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Ice-Cover and Jamming Effects on Inline Structures and Upstream Water Levels

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Abstract

River ice cover is a reoccurring phenomenon in the Northern United States every year. Sheets and layers of ice result in a rise of water surface elevation and may lead to ice jams in a river. This research explains the modeling of a river reach through Northern Illinois containing a structural weir and how the water profile is effected during ice cover and ice jam events. The Hydraulic Engineering Center's River Analysis System was used in conjunction with Esri ArcMap software to model a portion of the river for analysis. The study area of the Rock River flowing through Oregon, IL is known to freeze and ice over during the winter months in Northern Illinois. Data from the United States Geological Survey and National Oceanic and Atmospheric Administration were utilized to obtain cross-section and discharge measurements. The impacts of an ice jam occurring upstream of the weir and downstream of the weir were studied. The effects of the ice jam on the upstream water levels were also evaluated to observe if any flooding may occur inside the town or even farther upstream. Results of the ice cover and ice jam data were then compared to those of the Rock River under normal open flow conditions thus observing the change in water level, Froude number, and flow velocity. Results from this study help to point out the significance of ice jam occurrences and their effects on inline structures and future flooding concerns in the surrounding area.

1. Introduction

The effect of climate change on hydrologic cycles over a basin has become a growing concern for researchers (Carrier et al., 2013, 2016; Sagarika et al., 2015a,b; Ghimire et al., 2016). The extreme hydrologic events such as floods and droughts are connected to global climate change and understanding the relationship between climate change and hydrology may assist in more efficient water management (Kalra et al., 2013a,b; Sagarika et al., 2014; Tamaddun et al., 2016a,b; Thakali et al., 2016; Pathak et al., 2016a,b). Presence of ice in northern US rivers during winter months is common (Kalra and Ahmad, 2011) and availability of ice is fluctuating each year based on climate change. Ice jams may form on rivers, lakes, and streams in cold regions during winter season The Initial ice cover formation triggers accumulation of ice which then restricts water flow ultimately giving rise to ice jam formation (Sui et al., 2002). Ice jamming and ice induced scouring are some of the major issues that arise from ice interference in a river. The ice jams complicate normal flow processes causing impact on navigation system that depend on water levels (Derecki et al., 1986). Ice jam when continue to advance may cause severe bank and bed scouring in a river (Smith, 1979). There are several ways an ice jam can create complexities with the normal river flow causing serious economic and ecological effects (Prowse et al., 1994; Beltaos et al., 2001). Most scientific literatures (e.g., Bolsenga, 1968; Henoch, 1973; Smith 1980; Beltaos, 1983; Lu et al., 1999; She et al., 2006; Kalra and Ahmad, 2012; Paz et al., 2013; Carson et al., 2011) have depicted the ice jam-induced flooding and other effects on ecosystem. Growth of ice cover may initiate swift increase in river water level instigating inundation and destruction to

property and infrastructures such as bridges, roads, and buildings. . Ice movement can also affect the ecosystem through scouring and erosion of riverbeds and riverbanks, nearby vegetation, aquatic habitat, and wildlife. The rapidity of an ice event gives officials little time for evacuating and mitigating purpose that can prevent costly damage. Ice jam damage have been estimated to cost over $100 million annually in the United States (White, 2004).

It is crucial to anticipate the probable river stage resulting from ice jamming so that minimization of hazard and effective floodplain management can be achieved (Healy et al., 2006). Forecasting of ice jam at particular location is a challenging job but ice modeling can help in predicting the water levels caused by ice jam, extent of jam, channel bathymetry and flow condition of river (Beltaos et al., 2013). Analysis of river ice conditions for planning, design and operations of water resources can be done using computer models to simulate complex relationships of ice mechanisms (Shen, 2002). Modeling a river for ice jam effects can be helpful in studies related with the flood mitigation and other ice related studies (White, 2004). Ice modeling has broad usage in designs purpose to find normal and extreme flow conditions. Several computer models are available to account river ice jam like ICEJAM, JTT, RIVICE , RIVJAM and HEC-RAS.

In this current study, simulation of ice in a river is carried out using The Hydrologic Engineering Centers River Analysis System (HEC-RAS). Some of the salient features of HEC-RAS are easy to operate, convenient, suitable to apply in different open water, ice covered, and ice jam conditions within a given computational reach (Beltaos et al., 2013). HEC-RAS has capability to simulate ice-covered channels with existing ice parameters, or to simulate wide river jams by using the jam force balance equation, composite ice roughness formula and the standard step backwater equation (Daly et al., 2003). Based on cross section data of the river, ice cover thickness and roughness and streamflow data, ice jam analysis can be done. Location of the ice jam must be specified before the analysis. The study focuses on how the water profile changes under ice jam conditions. Comparison of water profile under different conditions such as open channel condition, ice covered condition and ice jam condition showed the effect of ice cover in a river. The accumulation of ice jam and the associated hydraulic parameters, such as water level, flow velocity and Froude number have been simulated and compared using the HEC-RAS model in this study.

2. Study area and data

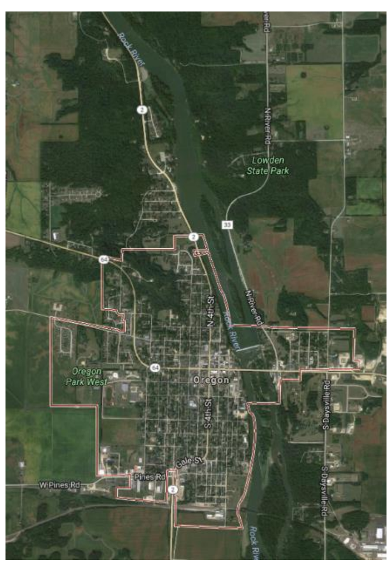

Figure 1: An overview of Oregon, IL along the Rock River in Northern Illinois

The study area in this research includes a river reach in the Rock River near Oregon, Illinois (Figure 1). The Rock River, approximately 300 miles in length, originates in Wisconsin flows through Illinois, ultimately joins the Mississippi River near Rock Island. Frequent ice jams and subsequent flooding during winter season have been reported in the past. This provided motivation to select this region for the current study. The reach length for HEC-RAS modeling is nearly 7000 ft flowing through the town of Oregon and lies in between Byron and Dixon that are upstream and downstream, respectively.

The datasets used comprise of cross section data, streamflow data, and ice cover data for the analysis. A brief description of the data and their sources is provided below.

2.1 Cross Section Data

Digital Elevation Model (DEM) data were obtained from United States Geological Survey (USGS) online database (https://viewer.nationalmap.gov/basic/). In this study 1 meter DEM for the Oregon region was downloaded.

2.2 Ice Cover Data

Unlike discharge measurements, inspection of ice cover thickness can be difficult in a river reach. Lack of existing data and complex physical process involved in the ice formation further complicate the estimation of ice thickness. Therefore, ice thickness is estimated based on meteorological data as suggested by US Army Corps of Engineers Cold Regions Research & Engineering Laboratory. The daily air temperature data of Dixon, Illinois is collected from National Oceanic and Atmospheric Administration (NOAA) website (https://www.ncdc.noaa.gov/data-access). Climate data from 1996 to 2008 is used to estimate the river ice thickness by freezing degree-days method.

2.3 Streamflow Data

Streamflow data of the Rock River is derived from USGS online database. Average long-term minimum and maximum value of the flow were obtained along with average streamflow from the gage stations at Byron and Dixon. To address the disparity in discharge values from tributaries of Rock river, upstream and downstream gage stations are chosen.

3. Methods

The following describes the methods used to obtain cross-sectional data for the Rock River reach. Equations and data used adopted in the study for ice sheet thickness and ice jam location determination are also explained below.

3.1 GIS and HEC-GeoRAS

The data input obtained for use in ArcMap 10.2.2 included a 1-meter digital elevation model (DEM). From the DEM river parameters were extracted into hydraulic modeling tool HEC-RAS. Extraction of cross-sections into HEC-RAS require river digitization with HEC-GeoRAS and the DEM be converted into a Triangulated Irregular Network (TIN) model. Cross-sections containing river channel depths and lengths were then imported into HEC-RAS. Flowrate data from the United States Geological Survey (USGS) was obtained from upstream and downstream stations of our study area. Maximum, minimum, and an average flowrate from the months of December, January, and February were used to set three profiles. Upstream and downstream

slopes for HEC-RAS boundary conditions were calculated in GIS with DEM elevation values extended beyond the extent of our modeled reach lengths.

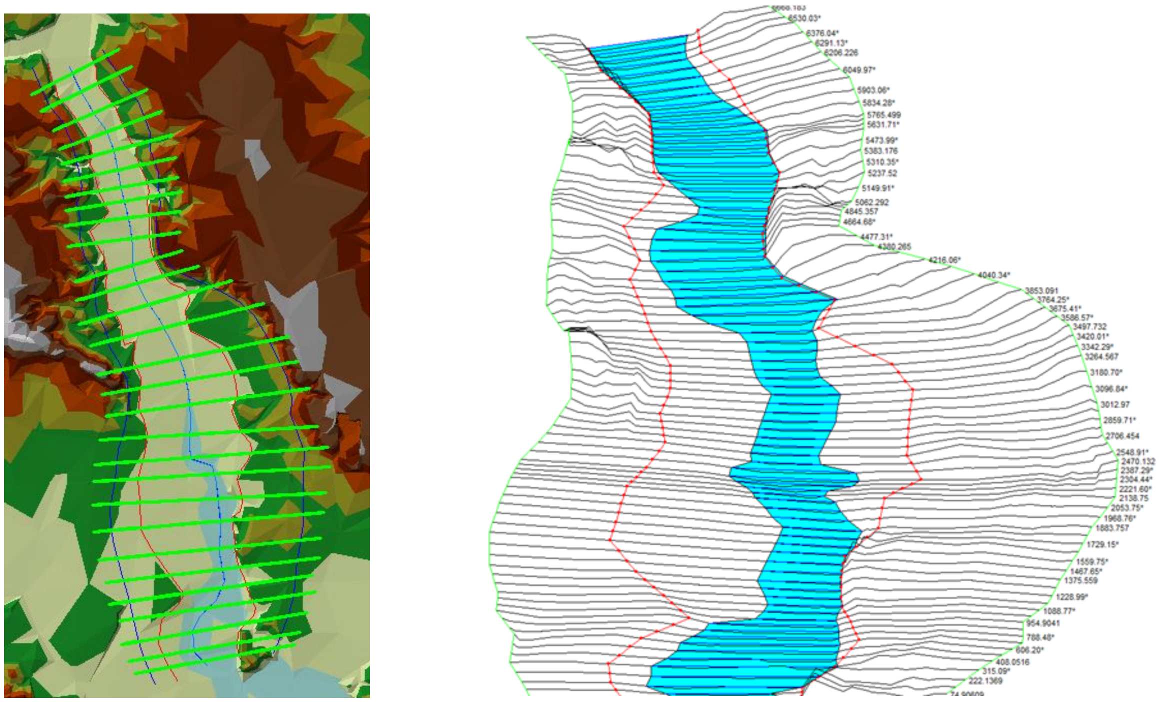

Figure 2: (left) GIS TIN of study area with HEC-GeoRAS river digitization (right) imported cross-section xyz plot of HEC-RAS model

3.2 Ice Calculations

Inputs for ice cover into HEC-RAS only require ice thickness measurement for the channel and banks, and the Manning's roughness coefficient for the ice cover. Historical temperature data from USGS in conjunction with Army Corps of Engineers river ice equation supplied the data and tools necessary to calculate the ice thickness value. The US Army Corp of Engineers has recommended to estimate ice cover based on ice formation due to heat transfer mechanism. The developed ice cover can expand further by heat transfer between atmosphere and ice. The ice thickness (t_{ice}) can be determined from accumulated freezing degree-days (AFDD). Freezing degree-days are measured for each day of winter as follows:

$$FDD= 32-T_{avg} \qquad (1)$$

Where T_{avg} is the mean value of daily air temperature in degrees Fahrenheit and thickness of ice is in inches. The AFDD value is obtained by summing the values of FDD for each day of a winter starting from October 1 to March 30. Maximum AFDD value for each winter year is selected. USACE (2002) recommends modified Stefan's equation to calculate the ice cover thickness:

$$t_{ice}=C\,(AFDD)^{0.5} \qquad (2)$$

where C is a coefficient depending on water condition and AFDD is in ^{o}F days. Based on the table of given C coefficients, 0.13 was used for the case of an average river with snow (White, 2004). The climate data from 2000 to 2010 are taken with the exclusion of years missing complete

readings, into MATLAB with the inclusion of the modified Stefan equation produced the normalized ice thickness value of 7.26 inches or 0.605 feet.

Manning's roughness coefficient was determined based on Army Corps of Engineers tables; this study area classifies as an average river with the assumption of the ice being a loose formed single layer with the recommended Manning's value of 0.02. Projected ice jam locations were selected for two separate cross-section margins. Selection was based on recommendations by Sui et al., (2005). The model was computed under open flow conditions and the cross-section stations with the lowest velocity and the stations occurring directly after the hydraulic jump non-uniform flow were selected as probable locations ice-jam formation.

4. Results

Results are described in separate sections as the methodology is broken down into multiple sections. GIS and HEC-GeoRAS analysis are outlined followed by HEC-RAS results. Finally, ice cover and ice jam profiles and tables are generated through HEC-RAS hydraulic modeling.

4.1 GIS and HEC-GeoRAS

Errors in earlier iterations of 1/9 arc-second DEM terrain files led to the search of more precise terrain maps of a 1-meter DEM. Converting DEM to TIN, HEC-GeoRAS was used to assign bank lines, streamline flow, and cut cross-sections of the study reach as shown in Figure 2. A total of 29 cross-sections were manually drawn with 53 more interpolated inside HEC-RAS, as shown in Figure 2. The final reach length of the channel of the study area starting North of Oregon, IL and continuing south all the way through the town is 1.26 miles. Using GIS, measuring upstream and downstream from the ends of the reach provided normal depth boundary condition slopes of 0.0000875 and 0.000222, respectively. All river parameters were then exported using GIS and HEC-GeoRAS.

4.2 HEC-RAS Analysis

Analysis of the Rock River model was completed in HEC-RAS. First, three different flowrate profiles were created with the same normal depth slope boundary conditions configured in GIS. 4620, 6500, and 8940 cubic feet per second were the three profiles entered as steady flow analysis. These values were observed from USGS archives for the lowest, median, and highest discharge values from river gauge station located upstream of the study area. The discharges for the winter months of December, January, and February were the only months considered and data archives were averaged from the previous 16 and 6 years from the upstream and downstream gauge stations, respectively.

As seen in Figure 3a, approximately 3000ft downstream in our reach, the weir across the river creates non-uniform flow with an increase in slope. This change in the flow regime produces a hydraulic jump under open flow conditions. When modeling the river with ice cover the layer of 0.605 feet thick ice restricts the flow and eliminates the occurrence of any hydraulic jump. This is reinforced by the data outputs of the ice cover computing run not having a Froude's number greater than 0.71 for any discharge value.

Ice cover on the Rock River increases flooding in lower elevation regions next to the river at stations 5310 and 730. As seen in Table 1 the added roughness factor associated with the ice cover on the river causes the water surface elevation to rise an average of 1.75 feet between upstream and downstream cross-sections. Flow under ice cover conditions is quite different than open flow conditions because of the additional shear stresses involved between the water and ice

sheet. Ice cover sheets on a river increases wetted perimeter of the river and consequently increases friction due to contact of water with ice at top.

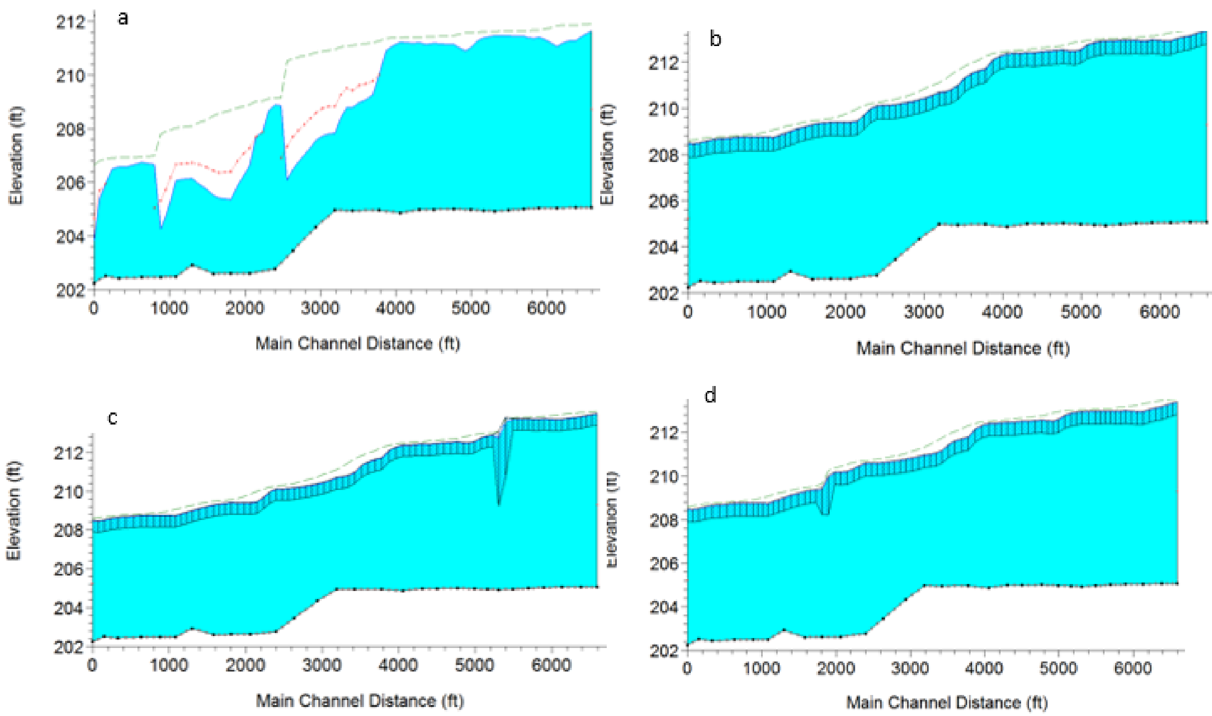

Figure 3: HEC-RAS simulation output water profiles for maximum discharge (8940 cfs), (a) open flow (b) ice cover simulation (c) ice cover with ice jam at point of lowest velocity (d) ice cover and ice jam at point of non-uniform flow occurring after weir

Forcing the model to create an ice jam in the upstream portion of the river where the lowest velocity occurs under plain ice cover does not have a great impact in the model. However, the ice jam thickness computed by HEC-RAS is larger in the upstream jam than compared to the ice jam thickness created in the downstream portion of the reach corresponding to the location of the highest velocity under plain ice cover conditions. Even with the smaller ice jam thickness downstream the river hydraulics are impacted greater, Table 1 states an upstream disturbance of increased water height of 2.5 feet.

Table 1: HEC-RAS simulation data of the four different geometric inputs. Upstream and downstream water surface elevations are recorded from river stations 6461 and 408, respectivily

	Maximum Discharge (8940 cfs)				Minimum Discharge (4620cfs)			
	Water Surface Elevation Upstream	Water Surface Elevation Downstream	Maximum Velocity	Minimum Velcoity	Water Surface Elevation Upstream	Water Surface Elevation Downstream	Maximum Velocity	Minimum Velcoity
	ft	ft	ft/s	ft/s	ft	ft	ft/s	ft/s
Open Flow	6.23	4.14	16.86	3.08	4.82	3.29	15.11	2.17
Ice Cover	8.05	6.19	6.69	2.59	6.43	4.52	5.30	1.84
Ice Jam Upstream	8.07	6.19	6.27	2.59	6.44	4.52	5.37	1.83
Ice Jam Downstream	8.73	6.19	6.69	2.50	6.64	4.52	5.73	1.80

5. Conclusions

The impacts of an ice jam occurring upstream of the weir and downstream of the weir were studied. The effects of the ice jam on the upstream water levels were also evaluated to observe that flooding may occur inside the town or even farther upstream. Comparison of ice cover and ice jam results with those of the Rock River under normal open flow conditions shows a water surface elevation rise between 1.8 and 2.5 feet. The velocity of the river lowers with the addition of ice cover and jam by a magnitude of 0.5 ft/s in the calmer sections and drops by 10 ft/s at the location of the hydraulic drop. Mainly our research helps to point out the significance of:

- The severity of ice cover on a river implementing a structural weir, by reducing the velocity downstream of the weir such that water surface elevations rise above the weir eliminating the designed hydraulic jump.
- The risk imposed of possible flooding due to an ice jam on certain rivers from the added Manning's friction due to ice cover and water surface elevation rise from the blocking of channel flows from ice.

Future studies focusing on Oregon, IL should include structural measurements of the weir that were not available to include it as an inline structure in HEC-RAS. The addition of the weir in the model would enhance the accuracy of results and should be included in any future studies. This study only used maximum and minimum observed discharge values over the previous 16 years; future research may be done for possible hydrologic events that might cause flooding considering a possible 100-year storm or another event.

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