Model Description of the Reach Scale Channel Simulator

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1. Introduction

The initial version of the Reach-Scale Channel Simulator (RSCS) was described in detail by *Eaton et al.* [2012], who also tested it against field data from Fishtrap Creek, British Columbia [*Eaton et al.*, 2010a, b], and from other similar field sites. The RSCS uses a stochastic modelling approach in which specified event probabilities are used to estimate the volume of large wood (LW), the number of jams and the volume of sediment stored by LW in a reach; the reach analyzed by *Eaton et al.* [2012] was 10 m wide, 0.5 m deep and 150 m long. Individual model runs of the RSCS produce realistic but highly variable set of estimates for the modelled time period: numerous runs (i..e Monte Carlo modelling) are used to estimate the distribution of estimates for the time period. This version of the RSCS is coupled with the regime model proposed in *Eaton* [2006] which is used to predict bed material transport rate (Q_{bm}) entering the reach and the reach-average channel width (W_{ch}) and depth (d_{ch}) of a stream with known formative discharge (Q), stream channel gradient (S), and bed surface texture (D_{50} and D_{84}). Thus, this version can be applied to forested gravel-bed streams with a range of reach characteristics.

2. Reach-Scale Channel Simulator

The RSCS has 6 separate modules that are run in sequence during each year of the simulation. Each module adds, modifies and/or removes data in a storage matrix that has an entry for each individual LW piece in the stream. The data recorded in the matrix includes: LW piece length (L_{LW}); LW diameter (D_{LW}); LW orientation (Θ_{LW}); time since the piece last moved (t_x); functional class (F_{LW}); jam identification number (if the piece is associated with a jam); volume of stored sediment (V_{sed}); and the total sediment storage capacity for the piece (V_{pot}). Using these data, estimates are made for each year in the simulation of the reach-average total wood load (and the wood load for each functional class), the volume of stored sediment, the volume of wood incorporated into jams, and the sediment stored in association with jams. In a separate data storage matrix, additional information is collected on individual jams once they reach their maximum size, including the jam age, the number of LW pieces in the jam and the volume of sediment stored by the jam.

The 6 modules in the RSCS are:

- **Module 1:** Riparian Forest Inputs
- **Module 2:** Small Wood Advection
- **Module 3:** Key Piece Identification
- **Module 4:** LW Movement and Jam Growth
- **Module 5:** Bed Material Sediment Storage
- **Module 6:** LW Decay

The modules are run in the sequence that they are listed. The details of each module are presented below. The reader is referred to *Eaton et al.* [2012] for a discussion and rationale for the modelling approach.

However, before the RSCS can be run, both the model domain and the boundary conditions need to be specified. To do this, the user specifies Q, S, D_{50}, D_{84} and the typical rooting depth of the riparian forest (H), which is used to parameterize bank erodibility: the regime model uses these inputs to calculate the channel dimensions (W_{ch} and d_{ch}), as well as the steady state bed material supply to the reach, Q_{bm}, assuming that the river is at the formative discharge for 1 day each year. The length of the reach (L_{ch}) is assumed to be 15 times the bank full channel width.

The user also specifies the average height and diameter of the trees in the riparian forest (H_{tr} and D_{tr}, respectively), as well as the density of the riparian forest (ρ_{tr}). Finally, the user specifies the length of time for which to run the simulation. The time required to reach steady state wood load from an initial condition with no in stream wood is about 200 years, so most simulations run for several centuries.

2.1. Riparian Forest Inputs

The first module to run estimates the annual input of LW to the stream channel. The number of tree mortalities in any given year is calculated by first determining the total number of trees that could potentially contribute wood to the stream reach, then applying a random mortality rate, M, with a mean of 0.2% and a standard deviation of 0.1%. The relevant equation is:

$$N_{mortality} = M \cdot \rho_{tr} \cdot 2H_{tr} \cdot L_{ch} \tag{1}$$

Then, a total of $N_{mortality}$ trees are assigned positions relative to the edge of the stream (X_{tr}). The position X_{tr} for a given tree is chosen randomly from a uniform distribution from 0 to H_{tr}. Each tree is assumed to fall to the ground immediately, and is assigned a fall direction (Θ_{tr}) that is randomly distributed from 0 to 360°. Once, the tree position and fall direction are known, the model determines how much (if any) of the tree falls above the stream channel, and calculates the length of the LW piece that enters the stream (L_{LW}) as follows:

$$L_{LW} = \frac{H_{tr} \cdot \sin\Theta - X_{tr}}{\sin\Theta} \tag{2}$$

If the tree reaches the other side of the channel (i.e. $L_{LW} \cdot \sin\Theta_{tr} > W_{ch}$), then the LW piece is shortened ($L_{LW} \to W_{ch}/\sin\Theta_{tr}$). LW that spans the channel in this way is assigned to the "spanning LW" functional class, for which it is assumed that only 5% of the piece interacts with the stream, modifying streamflow and affecting sediment storage in the channel, so that $F_{LW} = 0.05$. All other LW pieces are assumed to be suspended on the stream bank at one end, and are assigned to the "Hanging LW" functional class. For hanging pieces, 50% of the piece is assumed to affect sediment storage in the stream ($F_{LW} = 0.5$).

Since many LW pieces break when they fall into a stream, the RSCS evaluates the probability that an LW piece from a single tree will break into two pieces (P_{b-tr}). The probability is estimated using a scaled error function, such that pieces that are only 5 m long are very unlikely to break ($P_{b-tr} = 0.039$), 10 m long pieces have a reasonable chance of breaking ($P_{b-tr} = 0.36$), and 15 m long pieces are very likely to break ($P_{b-tr} = 0.86$). The equation for estimating the probability is:

$$P_{b-tr} = 1 + \frac{\text{erf}(0.2L_{LW} - 2.25)}{2} \tag{3}$$

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If a random number drawn from a uniform distribution (0 to 1) falls below P_{b-tr}, then the LW piece is broken into two pieces at a point randomly selected somewhere between 25% and 75% of the initial LW length. Once piece is assigned to the "Hanging" functional class, the other is assigned to the "In-channel LW" class, for which it is assumed that 95% of the LW piece interacts with the stream processes ($F_{LW} = 0.95$); both are assigned orientations that are identical to the tree fall direction. At this stage, the residence time (t_x) for each piece is set to zero.

2.2. Small Wood Advection

Once wood has been added to the channel, the RSCS examines the LW piece dimensions to ensure that they are large enough to be retained in the channel. All LW pieces with lengths less than 20% of the channel width are removed from the data matrix, since such pieces are much more likely to be transported through the reach without being re-deposited than larger pieces. While pieces larger than this can and do move, any pieces leaving the reach are assumed to be compensated by inputs of similar wood from upstream. Since piece mobility is strongly dependent on the length of the piece relative to the width of the channel, it is assumed that the small wood entering from upstream is not trapped within the reach. Similarly, once the LW diameter falls below 0.1 m, then the LW piece is removed from the matrix. See module 6 for the details on how LW diameter is modified by the RSCS.

2.3. Key Piece Identification

The next step in the simulation is to identify any LW pieces that could act as key pieces triggering the formation of an LW jam. All pieces that span more than some critical proportion of the channel are identified as potential key pieces. The default threshold is 80%, so that key pieces have the property that $L_{LW} \cdot \sin\Theta_{LW} > 0.80 \cdot W_{ch}$. Any new LW pieces ($t_x = 0$) are assigned a unique identification number that is used to associate other, smaller LW pieces with the key piece and thus form LW jams.

2.4. LW Movement and Jam Growth

At the next stage, LW pieces that are in the channel but not part of a jam are moved randomly, according to a probability of movement that depends on the dimensions of the piece relative to the channel dimensions. The first step is to determine if the diameter of the piece, D_{LW} is likely to limit the piece mobility. Generally, entrainment is thought to be possible so long as the water depth is at least half the LW diameter. The RSCS randomly chooses a local water depth (d_{local}) to associate with each LW piece from a normal distribution with a mean equal to d_{ch} and a standard deviation equal to $d_{ch}/3$. If the ratio $d_{local}/D_{LW} > 0.5$, then entrainment is deemed to be possible, and the RSCS proceeds to the next step.

Even when $d_{local}/D_{LW} > 0.5$, entrainment is most strongly controlled by the relative length (L_{ch}/W_{ch}) and orientation of the LW piece. The probability of movement (P_{move}) is calculated by first estimating the probability of movement for perpendicular pieces (P^L_{move}) as a function of L_{LW}/W_{ch}, then multiplying it by a second term that represents the effect of orientation on mobility (P^Θ_{move}). These probabilities are estimated using scaled conjugate error functions that represent the qualitative behaviour observed by *Davidson* [2011] during a set of experiments on wood mobility and sediment storage. The relevant equations are:

$$P^L_{move} = \frac{1}{2}\text{erfc}\left(3L_{LW}/W_{ch} - 0.5\right) \tag{4}$$

$$P^\Theta_{move} = \frac{1}{2}\text{erfc}\left(\frac{|\Theta_{LW}| - 90}{45}\right) \tag{5}$$

$$P_{move} = P^L_{move} \cdot P^\Theta_{move} \tag{6}$$

If the piece moves (i.e. a random number falls below the estimate of P_{move}), then the RSCS next considers whether or not it is likely to interact with one of the key pieces or jams in the reach. The model again uses a random number and an estimate of the probability that the piece will be trapped (P_{trap}) to decide whether the piece is trapped or not. The probability depends on the predicted distance that the LW will travel (L_{travel}), the length of the reach (L_{ch}), and the number of potential jam locations (N_J) in the reach. The equation is:

$$P_{trap} = 1 - \left(1 - \frac{L_{travel}}{L_{ch}}\right)^{N_J} \tag{7}$$

The term N_J is related to the number of key pieces in the reach, but also to the proportion of the piece in the channel. LW that is in the channel is more likely to develop into a jam than a piece suspended above the channel. Therefore, N_J is the sum of number of key pieces, weighted by their functional class. If $L_{travel} > L_{ch}$, then $P_{trap} = 1$ automatically (i.e. the piece will inevitably be trapped).

The travel distance (scaled by the channel width) is estimated using data on wood movement from Mack Creek as described by [*Eaton et al.*, 2012]. However, since the initial version of the RSCS was used to consider streams with d_{ch}/D_{LW} to similar to Mack Creek, we have added a scaling term (ϕ) that increases the normalized travel distance (L_{travel}/W_{ch}) for relative water depths larger than that for Mack Creek and decreases it for smaller ratios.

$$\frac{L_{travel}}{W_{ch}} = 10.33 \cdot e^{-3.824(L_{LW}/W_{ch})} \cdot \phi \tag{8}$$

Without information to constrain the behaviour of the scaling term ϕ, we have assumed that it is a linear function of d_{local}/D_{LW}, such that $\phi = \alpha \cdot d_{local}/D_{LW}$. For $\alpha \approx 1$ the relation conforms to the Mack Creek data, since $d_{local} \approx D_{LW}$ in that system, as it is in Fishtrap Creek.

If an LW piece moves, it releases any sediment that it may have stored, and takes up a new orientation within the stream. For pieces that do not interact with a jam, the piece will take up an orientation that is nearly parallel to the streamflow direction 2/3 of the time (between 150° and 180°, where 180° corresponds to the direction of stream flow), and will be skewed across the stream 1/3 of the time (between 120° and 150°). The pieces that do interact with a jam are assigned an identification number given to one of the existing key pieces, and assigned an orientation that is close to perpendicular to the flow (between 75° and 105°); they are also prevented from moving in the future until the key piece that trapped them breaks.

2.5. Bed Material Sediment Storage

This module links the wood load to channel morphology by storing fraction of the bed material sediment supplied to the reach in association with each LW piece in the system. The rules are based on experimental observations made by *Davidson* [2011] and they have been validated against field observations from Fishtrap Creek by *Eaton et al.* [2012]. The initial version of the RSCS assumed that bed material sediment trapping efficiency dropped off exponentially with time as the storage capacity behind each LW piece was progressively filled with sediment. That approach is only valid for systems with bed material sediment supply rates the are similar to Fishtrap Creek and to the Froude-scaled experiments conducted by *Davidson* [2011]. In order to make the RSCS more general, we have modified the trapping efficiency function so that it depends on the volume of sediment stored behind each piece (V_{sed}) relative to the maximum available sediment storage volume for the piece (V_{pot}). The equations relating the trapping efficiency to V_{sed}/V_{pot} were calibrated by choosing a set of coefficients that produced sediment storage volumes for a simulation of Fishtrap Creek that were similar to those reported by *Eaton et al.* [2012]. This removes time from the equation, and allows the model to describe systems with much higher and much lower bed material supply rates than Fishtrap Creek.

The first step is to calculate the maximum potential trapping efficiency of the wood in the reach, which was shown by *Davidson* [2011] to be functionally related to the reach-average wood load. In this version of the RSCS, we weight the contribution of each LW piece to the wood load by the functional class; suspended pieces contribute relatively little to the functional wood load, while in-channel pieces dominate the functional wood load. The bed material sediment trapping efficiency is assumed to be relatively linear for low wood loads, but reaches a maximum value for high wood loads. It is estimated using the same scaling function published in *Eaton et al.* [2012], which conforms to experimental data reported by *Davidson* [2011].

$$\zeta_{bm} = \mathrm{erf}\left(\frac{F_{LW} \cdot L_{LW} \cdot D_{LW}^2}{0.056 \cdot W_{ch} \cdot L_{ch}}\right) \tag{9}$$

The term ζ_{bm} is the reach-average trapping efficiency that would be observed if all of the wood were placed in the channel at the same time, which corresponds to the methodology used by *Davidson* [2011].

This potential bed material trapping efficiency is distributed amongst all of the LW pieces in the reach, based on the ratio $B/\sum B$, in which B is the area of each piece projected across the channel (weighted by the functional class).

$$B = F_{LW}\left(D_{LW} \cdot L_{LW}|\sin\Theta| + D_{LW}^2|\cos\Theta|\right) \tag{10}$$

Then, the volume of sediment trapped by an individual LW piece is calculated, considering the volume of sediment that is currently stores (V_{sed}) relative to the total potential sediment storage volume (V_{pot}), which is calculated from the projected area, B, the piece diameter, D_{LW} and the reach-average channel gradient, S:

$$V_{pot} = \frac{B \cdot D_{LW}}{2S} \tag{11}$$

The annual volume of sediment trapped by each LW piece (ΔV_{sed}) is determined by applying the scaled trapping efficiency to the bed material sediment supply rate, Q_{bm}, assuming that the trapping efficiency drops off exponentially as the available sediment storage space is filled with sediment.

$$\Delta V_{sed} = Q_{bm} \cdot \zeta_{bm}\left(\frac{B}{\sum_{i=1}^{n} B_i}\right) e^{\beta \cdot V_{sed}/Vpot} \tag{12}$$

The term β is a rate constant; when $\beta = 50$, the equation above produces similar sediment trapping behaviour to the time-based equations published in *Eaton et al.* [2012]. By making the dependence of the actual trapping efficiency on the volume of stored sediment explicit, the model becomes more generally applicable.

2.6. LW Decay

The final module in the RSCS modifies the diameter of each LW piece, using an exponential decay model that modifies D_{LW} as a function of the piece age (t_{LW}).

$$D_{LW} = D_{tr} \cdot e^{-K_{decay} \cdot t_{LW}} \tag{13}$$

The default decay constant, K_{decay}, is 0.01, which translates to a volumetric decay rate of 0.02.

Once D_{LW} is determined, the shape (L_{LW}/D_{LW}) is used to estimate the probability that the piece will break using the following equation:

$$P_{break} = K_{break} \cdot \frac{L_{LW}/D_{LW}}{100} \tag{14}$$

The default value of the coefficient K_{break} is 0.10; the equation is based on the assumptions that (a) the shape of the piece determines how likely it is to break, and that (b) a piece for which $L_{LW}/D_{LW} = 100$ has a 10% chance of breaking in a given year. Without data to constrain the model, we have assumed that the relation is linear. It is worth noting that this breakage rule, combined with the breakage rules for wood that falls into the channel, produce exponential LW piece distributions that are similar to those observed in the field and those specified by other (deterministic) LW models such as *Benda and Sias* [2003].

If a piece that is in the channel or hanging (rather than suspended) breaks, part of the piece is assumed to move downstream and adopt a new orientation similar to the orientations randomly imposed on moving pieces in module 4. It is also assumed that a proportion of the sediment stored by the initial LW piece is released, based on the length of the moving LW piece relative to the original total piece length. The other part of the original LW piece retains the original orientation. Both pieces are assigned to the in-channel functional class.

When pieces that are suspended above the channel break for the first time, only the functional class is changed (to hanging instead of suspended). The second time one of these channel-spanning pieces breaks, it generates two separate LW pieces, both of move downstream, releasing all sediment stored by the piece. Most of these pieces also form the nucleus of a larger LW jam; any smaller LW pieces associated with the jam are also moved and release their stored sediment. All pieces are assigned a new orientation following the procedure described for module 4.

Once this module is complete, the data in the storage matrix are interrogated to make reach-average estimates of the various parameters for the given year of the simulation. The RSCS then returns to module 1 and the sequence is repeated.

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