Geomorphology 110 (2009) 212–216

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Factors influencing the recession rate of Niagara Falls since the 19th century

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ARTICLE INFO

Article history:
Received 3 February 2009
Received in revised form 10 April 2009
Accepted 14 April 2009
Available online 17 April 2009

Keywords:
Waterfall recession
Knickpoint
Bedrock river
Erosion rate

ABSTRACT

The rate of recession of Niagara Falls (Horseshoe and American Falls) in northeastern North America has been documented since the 19th century; it shows a decreasing trend from ca. 1 m y^{-1} a century ago to ca. 0.1 m y^{-1} at present. Reduction of the flow volume in the Niagara River due to diversion into bypassing hydroelectric schemes has often been taken to be the factor responsible, but other factors such as changes in the waterfall shape could play a role and call for a quantitative study. Here, we examine the effect of physical factors on the historically varying recession rates of Niagara Falls, using an empirical equation which has previously been proposed based on a non-dimensional multiparametric model which incorporates flow volume, waterfall shape and bedrock strength. The changes in recession rates of Niagara Falls in the last century are successfully modeled by this empirical equation; these changes are caused by variations in flow volume and lip length. This result supports the validity of the empirical equation for waterfalls in rivers carrying little transported sediment. Our analysis also suggests that the decrease in the recession rate of Horseshoe Falls is related to both artificial reduction in river discharge and natural increase in waterfall lip length, whereas that of American Falls is solely due to the reduction in flow volume.

1. Introduction

Waterfalls, a typical form of knickpoint or knickzone, are commonly observed in bedrock rivers across the world, including active orogens, volcanic areas and glacially- or tectonically-deformed areas (Gilbert, 1907; von Engeln, 1940; Derricourt, 1976; Bishop et al., 2005; Crosby and Whipple, 2005; Hayakawa and Oguchi, 2006, in press; Lamb et al., 2007). Headward erosion of waterfalls, often referred to as recession, is one of the central themes in fluvial geomorphology because the rates of waterfall recession are usually much greater than the other erosional processes involving bedrock rivers, such as incision of the entire riverbed (Begin et al., 1980; Kukal, 1990; Wohl, 1998, 2000; Hayakawa and Matsukura, 2002). Bedrock erosion at waterfalls can be significant even if rivers lack transported sediment to act as a tool of abrasion, probably due to the frequent occurrence of plucking and/or cavitation by rapid stream flows including jet flows (Barnes, 1956; Young, 1985; Bishop and Goldrick, 1992; Whipple et al., 2000; Pasternack et al., 2006). Niagara Falls is a famous waterfall in northeastern North America that has long been studied by geologists and geomorphologists (Gilbert, 1907; Spencer, 1907; Tinkler, 1987). Historical changes of the waterfall shape are well documented, especially in the last 200 years, and the actual recession rates in that period are well known. The long-term average recession rate of Niagara Falls is estimated to have been ca. 1 m y^{-1} during the Holocene (e.g., Gilbert, 1907; Ford, 1968), but it has decreased to the order of 0.1–0.01 m y^{-1} in recent decades (Tinkler, 1993). The slowing of the waterfall recession rate is commonly attributed to the reduction in water flow over the waterfall as a result of the construction of several large power plants in the river (e.g., Tinkler, 1993, 1994). These plants divert water well above the falls and return it to the Niagara River well below the falls. The shape of the falls in plan has also changed during the recession process, and the curved shape of the waterfall crest (the 'horseshoe' shape) is supposed to be more stable in its stress distribution and thereby decreases the recession rate (Philbrick, 1970). The greater length of the curved lip may also cause the stream to be shallower with less tractive force at the lip, also reducing the recession rate, although the effects of lip length on the recession of Niagara Falls are yet to be quantified. Here we quantitatively examine the recession rate of Niagara Falls based on a previously proposed model, which estimates the waterfall recession rate from relevant physical parameters including the stream discharge (total flow) and waterfall shape.

2. Existing record of recession rates of Niagara Falls

Niagara Falls is located in the middle portion of the Niagara River, draining northward from Lake Erie to Lake Ontario (Fig. 1). The water of the Niagara River is supplied from the upstream Great Lakes, of glacial origin, and the stream discharge is controlled mainly by the water level in the lakes, not by immediate precipitation. The climate in the area is relatively cold, with active frost weathering of bare rocks exposed along the river from winter to spring.

The waterfall originally formed at the Niagara Escarpment running west to east between the lakes, when the Laurentide ice sheet had

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0169-555X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2009.04.011

Fig. 1. Study site. Niagara Falls at present comprises two major falls, Horseshoe Falls and American Falls.

receded and the river started draining over the escarpment approximately 12,500 years ago (Tinkler et al., 1994). Since then the waterfall has receded for ca. 11 km, leaving a deep narrow gorge downstream, called the Great Gorge. The long-term mean recession rate of the waterfall is therefore approximately 1 m y^{-1}, although the rate was considerably lower for about 5000 years during 10,500–5500 yBP (ca. 0.1 m y^{-1} at minimum), due to the abrupt decrease of flow caused by water level lowering and changes in stream courses in the upstream lakes (Lewis and Anderson, 1989; Tinkler et al., 1994). The mean recession rate prior to that interval was similar to that after 5500 yBP (ca. 1.6 m y^{-1}).

Niagara Falls at present consists of several falls, due to diversion of the stream slightly upstream of the site. The largest fall in the western Canadian side, named Canadian or Horseshoe Falls and henceforth referred to as the Horseshoe, has a horizontal curved 762-m-long rim, slightly overhanging face, and a single uninterrupted fall of water with a 51-m height. Another fall at the eastern side, named American Falls, has a relatively straight rim with a length of 335 m. The face of American Falls is nearly vertical but there is no overhang and the lower portion is filled with fallen rock blocks, like talus deposit, for nearly half of its total height of 54 m.

Changes to Niagara Falls during historical times have been recorded in various documents since the 1600s. The early records were provided simply as artists' pictures, but since the 19th century detailed topographic measurements have been conducted by geologists. Philbrick (1970) gave a detailed summary of the changes in horizontal morphology of Niagara Falls based on the literature, so that we can see the dimensions of the waterfalls in the past (Fig. 2). The lip length of the Horseshoe has increased dramatically as its horizontal shape became progressively more curved over recent centuries, whereas that of the American Falls has merely changed. The height

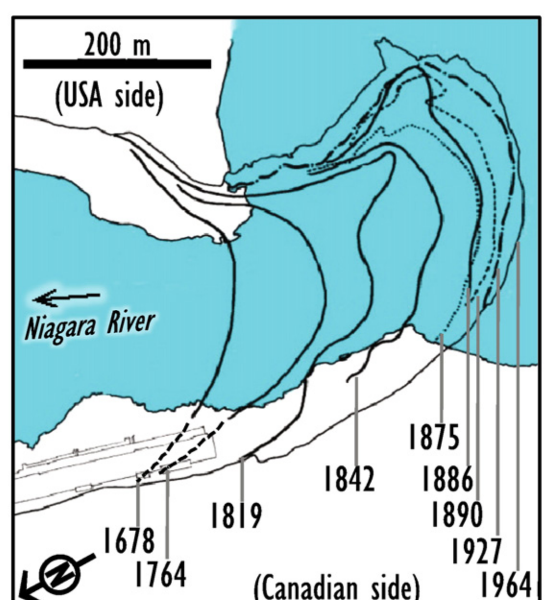

Fig. 2. Historical changes of the plan shape of Horseshoe Falls (after Philbrick, 1970).