The effect of the pool and riffle on dissolved, non-conservative mass transport in rivers
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ABSTRACT

One-dimensional substance transport models assume that the river reach modelled has a uniform cross-sectional shape which manifests as a constant average velocity in the model equations. Rarely do rivers meet this criterion. Their channels are seldom uniform in shape but rather alternate in a quasi-periodic manner between pool and riffle sections. This bedform sequencing imparts a corresponding variation in the average cross-sectional velocity which is not accounted for in constant velocity transport models. The literature points out that the pool and riffle planform may be the reason for the sometimes poor predictions obtained from these models. This paper presents a new variable velocity transport model and confirms that the fluctuation in average cross-sectional velocity caused by the pool and riffle planform does have a marked effect on transport in rivers. The pool and riffle planform promotes an enhanced decay of a substance when a first-order biochemical reaction is simulated with the new transport equation. Investigation of the analytical solution shows that the enhanced decay is the result of the overall lower velocity experienced in a pool and riffle channel as opposed to a uniform channel. This difference in transport velocity between a pool and riffle channel and a uniform channel becomes more pronounced as flow declines a critical finding for total maximum daily load calculations because these regulatory limits are usually determined for low flow levels by models that do not account for this phenomenon.

Key words | advection, pool and riffle, transport velocity

INTRODUCTION

Current one-dimensional substance transport models employing the advection-reaction equation treat river channels as having a constant cross-sectional shape. However, river channels are characterized by a quasi-rhythmic planform sequence of river bottom highs and lows – riffles and pools – which result in zones of accelerating and decelerating flow. This sequence creates obvious physical and biogeochemical differences between riffles and pools that are not accounted for in current one-dimensional river transport models. Incorporating this non-uniformity within the modelling structure is critical to simulating accurately the transport of substances in rivers.

The classic equation that describes substance transport in rivers is the advection-reaction equation:

$$\frac{\partial c}{\partial t} = -u \frac{\partial c}{\partial x} + kc \quad (1)$$

This equation suggests that the average cross-sectional concentration ($c$) at any time $t$, and place $x$, is a function of the average cross-sectional velocity $u$, and a first-order biochemical reaction, where $k$ is the rate constant. In practice, the average velocity and reaction rate are averaged on a reach basis and assumed to be constant over the reach. The steady-state solution to the differential equation for a
constant release of a substance at $x = 0$ is:

$$c = c_0 \exp \left( \frac{k}{u} \right)$$

(2)

where $c_0$ is the initial concentration of the substance.

Natural channels never meet the required assumption of uniform cross-sectional shape, which manifests itself as a reached averaged constant cross-sectional velocity in the advection-reaction equation. Instead, meandering river channels, where the pool and riffle bedform is the norm, experience a quasi-rhythmic change in average velocity. Many scientists, including Thackston & Schnelle (1970), Keller (1971), Day (1975), Valentine & Wood (1977), Nordin & Troutman (1980), Beer & Young (1985), Knighton (1988) and Deng et al. (2002), recognize the influence of irregular cross-sections along sinuous channels on river transport mechanics. Irregular channel shape is most commonly cited as the reason for the inability of the advection-reaction equation to simulate transport in rivers as well as it does for canals and flumes and pipes – channels with non-varying cross-sections.

The extensive literature on river channel morphology establishes that the pool and riffle planform develops and is maintained in both meandering and straight river channels (Leopold & Wolman 1957; Knighton 1998). Although the pool and riffle sequence is most commonly associated with gravel and sand bed rivers (Hudson 2002), Keller & Melhorn (1978) assert that the pool and riffle sequence is the fundamental macro-scale bedform of rivers irrespective of bed material type. Indeed the presence of the sequence has also been reported in bedrock streams (Hack 1957; Shepherd & Schumm 1974; Keller & Melhorn 1978; Wohl & Legleiter 2003), as well as in supraglacial streams (Dozier 1974, 1976). Yalin (1971, p. 570) states: ‘Past experimental and theoretical studies have shown that any fluid moving along an inclined boundary will develop alternating zones of fast accelerating, and slow decelerating flow, with subsequent sediment erosion and deposition creating a sequence of topographic lows (pools) and highs (riffles).’

In a meandering river channel, pools are usually located at the apex of bends in association with point bars, which form on the inside of the bend (Figure 1). This generally lends an asymmetrical cross-sectional shape to pools. Riffles, on the other hand, form in the transition between meander bends and tend to be wider and shallower than their counterpart pools.

However, the three-dimensional morphology of pools and riffles varies, depending on local scour conditions,
channel obstructions and type of bar formation (Church & Jones 1982).

The physical and hydraulic difference between pools and riffles are numerous. Pools experience a relatively lower average velocity than riffles under normal flow conditions. Water surface slopes are steeper over the riffle than the upstream pool (Richards 1976c, 1978; Leopold 1982), the riffle acting hydraulically as a weir and controlling the water surface elevation of the upstream pool. Three facets of the pool and riffle sequence that are important to developing a mass transport model for rivers are:

1. the velocity reversal pattern;
2. the periodicity of the sequence; and
3. the length of a pool and riffle.

First, the velocity reversal pattern, proposed by Keller in 1971, points out that at the low flow stage in the river, the average velocity in the riffle is greater than in the upstream pool (Figure 2). However, as flow increases the rate of change of average velocity in the pool is greater than in the riffle, leading to a point of convergence at approximately 70% of bankfull flow.

This pattern has been the subject of much investigation and debate in fluvial geomorphology studies since Keller’s article in 1971. The debate centers mainly on whether a reversal in average velocity occurs. However, all of the studies on this subject conclusively demonstrate that below the point of reversal, there is a marked difference in the rates of change in average velocity between a pool and riffle and that these rates are consistent with the pattern shown in Figure 2 (Keller 1970, 1971, 1972; Richards 1976a, b, 1978; Andrews 1979; Lisle 1979; Bhowmik & Demissie 1982a, b; Jackson & Beschta 1982; Teissyre 1984; O’Connor et al. 1986; Ashworth 1987; Petit 1987; Carling 1991; Clifford & Richards 1992; Keller & Florsheim 1993; Carling & Wood 1994; Sear 1996; Robert 1997; Thompson et al. 1999; Booker et al. 2001; Milan et al. 2001; Thompson & Wohl 2009). This difference in velocity response between a pool and riffle is not reflected in the current guise of the advection-reaction equation, which uses an average cross-sectional velocity.

Second, Leopold & Wolman (1960) noted the rhythmic nature of meander spacing and by extension, pool and riffle spacing. While there are differences in opinion regarding the exact spacing of the pool and riffle sequence (Leopold & Wolman 1960; Yalin 1971; Richards 1976c, 1978; Keller & Melhorn 1978; Church & Jones 1982; Carling & Orr 2000), the rhythmic nature of the sequence is clearly evident in all the studies.

Last, the measurements of Carling & Orr (2000) and Wohl et al. (1993) of the lengths of numerous pools and riffles on different rivers suggest that the length of the pool is approximately equal to the length of the riffle.

In summary, pools and riffles are the predominant macro-scale planform in a river channel. There are three characteristics of the planform important to deriving a transport model: (i) pools have a different velocity response than
do riffles to changes in discharge; (ii) pools and riffles are of equal length; and (iii) the pool-riffle sequence is regularly spaced. Applying these characteristics, a function is derived here to model the rhythmic fluctuations in cross-sectional velocity along a pool and riffle channel.

### METHODS

A cosine function was envisioned to model the fluctuation in average cross-sectional velocity between a pool and riffle. If the average length between pools is \( L_p \), then the position along the pool and riffle sequence in radians is given by \( \frac{2\pi x}{L_p} \), where \( x \) is downstream distance. From Figure 2, the average cross-sectional velocity at any point along the river channel, \( u(x) \), under steady flow conditions is given by:

\[
 u(x) = \frac{u_r + u_p}{2} + \frac{u_r - u_p}{2} \cos \left( \frac{2\pi x}{L_p} \right) \tag{3}
\]

where \( u_r \) is the maximum average cross-section velocity at the riffle and \( u_p \) is the minimum average cross-section velocity at the pool (Figure 2). The equation starts at the midpoint of the riffle \( (x = 0) \), which at low flow levels is the point of maximum average cross-sectional velocity within the pool and riffle sequence. A more succinct form for the equation is shown below:

\[
 u(x) = a + b \cos \left( \frac{2\pi x}{L_p} \right) \tag{4}
\]

where \( a \) is the average of the cross-sectional velocity of the pool and riffle (the first term in Equation (3)) and \( b \) is one half the amplitude of the velocity variation of the pool and riffle sequence (the second term in Equation (3)).

The variation in average cross-sectional area of the channel as a function of downstream distance, \( x \), can be stated in a similar fashion to Equation (3). Or, alternatively, the cross-sectional area at steady flow is related to the discharge, \( Q \), by:

\[
 A(x) = \frac{Q}{u(x)} \tag{5}
\]

Equations (4) and (5) provide a conceptually meaningful and efficient basis for determining the variation in average cross-sectional velocity and cross-sectional area along a pool and riffle channel.

Figure 3 illustrates a control volume within a pool and riffle river channel. The control section is located at position \( x \), has length \( \Delta x \), cross-sectional end areas \( Ax \) and \( Ax + \Delta x \), and average area \( \bar{A} \). The volume of the unit is \( \bar{A} \Delta x \). Consider a substance with concentration \( c(x, t) \). The flow \( Q \) entering the element is equal to the flow out of the element, implying a steady flow condition. The substance mass loading rate, \( W(x, t) \), is equal to \( Qc(x, t) \) and is a function of position, \( x \), and time, \( t \). Consider what happens over a time interval of \( \Delta t \), beginning at \( t \).

The mass-balance principle maintains that the change in the amount of mass in the control volume over the time interval must equal the amount of mass that flows into the unit minus the amount that flows out plus the net amount of mass produced within the unit. Translating this into a mathematical expression yields:

\[
 A(x, t + \Delta t)\Delta xc(x, t + \Delta t) - A(x, t)\Delta xc(x, t) = W(x, t)\Delta t - W(x + \Delta x, t)\Delta t + \bar{A}\Delta xc\Delta t \tag{6}
\]

The product on the left-hand side \( (A\Delta xc) \) is the total amount of substance in the control volume. The two terms on the left then represent the net increase in substance contained in the volume from the start \( t \), to the end, \( t + \Delta t \), of the time interval. On the right-hand side of the equation, the first term represents the total net flow of substance into the unit while the second term represents the total net flow of substance out of the unit. The third term expresses the net rate, \( kc \), of substance produced in the unit assuming a first-order reaction.

**Figure 3** | Representative element of a pool and riffle channel.
Next, dividing both sides by $\Delta x \Delta t$ yields:

$$\frac{Ac(x, t + \Delta t) - Ac(x, t)}{\Delta t} = \frac{W(x, t) - W(x + \Delta x, t)}{\Delta x} + \bar{A}kc \quad (7)$$

Taking the limit as $\Delta x$ and $\Delta t$ approach zero and realizing that $\bar{A}$ approaches $A(x)$ gives:

$$\frac{\partial c}{\partial t} = \left[ a + b \cos \left( \frac{2\pi x}{L} \right) \right] \frac{\partial c}{\partial x} + kc \quad (8)$$

This new form of the advection-reaction equation, the variable velocity model (VVM), can describe the transport of a substance under steady-flow and steady-state conditions in a pool and riffle channel, a channel that experiences a rhythmic fluctuation in average velocity.

The steady-state solution to Equation (8) for a continuous and constant release of substance at $x = 0$, where $c_0$ is the initial concentration of the substance, is:

$$c = c_0 \exp(\psi) \quad (9a)$$

where:

$$\psi = \frac{kL \arctan \left( \frac{(a - b) \tan \left( \frac{2\pi x}{L} \right)}{\sqrt{a^2 - b^2}} \right)}{\pi \sqrt{a^2 - b^2}} \quad (9b)$$

A unique feature of the solution is the role played by the velocity amplitude, $b$, as shown in Figure 4. When $b$ equals zero, the model reverts to the traditional form of the advection-reaction equation, depicting transport in a uniform channel. However, as $b$ increases from zero (average velocity in the pool and riffle begins to fluctuate), the rate of decay of the substance increases. Also, the oscillation along the curve is more pronounced, in step with the pool and riffle spacing.

**Theoretical analysis**

A comparison of the analytical solutions to the VVM and the traditional model explains why there is a difference between the model’s results and the importance of velocity amplitude $b$ to the determination of travel velocity and residence time. From a comparison of Equation (2) with Equations (9a) and (9b), it is obvious that the difference between the models lies in the exponential terms. For Equation (2), the exponent is $k/u$, the decay coefficient divided by average cross-sectional velocity, whereas in Equation (9b) the exponent is a more complicated expression. Eliminating the decay parameter, which is common to both expressions, exposes the difference between the exponential terms. For the traditional

![Figure 4](https://iwaponline.com/wqrj/article-pdf/48/3/232/379936/232.pdf)
approach, advection is described simply by average cross-sectional velocity (Equation (10a)); for the VVM, advection is described by the term on the right-hand side (Equation (10b)).

\[
\frac{1}{u} \text{ and } \frac{L \arctan \left[ \frac{(a - b) \tan \left( \frac{\pi x}{L} \right)}{\sqrt{a^2 - b^2}} \right]}{\pi \sqrt{a^2 - b^2}} \quad (10a \text{ and } b)
\]

Examining Equation (10b) reveals that it can be broken into two parts:

\[
\frac{L \arctan \left[ \frac{(a - b) \tan \left( \frac{\pi x}{L} \right)}{\sqrt{a^2 - b^2}} \right]}{\pi} \text{ and } \frac{1}{\sqrt{a^2 - b^2}} \quad (11a \text{ and } b)
\]

The first term (Equation (11a)) is responsible for the oscillation of the decay curve (Figure 4) while the second term describes the average velocity of a substance transported through a complete pool and riffle section. More on the second term later, as first the meaning of the first term is explored.

On the inside of the tangent function in Equation (11a) is the term \(\pi/L\). On the outside of the arctangent function is the inverse of this term, \(L/\pi\). If \(b\) is zero, these terms cancel. However, when \(b\) does not equal zero, the value of the imbedded term

\[
\frac{a - b}{\sqrt{a^2 - b^2}} \quad (12)
\]

modifies the value of the tangent function causing the oscillation of the decay curve.

A more intriguing role is played by the second term, Equation (11b). In the general case, where average cross-sectional velocity is described by Equation (4), the average velocity experienced by a substance over a complete pool and riffle sequence is:

\[
u_T = \sqrt{a^2 - b^2} \quad (13)
\]

where \(u_T\) is a new velocity quantity designated ‘transport velocity’. Proof for this assertion is found by an examination of residence time. The residence time \(T\) over a pool and riffle sequence of length \(2\pi\) is given by the definite integral:

\[
T = \frac{2\pi}{a + b \cos x} \int_0^\pi dx \quad (14)
\]

where \(a + b \cos x\) is the average cross-sectional velocity at any point \(x\) along the sequence. Integrating this expression results in:

\[
T = \left[ \frac{2}{\sqrt{a^2 - b^2}} \arctan \left( \frac{\sqrt{a^2 - b^2} \tan \frac{x}{2}}{a + b} \right) \right]_0^{2\pi} \quad (15)
\]

Since the arctangent function only returns values between \(-\pi/2\) and \(\pi/2\) for any value of \(x\), a suitable counter must be entered for values of \(x\) outside this range. Realizing this and evaluating the integrand between its bounds yields:

\[
T = \frac{2}{\sqrt{a^2 - b^2}} (\pi - 0) \quad (16)
\]

which can be simplified to:

\[
T = \frac{2\pi}{\sqrt{a^2 - b^2}} \quad (17)
\]

Since the length of the pool and riffle sequence is \(2\pi\) units, then the velocity of a substance transported through the pool and riffle is:

\[
u_T = \sqrt{a^2 - b^2} \quad (13)
\]

Further insight into substance transport through a pool and riffle sequence is given by an examination of the curves presented below. In Figure 5(a), the average cross-sectional velocity (Equation (4)), is plotted with downstream distance for a flow level of 22.4 cm over two pool and riffle sequences. The case where \(a\) is equal to 0.38 m/s and \(b\) is equal to 0.5 m/s is used for illustrative purpose. The pool and riffle sequence length, \(L\), is 956 m. A cosine curve fluctuating between 0.08 and 0.68 m/s depicts the relationship between average cross-sectional velocity and distance (Figure 5(a)). However, the average cross-sectional velocity...
versus time graph (Figure 5(b)) shows a markedly different picture. The cosine curve is distorted. It is compressed around the riffle and stretched over the pool illustrating the shorter time required by a substance to transit the riffle and the extra time required to transit the pool. The result is an increase in the overall travel time required by a substance to transit the pool and riffle sequence (as shown by the difference between the length of the black line and the end of the curve in Figure 5(b)). From the figure, the velocity experienced by a transported substance over a complete pool and riffle sequence, $u_T$, is the length of the sequence divided by travel time which in this case results in 0.23 m/s. This result agrees with the result of Equation (13). Thus Equation (13) expresses the velocity of a substance transported through a pool and riffle channel. This is a very different quantity than average cross-sectional velocity, $a$, the velocity component of the traditional advection-reaction equation.

This analysis conclusively establishes that the residence time is a function of average cross-sectional velocity and channel morphology as measured by $b$. Replacing average cross-sectional velocity with transport velocity in models like WASP and QUAL2K will enable these water quality models to more closely simulate the effect of the pool and riffle on transport.

Non-dimensional and sensitivity analysis

A characteristic feature of the velocity reversal pattern is that as flow level declines, the parameter $b$ increases (Figure 2). The effect of this dynamic on residence time was explored by a non-dimensional analysis of the effect of $a$ and $b$ on transport for the Virden reach of the Assiniboine River in Manitoba, Canada.

The Assiniboine River stretches 1,287 km from its headwaters in eastern Saskatchewan to its confluence with the Red River at Winnipeg, Manitoba. The reach of interest extends downstream from the confluence with the Qu’Appelle River to the confluence with the Little Saskatchewan River, a distance of approximately 280 km (Figure 6). Here, the river flows in a wide deep valley with a sinuosity of 2.3. The valley is a former glacial spillway incised into the Saskatchewan Till Plain, a relic of the Pleistocene glaciation of the region. The bankfull stage flow for the reach is 74 cm with a $Q_{10}$ flow of 5 cm. Average bed slope along the reach is 0.000083 m/m, the shallowest sloped reach of the river. The river bed is composed of sand (95%) and gravel (5%).

The historic metering records for four hydrometric stations (St Lazzare, Miniota, Virden and Griswold) plus information from cross-section surveys were used to establish the velocity reversal pattern of the reach. The higher sloped line in Figure 7 depicts the velocity-discharge relationship for the pool and the lower sloped line represents that of the riffle. As flow declines in the reach, the relative difference between the pool and riffle velocities grows, which is reflected in the ratio $2b/a$ (Table 1). The ratio ranges from zero at bankfull flow level to greater than one at the $Q_{10}$ level. Also, as flow stage declines the residence time in the pool relative to the time in the riffle, as shown by the ratio $t_p/t_r$, increases. Importantly, this ratio is 2.4 for the $Q_{10}$ flow, indicating that the travel time in the pool is more than twice the time spent in the riffle at this flow level.

In Table 2, the percentage differences in concentration between the predictions for the traditional model, which
employs a constant channel cross-sectional velocity and the VVM were calculated for 1,000 m stations downstream of a release site.

The difference between the predictions at low flow levels are of particular note, especially near the 7Q10 level. At 10,000 m downstream of the release site (between 10 and 11 pool and riffle sequences) at a flow level of 10 cm, there is a 45% difference between the predictions, while at the 7Q10 level there is a 78% difference in the results.

This analysis shows that the pool and riffle planform has a significant effect on transport at low flow levels. Since models like QUAL2K and WASP employ the traditional form of advection-reaction equation, the effect of the pool
and riffle planform is not accounted for in predictions from these models. However, a simple substitution of transport velocity for average cross-sectional velocity would allow these models to account for the role of the pool and riffle on transport.

The general case

So far the transition in channel shape between the pool and riffle has been modelled with a periodic function. But this is not the only type of function that could be used to model the transition. Two other functions that immediately spring to mind are the step function and the saw-tooth function. If the transition is modelled by one of these functions, the effect on travel time can be ascertained by rewriting Equation (14). Transforming Equation (14) for the general case:

$$T = \int_{0}^{L} \frac{dx}{u(x)} \quad (18)$$

Replacing the velocity function with its composite area function leads to:

$$T = \frac{1}{Q} \int_{0}^{L} A(x)dx \quad (19)$$

The integral is simply the volume of the pool and riffle unit at a particular flow stage, $V(q)$, and can be written as:

$$T = \frac{V}{Q} \quad (20)$$

| Table 1 | Comparison of hydraulic parameters |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Q (cms) | $u_p$ (m/s) | $u_r$ (m/s) | $a$ (m/s) | $b$ (m/s) | 2b/a | Residence time (sec) | $t_r/t_p$ |
| Bankfull | 74 | 0.86 | 0.72 | 0.79 | −0.07 | −0.18 | 1,189 | 1 |
| Reversal | 55 | 0.65 | 0.65 | 0.65 | 0.00 | 0.00 | 1,440 | 1.0 |
| | 50 | 0.59 | 0.63 | 0.61 | 0.02 | 0.06 | 1,535 | 1.0 |
| | 40 | 0.48 | 0.58 | 0.53 | 0.05 | 0.20 | 1,774 | 1.1 |
| | 30 | 0.36 | 0.53 | 0.45 | 0.08 | 0.37 | 2,114 | 1.3 |
| Cross-section measurements | 22.4 | 0.28 | 0.48 | 0.38 | 0.10 | 0.54 | 2,553 | 1.4 |
| | 20 | 0.25 | 0.46 | 0.36 | 0.11 | 0.60 | 2,731 | 1.5 |
| | 10 | 0.13 | 0.37 | 0.25 | 0.12 | 0.96 | 4,268 | 1.9 |
| 7Q10 | 5 | 0.07 | 0.29 | 0.18 | 0.11 | 1.26 | 6,569 | 2.4 |

| Table 2 | Comparison of differences in concentration |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Distance downstream and percentage concentration change |
| Q (cms) | 1,000 m (%) | 2,000 m (%) | 3,000 m (%) | 4,000 m (%) | 5,000 m (%) | 7,500 m (%) | 10,000 m (%) |
| Bankfull | 74 | 0 | 0 | 0 | 0 | 0 | 0 |
| Reversal | 55.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 50 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 40 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 30 | 0 | 0 | 1 | 1 | 1 | 3 |
| | 22.4 | 1 | 1 | 2 | 3 | 4 | 7 |
| | 20 | 1 | 2 | 3 | 4 | 6 | 10 |
| | 10 | 4 | 9 | 13 | 17 | 22 | 34 |
| 7Q10 | 5 | 12 | 22 | 31 | 40 | 48 | 66 | 78 |
Then the travel velocity of a substance through a pool and riffle sequence is:

\[ u_T = \frac{Q_{lp}}{V} \]  \hspace{1cm} (21)

Equation (21) can be used to evaluate the travel velocity when a function other than a periodic function is used to simulate the transition between a pool and riffle.

A comparison of travel velocities between a step function where the pool steps to the riffle at the half way point and back again, the cosine function and constant average velocity approach is evaluated in Figure 8. The analysis uses the aforementioned hydraulic characteristics of the Virden reach of the Assiniboine River. The constant velocity approach forms the upper bound for travel velocity and, by inference the maximum travel time. The cosine function describes an intermediate travel velocity domain.

**CONCLUSION**

This paper demonstrates that the pool and riffle morphology affects mass transport in a river. The prolonged residence time caused by the pool and riffle channel as opposed to a uniform channel results in a more severe decay of the substance transported, if a first-order reaction is assumed.

Using a periodic function that describes the variation in average cross-sectional velocity along a pool and riffle channel and incorporating this function into a mass balance analysis yields a new transport equation, the VVM, which has an analytical solution. Analysis of the solution leads to a new velocity expression, designated transport velocity, which describes the velocity of the mass transported through a complete pool and riffle sequence. Replacing average cross-sectional velocity with transport velocity in such models as QUAL2K and WASP will enable a more realistic prediction of advection and thus mass transport.

The analysis also points out that the pool and riffle planform exerts a greater influence on mass transport at low flow levels than it does at high flow levels. This finding is an important consideration for total maximum daily load calculations since these loads are calculated at low flow levels.

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