Journal of Hydrology 512 (2014) 274–284

Contents lists available at ScienceDirect

Journal of Hydrology

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

A method of estimating in-stream residence time of water in rivers

F. Worrall [a,*], N.J.K. Howden [b], T.P. Burt [c]

[a] Dept. of Earth Sciences, Science Laboratories, South Road, Durham DH1 3LE, UK
[b] Dept. of Civil Engineering, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK
[c] Dept. of Geography, Science Laboratories, South Road, Durham DH1 3LE, UK

ARTICLE INFO

Article history:
Received 14 October 2013
Received in revised form 14 February 2014
Accepted 17 February 2014
Available online 6 March 2014
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Transit time
Reaction kinetics
DOC
BOD

SUMMARY

This study develops a method for estimating the average in-stream residence time of water in a river channel and across large catchments, i.e. the time between water entering a river and reaching a downstream monitoring point. The methodology uses river flow gauging data to integrate Manning's equation along a length of channel for different percentile flows. The method was developed and tested for the River Tees in northern England and then applied across the United Kingdom (UK).

(i) The study developed methods to predict channel width and main channel length from catchment area.
(ii) For an 818 km^2 catchment with a channel length of 79 km, the in-stream residence time at the 50% exceedence flow was 13.8 h.
(iii) The method was applied to nine UK river basins and the results showed that in-stream residence time was related to the average slope of a basin and its average annual rainfall.
(iv) For the UK as a whole, the discharge-weighted in-stream residence time was 26.7 h for the median flow. At median flow, 50% of the discharge-weighted in-stream residence time was due to only 6 out of the 323 catchments considered.
(v) Since only a few large rivers dominate the in-stream residence time, these rivers will dominate key biogeochemical processes controlling export at the national scale.
(vi) The implications of the results for biogeochemistry, especially the turnover of carbon in rivers, are discussed.

1. Introduction

The time water spends travelling through a catchment is an important control of biogeochemical cycling and contaminant persistence. Water spends most time moving through subsurface storage before it enters the river channel (McGuire and McDonnell, 2006). Nevertheless, for a number of reasons it is important to understand how long water spends in a river channel, this can be called the in-stream residence time. This is not the same as the residence time or age of the water in the catchment since that encompasses the entire time between water entering the catchment as precipitation and leaving at the river mouth (McGuire and McDonnell, 2006; Heidbüchel et al., 2012). Here we are only concerned with the time between water entering the river channel and it passing a point of interest. In-stream residence time will be important if, for example, we wish to predict: how much of a pollutant will be lost in-stream; the in-stream turnover of a nutrient (e.g. Honti et al., 2010); the emissions of greenhouse gases from riverwater to the atmosphere (e.g. Battin et al., 2009); or, the in-stream algal abundance (Talling and Rzoska, 1967). It is often possible to know the kinetics of in-stream processes (e.g. Köhler et al., 2002) but knowing the rate of a process is only part of the solution as we need to know the amount of time over which the process will work, thus the in-stream residence time is critical. For example, soil and groundwaters are often highly concentrated in dissolved CO_2 with respect to the atmosphere (Worrall and Lancaster, 2005): when soil water containing excess dissolved CO_2 enters a river it will begin to degas CO_2 to the atmosphere (Billett and Moore, 2008). At the same time organic matter in the river water will be mineralised to produce dissolved CO_2 (Wickland et al., 2007). Rates of CO_2 degassing are known (Liss and Slater, 1974) and rates of DOC turnover in-stream are known (e.g. del Georgio and Pace, 2008), but it is only possible to estimate

* Corresponding author. Tel.: +44 0191 374 2535; fax: +44 0191 374 2510.
E-mail address: fred.worrall@durham.ac.uk (F. Worrall).

http://dx.doi.org/10.1016/j.jhydrol.2014.02.050
0022-1694/

the amount of CO_2 entering the atmosphere if the in-stream residence time over which rates of processes are to be integrated is also known.

In-stream residence time (t_r) can be defined as:

$$t_r = \int_{x_e}^{x_m} \frac{x}{v} dx \quad (1)$$

where v = the mean cross-sectional velocity at point x; x = the downstream distance along the river channel; x_m = the downstream monitoring point; and x_e = the point along the river length where the water enters the river. For example, x_m could be the river mouth and x_e would be the point at which, on average, water enters the river. The distance $x_m - x_e$ represents the length of the river travelled by water and henceforward we refer to this as the expected length of the river. Eq. (1) therefore shows that, if we are able to estimate the change in mean river velocity along a river length, we can also estimate the in-stream residence time.

Mean cross-sectional velocity is commonly estimated as part of the consideration of hydraulic geometry. Leopold and Maddock (1953) proposed a series of power law equations that relate channel depth and mean velocity to stream discharge. This approach has the advantage that continuity constrains the constant and exponent terms. The power law approach has been popular and several studies have published the empirical fit of these equations for many rivers worldwide (e.g. Griffiths, 2003) and related the form of these equations to flow resistance (e.g. Ferguson, 2007). In some early studies, discharge was related to depth and to a residence time (Leopold et al., 1964). However, these equations do not tend to consider independent variables other than discharge, if this the focus were changed to consider in-stream residence time, then this would view downstream river length as the key independent variable (Eq. (1)).

There have been a number of approaches to estimate the distribution of in-stream residence times using transient storage models (Bencala and Walters, 1983), but these approaches have a number of limitations. Firstly, they tend to rely on tracer studies and these have their own limitations – for example, irreversible adsorption of rhodamine dye (Lin et al., 2003). Secondly, the studies are based on solute transit times, i.e. they consider distribution of travel times from one point to another and, as observed by Gomez et al. (2012), these distances are typically short (of the order of 1000 m) rather <10 to >100 km which maybe the scale of interest for large-scale biogeochemcial processes. Thirdly, not only have studies not considered scales of interest, they have not used these results to scale up to larger catchment areas or indeed to a wider range of flows. Wondzell (2011) has shown that transit storage becomes negligible when considering catchments greater than approximately 1 km^2 and so either if they were or could be applied at larger catchments that would not be of much benefit.

Alternatively, some studies have considered transit times for water in whole catchments. Boning (1974) developed an empirical model of water transit times based on measured solute transit times from dye tracer tests. Soballe and Kimmel (1987) estimated annual average transit time (t_w) for a series of east-coast US rivers based on the following empirical formula from Leopold et al. (1964):

$$t_w = 0.08A^{0.6}Q_{ave}^{-0.1} \quad (2)$$

where A = catchment area (km^2); and Q_{ave} = arithmetic mean annual discharge (m^3/s).

A similar approach to calculate a transit time for flood peaks was proposed by Pilgrim (1987) and used by Robinson and Sivapalan (1997) and Sivapalan et al. (2002) where the mean channel response time (t_n – hours) is:

$$t_n = \tau A^{\omega} \quad (3)$$

where A = catchment area (km^2); and τ, ω = constants which for the case of Sivapalan et al. (2002) were 0.28 and 0.5 respectively.

Van Nieuwenhuyse (2005) proposed a method to calculate the transit time of surface water from its source as the water enters the river channel. Van Nieuwenhuyse (2005) showed there was a significant relationship with transit time based on dye tracer studies or average velocity at gauged sites based on discharge characteristics and catchment area. However, this empirical approach to the calculation of transit time has some limitations. Firstly, the method had to consider average conditions where "average" was defined as arithmetic mean rather than the expected value of the true distribution of the river discharge. Thus, an estimate of average transit time could not be used to consider actual (expected) in-stream residence time or its distribution as is also the case for the methods illustrated in Eqs. (2) and (3) above. Understanding the distribution of transit times is important because it is often the extreme values that represent the greatest risk. At low values of transit time there is a risk of causing excess pollution: a risk of exceedence causing excess release of, for example, greenhouse gases; or conversely, underestimating pollutant retention as short-term storage is ignored (Drummond et al., 2012). Second, Van Nieuwenhuyse (2005) admits that the proposed approach estimated transit time and not in-stream residence time. While transit time is useful for predicting the flushing time of a pollutant along a given reach, it is not the in-stream age of the water passing any point, as transit time can only consider one point to one point, whereas water enters the river along a continuum at an infinite number of locations stretching back along the length of river to the channel. Indeed, Eq. (1) could be used to estimate a transit time if x_e is a fixed point rather than the length of the river experienced by the water flowing past the point of interest. What is needed is a means of predicting the point at which the "average" water enters the river. The point at which the "average" water can be taken to enter the river could be understood in terms of the expected value of the downstream discharge profile of the river, i.e. it is the discharge weighted "average" river length. By using a discharge weighted approach, the "average" length is assessed on the basis of river length experienced by the volume of water passing down the channel.

Therefore, there is gap between the application of the transient storage models (e.g. Gooseff et al., 2005) and the empirical models used to predict in-stream residence time (e.g. Van Nieuwenhuyse (2005). The purpose of this study was to develop a method for estimating in-stream residence time of water in river channels where the method should work across a range of flows and across the full length of the river but rely on readily available information. The method developed needs to be applicable in different catchments and here it is applied across the United Kingdom (which includes the countries of England, Scotland, Wales and Northern Ireland – UK).

2. Approach and methodology

The approach of this study is (i) to develop a method for calculating in-stream residence time; (ii) apply this method to a UK river where there is sufficient high-frequency flow data to test the method; and (iii) apply the method to other UK rivers.

2.1. In-stream residence time

The in-stream residence time can be defined as in Eq. (1). For sub-critical flow velocites (Froude number < 1) the mean velocity of a river at any point can be estimated from the Manning equation (Manning, 1891):

$$v = \left(\frac{1}{n}\right)\left(\frac{a_{cross}}{p}\right)^{\frac{2}{3}} s^{\frac{1}{2}} \quad (4)$$