Future River Analysis & Management Evaluation (FRAME): A new approach to forecasting long-term morphological evolution and response in rivers

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Abstract

Long-term forecasting of river channel evolution and morphological response to river management is needed to make informed decisions and develop resilient adaptation pathways in an uncertain future. However, long-term forecasting in rivers with a wide range of plausible future conditions is beyond the scope of currently available morphological models that are entirely physics-based and deterministic. To address this limitation, the US Army Engineer Research and Development Center (USACE-ERDC) is leading an international consortium of universities in the development of a new type of one-dimensional model. The FRAME (Future River Analysis & Management Evaluation) model is being designed for use by river managers and planners. Its outputs will provide decision makers with (i) foresight regarding the evolution of river forms and functions and (ii) forecasts of both the short-term morphological impacts and long-term river responses likely to be triggered by management actions.

FRAME employs annual flow duration curves to simulate hydrology, enabling investigation of morphological sensitivity to a range of climate projections. Representative, reach-averaged cross sections with simplified geometries are used to increase computational efficiency. Sediment transport is calculated by grain size fraction with a simple hiding-exposure factor and active layer mixing to simulate fining or coarsening of bed material in response to erosion and deposition. However, unlike models that calculate sediment transport and channel change in response to time-stepping through hydrographs, FRAME performs its hydraulic and sediment transport calculations for discharge classes pertaining to each flow duration curve, with channel morphology adjusting in response to the imbalance in flow frequency-weighted, annual sediment loads between consecutive cross sections. Although morphology is updated annually, sub-annual time-steps ensure model stability and orderly convergence towards sediment transport equilibrium.

In addition to simulating responses to future flow regimes, FRAME currently includes functionality to simulate tributary inputs, bed material variation, bed erosion control, dikes, diversions and adjustment of sediment input. FRAME's ongoing development has been aided by two testbed models: a 200-mile reach of the Mississippi River upstream of Vicksburg, MS (Biedenharn et al. 2023); and Sabougla Creek, a tributary of the Yalobusha River, MS (Cox et al. 2023). Near-term priorities for transforming FRAME into a fully-operational, decision-support tool include adding capabilities for lateral channel adjustment (and bank stabilization), meandering and planform evolution, and implementing a beta testing program involving a working group of potential end-users. Complementary research on 'RUles-Based morphological Response In river Channels' (RUBRIC) interfaces with FRAME's development, which (i) relates morphological responses to imbalances in sediment transport (Thorne et al. 2023) and (ii) explores how forecasts can be translated into graphical indicators that are intuitive for management use (Downs et al. 2023).

On release, FRAME's ability to forecast river channel evolution rapidly over multiple decades with easy-to-test management options will support strategic decision-making that minimizes hazards to river users and communities while maximizing the functionality of the river and the ecosystem benefits it provides.

Introduction

Forecasting sediment transport and morphological response in river channels has the potential to inform sustainable river management and planning and deliver insights to stakeholders as to where and how best to target river engineering works, mitigate against undesirable long-term impacts and promote biodiversity. However, modeling approaches face a myriad of challenges in delivering results expediently and in a format commensurate with the needs of end users, while ensuring that physical processes are represented appropriately and with outputs within acceptable bounds of uncertainty. The task is significantly compounded for timeframes of interest spanning multiple decades or centuries with multiple future scenarios the focus of project feasibility studies. Modeling the long-term evolution of river channels and their morphological responses to natural perturbations and anthropogenic influences is a complex science at the interface between river mechanics, hydrology, sedimentology and fluvial geomorphology with much focus to date on qualitative trends of channel recovery following disturbance (e.g., Cluer and Thorne 2014) and computational models designed to operate over the short term, within project-design timescales, and within reaches of interest only due to computationally demanding algorithms and challenges with data collection.

Existing modeling platforms such as HEC-RAS have large communities of users and are regarded widely as best practice technologies but arguably are not well-suited for assessments of long-term morphological trends in response to future hydroclimatic conditions, variations in sediment supply and adjustments to river channel form and management activities. More advanced technologies, such as two-dimensional cellular models, tend to be tailored towards technical users with considerable modeling experience and generate results in formats that do not facilitate river management in a foresight analysis context. Critically, few river models have attempted to integrate sediment transport, erosion and deposition and where they do they restrict morphological adjustment to the vertical dimension only, thus limiting the ability to replicate stages of river channel evolution under a range of future environmental conditions.

Since 2016, a program of research steered by ERDC-CHL has sought to develop a new kind of river model, bringing together an international team from the Universities of Portsmouth and Nottingham in the UK and Saint Louis University and Mendrop in the US. The ongoing research attempts to bridge the wide gap between entry level screening methods and existing hydraulic and cellular models currently available, and in so doing provide an intermediate approach that is highly accessible to practitioners with limited modeling experience, highly flexible in its functionality for scenario-modeling river futures and computationally efficient so as to be useful in rapid decision making. In meeting this objective, FRAME (Future River Analysis and Management Evaluation) blends conventional hydraulic and sediment transport computations with a system of pragmatic geomorphic rules to guide the direction and magnitude of morphological responses, sidestepping computationally-intense and data hungry methods.

FRAME is being developed with river managers and strategists in mind where indicative results offer 'exploratory' insights into plausible river futures and their potential impacts; a new tool that is capable of performing multiple runs over annual, decadal and centennial time-periods with flexibility for changing inputs and boundary conditions quickly and expediently during and between model runs, providing the visioning needed to justify appropriate management interventions and mitigation measures. FRAME is currently coded in VBA to facilitate its ongoing development, with an Excel user interface for data input-output, designing scenarios, adding management interventions and visualizing results. On completing a model run, a suite of parameters pertaining to flow, sediment transport and morphology are available for export as an annual time series for each cross section location.

To date, much work has centred on prototype model development, initial testing and associated research (Biedenharn et al. 2023; Cox et al. 2023; Thorne et al. 2023), and conceiving what a management-style decision-support dashboard might look like to assist with strategic management/planning (Downs et al., 2023). The hope is that a fully-operational model will be released in due course. Here we present the FRAME approach, its theoretical underpinnings and a synopsis of the core methodology.

The FRAME Approach

The engine of FRAME is based on conventional one-dimensional hydraulic and sediment transport modeling along a river system based on a broad-scale network of representative cross sections. In this respect, it aligns well with other software familiar to modelers, such as HEC-RAS. However, with a focus on long-term channel change at the system scale, FRAME operates quickly in response to an adaptive timestepping algorithm and generates outcomes on an annual basis for simplified cross sections that represent reaches rather than locally specific conditions. With adoption of one year as the hydrological timestep, FRAME is highly original with channel morphology responding to discretized annualized flow duration curves rather than sequences of hydrographs but with sub-annual timesteps to ensure incremental adjustments are made in the direction of sediment transport equilibrium and safeguarding against computational instability.

The FRAME approach recognizes that any conceived river future is hypothetical only and so outputs cannot be truly verified quantitatively. However, where possible we can use hindcasting to achieve a degree of calibration against known historical changes and seek parallels with qualitative channel evolution models to give insights into likely directions and stages of channel evolution and provide some degree of certainty on long-term projections of morphological response. In this respect, when looking into the future through FRAME's lens, the relative differences between historical, current and future river scenarios are brought into sharp focus rather than absolute estimates of forecasted sediment yields and channel changes. Modeled intra-annual changes are not output as they are treated as indicative only, rather than a true time series of short-term morphological response, and as a stepping stone in deriving the probabilistically likely decadal-scale trajectory of channel evolution.

As an intermediate-complexity approach, FRAME represents quite a different way of modeling that blends a system of morphological rules with established methods. Geomorphic rules, controlled with calibration dials, are employed to reduce or bridge the complexity of physical processes and in accounting for management interventions. These might include, for example, simulating the impacts of changing sediment inputs from tributaries or bank erosion, exploring the effects of diversion options during water years with runoff that is higher than, similar to and lower than average, or revealing the performance of the channel in recovering from meander bend cut-offs. The functionality and special features of FRAME are introduced below.

Hydrology

Annualized flow duration curves (AFDCs) are required to run FRAME, thereby providing a basic hydrological time-step of one-year duration. The method of Harrell-Davis (Harrell and Davis 1982; Vogel and Fennessey 1994) is applied for generating smooth AFDCs and discretization to variable sized discharge classes is performed using the Ramer–Douglas–Peucker algorithm (Douglas and Peucker 1973), a GIS method appropriated for 'decimating' a curve according to a user-specified number of points, while preserving its shape. Its novel application here enables FRAME to operate with a small number of discharge classes, which is essential for rapid generation of outputs, but with confidence they provide a good representation of flow duration.

As conventionally the case, a flow input is required at the upstream limit of the modeled river length, with a series of flow change points sited at user-specified locations along the watercourse. Flow change points can correspond with gaging station locations but alternatively, AFDCs are simulated from other gaging stations found either within the drainage network or a donor catchment with similar hydrological character, and scaled linearly on drainage basin area. At each flow point, the AFDC is discretized into a user-specified number of discharge classes, each with a median discharge. The frequency of each discharge class is fixed for all input locations, with the set of frequencies derived from the period-of-record flow duration curve for one (designated as the primary) gaging station, with the modeling premise that discharges of the same frequency occur synchronously along the modeled river length. Each flow change point thus comprises a flow frequency histogram with discharge classes of fixed frequency; for intervening cross sections, discharge is linearly interpolated by stream length.

Currently, tributaries are treated as point-inputs only with no extension of the cross section network within the hydraulic model. The AFDC for the tributary is simply a scaled replicate of one of the main channel input AFDCs, based on drainage basin area ratio. At each confluence, the upstream drainage basin area in the main channel is also specified to enable interpolation of flows. This also applies for the most downstream cross section in the main channel.

The ability to increase or decrease flows along a watercourse in response to abstraction, diversion and (potentially) flow inputs is an important objective of the FRAME tool in providing functionality for managers/planners to investigate morphological impacts from management operations. Diversions are treated as inputs (or outputs) and can be assigned to any cross section with simple rules for setting flow at either a fixed rate or a percentage of the main channel discharge. Critically, diversions can be set to come on-line and begin having an impact at a specified future year and, optionally, once a minimum operating discharge has been exceeded in the main channel.

A tributary and diversion channel associated with a particular cross section, i, is assumed to impact flows and sediment transport upstream of the location in the order of tributary first, then diversion, such that the total flow at cross section i for discharge class j, $Q_{(i,j)}$, is the total flow at the upstream cross section, $Q_{(i+1,j)}$, plus tributary flow, $Q_{t(i,j)}$, plus or minus diverted flow depending on flow direction, $Q_{D(i,j)}$:

$$Q_{(i,j)} = Q_{(i+1,j)} + Q_{t(i,j)} \pm Q_{D(i,j)} \tag{1}$$

where $Q_{D(i,j)}$ can be set as a percentage of the sum $Q_{(i+1,j)} + Q_{t(i,j)}$.

FRAME accounts for hydroclimatic variability by designing ensembles of river futures based on sequences of AFDCs over periods spanning decades. For any future year, the user can change the input flows with a choice between: i) the period-of record flow duration curve; ii) any historical AFDC, or; iii) a future-year probabilistic AFDC. In addition, discharges can be adjusted by a user-defined multiplier, which might prove useful for simulating the impact of climate change. Probabilistic AFDCs are generated following the method of Vogel and Fennessey (1994), which involves the non-parametric analysis of quantile-based flow duration curves. Here, the 50th percentile AFDC represents typical flow conditions (the normal range of flows), the 75th percentile AFDC represents a hypothetical median wet year and the 25th percentile AFDC represents a hypothetical median dry year. In total, 99 probabilistic AFDCs are provided to give the user flexibility in designing a variety of hydrological storylines of wetter or drier than average years and investigating their respective morphological responses.

Morphological Representation

Channel morphology in FRAME is currently represented via a rectangular shape (avatar) that preserves the morphological bankfull width and with an invert level that satisfies bankfull conveyance of the full cross section. This representation facilitates far faster processing than detailed cross section geometries and acknowledges that attempting to predict the intricate nature of channel morphology over a period of multiple decades would be a spurious exercise. Overbank geometry is also simplified by setting each floodplain's elevation to that of the adjacent bank-top, with floodplain 'hydraulic' width set to provide an equivalent overbank flow area at the maximum floodplain elevation. Avatar creation thus rests on the availability of existing surveys and involves a three-step process, with all cross sections initially converted before generating a high resolution series of interpolates along the river length that are then employed to output reach-average cross section avatars according to a user-defined fixed spacing. Each cross section is interpreted as an average condition, representative of the longer reach within which it resides.

Backwater calculations have been compared between actual sections and their avatars using HEC-RAS with generally good agreement on slope and shear stress but with some expected discordance at low flows for geometries where the rectangle shape notably elevates the true thalweg. Alternative avatar designs are currently being explored that incorporate a shape factor and might better preserve thalweg elevation.

Hydraulics

FRAME's backwater model and associated hydraulic calculations follow reasonably closely to the procedures adopted by HEC-RAS, although FRAME is only applicable to subcritical flow conditions; where supercritical flow is encountered, FRAME defaults to critical flow. One-dimensional hydraulic and sediment transport computations are performed for each discharge class frequency in turn (the order is not important), thus generating a series of concomitant steady-state models for each timestep. In the current version, Manning n coefficients are held constant for hydraulic computations.

FRAME operates with an adaptive hydraulic timestep significantly smaller than the one-year hydrological timestep, that adjusts relative to user-defined thresholds of morphological change. FRAME apportions each hydraulic timestep according to the frequency distribution of the input flows; so each timestep encompasses a time-compressed version of the AFDC and involves updating the hydraulic calculations associated with each discharge class. Within each hydraulic timestep, the water surface profiles remain unchanged but material within the bed's active layer continues to mix and sediment transport capacity recalculates over an adaptive mixing timestep that grows as the degree of morphological change decreases and vice versa

Sediment Transport

Currently, FRAME accounts for bed material load only and washload does not feature; silt and clay material is assumed to pass entirely through the modeled reach without interacting with the channel boundary or floodplain surface. Bed and bank material gradations are defined by the user according to nine standard particle size classes between 0.063 mm and 256 mm: the smallest six classes of 1Φ interval and the largest three classes of 2Φ interval (Udden-Wentworth grain size scale). The user can specify gradation information at any location along the main channel to define a system of initially stepped bed and bank material change points (with no interpolation between).

To characterize sediment transport in FRAME, we adopt a subscript reference system of 's' (long-stream) and 'n' (cross-stream) for sediment input/output at each FRAME cross section. Thus, sediment transport rate per unit width in the s direction, $q_{s,s}$, for cross section i (numbered in the upstream direction) and performed on a grain size class, k, basis is denoted by $q_{s,s(i,k)}$. The prototype FRAME model includes a choice of sediment transport equations for computing the sediment transport 'potential' by particle size that have helped with the development and testing of the model to date. Bed material transport is calculated over the channel portion of the cross sections only. The transport potential, $\hat{q}_{s,s(i,k)}$, is simply the sediment transport rate of a particular particle size as it is calculated from the hydraulic parameters, assuming it is the only size in the bed. For each discharge in the AFDC, the series of transport potentials for the bed material size classes remains constant until the hydraulics are updated again. Akin to HEC-RAS, each time the bed material in the active layer is re-mixed, the transport capacity is re-computed by prorating transport potential according to the percentage of each particle size found in the current bed active layer, $P_{a(i,k)}$; sediment transporting capacity is thus proportional to the relative abundance of the particle size within the active layer, as follows:

$$q_{s,s(i,k)} = P_{a(i,k)}\hat{q}_{s,s(i,k)}\lambda_{(i,k)} \tag{2}$$

An optional hiding-exposure factor, $\lambda_{(i,k)}$, is currently coded into FRAME as an experimental feature, which is based on a simple linear scheme, as follows:

$$\lambda_{(i,k)} = 1 - 2a\left(0.5 - \sum_{f=1}^{k} P_{a(i,f)}\right) \tag{3}$$

where k increases with sediment size class and 'a' is a user-defined hiding-exposure 'strength' index (0 to 1). For example, if 50 percent of the active layer particles are coarser than the subject particle size k, then $\lambda_{(i,k)}$ takes a value of 1 regardless of the strength index. If the strength index is zero, then there is no correction for hiding-exposure and $\lambda_{(i,k)}$ takes a value of 1. However, a strength index of a = 0.5 gives a range of $\lambda_{(i,k)}$ between 0.5 for the finest particles (a 50 percent reduction in transport rate) and 1.5 for the coarsest particles (a 50 percent increase in transport rate), and a theoretical maximum strength index of a = 1 gives a range of $\lambda_{(i,k)}$ between 0 (fully sheltered) and 2 (very exposed and doubling of the transport rate). This simple hiding-exposure correction is based on an ordinal system of respective particle size and does not account for the shape of the size distribution.

A unique feature of the FRAME approach is that over each timestep it accounts for N_j discharge classes from an AFDC concurrently, whereby the potential transport rate for each particle size, k, at cross section i is aggregated from each discharge class, j, taking into account its frequency of occurrence, P_j, according to:

$$\hat{q}_{s,s(i,k)} = F_{Qs} \sum_{j=1}^{N_J} P_j \hat{q}_{s,s(i,j,k)} \tag{4}$$

where F_{Qs} is a user-defined global calibration factor for sediment transport rates.

FRAME adopts a simple two-layer scheme for mixing the bed material, comprising a dynamic active layer at the bed surface with sediment available for transport lying over an invariant parent material (inactive layer) of indeterminate depth. The method is somewhat analogous to the two-layer scheme in HEC-RAS. In the prototype FRAME model, initially both parent material and active layer exhibit the same gradation before fully mixing the bed after every timestep: if the bed erodes then the scoured active layer receives an equivalent vertical increment of the parent material, which is mixed with the residual active layer sediment; conversely, all deposited sediment is mixed with the existing active layer before cutting a new active layer and sending the residual mixed sediment to the inactive layer – although, the parent material gradation is not updated. Continued mixing can result in the active layer fining or coarsening over time. Initial test runs have focused on rivers with sandy beds and the thickness of the active layer length is set as 15 percent of the flow depth (as adopted in the Copeland mixing method in HEC-RAS), for either the time-averaged or maximum discharge class. To reduce the likelihood of the active layer being fully eroded, its thickness can be temporarily extended during a timestep by a user-specified multiplier, which involves mixing in an increment of the parent layer of sufficient thickness to preclude (if the multiplier is sufficient) the complete removal of any prevailing particle size.

Sediment input from upstream sources, expressed as unit sediment transport capacity (aggregated by flow class), delivered to a subject cross section, i, by particle size, k, is given by:

$$y_{s(i,k)} = \begin{cases} q_{s,s(i+1,k)} + q_{s,t(i,k)} + q_{s,o(i,k)}, & i < N_I \\ q_{s,s(i,k)}, & i = N_I \end{cases} \tag{5}$$

where $q_{s,s(i+1,k)}$ is the capacity of the upstream cross section (Equation 2), $q_{s,t(i,k)}$ is the capacity associated with a tributary located between i and i+1, if present, and $q_{s,o(i,k)}$ denotes capacity related to other sources (currently related to diversions and dikes); in all cases unit capacity is relative to the channel width of cross section i+1. Note, $q_{s,o(i,k)}$ could be negative if representing a net output of sediment associated with storage of sediment behind dikes and/or removal of sediment in a diversion channel.

In addition, lateral sediment supply, $y_{n(i,k)}$, from the net result of bank erosion/failure (positive) and accretion (negative) completes the set of sediment sources, expressed as contributing transport rate for particle size k, $q_{s,n(i,k)}$, per channel width of the subject cross section, i:

$$y_{n(i,k)} = q_{s,n(i,k)} \quad (6)$$

However, the current version of FRAME is restricted to vertical bed adjustments only, with development of a channel widening sub-module as a current research focus.

Tributaries:

Sediment delivered from tributaries is modeled implicitly as a function of the main channel's hydraulics and sediment transporting potential; as such, tributaries are treated as scaled replicates and not independent sub-models. Two options are available: a) dynamic concentration mode – the tributary input mirrors the sediment concentration of the main channel as it changes during a model run, assuming the bed material matches that in the main channel, and; b) static concentration mode – tributary inputs are based on a fixed sediment concentration, computed for the first timestep, with bed material reflecting that of the main channel at the model start and unit sediment transport potential adjusting only as the annual discharge and channel width change to maintain the fixed concentration. To facilitate scenario-modeling the impact of tributaries, the user has the option of adjusting either the dynamic or static concentrations for each tributary by a concentration multiplier, $F_{CT(i)}$.

Tributary mode A – dynamic concentration:

For mode A, the unit sediment transport potential, $\hat{q}_{s,t(i,k)}$, and capacity, $q_{s,t(i,k)}$, for sediment size class k, associated with a tributary sited upstream of cross section i are given by:

$$\hat{q}_{s,t(i,k)} = \begin{cases} F_{Qs} F_{CT(i)} \left[\sum_{j=1}^{N_J} P_j \hat{q}_{s,s(i+1,j,k)} \left(\frac{Q_{t(i,j)}}{Q_{(i+1,j)}} \right) \right], & i < N_I \text{ and } Q_{(i+1,j)} > 0 \\ 0, & i = N_I \text{ or } Q_{(i+1,j)} = 0 \end{cases} \quad (7)$$

$$q_{s,t(i,k)} = \begin{cases} \hat{q}_{s,t(i,k)} \left(\frac{q_{s,s(i+1,k)}}{\hat{q}_{s,s(i+1,k)}} \right), & i < N_I \text{ and } \hat{q}_{s,s(i+1,k)} > 0 \\ 0, & i = N_I \text{ or } \hat{q}_{s,s(i+1,k)} = 0 \end{cases} \quad (8)$$

Tributary mode B – static concentration:

For mode B, the unit sediment transport potential and capacity are given by:

$$\hat{q}_{s,t(i,k)} = \begin{cases} F_{Qs} F_{CT(i)} \left[\sum_{j=1}^{N_J} P_j \hat{q}_{s0,s(i+1,j,k)} \left(\frac{q_{(i+1,j)}}{q_{0(i+1,j)}} \right) \left(\frac{Q_{t(i,j)}}{Q_{(i+1,j)}} \right) \right], & i < N_I \text{ and } Q_{(i+1,j)} > 0 \\ 0, & i = N_I \text{ or } Q_{(i+1,j)} = 0 \end{cases} \quad (9)$$

where $\hat{q}_{so,s(i,j,k)}$ = initial unit sediment transport potential for timestep 1 in the main channel for cross section i+1, discharge class j and sediment size class k, $q_{(i+1,j)}$ = unit discharge at cross section i+1, for discharge class j, and $q_{o(i+1,j)}$ = initial unit discharge for timestep 1, cross section i+1 and discharge class j.

$$q_{s,t(i,k)} = \begin{cases} \hat{q}_{s,t(i,k)} \left(\dfrac{q_{s0,s(i+1,k)}}{\hat{q}_{s0,s(i+1,k)}} \right), & i < N_I \text{ and } \hat{q}_{s0,s(i+1,k)} > 0 \\ 0, & i = N_I \text{ or } \hat{q}_{s0,s(i+1,k)} = 0 \end{cases} \quad (10)$$

where $\hat{q}_{s0,s(i+1,k)}$ and $q_{s0,s(i+1,k)}$ = initial unit sediment transport potential and capacity (aggregated by discharge class), respectively, for timestep 1 in the main channel at cross section i+1 and for sediment size class k.

Inflow/Outflow Diversions:

The sediment transport rate in diversion channels is computed similarly to tributaries but with additional accounting for sediment input to the main channel from an upstream tributary, if present. If flow is diverted away from the main channel (outflow), the transport capacity of the diversion is computed using the dynamic concentration method (mode A) above and the impact on $q_{s,o(i,k)}$ in Equation 5 is negative. Alternatively, if flow and sediment is being diverted into the main channel (inflow), then either the dynamic (mode A) or static (mode B) concentration methods, above, can be chosen. As with tributaries, the user has the option of adjusting either the dynamic or static concentrations for each diversion by a concentration multiplier, $F_{CD(i)}$; for example, setting this to zero simulates a flow diversion with zero sediment removal.

Dike Fields:

The ability in FRAME to simulate the effect of dike fields is imperative in situations, such as the Lower Mississippi, where flow hydraulics are impacted beyond the local scale and sediment transport processes are sufficiently modified to incur reach-scale effects on bed level adjustment over periods of years and decades. Scenario-modeling options for dike design and implementation would enable managers to assess the proximate bed scouring potential, realize and compare the more distal morphological impacts both upstream and downstream and thus provide useful insights for feasibility studies. Flow and sediment transport dynamics over dike fields, though, are inherently complex, with processes extremely challenging to replicate in two- and three-dimensional models. However, adopting a rules-based approach, dike systems are designed in FRAME as simple channel constrictions over a specified reach length, with the user setting relative dike dimensions, sediment-trapping performance and the model running time (in years) when the system comes on-line, flow is constricted and the sediment begins to trap behind the notional dike structures. For computation, dike systems are located upstream of the assigned cross section location but downstream of any tributaries and diversions.

A user-specified trapping efficiency factor for the dikes defines the proportion of all incoming bed material load (with no weighting based on particle size) that is directed into a notional sediment reservoir rather than passing downstream and contributing to the sediment balance computations. The reservoir continues to fill until its capacity is reached, defined by the dike field dimensions. During the filling stage, sediment stored imparts a negative impact on $q_{s,o(i,k)}$ in Equation 5. Once full, the dike field no longer diverts sediment into the reservoir and all sediment passes along the channel according to the transporting capacity driven by the hydraulics. During a FRAME run, the time taken (in years) for a dike system to fill with sediment is output and this filling period can be used to calibrate the trapping efficiency factor if guidance is available on actual filling rates for historical dike fields. Currently, the rectangular cross section avatar permits only a crude representation of dike geometry, with constrictions extending to the banktop level and all modeled flows passing around the dike field in a reduced channel width cross section.

Morphological Adjustment

Working down the modeled reach from cross section N_I to 1, FRAME employs a discretized version of the Exner equation by particle size, k, which translates the difference between inflowing sediment load from upstream sources and bank erosion and outflowing sediment load into volumetric sediment change, $\Delta X_{(i,k)}$, over a modeled timestep, Δt (s), expressed (here, in imperial units of ft^3/s) as:

$$\Delta X_{(i,k)} = \begin{cases} \dfrac{43.2\Delta t}{G_s \gamma_w (1-\lambda)} \left\{ W_{c(i+1)} y_{s(i,k)} - W_{c(i)} \left(q_{s,s(i,k)} - y_{n(i,k)} \right) \right\}, & i < N_I \\ 0, & i = N_I \end{cases} \tag{11}$$

where G_s = specific gravity (assumed 2.65), γ_w = unit weight of water (62.4 lbf/ft^3), λ = porosity of bed material (assumed 0.3), W_c = channel width (ft), and the constant 43.2 converts transport rate from tons/day to lb/s. For small changes in bed elevation and channel width over Δt, the unit rates are assumed constant, which is a common assumption in river modeling.

In turn, the vertical adjustment of the bed over the modeled timestep, $\Delta Z_{(i,k)}$ (ft) defines the required bed deposition (positive) or erosion (negative) of particle size k necessary to satisfy the imbalance between its supply and transporting capacity. Here, FRAME employs an approach not dissimilar to the 'end-area' method in HEC-RAS, whereby ΔX is distributed according to back-to-back half-wedges, with maximum change at the subject cross section i and tapering linearly away to zero over contiguous reach lengths to bounding cross sections i+1 and i-1, and accounting for variation in channel width:

$$\Delta Z_{(i,k)} = \begin{cases} \dfrac{6\Delta X_{(i,k)}}{L_{i+1}\left(2W_{c(i)} + W_{c(i+1)}\right) + 3L_{(i)}W_{c(i)}} \text{ or } 0, & i = 1 \\ \dfrac{6\Delta X_{(i,k)}}{L_{i+1}\left(2W_{c(i)} + W_{c(i+1)}\right) + 3L_{(i)}W_{c(i)}}, & 1 < i < N_I \\ 0, & i = N_I \end{cases} \tag{12}$$

where $L_{(i+1)}$ = upstream reach length between cross sections i+1 and i and $L_{(i)}$ = downstream reach length between cross sections i and i-1. The upstream cross section ($i = N_I$) maintains a fixed bed (ΔZ = 0) as sediment supply is set to match transport capacity and the user specifies whether the bed at the downstream cross section (i = 1) is fixed (recommended) or relaxed.

For the case of bed scour, ΔZ is treated as potential change only as erosion might be restricted or arrested due to the presence of cohesive material, bedrock or if the active layer does not accommodate enough of particle size k to satisfy $\Delta Z_{(i,k)}$; in such cases, the full ΔZ is not achievable during the timestep (see below).

At the end of each timestep, FRAME aggregates change for the N_K particle size classes and computes the total bed elevation adjustment, $\Delta Z_{(i)}$, as:

$$\Delta Z_{(i)} = \sum_{k=1}^{N_K} \Delta Z_{(i,k)} \tag{13}$$

The first cross section remains fixed in terms of bed material composition and channel morphology, assumed to be an equilibrium reach, transferring sediment with no erosion or deposition, which might not transpire in the actual river. At the lower end of the model, there is also uncertainty as the bed profile is uncoupled from the downstream unmodeled reach. Thus, when interpreting the results of FRAME, it is recommended that several cross sections at the top and bottom of the modeled river length be treated as sacrificial and discounted from analysis.

Eventual completion of the bank erosion sub-module of FRAME and adding functionality for reach length change to simulate sinuosity adjustment (forthcoming) will enable channel widening-narrowing in addition to aggradation-degradation, with the energy gradient responding to meandering behaviour in addition to cross-sectional change.

Restricted Bed Erosion

Often, the process of bed erosion is hindered by the presence of cohesive material or bedrock, that becomes exposed with progressive degradation. This is often the case in river channels that are actively incising in response to a disturbance, such as channelization, as typified in well-established Channel Evolution Models (CEMs). The presence of superficial bedrock or tight clays might completely halt bed incision, arresting the sequence of post-disturbance channel evolution, leading to stabilization (Cluer and Thorne 2014); alternatively, erodible clays might enable continued bed scour but at significantly reduced rates of bed lowering. Simulating the hydraulic erosion of cohesive material requires an alternative method to sediment transport functions that are applicable to granular bed material only. A widely-applied approach for cohesive control derives erosion distance, E, based on excess shear stress and utilizes an erodibility coefficient, k, following the general form:

$$E = k(\tau - \tau_c)^b \qquad (14)$$

where τ = bed shear stress and τ_c =critical bed shear stress for erosion of cohesive material.

There is a significant literature base that discusses the value of the erodibility coefficient but with no clear consensus and reported wide-variation. Existing research has attempted to link the coefficient to the nature of the cohesive material, however there is no reliable, widely-tested and accepted relationship and, accordingly, there is general agreement on either relying on field-testing or calibrating computed erosion rates based on historical evidence (Daly et al. 2015). In addition, estimation of τ_c is not straightforward and the exponent b is often assigned a value of 1 without justification.

Whether for scour of cohesive beds or erosion of cohesive bank material, the FRAME approach recognizes that without calibration a deterministic prediction of erosion rate for cohesive material is a futile endeavor, given the wide-ranging uncertainty in estimates and, in particular, non-stationarity in material type and properties over the long-term as a channel evolves and bed elevations and banklines shift their positions. FRAME employs an excess-stream power version of Equation 14 that rests appreciably on calibration, in the dimensionless form:

$$\frac{E}{E_h} = \left(\frac{\omega_{c0}}{\omega_c}\right)^a \left(\frac{\omega - \omega_c}{\omega_h - \omega_{c0}}\right)^b, \qquad \omega_c > 0; \omega > \omega_c; \omega_h \gg \omega_{c0} \qquad (15)$$

where ω = specific stream power, ω_c = critical specific stream power for entrainment, relating to sediment properties prevailing in the subject reach, ω_{co} = 'reference' critical specific stream power for entrainment, ω_h = specific stream power at an arbitrary high intensity condition and E_h = calibration erosion rate at $\omega = \omega_h$ when $\omega_c = \omega_{co}$. Initial testing has adopted a pragmatic linear model with a value of 1 for exponents a and b.

Employing specific stream power relates erosion directly to available energy. Stream power has been adopted widely to identify the risk of erosion or deposition in river channels (Soar et al. 2017) and to predict broad scale bank erosion rates (e.g., Larsen et al. 2006). Also, for bank erosion, specific stream power responds directly as channel width changes, whereas shear stress in some cases might be rather insensitive to widening if a backwater-effect (ponding) limits slope and depth change.

By introducing a user-specified calibration factor for erodibility, $F_{E(i)}$ (default 1 for $\omega_c = \omega_{co}$), the threshold for cohesive scour at any location i can be adjusted to take into account lower or higher resistance to erosion than the reference value, ω_{co}, due to variations in cohesive strength, vegetation and other factors, whereby:

$$\omega_c = \frac{\omega_{c0}}{F_{E(i)}} \tag{16}$$

Inclusion of F_E is akin to the approach of Klavon et al (2017; their Equation 3), used to correct applied shear stress indirectly and account for additional resistance as a 'lumped' factor. Substituting Equation 16 into 15 and integrating the impact of all N_J discharge classes for a subject cross section's annual flow frequency histogram, a calibration-focused general model for erosion of cohesive bed material is given as:

$$E = \frac{E_h}{(\omega_h - \omega_{c0})} \sum_{j=1}^{N_J} P_j . \max\{(F_{E(i)}\omega - \omega_{c0}), 0\}, \qquad \omega_h \gg \omega_{c0} \tag{17}$$

where P_j is the frequency of occurrence of the j^{th} discharge class.

Accounting for multiple discharges in this way is somewhat comparable to total energy expenditure (time-integrated specific stream power) employed by Costa and O'Connor (1995) and the notion of cumulative stream power by Larsen et al. (2006). In the scheme here, E_h is purely the hypothetical upper-bound erosion rate if $\omega = \omega_h$ for 100 percent of the time.

Over time-step Δt (s), the change in bed-level associated with cohesive scour, $\Delta Z_{coh(i)}$ at cross section i and with local erodibility calibration factor $F_{E(i)}$ is given by:

$$\Delta Z_{coh(i)} = -\frac{E_h \Delta t}{86400(\omega_h - \omega_{c0})} \sum_{j=1}^{N_J} P_j . \max\{(F_{E(i)}\omega - \omega_{c0}), 0\}, \qquad \omega_h \gg \omega_{c0} \tag{18}$$

where $\Delta Z_{coh(i)}$ and E_h have consistent length units (L) and E_h is specified in L/day.

Equation 18, then, is conditional on appropriate setting of calibration factors, comprising global terms E_h, ω_h and ω_{co} and local erodibility factor $F_{E(i)}$. The ω_h term, though, is merely a bounding parameter and a value of 300 W/m^2 (20.56 ft.lb/sec.ft^2) is one possibility for a default value, corresponding to a reported threshold (after Magilligan 1992) for large-scale geomorphic change. The reference critical specific stream power, ω_{co}, can be set initially in the range 20-30 W/m^2 (1.37-2.06 ft.lb/sec.ft^2) and adjusted thereafter, in conjunction with E_h, to converge on sensible rates of bed scour based on available calibration information.

The user specifies ω_{co} indirectly by a stream power index, P_{SPo}, according to:

$$\omega_{c0} = P_{SP0}\omega_h \qquad (19)$$

If E_h and ω_{co} are considered to represent a worst case in terms cohesive material of least resistance found within the modeled river length, then $F_{E(i)}$ is less than 1 and represents additional resistance associated with local conditions, providing the user with an indirect means of increasing ω_c above the reference ω_{co} value at any location or over a series of cross sections; setting $F_{E(i)}$ to zero halts bed scour completely at location i, which might be relevant if bedrock is present or with management intervention, such as grade control structures.

During a model run, cohesive bed scour is activated when the initial bed elevation at a cross section is reduced by a user-specified scour depth, which defines the top elevation of the cohesive bed, Z_{coh}. Thus, the cohesive bed can be set to lie at the initial bed elevation or at a user-specified buried depth (if known or assumed). Once the cohesive bed is exposed, if over the following timestep the sediment balance computation based on material in the active layer suggests further 'net' bed erosion ($\Delta Z_{(i)} < 0$ in Equation 13), the scour depth is then specified by the cohesive scour model (Equation 18) and Z_{coh} is reduced accordingly. In the current model, material scoured from the bed is assumed to be washload and has no further influence on morphological adjustment. With continued cohesive scour, the active layer remains as a notional entity only and sediment balance computations proceed in the background based on notional bed material (that also continues to be mixed, if not all grain sizes are eroding), but they have no influence on bed level change until the sediment balance suggests 'net' bed deposition ($\Delta Z_{(i)} > 0$ in Equation 13). At this point, the cohesive scour sub-module is switched off and the bed subsequently responds to the sediment balance (Equations 11-13), initially lifting its elevation above the cohesive surface.

If during a time-step cohesive material or bedrock become exposed and the net erosion of bed material cannot be completely fulfilled to satisfy the sediment balance computation, FRAME back-calculates the unused sediment transporting capacity and transfers it instantaneously in the model to the next downstream cross section indirectly by reducing its sediment supply. During cohesive bed scour, this means for the case when the notional sediment balances for all particle sizes are negative (i.e., erosional), then all sediment supplied to a location is throughput to the next downstream cross section. Transfer of unused capacity also occurs on a particle size basis if erosion is restricted during a timestep because material within the active layer (after extending, if the option is enabled) is exhausted.

Summary and In-The-Pipeline Features

FRAME is a new type of model currently in development with some special features that facilitate rapid investigation of morphological response to a range of future-year scenarios, including management interventions and climate change, over the decadal scale. Blending conventional one-dimensional hydraulics and sediment transport computations with a set of geomorphic rules, the objective of FRAME is to provide the future visioning required to inform strategic planning and sustainable river management solutions.

The near-term research focus is the development of a reduced complexity approach for simulating channel widening and narrowing, which will provide the much needed functionality in FRAME for simulating morphological response in gravel bed rivers and widening of channels with cohesive banklines associated with bed incision and stepping through channel evolutionary stages. In addition, a method is being developed for enabling channel slope changes to be accommodated through channel lengthening and sinuosity development, in addition to the autogenic response of the energy gradient to bed elevation and lateral adjustments. The ability to simulate channel lengthening will improve the prospect for FRAME to reveal channel evolutionary trajectories following channelization and meander bend cut-offs. Ongoing tool development, refinement of methods and continued testing of FRAME against well-constrained and data-rich case studies will enable results to be better validated and FRAME to progress from its current prototype status to its intended release as a fully working model.

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