ALLUVSIM: A Program for Streamline-based Stochastic Modeling of Fluvial Depositional Systems

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Abstract

This paper presents a Fortran program, `alluvsim` for the construction of streamline-based fluvial models. The streamline-based approach may be applied to construct stochastic fluvial models for a variety of reservoir types, fluvial styles and systems tracts. Prior models are calculated based on all available soft information and then updated to honor channel intercepts in well data.
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1 Introduction

Interest in North Sea fluvial reservoirs led to the development of object based models for fluvial facies and geometries (see Deutsch and Wang, 1996 for a review of development). For these models conditioning is often problematic. These difficulties in conditioning spurred research in direct object modeling. Visuer et al. (1998) and Shmaryan and Deutsch (1999) developed methods to simulate fluvial object based models that directly honor well data. These algorithms segment the well data into unique channel and nonchannel facies and then fit channels through the segments. The channel center line is parameterized as a random function of departure along a vector and the geometry is based on a set of sections fit along the center line.

These techniques are only well suited to paleo valley (PV) reservoir types. The PV reservoir type geologic model is based on ribbon sandbodies from typically low net-to-gross systems with primary reservoir quality encountered in sinuous to straight channels and secondary reservoir rock based on levees and crevasse splays embedded in overbank fines (Galloway and Hobday, 1996; Miall, 1996).

More complicated channel belt (CB) fluvial reservoir types are common. Important examples include the McMurray Formation (Mossop and Flach, 1983, Thomas et al., 1987) and Daqing Oil Field, China (Jin et al., 1985, Thomas et al., 1987). These reservoirs include complicated architectural element configurations developed during meander migration punctuated by avulsion events. The application of the bank retreat model for realistic channel meander migration has been proposed by Howard (1992), applied by Sun et al. (1996) and Lopez et al. (2001) to construct realistic models of CB type fluvial reservoirs. These methods lack flexibility in conditioning.

A streamline-based paradigm is introduced with (**1**) improved flexibility to reproduce a variety of fluvial reservoir styles with realistic channel morphologies, avulsion and meander migration and (**2**) a new efficient approach to condition to well data and areal reservoir quality trends. The associated algorithm, `alluvsim`, includes a set of building blocks for the application of streamline-based simulation to fluvial depositional settings. This research code may be tailored to specific fluvial settings or adapted to other depositional settings.

This work was inspired by the developments of Sun et al. (1996) and Lopez et al. (2001), but it was conducted independent of Cojan and Lopez (2003) and Cojan et al. (2004). The reader is referred to this work for additional insights into the construction of geostatistical fluvial models.

2 Streamline-based Stochastic Fluvial Model

The basic building block of streamline-based models is the *streamline*. A streamline represents the central axis of a flow event and backbone for architectural elements (Wietzerbin and Mallet, 1993). This concept is general and may represent confined or unconfined, fluvial or debris flows.

Genetically related streamlines may be grouped into *streamline associations*. Streamline associations are interrelated by process. For example a streamline association may represent a braided stream related by avulsion or point bar related by meander migration. Fluvial architectural elements are attached to streamlines and architectural element interrelationships are characterized by streamline associations. This is a logical technique for constructing fluvial models since all architectural elements are related to "flow events". A conceptual geometric model of the associated architectural elements is shown in Figure 1.

2.1 The 3-D Streamline

The direct application of a cubic spline function to represent the plan view projection of a fluvial flow event is severely limited. As a function, a spline represented as $f^s(x)$ may only have a single value for any value x. In graphical terms, a function may not curve back on itself. This precludes the direct use of a spline function (i.e. channel streamline characterized by locations x, $f^s(x)$) to characterize high sinuosity channel streamlines.

A solution is to fit a separate cubic spline to characterize each coordinate (x, y and z) with respect to distance along the spline (s). This allows for high sinuosity streamlines to be modeled. A 2-D spline with a sinuosity of 1.4 is demonstrated in Figure 2.

The advantages of this streamline technique are: (**1**) continuous interpolation of streamline location in Cartesian coordinates at any location along the streamline, (**2**) relatively few parameters required to describe complicated curvilinear paths, (**3**) manipulation of splines is much more computationally efficient than modifying geometries and (**4**) other properties such as geometric parameters and longitudinal trends may be stored as continuous functions along the streamline. These issues are discussed in further detail below.

A nested search strategy is applied for efficient calculation of the nearest location along a streamline to any location within the model volume. First the nearest control node is located. Then finer intervals along the 3-D spline are checked between the adjacent control nodes.

The control nodes of a 3-D spline may be freely translated, rotated or otherwise modified. The only requirement is that the second derivatives of the spline location parameters is recalculated after modification. This operation is very fast. The calculation of complicated geometries generally requires a high level of computational intensity or simplification. In the streamline-based models the geometric construction is postponed to the end of the algorithm. This results in very fast calculation and manipulation of complicated geometric morphologies and associations represented as 3-D splines.

Any properties may be attached to the 3-D spline and interpolated along the length of the spline. In the fluvial streamline-based model, the channel width, local curvature, relative thalweg location and local azimuth are included in the 3-D spline. Other information including architectural element type, geometric parameters and additional property trends may be included. These properties are calculated at the control nodes and then splines are fit as with the location parameters. A single streamline with all its associated properties is denoted as $\kappa_{i,j}$ where j is the streamline index within a streamline association with index i.

2.2 Streamline Associations within Streamline-based Models

A streamline association is a grouping of interrelated 3-D splines. Streamline associations are characterized by their internal structure and interrelationship or stacking patterns. The internal structure is the relation of streamlines within the streamline association. The external structure is the interrelationship between streamline associations. Streamline associations may be tailored to reproduced features observed in a variety of fluvial reservoir style.

A variety of stacking patterns may exist in the fluvial depositional setting. Compensation is common in dispersive sedimentary environments such as proximal alluvial fans, vertical stacking with little migration is common in anastomosing reaches and nested channel belts often form in incised valleys. These patterns include important information with regard to the heterogeneity of a reservoir and should be included in fluvial models.

2.3 Streamline Operations

Streamline operations generate and modify streamlines in a manner that mimics fluvial processes. Architectural element models are calculated by sequentially apply the following operations; (**1**) initialization, (**2**) avulsion, (**3**) aggradation, (**4**) migration and (**5**) neck cutoff.

2.3.1 Streamline Initialization

The streamline initialization operator is applied to generate an initial streamline in a streamline association or to represent channel avulsion proximal of the model area. Given source and target locations and channel sinuosity this operator generates a realistic streamline from the source with a length (head to tail) equal to the spacing between the source and target, then a smooth translation is applied to correct the location of the streamline to honor the target location (see Figure 3).

A model is required to represent channel streamline morphology. The disturbed periodic model developed by Ferguson (1976) provides a realistic streamline model.

$$\phi(\mathbf{s}) + \frac{2h}{k}\frac{d\phi(\mathbf{s})}{d\mathbf{s}} + \frac{1}{k^2}\frac{d^2\phi(\mathbf{s})}{d\mathbf{s}^2} = \varepsilon(\mathbf{s}) \qquad (1)$$

where k is related to the primary wavelength $k = 2\pi/\lambda$, h is the dampening factor $(0 < h < 1)$ and $\varepsilon(\mathbf{s})$ is the disturbance value. The physical analogue for this model is a pendulum dampened by air resistance and continuously hit by rocks. The discrete approximation of this model may be applied to efficiently calculate streamlines with intuitive parameters and with periodicity and irregularity observed in fluvial channels.

Sinuosity is related to the dampening factor, h, the wavelength through k, and the variance of the disturbance RV, ε. Decrease in dampening results in more regularity and higher sinuosity. Decrease in the disturbance variance increases the regular periodicity of the model. A series of channels are generated with varying sinuosities in Figure 4.

2.3.2 Streamline Avulsion

Avulsion is the process of channel abandonment and the establishment of a new channel outside the active channel. Within model avulsion is handled with the streamline avulsion operator. Avulsion proximal of the model is handled by spontaneously initializing a new channel with the streamline initialization operator.

The avulsion operator creates a copy of a specific channel streamline, selects a location along the streamline, generates a new downstream channel segment with same streamline sinuosity and the same geometric parameter distributions. The geometric parameters (e.g. channel width) of the new streamline are corrected so that the properties are continuous at the avulsion location. The initial azimuth is specified as the azimuth of the tangent at the avulsion location. There is no constraint to prevent the avulsed streamline from crossing the original streamline distal of the avulsion location.

The avulsion location is drawn from the distribution of streamline control nodes weighted by the curvature at each node. This rule integrates the concept that avulsion is more likely to occur at locations of high curvature.

2.3.3 Streamline Aggradation

Aggradation occurs when a channel deposits sediments in the channel and over bank environments. This process is represented by a incremental increase in the elevation of a streamline. The current implementation is to add a specified constant value to the elevation, z, parameter for all streamline control nodes.

2.3.4 Streamline Migration

The streamline migration operator is based on the bank retreat model. The application of the bank retreat model for realistic channel meander migration has been proposed by Howard (1992), applied to construct fluvial models by Sun et al. (1996) and extended to construct meandering fluvial models that approximately honor global proportions, vertical and horizontal trends by Lopez et al. (2001).

In the `alluvsim` algorithm the meander migration along the streamline is standardized such that the maximum migration distance matches a user specified value. This removes the significance of hydraulic parameters such as friction coefficient, scour factor and average flow rate, since only the relative near bank velocity along the streamline is significant. Hydraulic parameters are replaced by the maximum spacing of accretion surfaces.

2.3.5 Neck and Chute Cutoffs

Neck cut offs (an entire meander loop is abandoned) and chute channels (the channel cuts across the point bar) are generated with the neck and chute cut off operation. The control nodes are searched for nonadjacent control nodes that are within a channel width of each other. When this occurs the segment between these control nodes is removed and coded as abandoned channel.

2.4 Fluvial Architectural Elements

The available architectural elements include (**1**) CH, (**2**) LA, (**3**) LV, (**4**) CS, (**5**) FF(CH) and (**6**) FF (refer back to the conceptual geometric model in Figure 1). The geometries and associated parameters are discussed for each element.

2.4.1 Channel Fill (CH) Elements

The geometry of the CH element is parameterized by a streamline, relative thalweg location, stochastic depth and a width to depth ratio. The cross section channel geometry is based on the definition from Deutsch and Wang (see Equations 22 - 24 and Figure 10 in Deutsch and Wang, 1996). The CH geometry and associated parametrization are shown in Figure 6. This geometry is consistent with the general form observed in meandering stream (Easterbrook, 1969).

The CH element parameters; thalweg location, depth and width to depth ratio are calculated at control nodes along the streamline. Cubic splines are fit to these properties to allow for a smooth transition along the streamline and efficient interpolation at any streamline location. The CH element average width to depth ratio and average depth are drawn from a Gaussian distributions specified in the input parameter. Conservation of cross sectional area is honored.

2.4.2 Lateral Accretion (LA) Elements

The lateral accretion deposits are represented as the volume of channel abandoned during channel migration. The complicated geometries of LA elements have been demonstrated by Diaz-Molina, (1993) and Willis (1993). LA elements are characterized by wedge channel fills distributed along the inside of meander bends.

2.4.3 Levee (LV) Elements

Significant reservoir quality facies may be represented by levees. The LV geometry and associated parametrization were shown in Figure 6. The equations for the LV top and base are shown in Equations 2 and 3 respectively.

$$LV_{top}(\mathbf{d},\mathbf{s}) = LV_{height}(\mathbf{s}) \cdot \left[\frac{\mathbf{d}}{LV_{width}(\mathbf{s}) \cdot F}\right] \cdot exp^{\left[\frac{-\mathbf{d}}{LV_{width}(\mathbf{s}) \cdot F}\right]} + CH_{elev}(\mathbf{s}) \tag{2}$$

$$LV_{base}(\mathbf{d},\mathbf{s}) = CH_{elev}(\mathbf{s}) - LV_{depth}(\mathbf{s}) \cdot \left[\frac{LV_{width}(\mathbf{s}) \cdot F - \mathbf{d}}{LV_{width}(\mathbf{s}) \cdot F}\right] \tag{3}$$

where $z_{top}(\mathbf{s},\mathbf{d})$ is the top elevation of the LV element and $z_{base}(\mathbf{s},\mathbf{d})$ is the elevation of the base of the LV element at a location $\mathbf{s}$ along the streamline and location $\mathbf{d}$ orthogonal from the channel edge. $CH_{elev}(\mathbf{s})$, $LV_{depth}(\mathbf{s})$, $LV_{width}(\mathbf{s})$ and $LV_{height}(\mathbf{s})$ are the elevation of the channel and the depth, width and height of the LV element at the nearest location along the streamline, $\mathbf{s}$. At locations with negative thickness (i.e. $z_{base}(\mathbf{s},\mathbf{d}) > z_{top}(\mathbf{s},\mathbf{d})$) no LV element is placed. F is a scaling factor described below.

The distribution of LV elements may not be uniform along the channel axis. Typically LV elements are more pronounced on the cut bank. This information is integrated with a LV width scaling factor, F, that scales the LV width to account for LV asymmetry on channel bends. The current implementation is applied to calculate the F multiplier with the following equations.

$$F_{pointbar}(\mathbf{s}) = 1.0 - LV_{asym} \cdot \frac{c(\mathbf{s})}{|c_{max}|} \tag{4}$$

$$F_{cutbank}(\mathbf{s}) = 1.0 + LV_{asym} \cdot \frac{c(\mathbf{s})}{|c_{max}|} \tag{5}$$

where LV_{asym} is a value between 0 and 1 that parameterizes the strength of the levee asymmetry, $c(\mathbf{s})$ is the local curvature along the streamline and c_{max} is the maximum curvature along the streamline. A LV_{asym} value of 0 results in symmetric LV elements and a LV_{asym} value of 1 results in no LV element on the point bar side and double width of LV element on the cut bank side at the location along the streamline with greatest curvature.

2.4.4 Crevasse Splay (CS) Elements

CS elements may also have significant reservoir quality. For each streamline the number of CS elements is drawn from a Gaussian distribution with mean and standard deviation supplied by the user. The location of each CS element along the streamline is drawn from a distribution of streamline locations, weighted by the curvature. Crevasse splays more likely occur at locations with high curvature since high near bank velocities erode the confining LV elements. The CS elements are modeled as a series of lobes fit to low sinuosity streamlines initiated from the crevasse location with initial azimuth normal to the channel streamline towards the cut bank.

The number of lobes and the lobe parameters (see Figure 7) are drawn from Gaussian distributions with user supplied mean and standard deviation. Fewer large lobes reproduce sheet geometries while many thin lobes reproduce inter fingering. This geometry taken from `lobesim` algorithm by

Deutsch and Tran (2002). Four example of CS elements constructed with the `alluvsim` algorithm (see Figure 8).

2.4.5 Abandoned Channel (FF(CH)) Elements

When channel abandonment is very abrupt (i.e. rapid avulsion, neck cut-off) there there is a strong contrast between the abandoned channel fills FF(CH) and CH elements. Slow abandonment leads to fining upward fills (Galloway and Hobday, 1996).

In the current implementation FF(CH) elements form; (**1**) along cutoff streamline segments, (**2**) in the channel reaches distal of avulsion locations and (**3**) in the last channel placed for a level.

The user specifies the mean and standard deviation of the proportion of abandoned channels fill with fine-grained FF(CH) elements. For a proportion of 0 the abandoned channel is coded as CH element and for a proportion of 1 the entire abandoned channel is coded as FF(CH) element. For a proportion between 0 and 1 the abandoned channel fill is partitioned with proportional coordinates (refer back to the geometric model in Figure 1).

2.4.6 Overbank Fines (FF) Elements

FF elements are not modeled directly. The model space is initialized as FF element. Other architectural elements displace FF elements during model construction.

2.5 Event Schedule

The `alluvsim` algorithm is able to reproduce a wide variety of reservoir styles with limited parametrization. This algorithm may reproduce braided, avulsing, meandering channels and may reproduce geometries and interrelationships of a variety of reservoir types (PV, CB or sheet (SH) type) and fluvial style within any systems tract. The algorithm is supplied with areal and vertical trends, distributions of geometric parameters, probabilities of events and architectural elements. Model is generated from bottom to top with constraints to honor areal and vertical channel density trends.

2.5.1 Areal Channel Density Trends

The technique for honoring areal trends is to (**1**) construct a suite of candidate streamlines with the desired morphology, (**2**) superimpose each streamline on the areal trend model and calculated average relative quality and (**3**) for each streamline initialization draw from this distribution of candidate streamlines (without replacement) weighted by the average quality index. This technique is efficient since the construction of hundreds or thousands of streamlines is computationally fast.

This technique is demonstrated in Figure 9. 30 streamlines are drawn from a suite of 500 candidate streamlines for three different areal trends. Note the impact of the areal trend on the drawn streamlines.

2.5.2 Vertical Channel Density Trends and Aggradation Schedule

Vertical trends may be honored by constraining the aggradation schedule. The current implementation is to apply the trend within a user defined number of constant elevation levels. Streamlines and associated architectural elements are generated at the lowest level until the NTG indicated by the vertical trend is reached for the model subset from the base of the model, z_0, to the elevation of the first level, z_1. Then the aggradation operator is applied to aggrade to the next level and the process is repeated through all user defined levels. For the highest level, z_n, the model is complete when the global NTG ratio is reached.

The assignment of a few constant elevation levels to model aggradation is a simplification, although this technique does allow for the flexibility to reproduce a variety of aggradation patterns. For example, few levels result in a stepped system with amalgamated reservoir elements separated by FF elements. The assignment of many levels and an overall low NTG results in isolated PV type shoestring or CB type labyrinth reservoirs. The assignment of many levels with an overall high NTG results in a amalgamated CB type jigsaw reservoirs.

With minor modification more complicated schedules may be applied that allow for continuous aggradation as opposed to discrete levels. Three example vertical trends with cross sections from the resulting models are shown in Figure 10.

3 Updating Streamline Associations to Honor Well Data

There are a variety of available methods that may be applied to condition complicated geologic models; (**1**) dynamically constrain model parameters during model construction to improve data match (Lopez et al., 2001), (**2**) posteriori correction with kriging for conditioning (Ren et al.,2004), (**3**) pseudo-reverse modeling (Tetzlaff, 1990), (**4**) apply as a training image for multiple-point geostatistics (Strebelle, 2002) and (**5**) direct fitting of geometries to data (Visuer et. al., 1998 and Shmaryan et. al., 1999). Each of these techniques has significant limitations either in efficiency, robustness or the ability to retain complicated geometries and interrelationships.

The streamline-based paradigm is amenable to a new method for the construction of conditional models. The proposed procedure is; (**1**) construct the prior streamline-based model conditioned by all available soft information, (**2**) interpret well data and identify CH′ element intervals (CH′ elements are channel fill elements without differentiation of CH, LA and FF(CH) elements), (**3**) sequentially update streamline associations to honor identified CH′ element intervals and (**4**) correct for unwarranted CH′ intercepts.

3.1 Interpreted Well Data

The geologic interpretation of well data is performed prior to the updating step. The input data includes the areal location for each vertical well and a list of CH′ element intervals with base and original top (prior to erosion). The geologic interpretation is often uncertain, especially with amalgamated CH′ elements. Alternate geologic interpretations may be applied to account for this uncertainty.

3.2 Updating Streamline Associations to Honor Well Data

The model is updated by modifying streamline associations to honor CH′ element intercepts. For each CH′ element interval identified in the well data the nearest streamline association is found and updated in the following manner. (**1**) The horizontal position is corrected such that the CH′ element intercept thickness is within tolerance of the CH′ element interval thickness. (**2**) Then the vertical location is corrected such that the CH′ element intercept top matches the top of the CH′ element interval. Entire streamline associations are corrected to preserve the relationships between streamlines within a streamline association. For example, if a streamline association includes a set of streamlines related by meander migration, the entire set of streamlines representing a point bar is shifted. If individual streamlines were modified independently this would change the nature of the streamline association.

The nearest streamline association is checked for previous conditioning. To prevent artifacts, a buffer distance, is set such that a streamline association may not be updated at a location that is too close to any previously updated location. Closely spaced updates may lead to a discontinuities in the streamline association.

3.3 Iterative Procedure for Updating Streamline Associations

Modifications of streamline associations has an impact on CH′ element geometry. It would be difficult to directly calculate the precise translation of a streamline to result in the correct interval thickness at a well location. An iterative method is applied to correct the well intercept thickness. The thickness of the CH′ element from a streamline association is calculated at the vertical well location. The error is calculated, if the thickness is less than indicated by the conditioning then the streamline association is shifted towards the well location. If the thickness is greater than indicated by the conditioning then the streamline association is shifted away from the well location. The parameters for this iterative technique are the initial step size, the dampening factor and the thickness tolerance.

$$s^i = s^0 \cdot (1 - \delta)^{(i-1)} \tag{6}$$

where s^n is the i^{th} step size, s^0 is the initial step size and δ is the dampening factor (between 1.0 and 0.0). The limit of the sum of infinite steps may be calculated to represent the maximum distance a streamline association may be shifted given an initial step size, s^0, and dampening factor, δ.

$$\sum_{i=1}^{\infty} s^i = \frac{s^0}{\delta} \tag{7}$$

By setting the initial step size to the maximum channel width and the maximum migration as the model extent transverse to the primary flow direction the required dampening factor may be calculated.

The thickness tolerance set to the vertical model resolution. When the difference between the interval from well conditioning and the CH′ element intercept is less than the tolerance the convergence criteria is satisfied. The closest node is locked and is not modified by subsequent updating.

Once the CH′ element intercept thickness is corrected then the vertical location is corrected by applying a vertical shift to the streamline association. The procedure is repeated for all identified CH′ element intercepts. If there is no previous conditioning the entire streamline association is shifted vertically. If there is previous conditioning then a smooth correction is applied (similar to the smooth correction applied for the horizontal correction). It is possible that CH′ elements may intercept wells where such intercepts are not indicated. These unwarranted intercepts are corrected next.

3.4 Correction for Unwarranted Well Intercepts

The correction for unwarranted CH′ element intercepts applies a robust iterative technique. For each unwarranted CH′ element intercept the associated streamline association is checked for conditioning. The streamline association is modified in a smooth manner while anchored to any previous conditioning.

The streamline association is modified until the thickness of the unwarranted CH′ element intercept reaches zero. For each iteration the step size of the modification is increased and the direction is reversed. This method is robust since it does not become trapped with complicated streamline associations. This methodology is illustrated in Figure 15 with a complicated setting.

4 Program Parameters

The `alluvsim` program is research code and suitable for experimenting with the ideas presented in this paper; the program has not been optimized for speed and with the support system of commercial software. Nevertheless, it may prove useful for testing and research in this area.

The `alluvsim` program follows GSLIB conventions. The parameters required for the program are listed below and a parameter file is shown on Figure 11:

- `line 1:` input file containing the channel fill element intervals from well data. The standard GSLIB/GeoEAS format is expected and the wells are assumed to be vertical.
- `line 2:` columns in the well data file for the X, Y, and Z (top and base) coordinates, the well number (used to identify different well intersections).
- `line 3:` input file with relative horizontal trend in channel density. The file should be in GEOEAS format and GSLIB grid convention.
- `line 4:` the column number for the horizontal channel density trend.
- `line 5:` input file with relative vertical trend in channel density. The file should be in GEOEAS format and GSLIB grid convention.
- `line 6:` the column number for the vertical channel density trend.
- `line 7:` the maximum number of streamlines, the constant elevation levels and a list of the associated levels. The former is applied to dimension streamline tables. The algorithm terminates when this number of streamlines are generated. The latter is applied to defined the vertical spacing of channels.
- `line 8:` the target net-to-gross ratio. The algorithm terminates when this net-to-gross ratio is exceeded.
- `line 9:` the number of candidate streamlines calculated prior to model construction and the number of discretizations for spline interpolation between control nodes. Set the former several times larger than the maximum number of streamlines.
- `line 10:` probability of avulsion proximal of the model (new streamline initialization) and the probability of avulsion within the model. One minus the sum of these probabilities is the probability of meander migration.
- `lines 11 - 15:` channel fill architectural element geometric parameters. Parameterized by mean and standard deviation of a Gaussian distribution.
  - `line 11:` primary azimuth of channel streamlines. Note current model assumes model proximal edge is $x = 0$ and distal edge is $x = xmax$.
  - `line 12:` source location in Y coordinates. Source is located along the proximal edge of the model (X = 0).
  - `line 13:` channel depth.
  - `line 14:` width to depth ratio.
  - `line 15:` sinuosity. Based on a calibration of the Ferguson (1976) model.
- `lines 16 - 20:` levee architectural element geometric parameters. Parameterized by mean and standard deviation of a Gaussian distribution.
  - `line 16:` levee depth below top of channel fill.
  - `line 17:` levee width from edge of channel fill.
  - `line 18:` levee height above top of channel fill.

  - `line 19:` factor for levee asymmetry on point bar and cut bank. For a value of 0, levees are symmetric and for a value of 1, levees are twice as wide on the cutbank side at the location of maximum curvature.
  - `line 20:` factor for proximal to distal thinning along the streamline. For a value of 0, there is no thinning and for a value of 1 levee widths are doubled at the proximal edge and halved at the distal edge of the model.

- `lines 21 - 28:` crevasse splay architectural element geometric parameters. Parameterized by mean and standard deviation of a Gaussian distribution.
  - `line 21:` number of crevasse splays along a single channel streamline.
  - `line 22:` number of lobes within a single crevasse splay.
  - `line 23:` lobe length along streamline.
  - `line 24:` lobe maximum width.
  - `line 25:` lobe length along streamline to position of maximum length.
  - `line 26:` lobe width at proximal edge.
  - `line 27:` lobe height to width ratio.
  - `line 28:` lobe depth to width ratio.

- `line 29:` the geometric parameters for fine grained abandoned channel fill element. The fraction of abandoned channel fill assigned as fine grained.

- `line 30:` the maximum meander migration step. Translations calculated by the bank retreat model are standardized by this value.

- `line 31:` the size of the model in the X direction.

- `line 32:` the size of the model in the Y direction.

- `line 33:` the size of the model in the Z direction.

- `line 34:` the random number seed (large odd integer) and the element code increment for differentiation of individual architectural elements

- `line 35:` output file containing the output gridded architectural element realization. The realizations are written from the lower left corner and then realization-by-realization (X cycles fastest, then Y, Z, and realization number).

- `line 36:` output file containing the the streamlines applied to construct the architectural element model.

4.1 Example Streamline-based Fluvial Models

The jigsaw reservoir type is characterized by high NTG with no major gaps. These reservoirs form from coarse grained meandering and braided fluvial styles. In these coarse grained systems the channels typically have high width to depth ratios. An example jigsaw reservoir model is shown in Figure 12. Note the braided and meandering streamline associations and the formation of FF(CH) baffles.

In Figure 13 a SH type model based on a distal setting is shown. The streamline associations show a high degree of meandering and little avulsion.

A prior and updated CH′ element model is shown in Figure 16. The streamlines include braided low to high sinuosity morphology. A single well is included with two CH′ element intervals identified. The morphology of the streamlines is preserved while the well intercepts are honored.

5 Limitations

This technique entails the translation of large-scale elements to honor small scale data; therefore, it is only suitable for settings with sparse conditioning data. Settings with dense data will be intractable and may result in artifacts.

The current implementation considers only CH′ elements. It may be useful to extend this algorithm to honor a variety of architectural elements identified in well data. Also, is is assumed that the wells are vertical.

6 Conclusions

The streamline based approach is a flexible and efficient tool for the construction of stochastic fluvial models. The building block approach allows for the modeling of a variety of fluvial reservoir styles, including the complicated architectures of CB type fluvial reservoirs. Streamline based models may be constructed based on all available soft geologic information and then updated to honor hard well data.

The research program `alluvsim` provides a useful starting point for geologic modelers considering streamline-based architectural element modeling.

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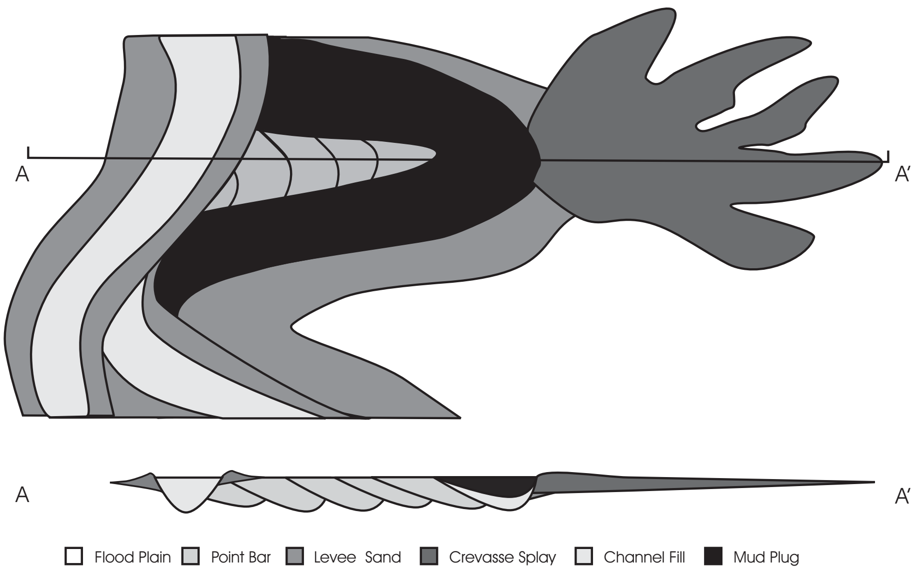

Figure 1: Plan and section view of conceptual model for fluvial facies: background of shales, meandering and avulsing channel with lateral accretion, levees, crevasse splays and mud plugs.

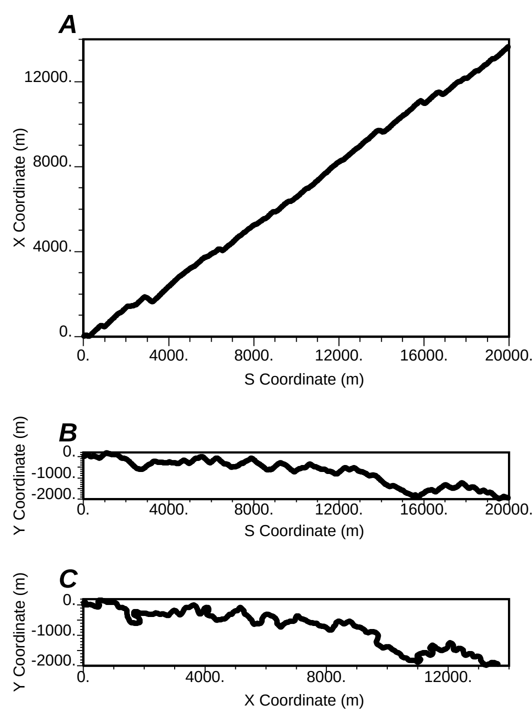

Figure 2: A demonstration of the construction of a 2-D spline by combining two splines. A - the X spline relative to length along the spline S, B - the Y spline relative to the length along the spline S and C - the resulting 2-D spline in the $X-Y$ plane.

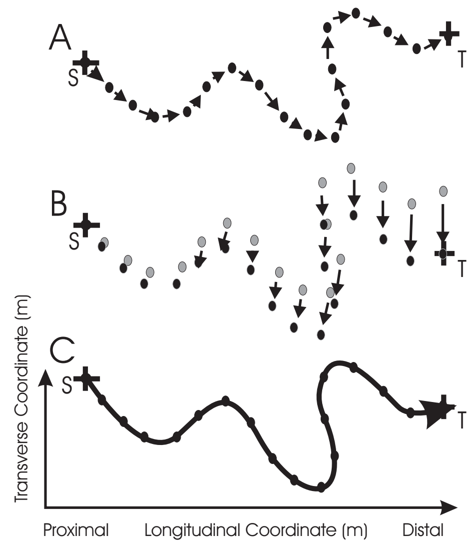

Figure 3: An illustration of the streamline initialization operator: A - apply process to generate realistic channel represented by regularly spaced control nodes, B - apply a smooth translation to correct to the target location and C - fit a 3-D spline. Note **S** is the source location and **T** is the target location.

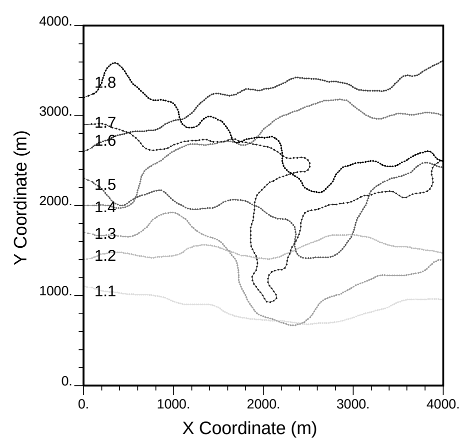

Figure 4: Example channel streamlines calculated with the disturbed periodic model. From bottom to top sinuosity = $1.1, 1.2, \ldots, 1.8$.

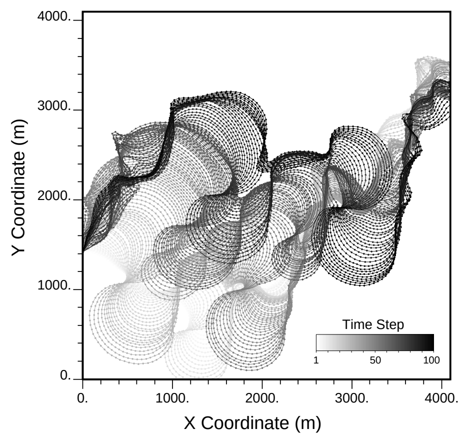

Figure 5: The migration of a channel streamline over 100 times steps (white to black). The source and target locations are kept constant. Note the neck cut offs. The end points are constrained.

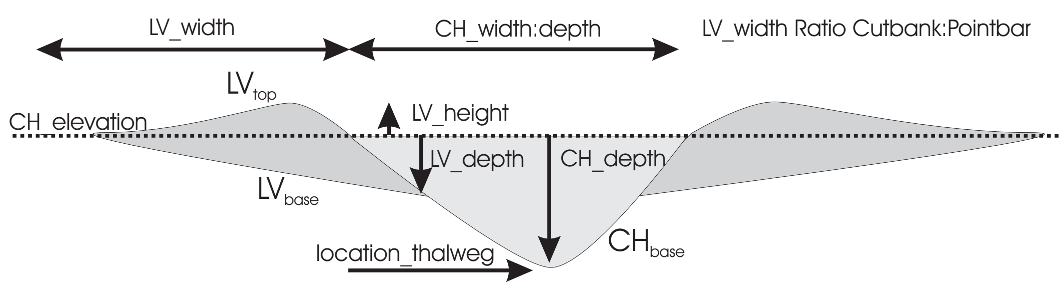

Figure 6: Channel and levee elements cross section and associated geometric parameters. Note the LV geometry is eclipsed by the channel geometry.

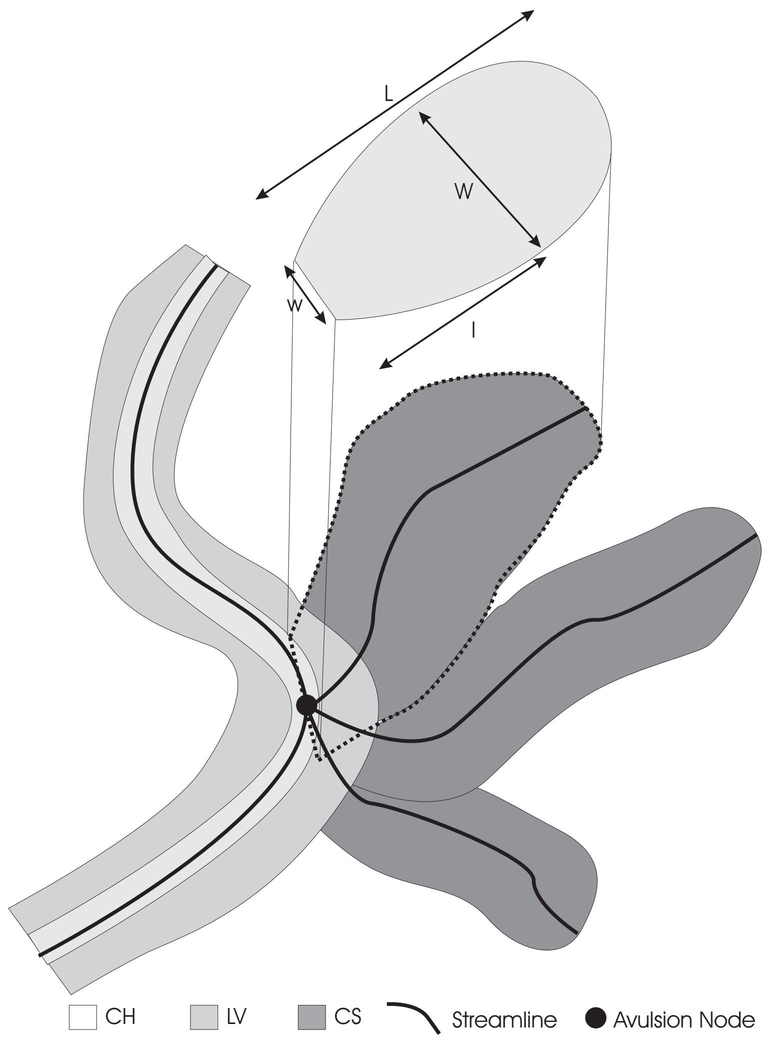

Figure 7: Crevasse splay architectural element geometric parameters. L is the length of the lobe, l is the length along the streamline where the lobe has its maximum width, W and w is the width along the proximal edge.

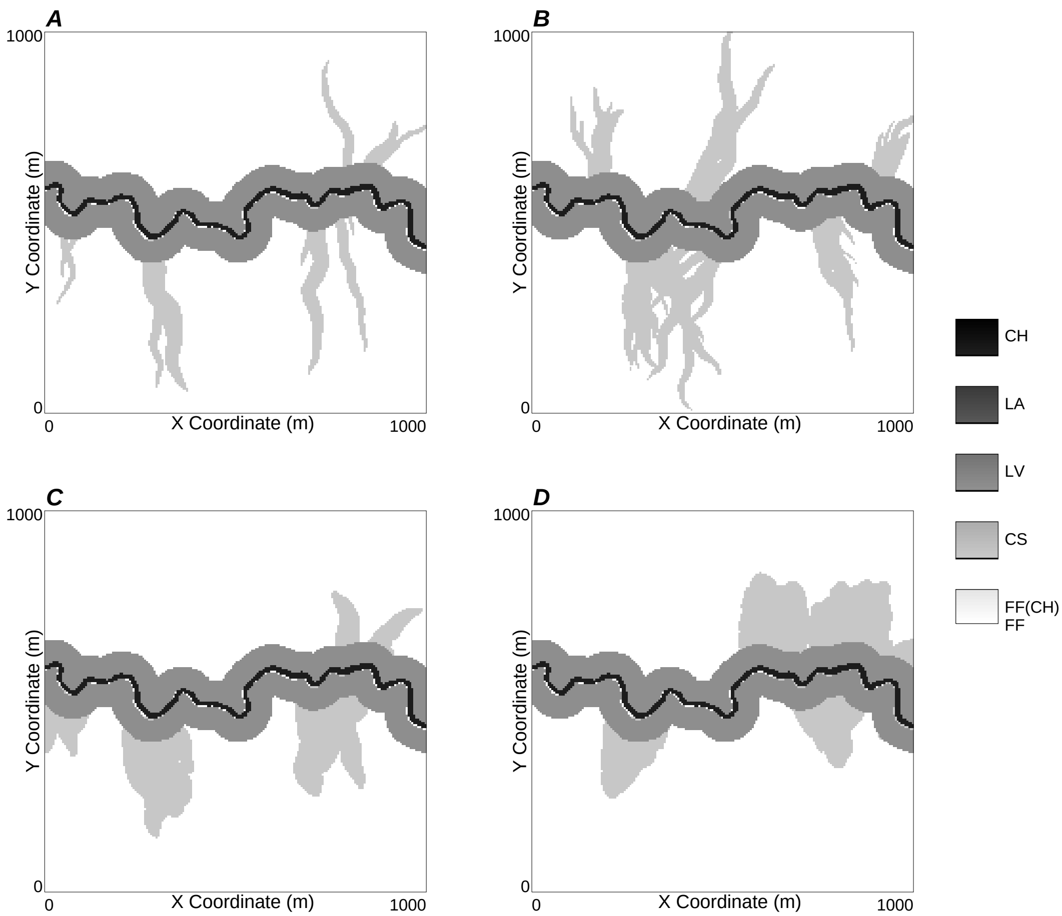

Figure 8: Example crevasse splay geometries calculated with the `ALLUVSIM` algorithm: A - isolated interfingered elements, B - amalgamated lobe and interfingered elements, C - isolated lobe elements and D - amalgamated lobe elements.

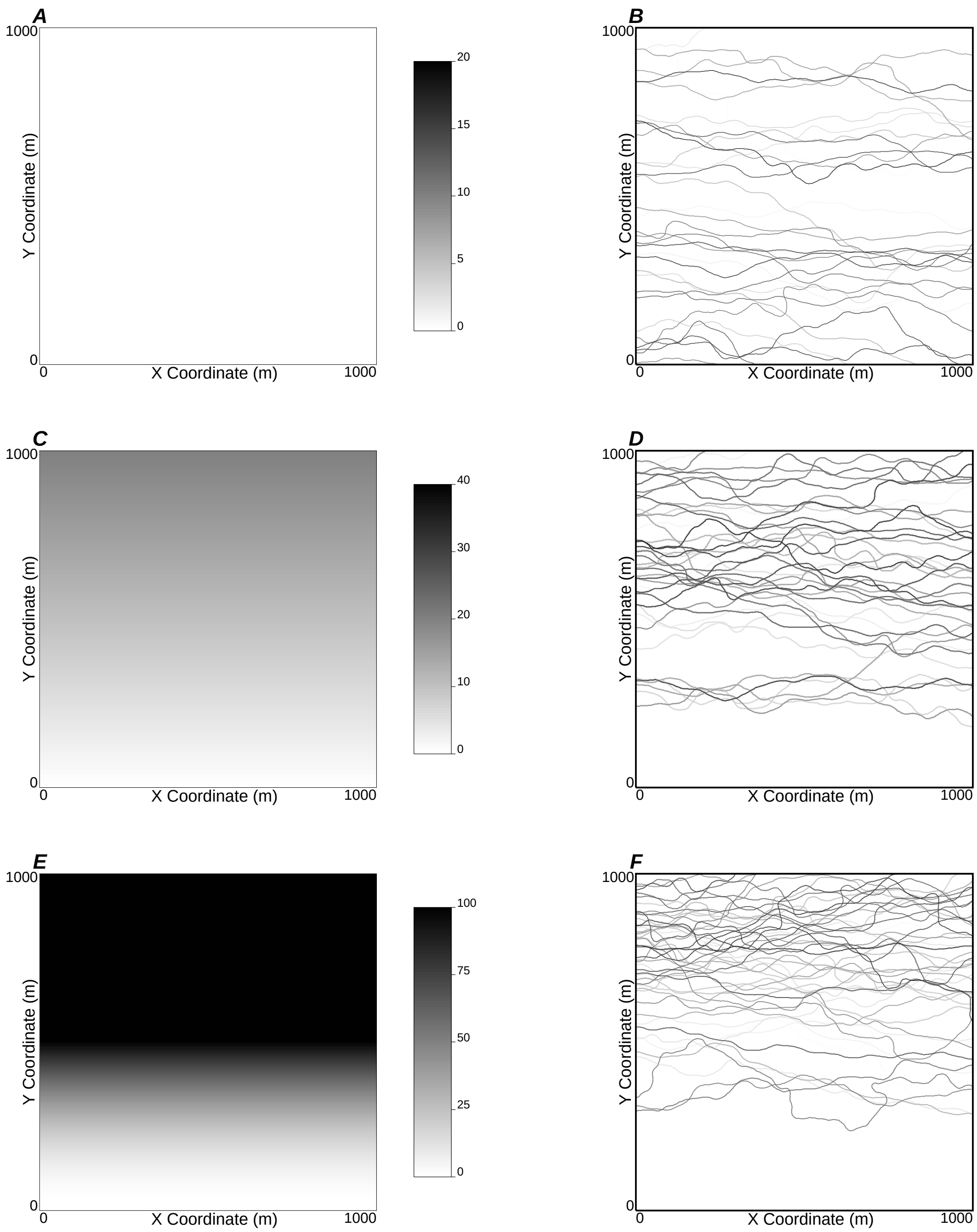

Figure 9: Example areal trends in channel density and the resulting streamlines. A and B - no areal trend supplied, C and D - a linear trend increasing in the y positive direction and E and F - a second order trend increasing in the y positive direction. Note areal trend is a relative measure without units.

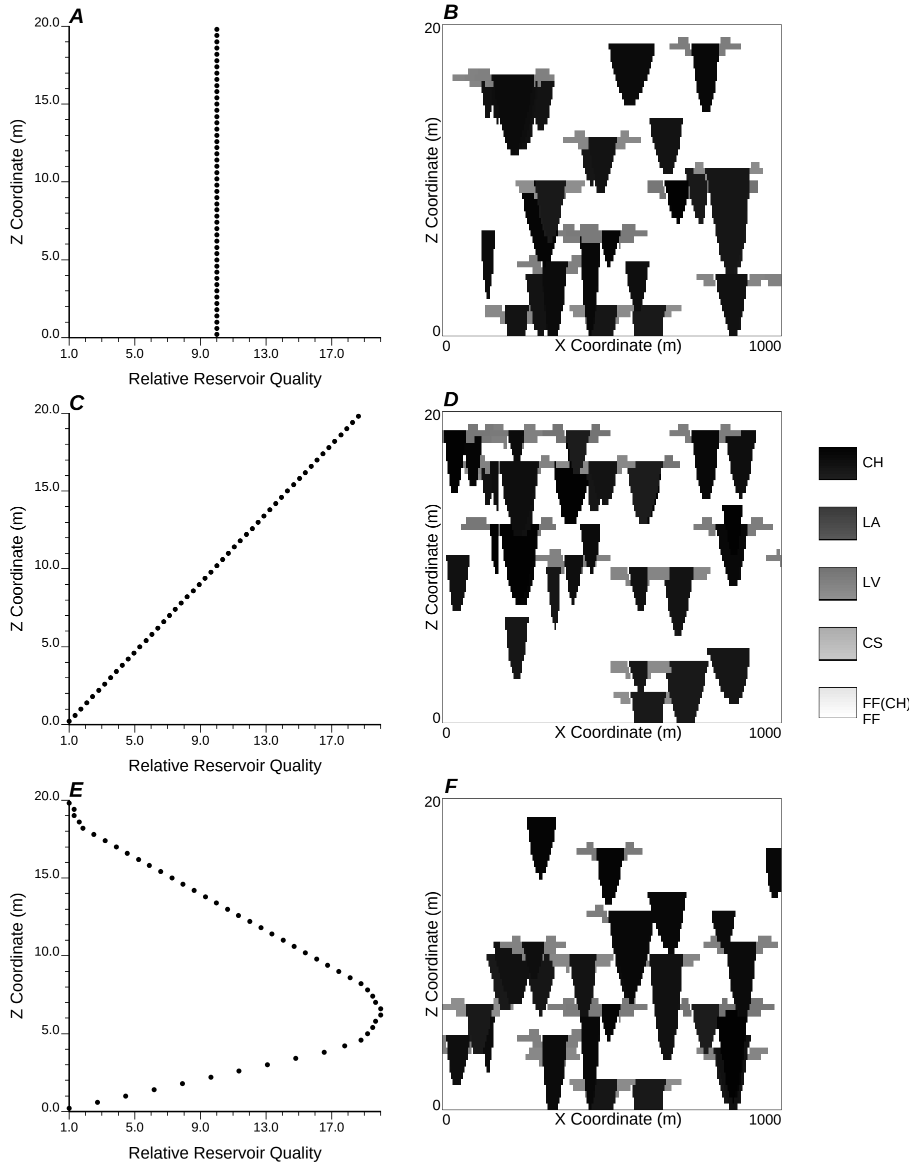

Figure 10: Example vertical trends in channel density and the resulting architectural element models. A and B - no areal trend supplied, C and D - a linear trend increasing in the y positive direction and E and F - a second order trend increasing in the y positive direction. The source locations are drawn from a uniform distribution along the proximal edge. Note vertical trend is a relative measure without units.

Parameters for ALLUVSIM
****

START OF PARAMETERS:		
welldata.dat	-file with CH' element intercepts	- line 1
1 2 3 4 7 9	- columns for well #, X, Y, Z_{top}, Z_{base}	- line 2
horitrend.dat	-file with the horizontal trend	- line 3
1	- column with horizontal trend	- line 4
verttrend.dat	-file with the vertical trend	- line 5
1	- column with vertical trend	- line 6
200 3 2.0 10.0 13.0	-max # of streamlines, # of levels, list of elevations	- line 7
0.30	-NTG target	- line 8
100 10	-# of candidate streamlines, fine search discretizations	- line 9
0.0 0.0	-P{proximal avulsion}, P{avulsion within model}	- line 10
90.0 1.0	-CH element:azimuth*	- line 11
500.0 50.0	- source location*	- line 12
4.0 0.5 0.2	- depth*	- line 13
2 20.0 2.0	- width:depth*	- line 14
1.3 0.2	- sinuosity*	- line 15
2.0 0.1	-LV Element:depth*	- line 16
160.0 5.0	- width*	- line 17
1.5 0.2	- height*	- line 18
0.3 0.1	- asymmetry factor*	- line 19
0.3 0.1	- thinning factor*	- line 20
2 2	-CS Element: number of CS / streamline*	- line 21
10 2	- number of lobes / CS*	- line 22
300.0 100.0	- lobe length*	- line 23
150.0 30.0	- lobe maximum width*	- line 24
50.0 10.0	- lobe length to maximum width*	- line 25
150.0 30.0	- lobe proximal width*	- line 26
0.000 0.000	- height:width*	- line 27
0.010 0.005	- depth:width*	- line 28
0.5 0.1	-FF(CH) Element:proportion of channel fill*	- line 29
50.0 20.0	-maximum migration step*	- line 30
200 2.5 5.0	-nx,xmn,xsiz	- line 31
200 2.5 5.0	-ny,ymn,ysiz	- line 32
50 0.20 0.4	-nz,zmn,zsiz	- line 33
69069 0.05	-random number seed,color_incr	- line 34
alluvsim.out	-file for output facies file	- line 35
streamlines.out	-file for output streamlines	- line 36

Figure 11: Parameter file for the `alluvsim` program. Conventions from the second edition of GSLIB are followed, that is, line number after "START" matters but not the column position.

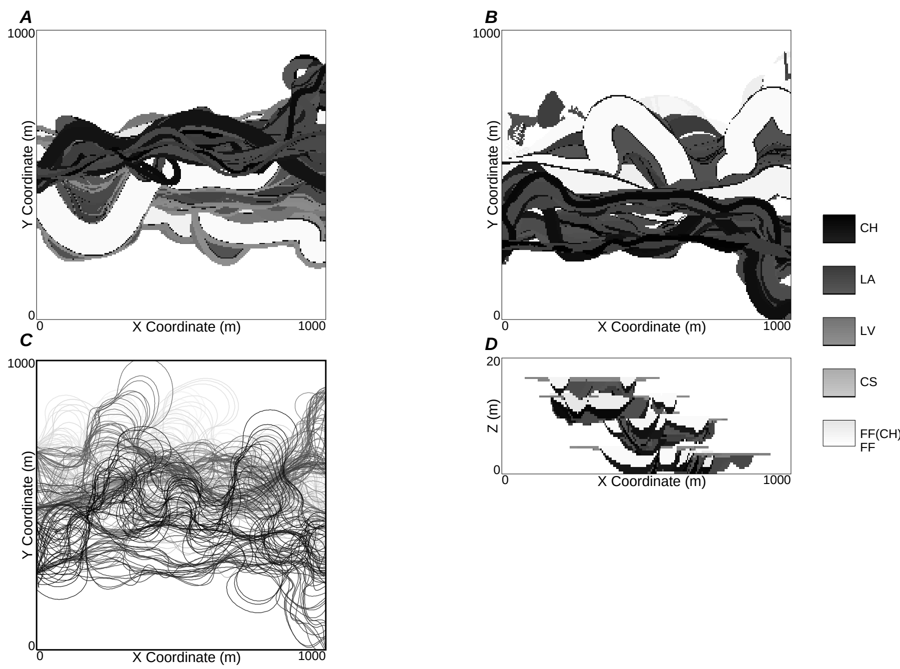

Figure 12: An example `alluvsim` CB type jigsaw reservoir model. A - plan section (z=5m), B - plan section (z=10m), C - all streamlines (grey scale from 1=white to n=black) and D - cross section (x=10m). Note grey scale assignment for architectural elements is varied to aid in differentiating amalgamated elements. Note the meandering and braided features in the streamlines.

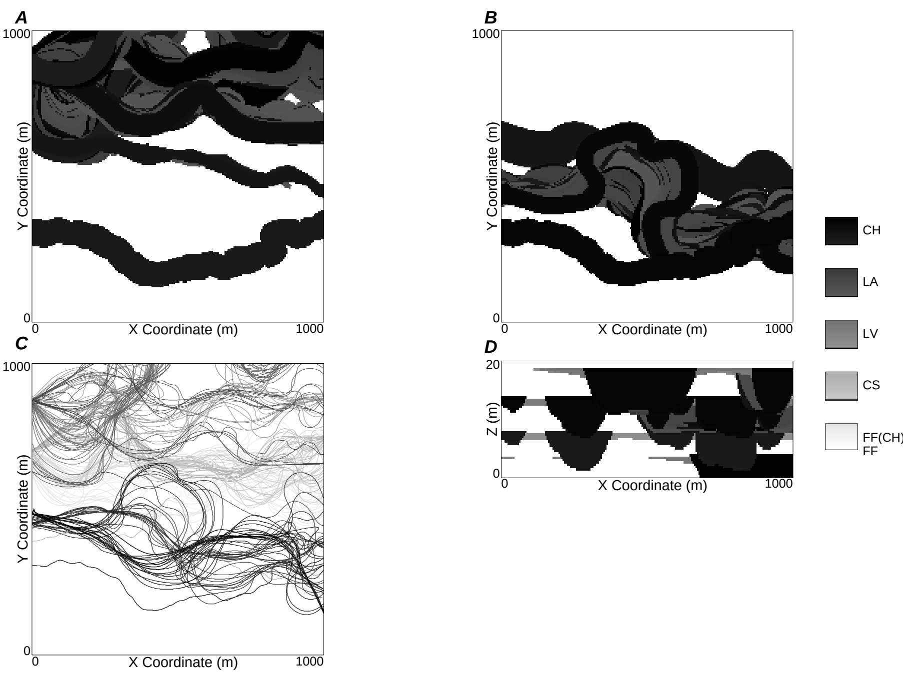

Figure 13: An example `alluvsim` distal SH type reservoir model. A - plan section (z=5m), B - plan section (z=10m), C - all streamlines (grey scale from 1=white to n=black) and D - cross section (x=10m). Note grey scale assignment for architectural elements is varied to aid in differentiating amalgamated elements.

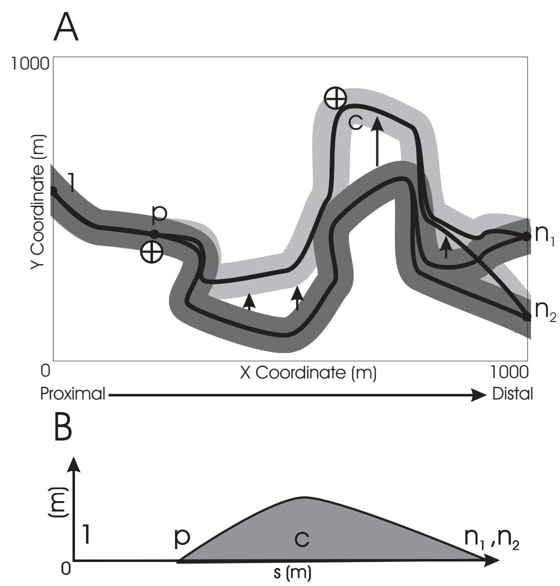

Figure 14: An illustration of methods for updating streamline associations to well data. For this example there are two streamlines in the streamline association representing an avulsion event that are corrected to honor conditioning data (c). A - the streamline is translated with a smooth difference distribution with the streamline held constant at the control node of previous conditioning (p) and beyond ($p \rightarrow 1$) and at the last control nodes (n_1 and n_2). B - the transverse correction with respect to location along the streamline ($\mathbf{s}$).

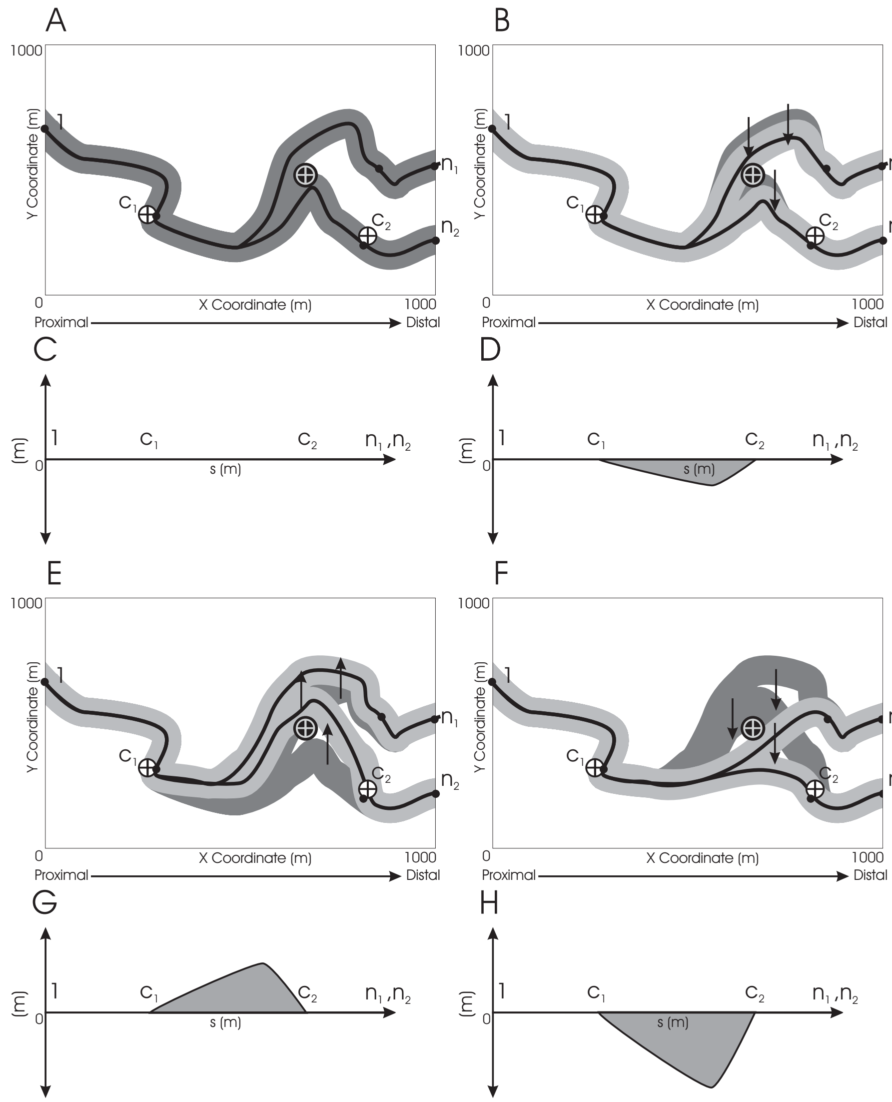

Figure 15: An illustration of methods for correcting streamlines associations to remove unwarranted well intercepts. The two streamlines are related by avulsion in the streamline association and there are two previously conditioned locations (C_1 and C_2). A and C - the initial streamline association prior to correction. B and D - the first smooth modification. E and G - the second iteration. F and H - the third iteration removes all unwarranted intercepts with this streamline association.

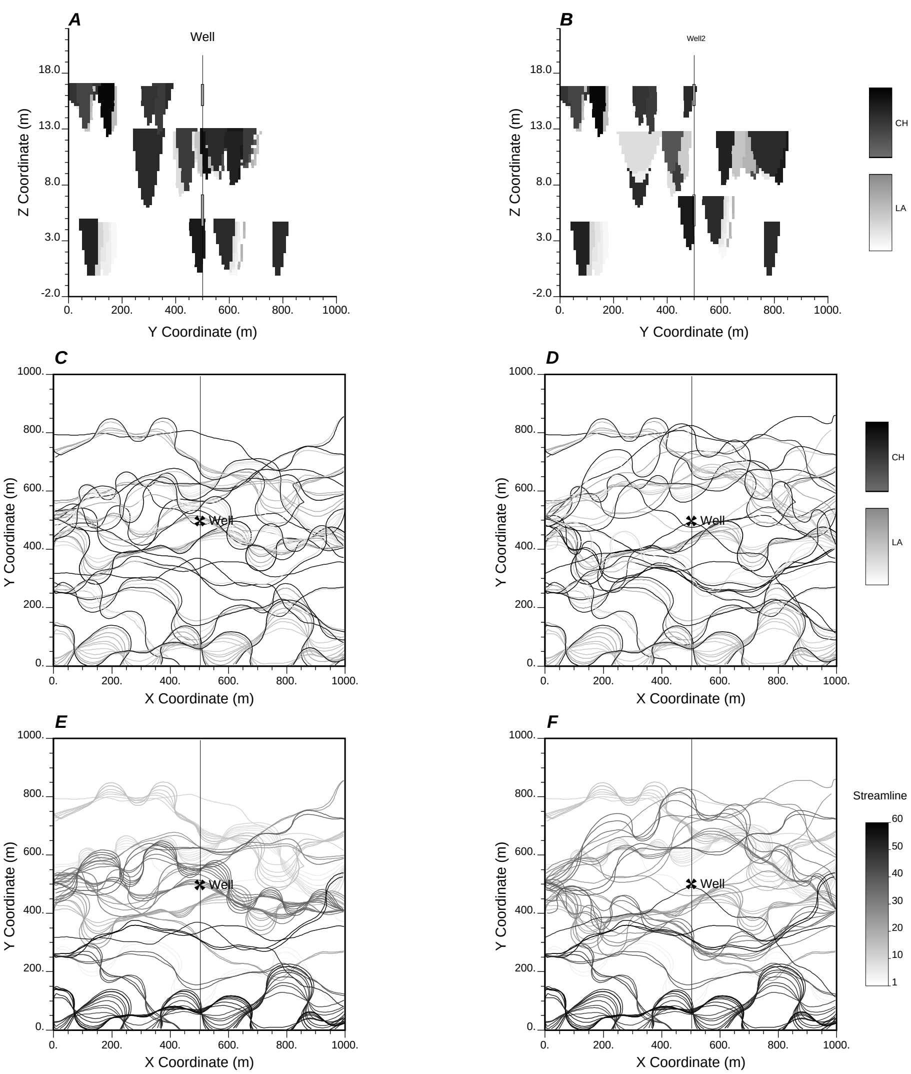

Figure 16: An example conditional streamline-based model from `ALLUVSIM` with CH and LA elements.