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Research article

Linear infrastructure impacts on landscape hydrology

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ABSTRACT

The extent of roads and other forms of linear infrastructure is burgeoning worldwide, but their impacts are inadequately understood and thus poorly mitigated. Previous studies have identified many potential impacts, including alterations to the hydrological functions and soil processes upon which ecosystems depend. However, these impacts have seldom been quantified at a regional level, particularly in arid and semi-arid systems where the gap in knowledge is the greatest, and impacts potentially the most severe.

To explore the effects of extensive track, road, and rail networks on surface hydrology at a regional level we assessed over 1000 km of linear infrastructure, including approx. 300 locations where ephemeral streams crossed linear infrastructure, in the largely intact landscapes of Australia's Great Western Woodlands. We found a high level of association between linear infrastructure and altered surface hydrology, with erosion and pooling 5 and 6 times as likely to occur on-road than off-road on average (1.06 erosional and 0.69 pooling features km^{-1} on vehicle tracks, compared with 0.22 and 0.12 km^{-1}, off-road, respectively). Erosion severity was greater in the presence of tracks, and 98% of crossings of ephemeral streamlines showed some evidence of impact on water movement (flow impedance (62%); diversion of flows (73%); flow concentration (76%); and/or channel initiation (31%)). Infrastructure type, pastoral land use, culvert presence, soil clay content and erodibility, mean annual rainfall, rainfall erosivity, topography and bare soil cover influenced the frequency and severity of these impacts.

We conclude that linear infrastructure frequently affects ephemeral stream flows and intercepts natural overland and near-surface flows, artificially changing site-scale moisture regimes, with some parts of the landscape becoming abnormally wet and other parts becoming water-starved. In addition, linear infrastructure frequently triggers or exacerbates erosion, leading to soil loss and degradation. Where linear infrastructure densities are high, their impacts on ecological processes are likely to be considerable. Linear infrastructure is widespread across much of this relatively intact region, but there remain areas with very low infrastructure densities that need to be protected from further impacts. There is substantial scope for mitigating the impacts of existing and planned infrastructure developments.

1. Introduction

Linear infrastructure such as roads, tracks, railways and pipelines are pervasive features of even relatively undisturbed landscapes, and can affect the soil, hydrologic, and biotic processes upon which ecosystems depend. However, their impacts on ecological functions and processes within these landscapes are not generally well understood, with particularly little quantification of how linear infrastructure affects the movement of water across landscapes. Rather, most studies of the environmental impacts of linear infrastructure focus on the effects of roads on wildlife and on fragmentation of the landscape from a biotic perspective (Duniway et al., 2010; Wang et al., 2014). This lack of data has led to

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predominantly descriptive rather than analytical and predictive planning and evaluation of hydro-ecological impacts, limiting the development of useful baselines and prognoses of potentially serious impacts (Karlson and Mortberg, 2015). Indeed, Duniway and Herrick (2013) named linear infrastructure 'one of the most pressing rangeland management concerns in arid and semi-arid lands globally'.

Hydrologic impacts of linear infrastructure can be subtle but may extend over large areas, well beyond the direct infrastructure footprint. They are generally a consequence of excess overland flow generated along relatively impermeable and unvegetated road surfaces, interception of overland or subsurface flows from upslope areas, and altered stream flows (Duniway and Herrick, 2011; King and Tennyson, 1984; Montgomery, 1994). Key impacts include erosion and vegetation changes in areas of increased runoff, altered stream function, and downslope starvation due to interception of flows; each with their own cascading or feedback effects.

1.1. Increased runoff

Increased runoff resulting from reduced infiltration into the surfaces of linear infrastructure can be a major cause of chronic erosion, both along the linear infrastructure corridor and downslope of it; while some erosion can even move upstream (Donaldson et al., 2004; Duniway and Herrick, 2011; Montgomery, 1994; Ziegler et al., 2001). Excess flows can potentially breach road edges and flow downslope, initiating channel formation downstream of the road where no channel existed naturally (Katz et al., 2014; Montgomery, 1994). Excess surface water can also pool in roadway depressions, enter subsurface soil profiles and produce minor landslides and slope instability (Montgomery, 1994). Erosion and increased water availability in proximity to linear infrastructure affect a range of ecological functions and processes (Duniway and Herrick, 2011).

1.2. Sheetflow interception

Interception of sheetflow (also called Hortonian overland flow; Montgomery, 1994) and subsurface flows from upslope areas can also cause water to concentrate or pool on linear infrastructure or immediately upstream of it, or be laterally redistributed (Duniway and Herrick, 2011; Luce, 2002; Switalski et al., 2004). This can starve downstream areas that would have otherwise received the flow, with sometimes severe effects on downstream vegetation communities (Duniway and Herrick, 2011; Waddell et al., 2012).

1.3. Altered stream flows

Water flow in streams can also be altered through impeding, concentrating, channelling, and/or intercepting of water by linear infrastructure, with consequences for stream functional health and stability and for soil and organic matter movement (Donaldson et al., 2004; King and Tennyson, 1984; Montgomery, 1994). Excess overland runoff on linear infrastructure can also enter streams, changing flow regimes far downslope. Artificially high flows can also cause significant downstream erosion and gully incision, particularly given highly erosive, high-velocity flows that may result from on-road runoff generation (Luce, 2002; Wemple et al., 1996).

1.4. Feedbacks, synergistic interactions, and drivers of impacts

These different effects of linear infrastructure on hydrological processes can result in feedbacks or synergistic interactions with other stressors that further degrade the hydrological integrity of a landscape. For example, reduced vegetation productivity in areas starved of sheetflow provides less protection of soil surfaces from UV and raindrop impacts, leading to soil crusting and reduced infiltration and hence further diminishing the available water in that area (Duniway and Herrick, 2011). Similarly, a dense network of linear infrastructure in a catchment can act synergistically with other activities facilitated by that infrastructure, such as reduced vegetation cover following timber harvesting, producing larger and higher energy flows, with increased erosion and soil loss (Bruijnzeel and Vertessy, 2004).

Hydrologic impacts of linear infrastructure will also be influenced by the characteristics of the environment which they pass through, including rainfall, topography, soils and vegetation cover (Huang et al., 2013; Katz et al., 2014; Webb et al., 2014). Beyond environmental factors, linear infrastructure type, location, orientation to slope, density, and design can all affect the type and degree of impacts (Katz et al., 2014; Keshkamat et al., 2013; Pechenick et al., 2014; Wang et al., 2014).

In this paper we present a regional-level evaluation of the effects of linear infrastructure on surface and near-surface hydrology. We characterise and quantify the range of impacts observed in the semi-arid landscapes of south-western Australia's Great Western Woodlands (GWW), and identify underlying drivers of these impacts. The 16 million hectare GWW is the largest intact temperate woodland left on Earth; a region of global biodiversity significance, and the driest temperate area in the world in which extensive tracts of woodland occur (Prober et al., 2012; Watson et al., 2008). To achieve these objectives, we use a combination of field-based assessments, GIS techniques and data analyses to test the following hypotheses:

Hypothesis 1. Indications of altered water movement (erosion and pooling frequency, and erosion severity) are associated with linear infrastructure, and increase with increased engineering of the infrastructure.

Hypothesis 2. The probability that linear infrastructure will impact on ephemeral streams increases with level of engineering of the infrastructure, for each of the following categories of impact:

a) flow impedance
b) flow diversion (away from natural course)
c) flow concentration
d) stream channel initiation (as a result of flow concentration or diversion).

We also quantify the regional extent of infrastructure impacts on surface hydrological processes in the GWW, and identify options for mitigating those impacts.

2. Methods

2.1. Study area

The GWW is situated in the interzone between the mesic south-west corner of Western Australia, and the continent's arid interior (Fig. 1). It comprises a mosaic of vegetation types and landforms including salt lakes, banded ironstone formations, and rock outcrops. The landscape is ancient, deeply weathered, and very subdued except around banded ironstone formations, with shrublands typically occurring in higher parts of the landscape on deep sands, and woodlands predominating on lower parts of the landscape on red clay or duplex (loam over clay) soils (Berry et al., 2010; Burnside et al., 1995; Prober et al., 2012). The region has a low and variable rainfall, with mean annual averages ranging from approximately 400 mm in the south-west to 200 mm in the north-east (Prober