On the estimation of transport timescales – case study: the Dez reservoir

Davood Hasanloo and Amir Etemad-Shahidi

ABSTRACT

The purpose of this study is to demonstrate an application of a hydroinformatics methodology for analysis of transport timescales in a large reservoir. Therefore, a laterally averaged two-dimensional numerical model was used to estimate the transit time, flushing times and combination of these two timescales by modeling about 230 scenarios in the Dez reservoir. The model was calibrated using temperature profiles and then executed for a period of two years (2002–2004). A possible characterization of the flushing time as e-folding time was investigated and the results revealed that the e-folding time, which is simpler to estimate, can be used in place of the flushing time in the Dez reservoir. The effects of the location of the outlet on each of these timescales were also investigated. Results indicated that the mean residence and flushing times have their smallest value when the outlet is set in the middle of the Dez dam. The mean flushing times were also less sensitive to thermal structures of the Dez reservoir than the transit times. Finally, the temporal patterns of these timescales were elucidated. It was found that no single transport timescale can be used for all conditions.

Key words | Dez reservoir, e-folding time, flushing time, transit time, transport timescales

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LIST OF SYMBOLS

C_0	initial concentration
$C(t)$	concentration temporal function
FTD	flushing time distribution
M	mass
M'	tracer loading rate
m_0	initial mass
$m(t)$	mass temporal function
Q	volumetric flow rate
$r(t)$	residence time distribution temporal function
RTD	residence time distribution
t	time
T_a	air temperature
T_f	flushing time
T_w	water temperature
V	volume

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INTRODUCTION

The water quality of aquatic systems relies mainly on the hydrodynamic processes that transport water and its constituents. Residence times and flushing times are measures of water-mass retention within defined boundaries. These timescales are a first-order description of a set of multiple processes involved in transport and are the key parameters controlling the system behavior (Monsen *et al.* 2002). By estimating the retention time, the fate of the substances transported within the water can be understood. Moreover, by comparing the water retention time and timescales of biogeochemical processes, the dynamics of populations and chemical properties can be described (e.g. Abdelrhman 2005). There are many biological and chemical implications about these timescales, yet engineers and scientists have widespread misconceptions and confusion about suitable methods for the determination of these timescales (Monsen *et al.* 2002). These confusions are the result of ignoring the underlying concept used (e.g. Hecky *et al.* 1993) or idealizing the circumstances that are constrained by critical assumptions (e.g. Andrews & Muller 1983).

A broad range of water quality phenomena are described by means of hydraulic timescales. For instance, Vollenweider (1976) described algal biomass as a function of phosphorus loading rate scaled by the flushing time using an empirical model of lake eutrophication. Hilton *et al.* (1997) analyzed the residence time of freshwater in Boston's inner harbor and evaluated the water quality impacts of combined sewer overflows. Hamilton & Lewis (1987) used the concept of water retention to explain the thermal stratification in a lake. Other applications of transport timescales in lakes and reservoirs can be found in the work of Foy (1992), Sivadier *et al.* (1994), Straskraba *et al.* (1995) and George & Hurley (2003).

To estimate the exchange and transport processes in water bodies, different transport timescales such as residence time, age, flushing time, transit time, etc., have been proposed. Zimmerman (1976) and Dronkers & Zimmerman (1982) introduced the basic concepts of transport timescales and their application in water bodies. In their works, they carefully defined the commonly used terms to measure the retention of water or scalar quantities transported in the water. Takeoka (1984) introduced the residence time analogous to the definition of age and transit time. Deleersnijder *et al.* (2001) demonstrated the potential of age as a tool for understanding complex marine flows by analyzing the results of two numerical models.

To analyze the transport processes in the Dez reservoir, the CE-QUAL-W2 model (Cole & Wells 2002), a two-dimensional laterally averaged model, was used. The Dez reservoir was selected because it is one of the most important water bodies in Iran and the outcomes of this study can be used in the prediction of its water quality, thermal stratification and also optimized planning and management. In addition, limited studies have been carried out on this type of aquatic environment and this study can increase our knowledge of reservoirs' dynamics. The CE-QUAL-W2 model was appropriate for the Dez reservoir considering its shape and hydrodynamic behavior. In this study, first, the flushing time of the Dez reservoir was estimated using different methods. Second, the transit time in the Dez reservoir and the mean flushing time (Rueda *et al.* 2006) of the Dez reservoir were estimated by physically based approaches. As the Dez reservoir is one of the key aquatic environments in Iran, therefore, precise and convenient methods were needed to calculate its parameters. Hence, possible characterizations of flushing timescales as e-folding times (which are simpler to calculate) in steady and unsteady flows (which are simpler) were investigated.

As one of the important parameters to further development of the Dez dam, the effect of the location of the outlet on each of these timescales was researched. Also, in order to achieve an overall estimate of the Dez reservoir's retention times, integrated timescales composed of the transit time and mean flushing time were estimated. Lastly, these hydraulic timescales were compared and their temporal patterns and the hydrodynamic processes causing these temporal variations were discussed.

STUDY AREA

The Dez dam is located in southern Iran, 25 km northeast of Dezful and is constructed over the Dez River. It is a double-curvature concrete arch dam, 203 m in height. The main roles of the Dez dam are in the areas of power generation (520 MW), water supply (125 thousand ha of irrigation) and flood control (Emamgholizadeh & Samadi 2008). It has been extended from northeast to southwest in the Khuzestan province. The location of the Dez reservoir is shown in Figure 1.

The total area of the entire watershed is about 17,430 km^2. The watershed maximum and minimum heights are 4,124 and 175 m, respectively, and its average height is 1,676 m. The reservoir's total storage capacity at the reservoir normal elevation (352 m from the sea surface) is $3,339 \times 10^6\,\text{m}^3$. The reservoir has an area of 63 km^2 and a length of 53 km at a water elevation of 352 m. The depth of the reservoir near the dam is about 102 m.

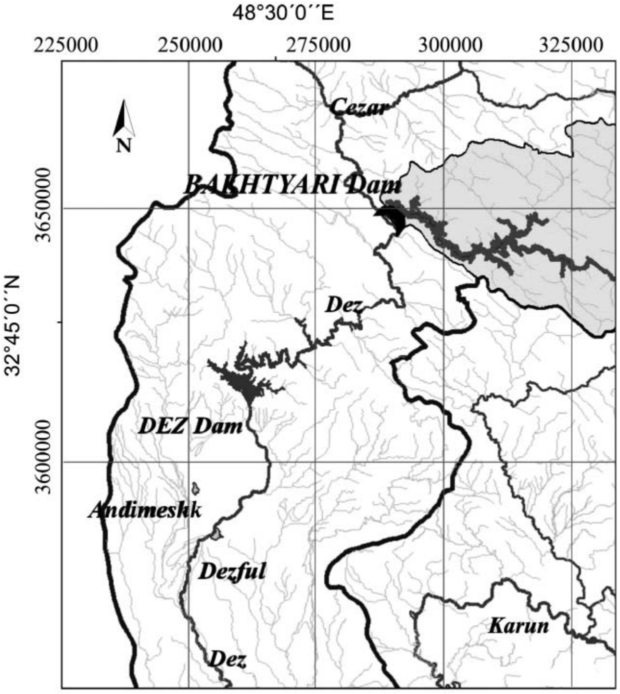

Figure 1 | Dez reservoir in southwestern Iran.

HYDRAULIC TIMESCALES

Basin average residence time

Basin average residence time or flushing time (T_f) refers to an integrated quantity. As defined by Geyer *et al.* (2000), it is "the ratio of the mass of a scalar in a water body to the rate of renewal of the scalar". Therefore, the flushing time can be estimated by dividing the water body volume (V) by the volumetric flow rate (Q) (Equation (1)). The main limitation of the flushing time estimated by this approach is that it describes the exchange characteristics of a water body without consideration of the physical processes and their spatial distribution:

$$T_f = \frac{V}{Q}. \quad (1)$$

Since the quantities of V and Q cannot be obtained easily, T_f is usually estimated using another method. In this other method, the water body is assumed to behave as a completely stirred tank reactor (CSTR), and flushing time is estimated by observing the outflow concentration over time. The major assumption for the CSTR model is that any entrance of mass is instantaneously and evenly mixed throughout the system, so the concentration of a constituent exiting the system is equal to the concentration everywhere inside the CSTR (Monsen *et al.* 2002). However, in Equation (1), it is only assumed that the system is in a steady state yet without mixing. If both the volume and flow remain constant over time, the concentration inside the CSTR is (Thomann & Mueller 1987)

$$C(t) = C_0 \exp\left(-\frac{Q}{V}t\right) = C_0 \exp\left(-\frac{t}{T_f}\right) \quad (2)$$

where C_0 is the initial concentration. If, in the above equation, t equals the flushing time, then the ratio of C/C_0 will be 37% (e^{-1}). This means, although the flushing time implies complete renewal of the system, the flushing is never complete in a CSTR, and the flushing time of the CSTR only reflects the average amount of time the mass spends in a system.

Dronkers & Zimmerman (1982) proposed an alternative method, accounting for dispersion, for estimation of flushing time in a water body. If the system is loaded with a continuous point source, assuming that the system will finally reach equilibrium, the flushing time can be estimated as

$$T_f = \frac{M}{M'} \quad (3)$$

where M is the mass of scalar within the domain and M' is the loading rate of tracer (mass time^{-1}). When applying this method in tidal, river-influenced systems, it should be noted that currents and transport vary continuously over multiple frequencies. Hence, the assumption of steady state for these kinds of water bodies would lead to incorrect results.

Transit time and residence time distribution

When a particle enters a water body at time t_0 and position α, it has a trajectory $x(\alpha, t, t_0)$. This particle will leave the water body at time t_n. The time that this particle needs to pass from inlet to outlet (from time t_0 to t_n) is called the transit time (Bolin & Rodhe 1973). The period of transit time beginning when the particle reaches x_0 in the system and ends at t_n is called the residence time. As a random variable, from starting time t_0 and starting position α, the residence time is described by its probability density function (pdf). This pdf is called the residence time distribution (RTD).

In order to determine the RTD, a known mass, m_0, is released at time t_0 and location α. Then the time-varying tracer mass, $m(t)$, remaining in the water body as a fraction of the initial mass m_0, is tracked. $m(t)$ is the amount of the material whose residence time is larger than t. The quantity $m(t)$ is obtained from the spatial integration of the measured concentration within each of the cells in the water body. The residence time of a tracer particle is the time needed for that particle to leave the domain, provided that none of the tracer particles leaving the water body ever return. The RTD can then be defined as the rate of mass loss versus time (Hilton *et al.* 1997):

$$r(t) = -\frac{1}{m_0}\frac{\mathrm{d}m(t)}{\mathrm{d}t}. \tag{4}$$

By definition, the mean residence time can be calculated based on the first moment of $r(t)$ or the zeroth moment of $m(t)$:

$$T_r = \int_0^\infty r(t)t\mathrm{d}t = -\frac{1}{m_0}\int_0^\infty \frac{\mathrm{d}m(t)}{\mathrm{d}t}t\mathrm{d}t = \frac{1}{m_0}\int_0^\infty m(t)\mathrm{d}t. \tag{5}$$

If, instead of tracking the particles released in a singular location at $t = 0$, one tracks the group of water particles released homogenously in the whole water body, a bulk or integrative description (with no spatial dependence) of the transport properties of a water body can also be defined. The probability density function of residence time for this integrative timescale is called the flushing time distribution (FTD). In order to estimate the FTD for time t_0, the tracer should be released uniformly throughout the system. Then, the FTD can be calculated from Equation (4) and the mean flushing time from Equation (5) (Rueda *et al.* 2006).

Considering the fact that the RTD (or FTD) has an exponential form in a CSTR, the mean residence time is equal to the flushing time T_f and e-folding time, i.e. 37% (e^{-1}) of initial mass still remains in the system after $t = T_f$. This suggests that flushing timescales in non-CSTR systems can probably be characterized as the e-folding time, the time needed that the mass remaining in the system reaches 37% (e^{-1}) of the total mass initially released (Rueda *et al.* 2006).

METHODS

Model description

To estimate the timescales in the Dez reservoir, a set of conservative tracer release experiments were simulated using the CE-QUAL-W2 model, a two-dimensional laterally averaged hydrodynamic and water quality model. This model is capable of modeling stratified water bodies and has been applied in a vast range of studies (Garvey *et al.* 1998; Liu *et al.* 2006; Chung & Oh 2006). Regarding the large ratio of the length to the width of the Dez reservoir and intense temperature gradients both in vertical and longitudinal directions, the CE-QUAL-W2 model was selected as an appropriate model for this simulation.

CE-QUAL-W2 is based on a finite-difference approximation to the laterally averaged equations of the free surface wave equation, hydrostatic pressure, horizontal momentum, continuity, constituent transport and equation of state. The restriction of the Courant surface gravity wave stability criterion is overcome by solving implicitly the free surface elevation, thereby allowing longer and more efficient computation timesteps. The ULTIMATE scheme is used in the advection term of the mass transport equation to reduce the numerical dispersion and oscillation (Cole & Wells 2002). To estimate the rate of the vertical eddy diffusivity, different formulations can be used in the model. Since general mixing intensity in a lake is governed by the ratio of the stratification to the wind forcing (Etemad-Shahidi & Imberger 2006), the W2N and W2 formulations were selected for the simulations. Both these closure schemes were tried and were similar to the recent studies (e.g. Etemad-Shahidi *et al.* 2009); the simulations revealed that W2N performs better than W2 and it was used for further steps.

For simulating the Dez reservoir, the reservoir was divided into 55 segments and 49 layers. The datasets used to simulate the hydrodynamic processes in the Dez reservoir were collected through 2002–2004 by Khuzestan Water and Power Authority (KWPA). These datasets included daily inflow and outflow (Figure 2) and daily records of meteorological variables (air temperature, dew point, wind speed and cloud cover (Figure 3)), measured by the Dez reservoir's meteorology station and Dezful synoptic station.

The model was executed for a period of two years (23 September 2002 until 22 September 2004) and calibrated with the aim of minimizing the difference between observed and simulated profiles of water temperature. The shade (SHD) and wind sheltering coefficient (WSC) were the most influencing parameters on temperature profiles. Shade fraction was set to 0.55 for all the segments. The wind sheltering coefficient was chosen to be 0.65 for the last ten segments of the Dez reservoir where the area is mountainous and was set to 1 for the other segments. Besides, to help ensure stability requirements for the hydrodynamics imposed by the numerical solution scheme are not violated, the CE-QUAL-W2 model includes an automatic variable timestep algorithm (Cole & Wells 2002). The extinction coefficient due to water, inorganic suspended solids and organic suspended solids were chosen to be 0.45, 0.01 and 0.2, respectively. After calibration, the scatter indexes (the root mean square error divided by the mean value of the observations) for all of the temperature profiles were less than 8%. This point shows that there exists good agreement between the observed and measured data (Figure 4).

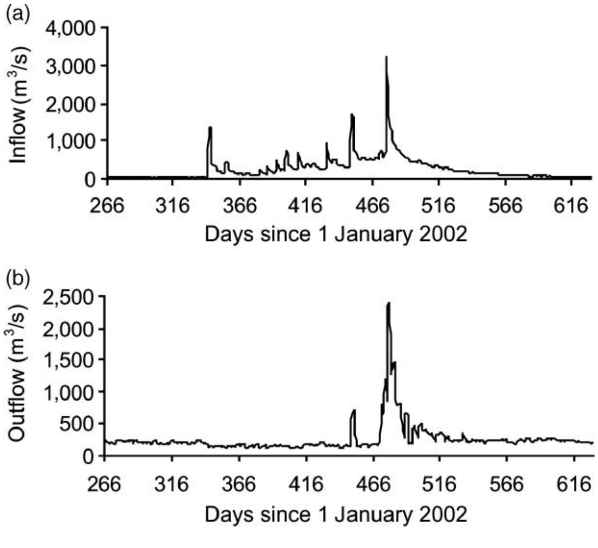

Figure 2 | Daily time series of hydrologic variables for 2002–2003: (a) inflow and (b) outflow.

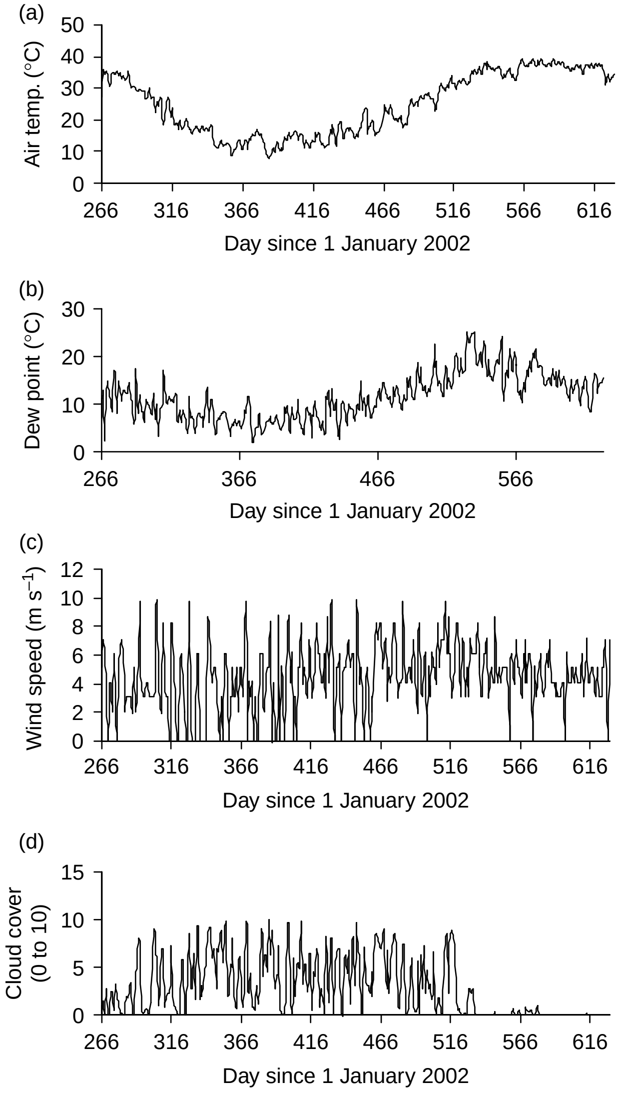

Figure 3 | Daily time series of meteorological variables for 2002–2003: (a) air temperature, (b) dew point, (c) wind speed and (d) cloud cover (0 to 10, dimensionless).

Tracer release experiment

To simulate the transit of river water in the Dez reservoir, a conservative tracer with a concentration of 100 g/m^3 was released in the inflow section of the Dez reservoir. A total of 73 release experiments (once every five days in 2002–2003) were simulated to assess the temporal pattern of the transit time in the reservoir. Each release experiment was identified by the day when the experiment was conducted. The numbers of days were counted from 1 January 2002.

To estimate the transit time, the time-varying tracer mass was computed. In order to form the $m(t)$ for each

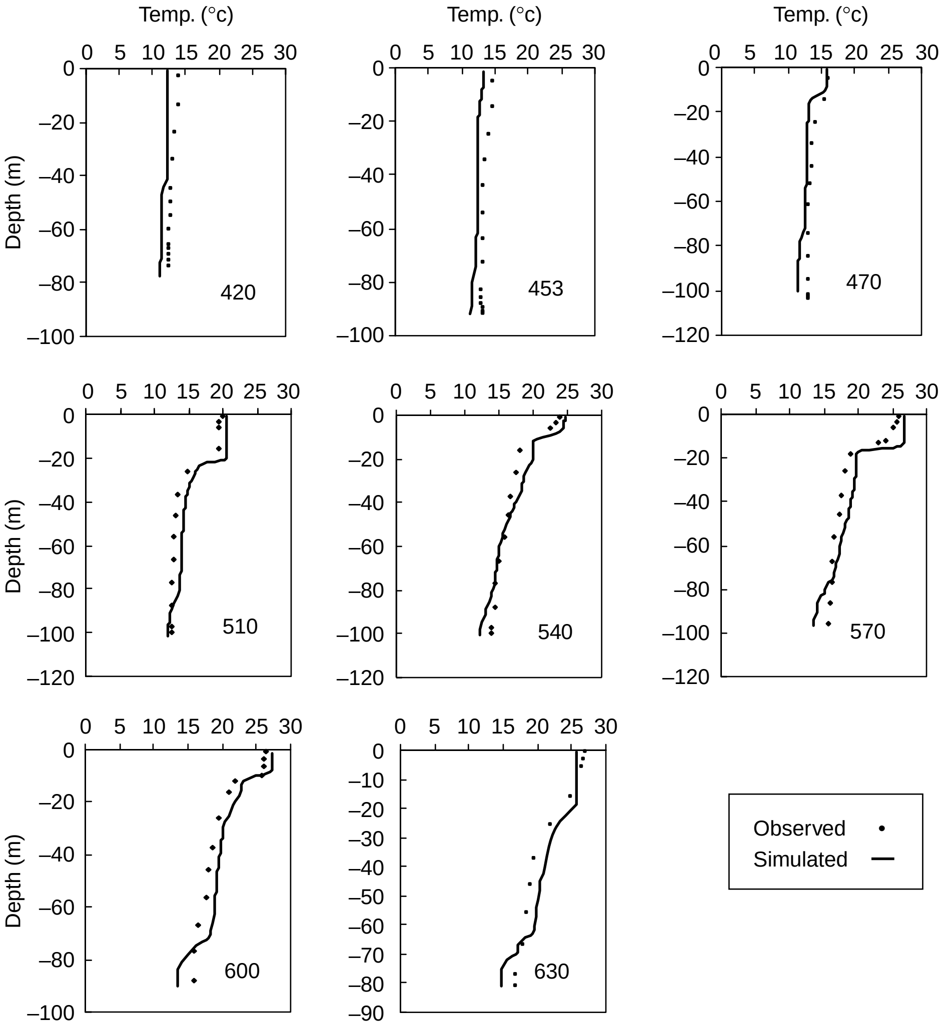

Figure 4 | Comparison of observed and simulated temperature profiles in the Dez reservoir. The numbers on the right lower corner of each graph indicate days starting from 1 January 2002.

experiment, a code was written in the MATLAB environment to compute the spatial integration of concentration in the water body once every two days. Knowing the initial amount of released mass and using $m(t)$, we developed the RTD and estimated the transit time in the reservoir.

Similarily, a total of 37 release experiments were simulated to reconstruct the FTD and consequently the mean flushing time in the Dez reservoir. Since the flushing time is only influenced by the outflow with no severe fluctuations, its temporal variation would be slow. Hence, instead of using a five day interval, the mean flushing times were estimated once every ten days. On the other hand, the variations in the factors influencing the transit time were more than those of the mean flushing times. Therefore, experiments were conducted once every five days to estimate the transit times. In the definition of flushing time given by Geyer *et al.* (2000), it has not been stated that the mass of the scalar is uniformly distributed at the initial time, yet the tracer was released homogeneously in the water body to approximate the values of flushing times. The difference between the estimation of mean flushing time and the transit time in the reservoir was due to their initial release methods. To estimate the mean flushing time, the tracer was released uniformly in the domain. However, for estimation of the transit time, the tracer was released as a pulse load in the river flow.

In order to fully develop the RTD and FTD, a two-year-long time simulation was conducted. In fact, to estimate the mean flushing time and transit time for the last days of the first simulation year, the remaining mass in the reservoir had to be tracked during the second year of the simulation.

RESULTS AND DISCUSSION

Flushing time and (mean flushing time) in the Dez reservoir

The flushing time of the Dez reservoir was estimated to be 111 days using Equation (1), where the volumetric flow rate and V were 252 m^3/s and 2,417 × 10^6 m^3, respectively. This estimation is very rough, because the inflow, outflow and thermal structure of the Dez reservoir experienced dramatic variations during the year of simulation (which are not considered in Equation (1)).

Assuming that the inflow and outflow are equal and constant in time, flushing time was estimated from three other methods. By releasing the tracer uniformly in the reservoir the e-folding flushing time was estimated to be 74 days. Using the same experiment, after developing the FTD, the flushing time was estimated to be 77 days using Equation (5). In the third case, a continuous point loading rate $M' = 50$ kg/s was specified in the inflow section of the reservoir. In Equation (3), it is not necessary for the system to have constant flow. However, to approximate the flushing time of the Dez reservoir by this method, it was assumed that the inflow equals the outflow and both were considered to be steady. After about 300 days since the first day of simulation, the system reached equilibrium and the total amount of mass in the system at that time was about 3.5 × 10^8 kg. Therefore, flushing time from Equation (3) was estimated to be 81 days.

The majority of the previous studies on the estimation of transport timescales were carried out in environments other than lakes and reservoirs, and those trivial studies which were carried out in lakes or reservoirs only dealt with the estimation of transit time, not the mean flushing time. In this study, the mean flushing times of the Dez reservoir were comprehensively investigated. Assuming that the system had an inconstant inflow and outflow, the flushing time for the 37 release experiments (once every 10 days starting at the first day of simulation) were estimated. Figure 5 shows the values of the mean flushing time for these experiments. The average value for the 37 estimated mean flushing times, which were calculated from Equation (5), was 76 days.

According to Figure 2(b), two significant withdrawal episodes, between days 450 and 455 and days 470 and 516, were dominant. The outflow was constant between days 266 and 366; as a result, the mean flushing time was relatively constant between these days. From day 366 until 450, as the release day neared the withdrawal episodes, the mean flushing time started to decrease. When the release days passed the first episode, the mean flushing time increased slightly until day 470. From this time on, as the release days passed the major withdrawal episode, the mean flushing times started to increase rapidly until day 516, when the outflow became constant.

For each of these release experiments, the curves of the total remaining concentration in the system against time were plotted and the e-folding times were computed. The correlation coefficient and the scatter index of the mean flushing times and e-folding times were respectively 0.81 and 9%. These imply that the mean flushing times of the Dez reservoir with unsteady flow can be characterized as e-folding times. Regarding the closeness of the average value of these 37 mean flushing times to the steady flow e-folding times and the satisfying correlation stated above, it can be concluded that the concentration in the Dez reservoir, whenever the mass is injected uniformly, decreases almost exponentially.

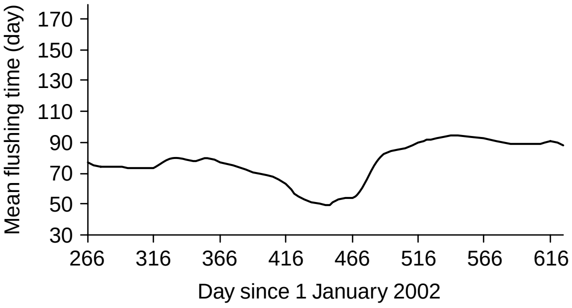

Figure 5 | Estimated mean flushing time for 37 release experiments in the Dez reservoir.

Transit time in the Dez reservoir

A total of 73 tracer river experiments, each of them identified with a letter (R for river release) and a number identifying the day of release since 1 January 2002, were simulated in the Dez reservoir. Figure 6 shows the transit times (T_R) for these experiments. To further explain the hydrodynamic processes affecting the transit time in the Dez reservoir, the residence time distribution of the two experiments R_{426} and $R_{516,}$ in addition to their four tracer concentration profiles, are illustrated in Figure 7. As shown, the residence time distribution curves consist of a series of spikes. The first RTD, which represent R_{426}, consists of two major humps with peaks on days 24 and 57 since the release day, coinciding with the large withdrawal outflows (Figure 2). As discussed by Levenspiel (1999) this RTD represents an advective system. In fact, 24 days after the injection of the tracer, the released mass reached the outlet level and a large amount of this mass quickly quit the reservoir (Figure 7(b)). After 27 days from this event, the largest withdrawal episode occurred and evacuated the remaining mass of the tracer from the reservoir. Figure 7(c) shows the RTD curve for day 516, which consists of several humps. The first hump appears two days after the release and is followed by several other humps. The RTD curve for this experiment has a long tail, which represents the behaviors of a diffusive system. The tracer mass takes more time to leave such systems and therefore the transit time in these systems often has a larger value than that of an advective system. Figure 7(d) shows that the tracer cannot plunge deep into the reservoir and instead enters the surface layers. Then it quickly mixes with the adjacent layers and gradually spreads out through the reservoir. In fact, the transit time for this experiment can be separated into two periods. The first one starts with the release day and ends when the tracer spreads out through the system. From this moment on, the second period starts. This period can be regarded as a flushing event because, at the beginning of this period, the tracer is nearly uniformly distributed in the reservoir.

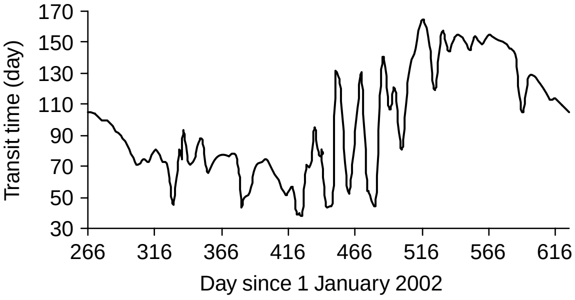

Figure 6 | Estimated transit time for 73 release experiments in the Dez reservoir.

Now, an explaination of why the values of the transit time had both sub-annual and sub-seasonal variations in the Dez reservoir (Figure 6). These variations can be mostly characterized by inflow and outflow fluctuations and the difference between the river water temperature and reservoir water temperature. This difference determines the depth of the river water intrusion. The river water intrudes a level at which the density is equal to that of the river water (level of neutral buoyancy). The withdrawal level is located near the bottom of the reservoir; hence, the deeper the river water intrudes, the shorter the transit time becomes. To further explain the effects of the above-mentioned parameters on the transit time, Table 1 is presented. This table embodies six different days and their properties as the transit time, inflow, outflow and inflow temperature. As shown, the difference between the river water and the reservoir temperature for days 449 and 451 was negligible. Thus, the ratio of inflow to outflow for day 451 was significantly more than that of day 449. Hence, the tracer mass remained longer in the reservoir in R_{451} and its transit time was considerably longer than that of R_{449}. In the second case, the difference between the inflow and reservoir temperature for days 482 and 486 were close to each other, yet the ratio of outflow to inflow on day 482 was considerably greater than that on day 486, causing a greater difference in their transit times. Finally, the ratios of inflow to outflow for both days 426 and 526 were nearly the same, but the river water was warmer than the reservoir water for day 526. Therefore, the tracer in R_{526} flowed over the surface layers and mixed in the reservoir and its transit time became longer.

In natural water bodies, the retention timescale of a transported material is the combination of the transit time and mean flushing time. Simulations were conducted in the Dez reservoir to compare its retention times to the transit and mean flushing times, and to identify the dominant timescales. To set up the model in these simulations it was required to modify the initial conditions to consider both

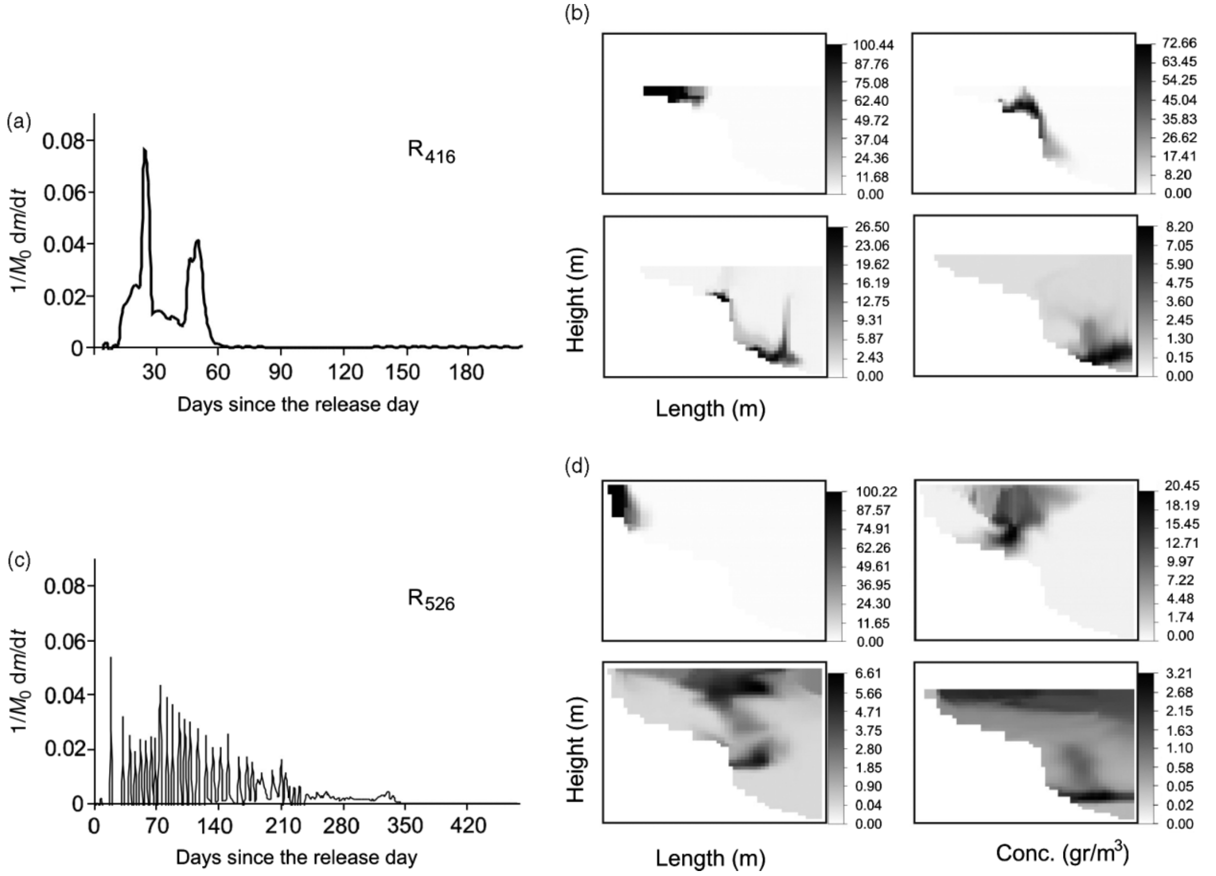

Figure 7 | RTD for experiments: (a) R_{426} and (c) R_{516} in Dez reservoir. Tracer concentration profiles in the Dez reservoir for experiments: (b) R_{426} and (d) R_{516}. Highlights symbolize the concentration of tracer.

the transit time and flushing time, which was very time-consuming. Hence, for comparison of the results and to identify the dominant timescales, it was decided to estimate the retention times once every fifteen days (Figure 8). As seen, this figure is more similar to the curve of the transit time rather than to the curve of the mean flushing times, implying that the transit times were dominant in this set of retention timescales in the Dez reservoir. The average value of these 24 release experiments was found to be 110 days.

Finally, the effect of the location of the outlet on the mean flushing and transit times was investigated. The location of the outlet was set in three different elevations. The centerline of the outlet was set, respectively, 266, 300 and 334 m above the sea level. For each of these three cases, the average values of the mean flushing time and transit time were estimated by simulating 24 tracer release scenarios. In total, 144 release experiments were carried out and the results showed that the average values for both

Table 1 | Transit time, inflow, outflow, inflow temperature and reservoir temperature for six different release days

Days since 1 January 2002	426	449	451	482	486	526
Transit time (day)	38	46	131	45	139	119
Inflow (m^3/s)	263	290	1,385	922	740	233
Outflow (m^3/s)	191	186	670	1,475	780	233
Inflow temperature (°C)	10.83	13.1	14.1	14.3	15.7	19.43
Reservoir temperature (°C)	13.5	13.7	13.8	14.45	14.50	15.2

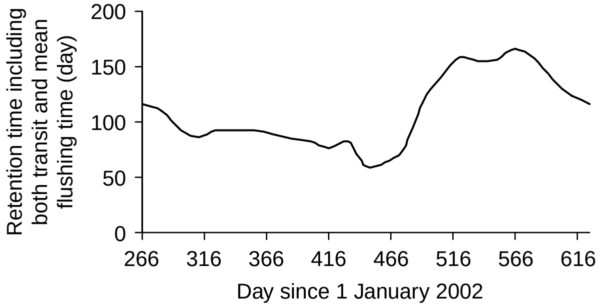

Figure 8 | Estimated retention time for 24 release experiments, accounting for both the transit and mean flushing time in the Dez reservoir.

the mean flushing time and transit time were the least when the outlet was set at 300 m above the sea level (Figure 9). As the only effective parameter on the mean flushing time is the outflow volume, the difference between the mean flushing times in the three curves of Figure 9(a) is not considerable. However, as explained before, the difference between the river water temperature and the reservoir temperature, which determines the depth of intrusion, is a key parameter in the estimation of transit times. Hence, during warm days, when the river water mostly flows on the surface, the transit times lessen and, during the cold days, it is vice versa. Regarding this point, the difference between the transit times in three curves of Figure 9(b) is remarkable. If the transit time curve is divided into two sections on the basis of the warm and cold seasons, the transit times for the case in which the outlet is set at 300 m above sea level is always placed among the two other curves, resulting in lower average values of transit times.

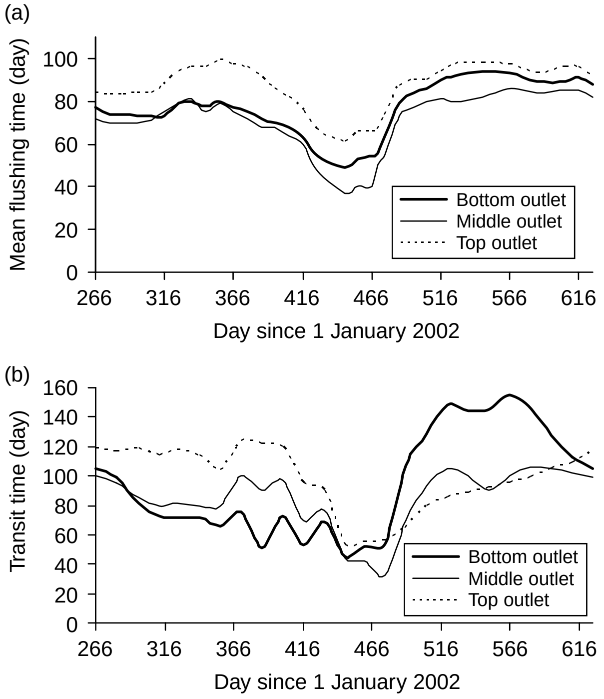

Figure 9 | (a) Estimated mean flushing time for three different outlet locations in the Dez reservoir. (b) Estimated transit time for three different outlet locations in the Dez reservoir.

The comparison between mean T_f and transit time

As mentioned before, the transit and flushing time variations in the Dez reservoir are mainly due to the inflow and outflow volumes and the difference between the river water temperature and reservoir water temperature, which determines the depth of intrusion. Due to the difference between the methods used in releasing the tracer for estimation of transit time and mean T_f, variations in these parameters caused more deviation in the values of the transit times than in the values of the mean flushing times. In these experiments, the standard deviation of the transit times and mean flushing times were, respectively, 35 days and 12 days, indicating that the transit time had more deviation than the mean flushing time in the Dez reservoir. Besides, the average and inflow weighted average of T_R (Equation (6)) for 2002–2003 were 92 and 98 days, respectively:

$$T_R(2002) = \frac{1}{Q_{y2002}} \sum_{i=1}^{73} Q_{di} T_R(i) \qquad (6)$$

where Q_{y2002} is the total inflow for year 2002, Q_{di} is the inflow volume entering the reservoir during days $i-4$ to i and $T_R(i)$ is the transit time for river water entering the reservoir on day i (Rueda *et al.* 2006).

The average and inflow weighted average values of T_R are more than the average value of the mean flushing times (77 days). This is mainly due to the thermal structure of the Dez reservoir as the river water, in the warm season, often flowed over the surface of the reservoir. So the bulk of the tracer took more time to leave the system. In contrast, the effect of this phenomenon on the mean flushing time was not as significant as that of the transit time because the methods used in releasing the tracer for estimation of transit time and mean T_f were different.

SUMMARY AND CONCLUSIONS

In this study, the transport timescales in the Dez reservoir were investigated using the CE-QUAL-W2 model. A conservative tracer was released into the Dez reservoir according to 230 scenarios in order to analyze different timescales. These timescales were compared to each other, and in order to explain the difference between them, the major hydrodynamic processes in the Dez reservoir influencing these timescales were illustrated. The approaches used to estimate these timescales were based on a physically based transport model with no limitation caused by idealized assumptions.

The flushing time was estimated using four methods, while the mean flushing time was estimated using two. The approaches used to estimate the flushing time had some idealized assumptions. Among the approaches used to estimate the flushing times, the e-folding flushing time in the system with a steady flow had the most agreement with the average value of the mean flushing times. Besides, the e-folding flushing times estimated in the system with an unsteady flow were correlated to their corresponding mean flushing times. These results showed that flushing timescales in the Dez reservoir can be characterized as e-folding times.

Both the mean residence and flushing time had sub-annual and sub-seasonal variations. These variations were described by fluctuations in inflow, outflow and thermal structure of the Dez reservoir, each of which determines the advective and diffusive patterns of transport. The effect of the location of the outlet on each of these timescales was investigated and the results indicated that the transit times and mean flushing times are the least when the outlet is set in the middle of the dam. A set of tracer release experiments was carried out to estimate retention timescales which embody both the transit times and mean flushing times. The average value of these retention times were greater than those of the transit times and mean flushing times. Due to the different methods used to release the tracer, these timescales had different sensitivities to the mentioned parameters. As a result, the average values of the mean flushing times and their standard deviation were less than those of the transit times in the simulation year. The differences between the results of the idealized and non-idealized methods showed that the transport timescales should not be estimated using idealized methods unless the validity of the underlying assumptions is identified. In addition, the difference between the values of the mean flushing times and their corresponding transit times revealed that these timescales could not be used in place of each other. In fact, there is no single hydraulic timescale that can be used for all periods and locations in the Dez reservoir, and no single hydraulic timescale can illustrate all the transport processes in this reservoir. The biogeochemical rates of pollutants, such as sewer overflows or farming nutrients entering the Dez River, need to be compared to the transit time. The local biogeochemical rates, except those in the inflow section, should be compared to the residence time rather than to the flushing time, which might not include local conditions. In the cases that both a local and a system-level measure of transport are involved, the use of integrated retention timescales, which include both the transit and flushing time, is suggested. Therefore, by selecting the most proper timescales for the questions being addressed and properly defining the calculation approach, we can improve the application of transport timescales for describing the dynamic of aquatic systems.

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