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Modeling low-flow bedrock springs providing ecological habitats with climate change scenarios

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SUMMARY

Groundwater discharge areas, including low-flow bedrock aquifer springs, are ecologically important and can be impacted by climate change. The development of and results from a groundwater modeling study simulating fractured bedrock spring flow are presented. This was conducted to produce hydrological data for an ecohydrological study of an endangered species, Allegheny Mountain Dusky Salamanders (*Desmognathus ochrophaeus*), in southern Quebec, Canada. The groundwater modeling approach in terms of scale and complexity was strongly driven by the need to produce hydrological data for the related ecohydrological modeling. Flows at four springs at different elevations were simulated for recent past conditions (2006–2010) and for reference (1971–2000) and future (2041–2070) periods using precipitation and temperature data from ten climate scenarios. Statistical analyses of spring flow parameters including activity periods and duration of flow were conducted. Flow rates for the four simulated springs, located at different elevations, are predicted to increase between 2% and 46% and will be active (flowing) 1–2% longer in the future. A significant change (predominantly an increase) looking at the seasonality of the number of active days occurs in the winter (2–4.9%) and spring seasons (−0.6–6.5%). Greatest flow rates were produced from springs at elevations where sub-horizontal fractures intersect the ground surface. These results suggest an intensification of the spring activity at the study site in context of climate change by 2050, which provides a positive habitat outlook for the endangered salamanders residing in the springs for the future.

1. Introduction

Springs, a nexus between groundwater and surface water, play a vital role in the hydrologic cycle and provide critical ecological habitats. As expressions of subsurface flow, they maintain and support abundant ecosystems both near their outlets and downstream (Roy et al., 2011; Worthington et al., 2008; Barquín and Scarsbrook, 2008; van der Kamp, 1995), and they also provide important sources of surface water flow (Meyer et al., 2007; Boulton and Hancock, 2006; Smith et al., 2003; Merz et al., 2001). Considerable research has been conducted for many years to characterize flow mechanisms for high-flow springs (e.g., 1st, 2nd or 3rd magnitude flowing greater than 0.028 m^3/s) for anthropogenic uses including potable water supply and thermal baths (e.g., Malvicini et al., 2005; Bargar, 1978; Meizner, 1927), especially in karst environments (e.g., Brassington, 2007; Padilla et al., 1994; Fairleitner et al., 2005).

Low-flow intermittent (e.g., seasonal) or continuously flowing springs located in headwaters typically do not produce enough water for anthropogenic supply. For this reason, they are not a frequent research topic. However, these small springs provide important habitats for many plant and animal species (e.g., Wood et al., 2005). Knowledge about local seepage, or discharge, processes is also necessary to understand the dynamics of headwater streams which are the source of rivers and contribute to biodiversity (Meyer et al., 2007; Winter, 2007).

In the context of hydrological stressors such as climate change and increasing land development, it is critical to understand mechanisms that control spring flow to determine future viability of these important hydrological habitats. Regional or local-scale predictive studies about the impacts of climate change on groundwater resources are increasingly conducted. They show, for example, the future trends in hydraulic head and baseflow (or discharge) values stemming from a variety of recharge scenarios (e.g., Scibek et al., 2007; Jyrkama and Sykes, 2007). Climate change-induced variations in precipitation patterns (including volume and intensity) and evapotranspiration rates due to hotter temperatures, for

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example, can lead to shorter durations of spring activity and changing spring flow rates (e.g., Frisbee et al., 2013; Tambe et al., 2012; Rice, 2007). Seasonal changes in groundwater discharge are more pronounced for springs in headwater environments (where the flow paths are shorter) in contrast to discharge observed at the outlets of regional flow systems, which are more resilient to climate changes (Waibel et al., 2013; Dragoni and Sukhija, 2008).

Groundwater discharge, in the form of springs, can be represented using numerical models. These subsurface-focused or integrated (surface and subsurface flow) models can be used to conduct predictive scenarios to determine the effects of climate change, urbanization, or increasing groundwater use on small (and large) springs, which is required to implement mitigation measures to protect ecological habitats. Numerical modeling studies mostly focus on karstic settings in terms of interpretation of spring flow mechanisms using parsimonious lumped-parameter models (Hao et al., 2012; Amoruso et al., 2013; Barrett and Charbeneau, 1997; Bonacci and Bojanic, 1991) distributed and/or lumped parameter equivalent porous media models (Dragoni et al., 2013; Chen et al., 2013; Doummar et al., 2012; Scanlon et al., 2003); and channel flow (Eisenlohr et al., 1997) or purely conduit flow (Halihan and Wicks, 1998) formulations. Equivalent porous media approaches for non-karstic fractured bedrock springs are also reported in the literature (e.g., Farlin et al., 2013; Swanson et al., 2006; Swanson and Bahr, 2004). In contrast to continuum and multi-continua approaches, discrete fracture network models in sedimentary and crystalline rock aquifer settings can be used to investigate the effects of individual fracture features on groundwater flow incorporating parameters including aperture, spacing, density and length (Voeckler and Allen, 2012; Levison and Novakowski, 2012; Blessent et al., 2009; Gleeson et al., 2009; Berkowitz, 2002).

Simulating small scale, low-flow springs using groundwater flow models in fractured bedrock aquifer settings that provide ecological habitats is challenging because the typical groundwater model discretization scale may be too large to represent individual springs. Moreover, fracture-dominated preferential flow introduces complexity that may not be adequately represented using equivalent porous media models. Groundwater flow modeling is often conducted at large scales (i.e., tens to thousands of meters per cell) to quantify for example hydraulic heads, river baseflows, groundwater renewal rates and residence times, or to understand anthropogenic impacts on groundwater resources (Levison et al., 2013; Sun et al., 2012; Michael and Voss, 2009). In ecohydrological modeling where connections to sensitive water-dependent habitats are made, it is important to accurately represent small-scale groundwater discharge features which may otherwise be overlooked.

This modeling study was driven by the need to obtain spring flow data (e.g., periods of activity) to be used as input to a salamander population model for an ecohydrological study (Larocque et al., 2013; Girard et al., 2014b). The aim of this research is to simulate a typical headwater hillslope using a robust numerical model to better understand: (1) the hydrodynamics of small, low-flow bedrock aquifer headwater springs that support the habitat of endangered salamanders, and (2) the impact of climate changes on the spring dynamics. A fully integrated, or fully coupled, groundwater flow model is developed using HydroGeoSphere software (Therrien et al., 2010), a 3D model with discrete fracture and surface to subsurface simulation capability. The advantage of using an integrated model is that there is no need to estimate recharge separately (i.e., precipitation is divided into runoff and infiltration) (Brunner and Simmons, 2012). The modeling domain is based on a slice of a typical headwater catchment hillslope with numerous low-flow springs discharging from discrete fractures of a bedrock aquifer. This hydrological modeling representation and approach can be extended to other locations with similar topography and geology, and is especially important for investigating the sustainability of groundwater-dependent ecosystems. The results of this hydrological modeling have been applied to ecological modeling of salamander populations (Girard et al., 2014b).

2. Materials and methods

2.1. Study area

The headwater hillslope used for this study is located in the Covey Hill Natural Laboratory on mount Covey Hill near the Canada–USA border in the Chateauguay River watershed (Larocque et al., 2006; Fig. 1). This field site has been used for several previous hydrogeological and ecological investigations (e.g., Lavoie et al., 2013; Levison et al., 2013; Gagné, 2010; Pellerin et al., 2009; Fournier, 2008). Covey Hill is the most northward extension of the Adirondack Mountains. It is a 20 km by 10 km E–W morphological feature (Nastev et al., 2008) and the highest elevation is approximately 345 m above sea level. The hill is mostly forested with limited areas of agriculture, including apple orchards and grazing.

Covey Hill comprises Cambrian sandstone of the Potsdam Group (Covey Hill Formation), deformed and fractured during the Appalachian orogeny (Globensky, 1986). The beds are relatively flat with horizontal to sub-horizontal bedding planes having dips of 1–5° (Clark, 1966). The last ice advance (12 ky) eroded the surface deposits near the hilltop and south of the border. Locally the thin, permeable and sandy Saint-Jacques till is found on the hill (Lasalle, 1981). Glaciolacustrine sediments are found below 220 m above sea level (masl) and sandy beach deposits are located between 80 and 100 masl at the foot of the hill (Tremblay et al., 2010). Near the end of the last glaciation, the breakout of paleo lake Iroquois through an outlet near Covey Hill created a sandstone pavement (also called *Flat Rock*) that extends approximately 30 km southeastward into the Champlain Valley (Franzi et al., 2002). Covey Hill is considered an important recharge area for the Chateauguay aquifer (Croteau et al., 2010).

2.2. Hydrogeological conceptual model

A hydrogeological conceptual model of the Covey Hill Formation was developed by Nastev et al. (2008). This work forms the basis of the development of the discrete fracture numerical model used in the present study. The shallow bedrock aquifer is generally unconfined over the Covey Hill Natural Laboratory. Groundwater flows radially, generally to the north, from the hilltop predominately through bedding planes and joints. Flow through the very low permeability rock matrix is considered negligible. Following an extensive series of well pumping, packer and flow meter tests and an analysis of structural geology, Nastev et al. (2008) concluded that a permeable subhorizontal fracture is found every few tens to hundreds of meters. The lateral fracture continuity is hundreds of meters up to kilometers (Nastev et al., 2008). Similarly, Williams et al. (2010) found extensive lateral continuity in the sub-horizontal flow zones which are connected by high angle fractures in the Potsdam sandstones south of the Quebec-New York border. They commonly encountered horizontal flow zone spacing of less than 10 m. Groundwater discharge, in the form of low flowing springs, occurs where bedrock fractures intersect the ground surface (Nastev et al., 2008; Williams et al., 2010).

Contributing to the Nastev et al. (2008) study, Lavigne (2006) conducted straddle packer constant head injection tests (3.75 m intervals) in three monitoring wells drilled (40–76 m depth) into