Agriculture, Ecosystems and Environment 268 (2018) 90–102

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Interacting land use and soil surface dynamics control groundwater outflow in a montane catchment of the lower Mekong basin

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ARTICLE INFO

Keywords:
Hydrologic connectivity
Storm and inter-storm streamflow
Hydrological modelling
Tracer-based hydrograph separation
Electrical resistivity tomography (ERT)

ABSTRACT

Groundwater contribution to streamflow sustains biodiversity and enhances ecosystem services, especially under monsoon-driven climate where stream baseflow is often the only available water resource during the dry season. We assessed how land use change influences streamflow and its groundwater contribution in a small headwater catchment subject to shifting cultivation in Montane Southeast Asia. Continuous time series of rainfall, reference evapotranspiration, groundwater level, stream discharge and electrical conductivity (EC) of surface and groundwater were monitored from 2002 to 2007. With the rainfall-runoff model GR4J, we investigated temporal changes in the hydrological behaviour of the study catchment to verify consistencies with observed land use change. An EC-based hydrograph separation method allowed estimating the groundwater contribution to 104 stormflow events. Mean soil surface crusting rates corresponding to each of the nine land uses identified in the catchment were determined using 236 standard 1-m^2 micro-plots. Mean plant cover for each land use was assessed in 10 × 10-m^2 plots. Bedrock topography and soil layers' structure were assessed by electrical resistivity tomography to determine pathways of subsurface storm flows. Our results indicate that an increase in the catchment's areal percentage of fallow from 33% to 71% led to a decrease in the annual runoff coefficient from 43% to 26%. The concurrent reduction of soil crusting rate over the catchment, from 48% to 30%, increased rainwater infiltration. Consecutively, groundwater contribution to storm streamflow increased from 83% to 94%, highlighting the protective role of a dense vegetation cover against flash floods. The overall reduction of the annual basin water yield for inter-storm streamflow from 450 to 185 mm suggests that the potential gain in groundwater recharge was offset by the increased root water uptake for evapotranspiration, as confirmed by the drop in the groundwater level. This analysis illustrates how two different land uses with opposite impacts on soil permeability (i/ extensive soil surface crusting under annual crops resulting in limited runoff infiltration or ii/ fallow regrowth promoting both infiltration and evapotranspiration) both inhibit groundwater recharge. The maintenance of strips of fallow buffers between annual crop plots can slow down runoff and locally promote infiltration and groundwater recharge while limiting evapotranspiration.

1. Introduction

Groundwater, i.e. water in soil pores or bedrock cracks, is a major supplier to streamflow in various ecosystems worldwide. Due to its interaction with surface water systems, groundwater is often the sole source of streamflow between storm events, and particularly during the dry season of monsoonal climate (Kirkby, 2010). During these critical periods, stream low flow from montane headwater catchments sustains

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https://doi.org/10.1016/j.agee.2018.09.005
Received 27 June 2018; Received in revised form 4 September 2018; Accepted 7 September 2018

downstream water supplies and provide many other ecosystem services (Sophocleous, 2002; Blumstock et al., 2015).

The varying contribution of groundwater to streamflow (i.e. groundwater outflow) affects streamflow regime and the quality of water thus having important environmental, socio-economic, and public health consequences (Boithias et al., 2016). During storm events, groundwater outflow dilutes pollutants (e.g. faecal bacteria) transferred by soil surface wash-off (Ribolzi et al., 2016) or discharged from sanitations.

Tracer-based studies show that mean groundwater contribution to storm streamflow is highly site-specific. It varies from less than 10% in semi-arid areas (Ribolzi et al., 2007) and bad lands (Cras et al., 2007), to more than 80% in forested catchments under temperate (Genereux and Hooper, 1998) and tropical humid climates (Bariac et al., 1995; Grimaldi et al. (2004)). Using stable isotopes of water in tropical montane catchments, Geissert et al. (2015) showed that the catchment slope and permeability of the soil–bedrock interface are the main factors controlling baseflow, and that deep and presumably long subsurface flow paths contribute to sustain baseflow, particularly during dry periods. However, processes and factors that determine groundwater outflow to streams remain poorly understood. The spatial and temporal variability of groundwater outflow depends on a complex cascade of processes (Blumstock et al., 2015). Rainfall amount and intensity determine the potential for groundwater recharge and trigger groundwater mobilisation during storm events (Zomlot et al., 2015). Soil surface morphological and hydrodynamic properties control rainwater infiltration. Soil's structure and its physical properties, including that of its deep layers (regolith and saprolite), as well as the complex geology and pedology of montane areas (Sorbotten et al., 2017), determine subsurface vertical and lateral drainage, groundwater storage capacity, transient storage time and ultimately the groundwater contribution to streamflow (Sophocleous, 2002; Hale et al., 2016). Land use influences the hydrodynamic properties of soil surface, which control the partition of rainfall between infiltration and overland flow (Lacombe et al., 2018), and ultimately, groundwater contribution to streamflow. Land cultivated with annual crops is usually prone to crusting as a consequence of the splash effect that occurs when rain drops hit the soil surface, resulting in runoff coefficients greater than that observed in forested or fallow land (Patin et al., 2012). The effect of land-use change on groundwater recharge and streamflow production, dry-season flow in particular, depends on highly site-specific competing processes between rainfall interception, infiltration, and evapotranspiration, that have been studied under various climatic conditions (Calder, 1998; Keesstra, 2002; Giambelluca et al., 2003; Bruijnzeel, 2004). In tropical areas, afforestation can, through increased evapotranspiration, reduce runoff and more specifically dry-season flows to the point of jeopardizing hydropower operations and drinking water supplies (Sidle et al., 2006). However, in other situations, afforestation with tree planting can lead to an increase in both dry and wet season streamflow (Lacombe et al., 2016) due to changes in soil surface properties altering infiltration processes (Patin et al., 2012). Infiltration rates are not only controlled by soil permeability but also slopes with contradictory relationships observed over scales and regions (Ribolzi et al., 2011).

Our work contributes to the conceptual connectivity framework (Poeppl et al., 2017), which aims at better understanding the complexity of catchment systems and their response to changes. Introduced in geomorphology several decades ago (Chorley and Kennedy, 1971), it has been extended to hydrology (Bracken et al., 2013) to encompass the diversity of human-environment interactions. Our paper aims to supplement and clarify the concept of hydrologic connectivity (Pringle, 2001) by studying the influence of land-use change and the related soil surface dynamic on the stream-hillslope continuum. Specifically, our overall objective was to improve the understanding of hydrological processes controlling the inter-annual variability of groundwater contribution to streamflow in a small montane tropical headwater catchment subject to rotational shifting cultivation, including a one- to two-year cropping phase followed by several years of fallow regrowth (Gafur et al., 2003). The study catchment (50.8 ha) corresponds to the spatial scale at which farmers operate and at which the related hydrological impacts can be assessed. In particular, we aimed to address specific questions: how does land use influence groundwater reserves that are mobilized during a storm event? How does vegetation cover management influence soil surface crusting, hence rainwater infiltration and overland flow? During a storm event, what are the subsurface pathways of rainwater and pre-event groundwater that connect infiltration areas along hillslopes to the stream?

2. Material and methods

2.1. Methodological approach

Four complementary approaches were deployed: **(i)** The influence of land use types on storm and inter-storm streamflow was explored by comparing hydro-meteorological and land-use records over a multi-year period. Hydrological modelling was used to isolate the hydrological effect of rainfall variability from that of land-use change; **(ii)** The contribution of groundwater to storm streamflow was analysed over the same multi-year period, by indirect mixing-model quantification using hydrograph separation based on electrical conductivity; **(iii)** Soil surface crusting rates, measured in 1-m^2 micro-plots, were extrapolated to the catchment scale, and compared to overland flow and groundwater outflow; **(iv)** Sub-surface morpho-pedological layers were characterized by 2D Electrical Resistivity Tomography (ERT) to assess preferential groundwater pathways.

2.2. Study site

The Houay Pano catchment (50.8 ha) is located about 10 km South from the city of Luang Prabang, (19°51′10″ N; 102°10′45″ E), in the uplands of Northern Lao PDR (Fig. 1a). It is part of the M-Tropics agro-hydrological observatory (https://mtropics.obs-mip.fr/), which is part of OZCAR (French network of Critical Zone Observatories: Research and Applications).

The catchment includes a 1300-m second-order perennial stream flowing along a rather variably steep topography (mean slope = 19%) that drains several ephemeral streams (Fig. 1b). Elevation ranges from 489 m to 722 m a.s.l. The terrain of the whole catchment is steep (mean slope = 54%). The monsoon tropical climate has an average annual rainfall of 1300 mm over the study period (2002–2007). Rainfall is highly seasonal with 77% of annual depth accumulating during the rainy season from mid-May to mid-October, whereas the November to March period is mostly dry.

The geological substrate consists of Permian to Upper Carboniferous argillites, siltstones and fine-grained sandstones. Soil thickness ranges from a few tens of centimetres along hill tops up to 20 m toward the catchment outlet (Chaplot et al., 2005a). Riparian soils are mainly Dystrochrepts with redoximorphic features and clay loam topsoil. Riparian areas are mainly of convex or convex-concave morphology, steep (mean slope = 10–130%), and narrow (4–23 m) (Vigiak et al., 2008). Groundwater outflow and seepage zones locally occur along stream banks (Ribolzi et al., 2010).

The catchment is representative of the no-input slash-and-burn farming system of Southeast Asia, with alternations of annual crops and multi-year fallow regrowth. In response to land conservation policies and the population pressure (Roder et al., 1997; Lestrelin et al., 2005), fallow periods have shortened from 10 to 15 years, 30 years ago, to 2–5 years currently (de Rouw et al., 2005; Huon et al., 2013) whereas ecological sustainability may require from 10 (de Rouw et al., 2005) to 50 years (Brown and Lugo, 1990). Over the last 15 years, the most common land uses in this catchment were fallow (i.e. rotating land), secondary forest (*i.e.* deciduous and dipterocarps) and several annual