# From *forecast* to *foresight*: a decision-support framework for visioning channel evolution in river management

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## Abstract

Pre-empting evolutionary changes in river morphology is essential for resource managers involved in strategic decision making in riverine environments, whether related to land use, flood risk alleviation, channel stability, or river restoration. Being able to better forecast and communicate expected channel morphological evolution over management timeframes is part of developing *foresight competency* in river management, allowing resource managers to envisage several plausible futures in channel evolution and to plan towards the most preferred. Foresight competency consists of six stages (framing-scanning-forecasting-visioning-planning-acting) of which the forecasting and visioning components are the least well developed. Development of an intermediate complexity forecasting tool, FRAME, simulating likely modes of channel morphological evolution over decadal to centennial timeframes over long distances, is the subject of a companion paper (Soar, *et al.* this volume). Here we focus on the weakest link in providing channel evolutionary foresight, visioning. Visioning involves translating scientific forecasts into an interactive decision support tool that supports transparent decision making. Critically, model outputs need conversion into metrics that alert managers to the likelihood of progressive or threshold-based transitions within or between channel morphology states. Bound by two constraints, namely, the 'dimensions' of channel morphology change supported by the numerical forecast model (here, FRAME) and the management requirements related to land-use planning, hazard diminution/asset maximization, and river conservation, seven process-based state-transition metrics are proposed. The metrics are subsequently converted into graphical indicators designed for management application and assembled into several prototype dashboard-style displays intended to facilitate interactive decision support.

A proof-of-concept application of this prototype visioning system (provisionally, RUBRIC, 'RUles-Based morphological Response in River Channels') is illustrated for the lower Mississippi River, simulating morphological changes under hypothetical conditions of climate stationarity, a wetter climate and flow diversion for the period 2020-2080. Dashboard displays are developed semi-automatically from the metrics calculated from the numerical model outputs and consist of multiple graphical indicators derived using Excel's in-built graphing functions. This example illustrates a relative consistency of conditions in this heavily engineered lowland sand-bed river that will likely not be replicated in other riverine settings. Near-term priorities in developing RUBRIC towards a fully-operational decision support tool will include incorporating new forecast outputs from FRAME, improvements in dashboard design and functionality, and modifications to facilitate user interactively. Developing foresight competency for channel evolution has the potential to greatly improve strategic decision-making in river management, but it is highly demanding of the underlying database of empirical and theoretical knowledge in fluvial geomorphology.

## Introduction

Understanding the evolutionary trajectory of river channels is essential for those involved in river corridor planning, flood risk alleviation, maintaining channel stability, and river restoration. Improvements in the ability to simulate and communicate anticipated channel evolutionary responses to changes in environmental forcing should, therefore, improve strategic approaches to river management as an example of *foresight competency* (e.g., Hines and Bishop, 2006; Hines *et al*., 2017). Such competency would allow resource managers to assemble multiple contingent predictions and to take actions towards a preferred future condition (Voros, 2003), such as a dynamic channel with significant habitat diversity, rather than a less desirable future (*e.g*., severe channel instability) which may currently be the most likely according to trends in prevailing environmental boundary conditions.

Strategic foresight is argued to consist of six sequential competencies involving framing, scanning, forecasting, visioning, planning and acting (Hines and Bishop, 2006; Hines and Zindato, 2016; Hines *et al*., 2017, Figure 1). The initial phases of *framing* the project's objectives and baseline conditions and *scanning* for information about past and likely future changes, are quite well advanced. So too are latter phases related to guidance for river management *planning* and regulatory control on *acting* to implement plans. Conversely, aspects related to *forecasting* (or *futuring*) of river channel evolution via scenario-based models, and *visioning* the modeled outcomes to pursue favorable channel evolution scenarios are far less well developed. Challenges related to modeling river channel evolution are examined in a companion paper (Soar *et al*., this volume). Such predictive models provide applicable information, but foresight competency also demands *visioning* of evolutionary outcomes via a decision support system (DSS) to make such contributions truly applied. Visioning is the least well-developed component of foresight competency and requires the DSS to make the investigation of channel evolution interactive and manager-driven (Matthies *et al*., 2007), and transparent (Mcintosh *et al*., 2011). That the DSS must manage and present data via an interactive interface is particularly important in the scenario simulations that often form the core of strategic planning (Matthies *et al*., 2007).

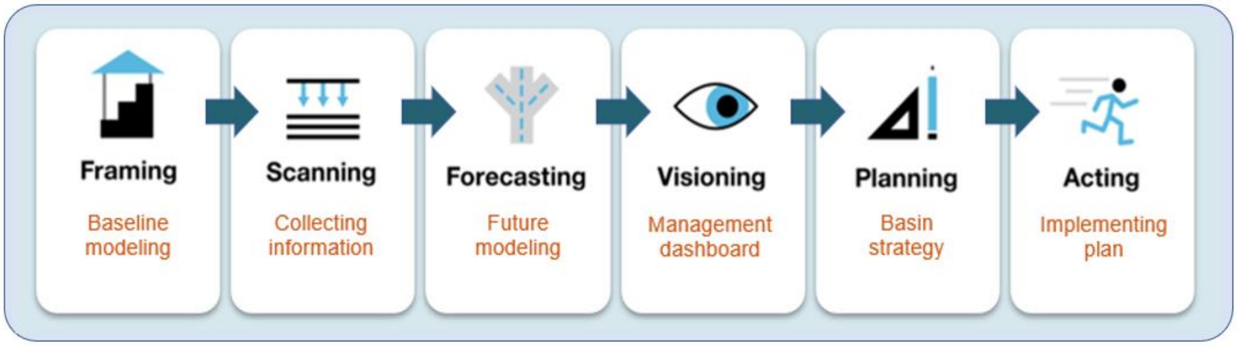


**Figure 1.** Management foresight, adapted for river basin management from Hines & Bishop 2006

DSSs for visioning channel evolution in river management are rare. Some development has been made in relation to the river's *current* biophysical condition (Boitsidis *et al.*, 2006; Shuker *et al.*, 2012; Marttunen *et al.*, 2019; Gurnell *et al.*, 2020), but DSS to support channel *evolution* are limited to nascent developments deriving management indicators from changes in hydraulic geometry parameters according to water management scenarios (Van der Waal and Rowntree, 2010) and for predicting the likelihood and local channel changes using a Bayesian Belief Network (Glendining and Pollino, 2012). The system for visioning channel evolution under development here is based on (1) predictions of state-transition changes in river morphology based on a custom-built intermediate complexity hydrodynamic numerical model (see Soar *et al.*, this volume) and (2) the assumed needs of resource managers involved in strategic planning of river management (Downs and Booth, 2011). From these starting points a decision support tool is developed that, first, derives multiple channel evolution *metrics* from the numerical model outputs based on describing common threshold-based risks in river management, second, translates those metrics into graphical *indicators* of evolution suitable for resource managers and, third, communicates the indicators using a *dashboard*-style graphical user interface. Provisionally titled RUBRIC (RUles-Based morphological Response in River Channels'), the process is illustrated in Figure 2. A brief overview and illustration of these process is provided herein – greater detail is forthcoming (Downs *et al.*, *in prep.*).

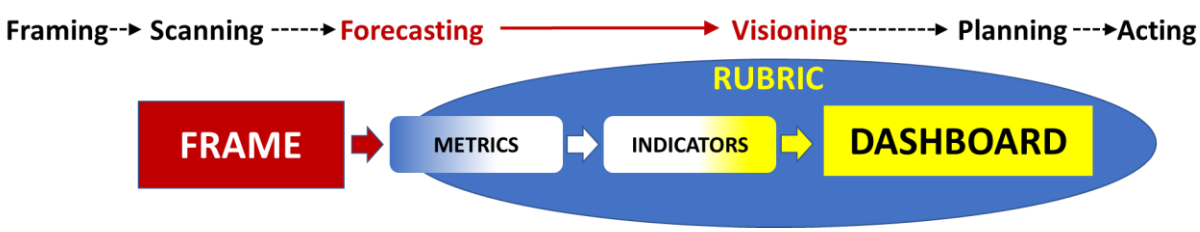


**Figure 2.** Overall approach to the RUBRIC decision support tool, as the 'visioning' component of the six-stage foresight competency process (top line) and deriving from forecasting capabilities provided by the FRAME numerical model.

# Visioning for decision support

Predictions of channel evolution generally describe channel morphology changes according to changes in imposed boundaries conditions at the watershed scale. Channel evolution is normally progressive in response to progressive changes in boundary conditions such as climate, land use and resource management, but the existence of step changes in boundary conditions (*e.g.*, building of a dam, rapid urban development) and extrinsic and intrinsic thresholds in geomorphic 'states' (Schumm, 1973), provides the possibility of abrupt morphological responses. Capturing the variety of within-state and between-state evolutionary transformations requires a 'state-transition model' basis for characterizing evolution (Phillips and Van Dyke, 2017). Prior state-transition modeling in fluvial geomorphology has been based largely on characterizing repeatedly observed sequences (*i.e.*, patterns) of channel morphology change and linking this to causal mechanisms, or using a process-based analytical approach predicting changes based on 'regime theory' (Mackin, 1948; Millar, 2005) related to governing conditions of sediment flux, stream flow and channel boundary conditions. The pattern-based approach is most identifiably linked to so-called 'Channel Evolution Models' (CEMs) that devolve on changes in the channel's width-depth ratio and bed elevation related to changes in upstream-to-downstream sediment transport processes (*e.g.*, Schumm *et al.*, 1984; Simon and Hupp, 1986; Simon, 1989). As an empirical technique there are frequently exceptions and variations in specific applications. The process-based approach links channel morphology changes to controlling variables and so is well-suited to scenario setting and channel design applications (*e.g.*, Soar and Thorne, 2001, 2011; Bledsoe *et al.*, 2017; Eaton and Millar, 2017; Stroth *et al.*, 2017) but the data requirements needed to accurately parameterize channel evolution prevents application over long reaches and planning timescales, as required in a 'foresight' application. An alternative approach, utilized here, involves application of simplified process-based hydrodynamic and sediment transport equations through an intermediate complexity one-dimensional numerical forecasting model, FRAME (Future River Analysis and Management Evaluation, see the companion paper in this volume).

**Metrics of Channel Evolution:** Developing a decision support tool from a numerical model requires a clear conceptual understanding of the constraints and capabilities resulting from the predictive 'engine'. Although river evolution in fluvial geomorphology has five dimensions related to changes in the vertical, lateral, length, time, and 'fractal' (*i.e.*, textural) dimensions, numerical models are limited by their formulation to a sub-set of these concerns. For instance, FRAME is currently a one-dimensional hydrodynamic model and can provide insights about evolutionary changes in three of the dimensions, namely the vertical (bed elevation), changes over time (according to sequencing of flow duration curves), and changes in the fractal dimension (grain size distribution of the channel bed). It cannot provide insights about lateral and length dimensions. Further, 'visioning' of channel evolution requires that the model outputs are translated into metrics that address the needs of resource managers involved in strategic planning near rivers. Such fundamental concerns for fluvial geomorphology in river management have been categorized as relating to sustainable land-use planning, avoiding hazards and maximizing assets, and conservation management activities such as river restoration (Downs and Booth, 2011).

Seven metrics were derived (Table 1) – five can be computed currently from FRAME outputs, and those related to the lateral and length dimensions await further development of the model. Preference was given for metrics drawn from physically-based studies on the basis that this provides both a strong theoretical justification and that the metrics will be responsive to changes in numerical model simulations. An analytical foundation also increases the prospect of developing state-transition relationships and that the metrics can be communicated as probabilities of positive or negative risk related to current channel morphology and the evolved future condition. Preference was also given for metrics that were generated inherently within FRAME to delay the point at which interpretative decisions are required. Clearly, not all metrics will be suitable or required in all applications, according to river type, evolutionary trajectory and the suite of external boundary conditions involved. Progress in defining these seven metrics is outlined below – more details can be found in Downs *et al*., (*in prep*).

**Table 1.** Seven metrics of channel evolution that address the needs of source managers involved with strategic matters related to land use planning, hazard avoidance and asset maximization, and conservation management near river channels.

| Category | Metric | Predicts | Basis (or status) | Inputs |
|---|---|---|---|---|
| Land use planning | **Planform type** | Planform change hazard / existing disequilibrium | Planform **state** & **proximity**: Eaton *et al*., 2010 | $S_{OT}$, $Q_{OT}$, $D_{50}$, μ' |
| | **Morphological stability** | Bed and bank instabilities | Bed & bank **states** & **proximity**: Watson *et al*., 2002, Simon 1995 | Hyd. stability = ΔH Bank stability = $H_c/H$ |
| | Erodible corridor | Meander belt width | Pending FRAME sinuosity evolution functionality | - |
| Hazard avoidance / asset increase | **Floodplain connectivity** | Flood duration hazard / asset | Overtopping **duration** | FDC/capacity |
| | Bank erosion rate | Bank erosion hazard / asset | Pending FRAME width adjustment functionality | - |
| Conservation management | **Bedform habitat** | Aquatic habitat type | Highest likelihood **state** & **proximity**: Buffington 2012 | LogReg: $S_{ot}$, $d_{50}$, W, $H/d_{50}$, XS Shields |
| | **Ecohydraulic diversity** | Relative instream habitat suitability | 'Interquartile' **ranges**: PHABSIM-like | $V_{25\text{-}75}$, $V_{50}$, $D_{25\text{-}75}$, $D_{50}$, $d_{50\text{-}84}$, $d_{16}$ |

Metrics related to land-use planning involve aspects of river evolution as it relates to the land area required to ensure healthy natural functioning of the river and to ensure that proposed land use changes in the river corridor do not create avoidable river-related risks. A metric related to *planform type* is critical because there are profound implications for river corridor width if the river's evolutionary trajectory includes the likelihood of crossing a threshold whereby a single-thread channel becomes multi-threaded or vice versa. We adopt the process-based 'discriminant function' of Eaton *et al*., (2010) who derive thresholds between dynamically stable single-thread channels, unstable multi-thread channels, and transitional anabranching channels based on Lane's conceptual process-response balance. A metric related to *morphological stability* is vital. Understanding the likelihood of channel incision or aggradation, or the prospect of riverbank failure is especially important when floodplain infrastructure occurs close to the channel's banks. Watson *et al.* (2002) develop a dimensionless two-threshold state transition index based on changes in 'hydraulic stability' and 'geotechnical stability' – FRAME provides bed elevation changes directly as a finite balance in sediment transport, and the simplified approach to mass bank instability from Simon (1995) is adopted. Finally a 'within state' metric focused on the belt width of the *erodible river corridor* has multiple potential applications related to prospective erosion hazards and land requirements over management timeframes. Projected rates of lateral adjustment in rivers and implied meander belt width changes can be based on several different approaches that require development of a length adjustment function in FRAME. One significant challenge is that all model-based meandering simulations (ideally) require site-specific calibration of riverbank erodibility coefficients (*e.g*., Castro-Bolinga and Fox, 2018).

The primary metrics related to minimizing hazards and maximizing riverine assets relate to *flood risk* and *bank stability*. The risk of floodplain inundation will change according to variability in the annual climate signal and according to channel capacity. In highly populated areas, an increased flood risk will be perceived as a hazard whereas in assuring channel-floodplain connectivity such a change is a critical asset. The metric is generated as a function of the flow duration curve for an individual year and whether channel bed-level changes increase or decrease flow conveyance. The risk of bank instability can likewise be viewed as a risk to critical floodplain infrastructure or vital in fostering healthy river and riparian functioning (*e.g.*, Florsheim *et al.*, 2008). Like the erodible river corridor, multiple approaches exist for characterizing this metric, with the most process-based requiring local information about bank material and bank erodibility coefficients which sit uneasily with the demands of long-term forecasting. A simplified metric of bank erosion is planned for FRAME and will represent introduction of a lateral (*i.e.*, width) adjustment function that extends the current capabilities of this one-dimensional model.

Metrics related to river conservation relate to changes is *bedform habitat* state, as an indicator of aquatic habitat potential, and changes in *ecohydraulic diversity* as a measure of hydraulic habitat potential. The former is derived from a state diagram of channel types based on an interpretation of rational regime equations in the widely used 'Montgomery-Buffington' channel classification system (Montgomery and Buffington, 1997). Because bedform habitat types overlap significantly, the state type is predicted as the most probable outcome from multiple state-specific binary logistic regression equations. Using the Buffington (2012) data set, the most commonly significant predictors were channel slope, relative submergence and channel width. We assume that changes in the alluvial structure of the channel bed will have repercussions for aquatic habitat type and typical species composition. Related, the metric for ecohydraulic diversity assesses whether channel evolution will change instream habitat conditions for better or for worse for valued fish species. As a simplification of models such as PHABSIM (Bovee 1982; Milhous *et al.* 1989) and CASIMIR (Mounton *et al.*, 2007; Noack *et al.*, 2013), the metric provides cross-sectionally averaged values for velocity, flow depth and bed surface grain sizes on annual time steps. The metric thus provides an indication about whether average values are changing, and could be the basis for the resource manager contracting a 'full' multi-dimensional assessment of fish habitat suitability.

**Indicators and Dashboard Development:** Visioning for decision support requires that the metrics – measures of the best scientific capacity of the numerical simulation model to address foresight in channel evolution – are transformed into visually accessible *indicators* that address concerns typical to resource managers involved with strategic river management. Where possible indicators should provide probabilities of risk related to the river's evolutionary trajectory. After calculation, indicators need to be communicated graphically in a manner designed to provide a high-level overview of forecast trends for the resource manager. Commonly, the solution is to provide an interactive graphical user interface (GUI) in the style of 'heart-rate monitor' dashboard that indicates analytical expectations of changes in time and space in proximity to thresholds in channel conditions. The dashboard must be user-friendly and facilitate interactivity in scenario setting, a hallmark of decision support that encourages interaction and widespread adoption of the tool.

Designed initially in Excel to facilitate compatibility with the FRAME numerical model and to be accessible without specialist software training, several pilot dashboards were developed with future interactivity in mind. The large matrix of indicator values and channel cross-sections that result from each analysis necessitated several dashboards. The first displays indicators as they vary from upstream to downstream for a user-chosen year, and the second displays indicator changes in time for a user-chosen cross-section.

The basic architecture for the proof-of-concept RUBRIC visioning system is illustrated in Figure 3. Data outputs are chosen via a menu system in the numerical forecasting tool FRAME and these form the data import to RUBRIC. Imported data is pasted into a structured spreadsheet that facilitates the semi-automatic computation of the various metrics. The metrics are transferred to a separate spreadsheet that allows the indicator graphics to be generated. A replicate of each graphic is contained within the dashboard display sheets so that as changes are made to the indicators, the dashboard updates. Computations were intentionally segmented at this phase to allow for easier error checking. User input screens have been coded into FRAME allowing the simple characterization of cross-sections, riverbanks, instream structures, tributary inputs, and flow diversions. This allows for simulation setting of possible management actions related to engineered changes in channel cross-sections, bank protection or restoration, the addition or removal of instream structures, and changes in flow abstraction or imports. Choices can be made regarding the annual flow duration curve and sediment regime to simulate 'external factors' such as climate changes, watershed build-out, dam construction or removal.

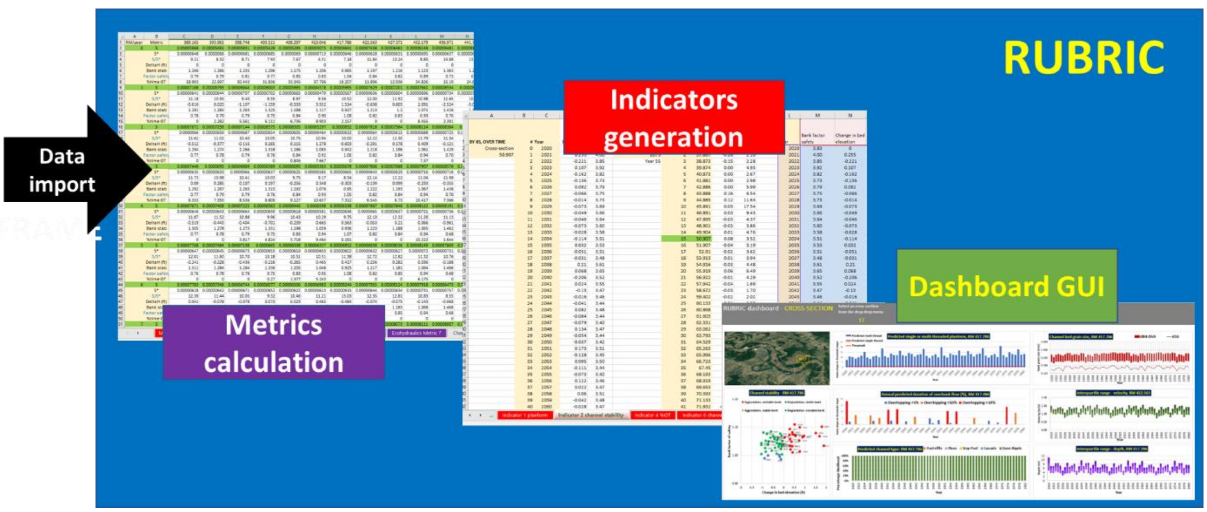


**Figure 3.** Overview of the conversion process from FRAME's data outputs through to the production of a dashboard -style graphical user interface in RUBRIC.

## Application – lower Mississippi River

Several case studies were developed to examine the operation and utility of the proof-of-concept dashboard. They included a 305-km (190-mile), 40-cross-section reach of the Lower Mississippi River (LMR), MS. This reach was used extensively in developing the FRAME hydrodynamic model which was initially coded to use the Toffaleti (1968) sediment transport equation designed for sand-bed rivers. Note that such sand-bed applications may run somewhat sub-optimally for the metrics, many of which were developed primarily for gravel-bed rivers.

The LMR test reach extends from the Arkansas River to the Yazoo River at Vicksburg with cross-sections situated at crossings or straight sections (avoiding pools) at an average spacing of approximately 6.1 miles, based on a 2004 hydrographic survey. The reach has been constrained by bank revetments since the 1960s thus morphological change is focused on bed level change rather than width adjustment, ideal for initial tests using the one-dimensional FRAME numerical model. Annual flow duration records were derived from the Arkansas City and Vicksburg gaging stations for the period 1963–2013 and discontinuous suspended sediment load data is available from the same gages. Bed material particle distributions were derived using a comprehensive dataset collected at numerous sampling locations in the period 1966–1974. Bedload data are available for Vicksburg based on high resolution bathymetric data.

Four scenarios were run for the future period 2020–2080. The first envisages a continuation of flow conditions from the recent past and uses three 20-year cycles of annual flow duration curves from 1994–2013. The 1994–2013 period has a median rank for flow peaks of 25.5 and flow volumes of 23.5 from the 50-year record set, illustrating the 'average' nature of this record. A 'wetter climate' simulation was then tested, using one 20-year cycle of the 1994-2013 flow duration curves followed by three 13-year sequences of higher flow years extracted from the overall flow records. The chosen flow years had a median and mean rank both at 7.0, indicating the simulation to include both larger than usual discharge volumes and higher magnitude flow peaks. Illustrating a hypothetical management intervention, a third scenario used the three 20-year flow cycles from the recent past in combination with the opening of a diversion downstream of cross-section 20 that diverts one-quarter of the flow and one-quarter of the sediment load at flows over 400,000 cfs. The final scenario combined the diversion scenario with the wetter flow conditions.

Several illustrations are provided below. One illustrates the proof-of-concept dashboard at a single cross-section (17) for the entire period of record using flows conditions of the recent past (Figure 4). The other illustrates variations along the entire reach for a particular year (2075) under the conditions of a wetter climate and with the flow diversion in place (Figure 5). As indicated in the previous section, the dashboards were developed in Excel using a 'semi-automated' system of data processing and using Excel's in-built graphing functions. The menu systems across the banner are illustrative rather than functional and point towards intended future interactivity. Likewise, aerial photo display is notional with the intention that the chosen cross-section, groups of cross-sections, or reach will eventually be highlighted using links to Google Earth or a similar system.

In brief, the results in part indicate a relatively limited morphological evolution of the LMR in the 2020–2080 period which is perhaps of little surprise given the reach's continuous bank protection. The results do indicate that cross-section 17 is consistently predicted to be multi-threaded by a large ratio (blue bars Figure 4) and this is matched by the entire reach (blue bars in Figure 5). This may indicate the extent to which the bank revetements prevent multiple channel threads developing in the LMR, but it is also likely that the LMR sits outside of the range of test environments encapsulated by the metric from Eaton *et al.* (2010). Accurate or not, there is no suggestion of change in planform type in time or space for the test scenarios. Likewise, the cross-section and reach show no indication of being anything other than a dune-ripple bedform type based on the aquatic habitat type metric derived using the Buffington (2012) data set: the green bars are part of a stacked bar chart adding to 100% wherein the probabilities of other bedform types would indicate as other colors. While such a result might be expected, it also reflects the sensitivity to slope values in the Buffington data set whereby low gradient channels (such as the

LMR) are always predicted to be sand-bedded. This indicator is likely to be more sensitive to changes in time or space in gravel-bed rivers.

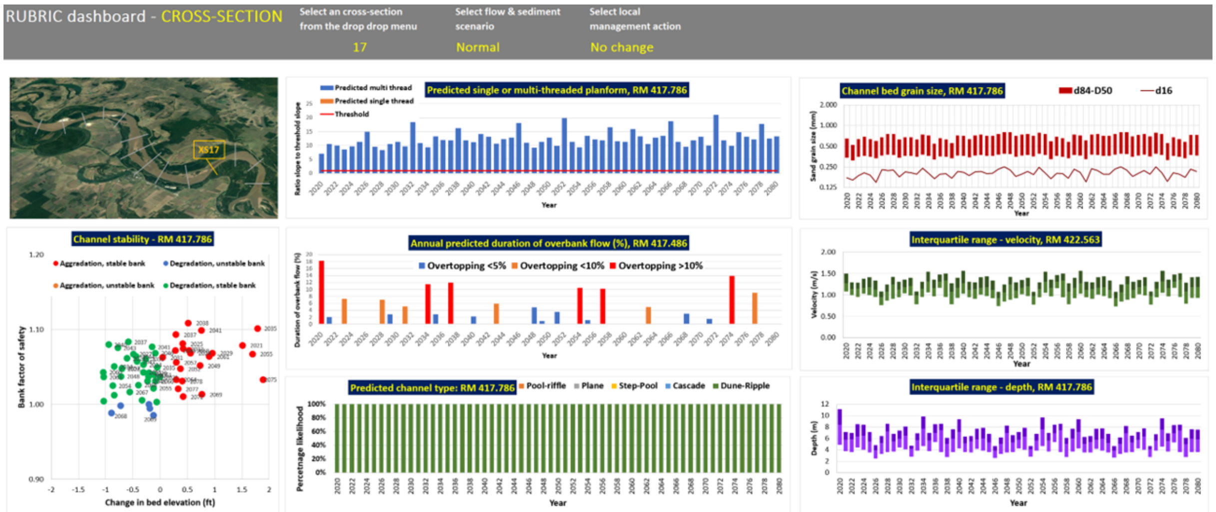


**Figure 4.** Example dashboard for channel evolution through time (2020–2080) at an individual cross-section. Simulation for cross-section 17 on the lower Mississippi River assuming a sequence of future flows very similar to those of the recent past (see text for details).

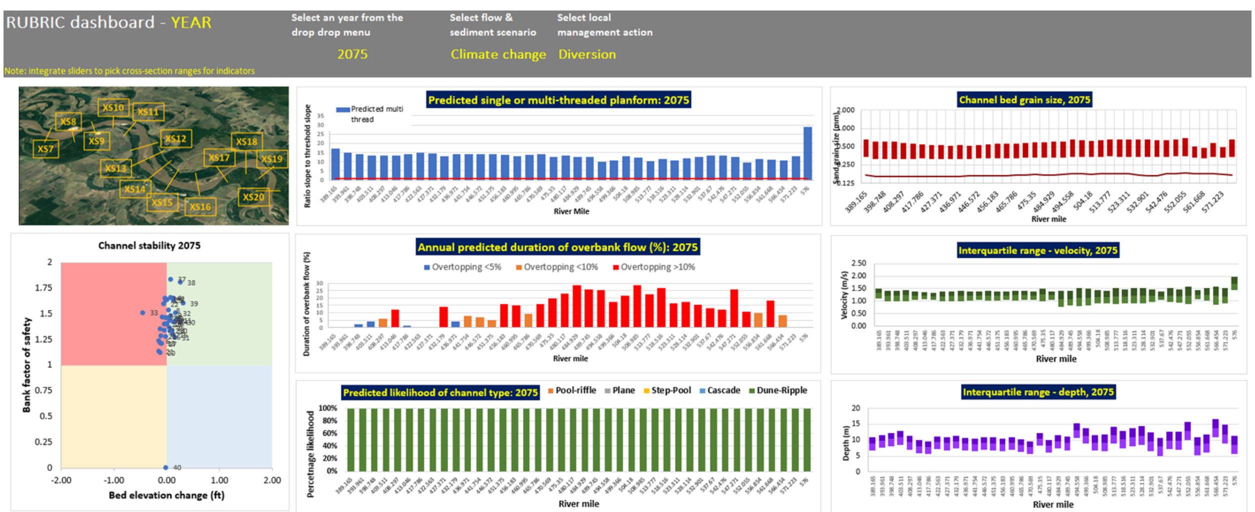


**Figure 5.** Example dashboard for channel evolution along a reach for an individual year. Simulation of change along the lower Mississippi River by 2075 (part of a simulation 2020–2080) assuming a flow diversion operates during flows >400,000 cfs part way along the reach, and that flow conditions are significantly wetter than in the recent past (see text for details).

Several two-dimensional plots were trialed to indicate the morphological stability metric (left hand plot in Figures 4 and 5). Each case shows overwhelmingly stable banks (y-axis factor of safety >1) in time (for cross-section 17) and for the entire reach in 2075. The bed alternates annually between small amounts of degradation and aggradation for cross-section 17 and along the reach in 2075. Better means of displaying trends through time will be considered in later iterations of the dashboard. The intermittent overtopping at cross-section 17 through time according to flow (Figure 4) is replaced in Figure 5 by far more consistent flooding along the reach in 2075 under wetter conditions (which in our scenario began in 2040), even with the removal of a significant flow by the hypothesized diversion.

The multiple indicators chosen to represent the metric of ecohydraulic diversity (right hand panels in Figures 4 and 5) show no trends in the coarser ($d_{50}$-$d_{84}$, red bars) and finer ($d_{16}$, red trace) grain sizes, or the interquartile ranges for velocity (green bars) and depth (purple bars) in time or space. Instead, there is a mild cyclicity of velocities and depths for cross-section 17 over the 2020–2080 period (Figure 4) and a reduction in the velocity and depth ranges downstream of the diversion by 2075 (Figure 5). The former is assumed to relate to the grain size transporting capacity of different flow years while the latter reflects how the threshold-driven operation of the diversion reduces higher magnitude flow discharges downstream of the diversion. If such changes appeared to have potential consequences for valued fish species, these results could be a trigger for more detailed ecohydraulic studies. Other than emphasizing the limited morphological 'freedom' of the LMR, the proof-of-concept dashboards indicate the potential for indicator displays of the channel evolution metrics, even at this rudimentary phase.

## Prospects

The research outlined above represents initial developments in trying to 'vision' channel evolution suitable for communication to managers involved in strategic resource planning for riverine environments. As such, it is part of developing a foresight competency component in river management using metrics of evolution drawn from applicable research. Calculations are developed from (and constrained by) a numerical model. To aid communication, the metrics are translated into multiple graphical indicators and displayed using a dashboard-style graphical user interface using (at present) in-built Excel functionality.

Near-term priorities for the RUBRIC system devolve upon three aspects. First, to exploit on-going improvements in the forecasting capability of the FRAME numerical model. The improvements may facilitate estimates of the currently missing metrics related to the erodible river corridor and to bank erosion rates, and incorporate displays of computational uncertainties. Second, to improve dashboard design and functionality. Dashboard improvements will include revisions to the individual displays, development of a third dashboard type that focuses on comparison of multiple scenarios for single indicators, and experiments in developing displays that use mapping from satellite imagery to provide visually intuitive indications of change. The third development is to facilitate greater user interactivity that allows managers to set and run prospective scenarios and/or view subsets of the indicators. This will require refinements in the menu systems but also, critically, integration of many of the 'RUBRIC' operations shown in Figure 2 into the FRAME numerical model so that users can run the models themselves. Testing on user groups will be vital.

Such developments will advance the FRAME-RUBRIC system towards a fully-operational decision support tool for forecasting and visioning decadal-scale channel evolution. It has the potential to greatly improve decision-making in river management by enabling resource managers to steer rivers towards preferred futures that include resilient functions and sustainable ecosystem attributes. However, the developments outlined herein also indicated that foresight competency is highly demanding of the underlying database of empirical and theoretical knowledge in fluvial geomorphology. Parallel efforts to establish more rigorous and replicable geomorphic relationships would greatly assist foresight competency capabilities.

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