (4)$$

where, E is water elevation of the water in lake in meters and S is water storage in millions of cubic meters.

4. Outflow-Storage relationship: An outflow-storage relationship was developed from transects and thalweg profiles of the data documented in Chasco et al. (2003). The analysis of the data showed that the average width and base-elevation

of the lake at the exit are 100 m and 998.75 m (-1.25 m USGS bench mark) respectively. The following broad-crested weir equation was used to establish the relationship between outflow and storage in the Black Lake:

$$O = \frac{2}{3} C_d B \sqrt{2g} (E - E_{le})^{1.5} \tag{5}$$

where, C_d denotes the coefficient of discharge, E is water elevation of the water in lake, B is the mean width of the lake exit and E_{le} is the mean base-elevation of the lake exit.

5. Equation 5 (the outflow /storage equation) was calibrated from the field data collected by Papanicolaou in August 2003. For a daily inflow to the Alec River of 68.16 m^3/s, the corresponding lake elevation was about 999.34 m (-0.66 m USGS bench mark). It was found that the C_d value of 0.5 gives the value of 999.34 for the lake water elevation when the daily inflow from the Alec River is about 68.16 m^3/s. Thus, the coefficient of discharge, the average lake exit width and base-elevation for the Black Lake were estimated to be 0.5, 100 m and 998.75 m respectively.

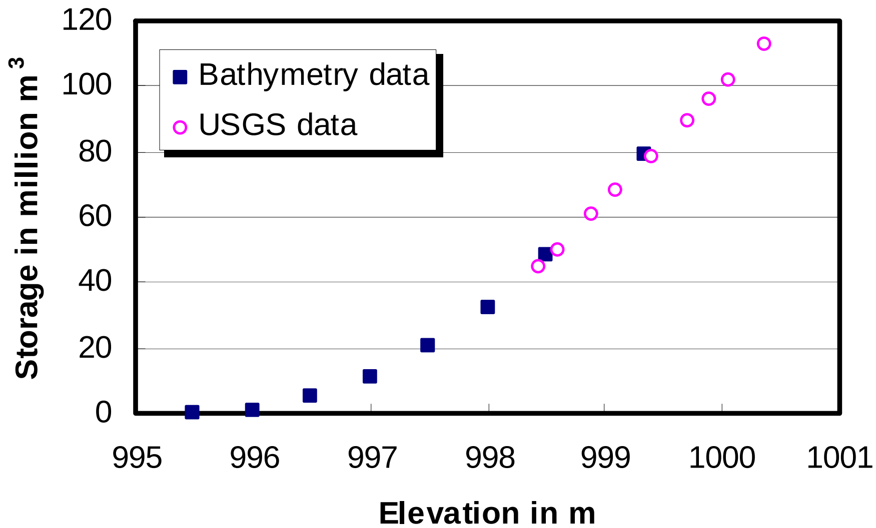


Figure10. Elevation-storage relationship.

6. Based on the existing data, a relationship between the total inflow from the Alec River and the inflow from the southern channel was developed to split the total flow of the Alec River (Figure11). The mathematical relationships for inflow are:

$$Q_N = Q_T - 1.795 Q_T^{0.7731}; \quad Q_S = 1.795 Q_T^{0.7731} \tag{6}$$

where, Q_N and Q_S are daily discharges of the northern and southern channel of the Alec River in m^3/s (The minimum value Q_S is $0.4Q_T$) and Q_T is total daily discharge of the Alec River in m^3/s.

7. To route the rates of sediment discharges entering into and exiting from the lake, sediment discharge- inflow discharge relationships were developed for the Alec River's northern and southern channels. The 3ST1D model developed by Papanicolaou et al. (2004) and Hobbs et al. (2005) was used to determine the rates of sediment discharges entering into the lake. Due to a lack of quantitative information about the sediment rates exiting the lake, these rates were determined via the use of a generic trap efficiency curve adapted from Linsley and Franzini (1979). The curve relates the percent of trapped sediment to the ratio of annual inflow to reservoir or lake storage capacity (Figure12).

8. In performing the analysis using the hydrologic routing model, the lake base-level exit was changed and the storage in the lake was tested at different inflows.

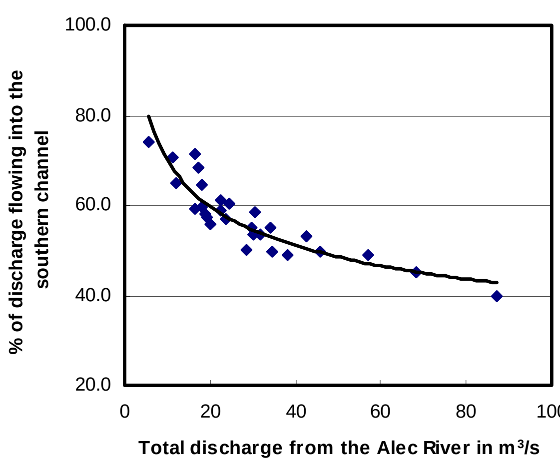


Figure 11. Total inflow from the Alec River versus inflow from the southern channel.

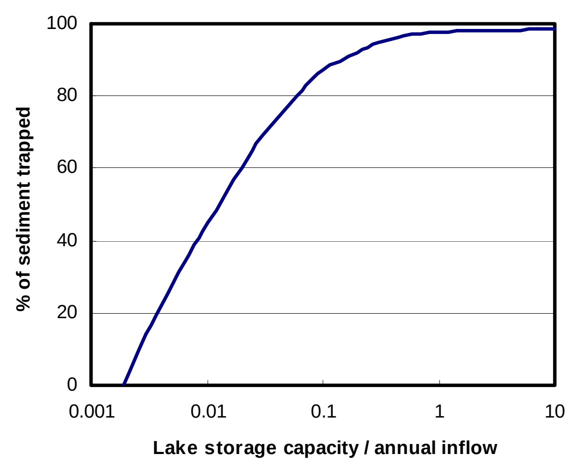


Figure 12. Trap efficiency of reservoirs as a function of the ratio of annual inflow to reservoir storage capacity.

The 2-D numerical model: The velocity, water depth, sediment concentration and bed shear stress distribution patterns in the lake were simulated using a 2-D numerical hydrodynamic/ sediment model. The model was also used to examine the flow and sediment circulating patterns within the Lake by accounting for the effects of currents and wind.

A 2-D depth-averaged hydrodynamic model is well suited for modeling the hydrodynamic and sediment patterns of a shallow environment like Black Lake. The simulation is performed through an interface window, named the Surface Water Modeling System (SMS). The SMS version 8.1 is a commercially available modeling package that combines a pre- and post-processor with hydrodynamic models and allows visualization of the results. Of these, RMA-2 is best suited for modeling the Black Lake. Resource Managements Associates-2 (RMA-2) is a finite element (FE) model that solves the non-conservative form of the 2-D shallow water equations using the Galerkin Method of Weighted Residuals (King, 1997). RMA-2 employs a FE grid based on bathymetry data from maps and field measurements. Elements are of a triangular shape. The model is also able to simulate the sediment concentrations in the lake.

Survey data of Black Lake was obtained from Chasco et al. (2003). The lake bathymetry was determined from this data through relative comparison to the Fisheries Resource Institute (FRI) benchmark near Black Lake. The data contained the latitude and longitude of each measurement and the lake level at the time of measurement, a set of points at the water's edge, and the water depth at various points in the Black Lake. The elevation of the bottom of the lake was then calculated by subtracting the lake level from the benchmark elevation to obtain the water surface elevation. Wind can play an important role in the resuspension of sediments and affects the currents within the lake. RMA2 has the capability to model wind shear via the following equation:

$$\tau_w = \rho_a C V_a^2 \tag{7}$$

where, ρ_a is the density of air, C is a wind coefficient and V_a is the wind velocity. The wind direction and velocity were obtained directly from Ruggerone (pers. comm., 2005).

5. RESULTS AND ANALYSIS

The inputs required for 1-D hydrodynamic/sediment model, hydrologic and 2-D numerical models include the hydrologic records, the Alec River cross-sectional geometry, bed sediment gradation, channel resistance values, the Black Lake exit cross-sectional geometry, storage-elevation and storage-outflow relationships, the Black Lake bathymetry and wind information.

The outputs of the models are: total material transported from the Alec River into the lake as a function of the Alec's River daily discharge, the best outlet base-level for the lake to maintain the 1950s storage capacity for a longest period of the year under various flow events, velocity, water elevation, sediment concentration and bed shear stress distribution patterns in the lake, and the flow velocity vector field in the lake. A prediction of the possible variations in the lake water surface and storage via extrapolation of the changes that may occur in the system over a period of 100 years are also presented at the end of this section.

The physical changes in the Black Lake system: The physical changes of the Black Lake system and its effects to the sockeye salmon habitat have been interpreted by accounting for the complex interactions of wind, water and sediment with the lake. The interpretations were as follows: when the snow pack melts, sediment ends up in the Alec River and eventually in the Black Lake. Due to differences in the velocity between the Alec River and the Black Lake inflows, the coarse sediment settles at the lake entrance and forms a delta (Figure13). While the coarse particles settle, the finer sediment particles get entrained downstream by the jet flow occurring at the northern and southern channels. During low flows and low wind intensities, the fine sediment tends to settle inside the lake between its entrances forming a sand-spit (Figure13). According to Ruggerone (2003), the length of the sand-spit has increased 30% over the past 20 years and extends across nearly 80% of the lake width.

Formation of the delta and sand-spit started to control the direction and amount of inflow arriving at the lake from the northern exit of the Alec River, reducing the circulation inside the lake and hence, the amounts of the sediment arriving at the lake exit.

While the formation of the sand spit was well-explained, the causes for the low-water storage capacity found in the Black Lake were not identified in prior studies. Possible causes could be the sedimentation in the lake, low water influx and changes at the outlet geometry of the Black lake. This study examined all three causes.

With respect to the sedimentation issue, it was found that the deposition of the incoming sediment, originated from Alec (Sqaw) River, into the lake over the past 50 years has not substantially affected the lake storage capacity. It reduced the lake storage capacity by only about 1.0 % for the period of 1950-2005. Hence although the average trapping efficiency of the lake is about 92 % as can be estimated from Figure12, sediment trapping in the lake in the big scheme of things has a minimal contribution to low-water storage capacity comparatively to the sediment influx from the West Fork River.

With respect to the lake water influx, results suggest that the lake receives sufficient water influx to be able to fill to its 1950s storage capacity.

It was concluded that the reduction in the lake water storage is mainly attributed to changes in the lake outlet geometry. The lake outlet base-level has been dropped by at least 1.0 m compared to the 1950s base-level. This drop can be attributed to the high differential found in sediment transport rates between the lake exit or the entrance of the Black River and the confluence of the West Fork with the Black River. Prior studies have recorded that the sediment influx from the West Fork has been significantly high and has affected the longitudinal gradient of the Black River downstream of the confluence point due to the occurrence of significant sediment deposition. Because the sediment rates entering the Black River are low comparatively to the rates from the West Fork, the river tends to degrade its bed upstream (headwards) from the confluence in order to reach to the same level of longitudinal slope with the downstream section.

The headward erosion tends to flatten the river bed and to oversteepen the banks in that segment. Bank oversteepening yields bank mechanical failure. This failure is complemented with failure triggered by the action of the flowing water. Figure 14 illustrates the bank failure which occurred within the Black River headwaters-West Fork segment.

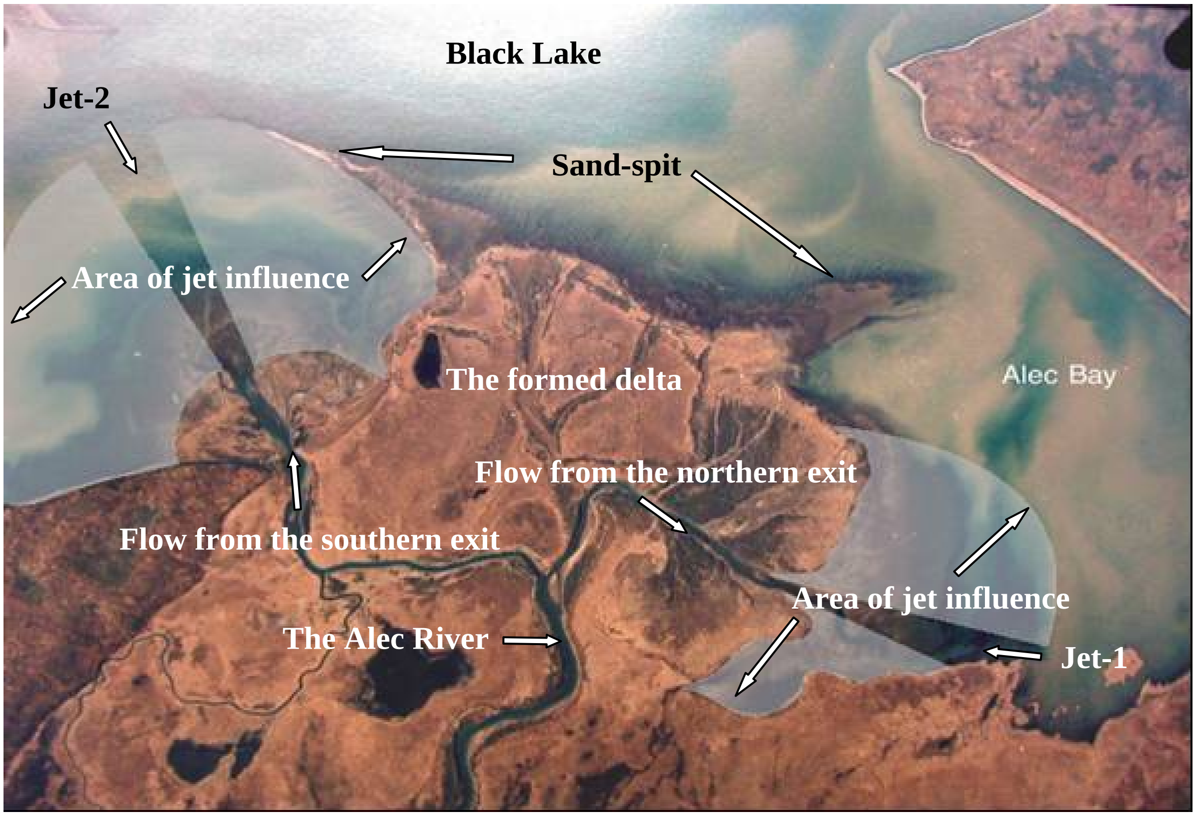


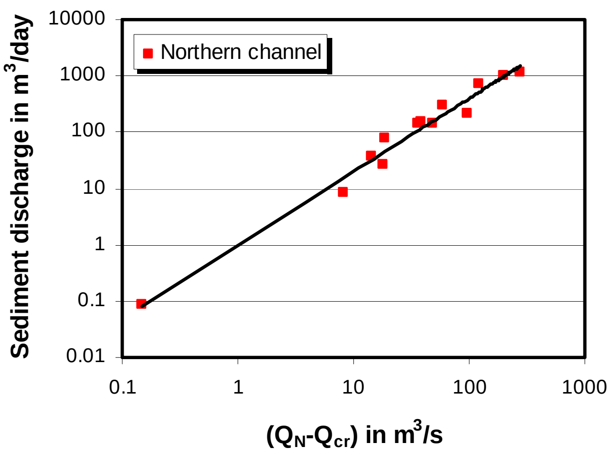
Figure 13: Aerial photo for the Alec River exit into the Black Lake showing the formed delta, sand-spit, water jets and their extended influence inside the lake.

Figure 14: High banks erosion of the Black River at the lake exit (Sept. 2001).

Results of the 3ST1D model: The 3ST1D model developed by Papanicolaou et al. (2004) was used for predicting the Alec River sediment transport rates. The difference between measured data and predicted results was less than 25% which is quite satisfactory for making sediment comparisons/predictions. Figure 15 shows the sediment discharge- inflow discharge relationships developed for Alec northern and southern channels using 3ST1D. The mathematical relationships for sediment are:

$$Q_{TSLN} = 0.9891(Q_N - Q_{cr})^{1.31}; \quad Q_{TSLS} = 1.3805(Q_S - Q_{cr})^{1.33} \qquad (8)$$

where, Q_{TSLN} and Q_{TSLS} are the total sediment load of the northern and the southern channel of the Alec River in m^3/day, Q_N and Q_S are daily discharges of the northern and the southern channel of the Alec River in m^3/s and Q_{cr} is critical discharge in m^3/s (Q_{cr} is 1.85 for both channels).



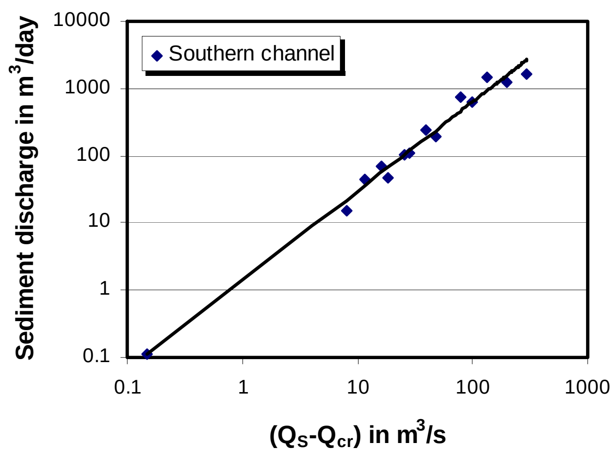


Figure 15. Sediment discharge- inflow discharge relationships for Alec northern and southern channels.

Results of the hydrologic model: The results of the hydrologic model revealed for the first time that the reduction in the water capacity of the lake is mainly due to changes in the lake outlet geometry; primarily changes occurring at the base-level due to shortage in the amount of sediment arriving at the outlet. The drop in the elevation of the Black Lake outlet was caused by limited sediment supply in the outflowing Black River. Limited sediment supply triggers the accelerated degradation of the Black Lake outlet (or equivalently the entrance of the Black River). The analysis of the available inflow records of the Alec River and the possible variations on its mean annual inflow (Figure9) showed that the lake receives sufficient amount of water to reach its previous historic high stages (e.g., the maximum water storage of 1950s). Even at very low flow events (*Q*

= 0.25 Q_R) the ratio of the annual inflow entering the lake to its maximum storage capacity (Q / S_R) is greater than 1.0.

Routing of the lake (Figure16) with the present exit base-level (E_{le} = 998.75m; S = 55 millions m^3) showed that regardless of the annual mean inflow entering the lake, the lake is not able to reach its previous stages except at very high events. These events occur rarely, probably with a 200 year return period, and for very short periods. For the greater part of a year, the lake storage is approximately less than 58 % of the storage reference (S_R = 112.78 millions m^3 established in 1950). The above findings suggest that a structural modification needs to occur at the outlet of the lake in order to increase the water storage capacity. A small earth dam, spillway, crested weir, or LWD could be used, for example, in order to raise the exit base-level.

The optimum base-level at the lake exit was determined by the method of iteration for different hypothetical flows. Figures 17 and 18 show the effect of raising the exit base-level by 1.0 m and 1.25 m respectively. It can be seen from Figure17 that raising the exit base-level by 1.0 m will guarantee that the lake is 84 % full for most of the year under different flow conditions, while raising the exit base-level by 1.25 m will guarantee that the lake is 92 % full for most of the year under different flow conditions. However, for the highest flow event, water storage can exceed the reference storage (S_R = 112.78 millions m^3). Therefore, it is suggested to increase the lake base-level exit by only 1.0 m and observe the changes in its physical characteristics. Figure19 shows the annual cumulative amount of sediment entering (trapped) in the lake under different flow conditions. The results also show that the annual amount of sediment trapped in the lake is very small compared to the lake gross volume. For example, for $Q = Q_R$ = 18.9 m^3/s, the ratio of the annual total sediment load entering the lake to its maximum capacity (Q_{TSL} / S_R) is less than 0.00015. Thus, the reduction in lake storage capacity over the past 50 years (1950-2000) due to deposition of incoming sediment from the Alec River is less than 1.0 %. From the above analysis, it can be seen that the reduction of the lake storage capacity is attributed mainly to the drop in the lake outlet base-level rather than an increase in the lake bed-level due to the deposition of the incoming sediment.

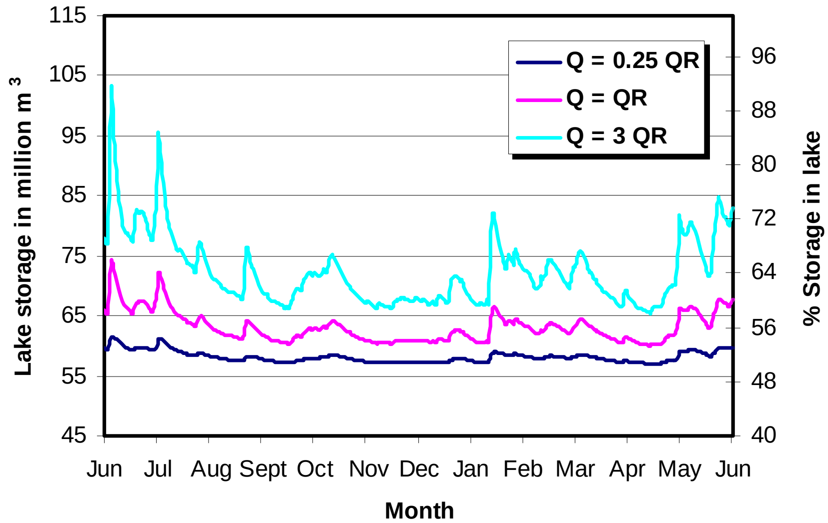


Figure 16. Black Lake water storage for the present exit base-level (E_{le} = 998.75m; S = 55 millions m^3) under different flow events, Q_R = 18.9 m^3/s.

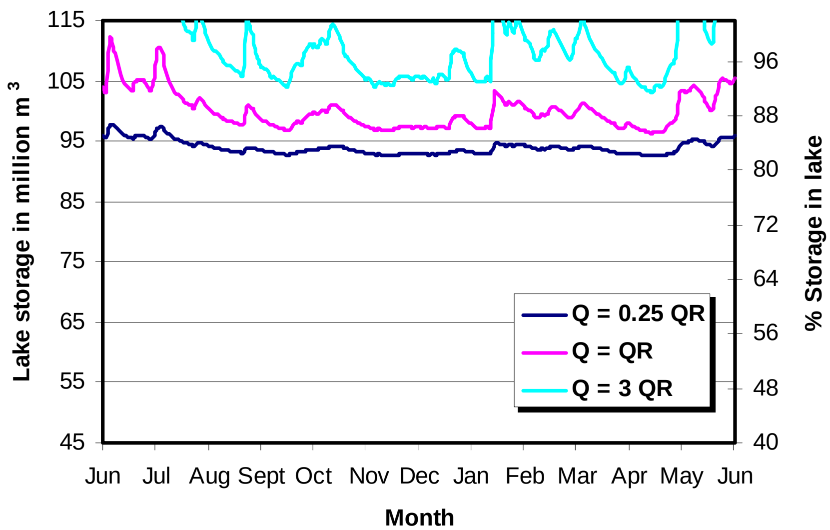


Figure 17. Black Lake water storage for the exit base-level (E_{le} = 999.75m; S = 90 millions m^3) under different flow events, Q_R =18.9 m^3/s.

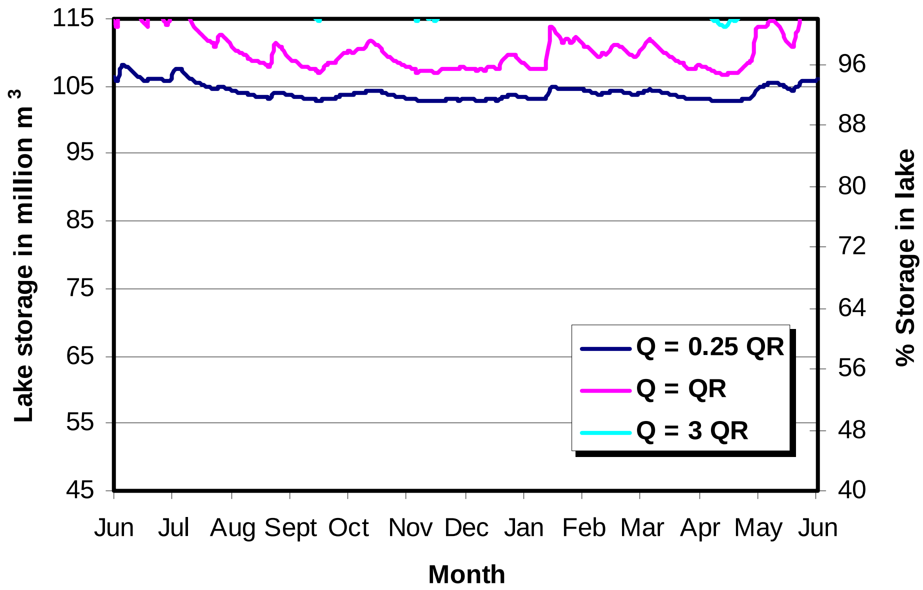


Figure 18. Black Lake water storage for the exit base-level (E_{le} = 1000 m; S = 100 millions m^3) under different flow events, Q_R = 18.9 m^3/s.

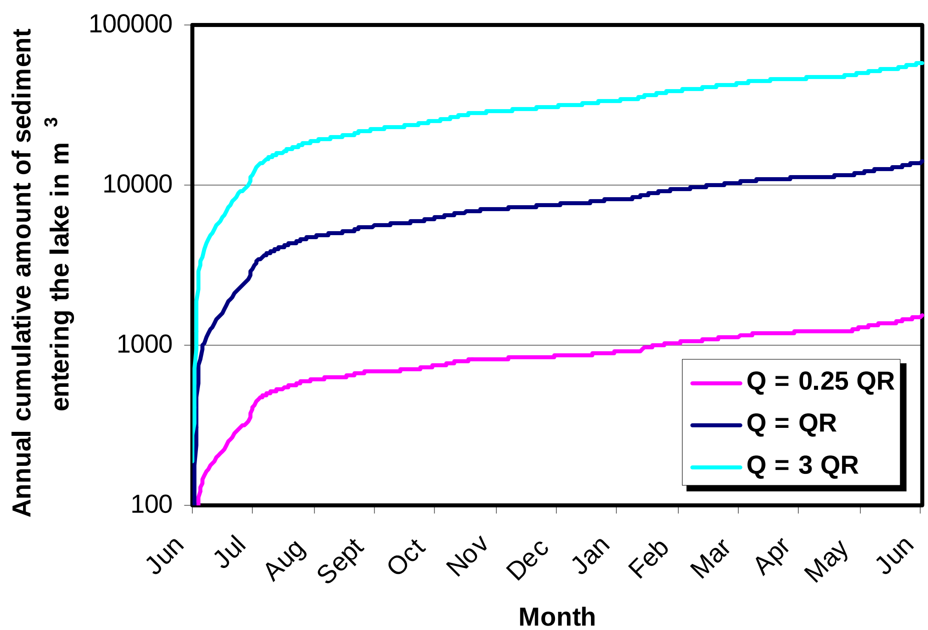


Figure 19. Annual cumulative amount of sediment enters (trap) into the lake under different flow conditions, Q_R = 18.9 m^3/s.

Results of the RMA-2 model: Although the described hydrologic model provides unique information about the minimum, average and maximum water storage in the lake, the role of the 2-D model is to depict the lake's velocity, water depth, sediment concentration and bed shear stress distribution patterns. The model was, also, used to examine the circulation patterns and velocity vectors by accounting for the effects of currents and wind. The flow and sediment results for the RMA-2 modeling effort of Black Lake are shown in Figures 20 to 26. Three flow events were tested using RMA-2: the first event represents one of the highest recorded daily inflows (the 3rd highest event within 6/1/2004 - 5/31/2005), the second event is close to the daily mean inflow for this year, while the third event represents the lowest daily inflow for the same period. The Manning's roughness *n* value of 0.013 and eddy viscosity of 4000 N-s/m^2 were used in the model. The eddy viscosity parameter defines the turbulence level in the water. Table 2 shows the inputs used in the model. Note that the discharge from the northern inlet was greater than the southern inlet for event 1; however, the rate of sediment load from the south channel was higher than for the northern channel.

Table 2. The parameters used in running the model.

Event	**1**	**2**	**3**
North channel daily inflow in m^3/s	37.43	8.28	2.44
South channel daily inflow in m^3/s	30.43	12.14	6.3
North channel daily sediment rate in m^3	104.55	11.13	0.5
South channel daily sediment rate in m^3	122.58	30.65	10.65
Lake elevation in m^3	999.34	999.12	999.06

Figures 20 and 21 illustrate the water surface elevation and the water depth of the lake for the first event (Q_T = 68.16 m^3/s). The elevation is almost constant in the lake except at the lake inlets and exit. A similar pattern is found for the second event (Q_T = 20.42 m^3/s) and third event (Q_T = 8.74 m^3/s). Figures 22 to 24 provide the velocity distribution in the lake for the three events. Except for the inlets and exit portions of the lake which show high velocities, the velocity is less than 0.05 m/s, 0.03 m/s and 0.02 m/s for the first, second and third event respectively. Figures 22 to 24 show a typical pattern of the velocity distributions inside lakes and reservoirs; the magnitude of the velocity is locally quite high near the entrances and exit, as would be expected as a fluid submerged jet enters a large body of water, but this velocity quickly slows down as distance from that entrance increases. Note that in the second event the discharge from the southern inlet became greater than the northern inlet, unlike the first event. Note also its effect on the velocity magnitude of the northern inlet in all three events. Figure 24 shows the shear stress of the first event; it has the same distribution pattern of the velocity with higher values of shear stress at the lake inlets and exit. A similar pattern was found for the shear stress of the other two events.

Figures 25 and 26 show the sediment concentration distribution for events 1 and 2 respectively. The figures show a limited dispersion of the sediment far from the inlets with almost no sediment inside the lake and at its exit. Due to the low discharge of the northern channel in event 2, the sediment concentration in that case has a limited dispersion compared to event 1. For the third event, the model was not able to run due to the low discharges and concentrations.

Figure 20. Water surface elevation in the lake (event-1); Q_T = 68.16 m^3/s; dimensions in m.

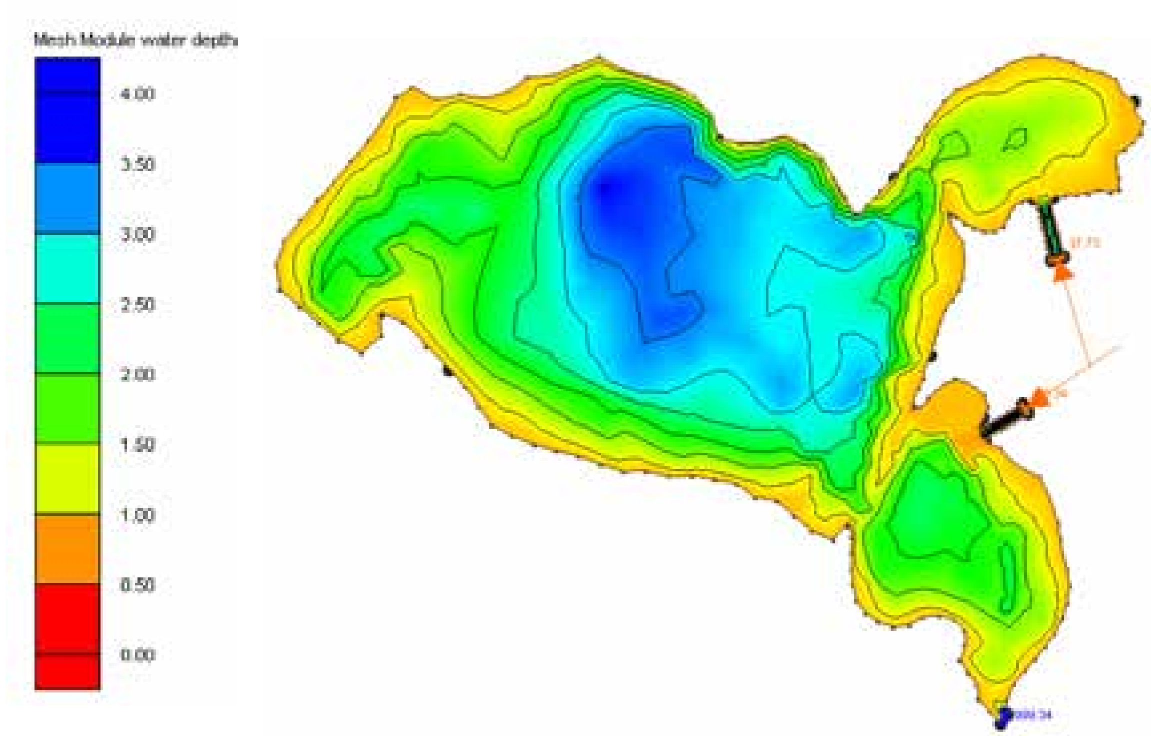


Figure 21. Water depth in the lake (event-1); $Q_T = 68.16\ m^3/s$; dimensions in m.

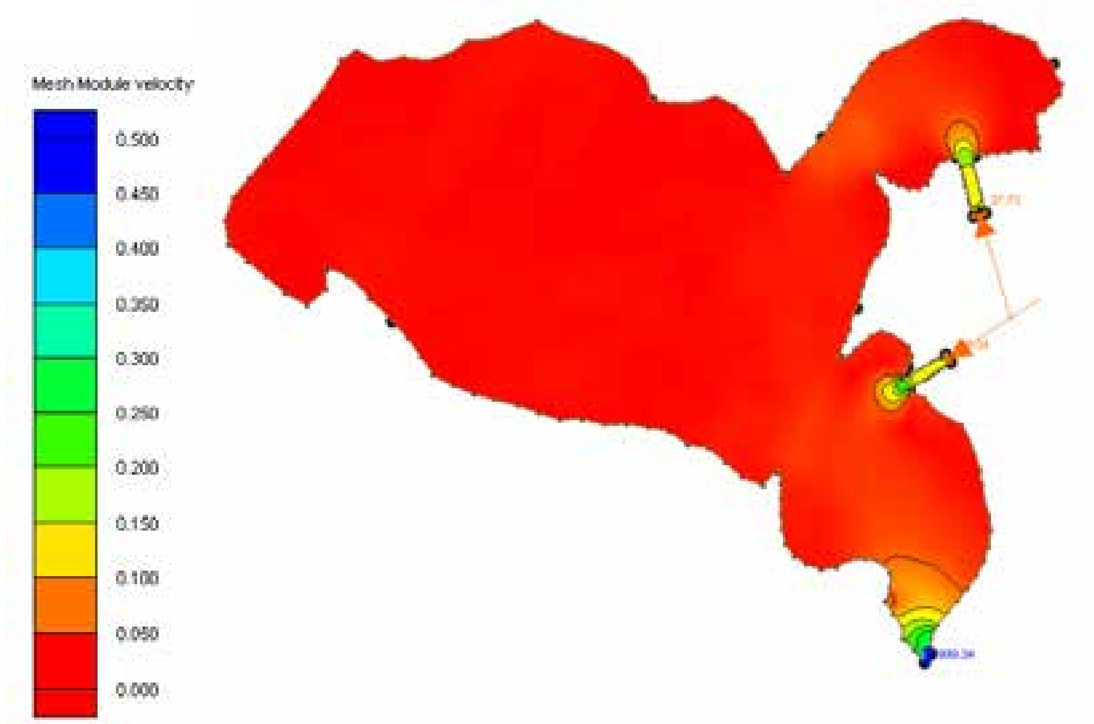


Figure 22. Velocity distribution in the lake and its inlets and exit (event-1); $Q_T = 68.16\ m^3/s$; dimensions in m/s.

Figure 23. Velocity distribution in the lake and its inlets and exit (event - 2); Q_T = 20.42 m^3/s; dimensions in m/s.

Figure 24. Velocity distribution in the lake and its inlets and exit (event - 3); Q_T = 8.74 m^3/s; dimensions in m/s.

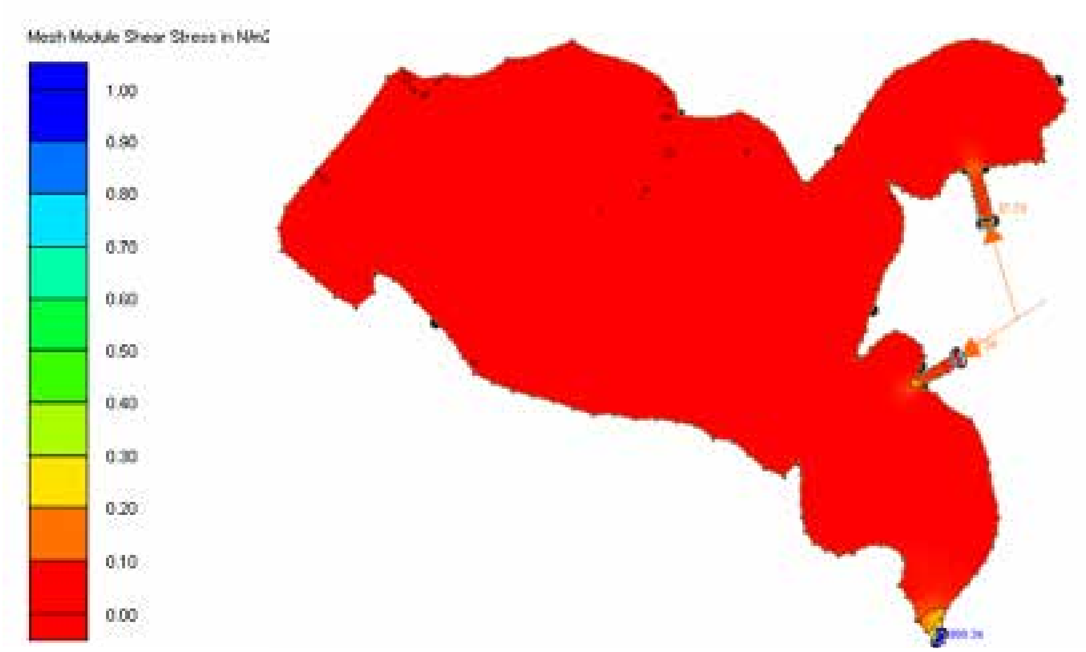


Figure 25. Shear stress distribution in the lake and its inlets and exit; Q_T = 68.16 m^3/s; dimensions in N/m^2.

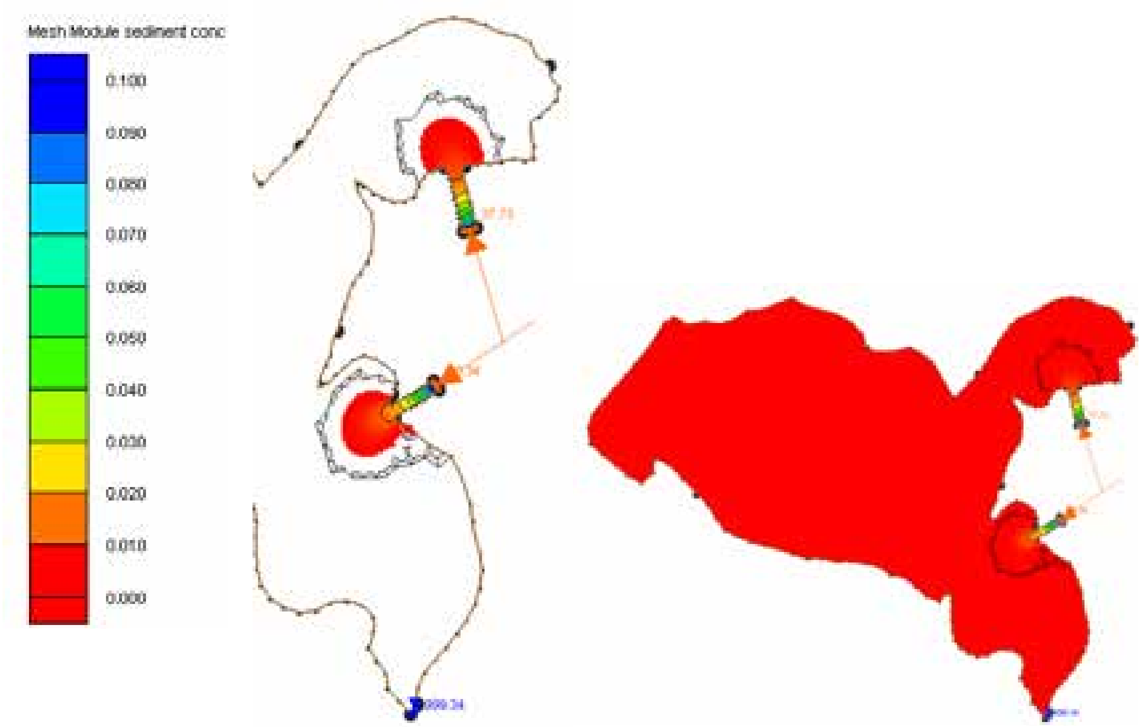


Figure 26. Sediment concentration distribution in the lake and its inlets and exit (event – 1); Q_T = 68.16 m^3/s; dimensions in ppm×10^3.

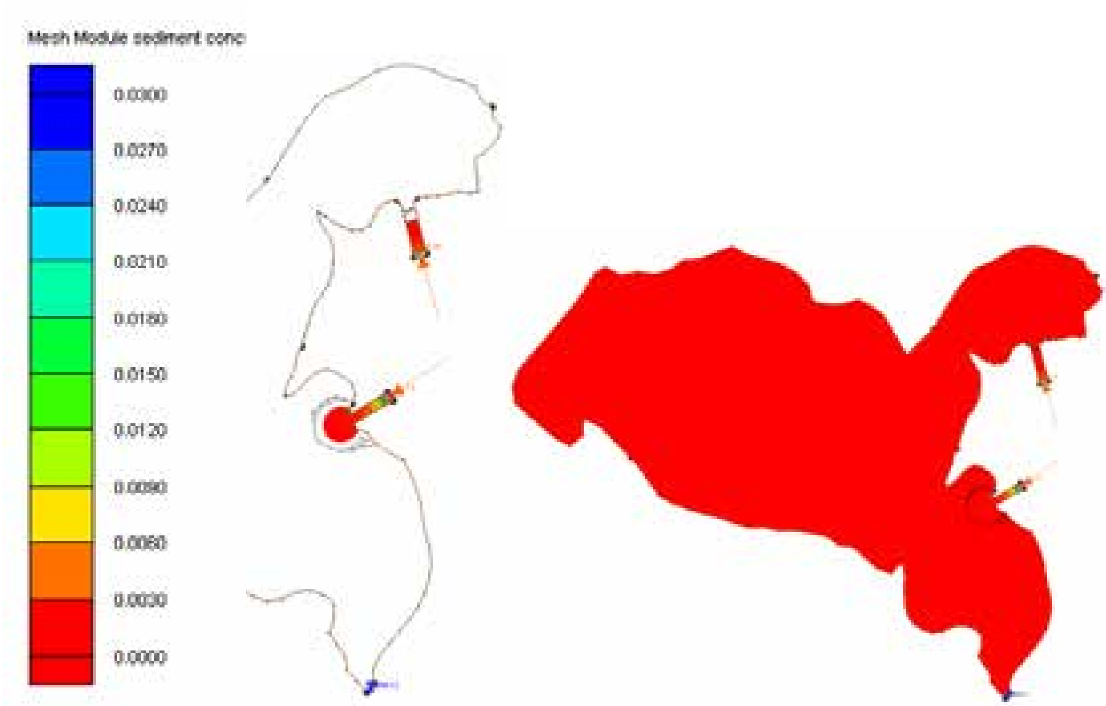


Figure27. Sediment concentration distribution in the lake and its inlets and exit (event -2); Q_T = 20.42 m^3/s; dimensions in ppm×10^3.

Figures 28 to 30 show the circulation flow patterns of the three events, respectively. It can be seen from Figs 28 to 30 that the circulation pattern is very complex and not the same for each event as it is a function of the geometry of the northern and southern parts of the lake, the water elevation, the amount of water entering each inlet and the amount of water leaving the lake. At high discharges (event 1), the flow enters the northern inlet causing a recirculation pattern that seems to turn back in on the jet (flow in a pipe with an orifice). The same pattern can be observed at the southern inlet, though the southern entrance flow pattern reflects the presence of the sand-spit and the proximity of the lake exit. The bulk of the flow seems to turn quickly and travel directly to the exit with much less recirculation than the northern entrance shows. It should be noted that some of the flow appears to follow the bank up to the sand spit and curve back towards the lake exit. This may help explain why the sand spit is forming; sediment-laden flow is flowing along the sand spit, slowing down, and depositing more material. For moderate/low discharges (second and third event), the flow enters the northern inlet however, it doesn't recirculate directly back to the jet. For the southern inlet, the pattern is not much different than the high discharges event; it appears that it is controlled by the shape of this portion of the lake and the lake exit rather than the amount of water entering the southern inlet. Several large, slow recirculation patterns within the lake are also predicted for the three events.

The wind effects are much more difficult to judge from these results. On June 4 and 5, 1992, there was a wind out of the southeast between 4.47 and 8.94 m/s. This model was run with and without the wind, and on the scale of the whole lake, it was difficult to see any major differences in the flow recirculation patterns, either in terms of flow directions or of velocity magnitudes. More study with a finer mesh should be devoted in the future to this question, as it is assumed that the wind plays a much larger role across this lake. With the coarseness of the mesh used in this study, the wind effects were not captured.

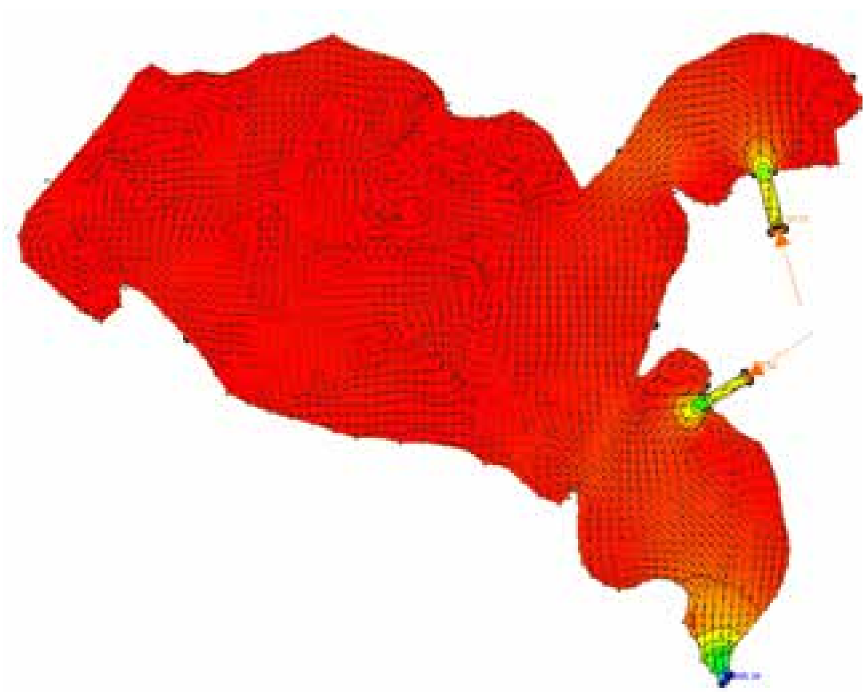


Figure 28. Re-circulation pattern for event -1 ; Q_T = 68.16 m^3/s.

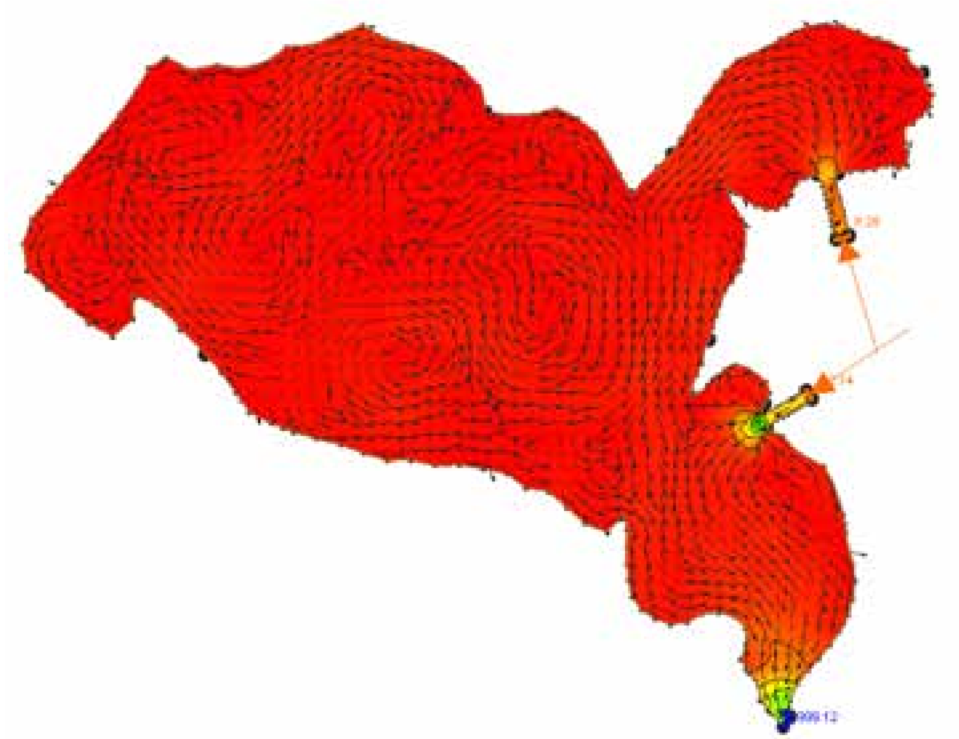


Figure 29. Re-circulation pattern for event -2; Q_T = 20.42 m^3/s.

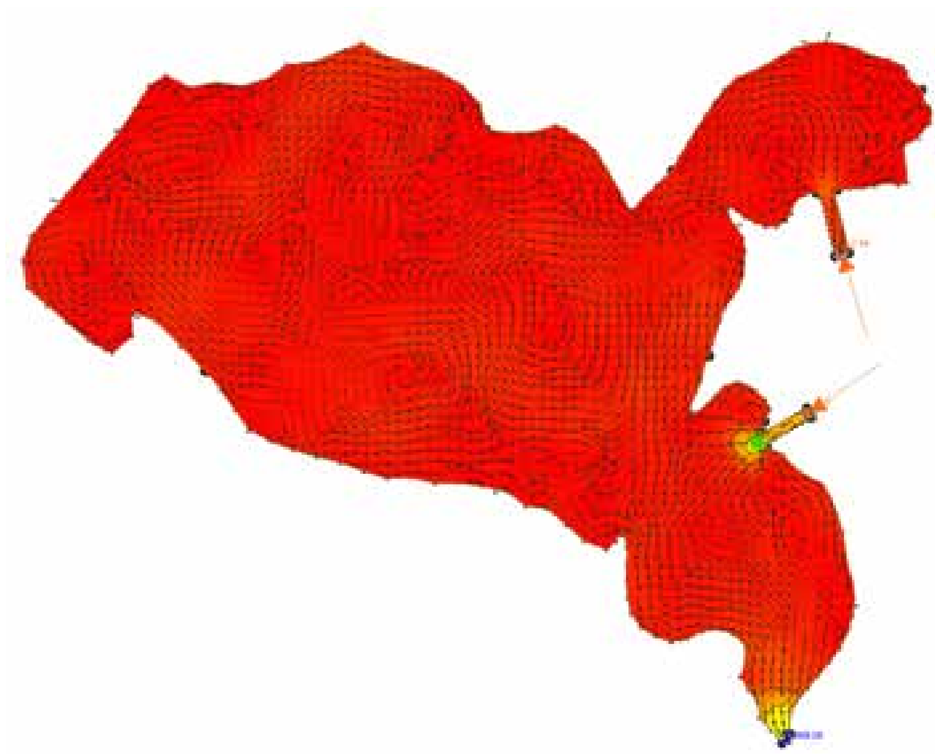


Figure 30. Re-circulation pattern for event -3; Q_T = 6.74 m^3/s.

The expected possible future variations in the Black Lake system: Based on the historical data of the 1950s and the recent records of the Alec River's inflows on 2004-2005 a relationship between the average yearly storage and time was developed and fitted with an exponential curve to extrapolate the average yearly storage beyond the available data as given in Figure 31. The expected possible changes in the lake boundaries after 22, 57 and 100 years are given in Figs. 32 to 34, respectively. The solid outer line shows the present boundaries while the colored areas show the future boundaries of the lake. As can be seen from these figures, the water surface area and hence, the storage of the lake continue to diminish with the passage of time. This diminishing of water surface area and storage may cause a complete destruction to the ecosystem in the lake if action is not taken within a few years. Because of the diminishing of the lake water surface area, it is expected the formation of some swamp areas at the lake inlet and exit zones. It can be seen in Figure34 that at that stage, the northern exit of the Alec River may be completely dry. Figure 35 shows the expected possible changes in Black Lake's water surface elevation over a period of 100 years. A comparison of Figures 31, 34, and 35 shows that there is not only a drop in the lake water surface elevation, but also in surface area. The actual shape of the connections between the lake and the Alec River exits and the lake and the Black River inlet can not be easily predicted. It is expected that swamps will form in these zones with bank failure and widening of the rivers at the connections with the lake.

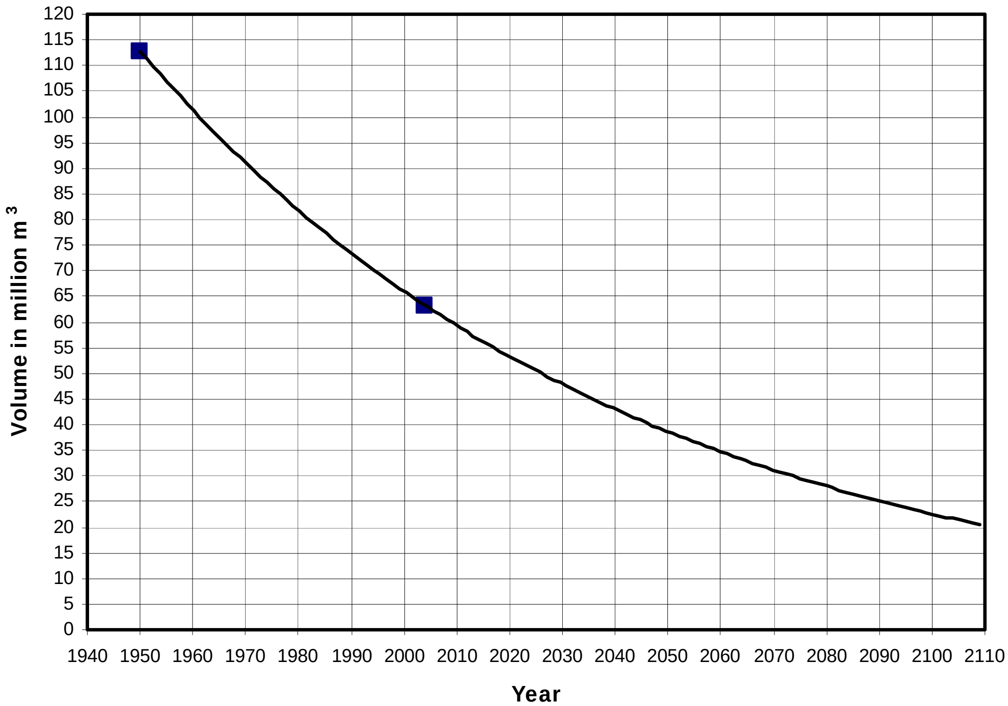


Figure 31. Expected possible change in the Black Lake water volume with respect to time (exponential fit).

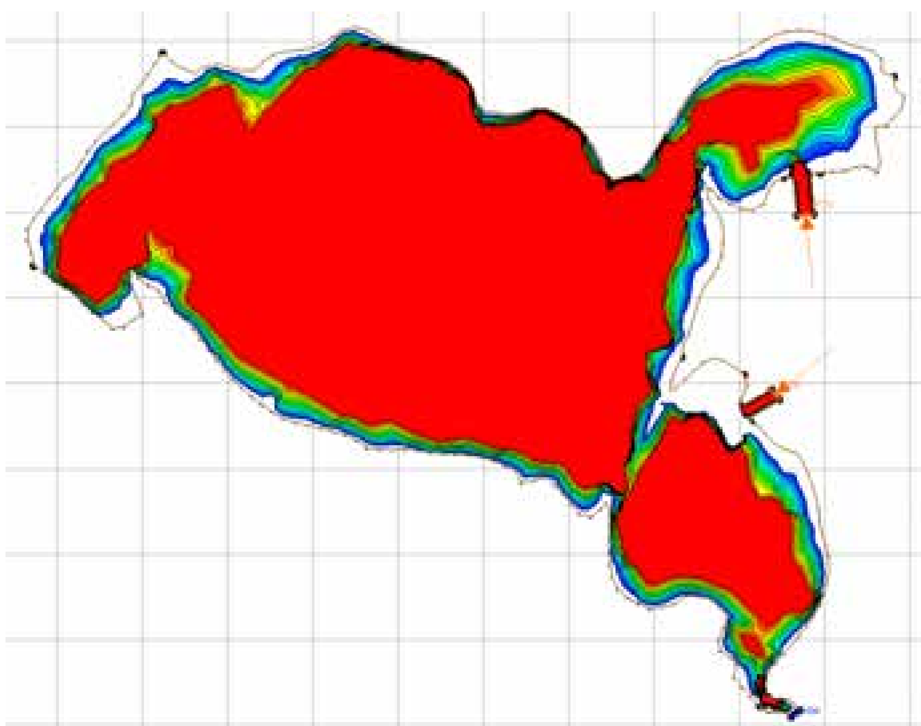


Figure 32. Expected possible changes in the Black Lake boundaries at 2027 (after 22 year); S = 48 millions m^3 and Q_R = 18.9 m^3/s.

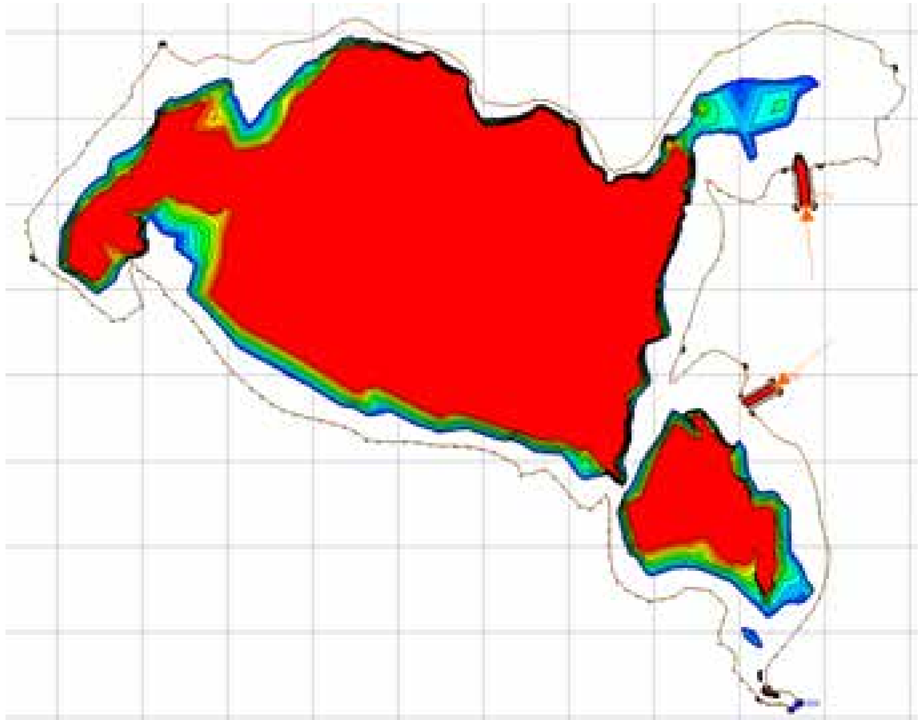


Figure 33. Expected possible changes in the Black Lake boundaries at 2062 (after 57 year); S = 34 millions m^3 and Q_R = 18.9 m^3/s.

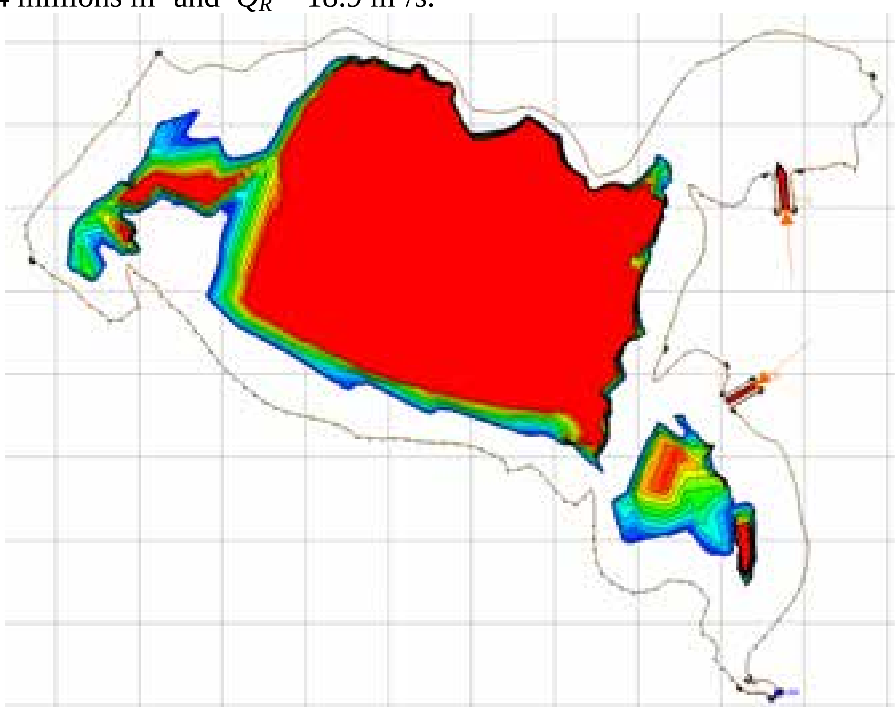


Figure 34. Expected possible changes in the Black Lake boundaries at 2105 (after 100 years); S = 22 millions m^3 and Q_R = 18.9 m^3/s.

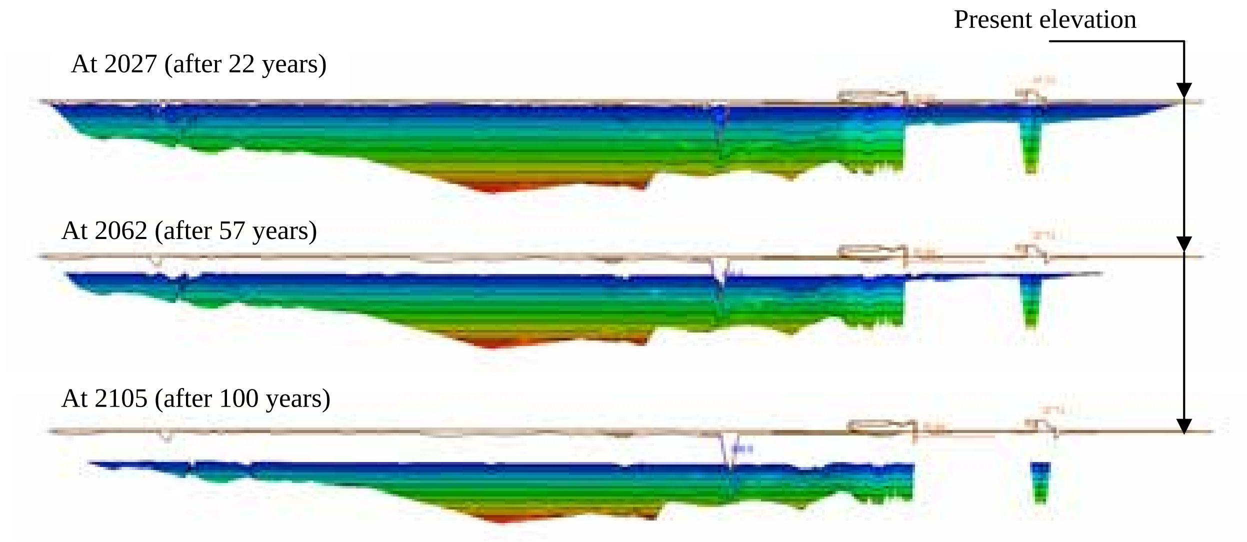


Figure 35. Expected possible changes in the Black Lake water surface elevation over a period of 100 years.

6. CONCLUSIONS AND RECOMMENDATIONS

This study is the first quantitative study for sediment transport and water storage for the Black Lake system. It was concluded that the reduction in the lake water storage is mainly attributed to changes in the lake outlet geometry. The lake outlet base-level has been dropped by at least 1.0 m compared to the 1950s base-level. This drop can be attributed to the high differential found in sediment transport rates between the lake exit or the entrance of the Black River and the confluence of the West Fork with the Black River. Prior studies have recorded that the sediment influx from the West Fork has been significantly high and has affected the longitudinal gradient of the Black River downstream of the confluence point due to the occurrence of significant sediment deposition. Because the sediment rates entering the Black River are low comparatively to the rates from the West Fork, the river tends to degrade its bed upstream from the confluence in order to reach to the same level of longitudinal slope with the downstream section. In a nut-cell, the drop at the lake's outlet describes the response of the Black River to significant sediment influx from the West Fork.

To increase the water storage capacity in the Black Lake system, the researchers' recommendation is the raising of the lake outlet base-level by 1.0 m and the placement of a temporal sill (e.g. inflatable sill, or a broad crested weir) at the outlet of the lake. The temporal sill would allow an increase in the storage of the lake. This increase is quantitatively described for the first time in this report. The sill should be installed during low flow conditions and removed during high flows. The placement of the sill will help the lake to temporarily regain its storage capacity. To get a complete answer to the Black Lake problem, the authors suggest carrying out an experimental study by building a physical model for the lake and its inlets and outlet to evaluate the performance of the outlet structure under various flow conditions. The physical model study also will explore ways to control excess sedimentation from the West Fork.

7. FUTURE STUDIES

A further study is required to design an appropriate outlet structure for the Black Lake. Special care should be taken when designing the outlet structure such that the design does not negatively impact the ecosystem of the lake. Thus, more studies should be considered using physical models to determine a design for this outlet structure and to account for fish passage. The effects of the removal of the sand-spit and rerouting of the flow only to the northern Alec River exit or to examine the effects of West Fork on the degradation of the lake outlet would also require the building of a physical model or a numerical model to evaluate the costs and benefits of making these changes with regard to the overall performance of the system. Since possible future changes on the Black Lake system can be evaluated and simulated with both physical and numerical models, it is suggested to perform a complete physical and numerical study on the system to evaluate and simulate its performance before and after the suggested modifications.

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