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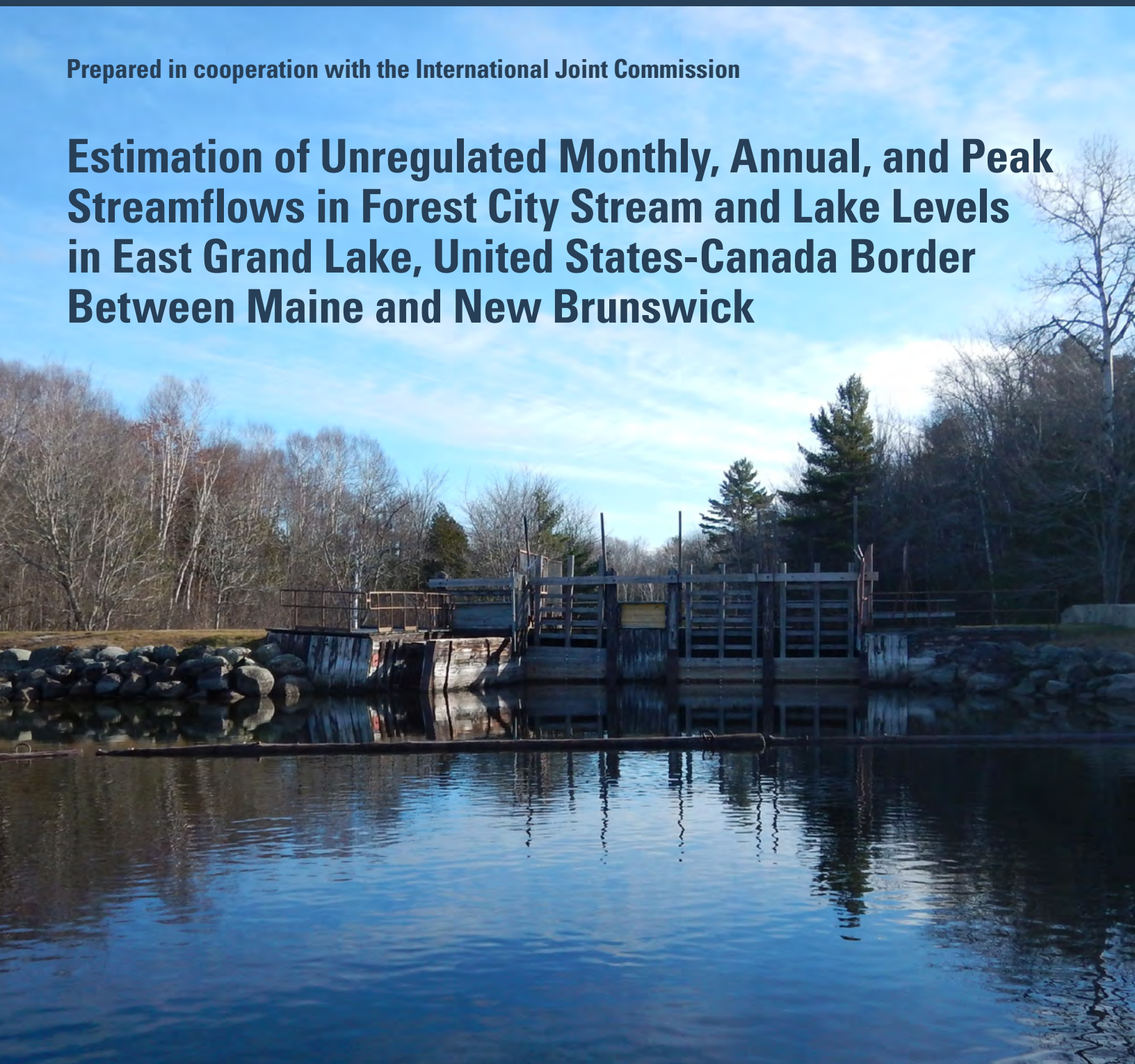
Estimation of Unregulated Monthly, Annual, and Peak Streamflows in Forest City Stream and Lake Levels in East Grand Lake, United States-Canada Border Between Maine and New Brunswick



Scientific Investigations Report 2018–5044

U.S. Department of the Interior
U.S. Geological Survey

Cover. Forest City Dam, Forest City, Maine, November 18, 2015. Photograph by Jeff Kinsey, U.S. Geological Survey.

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U.S. Department of the Interior
RYAN K. ZINKE, Secretary

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

ADCP	acoustic Doppler current profiler
EC	Environment Canada
HEC–RAS	Hydrologic Engineering Center's River Analysis System
PRESS	prediction error sum of squares
TRDI	Teledyne RD Instruments
USGS	U.S. Geological Survey

Estimation of Unregulated Monthly, Annual, and Peak Streamflows in Forest City Stream and Lake Levels in East Grand Lake, United States-Canada Border Between Maine and New Brunswick

By Pamela J. Lombard

Abstract

The U.S. Geological Survey, in cooperation with the International Joint Commission, compiled historical data on regulated streamflows and lake levels and estimated unregulated streamflows and lake levels on Forest City Stream at Forest City, Maine, and East Grand Lake on the United States-Canada border between Maine and New Brunswick to study the effects on streamflows and lake levels if two or all three dam gates are left open. Historical regulated monthly mean streamflows in Forest City Stream at the outlet of East Grand Lake (referred to as Grand Lake by Environment Canada) fluctuated between 114 cubic feet per second (ft^3/s) (3.23 cubic meters per second [m^3/s]) in November and 318 ft^3/s (9.01 m^3/s) in September from 1975 to 2015 according to Environment Canada streamgaging data. Unregulated monthly mean streamflows at this location estimated from regression equations for unregulated sites range from 59.2 ft^3/s (1.68 m^3/s) in September to 653 ft^3/s (18.5 m^3/s) in April. Historical lake levels in East Grand Lake fluctuated between 431.3 feet (ft) (131.5 meters [m]) in October and 434.0 ft (132.3 m) in May from 1969 to 2016 according to Environment Canada lake level data for East Grand Lake. Average monthly lake levels modeled by using the estimated hydrology for unregulated flows, and an outflow rating built from a hydraulic model with all gates at the dam open, range from 427.7 ft (130.4 m) in September to 431.1 ft (131.4 m) in April. Average monthly lake levels would likely be from 1.8 to 5.4 ft (0.55 to 1.6 m) lower with the gates at the dam opened than they have been historically. The greatest lake level changes would be from June through September.

Introduction

The St. Croix River forms the border between eastern Maine in the United States and southwestern New Brunswick in Canada. East Grand Lake (referred to as Grand Lake by Environment Canada) drains an area of 133 square miles (mi^2) (344 square kilometers [km^2]) in the upper part of the St. Croix River Basin (fig. 1). The impoundment at its outlet (Forest City Dam) provides storage for hydropower operations. Minimum streamflows in Forest City Stream are maintained for environmental compliance. Forest City Stream runs between the outlet of East Grand Lake and Spednic Lake. The U.S. Geological Survey (USGS), in cooperation with the International Joint Commission, estimated unregulated streamflow in Forest City Stream and lake levels in East Grand Lake in the interest of understanding streamflow and lake level conditions in the basin in the event that the gates at the dam are left open.

This report presents historical streamflow data and estimates of unregulated monthly and annual streamflows and flood flows for Forest City Stream at the outlet of East Grand Lake, calculated by statistical methods. The report also presents historical East Grand Lake level data and estimates of levels, as calculated from hydraulic modeling and bathymetric data, associated with the unregulated streamflows and the opening of the gates at the dam.

Data Collection and Analysis

Hydrologic and hydraulic data collection and analyses in this study included the compilation of historical streamflows in Forest City Stream and lake levels in East Grand Lake, calculations using regression equations to estimate unregulated streamflows at this site, and differential leveling and bathymetric surveys to define the Forest City Dam outlet structure. The data were used to build a Hydrologic Engineering Center's River Analysis System (HEC–RAS) hydraulic model at the outlet dam, for a run condition with the gates open, to compute unregulated lake levels at this site. Lake bathymetry data and dam survey data from this study are available as a USGS data release (Lombard, 2018).

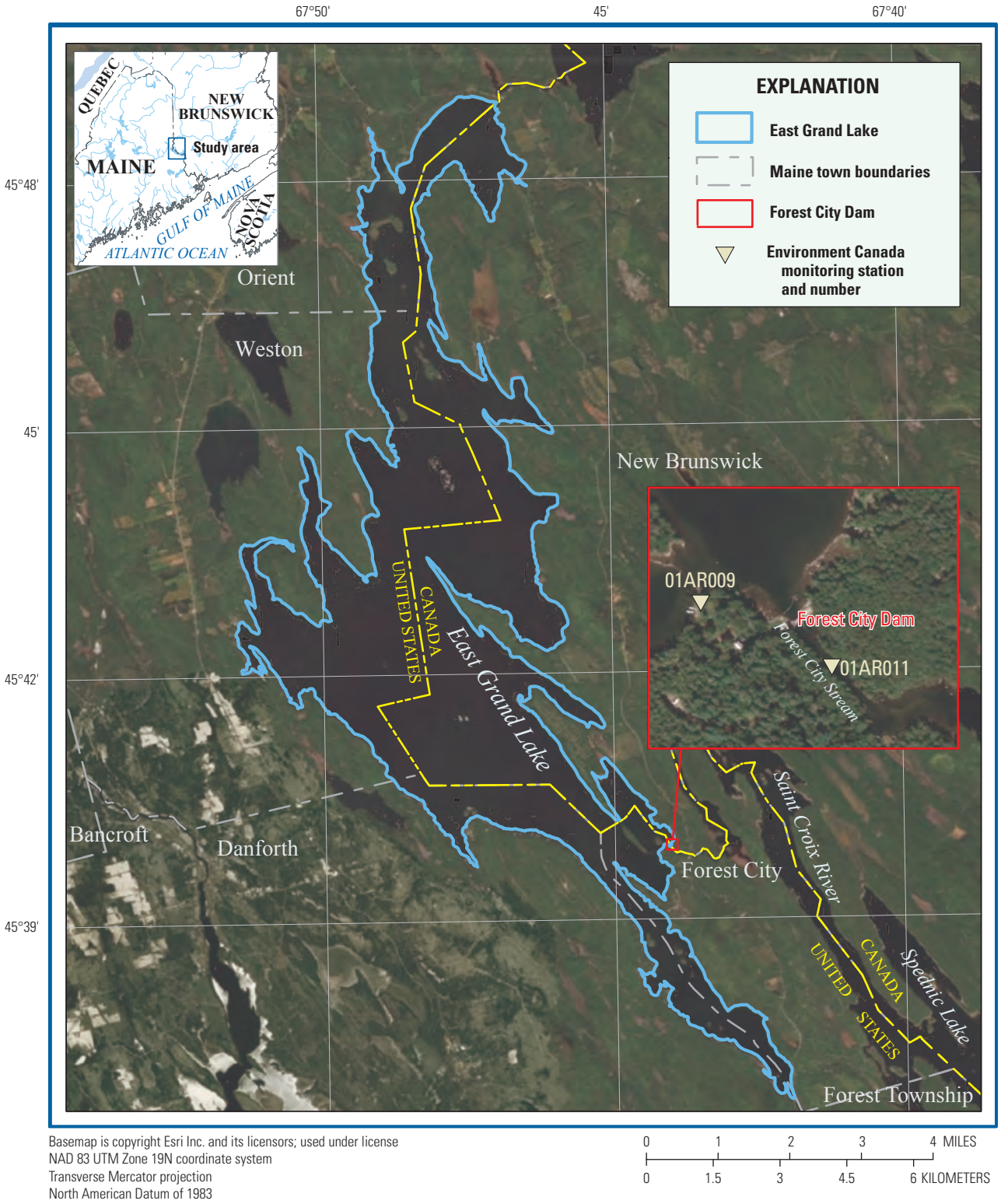

Figure 1. The East Grand Lake study area in Maine, United States, and New Brunswick, Canada.

Historical Streamflow and Lake Level Data

Historical regulated daily mean streamflows at Forest City Stream below Forest City Dam at Forest City, Maine, collected at Environment Canada (EC) monitoring station 01AR011 from 1975 to 2015 and historical daily mean lake levels at Grand Lake at Forest City, Maine, collected at EC monitoring station 01AR009 from 1969 to 2016 (Environment Canada, 2017) were used in the analysis. Daily mean streamflows from 1975 to 2015 were averaged to compute historical monthly means and mean annual streamflow. Monthly mean streamflows historically were lowest in November (114 ft^3/s; 3.23 m^3/s) and highest in September (318 ft^3/s; 9.01 m^3/s) (table 1); mean annual streamflow over this same period was 235 ft^3/s (6.66 m^3/s). Monthly mean lake levels for the period 1969 to 2016 in East Grand lake ranged from 431.3 ft (131.5 m) (October) to 434.0 ft (132.3 m) (May), with an average annual value of 432.5 feet (131.8 m) (Environment Canada, 2017) (table 2).

Estimates of Unregulated Streamflows

Estimated unregulated streamflows at the Forest City Stream station were calculated by using regression equations. The USGS recently completed an investigation in cooperation with the Maine Department of Transportation to derive state-wide regression equations that can be used to estimate monthly and annual mean streamflows for ungaged, unregulated rivers in Maine (Dudley, 2015). All of the regression equations used were derived on the basis of streamflow and basin characteristics from unregulated, rural drainage basins without substantial drainage improvements; therefore, application of the regression equations to any given basin assumes unregulated conditions. Variables used to estimate monthly mean and mean annual streamflows and their accuracy include drainage area (all monthly and annual flows), mean basin elevation (annual flows and July, August, September, and October flows), maximum basin elevation (November flows), the fraction of sand and gravel aquifers in the basin (July,

Table 1 Historical regulated monthly mean streamflows at Forest City, Maine, Environment Canada streamflow monitoring station 01AR011 from 1975 to 2015, and unregulated monthly mean streamflows calculated with Dudley (2015) regression equations and Dudley (2004) regression equations.

[ft^3/s, cubic foot per second; m^3/s, cubic meter per second]

Month	Historical regulated monthly mean streamflow calculated from streamgaging data[1]		Unregulated monthly mean streamflowcalculated with regression equations			Difference between historical regulated streamflows and estimated unregulated streamflows	
	(ft^3/s)	(m^3/s)	(ft^3/s)	(m^3/s)	Prediction error(percent)[4]	(ft^3/s)	(m^3/s)
January	234	6.63	[2]180	5.10	-18.0 to 21.9	54	1.53
February	250	7.08	[2]128	3.62	-11.4 to 12.9	122	3.46
March	259	7.33	[3]242	6.85	-22.4 to 28.8	18	0.51
April	241	6.83	[3]653	18.5	-16.7 to 20.0	-412	-11.7
May	264	7.48	[3]521	14.8	-16.8 to 20.2	-258	-7.31
June	260	7.36	[3]212	6.00	-15.2 to 17.9	48	1.36
July	237	6.71	[2]102	2.89	-14.4 to 16.8	135	3.82
August	222	6.29	[2]63.5	1.80	-19.1 to 23.7	159	4.50
September	318	9.01	[2]59.2	1.68	-18.5 to 22.7	259	7.33
October	228	6.46	[2]184	5.21	-19.6 to 24.4	44	1.25
November	114	3.23	[2]313	8.86	-12.9 to 14.8	-199	-5.64
December	198	5.61	[2]286	8.10	-16.6 to 20.0	-88	-2.49
Annual	235	6.66	[2]261	7.39	-9.9 to 10.9	-26	-0.74

[1]Environment Canada (2017).

[2]Dudley (2015).

[3]Dudley (2004).

[4](PRESS/*n*)1/2, prediction error sum of squares, in percent, where *n* is the number of streamgages used in the regression equation derivation(Dudley 2004, 2015).

Table 2. Historical monthly mean lake levels at Grand Lake at Forest City, Maine, Environment Canada monitoring station 01AR009 from 1969 to 2016, and monthly mean lake levels associated with unregulated flows calculated by using a hydraulic model.

[ft, foot; m, meter]

Month	Historical regulated monthly mean lake level[1]		Modeled Unregulated monthly mean lake level (all gates open)		Modeled unregulated monthly mean lake level (two gates open)		Difference in historical regulated monthly mean lake levels and modeled unregulated monthly mean lake levels with all gates open	
	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
January	432.1	131.7	428.5	130.6	428.5	130.6	3.6	1.1
February	431.9	131.6	428.2	130.5	428.2	130.5	3.8	1.2
March	431.8	131.6	428.8	130.7	428.8	130.7	3.0	0.91
April	432.9	131.9	431.1	131.4	432.5	131.8	1.8	0.55
May	434.0	132.3	430.4	131.2	431.6	131.6	3.5	1.1
June	433.9	132.3	428.6	130.6	428.6	130.6	5.2	1.6
July	433.5	132.1	428.0	130.5	428.0	130.5	5.4	1.6
August	432.9	131.9	427.8	130.4	427.8	130.4	5.2	1.6
September	432.1	131.7	427.7	130.4	427.7	130.4	4.4	1.3
October	431.3	131.5	428.5	130.6	428.5	130.6	2.8	0.85
November	431.5	131.5	429.1	130.8	429.1	130.8	2.4	0.73
December	432.0	131.7	429.0	130.8	429.0	130.8	3.1	0.94
Annual	432.5	131.8	428.9	130.7	428.9	130.7	3.7	1.1

[1]Environment Canada (2017).

August, September, October, and annual flows), distance from the coast (February, March, and May flows), mean basin slope (February flows), mean annual precipitation (April flows), and the percent of hydrologic group A (well drained soils; Soil Survey Staff, Natural Resources Conservation Service, 2017) (December and January flows). Variables needed to estimate peak flows for selected recurrence intervals and their accuracy include drainage area and percent wetlands (the areal percentage of all types of wetlands including lakes, ponds, reservoirs, and rivers) in the basin (Hodgkins, 1999). Characteristics of East Grand Lake Basin upstream of the station on Forest City Stream are presented in table 3.

The Dudley (2015) equations were used to estimate unregulated mean monthly and annual streamflows at Forest City Stream for the months July through February (table 1). For March, April, May, and June, however, equations developed by Dudley (2004) rather than the 2015 equations were used because the 2004 equations did not require the dependent variable "percent open water in the basin" for estimation of mean monthly streamflow. Percent open water in the basin for this site is well outside the range of the percent open water at sites used to develop the 2015 equations; hence, the 2015 equations are not necessarily appropriate for estimating streamflow at this site for those months because errors would be unknown. Calculations for 2- to 100-year peak flows were made using regression equations developed by Hodgkins

Table 3. Drainage basin characteristics of East Grand Lake in Maine, United States, and New Brunswick, Canada, as determined through the U.S. Geological Survey web application StreamStats.

[StreamStats is available at https://water.usgs.gov/osw/streamstats/. mi^2, square mile; km^2, square kilometer; ft, foot; m, meter; km, kilometer]

Basin characteristic	Value
Drainage area[1]	133 mi^2 (344 km^2)
Mean basin elevation	518.9 ft (158.2 m)
Maximum basin elevation	1,202 ft (366.4 m)
Fraction of sand and gravel aquifers	0.003 (unitless)
Percentage of area with hydrologic soil type A (well drained soils)[2]	0.23 percent
Shortest distance from coastline to basin centroid	101 miles (162 km)
Mean basin slope	4.46 percent
Percentage of wetlands	19.3 percent

[1]Drainage area determined with a geographic information system (GIS) using USGS StreamStats (https://water.usgs.gov/osw/streamstats/) and delineated from a point at latitude 45.66467, longitude -67.7341. Does not supersede the drainage area of 357 km^2 published by Environment Canada.

[2]U.S. Department of Agriculture Natural Resources Conservation Service SSURGO database (Soil Survey Staff, Natural Resources Conservation Service, 2017).

(1999) (table 4). The calculated basin characteristics, peak flows, and most monthly estimates of streamflow were from the USGS web application StreamStats (U.S. Geological Survey, 2017; https://streamstats.usgs.gov/ss/). The exception to this is that the March through June mean monthly streamflows were calculated manually with basin characteristic values determined in StreamStats and by the Dudley (2004) equations.

The unregulated mean annual streamflow at Forest City Stream estimated using the regression equation in Dudley (2015) is 261 ft^3/s (7.39 m^3/s). This shows good agreement with the mean annual flow calculated at the Forest City Stream station of 235 ft^3/s (6.66 m^3/s) (Environment Canada, 2017) (table 1). Although the streamflows are currently (2017) regulated, the amount of water that passes annually should be similar to natural mean annual flow. The agreement lends additional confidence to the monthly estimates. Unregulated monthly mean streamflows calculated by using the regression equations range from 59.2 ft^3/s (1.68 m^3/s) in September to 653 ft^3/s (18.5 m^3/s) in April (fig. 2, table 1). Estimated unregulated flood flows range from a 2-year peak flow of 1,650 ft^3/s (46.7 m^3/s) to a 100-year peak flow of 4,210 ft^3/s (119 m^3/s) (table 4) (Hodgkins, 1999). Prediction errors for regression equation estimates are calculated as the prediction error sum of squares (PRESS statistic) in percent (tables 1 and 4). The PRESS statistic is a validation-type statistic analogous to the average standard error of prediction (Hodgkins, 1999).

Table 4 Unregulated flood flows for Forest City Stream at Forest City, Maine, calculated with regression equations.

[ft^3/s, cubic foot per second; m^3/s, cubic meter per second]

Annual peak-flow recurrence interval	Estimated unregulated flood flows[1]		Prediction error for unregulated flood flows[2]
	(ft^3/s)	(m^3/s)	(percent)
2-year peak flow	1,650	46.7	-29.7 to 42.2
5-year peak flow	2,300	65.1	-30.3 to 43.5
10-year peak flow	2,760	78.2	-31.1 to 45.2
25-year peak flow	3,330	94.3	-32.5 to 48.3
50-year peak flow	3,760	106	-33.8 to 51.0
100-year peak flow	4,210	119	-34.8 to 53.5

[1]Hodgkins (1999).

[2](PRESS/n)1/2 , prediction error sum of squares, in percent, where n is the number of streamgages used in the regression equation derivation (Hodgkins, 1999).

Field Surveys

Dam geometry and the surrounding topography and bathymetry at the Forest City Dam outlet of East Grand Lake were surveyed by using differential leveling and acoustic Doppler current profiler (ADCP) measurements in October 2017 (Lombard, 2018). A Topcon DL–500 digital autolevel with a Sokkia BGS50G3 fiberglass digital level rod was used in accordance with USGS policy outlined in Kenney (2010) to collect water-surface elevations before the ADCP transects were run. The autolevel also was used to collect elevations on the upstream and downstream faces of the dam and water-surface elevations at the beginnings and ends of the field surveys. Tape-downs were obtained from these points to determine the elevations of the three dam gates and the fish ladder. The beginning point for the level loop was a brass monument (tablet) labeled "International Boundary Commission, Reference, Mon. 56, 1919, 1999" established as USGS control point FC_IBC56 in 2013 (Lombard, 2013). Monument FC_IBC56 is just north of the road to the dam and 164 ft (50 m) southwest of the dam and has an elevation of 438.05 ft (133.516 m) above the North American Vertical Datum of 1988. It is also an EC control point for the 01AR009 Grand Lake gage; however, it is in Maine.

Depth data upstream and downstream from the Forest City Dam were collected with a Teledyne RD Instruments (TRDI) 1,200-kilohertz (600-kilohertz vertical beam) RiverPro ADCP. The data were collected and processed with TRDI WinRiver II software (version 2.18) in accordance with USGS policy in Mueller and others (2013). Location information for the ADCP was collected with a Hemisphere A101 differential global positioning system. Single transects were observed starting at the upstream face of the Forest City Dam and moving lakeward in alternating directions, with one person on either bank of the lake pulling the tethered ADCP from one bank to the other.

ADCP depths were converted to bottom elevations by using the surveyed water-surface elevations described above. During the bathymetric data collection water-surface elevations averaged 430.5 ft (131.2 m) upstream from the dam and 428.4 ft (130.6 m) downstream from the dam (Lombard, 2018). Latitudes, longitudes, and bathymetric elevations were converted to stations and elevations for the HEC–RAS hydraulic model by using U.S. Army Corps of Engineers HEC–GeoRAS software (U.S. Army Corps of Engineers, 2009).

Modeled Unregulated East Grand Lake Levels

A HEC–RAS version 5.0.3 hydraulic model was used to compute water-surface profiles through the dam (U.S. Army Corps of Engineers, 2016) from the unregulated monthly and annual streamflow and peak flow estimates and bathymetric data described above. HEC–RAS is a one-dimensional step-backwater model with steady-state or unsteady-state options for flow computation. Hydraulic analyses require the estimation of energy losses that result from frictional resistance exerted by a channel on flow. Energy losses are quantified by the Manning's roughness coefficient (n-value). The channel n-values were estimated at 0.04 and the overbanks

n-values at between 0.08 and 0.1. All unregulated monthly and annual streamflows and peak flows calculated by using regression equations were routed through the hydraulic model; the steady-state computation option was used for two gate scenarios: (1) with all three gates open, and (2) with two of the three gates open. The fish ladder was not included in the hydraulic model because it likely would have negligible effect on unregulated lake levels because of its elevation relative to the bottom of the gates and its low conveyance. The datasets used in this study are available through a data release (Lombard, 2018).

Modeled unregulated mean monthly lake levels resulting from estimated unregulated streamflows, when run through the Forest City Dam with all three gates open, range from 427.7 ft (130.4 m) in September to 431.1 ft (131.4 m) in April. When the same flows are run through the dam with two gates open and one gate closed, lake levels range from 427.7 ft (130.4 m) in September to 432.5 ft (131.8 m) in April (fig. 3, table 2). Modeled unregulated mean monthly lake levels are roughly the same with all gates open as with only two gates open in all months of the year except April and May, when they differ by 1.4 ft (0.43 m) and 1.2 ft (0.37 m), respectively. Estimated monthly unregulated lake levels with all gates open would be from 1.8 to 5.4 feet (ft) (0.55 to 1.6 m) lower than they have been historically in all months, with the biggest differences in summer and early fall (fig. 3, table 2).

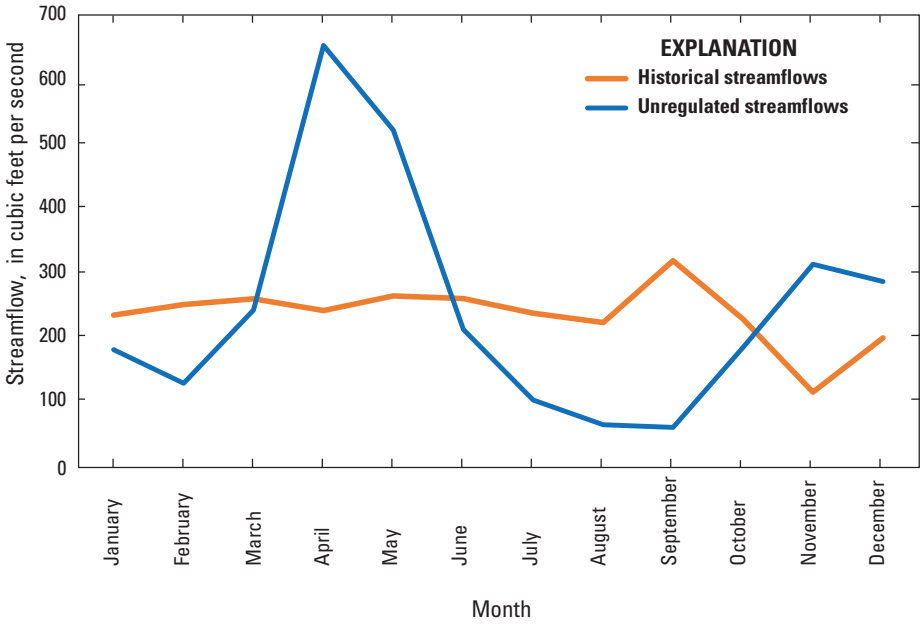

Figure 2. Historical regulated monthly mean streamflows at Forest City, Maine, Environment Canada streamflow monitoring station 01AR011 from 1975 to 2015, and estimated unregulated monthly mean streamflows calculated by using regression equations (Dudley, 2004; 2015).

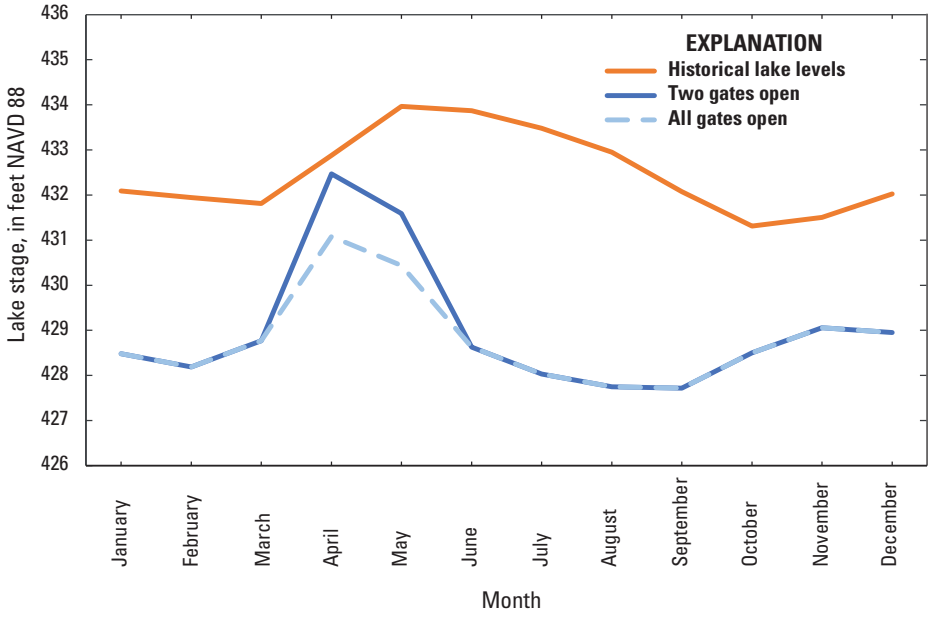

Figure 3. Historical lake levels at East Grand Lake at Forest City, Maine, Environment Canada monitoring station 01AR009 from 1969 to 2016, and unregulated mean monthly lake levels calculated by using a hydraulic model.

Lake levels resulting from peak flows run through the outlet dam with all three gates open range from 435.3 ft (132.7 m) for a peak flow with a 2-year recurrence interval to 438.3 ft (133.6 m) for a peak flow with a 100-year recurrence interval (table 5). Lake levels resulting from peak flows run through the outlet dam with two gates open range from 437.2 ft (133.3 m) for a peak flow with a 2-year recurrence interval to 438.7 ft (133.7 m) for a peak flow with a 100-year recurrence interval (table 5). Differences in lake levels associated with peak flows run through the model with three gates open versus with two gates open range from 1.9 ft (0.58 m) lower for 2-year peak flows to 0.4 ft (0.12 m) lower for 100-year peak flows.

Table 5. East Grand Lake levels associated with unregulated flood flows calculated by using a hydraulic model, Maine, United States, and New Brunswick, Canada.

[ft, foot; m, meter]

Annual peak-flow recurrence interval	Modeled lake levels (all three gates open)		Modeled lake levels (two gates open)	
	(ft)	(m)	(ft)	(m)
2-year peak flow	435.3	132.7	437.2	133.3
5-year peak flow	437.1	133.2	437.7	133.4
10-year peak flow	437.5	133.4	438.0	133.5
25-year peak flow	437.8	133.4	438.3	133.6
50-year peak flow	438.1	133.5	438.5	133.7
100-year peak flow	438.3	133.6	438.7	133.7

Summary

The U.S. Geological Survey, in cooperation with the International Joint Commission, compiled historical data on regulated streamflows and lake levels and estimated unregulated streamflows and lake levels on Forest City Stream below Forest City Dam at Forest City, Maine, and East Grand Lake on the United States-Canada border between Maine and New Brunswick to study the effects on streamflows and lake levels if all three or if two dam gates are left open. Opening the gates at the Forest City Dam on the St. Croix River will likely lead to a wider range of streamflows. Historical regulated mean monthly streamflows remained relatively flat throughout the year, fluctuating between 114 cubic feet per second (ft^3/s) (3.23 cubic meters per second [m^3/s]) in November and 318 ft^3/s (9.01 m^3/s) in September. Mean monthly flows would likely range between 59.2 and 653 ft^3/s (1.68 and 18.5 m^3/s) if all three of the gates of the dam were opened and flow were unregulated; lower flows would occur in the summer and early fall, particularly August and September and the higher flows would occur in April and May. Mean monthly lake levels for the period 1969 to 2016 in East Grand lake ranged from 431.3 feet (ft) (131.5 meters [m]) (October) to 434.0 ft (132.3 m) (May), with an average annual value of 432.5 feet (131.8 m). Monthly unregulated lake levels would be from 1.8 to 5.4 feet (ft) (0.55 to 1.6 meters [m]) lower than they have been historically during all months, with the biggest differences in summer and early fall.

Estimated unregulated peak flows range from 1,650 ft^3/s (46.7 m^3/s) for a 2-year recurrence interval to 4,210 ft^3/s (119 m^3/s) for a 100-year recurrence interval. Lake levels corresponding to unregulated peak flows with all of the gates at the outlet dam open range from 435.3 ft (132.7 m) for a streamflow with a 2-year recurrence interval and 438.3 ft (133.6 m) for a streamflow with a 100-year recurrence interval.

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