Land Use Policy 36 (2014) 171–181

Contents lists available at ScienceDirect

Land Use Policy

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

Impacts of land-cover change on the water flow regulation ecosystem service: Invasive alien plants, fire and their policy implications

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ARTICLE INFO

Article history:
Received 7 December 2012
Received in revised form 12 July 2013
Accepted 20 July 2013

Keywords:
Flow regulation
Invasive plants
Fire severity
Water repellency
Flood risk
Land-use policy

ABSTRACT

Land and water resource issues typically fall under separate governance systems. For example, agricultural policy regulates land-cover change while water departments regulate water quality. However, land-use changes can directly affect water resources. Water flow regulation is a key service which is affected by changes in land-cover but its dynamics are poorly understood by most policy makers and land management organisations. We simulated and quantified the effects of plant invasions on land-cover, hydrological soil characteristics and catchment responsiveness on flow regulation using a hydrological model. The case study was located in the indigenous fynbos shrublands in South Africa. Fynbos requires fire to regenerate, has moderate biomass, occurs mostly in areas with a potential to erode and is prone to invasion by woody plant species, particularly trees. Invasions can affect flow regulation by changing community structure and function and increasing fuel loads. The greater fuel load increases fire intensity and severity which, in turn, changes the hydrological responses of catchments. Few studies have assessed the effects of invasion on hydrological responses but studies on plantations have recorded significant increases in soil water repellence following fire, resulting in increased overland flow similar to impacts of fires in invaded areas. Simulation of clear-felling of pines and different degrees of water repellency increased both the responsiveness of the catchment to rainfall and extreme rainfall events. The simulated fire effects were consistent with other studies of hydrological responses to fire. Our study indicates that invasions of pines and acacias in the study area could substantially increase the risk of flood damage even from moderate rainfall events, and highlights the importance of maintaining flow regulation capacity. New policy approaches are required which take account of the linkages and interactions between land-use choices, water resources and ecosystem services, and address them when considering governance arrangements.

Introduction

Ecosystem services have become an important concept in policy making with decision makers having to trade-off competing demands for various benefits from agriculture, tourism and potable water from a broad range of stakeholders (de Groot et al., 2010). However, the ecosystem processes that underpin and contribute to a service often reside under different legal and policy domains and management agencies (Rounsvell et al., 2012). For example, land-use legislation and policy guide land-use (and land-cover) change and typically fall under agricultural governance systems, while water quality issues fall within in the domain of water services governance systems, and riverine systems under natural environmental governance systems. The separation of mandates and jurisdictions, as well as their focus on domain-specific expertise, can lead to decisions on different land-use options overlooking the impacts on water regulatory services. The resulting changes in land-cover and use could have important implications for the vulnerability of human settlements within, and downstream of, these areas if the changes in land-use alter river flow regimes, particularly the likelihood of floods. This counter-productive separation of governance systems is found in South Africa. Here, despite water legislation requiring that a flow of water must be set aside for an ecological reserve to protect the ecological functioning of these systems, before water is allocated for human use (Rogers et al., 2000), there is widespread over-utilisation and degradation by unwise land management practices (Nel et al., 2007). Catchment Management Agencies are seen as the solution to these governance problems but their establishment has proved to be more complex than anticipated largely because most of the issues are not technological but result from inappropriate institutional arrangements and interactions and disconnects between scientists, managers and other affected parties (Rogers et al., 2000; Rogers, 2006; Roux et al., 2006). This paper examines the impacts of land-cover change

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http://dx.doi.org/10.1016/j.landusepol.2013.07.007

caused by plant invasions on the ecosystem service of flow regulation as an example of a problem which transgresses governance system boundaries and requires a new approach if the benefits of ecosystem services are to be sustained. We chose invasions because they are an example of a gradual change which has hydrological effects that are often overlooked by land management organisations.

The ecosystem service of water flow regulation is widely recognised as critical for sustaining aquatic ecosystem biodiversity and function, and for the delivery of important benefits such as sustained yields of water (Daily, 1997; Brauman et al., 2007; Jackson et al., 2009). However, it is a service which is generally not well understood and requires knowledge of how climatic factors, mineral soils and living organisms interact to regulate the fluxes of water in a watershed or catchment from rainfall through to water in an aquifer or river (Ojea et al., 2012). The processes involved in flow regulation form a key part of the terrestrial water cycle and link directly with land productivity. Water infiltration through the soil surface and percolation through the soil are key processes in flow regulation because they determine how much water flows off immediately over the surface and how much is retained in the soil (Fig. 1 overland flow; Hewlett and Hibbert, 1967; Beven and Germann, 1982). The overland flow, and some of the soil water moves rapidly into streams increasing their flow rates in a matter of hours; this component is therefore called quickflow (Fig. 2; Hewlett and Hibbert, 1967; Kirkby, 1988; Beven, 2001). Most of the water retained in the soil is used by plants to transpire and, thus to produce cover, fodder and food (Brauman et al., 2007). The rest of the water percolates down to the water table, recharges the groundwater and is slowly discharged to sustain river flows (Fig. 1). Vegetation cover is critical because it provides organic matter and a habitat for soil fauna which interact to maintain soil structure, stabilise soils, and facilitate the infiltration and retention of rain water (Hewlett and Hibbert, 1967; Gregory et al., 1991; Dominati et al., 2010). Vegetation also transpires much of the soil water, with tall, evergreen vegetation typically transpiring more water than short, seasonally deciduous vegetation (Fig. 1; Zhang et al., 2001).

The water capture and through flow control components of flow regulation can be maintained when land-cover is modified, provided sufficient vegetation canopy or basal cover is retained, for example when natural vegetation is converted to artificial pastures or tree plantations (Guo et al., 2007; Brauman et al., 2007). Similarly, flow regulation still operates in cultivated lands provided that tillage patterns are designed to capture and retain rain water (e.g. contouring) and suitable riparian buffers are retained (Gregory et al., 1991; Pert et al., 2010). When land is degraded, for example, by overgrazing the interactions between vegetation and soil fauna are disrupted, the soil structure collapses, mineral crusts are formed and overland flows increase significantly (Fig. 1; Le Maitre et al., 2007; Dominati et al., 2010) generating more quickflow (Fig. 2). The ability of plant root networks to physically stabilise soils is important, particularly in fire-prone ecosystems where the vegetation canopy is periodically removed and the soil surface is exposed to raindrop and overland flow induced erosion (Shakesby and Doerr, 2006).

The flow regulation function can thus be defined as the ability of watersheds and catchments to capture and store water from rain storms, reducing the direct runoff and flood peaks as well as releasing the water more slowly so that flows are sustained into or through the dry season. It is essentially a buffering system but the buffering capacity does have limits and intense and prolonged rainfall events can saturate the catchment and result in flooding (Hewlett and Hibbert, 1967). The ability to store and release rain water is important because the amount of water available for human use on a sustainable basis from water supply systems is directly related to the volume and evenness of the flows (Vogel and Stedinger, 1987; McMahon et al., 2007).

Invasions of natural vegetation by many alien plant species are known to change community structure and processes (Levine et al., 2003; Strayer et al., 2006; Ehrenfeld, 2010), modify river flows (Le Maitre et al., 1996; Görgens and van Wilgen, 2004; Stromberg et al., 2007) as well as increase fuel loads and change fire regimes (Richardson and Van Wilgen, 1986; Mack and D'Antonio, 1998; Brooks et al., 2004). Research has shown that overland flow and soil loss generally is minimal in areas under natural vegetation after fires, but there are circumstances which lead to very high flows and soil loss after fires and other impacts on water quality (Scott, 1993; Scott et al., 1998; Shakesby and Doerr, 2006; Moody et al., 2007; Shakesby, 2011; Smith et al., 2011a,b).

Fynbos vegetation has a relatively low biomass, occurs in rugged terrain where erosion risk is high, and is particularly prone to invasions by woody plant species which substantially increase the fuel loads and change fire behaviour and severity (Van Wilgen and Richardson, 1985; Scott et al., 1998; Van Wilgen and Scott, 2001). This is particularly so for invasions by acacia and pine species which are also known to spread rapidly (Richardson and Brown, 1986; Higgins et al., 1999). Past experience has shown that it is essentially impossible to exclude fires from fynbos vegetation and that periodic fires are needed to rejuvenate this vegetation. So, fires in fynbos are inevitable and the real issue is how to find a way of facilitating fires while containing the risks they pose (Van Wilgen, 2009; Van Wilgen et al., 2010).

Invasions by woody plants in fire-prone vegetation like fynbos can, therefore, lead to changes in the water flow regulation service. We examine the potential changes in hydrological response and their impact on flow regimes and flooding using a simulation model and describe and discuss the results and their implications for policy makers and society.

Methods

Study area selection

A number of criteria were used in selecting the case study area to undertake the catchment response modelling. We required a catchment which was: (a) in the fynbos biome because it is prone to invasion by alien species with a high biomass; (b) in a relatively intact condition without extensive areas transformed to agricultural land; (c) recently mapped for invasions; (d) one where river flows were measured and had a representative rainfall record which was up-to-date.

The catchments which best met these requirements were those on the southern slopes of the Outeniqua Mountains in the Garden Route area of the Western Cape, South Africa. A number of these catchments are gauged and include plantations and fynbos with various degrees of invasion. We chose the upper Diep River catchment near Sedgefield (Fig. 3), because it had mountain fynbos and indigenous forest, a large area of pine plantations, and some wattle plantation (Table 1) and was lightly invaded by a range of plant species (Fig. 4).

Climate data

The hydrological model requires daily rainfall and daily maximum and minimum temperature to estimate the potential and actual daily evaporation. We used daily rainfall data from Lynch (2004) for the Bergplaas raingauge which is situated in the study catchment. The record covered the period from 1928 till 31/12/2004. We supplemented this with data for the period from 01/01/2001 to 31/12/2008 from D. Lötter (pers. comm., 2010).