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Postglacial Recession Rates of Waterfalls in Alpine Glacial Valleys

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Abstract

The timing of formation of waterfalls at the outlet of glacial hanging valleys correspond to that of disappearance of glaciers. Since the original location of such waterfalls is at the wall of the U-shaped valley sculpted by the mainstream glacier, average rates of postglacial recession of the waterfalls can be estimated by dividing the distance from the wall by the formative age. This study examines recession rates of such waterfalls in the Swiss Alps and in the western North America, with regard to the factors affecting the recession rates using an empirical model. Despite possible abundant supply of rock particles from upstream glaciers, the recession rate of the waterfalls matches well with the model, suggesting insufficient transport capacity in these areas.

Key words: *waterfall, U-shaped valley, fluvial erosion, bedrock*

Introduction

Deeply incised V-shaped valleys are often formed by fluvial incision, whereas U-shaped valleys are usually formed by glacial erosion. Because the erosion rate by glacial processes are much higher than that by fluvial erosion, the role of glacial erosion in shaping mountainous areas is often considerably higher than fluvial erosion particularly in cold, high mountains and plateaus. However, fluvial erosion dominates even in such places if climate gets warm and glaciers disappear. Post-glacial erosion by rivers in the Holocene are thus an important process shaping the landforms in areas where glaciers are once dominant but presently disappeared.

In glacially sculpted U-shaped valleys, hanging valleys are often exposed and waterfalls are formed at the outlet of the hanging valleys after the disappearance of glaciers. Due to the erosion at these waterfalls, smaller V-shaped valleys are formed cutting the sidewalls of the U-shaped valleys. There remains a question: how rapidly this kind of fluvial valleys are eroded after the disappearance of glaciers? The rate of waterfall recession is an important issue to answer this question, because the waterfall recession rate is often considerably higher than the other processes of fluvial erosion

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into bedrock (e.g., Begin et al., 1980; Wohl, 1998). In this study recession rates of some waterfalls in glacial U-shaped valleys in the Swiss Alps and western North America are examined in terms of a waterfall recession rate model proposed by Hayakawa and Matsukura (2003a), and the factors causing the fluvial erosion in the post-glacial period are investigated.

Study sites

Study sites in the Swiss Alps are two tributary rivers, the Fedacla and Fedox Rivers, flowing into the Sela River. The Sela River flows on the bottom of a U-shaped valley in upper Engadin (Fig. 1A). The two waterfalls, here referred to as Sils Falls and Isola Falls, are located tens to hundreds of meters apart from the original location at the sidewall of the U-shaped valley. Although there still remain actual glaciers in the uppermost portion in the watersheds of the tributary rivers, the main valley glacier occupied the U-shaped Sela River valley has disappeared in approximately 11,000 years ago (Ivy-Ochs et al., 2008, 2009). Lithology in the area is sedimentary rock, and mean annual precipitation is approximately 1600 mm/y. The height and width of the waterfalls are measured using a laser range finder: 50-m high and 9-m wide at Sils Falls and 60-m high and 12-m wide at Isola Falls (Table 1).

Study site in the western North America is the lower Yosemite Falls, located in the mid portion of the Yosemite Valley, California (Fig. 1B). The waterfall is readily accessible in the Yosemite Valley, with less surface water flow in the winter season. The last glacier which had covered the Yosemite area has disappeared in approximately 13,000 years ago. Lithology in the Yosemite Valley is granite, and mean annual precipitation is approximately 950 mm/y. The height and width of the waterfall is known to be 100 m and 20 m, respectively (Table 1).

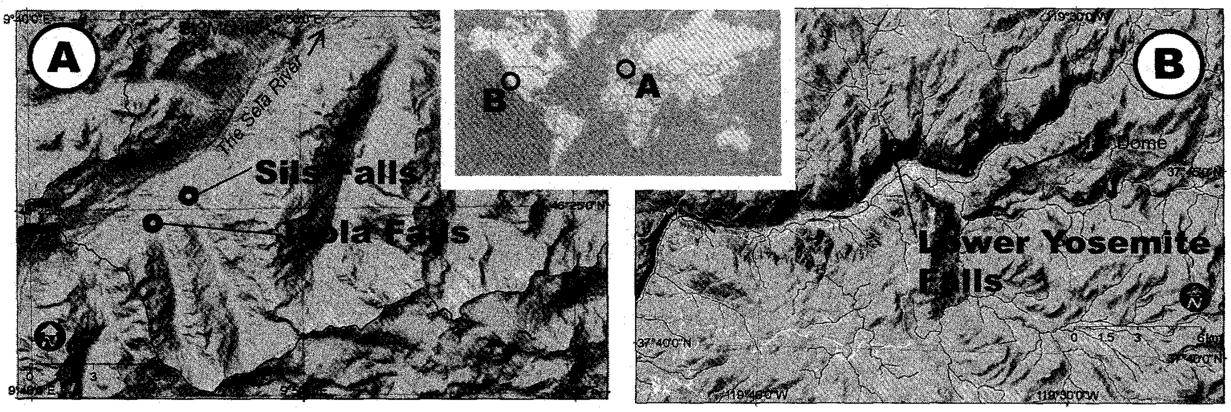

Fig. 1. Study sites in the upper Engadin, Swiss Alps (A) and the Yosemite Valley, North America (B). The terrain hillshade images area created from Swisstopo DHM25 (Digital Height Model, 25-m resolution) for (A) and NED (National Elevation Dataset, 10-m resolution) for (B).

Recession rate model

To quantify the effects of factors on the recession rate of the waterfalls, an empirical equation describing the relationship between waterfall recession rate and relevant physical parameters by Hayakawa and Matsukura (2003a) is used. Supposing that the rate of waterfall recession depends on the erosional force of the stream and the strength of the resisting bedrock, dimensional analysis finds a dimensionless index, *FR*, based on these variables:

$$FR = \frac{AP}{WH}\sqrt{\frac{\rho}{S_c}} \quad (1)$$

where A [L^2] is the upstream drainage area of a waterfall; P [$L\ T^{-1}$] is the mean annual precipitation in the drainage basin, so that the product of A and P accounts for the annual stream flow over the waterfall; W [L] and H [L] are the width (lip length) and height of the waterfall accounting for the area suffering from erosion, ρ [$M\ L^{-3}$] is the water density (10^3 kg m^{-3}), and S_c [$M\ L^{-1}\ T^{-2}$] is the unconfined compressive strength of bedrock. The dimensionless index *FR* represents the balance between the erosional force and bedrock resistance as a whole, where all these parameters are given in the SI unit.

The relationship between the *FR* index and the waterfall recession rate, E, using data for nine waterfalls in the Boso Peninsula of eastern Japan, is given as follows (Hayakawa and Matsukura, 2003a):

$$E = 99.7FR^{0.73} = 99.7\left(\frac{AP}{WH}\sqrt{\frac{\rho}{S_c}}\right)^{0.73} \quad (2)$$

This equation has been found to give valid order-of-magnitude estimates of waterfall recession rates in various study areas (Hayakawa and Matsukura, 2003b; Hayakawa, 2005; Hayakawa and Wohl, 2005; Hayakawa et al., 2005, 2008a; Hayakawa and Matsukura, 2009), with the exception of rivers carrying abundant transported sediments (Hayakawa et al., 2008b; Hayakawa et al., 2009).

Data collection and result

The data of the parameters for the study sites were collected from the field and literatures. The size of the waterfall, W and H, were measured using a laser range finder in the field with supportive use of detailed topographic maps. Drainage area (A) was obtained from digital topographic maps (DEMs), DHM25 for the Swiss area and NED for the American area, by delineating the drainage boundaries from the DEMs using GIS. The compressive rock strength S_c was converted from Schmidt hammer rebound values R_N obtained in the field. The measurement method of R_N was the repeated impact method (Matsukura and Aoki, 2004), which carries out multiple impacts

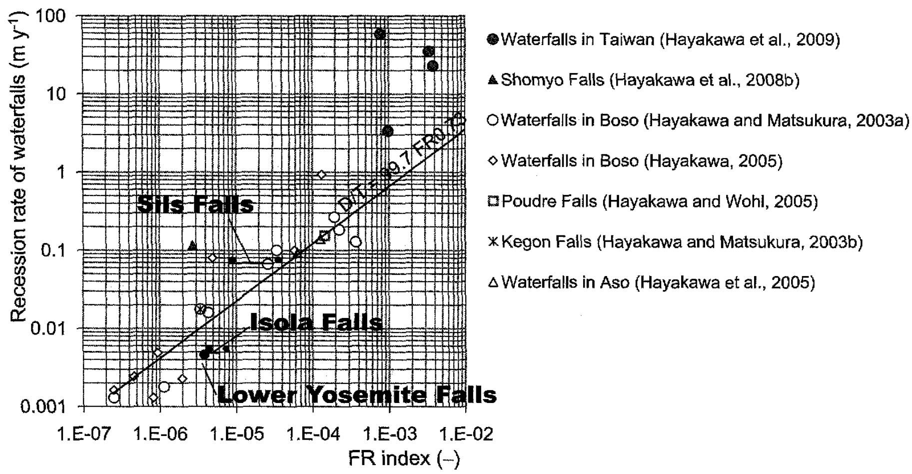

Fig. 2. Relationship between FR index and recession rates of the waterfalls. Gray-fill plots are waterfalls in rivers with abundant transported sediments, which cannot be fully described by the empirical equation. The plots for the waterfalls studied in this study are basically on the same order as those along the empirical equation.

Table 1. Recession rates and FR index components for the waterfalls studied.

	Distance of recession, D (m)	Time, T (y)	**Rate of recession, D/T (m y^{-1})**	Drainage area, A 10 (m^2)	Mean annual precipitation, P (mm y^{-1})	Width of waterfall, W (m)	Height of waterfall, H (m)	Schmidt hummer rebound value, R_N (%)	Unconfined compressive strength, S_c (10^6 N m^{-2})	**FR index, (AP/WH) (ρ/S_c)$^{0.5}$ (−)**
Sils Falls	828	11,000	**0.0753**	32.6	1600	9	50	20.8	10.76	**0.0000354**
								59.9	170.03	**0.0000089**
Isola Falls	60	11,000	**0.0055**	17.3	1600	12	60	33.7	26.77	**0.0000075**
								48.4	75.42	**0.0000044**
Lower Yosemite Falls	60	13,000	**0.0046**	109.52472	949.198	20	100	61.3	188.82	**0.0000038**

at same point location to obtain intact rock mass strength, i.e., removing the effects of weakening by weathering of surface layer in the rock. The parameter values are listed in Table 1.

Substituting the resultant parameter values into Eq. (2), the relationship between the waterfall recession rates and *FR* index is obtained (Fig. 2). The data from previous studies are also plotted in Fig. 2.

Discussion and conclusions

The plots of the recession rate data on the waterfalls studied follow the previously derived equation. The recession rate of the waterfalls is therefore basically controlled by the factors within the FR index, i.e., erosional power of streams and bedrock resistance.

Among the waterfalls, Sils Falls has relatively high recession rate, whereas Isola and Lower Yosemite Falls have lower recession rates than expected. This may reflect local variability of environmental conditions, such as the differences in lithologic structure, amount of transported sediments, and/or initial condition after deglaciation. Because these rates of recession are simply derived by dividing the total distance by total time duration, the actual recession history of the waterfall could have been more complex and various. The time of the beginning of recession of the waterfalls are particularly reinvestigated. The order-of-magnitude analysis is, however, supposed to be still in success for this kind of analysis.

In rivers below valley glaciers, there could be much amount of transported sediments supplied from the glaciers. However the data of this study do not show the discrepancy of the recession rates from the estimated values by the empirical equation. This might be due to the less intensity, or less variability of rainfall and flow discharge of rivers in these areas, so that the coarse particles from glaciers are not easily transported and most of them could have remained in the catchment basin as till deposits. The wide valley bottom of the catchments above the waterfalls of Sils and Isola is actually covered with thick sediments, but there seems less sediment output to the downstream U-shaped mainstream valley only with formation of small fan deltas. Relatively fresh landslide bodies supplied from the valley-side slopes also remain in the upper area keeping their original rectangular shape, suggesting the inactive fluvial erosion therein.

The post-glacial fluvial erosion and associated waterfall recession after deglaciation can therefore be often inactive despite the potential of abundant coarse sediment supply from the former or upstream present glaciers. The important factor should be the amount of transported sediments, which depends on the stream power, for which rainfall intensity is largely responsible. The post-glacial rainfall conditions in these areas are thus supposed to be weak, unlike Japan and some other areas where abrupt increase in rainfall intensity caused rapid landform changes. Also, snowmelt flood in these regions could have been less effective. To confirm this, further investigation should be necessary for many other sites where once glacially-covered but currently suffering from fluvial erosion.

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