The Alluvial Phase Space Diagram (APSD) and its potential application in the FRAME-RUBRIC model

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Abstract

The Alluvial Phase Space Diagram (APSD) was created jointly at the USGS Cascades Volcano Observatory and the University of Nottingham. It provides a template for visualizing, quantifying and evaluating morphological adjustments, and sequences of adjustments, in river form. The APSD is being applied in three elements of the USACE's FRAME (Future River Analysis & Management Evaluation) project development:

1. testing the performance of FRAME in simulating morphological responses to river management and natural disturbance,
2. training FRAME for application to individual study rivers, based on their past behavior,
3. evaluating the implications of future responses to river management with respect to changes in river form, phase shits, evolutionary trends, and river functions.

In this paper, we introduce the APSD and then illustrate its potential for application in the FRAME model using a case study of the Lower Mississippi River (LMR). The APSD reveals that between 1960 and 2015 the Lower Mississippi between Cairo, IL and Old River, LA adjusted its thalweg elevations and x-section areas in response to long-term trends of net erosion in the fluvially-dominated reach, upstream of Vicksburg, MS and net deposition in the downstream, backwater-influenced reach below St Joseph, LA. Application of the APSD to the 200-mile reach upstream of Vicksburg, MS selected for a pilot application of FRAME provided the opportunity to explore whether the APSD provides the basis for comparing model outcomes for a test run between 2004 and 2013 to the channel changes observed during that period.

Introduction

The Alluvial Phase Space Diagram (APSD) was developed to quantify the direction and stages of morphological channel change that occur in a river system (Major et al. 2018). Presenting the APSD in various formats creates the potential to chronicle the evolutionary trends, patterns, sequences, and cycles of channel change that occur in response to both normal flows and extreme events (floods, droughts, and events that input a large volume of sediment to the river system in a short period of time, such as landslides and volcanic eruptions, etc.).

Conceptually, imbalances between the supply of bed material sediment load from upstream and the local capacity of the river to transport bed material sediment load result in lowering or raising of the bed (i.e., degradation or aggradation). These vertical adjustments tend to increase or decrease the x-section area of the channel. If the width of the channel does not change, degradation increases the x-sectional area, while aggradation reduces it. The amount of area increase or decrease is a simple, geometric function of the distance by which the bed is lowered or raised, and can be calculated on this basis. If the actual change in x-sectional area differs from that attributable to lowering or raising of the bed, it follows that the width of the channel must also have changed, with amount of widening or narrowing being a function of the difference between the actual change in x-sectional area and that attributable directly to raising or lowering of the bed. In the APSD, six 'phase spaces' define and delineate the possible combinations of changes in bed elevation and x-sectional area. In essence, the APSD provides a window on the characteristic ways that the x-section geometry (or morphology) of the study river has changed through time at a given location.

In the FRAME Project, the potential utility of the APSD in assessing how well the FRAME model's 'avatar' representation of changes in the study reach of Lower Mississippi River, simulates patterns of long and short-term of channel change observed between 2004 and 2013.

The Alluvial Phase Space Diagram

The APSD is a triple axis graph that delineates 6 'Phase Space Domains' (Figure 1). The value of the APSD is that it provides a 2-dimensional area within which diverse, complex and highly variable data on x-sectional changes can be plotted and displayed, allowing typical combinations of vertical and lateral adjustment to be differentiated from unusual ones, and facilitating identification and chronicling of sequences, trends, and cycles of channel disturbance, response and evolution. In short, the APSD is a thinking space within which users can unravel, understand and begin to explain how the study river system responded to past disturbances through either relaxation, recovery or adjustment towards a new, dynamically-stable condition.

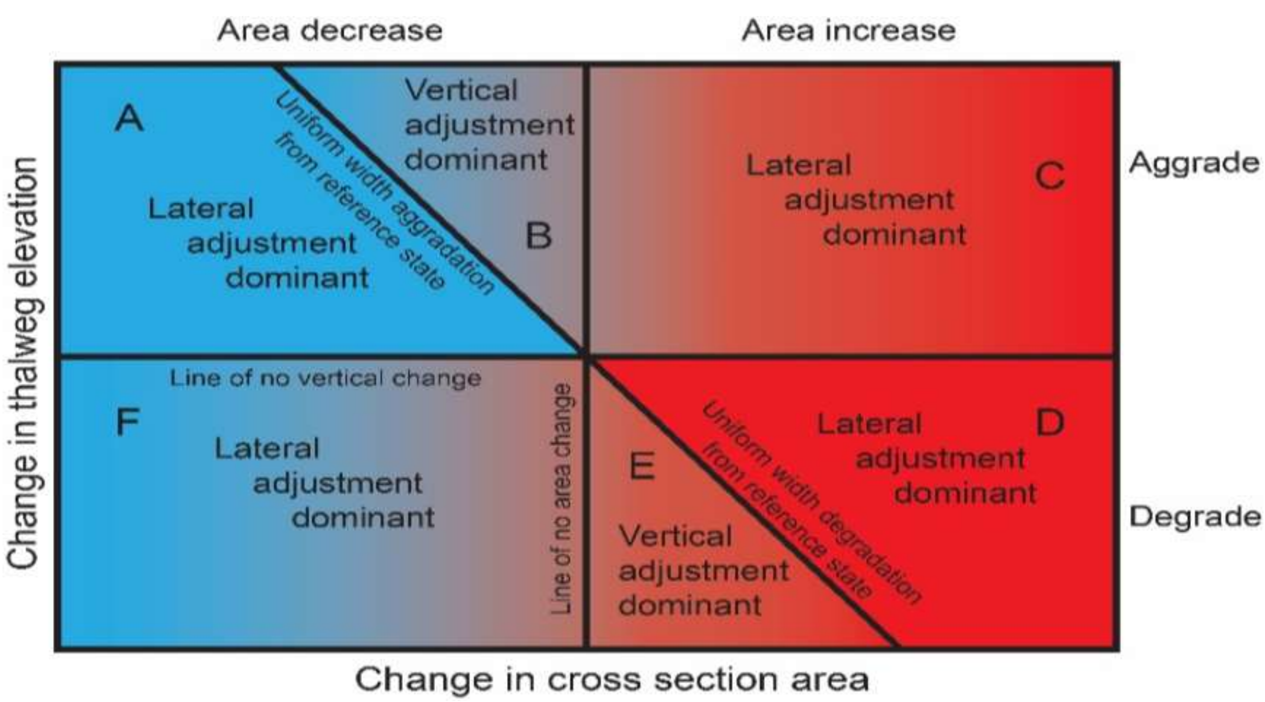

Figure 1. Alluvial Phase Space Diagram. Domains A to F define six possible combinations of vertical and lateral adjustment in x-sectional geometry (modified from Major et al., 2018).

In Figure 2, the three axes on the APS Diagram are labelled with pictograms illustrating the *types* of channel change associated with points that plot that on one of these axes.

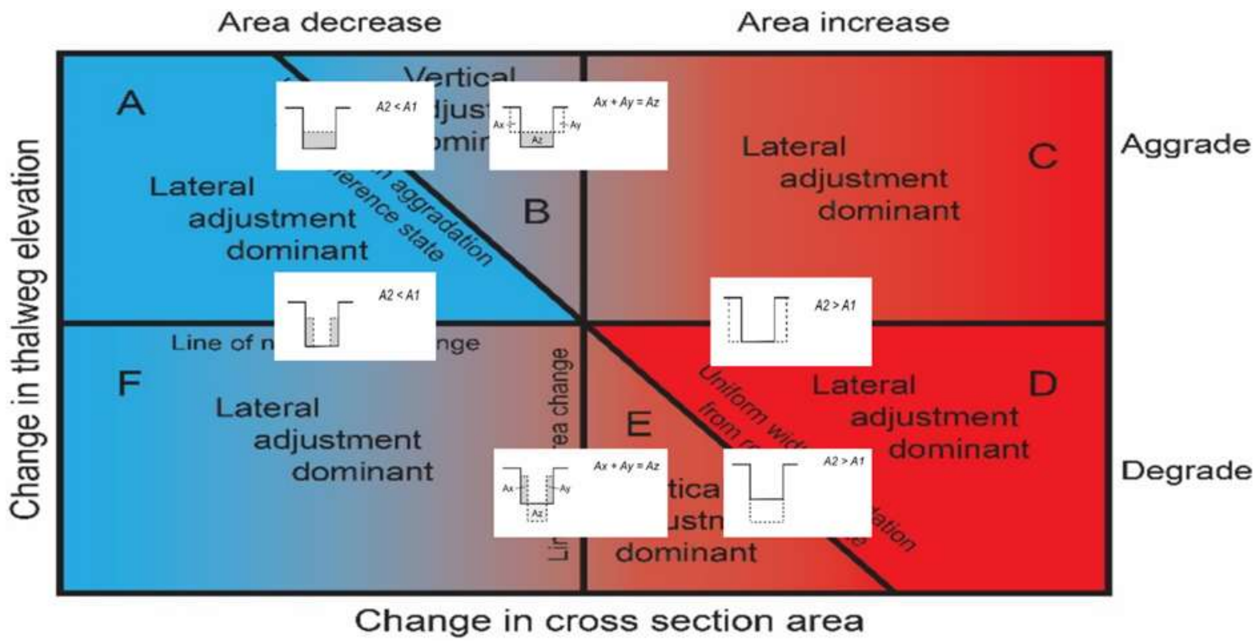

Figure 2. APSD with pictograms of the types of channel change that plot actually on each of the three axes.

In Figure 2 the vertical (Y) axis represents change in bed level, expressed in length units (feet or meters), and represented by changes in thalweg elevation. Positive values on the Y-axis represent aggradation and negative changes represent degradation. If the Y-value has not changed between resurveys, this indicates that the elevation of the channel bed (usually represented by the thalweg) did not change between those resurveys.

The horizontal (X) axis represents change in x-section area (feet or meters squared). This is plotted as change relative to the 'hypothetical area relative to greatest hypothetical change in thalweg elevation' (for full details refer to Major et al. 2018)). Positive values indicate an increase in x-sectional area, while negative values indicate a decrease. If the X-value has not changed between resurveys, this indicates that the x-section area of the channel did not change between those resurveys. It follows that points that plot at the origin of the X and Y axes indicate no change in either bed elevation or x-section area between the resurveys.

The diagonal axis defines vertical channel changes for which the change in x-section area is entirely and exactly explained by the change in bed elevation. In the case of aggradation, this means that the observed reduction in x-section area is solely attributable to the observed rise in bed elevation, indicating that channel width did not change. For degradation, this means that the observed increase in x-sectional area is solely attributable to the observed lowering of bed elevation, again indicating that channel width did not change.

The X- and Y-axes divide the APSD into four quadrants, two of which are themselves sub-divided by the diagonal axis, creating 6 channel process-response domains. In Figure 3, these domains are labelled with pictograms illustrating the types of channel change associated with points that plot in each of the domains. From upper left, clockwise, the quadrants indicate geomorphic changes featuring;

Upper left	=	aggradation and a decrease x-sectional area,
Upper right	=	aggradation and an increase in x-sectional,
Lower right	=	degradation and an increase in x-sectional area,
Lower left	=	degradation and a decrease in x-sectional area.

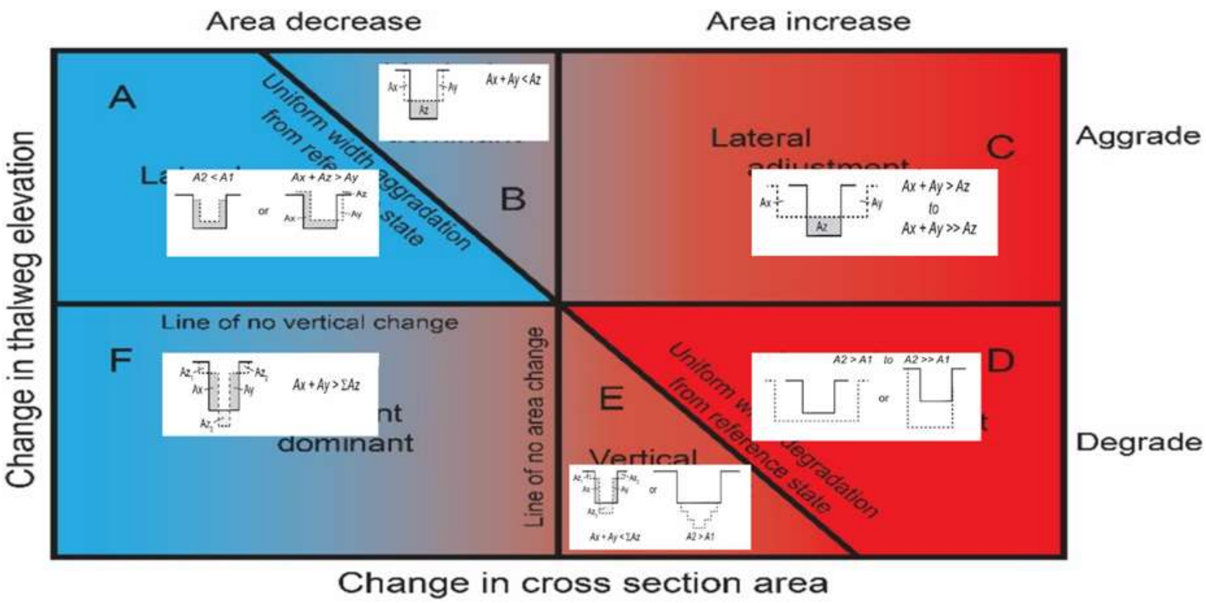

Figure 3. APSD with pictograms of the types of channel change indicated by points that plot in each of the six geomorphic process-response domains.

The morphological response mechanisms in the six 'phase spaces' or process domains are:

A. Aggradation and marked channel narrowing that together result in a notable decrease in x-sectional area;
B. Aggradation and modest channel widening that offsets some of the decrease in x-sectional area expected in an aggrading channel, but which is insufficient to result in a net increase in x-sectional area;
C. Aggradation and marked channel widening that is sufficient to result in a net increase in x-sectional area even though the channel is aggrading;
D. Degradation and channel widening that together result in a marked increase in x-sectional area;
E. Degradation and modest channel narrowing that offsets some of the increase in x-sectional area expected in a degrading channel, but which is insufficient to result in a net decrease in x-sectional area;
F. Degradation and marked channel narrowing that is sufficient to result in a net decrease in x-sectional area even though the channel is degrading.

A full description of the function and development of the APSD can be found in its inception paper by Major et al. (2018).

Application of the APSD to the Lower Mississippi River

Initial, system-scale study

Trial applications of the APSD analysis were performed at ERDC by Casey Mayne, who created a variety of APSDs for the Lower Mississippi River (LMR) between Cairo (~RM 1000 Above Head of Passes - AHP) and Old River (~RM 300 AHP). The period of record was 1960 to 2015.

In this application, changes in mean depth were plotted on the horizontal, X-axis as a surrogate for x-sectional area. Mean depth can act as a surrogate for x-sectional area because the overall width of the Mississippi River is stabilized by revetments and dikes. As x-sectional area is, by definition, channel width multiplied by mean depth it follows that, if channel width is constant:

X-section area = Mean depth x a constant

and hence, an increase in mean depth corresponds to an increase in x-sectional area, and *vice versa*. Also, in these trial APSDs, maximum depth was used as a surrogate variable for thalweg elevation.

In applying the APS analysis to the Lower Mississippi River , three matrices of APS diagrams were generated, based on comprehensive bathymetric surveys conducted in 1960, 1970, 1988, 1996, 2004, 2007, 2008 and 2015. The first matrix is for all x-sections, while the second and third matrices display the results for crossings and pools, respectively (Figures 4, 5 and 6).

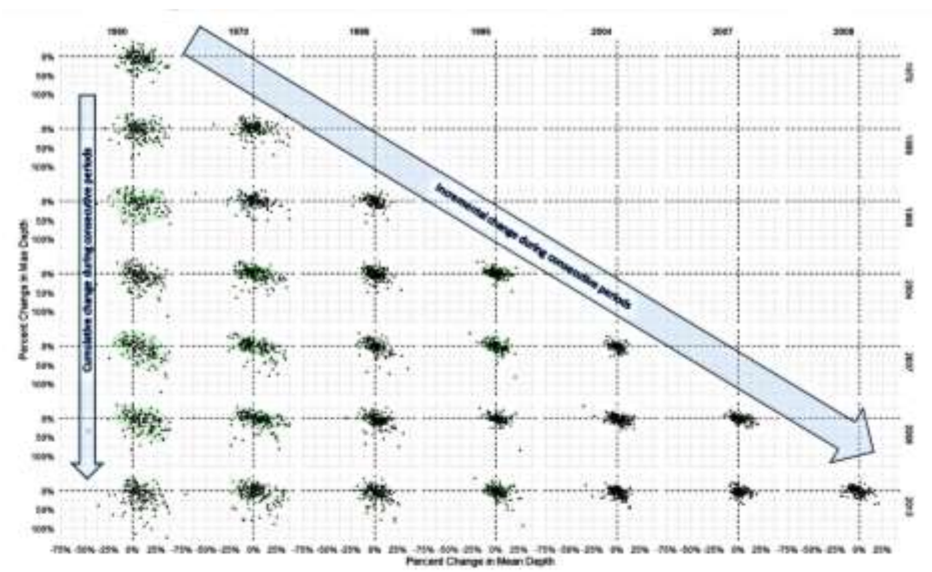

Figure 4. Space-time matrix of APSDs for all x-sections in the LMR 1960 - 2015.

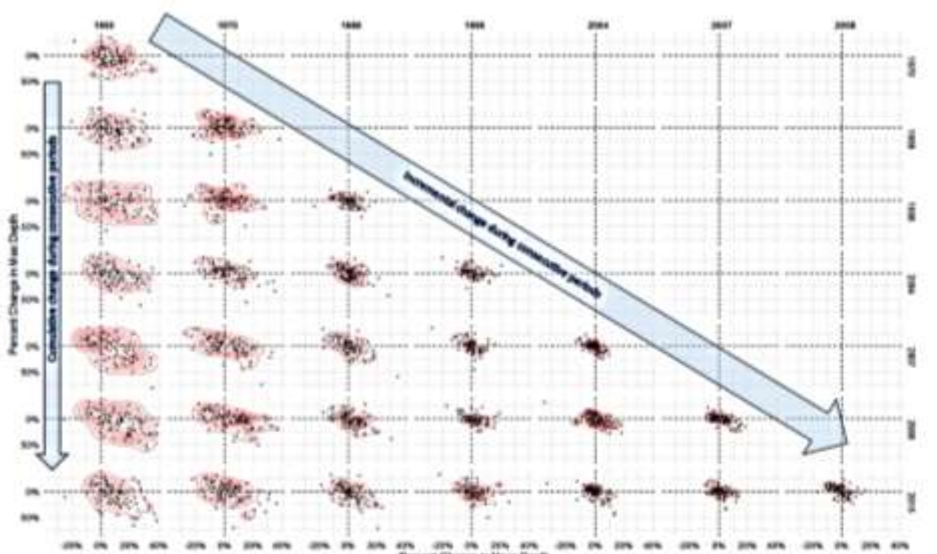

Figure 5. Space-time matrix of APSDs for crossings in the LMR 1960 - 2015.

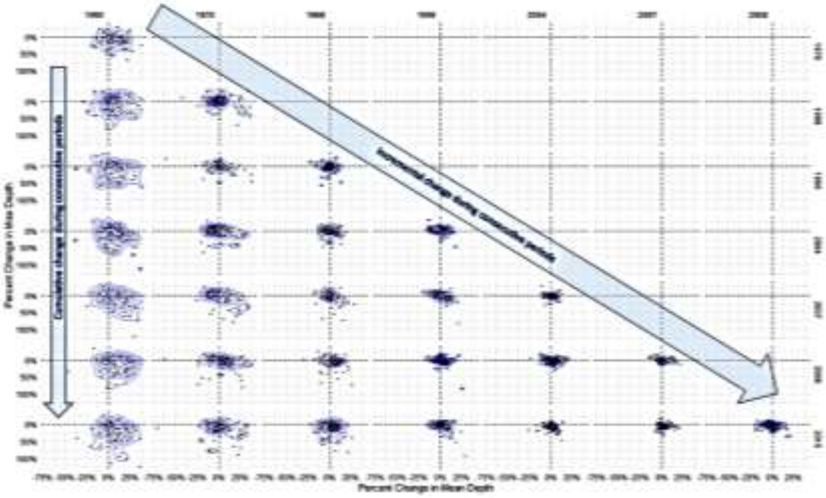

Figure 6. Space-time matrix of APSDs for pools in the LMR 1960 - 2015.

In Figure 4, the matrix of APS diagrams shows that most points plotted in either the upper left or lower right quadrants, indicating either aggradation and decreasing mean depth (that is, decreasing x-sectional area), or degradation and increasing mean depth (that is, increasing x-sectional area), respectively. The magnitudes of incremental changes peaked between 1970 and 1988, and then decreased through time up to 2015. Cumulative changes accrue through time, with overall change between 1960 and 2015 (bottom left APSD in the matrix), showing that degradation coupled with increasing mean depth (that is, increasing x-section area) dominated over aggradation coupled with decreasing mean depth (that is, decreasing x-section area). Comparison of Figures 5 and 6 shows that changes were larger and had a more pronounced trend at meander crossings compared to meander bend pools. Long-term studies of the lower Mississippi between river miles 300 and 1,000 AHP have identified that the Lower Mississippi between RM 300 and RM 750 can be divided into 5 sub-reaches with distinctly different geomorphic regimes (Figure 7).

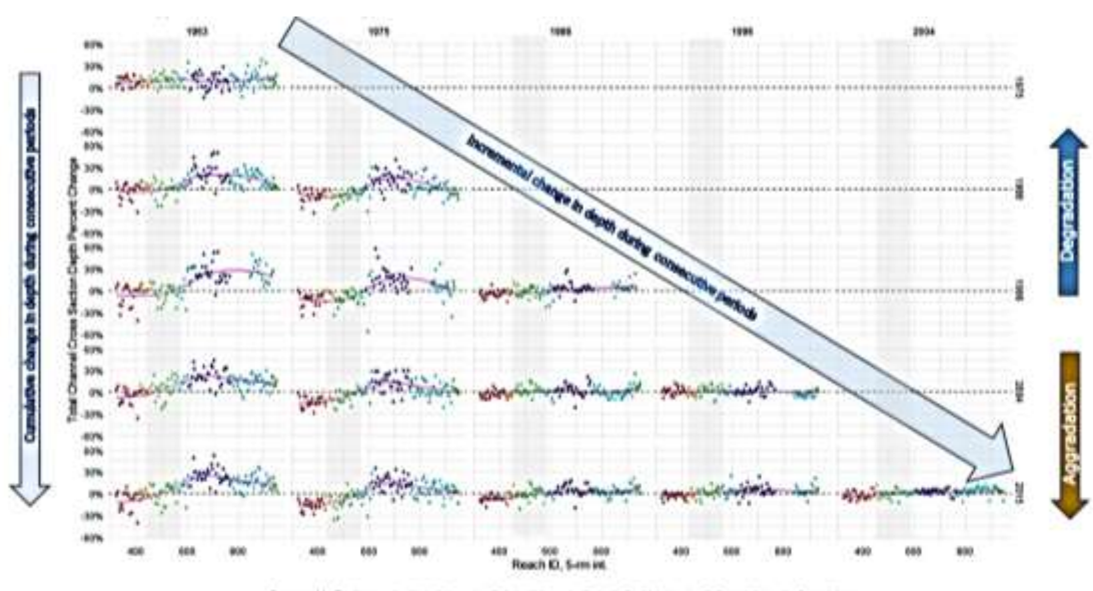

Figure 7. Space-time matrix of channel changes at all the x-sections in five sub-reaches of the LMR 1963 – 2015. Note: for reference later in this paper, the approximate extent of the FRAME study reach is indicated by the semi-transparent, gray bands in this plot. In each of the graphs in the matrix, an increase in maximum depth indicates degradation while a decrease in maximum depth indicates aggradation.

Alluvial phase changes in the five sub-reaches range from aggradation (RM 300 – 400), through slight aggradation (RM 400 – 450), to dynamic equilibrium (RM 450 – 550), slight degradation (RM 550 – 600), and degradation (RM 600 – 750) In Figures 8 and 9, space-time matrices of APS diagrams are plotted with these five geomorphic regime sub-reaches color coded for x-sections at crossings and pools, respectively.

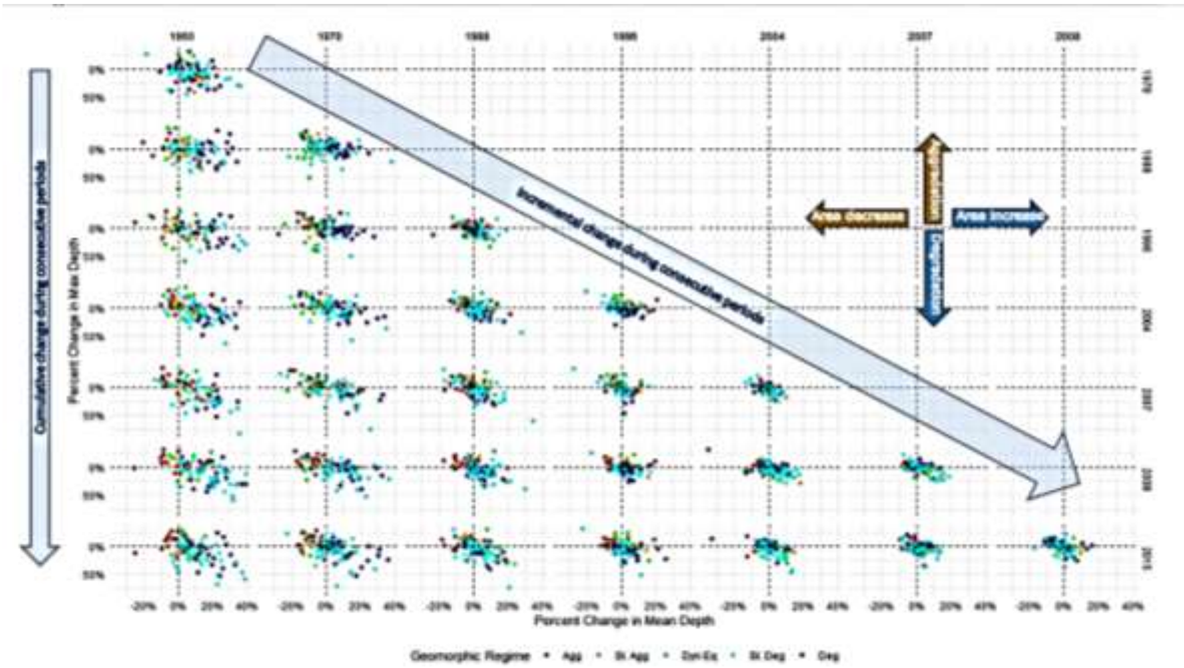

Figure 8. APSD matrix for crossings in sub-reaches: 1960 - 2015. Colours indicate geomorphic regime. Note: for later reference, geomorphic regime in FRAME study reach (green points) is mainly in dynamic equilibrium.

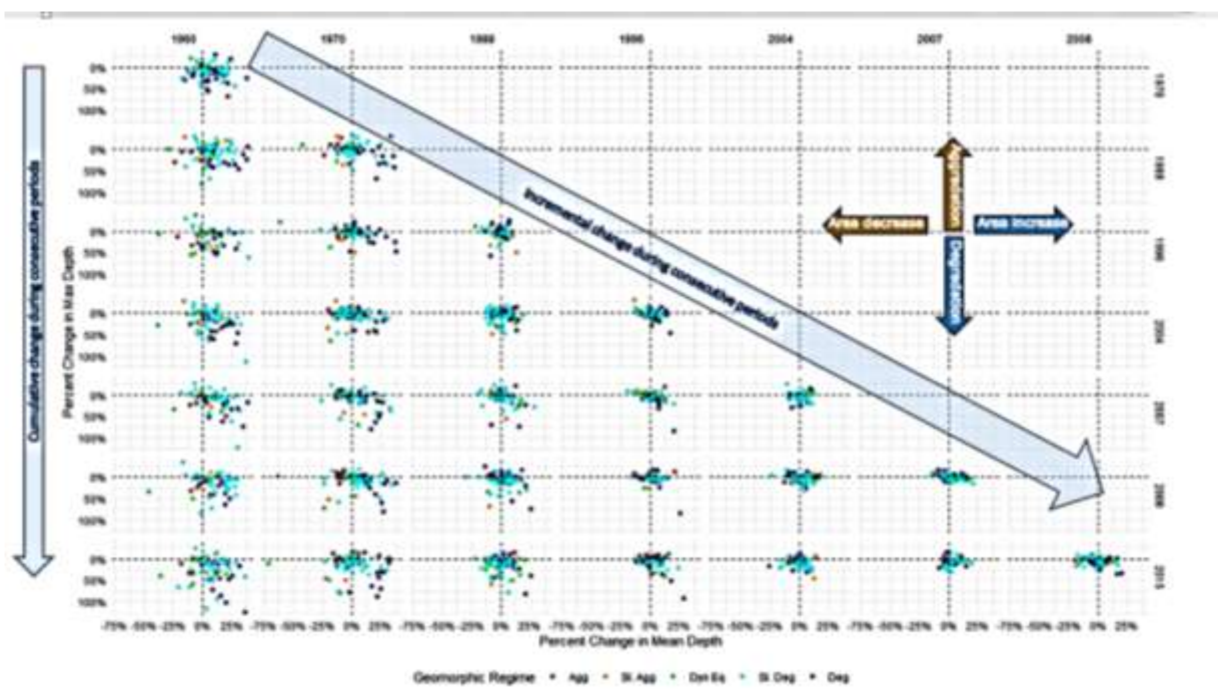

Figure 9. APSD matrix for pools in sub-reaches: 1960 - 2015. Colours indicate geomorphic regime. Note: for later reference, geomorphic regime in FRAME study reach (green points) is mainly in dynamic equilibrium.

The distributions of points in the APS matrices in Figures 8 and 9 show that although changes in particular sub-reaches do tend to plot in the expected quadrants, channel evolution is complex and involves multiple phases of short-term adjustment superimposed on the longer-term trends.

In Figure 10, APS diagrams for crossings and pools in the five geomorphic sub-reaches are plotted with the point color bar indicating the length of time between re-surveys. Figure 10 shows the trends in cumulative change expected for a given geomorphic regime, but also reveal that short periods of degradation may still feature in a sub-reach that, over the longer-term, is actually aggrading, while short episodes of aggradation can feature in a sub-reach that is degrading when considered over the longer-term.

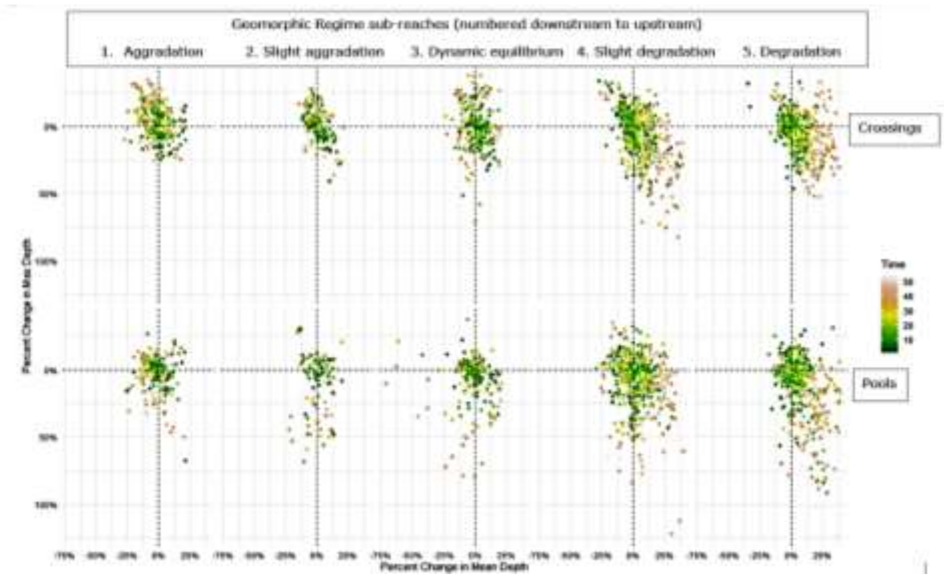

Figure 10. APSD matrix for crossings and pools in five geomorphic sub-reaches of the LMR. Colors indicate length of time between resurveys. Note: for later reference, the FRAME study reach corresponds to sub-reach 3.

Application to the FRAME Study Reach

The FRAME study reach of the Lower Mississippi extended from RM 576 AHP, just downstream of the Arkansas River confluence, to RM 389 AHP, near St. Joseph LA. For analytical purposes, the FRAME study reach was divided into 5 sub-reaches (Figure 11).

The study reach corresponds approximately to the third sub-reach (between about RM 450 and RM 550 AHP) in Figure 7 (above). Between 1960 and 2015, that sub-reach was in dynamic equilibrium. However, the study reach extends both up and downstream a few river miles further than sub-reach 3, meaning that the geomorphic regime at the downstream limit of the study reach was slight aggradation, while that at the upstream limit was slight degradation (see Figure 7, above).

In Figures 8 and 9 (above) the plotting points in the matrices of APS diagrams for the third sub-reach (which includes the FRAME study reach) are colored green. The green points cluster around the origin, although with variable scatter. This indicates that there were multiple, short-term episodes of channel adjustment that, over the longer-term, mostly cancelled each other out (see also results for sub-reach 3 in Figure 10). That said, Figure 10 suggests that there was a tendency for at least some x-sections to degrade and decrease in x-sectional area. This could be explained by the construction of dike fields at multiple locations in the FRAME study reach. These dike fields are designed to narrow the flow width and accelerate velocities at low and intermediate stages, which induces local bed scour within the navigation channel, while slightly reducing the x-sectional area of the channel. As the crest heights of the dikes are low, their morphological impacts diminish as stage in the river rises, being eliminated at stages approaching bankfull.

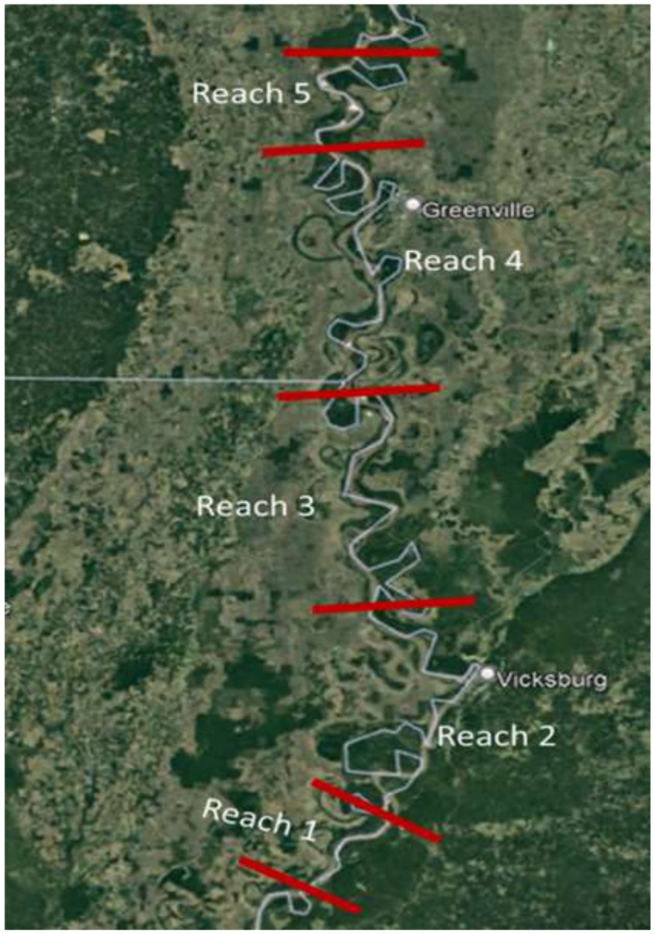

Figure 11. FRAME study sub-reaches in the Lower Mississippi River.

Details of the FRAME model set up are provided in a companion paper (Biedenharn et al. 2023) and are not repeated here. In summary, the model was initially calibrated in a run from 1983 to 2013, using flow duration curves for each year and the Toffaleti sediment transport function. Manning n values for the main channel and overbank areas ranged from 0.027 to 0.032, and 0.12 to 0.2, respectively.

The FRAME study reach included 130 x-sections, which were resurveyed in 2004, 2008 and 2013. The research team converted the surveyed, 'raw' x-sections into equivalent, but simpler, 'avatar' x-sections, comprising an upper rectangle representing the floodplain and a lower rectangle representing the channel. The 130 avatar x-sections were then averaged to produce 40 representative x-sections in each of the five sub-reaches delineated in Figure 11 (above).

The FRAME model was then run, with its outputs reported for the 40 representative, 'avatar' x-sections. Model inputs and outputs were used to create APS diagrams that characterize changes in x-sectional morphology and support comparisons between changes in the morphologies of the raw x-sections and (a) those represented in the 'avatar' x-sections input to the model for 2004, 2008 and 2013, and (b) the 2008 and 2013 'avatar' x-sections simulated using the FRAME model.

In summary, channel changes observed in the 'raw' and 'avatar' x-sections, and output by the FRAME model for the periods 2004 to 2008, 2008 to 2013, and 2004 to 2013 provided the input data for this application of the APSD approach.

Initially, we compared changes at all 40 x-sections in the study reach between 2004 and 2013, to those output from the model. The results are displayed in Figures 12 – 15.

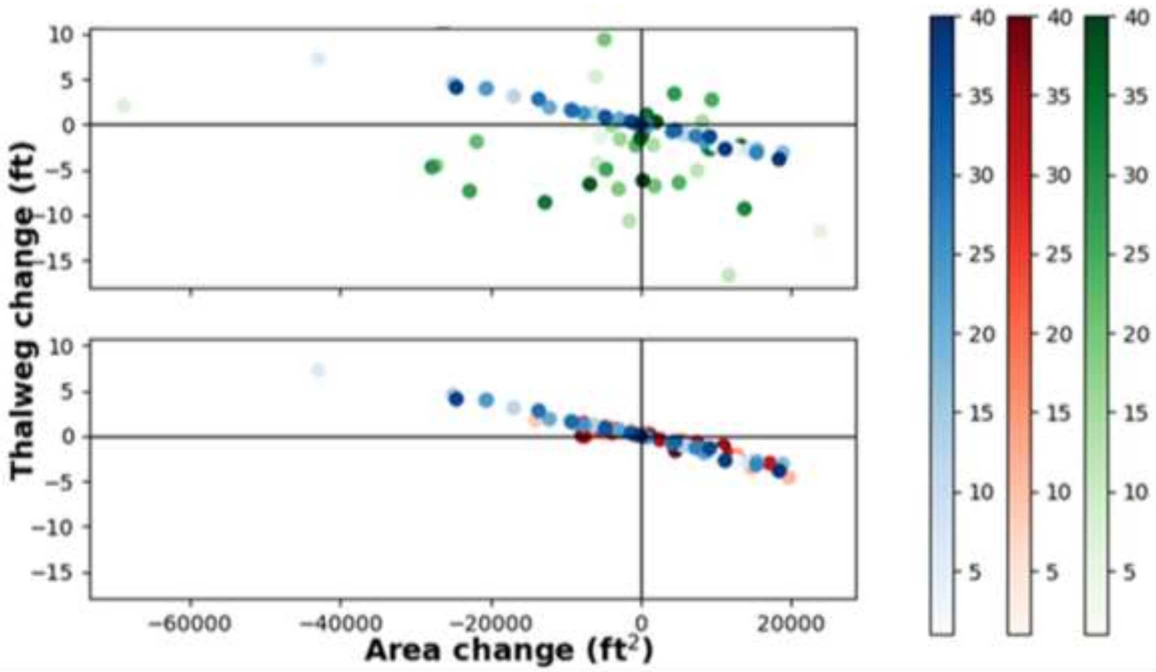

Figure 12. APSDs comparing channel changes observed and modelled at all 40 of the x-sections in the study reach of the Lower Mississippi River. Upper graph: 'raw' (green) and model (blue) data, Lower: 'avatar' (red) and model (blue) data. Color shade deepens from downstream to upstream.

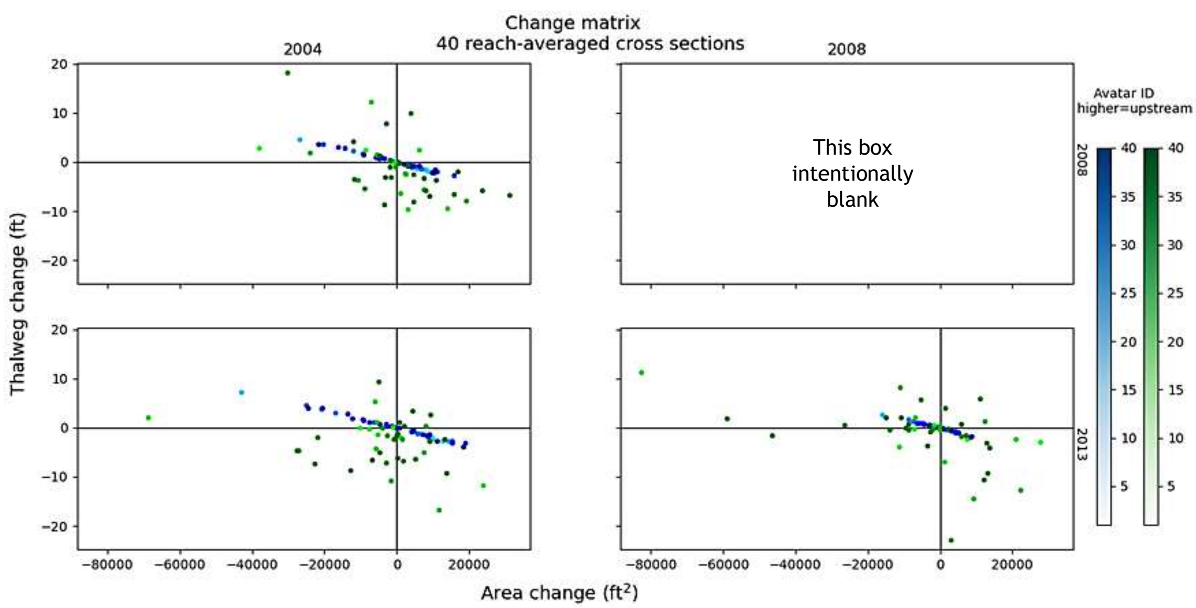

Figure 13. Space-time matrix of channel changes at all 40 x-sections in the study reach of the Lower Mississippi River. Observed, 'raw' data points are green. Modelled data points are blue. Color shade deepens with x-section number, from downstream to upstream.

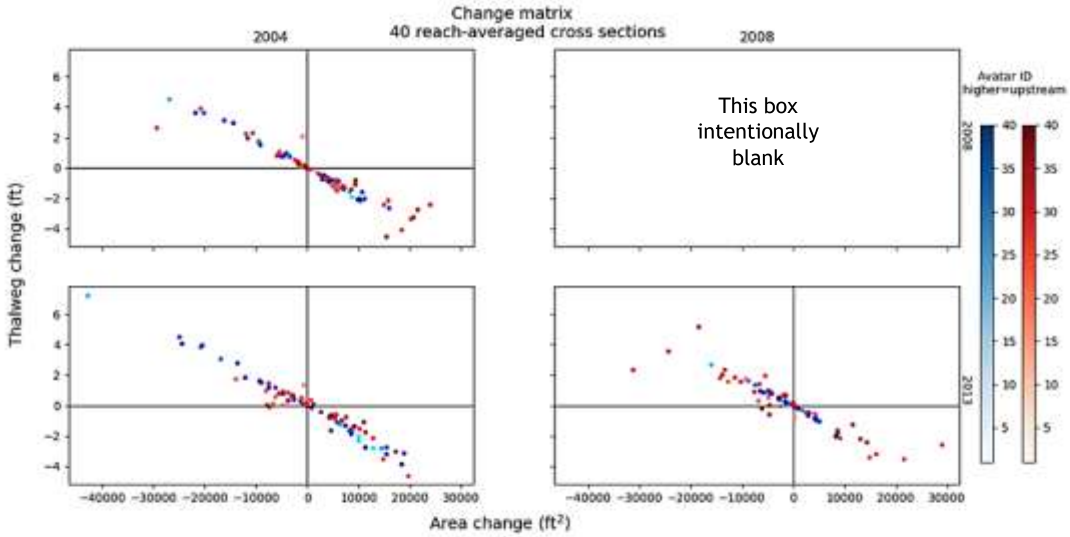

Figure 14. Space-time matrix of channel changes at all 40 x-sections in the study reach of the Lower Mississippi River. Observed, 'avatar' data points are red. Modelled data points are blue. Color shade deepens with x-section number, from downstream to upstream.

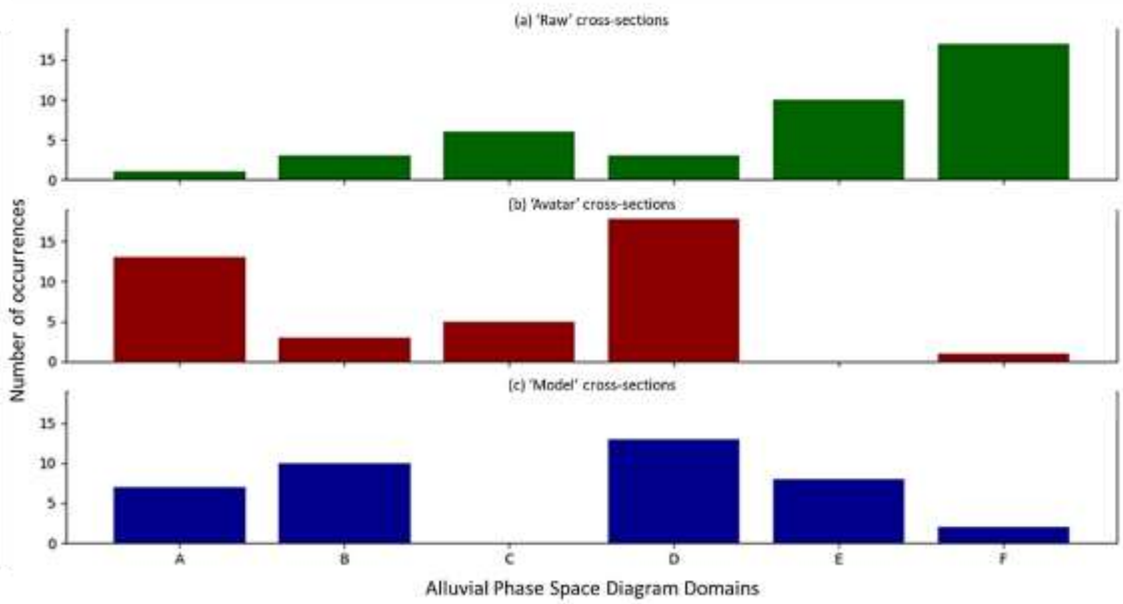

Figure 15. Alluvial phase space domains for all 40 x-sections in the study reach of the Lower Mississippi River: (a) 'raw' x-sections, (b) 'avatar' x-sections, (c) modelled x-sections.

We also produced APSDs for each of the sub-reaches in the FRAME study reach (see Figure 11, above). We discounted the data for sub-reaches 5 and 1, as the model results for these sub-reaches would have been affected by entrance and exit conditions, respectively. Hence, results for sub-reaches 4 (upper), 3 (middle), and 2 (lower) are displayed in Figures 16 and 17.

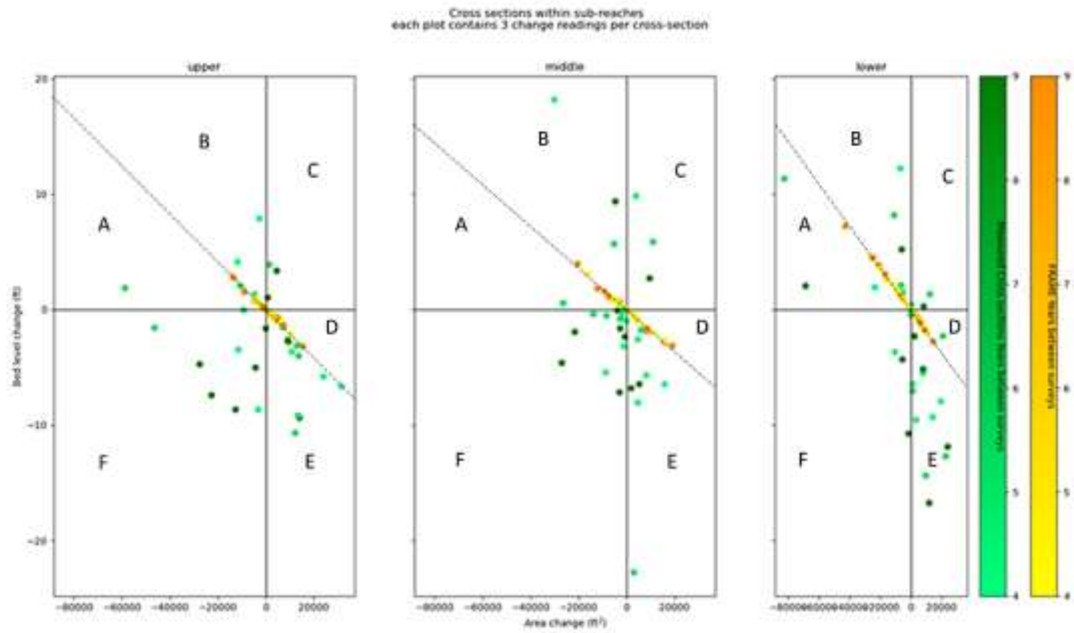

Figure 16. APSDs showing FRAME modelled channel changes between 2004 and 2013 in sub-reaches 4 (upper), 3 (middle), and 2 (lower) of the study reach in the Lower Mississippi River. Green and yellow points represent changes in 'raw' and 'modelled' x-sections, respectively. Color shades darken as time between resurveys increases from 4 to 9 years. Dashed line indicates approximate position of third axis in the APSD, as indicated by model outputs, which indicate that vertical adjustments in the bed level generate associated changes in x-sectional area, with no change in channel width. This is as expected, given the assumption of a fixed width in this study.

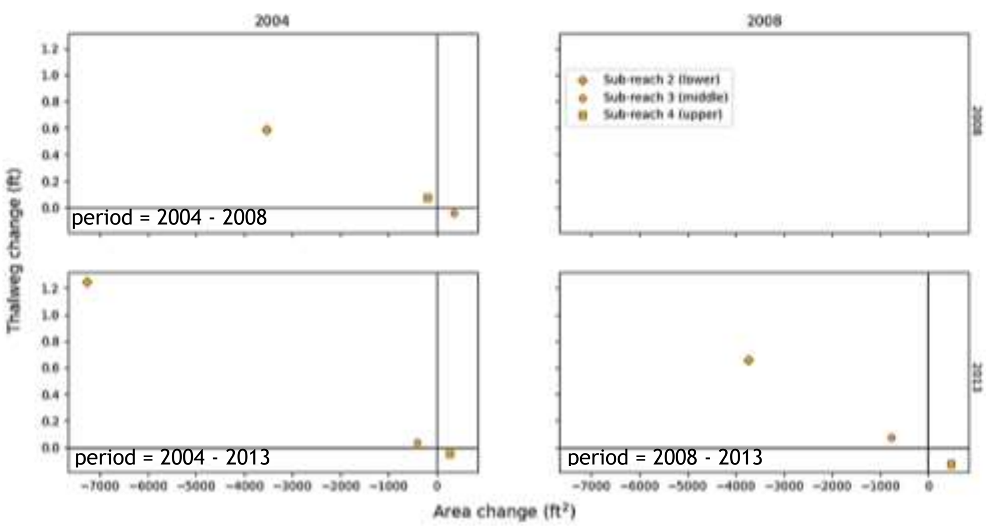

Figure 17. Space-time matrix of channel changes. in sub-reaches of the study reach in the Lower Mississippi River.

Discussion of Results for the LMR Study Reach

In Figure 12, the upper APSD compares changes in the 'raw' x-sections with those output by the FRAME model. Clearly, FRAME is unable to simulate the scatter of changes spread between all the different phase spaces that is evident in the data for the 'raw' x-sections. This is because the 'avatar' x-sections input to the FRAME model are geometrically much simpler, than the actual (raw) x-sections surveyed in the Mississippi River. When FRAME model results are instead compared to changes in the 'avatar' versions of the 'raw' x-sections, in the bottom APSD in Figure 12, there is an excellent match between observed and modelled changes. This demonstrates that the FRAME hydraulic and sediment transport model is able to closely simulate the morphological adjustments that actually occurred in the 'avatar' version of the this reach of the Lower Mississippi River.

In both Figures 13 and 14, a space-time matrix of APSDs is used to break the study period (2004-2013) into two, shorter periods (2004-2008 & 2008-2013). These APSDs again show that model results under-represent variability in the 'avatar' and, especially, the real river. That said, there is again close agreement between changes observed in the 'avatar' version of the river and those output by the FRAME model, while the model does mimic the tendency to adjust either by aggrading and narrowing (upper left quadrant in the APSDs) or degrading and widening (lower right quadrant in the APSDs). Due to the short duration of the model period, and lack of multiple, repeat surveys between 2004 and 2013, the space-time matrix has only three APSDs. Nevertheless, Figure 13 demonstrates that while trends on channel change were similar between 2004-2008 and 2008-2013, they were not the same. This indicates that short-term changes in the morphology in the Lower Mississippi River can diverge widely from longer-term trends.

Figure 15 compares the distributions of observed and modelled x-section changes between the six phase spaces in the APSD. The first thing to note is the close agreement between model and 'avatar' histograms. This establishes that FRAME was able to simulate faithfully most phases of change observed in the Mississippi River's 'avatar'. In contrast, agreement between model and 'raw' distributions is limited. Specifically, the model was unable to simulate aggradational channel changes that plotted in Domain C, and it underestimated the number of degradational channel changes plotting in Domain F.

There are also mismatches between phase space distributions for the real river and its 'avatar'. Specifically, only one of the degradational changes in the 'avatar' x-sections plotted in Figure 15 fell in domains E or F, although these were the two most common phases of adjustment observed in the 'raw' x-sections.

The types of x-sectional change that characterize the under-represented phase spaces are:

C. Aggradation and <u>marked channel widening</u> that is sufficient to result in a net increase in x-sectional area even though the channel is aggrading;
F. Degradation and <u>marked channel narrowing</u> that is sufficient to result in a net decrease in x-sectional area even though the channel is degrading.

There are two reasons why these phase spaces are under-represented in model inputs and outputs. The first reason stems from the way that 'raw' x-sections are converted into their 'avatar' equivalents, which are then input to the FRAME model. This is achieved by replacing the morphological complexity of each 'raw' x-section with a simplified 'avatar' x-section that has the same conveyance capacity, but is made up of two rectangles: an upper one for the floodplain and a lower one for the channel. It follows that changes in the 'avatar' x-sections between 2004 and 2013 reflect not only changes in the 'raw' x-sections, but also changes arising from contrasts in the morphological simplifications made convert the 'raw' x-sections observed in 2004 and 2013 to their 'avatar' equivalents.

The second reason reflects limitations inherent to the FRAME model as it is currently configured. In the model, the width of the channel is fixed, reflecting the fact that the banklines of the Mississippi River are stabilized by articulated concrete mattress (which prevent widening) and dike fields (which prevent narrowing). Also, it was assumed, *a priori*, that the channel of the Mississippi River could be represented by a single rectangle, and that the elevation of the floodplain would not change during the decade long duration of the model run. In the real river, although width adjustments are limited, they are not precluded entirely - as they are in the model, and changes in the difference between the elevation of the thalweg and that of the average bed level can, and do occur.

In summary, the assumptions made in setting up the FRAME model limited the model's capacity to simulate the types of channel changes that would plot in domains C and F (see Figure 3, above). Also, an unintended consequence of the way 'raw' x-sections were converted to their 'avatar' equivalents was that almost all degradational changes in 'avatar' x-sections plotted in domain D and most aggradational changes plotted in domain A (Figure 15).

Figure 16 displays APSDs for sub-reaches 2, 3 and 4. Points are plotted for the periods 2004-08, 2008-13 and 2004-13. Variability in the 'raw' results is again greater than that in the model results, reflecting the greater morphological complexity of the river compared to its 'avatar'. Notwithstanding high variability in the 'raw' data, for the upper and lower sub-reaches the trends of adjustments in the model outputs mimic the tendency for 'raw' data to plot preferentially either in the upper left, or lower right quadrants of the APSDs. The orderly, linear distribution of model outputs in Figure 16 indicates that in this study constraints place on the possible phases of morphological change resulted in the data following the third axis of the APSD, and those axes have been added in Figure 16. The third axis matches the change in bed elevation to the changes in x-section area that would result if there were no change in width. Given the limited range of phase spaces possible in the geometrically-simplified, 'avatar' x-sections, the assumptions that the channel width is fixed and the elevation of the floodplain does not change, these results are just what would be expected.

Figure 17 represents what might often be the target outcome for a FRAME application, which is a space-time matrix of APSDs representing changes in a series of geomorphic sub-reaches within the study reach of an alluvial stream. In this ASPD matrix, x-sectional adjustments in each sub-reach are aggregated over the decade-long study period, to generate a single point that indicates the phase of adjustment forecast for that sub-reach, during each period of adjustment. In the upper sub-reach (#4), aggradation in 2004-08 is more than offset by degradation in 2008-13, resulting in slight degradation and a small increase in x-sectional area during the study period (2004-13), both of which are probably negligible. The time distribution of aggradation and degradation is reversed in the middle sub-reach (#3), but in this sub-reach the shorter-term adjustments result in slight aggradation and a small decrease in x-sectional area, both of which are also probably negligible. In contrast, aggradational adjustments in the lower reach (#2) are progressive and result in a marked rise in thalweg elevation (>1.2 ft) and an associated reduction of ~7,000 ft^2 in x-sectional area. These findings are consistent with historic and recent trends of channel adjustment observed in the study reach, which trend from slight degradation immediately upstream of the study reach around the Arkansas confluence, to slight aggradation just downstream of the study reach in the vicinity of St Joseph, LA (see Figure 7, above).

CLOSURE

The model correctly forecast that, overall, the study was in a condition of dynamic equilibrium between 2004 and 2013, and it also indicated that local adjustments up and downstream the model reach would trend from a tendency for degradation in the upper sub-reach, through very slight aggradation in the middle sub-reach, and measurable aggradation in the lower sub-reach.

The main limitation of the model was its limited capacity to simulate the distribution of alluvial phase spaces observed in both the 'raw' and 'avatar' results. This is largely explained by the limited range of alluvial phase space adjustments resulting from assumptions that the width of the Mississippi River was fixed, the channel was rectangular and the elevation of the floodplain would not change.

One way to improve agreement between the distributions of 'raw', 'avatar', and model output data would be to introduce tolerance bands around the three axes in the APSD (Figure 18). The great advantage of this step is that it would negate another limitation present in the treatment presented here, which is that it is virtually impossible for a plotting point to fall actually on any of the axes. This forces all points to be allocated a phase space, even if the point was very close to one of the axes.

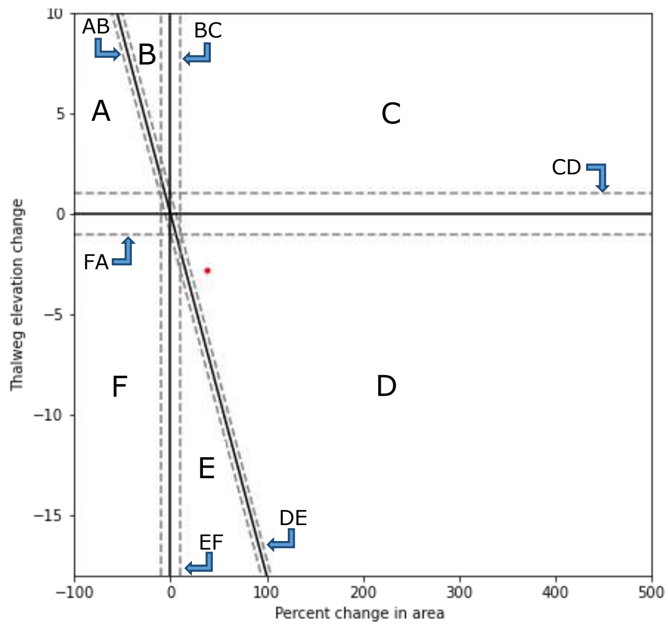

Figure 18. APSD with six tolerance bands (AB to FA) added to the three axes. The point for change between 2004 and 2013 at one of the 40 'raw' x-sections x-section falls within alluvial phase space D.

A second way to improve agreement between 'raw' and model results would be to reverse the process used to convert 'raw' x-sections to their 'avatar' equivalents after the model has run. Post-process 'de-avataring' would be guided by existing knowledge of the range of hydraulic geometries characteristic of the study river. For example, detailed hydraulic geometry relationships exist for the Mississippi River (Soar et al., 2007). Essentially, de-avataring depends on the assumption that probabilistic relationships between channel curvature & x-sectional area, and hydraulic geometry parameters such as width, maximum depth, mean depth, & channel asymmetry are invariant. In addition to this 'rule', 'de-avataring' would take into account knowledge gained from APSD analyses relating characteristic x-sectional geometries to the positive and negative sediment imbalances that drive morphological change. This will be explored, as FRAME develops.

FRAME was conceived and programmed to evaluate long term, systemic morphological responses to alternative river management strategies and actions. Hence, using FRAME to forecast changes at individual x-sections of a river and over short periods of time is not its intended purpose and, given the model's reduced complexity, its performance in the study reach matched expectations. Application of FRAME with respect to decadal changes in a study reach known to be in dynamic equilibrium provided a significant test for the model, and it has demonstrated the limitations of the current version. Nevertheless, the model successfully simulated morphological trends known to have occurred within the study reach, providing evidence that the FRAME approach has value and merits further development.

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