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Understanding the impacts of climate and landuse change on water yield

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Climate and landuse change impact the hydrologic cycle resulting in changes in catchment water yield and streamflow characteristics. Understanding the combined effect of climate and landuse change on water is essential for developing sustainable water resources plans. Most studies consider only the isolated effect of climate alone or landuse alone, and this could skew the picture of hydrologic responses by attributing too little or too much importance to climate or landuse change. Quantifying the combined impact of climate and landuse change is a significant challenge as water yield is the convolution of both these factors. This paper briefly reviews key literature on quantifying climate and landuse change impacts on water yield with an emphasis on the framework developed over the last decade. We discuss the assumptions embedded in the framework and the potential for predicting climate and landuse impact on future water yield.

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Introduction

Water yield from a catchment is controlled by climatic factors (e.g. rainfall and potential evaporation) and catchment characteristics (e.g. vegetation types and landuse). While the effect of climatic factors on water yield is well understood and hydrologic models are commonly used to quantify the impact, estimating the effect of regional landuse change on water yield is still problematic. Landuse change can affect water yield by altering hydrological processes through changes in evapotranspiration and soil moisture dynamics. In many cases we are dealing with catchments where both climatic factors and catchment characteristics are changing [1••]. This makes quantifying the combined impacts of climate and landuse change on water yield a challenge as landuse and climate change influence hydrological processes in complex ways exhibiting positive or negative feedbacks. The issue is further complicated by the lack of reliable landuse change information and 'control' catchments, and complex nature of landuse change at regional scales.

Vegetation cover change (e.g. afforestation and deforestation) is a common landuse change and our understanding of the vegetation impact on mean annual water yield is well advanced and there are robust methods for quantifying the impact [2,3]. It is well established that conversion of agricultural lands to plantations will reduce water yields and impact downstream water availability [2,4–6]. Paired catchment studies have contributed considerably to our understanding of the effect of vegetation change on water yield and some generalisations have been made based on paired catchment studies [3,4,7,8]. However, paired catchments studies generally involve small catchments (e.g. less than 1 km^2) and are expensive to conduct. It is also difficult to infer and upscale results from small paired catchment to estimate the impact over large basin and regional scales.

An alternative method is to use time-trend analysis based on relationship between streamflow and precipitation, which can be applied to large catchments for after-the-fact analysis of existing data [4]. Although Bosch and Hewlett [4] concluded that the time-trend analysis method is less accurate than the paired catchment method simply because there is no control to use in separating vegetation effects from climatic effects, the time-trend analysis method is still widely used [1,9–12]. One of the advantages of the time-trend analysis method is that it can be applied to single catchments that have undergone vegetation cover change without the need of control catchments.

Another method applicable to single catchments is to use hydrologic models to discern the effect of vegetation change on streamflow [13,14]. This method has the potential to estimate the effect of site-specific changes in vegetation on streamflow over different time scales.

However, it should also be noted that uncertainty issues associated with change detection using hydrologic models need to be considered.

Climate variability is an important factor to consider when estimating the effects of vegetation change on water yield [15]. It is understood that climate interacts with vegetation in determining water yield responses. Methods have been developed to separate the effect of vegetation change from that of climate variability on water yield [16,17•,18•]. The general approach in these methods is to first estimate one effect, such as that of vegetation, and then attribute the remaining effect to other factors, such as climate variability. Zhao *et al.* [18•] evaluated the performance of these methods using data from paired catchments in Australia, New Zealand, and South Africa and showed that these methods generally provide consistent estimates of vegetation and climate effects on streamflow for the catchments considered.

Many hydrological studies have mainly considered the effect of either climate change or landuse change on water yield. In assessing the impact of climate change on water yield, for example, we generally select catchments under natural conditions and attribute changes in water yield to climate change. However, in many regions, there are few catchments under natural conditions or without landuse change. Zhang *et al.* [17•] showed that landuse changes have contributed to over 50% of the reduction in water yield in the Loess Plateau. Quantifying the relative impacts of climate and landuse change on water yield is increasingly important to enhance our ability to manage water resources in a changing environment.

This paper aims to review the recent literature on quantifying the effects of climate and landuse change on water yield with emphasis on the methodology and assumptions of the methods used. It will also discuss some practical issues and uncertainty involved and future challenges.

Framework for quantifying the impacts of climate and land use change on water yield

Catchment water yield is determined by climatic variables (e.g. precipitation and potential evapotranspiration) and catchment characteristics (e.g. land use and cover) as shown schematically in Figure 1. At a broad level, any hydrological models for estimating water yield can be expressed as:

$$Q = f(P, E_o; \theta) \tag{1}$$

where Q is water yield, P and E_o are precipitation and potential evapotranspiration respectively representing dominant climate factors on hydrological cycle, θ is a vector of model parameters representing the integrated effects of catchment characteristics on water yield.

Any change in water yield due to changes in P, E_o, andθ can be expressed as:

$$dQ = \frac{\partial f}{\partial P}dP + \frac{\partial f}{\partial E_o}dE_o + \frac{\partial f}{\partial \theta}d\theta \tag{2}$$

Eq. (2) is not directly applicable in practice as dP, dE_o and $d\theta$ can't be determined from observed data. For practical purposes, changes in water yield due to climatic variables such as precipitation (ΔQ_p), or potential evapotranspiration (ΔQ_{E_o}), or catchment characteristics (ΔQ_θ), or both climatic and catchment characteristics (ΔQ) can be estimated based the Taylor series:

$$\Delta Q_P = f(P + \Delta P, E_o, \theta) - f(P, E_o, \theta) \approx \frac{\partial f}{\partial P}\Delta P + \frac{1}{2!}\frac{\partial^2 f}{\partial P^2}\Delta P^2 + \cdots \tag{3a}$$

$$\Delta Q_{E_o} = f(P, E_o + \Delta E_o, \theta) - f(P, E_o, \theta) \approx \frac{\partial f}{\partial E_o}\Delta E_o + \frac{1}{2!}\frac{\partial^2 f}{\partial E_o^2}\Delta E_o^2 + \cdots \tag{3b}$$

$$\Delta Q_\theta = f(P, E_o, \theta + \Delta\theta) - f(P, E_o, \theta) \approx \frac{\partial f}{\partial \theta}\Delta\theta + \frac{1}{2!}\frac{\partial^2 f}{\partial \theta^2}\Delta\theta^2 + \cdots \tag{3c}$$

$$\begin{aligned}\Delta Q &= f(P + \Delta P, E_o + \Delta E_o, \theta + \Delta\theta) - f(P, E_o, \theta) \\ &\approx \Delta Q_p + \Delta Q_{E_o} + \Delta Q_\theta + \frac{1}{2!}\frac{\partial^2 f}{\partial P \partial E_o}\Delta P \Delta E_o \\ &\quad + \frac{1}{2!}\frac{\partial^2 f}{\partial P \partial \theta}\Delta P \Delta\theta + \frac{1}{2!}\frac{\partial^2 f}{\partial E_o \partial \theta}\Delta E_o \Delta\theta + \cdots\end{aligned} \tag{3d}$$

As a first-order approximation, changes in water yield due to changing climate and catchment characteristics can be expressed as:

$$\Delta Q = f'_P \Delta P + f'_{E_o}\Delta E_o + f'_\theta \Delta\theta \tag{4}$$

where ΔQ, ΔP, ΔE_o, and $\Delta\theta$, are changes in water yield, precipitation, potential evaporation, and catchment characteristics respectively, with $f'_P = \partial Q/\partial P, f'_{E_o} = \partial Q/\partial E_o$, and $f'_\theta = \partial Q/\partial\theta$.

Eq. (4) can be rearranged as:

$$\Delta Q = \Delta Q_C + \Delta Q_\theta \tag{5a}$$