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Factors controlling inter-catchment variation of mean transit time with consideration of temporal variability

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SUMMARY

The catchment transit time, a lumped descriptor reflecting both time scale and spatial structure of catchment hydrology can provide useful insights into chemical/nuclear pollution risks within a catchment. Despite its importance, factors controlling spatial variation of mean transit time (MTT) are not yet well understood. In this study, we estimated time-variant MTTs for about ten years (2003–2012) in five mesoscale sub-catchments of the Fuji River catchment, central Japan, to establish the factors controlling their inter-catchment variation with consideration of temporal variability. For this purpose, we employed a lumped hydrological model that was calibrated and validated by hydrometric and isotopic tracer observations. Temporal variation patterns of estimated MTT were similar in all sub-catchments, but with differing amplitudes. Inter-catchment variation of MTT was greater in dry periods than wet periods, suggesting spatial variation of MTT is controlled by water ‘stock’ rather than by ‘flow’. Although the long-term average MTT (LAMTT) in each catchment was correlated with mean slope, coverage of forest (or conversely, other land use types), coverage of sand–shale conglomerate, and groundwater storage, the multiple linear regression revealed that inter-catchment variation of LAMTT is principally controlled by the amount of groundwater storage. This is smaller in mountainous areas covered mostly by forests and greater in plain areas with less forest coverage and smaller slope. This study highlights the topographic control of MTT via groundwater storage, which might be a more important factor in mesoscale catchments, including both mountains and plains, rather than in smaller catchments dominated by mountainous topography.

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1. Introduction

Given a scenario of a water pollution accident, such as that following a nuclear bomb, it is imperative to know how long it would take the polluted water to reach any specific location, especially sources of domestic water supply systems. The catchment transit time, which is defined as the elapsed time from when a water molecule enters a catchment across the land surface until it exits at the catchment outlet through the stream network (Bolin and Rodhe, 1973; McDonnell et al., 2010), has been one of the major research topics in the field of catchment hydrology. It reflects the storage, flow pathway, and sources of water within the catchment, in addition to how the catchment retains and releases water (McGuire and McDonnell, 2006). Therefore, knowledge of the catchment transit time can provide useful insights with regard to taking prompt appropriate measures against chemical/nuclear pollution events.

As the transit time differs for each individual water molecule, we have to consider the mean transit time (MTT) and transit time distribution (TTD) for a mass of water molecules. In earlier works (Maloszewski and Zuber, 1982; Maloszewski et al., 1983; DeWalle et al., 1997; Ozyurt and Bayari, 2003), MTT has usually been estimated by modeling input–output relationships of conservative tracers such as stable isotopes or chloride under the assumption of steady-state and using hypothetical TTD functions. These simple treatments for estimating MTT have become controversial and new methods based on time-variant TTDs or without an explicit form of TTD have been developed to estimate MTT (McGuire et al., 2002; Sayama and McDonnell, 2009; Duffy, 2010; Ma and Yamanaka, 2013). These studies demonstrated that TTDs can change rapidly over time and through responding to rainfall and drought events, they are highly irregular in shape, which introduces considerable temporal variability to the MTT. Recently, other tracers were newly applied to relative research destinations. Such as, nutrient was testified identifiable during hydrological and

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biogeochemical responses (Hrachowitz et al., 2015), as well as Fovet et al. (2014) estimated the nitrogen transit time in headwater catchment; Peters et al. (2014) combine used groundwater $^3H/^3He$ ages and dissolved silica (Si) concentrations for investigating mean streamwater transit time; hexavalent chromium (Cr(VI)) and chromium hydroxide (Cr(OH)3(s)) were used by Druhan and Maher (2014) in structurally correlated subsurface heterogeneous porous media.

Hydrological variations are generally introduced by many factors such as climate, soil and soil water transit time were carried out by Tetzlaff et al. (2014), Kim and Jung (2014), Stockinger et al. (2014), Timbe et al. (2015), vegetation, topography, geology, snow (Seeger and Weiler, 2014), and anthropogenic activities (Blöschl, 2005). Therefore, catchment transit time is variable in space. Previous studies reported that MTT depends upon topography (McGuire et al., 2005), soil (Soulsby et al., 2006a), or both (Soulsby et al., 2006b; Tetzlaff et al., 2009; Hrachowitz et al., 2010). However, the correlation between MTT and catchment size was not obvious, while inter-catchment variance of MTT decreased with increasing catchment size (Soulsby et al., 2006a; Hrachowitz et al., 2010). Although these studies clarified the factors controlling transit time, the temporal variabilities of MTT and TTD were not considered in their analyses and thus, the understanding of the inter-catchment variation of time-variant MTT and its controlling factor(s) is incomplete. McDonnell et al. (2010) stated as one of four research needs: “We need more work that relates transit times to geographic, geomorphic, geologic, and biogeochemical characteristics of catchments.” Stream MTTs in tropical montane regions (Muñoz-Villers et al., 2015), and temporal dynamics of catchment transit times (Klaus et al., 2015) related to catchment characteristics were discussed, and both of these researches were carried out in small catchment.

The objectives of the present study are to compare MTTs among catchments with consideration of their temporal variability and to establish the factors controlling inter-catchment variation. A lumped hydrologic model, which was calibrated/validated with hydrometric and isotopic measurements (Ma and Yamanaka, 2013) was employed for this purpose. Here, we focus on mesoscale catchments. Mesoscale catchments are commonly associated with anthropogenic activities and thus, they are often of great interest regarding the development of water resources and interventions intended to enhance rural livelihoods (Love et al., 2011). Nevertheless, in mesoscale catchments, hydrological processes occurring on smaller scales develop in complex ways to produce an integrated response (Scherrer and Naef, 2003; Uhlenbrook et al., 2004), such that storm-runoff generation on the mesoscale has not yet been clarified. Therefore, studies on mesoscale catchments are both significant and imperative.

2. Material and methods

2.1. Site description

The catchments investigated in this study are five subcatchments (SCs) comprising the Fuji River catchment (35.5–36.0°N, 138.2–138.9°E), central Japan (Fig. 1). The area of the total (i.e., Fuji River) catchment is 2172.7 km^2 and its elevation ranges from approximately 234.7 to 2962.8 m. Annual precipitation is about 1135.2 mm, mean relative humidity is 65%, mean temperature is 14.7 °C, and the mean wind speed is 2.2 ms^{-1} (based on records of meteorological observations between 1981 and 2010 at Kofu station, operated by the Japan Meteorological Agency (JMA)). Northern, eastern, and western parts of the catchment are characterized by mountainous topography, whereas the central and southern areas are alluvial fans and lowlands. The mountains are formed mostly by granite and partly by andesitic/basaltic rocks. The following geological compositions were found within the study area and taken into consideration: basalt of undefined geological time (Ba), welded tuff of Quaternary age (Wt), sand–shale conglomerate of Mesozoic age (Ss), and granite of undefined geological time (Gr). Forest is the dominant land-use type over the entire study area with its percentage coverage ranging from 67% to 94%. The residual percentages are mainly given over to agricultural land and range grassland. The land use/land cover is mainly formed by forests in the mountainous areas, orchards and vegetable fields in the alluvial fans, and residential areas and paddy fields in the alluvial lowlands. The five SCs were defined with consideration of the location of gauging stations maintained by the Ministry of Land, Infrastructure, Transport, and Tourism.

2.2. Data

For the period from January 1, 2006 to September 30, 2012, AMeDAS (Automatic Meteorological Data Acquisition System) radar precipitation data produced by the JMA were used to consider the spatial variability of precipitation. These data provide maps of hourly accumulations of precipitation estimated from combined observations from radars and rain gauges (e.g., see Makihara, 1996). The spatial resolution is approximately 1 × 1 km. Before this period (i.e., 2003–2005), point precipitation data from hydro-meteorological stations were used and the Thiessen polygon method applied to obtain areal mean precipitation in each SC. The locations of the hydro-meteorological stations are shown in Fig. 1.

Data of observed daily river discharge produced by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) were used for each SC. For calculating the evapotranspiration, we applied the FAO Penman–Monteith method (Allen et al., 1998). Meteorological data (solar radiation, air temperature, relative humidity, and wind speed) observed by the JMA at three weather stations (Fig. 1) were used. Based on the relationships between the elevation of the stations and the meteorological variables, representative values were estimated considering the mean elevation of each SC, which were then used for the evapotranspiration computation. Here, temperature was regressed considering elevation affect, around −0.57 °C difference of 100 m elevation increased for the local catchment. For other meteorological parameters, we applied values at a nearest station for the whole catchment (Fig. 1).

In addition to the existing data set, we performed monthly isotopic monitoring of river water at the Ministry of Land, Infrastructure, Transport, and Tourism gauging stations from April 2010 (or April 2011) to March 2012. Monthly monitoring of the precipitation isotope was also performed at Kofu (Fig. 1). A precipitation collector (Shimada et al., 1992; Yamanaka et al., 2004) that can prevent the evaporation of stored precipitation was used for collecting monthly precipitation, and the mixed value representing average of precipitation isotope composition for the relative month (Ma and Yamanaka, 2013). Hydrogen and oxygen stable isotope ratios ($^2H/^1H$ and $^{18}O/^{16}O$) of the collected water samples were measured using a tunable diode laser isotope analyzer (L11020-I, Picarro, CA, USA). The measurement errors for this analyzer were 0.1‰ for $\delta^{18}O$ and 1‰ for δD (Yamanaka and Onda, 2011). For each SC, the mean values of $\delta^{18}O$ and δD of precipitation were estimated considering regional altitudinal effects (1.6‰/100 m for $\delta^{18}O$ and 6.4‰/100 m for δD), which were determined from the data set of Makino (2013).

3. Theory

The lumped hydrologic model for estimating time-variant MTT (and TTD) has been successfully applied in the Fuefuki River

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