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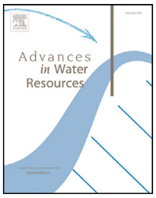

Assessment of alluvial trends toward dynamic equilibrium under chronic climatic forcing

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ABSTRACT

A remote proglacial stream in Chilean Patagonia was examined at two temporal scales to evaluate the downstream spatial progression of morphodynamics in response to chronic climatic forcing. Historic aerial imagery indicates alluvial channel response to a reduction in glacigenic sediment delivery that is driving reach-scale alterations to the channel planform and affecting the extent and character of geomorphic reaches at centurial timescales. At the decadal timescale, fluvial morphodynamics show a downstream spatial convergence toward dynamic equilibrium. The attainment of dynamic equilibrium is not considered herein, but the trend toward such a condition is discussed. Metrics of flood magnitude, hydraulic energy thresholds, inter-annual energy expenditure, variability of channel dimensions, and continuity of sediment transport capacity illustrate how alluvial systems respond to chronic climatic forcing and deglaciation subject to the constraints of valley conditions. A conceptual proglacial alluvial model is proposed in order to characterize expected fluvial changes and to evaluate the downstream spatial progression. This model is based on a combination of previous observations of alluvial evolution and a location-for-time-substitution approach validated by an intensive 3 year field data collection program.

1. Introduction

River corridor evolution and disturbance recovery depend on upstream hydraulic and sediment fluxes driving cross sectional and planform adjustment in relation to the relative geologic and valley setting (Lane, 1955; Montgomery, 1999; Surian et al., 2009). The ability to predict this downstream spatial progression of morphodynamic response to the upstream boundary conditions illustrates the evolution toward the condition of dynamic equilibrium. In glaciated watersheds the temporal trend in glacial recession and sediment delivery is already evident at low latitudes (Stott and Mount, 2007; Knight and Harrison, 2014; Frans et al., 2015) and will increasingly affect alluvial systems at higher latitudes as climate change advances; therefore a better understanding of how river morphodynamics will respond to this forcing is necessary. This understanding influences geohazard risks, infrastructure sustainability, persistence of geomorphic landscape features, sediment delivery to populated areas, aquatic biodiversity, and freshwater resources that must be addressed by river management and government policies (Chevallier et al., 2011; Jacobsen et al., 2012; Baraer et al., 2012; Beylich and Brardinoni, 2013; Fryirs, 2013; Knight and Harrison, 2014; Huggel et al., 2015; Frans et al., 2015).

The concept of dynamic equilibrium in fluvial networks is not that of a static system in the landscape, but a statistical condition that the fluvial system will evolve toward to maintain uniform sediment flux at the reach scale under the prevailing hydrologic and sedimentologic drivers (Mackin, 1948). In a laterally unconstrained system, with consistent hydrologic and sediment regimes, the river channel will migrate across the floodplain while maintaining predictable sinuosity and cross sectional characteristics until a perturbation is introduced. When a river system is subject to an episodic event (i.e. acute forcing), such as an extreme flood or debris flow, it is assumed that the system will gradually return to its prior sinuosity and channel characteristics unless any critical geomorphic threshold has been crossed (Schumm, 1973; Renwick, 1992; Richards, 2004). Chronic forcing of the hydrologic or sediment regime, such as changing climate or land cover, will adjust the channel toward the prevailing contemporary conditions (Wohl, 2005; Montgomery, 2008; Yarnell et al., 2015).

Many numerical models and empirical relations are built around the fundamental concept of dynamic equilibrium, which are frequently employed for river management and restoration activities (Leopold and Maddock, 1953; Copeland et al., 2001; Naito and Parker, 2016). However, these methods rely on empirical

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relations or regime-type equations that were developed in laboratories, canals, or streams with significant human impact (Lane, 1955; Ferguson, 1986; Leon et al., 2009; Davidson and Hey, 2011). Relations developed in laboratories can be challenged by effects of scale, in addition to omitting pertinent variables found in natural systems (i.e. vegetation, grain size distribution, bank cohesion), whereas channels impacted by anthropogenic perturbations, both current and historic, can disrupt the trajectory of alluvial evolution by constraining planform evolution or altering the geomorphic drivers (hydrology and sediment) in the watershed (Walter and Merritts, 2008; Tal and Paola, 2010; Comiti, 2012). Furthermore, the variability in hydrologic drivers makes the assumption of stationarity no longer possible in most watersheds and consequently assessing the evolutionary response toward dynamic equilibrium in sensitive alluvial systems may be problematic (Milly et al., 2008; Wyzga et al., 2012; Yarnell et al., 2015). These collective impacts on fluvial networks will alter the geomorphic drivers in the basin, thereby limiting the ability to assess whether a natural channel is approaching dynamic equilibrium owing to the myriad degrees of freedom, as well as changing the implicit relationships of coefficients in current models derived from those assumptions.

To successfully evaluate alluvial channel evolution with respect to the above challenges at a specific location or reach, long-term datasets are needed that reflect the energy level of the system, with required data in high-energy rivers needing decades to centuries and low-energy streams requiring millennia. When long-term datasets are not available an alternative method for analysis is necessary and under certain circumstances a location-for-time-substitution (LFTS) approach can be employed, whereby the spatial scale can be used as a temporal proxy to assess evolutionary trends (Paine, 1985). To effectively apply the LFTS approach (also known as ergodic approach) in an alluvial landscape, a progression from upstream to downstream must be present that is driven by a consistent range of upstream boundary conditions (i.e. discharge and sediment). The alluvial channel will adapt in the downstream direction to the introduced boundary conditions until it approaches uniform sediment flux and dynamic equilibrium (Fryirs et al., 2012; da Silva, 2013).

Such an approach was assessed in an undeveloped proglacial river system in a remote part of Chilean Patagonia through aerial imagery and repeat field surveys. Field measurements can quantify the current state of the fluvial system via the available hydraulic energy, alluvial geometry, and sediment transport capacity that are subject to the imposed valley conditions of lithology, grain size distribution, vegetation communities, as well as valley slope and width. These metrics determine the trend toward dynamic equilibrium within the fluvial system that can maintain uniform sediment flux at the reach scale; however, to understand fluvial evolution, a longer geomorphic perspective must incorporate the basin-scale drivers and how they change through time. In this study an evolutionary alluvial trend subject to chronic climatic forcing of the upstream glacial boundary conditions was recognized at the centurial timescale and a longitudinal geomorphic response toward dynamic equilibrium was identified at the decadal timescale. Collectively, data from these separate timescales indicate that the study site supports a conceptual LFTS model, which is used to explain the evolutionary trend of the fluvial system toward dynamic equilibrium under known and relatively constant upstream boundary conditions. Thus, this study 1) synthesizes the conceptual models of a number of proglacial and river corridor evolution studies and combines it with a location-for-time-substitution approach to account for channel response to a chronic, but diminishing upstream glacial influence in the watershed, 2) validates the evolutionary trajectory of the geomorphic system, via a LFTS model, through field observations to make it transferable to other deglaciating basins, 3) identifies the methodology and data requirements to effectively employ the spatial scale as a temporal analog for channel evolution, and 4) elucidates an evolutionary trend in the fluvial system toward dynamic equilibrium.

2. Rio Murta study site

Located along the periphery of the Northern Patagonian Ice Field in Chile (Fig. 1a, b), Rio Murta emanates from the glaciated hanging valleys bordering Mount Hudson (11% basin ice coverage). Valley lithology consists of mixed granodiorite and hornblende throughout the valley (Sernageomin, 2003). Receiving 1.5–2 m of precipitation annually, the upper Rio Murta Watershed is historically undeveloped, consisting of old growth temperate rainforest of mainly southern beech varieties (*Nothofagus* spp.). Aerial photographs indicate glaciers in the Murta basin terminate in stable proglacial lakes (see supplementary materials), with current glacial recession occurring in the headwaters at an estimated rate of 300–400 m/decade (from data of Aniya, 2001). Estimates of regional glacial retreat place glacial ice on the valley floor between 200 and 500 years ago during the Little Ice Age (Harrison and Winchester, 2000; Douglass et al., 2005). The valley width fluctuates between 450 and 1200 m with one active floodplain level developing between lateral moraine features. The study site (Fig. 1c) consists of a 16 km gravel-bed piedmont river (23% of total stream length that corresponds to the upper 38% of the river basin, 466 km^2). The study site incorporates a longitudinal continuum of stream morphodynamics, which was investigated as four reaches that depict unique geomorphic planforms (Fig. 1d).

The current reach-scale morphodynamics are controlled by valley conditions (Table 1), but are subject to changing climatic controls in the basin and concurrent deglaciation. The Rio Murta is a simple fluvial system that provides conditions ideal for evaluating evolutionary trajectories through a location-for-time-substitution approach. The compelling aspects of this location are the small drainage area, constant discharge through the study site with no significant tributary inputs, consistent riparian vegetation and grain size distribution, and a long-term diminishing glacial influence and related glacigenic sediment supply at the upstream end of the study site. The uppermost Reach 1 (1.8 km) is made up of a valley-wide multi-thread stream network that has 2–4 primary channels that operate during low flow periods (see supplementary materials for example cross sections). Under bankfull flow conditions (205 m^3/s) the entire width of the valley is inundated and reorganization of the primary channels occurs. A 2.4 km longitudinal survey of the bar tops indicates no break in valley slope or topographic irregularity indicative of a sediment pulse within Reach 1. In Reach 2 (4.5 km), a wandering planform exists that retains a network of shallow secondary channels spanning the entire valley similar to Reach 1, but is inset with one or two primary channels that split around vegetated bars and islands at low flow conditions. Channel reorganization is common in this reach during bankfull discharge and above as avulsion and secondary channel capture occur. Reach 3 (1.3 km) displays the transition to a sinuous single-thread channel with the presence of pool-riffle structures and overflow channels along the valley periphery that are inundated with only the highest overbank discharge events. Reach 4 (1.9 km) displays a stable sinuous pool-riffle structure with broad gravel bars and active outer bank erosion that drives lateral and downstream migration.

3. Methods

The four reaches described in the study site (Fig. 1, Table 1) were delineated from aerial photographs and field surveys depicting unique geomorphic units and breaks in longitudinal valley