Conditioning 3D Object-Based Models to a Large Number of Data

by

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Abstract

Object-based stochastic simulation models are commonly applied for generating facies or rock models with more realistic representation of complicated reservoir heterogeneity. A limitation of object-based modeling is the difficulty of conditioning to dense well data. One method to achieve conditioning is by applying optimization techniques. The optimization algorithm accesses an objective function measuring the conditioning level of objects and the geologic realism. The objective function is optimized with implicit filtering which can consider constraints on object parameters. Thousands of locally optimized objects are generated and stored in a database. A set of the objects are selected with linear integer programing and populated into the model to honor all well data, proportions and other geologic features.

To illustrate the conditioning of object-based modeling with complicated geologic features, objects from fluvial reservoirs are used, although any parameterizable object can be considered with the proposed methodology. Channels, levees, crevasse splays and oxbow lakes are parameterized based on location, path, orientation and profile shapes. Functions mimicking natural river meandering are used for the centerline model. Channel stacking pattern constraints are also included to enhance the geological realism of object interactions. Correlations between different types of objects are modeled as well.

Case studies considering the geology of different styles of reservoirs demonstrate the flexibility of the methodology. The reservoir styles modeled include bifurcating channels, braided channels, fragmented channels and reservoirs with four types of objects. In all cases the proposed method robustly adheres to realistic feature geometries and matches the dense well constraints. The methodology can be easily modified and applied to many different geologic settings.

Dedicated to my family.

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My family always believe in me and support me without reservation. It motivates me to work hard. I am grateful to have family support all the time.

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List of Abbreviations and Symbols

NTG	net to gross
OBM	object-based modeling
a_{ij}	variable indicating if channel i and well j are matched
$\epsilon(s)$	random disturbance at a distance s
D	variable controlling the organized level of a channel stacking
h	damping factor
H	movement distance for a control node
I_m	a set of m channels
J_n	a set of n wells
k	scale parameter
λ	wavelength of a channel
L_i^1	channel mismatch length of well i
L_i^2	channel match length of well i
L_i^3	buffering distance of well i
m	number of qualified channels in a candidate database
M	a large number regarding to an objective function value
N	number of objects built for a candidate database
obj	objective function value
ω_1	weight for mismatch in an objective function
ω_2	weight for match in an objective function
ω_3	weight for buffering variable in an objective function
o_{ij}	number of overlapping points between channel i and j
s	distance along the channel
S	a binary variable indicating violation of hard constraints
t_i	variables indicating the intersection location of line segments
$\theta(s)$	channel flow direction
x_i	the i_{th} parameter describing an object
xs_i	variable indicating whether the i_{th} channel is selected

Chapter 1

Introduction

One peculiar feature in the mining and petroleum industries is that the practitioners do not know the underlying true values of the properties of interest. Modeling of a petroleum reservoir is necessary before exploitation. Decision making, such as whether the deposit is worth exploiting, where to locate production facilities and what quantity to produce per day all rely on numerical models. Even a minor improvement in the accuracy of modeling can result in substantial rewards in terms of economics, environmental impact or efficiency of the operation.

Deterministic modeling for generating a single best model is common in geologic modeling when making a production plan in mining industry. However, estimation based on limited data is uncertain. When planners examine estimated models, they would like to know the uncertainty in estimation. Stochastic modeling is then applied to quantify uncertainty. Statistical techniques have been adapted to geological modeling and have been used to model properties of the subsurface. They are gradually developed into a new branch of statistics, geostatistics.

Geostatistical models reproduce statistics of data samples. Mathematical procedures are embedded in the stochastic modeling to ensure the reproduction of statistics. However, it is difficult to ensure the proper geologic features of the reservoir in the stochastic modeling by simple mathematical formulas. Often, elaborate work flows are required to integrate geologic information into reservoir modeling. This thesis attempts to develop a modeling methodology that honors both geologic features and available data.

1.1 Reservoir modeling

A petroleum reservoir is a porous rock formation that contains hydrocarbons. Reservoir modeling aims to best estimate the inherent but unknown subsurface properties of the reservoir which help in the economic development of resources. Typically, reservoir modeling is divided into two categories, facies models and property models (Ringrose and Bentley, 2015). Usually facies modeling precedes property modeling; the facies model can offer rock boundary constraints as an input to property modeling. These constraints improve modeling especially when facies control the main heterogeneity seen in reservoir properties.

1.1.1 Facies modeling

Facies modeling (or rock modeling) focuses on capturing contrasting facies identified from sedimentology and generating 3D models (Ringrose and Bentley, 2015). Many factors are involved in dividing the reservoir into different categories. For example, in fluvial reservoirs the rock can be divided into sandstones, mud-stones and coarse-grained materials according to lithofacies; genetically it can fall into channel, levee, floodplain etc; or the classification can consider the stratigraphy, diagenesis, structure and mineralization procedure, as long as the categories have differences and the classification makes sense for the application.

The purpose of facies modeling is to define the boundary for each rock category in the 3D numerical model. Various modeling methods have been developed including variogram-based modeling, multiple-point statistics modeling, object-based modeling (OBM), process-based modeling and surface-based modeling. These methods are introduced in the following sections while the main focus of this work is OBM.

Variogram-based modeling

The variogram measures the spatial correlation between two different locations (Cressie, 1993). It is a function of spatial distance and normally its value rises as distance increases. The higher the variogram value is, the less the two points are related. Based on the spatial continuity quantified by the variogram, a model of the domain can be simulated. When considering facies (or rock types), indicator variograms can be modeled (Journel, 1983). The indicator variogram summarizes the measure of spatial continuity for categorical variables. One modeling method for generating 3D categorical models using the indicator variogram is sequential indicator simulation (Journel and Alabert, 1989a).

Sequential indicator simulation divides the domain into a grid and simulates a category at each gridded node sequentially. The previously simulated values are used as data for nodes simulated later. Indicator variograms control the spatial distribution of the categories. Data from well, seismic and geological interpretations can be integrated into the simulation (Journel, Alabert, et al., 1990). One modeling example generated from BlockSIS (Deutsch, 2006) is shown in Figure 1.1. It is a simulation for a fluvial reservoir comprised of channels, levees, crevasses and flood plains. Each facies does gather together like objects but the object shapes are not well reproduced in the simulation. The modeling method does not properly integrate the geologic information.

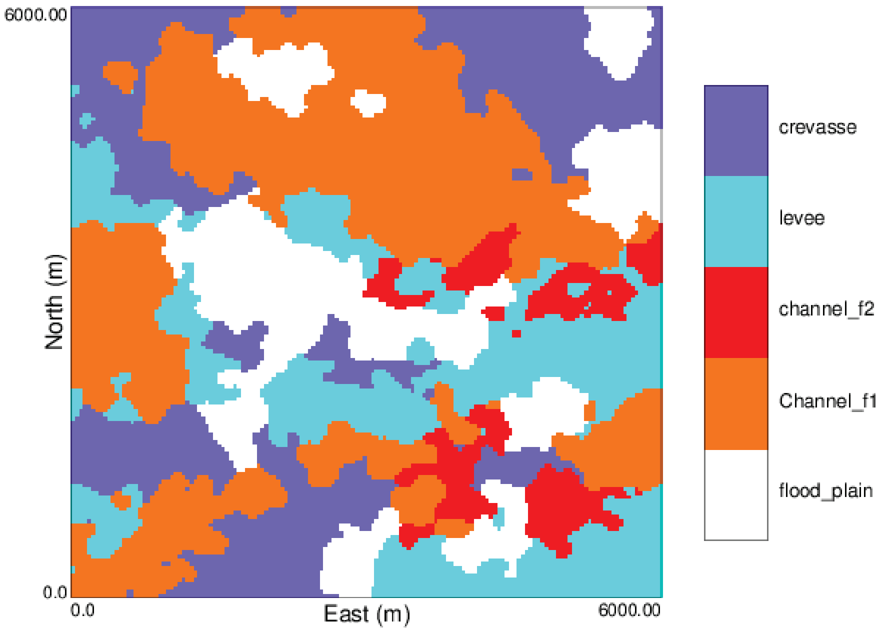


Figure 1.1: Fluvial simulation from sequential indicator simulation.

Truncated Gaussian simulation (Matheron et al., 1987) is another modeling method based on variograms. It was first used by Matheron to condition fluvio-deltaic reservoirs. The first step is to generate one Gaussian simulation of a continuous variable. Then the Gaussian distribution of the modeled variable is divided into several zones according to the value of the variable. Each zone represents one facies. The threshold values of zones are set in a way that each facies has the right proportion, globally (and locally). The simulated values change smoothly within neighborhoods in the modeling domain. There is no discontinuity in the value of the variable, thus the rock types show a strong ordering. A rock represented by a high value zone never abuts a rock represented by a low value zone. Sometimes this is a useful modeling constraint when the categories have a known ordering, but sometimes it is an undesired feature. Furthermore, the simulation can only use one variogram while there are several facies with different spatial continuity. It is not possible to integrate all relevant geologic boundary information with one variogram.

To overcome these drawbacks, Le Loch and Galli introduced truncated pluri-Gaussian simulation (Le Loch and Galli, 1997). The idea is to use multiple Gaussian variables. With a multivariate distribution, the truncation (i.e. dividing of zones) is considered in multiple dimensions. The ordering is more flexible. Since modeling incorporates information from multiple simulations, multiple variograms can be used. Figure 1.2 shows an example generated by truncated pluri-Gaussian simulation (Sadeghi and Boisvert, 2015). The strong ordering is obvious. The channel is surrounded by levee and sometimes crevasse, and never meets flood plain directly. Though the boundaries of facies are not obvious nor consistent with features known to exist such as channels and levees.

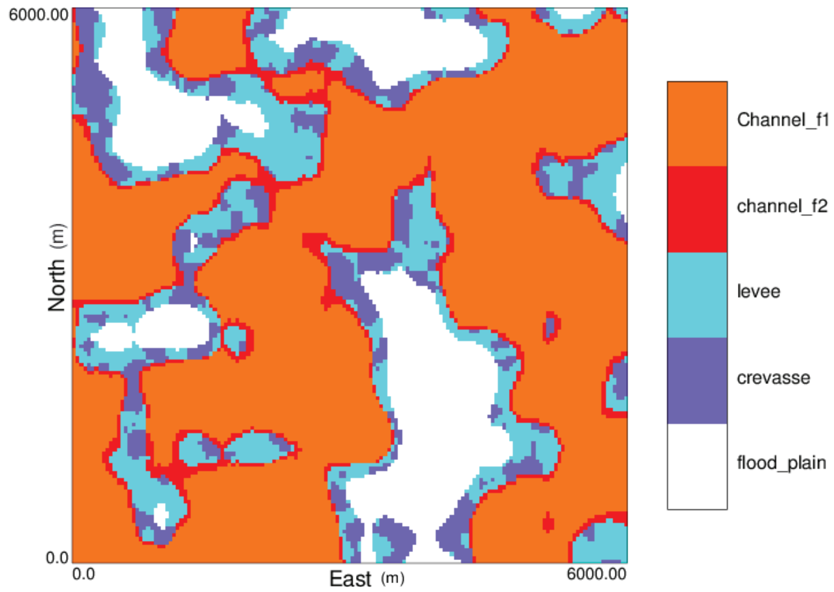


Figure 1.2: Fluvial simulation from truncated pluri-Gaussian simulation.

Multiple-point statistics modeling

The variogram function summarizes the relationship between two points. When it comes to a complex geological modeling, a function using two points cannot offer sufficient information for the model to reproduce complex features. Multiple-point statistics can be used to reproduce complex features. The idea is to count the frequencies of patterns showing up in a training image, which is a representative sampling model with desired geological characteristics. The modeling value at each grid is assigned according to its surrounding data and the frequencies of the patterns from the training image. Geologic data about complicated structures are transmitted to models through the frequencies statistics.

The use of multiple-point statistics can be traced back to Journel and Alabert (1989b). Guardiano and Srivastava (1993) wrote a direct (noniterative) algorithm using this method in stochastic simulation. However, due to the high computer memory requirement, it was not commonly used until Strébelle and Journel (2000) adapted search tree and Strebelle (2002) adapted multi-scale simulation technique. Figure 1.3 shows an example of fluvial simulation generated by SNESIM (Strebelle, 2002). The channels, levees, crevasses are well reproduced. The problem, and the key, for a successful application of multiple-point statistics is the training image. Great efforts are required for modeling a training image (Boisvert et al., 2007). OBM, outcrops, shallow seismic data and production data are some common sources of training images.

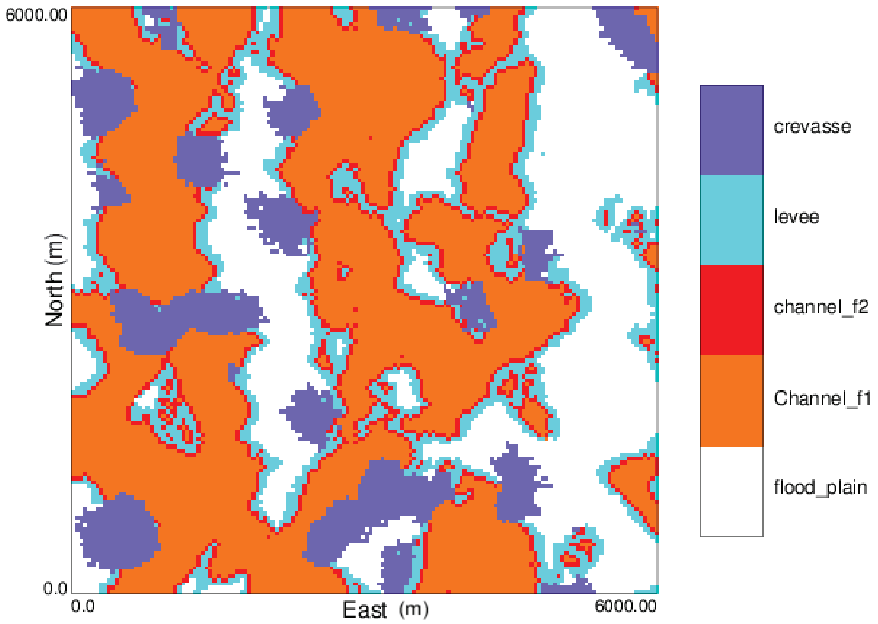


Figure 1.3: Fluvial simulation from multiple-point statistics modeling. The training image used is generated from object-based modeling.

Object-based modeling

OBM involves the following processes: parameterize architectural objects; infer constraints on these parameters; sequentially draw from these distributions to simulate and place objects into a reservoir model initialized with one background facies until some criteria, such as target global proportion and data conditioning are met (Pyrcz and Deutsch, 2014). If the goal is to model facies boundaries that are known geological shapes, OBM is appropriate and results in models with the desired geometries. For example, in a fluvial reservoir many elements have consistent geometries and OBM has been widely used. Miall (1996) has listed 16 common objects from fluvial reservoirs with description of facies and detailed information on architectural elements. Objects such as channel, levee (Deutsch and Tran, 2002), crevasse (Deutsch and Wang, 1996), send lenses, point bars (Hassanpour et al., 2013; Pyrcz, 2005) and oxbow mud fills (Pyrcz et al., 2009) have already been reproduced in numerical modeling.

Figure 1.3 is a fluvial reservoir OBM example generated by FLUVSIM (Deutsch and Tran, 2002). Clearly, in terms of generating identified geometry as facies boundaries, OBM is the best.

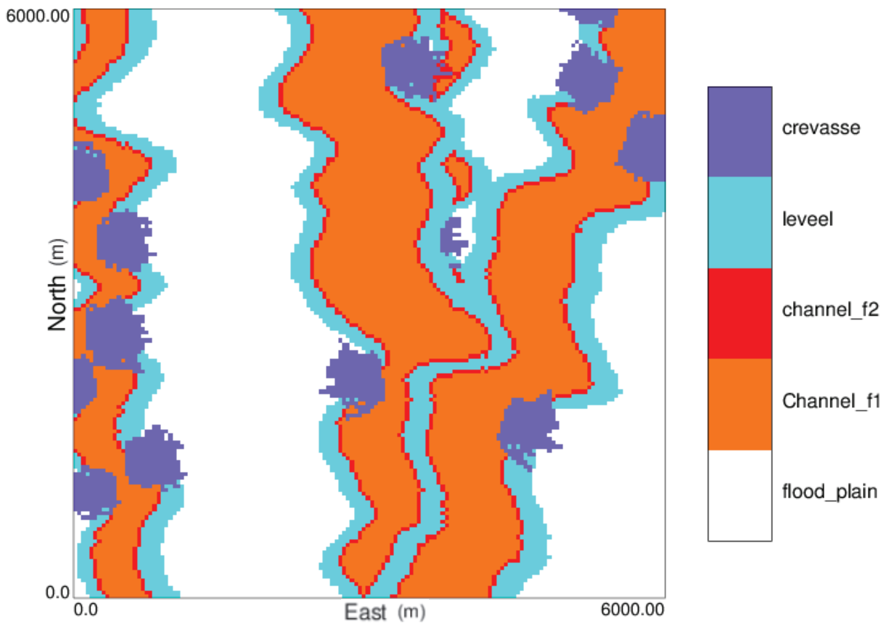


Figure 1.4: Fluvial simulation from FLUVSIM (Deutsch and Tran, 2002).

However, OBM also has its own issues. The difficulty of conditioning OBM to data stopped OBM from being more prevalent. This leads to the frequent use of multiple-point statistics. More details about the difficulty are discussed in section 1.3. Besides, some facies do not keep consistent shapes, therefore, cannot be parameterized by one invariant method. OBM is not suitable for modeling these rock boundaries.

Process-based modeling

Process-based modeling extends the parameterization of objects. Instead of a set of static objects, a reservoir is modeled as a set of known complicated geological processes over time. A set of stacked objects in one domain might be the impressions of one object from different time periods. The stacked objects have strong connections between each other. Traditional OBM cannot reproduce the complex features brought by geological processes such as sediment, migration, erosion and faulting. Process based modeling is applied to add a further degree of geologic realism (Pyrcz et al., 2009; Miller et al., 2008; Bertoncello et al., 2013). After the objects are initialized, processes mimicking natural physical and geological rules are adapted to modify the object models. For example, in the modeling by Pyrcz (2005), channel streamline processes are simulated including avulsion, aggradation and migration.

1.1.2 Property modeling

The overall aim in reservoir model design is: "*To capture knowledge of the subsurface in a quantitative form in order to evaluate and engineer the reservoir*" (Ringrose and Bentley, 2015). Facies modeling is a supportive tool offering boundary constraints as inputs to property modeling. The constraints lead to more precise quantitative simulation. Property modeling is the key step in quantifying a continuous variable of interest in a reservoir. Engineering and financial decisions are usually made based on these properties. For example, the porosity and permeability modeling are used for flow simulation in reservoir characterization; the grade modeling in mining decides whether the mine is worth exploiting. These properties are often continuous variables.

Geostatistics

Geostatistics is the common toolbox for property modeling. One prevalent technique is to mesh the reservoir and simulate the variable values at each grid node separately. After modeling every grid, upscaling or downscaling can be applied to obtain the properties of interest at a desired scale. Values at an unsampled locations are calculated through weighted averages of sample data. The weights are assigned based on variograms. Sequential Gaussian simulation (SGS) is commonly used for property modeling. Different from conventional geologic modeling, the geostatistical model does not focus on giving a single "best" estimate. Instead, it gives a set of equiprobable simulations. The simulations are different to each others but honors the available data and statistics including the variogram, histogram, mean and variance. The difference in how the realizations behave represents uncertainty resulting from limited available data.

1.2 Channelized reservoirs

A channelized reservoir refers to a reservoir generated in sediments brought by river water flowing within channels, including channels from fluvial, estuarine and deep-water environments. Channel type reservoirs containing oil are located world wide (McHargue et al., 2011; Posamentier, 2003; Alpak et al., 2013; Deptuck et al., 2003; Babonneau et al., 2010). In a channel based reservoir, there are different sedimentary lithofacies including channel, levee, crevasse splay, flood plain and so on (Miall, 1996). They are generated by different geologic procedures and behave very differently. In general, facies modeling is necessary for this type of reservoir modeling. Moreover, the objects have unique and well understood geometries. OBM is applicable for facies modeling of a reservoir comprising of these known objects. In this thesis, the channel based reservoirs are the modeling target.

1.2.1 Geologic interpretation

Channels from different environments have different features. Some are sinuous and others are straight; some are braided and some are anastomosing (Miall, 1996; Hartley et al., 2010). To model the reservoir more realistically, a review of the geology of objects is necessary.

With increasing research based on outcrop, well log and especially seismic data, detailed interpretations of the geology have been developed (Abreu et al., 2003; Sylvester et al., 2011; Deptuck et al., 2003; Deptuck et al., 2007; McHargue et al., 2011; Macauley and Hubbard, 2013). It is believed that the channel system reservoir is structured hierarchically from a single channel element to a channel set to a channel complex. Channel behavior such as migration, accretion and avulsion generate features such as crevasse splays, inclined heterolithic stratifications (Thomas et al., 1987) and stacking patterns. OBM in this thesis mimics the reservoir hierarchy and simulates domains consisting of multiple channels with stacking features. Geological connections between different objects are honored.

1.2.2 Parameterization

The interpretation describes the origin, evolution and final stage of the modeling objects. To generate numerical models, the objects must be digitized. A number of parameters are used to describe the objects. With the set of parameters, the objects can be reproduced in the numerical realizations.

Objects such as channels created by nature are irregular. To fully digitize an irregular object, a considerable number of parameters are required. Excessively detailed parameterization increases the amount of calculation in modeling. A balance between discretization and CPU requirements is needed. Simplifying the parameterization and only capturing key parameters is appropriate.

Channels and levees are generally long objects with similarly shaped cross sections. A reasonable parameterization is using a centerline to adjust the layout and cross sections to control depth, width and boundary shapes. Alternative parameterization methods can also be adapted. The only requirement for parameterization is that the key features of objects are captured by a reasonable number of parameters. For example, bow shaped profiles rotating around the straight edge are suitable for the parameterization of round objects like lobes (Chan and So, 2006). Many examples of parameterization can be found in the literature related to OBM, including channels (Wietzerbin, Mallet, et al., 1994; Hauge et al., 2007; Viseur et al., 1998; Gibling, 2006; Deutsch and Wang, 1996; Holden et al., 1998), levees (Shmaryan and Deutsch, 1999; Deutsch and Tran, 2002; Pyrcz et al., 2009), crevasse splay (Shmaryan and Deutsch, 1999; Pyrcz et al., 2009), lobes (Bertoncello et al., 2013) and point bars (Hassanpour et al., 2013).

1.3 Challenges of conditioning OBM to data

While OBM precisely reproduces the boundary features for facies modeling when the object geometry is known, it is difficult to condition to well data. The OBM has specific geometry designs for objects. This constraint restricts the modification on an object parameters and makes conditioning OBM to data challenging. Numerous attempts have been attempted. In pixel based method the conditioning of OBM can be achieved by erosion and dilution process (Henrion et al., 2010) but the object boundary restriction is actually not honored.

1.3.1 Optimization

First an object is generated and then modified to match conditioning data. An objective function is used to measure the conditioning level between objects and data. When the objective function value is optimized, the data tend to be conditioned by the objects. Due to conditioning difficulty and the constraints on the optimization procedure to keep objects geologic realism, the optimized objects are local optimum and certain objects may violate well data.

Viseur et al. (1998) and Shmaryan and Deutsch (1999) conducted quick conditioning of channel based reservoirs by direct object placement of 1D-centerline channels. The parameterization of channels and geological setting in their modeling are very simple. Pyrcz and Deutsch (2005) present conditioning through efficient simulation of many channel centerline candidates and rejection sampling along with local morphing for conditioning. However, the conditioning results are not satisfying. Simulated annealing (Deutsch and Wang, 1996) and Metropolis-Hastings (Holden et al., 1998; Oliver, 2002) algorithms have been effective with data conditioning but with slow run times, challenging set up and a low rate of convergence. Bertoncello (2011), Boisvert and Pyrcz (2014) and Wingate et al. (2015) precisely conditioned OBM to well data with grid free modeling rather than rasterized to gridded objects resulting in loss of heterogeneity detail below the resolution of the grid.

Among the various channel conditioning methods, some build an initial unconditional object model by sampling randomly from the parameter distributions (Deutsch and Wang, 1996). Conditioning is achieved by perturbing the objects resulting in high computation cost. Other methods directly initialize objects to condition to well data (Viseur et al., 1998; Shmaryan and Deutsch, 1999), which significantly improves efficiency, but dramatically restricts the channel paths; as a result, limiting the space of uncertainty explored by these stochastic simulations. Methods that initialize objects randomly from a distribution and rely on rejection sampling and local morphing may still have a very low acceptance rate (Holden et al., 1998; Pyrcz and Deutsch, 2005). Given the rapid increases in computational speed in last decade, there are new opportunities to improve OBM conditioning.

1.3.2 Thesis statement

This research develops methodologies for conditioning OBM to well data. The proposed method applies existing optimization algorithms to candidate objects in order to efficiently and effectively build a better conditioned set of objects. An optimization algorithm called Implicit Filtering (Kelley, 2011) is adapted to achieve conditioning. The optimized objects are then placed in a domain for the final realization construction. By using currently available computational techniques, conditioning of more complicated objects to denser data is possible. This method can be used on any object that can be parameterized. The thesis statement:

Conditioning OBM to well data through optimization can integrate geologic properties such as heterogeneity and object hierarchy into reservoir modeling and results in models that are compatible with information from diverse sources.

1.4 Dissertation outline

Chapter 2 describes the geologic features of objects from fluvial reservoirs that are modeled. Five representative types of objects are selected including channels, levees, oxbow lakes, crevasse splays and the background flood plains. Geology and parameterization for each object are discussed. Channel stacking is also parameterized.

Chapter 3 presents the optimization procedure for the conditioning of one single object. Examples of the data used in conditioning are illustrated. An objective function measuring the level of conditioning between objects and well data is explained. Objects are optimized by changing their parameters and minimizing the value of the objective function. Optimized objects are selected to construct a single-layer simulation conditioned to available data. Different objects can be modeled in the domain sequentially. Three synthetic modeling examples for different environments are presented.

Chapter 4 displays two modeling examples of realistic reservoirs. A reservoir is divided into multiple layers and is separately modeled in each layer. Geologic differences in the reservoirs are considered. The two examples are modeled through different procedures. Modeling results are displayed as grid free models.

Chapter 5 summarizes the contributions. Future research aimed at improving modeling realism is suggested.

Chapter 2

Modeling fluvial objects

Fluvial reservoirs are used to illustrate a novel modeling method. Two reasons support the selection. First, a significant amount of petroleum has been produced from this type of reservoir and they remain of great economic value. Second, the lithofacies in this reservoir including channels, levees, crevasse splays, send lenses, point bars, etc. all have unique and well reserved geometric shapes. This is a suitable situation for OBM.

In OBM, understanding the object sizes, geometries and interactions is essential. Sufficient data is rarely available to completely define these parameters (Bridge, 2009), but estimates are available from wells, outcrops and forward geologic modeling. The research in this thesis demonstrates a method that can condition models to facies observed at well data. However, the objects must be understand and parameterized first.

Various interpretations on the geometry and architecture of fluvial reservoirs are considered. Modern sedimentological interpretations began in the 1950s (Miall, 2014) when Nanz Jr (1954) discovered the repetition of zonation on well logs. Based on observations of modern fluvial rivers, Allen (1965) built three-dimensional facies models as an aid to the identification of ancient alluvial sediments. Mackey and Bridge (1995) simulated alluvial architectures with parameterized coarse-grained channel deposits within overbank deposits.

These interpretations use modern rivers as analogues of ancient fluvial reservoirs, though differences between the two should be noted. The ancient reservoir is an accumulation of preserved channel fill over a long geological period. The river migrates, erodes older sediments and aggrades with time. As a result, an ancient fluvial reservoir consists of a set of channel objects or, more hierarchically, a complex of channel sets.

Modern exploration techniques are used to "see" large scale internal structures of a reservoir with interpreted seismic data. More detailed interpretations on reservoir hierarchy have been developed. For example, McHargue et al.

(2011) developed a conceptual model of turbidite channel architecture in Magallanes Basin. Channelized turbidite reservoir interpretation examples in the Gulf of Mexico (Posamentier, 2003), west Africa (Alpak et al., 2013), Niger Delta, Arabian Sea (Deptuck et al., 2003), Congo (Babonneau et al., 2010), etc. have been published. Though these studies are on deepwater reservoirs, they are reasonable analogues to fluvial reservoir modeling in regard to certain aspects of channeling and channel objects.

Not only do the fluvial objects have a complicated hierarchy, but also the lithofacies in fluvial reservoirs are diverse. Miall (1996) has listed the common 16 types of fluvial reservoir objects with a description of facies and geometry shape. According to the economic and engineering value, this thesis selects five types of lithofacies including channel, levee, crevasse splay, oxbow lake and floodplain for modeling. Floodplain is the background for the modeling while others have their own unique shapes. Some key features of the objects such as stacking patterns are also important. Basic geology and parameterization methods of the modeling objects and features are described in the following sections.

2.1 Geological concepts of channels and levees

The definition of a channel given by Mutti and Normark (1991) (summarized by Weimer and Slatt (2004)) says: [Channels] are elongate negative-relief features produced and/or maintained by turbidity-current flow ... (they) represent relatively long-term pathways for sediment transport. Channel shape and position within in a turbidite system are controlled by depositional processes ... or erosional downcutting ... Channel relief can be dominantly erosional or depositional in origin or can result from a combination of both processes.

Technically, a channel refers to the surface or boundary surrounding the channel fill. But the modeling in this thesis treats the boundary together with the space inside the boundary as the channel object. This concept is also applied to other modeling objects. The channel fill may constitute the reservoir for petroleum. The hydrocarbon is often stored in the porous rock sediments.

There are four types of channels in general according to morphology, including low sinuosity, meandering, braided and anastomosed. The width, depth and sinuosity in each type differ. The preservation of different channels differs between the types of channels. As a result, the geometry of channel objects in different reservoirs should be customized for modeling.

Many interpretations of turbidite channels in deepwater system give likely prototypes of the channel modeling in this thesis. Alpak et al. (2013) developed a hierarchy of turbidite channel systems and drew the structures in schematic diagrams (Figure 2.1). A channel consists of a set of beds; channels make up a channel set and many channel sets may gather together and become a channel complex. The internal architecture changes along the longitudinal channel axis. There is coarse sediment upstream. The number of sandstone beds increases downstream. The architecture cannot be fully parameterized for numerical modeling. However, a list of parameters related to the reservoir performance is summarized in the paper and offers some ideas about what properties of channels should be parameterized in the modeling.

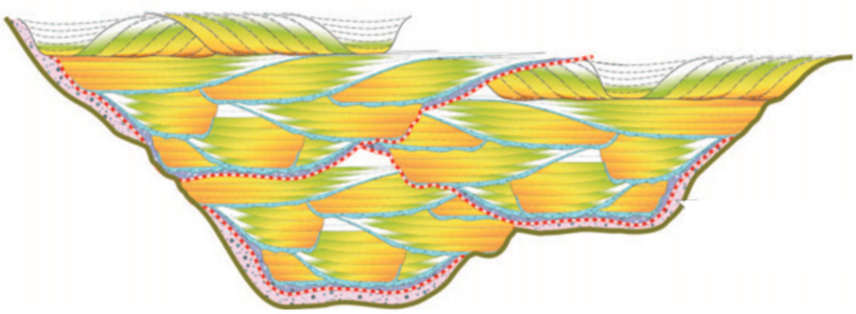


Figure 2.1: Hierarchy of a channel complex (Alpak et al., 2013). This cross section represents a thickness of 50-200 m and a width of 800-4000 m.

McHargue et al. (2011) hypothesize that there are four stages in the deposition of channel systems (Figure 2.2). First, the channels erode the bottom of valley. Secondly, the channels within the valley start to amalgamate. In the third stage, as the energy in the system wanes, the channels in the valley start to aggrade but are disorganized. Finally, with a high aggradation rate, the channels eventually become organized. These procedures create stacking patterns for the channels. Coming from different stages, the stacking pattern can be organized or disorganized. Clear stacking features can be seen in some current seismic data. (Deptuck et al., 2003; Deptuck et al., 2007) displayed the migration and aggradation history of the channels on the Niger Delta slope. Seismic profiles (Figure 2.3) offer a geometry prototype for channel cross sections.

A levee is the elevated partitions between channels and floodplains (Brierley et al., 1997), and is part of channel margins. As stand-alone reservoirs, levee may not be sufficiently economic for exploitation. But as secondary reservoirs, they can be quite important (Weimer and Slatt, 2004). The submarine channels flanked by levees have been recognized as important components of deep water systems (Deptuck et al., 2003). As mentioned, shape and layout parameters of

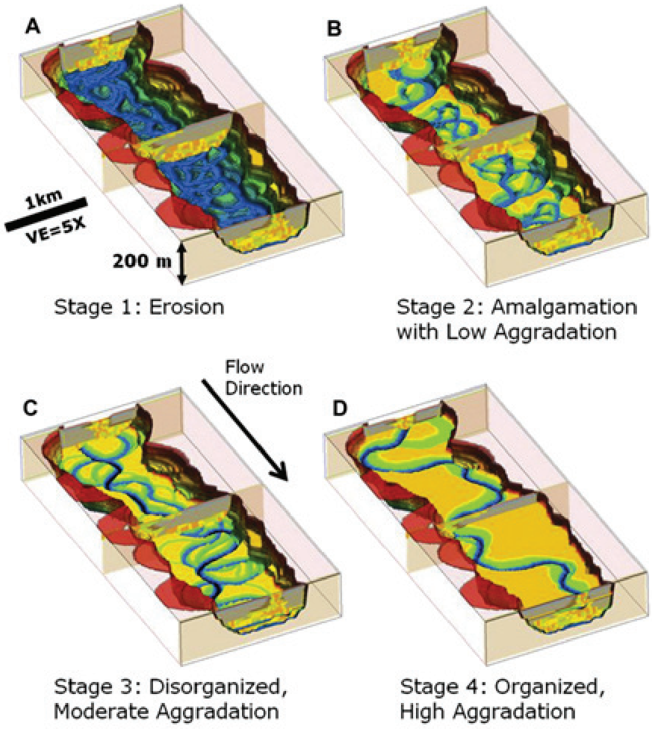


Figure 2.2: Four stages during the evolution of channel system with different stacking patterns (McHargue et al., 2011).

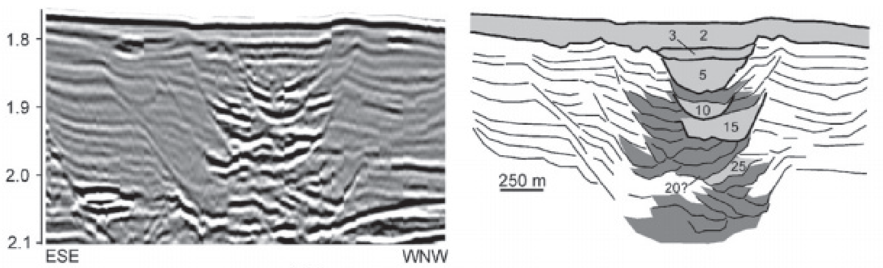


Figure 2.3: Channel profiles interpreted from seismic data (Deptuck et al., 2007). The left one is uninterpreted and the right one is interpreted.

fluvial reservoirs are analogized from research results of deep water system, which have been more thoroughly studied.

2.2 Parameterization of channels and levees

The interpretations of channel reservoirs are too complicated for numerical modeling and may not add value compared to simplified models. This thesis honors common key features such as stacking patterns. The channels are modeled independently in a simplified manner; however, every effort is taken to integrate geological interpretation. Each object is described as a set of parameters.

The parameterization of a channel and levee considers a centerline and cross sections perpendicular to it. The two characteristics together can reasonably describe the morphology of elongated channels. The centerline records the position, sinuosity, etc. while the channel and levee width, depth, shape, etc. are stored on the cross sections. Given a center line, a cross section can be drawn at each point on the line. Each cross section represents a partial boundary of a channel. With infinite cross sections, the boundary of a channel can be defined (Figure 2.4).

Figure 2.4: An example of channel parameterization.

2.2.1 Channel centerline

A center line determines the position of the channel and levee. Different depositional settings have different types of channels. The functions of center lines should be customized accordingly, as they mimic the movement of channels. The center line design must be flexible and customizable. Different equations are tested to represent the center line of a channel. Significant feature points along the center lineare extracted as control nodes. They are used for center line reproduction through a curve fitting function.

Functions generating centerline

A simple method to produce a center line is the use of a straight line with deviation (Figure 2.5). The goal is to generate n feature points as control nodes which can reproduce a control spline (center line). Here the n points generated are along a straight line, $y = mx + b$, with a random slope of m and a random intercept of b expressed as a function of the X, Y coordinates. Each control node is located at a random offset distance away from the control straight line. The parameterization of a centerline requires $2n$ variables, for n control node X/Y coordinates.

There are other optional centerline models. Ferguson (1976) applied a disturbed periodic model to represent river meandering. Sylvester et al. (2011) reproduced channels based on streamline which also presents promising river

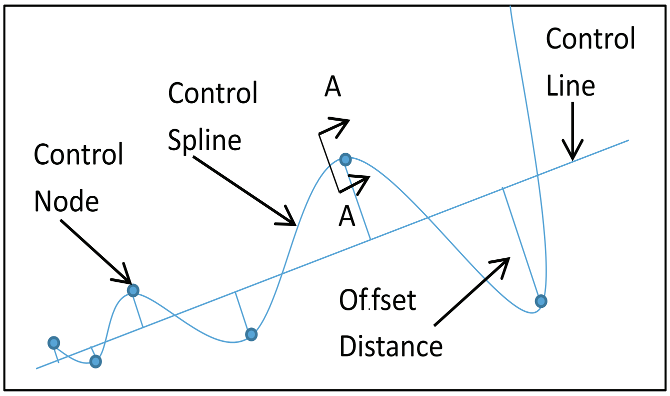


Figure 2.5: An example of parameterization for a center line. This is a plan view approximately 100s of meters in extent.

meander results. The centerline function mainly used in the modeling examples is a simple stepped cosine model, i.e. a combination of truncated cosine functions, from Pyrcz et al. (2012).

The disturbed periodic model is a second order linear differential equation (Equation 2.1). It describes the relation between the accumulated distance from the start point to the current point and its moving direction at the current point. The model is developed from the sine function. The difference is that this function adds a random disturbance factor to the moving direction and the moving is not periodic. An example centerline generated by the disturbed periodic model is shown in Figure 2.6. The centerline, with carefully selected parameters for Equation 2.1, appears like a natural channel path. However due to the random factor, the selection of parameter values leading to a reasonable centerline may not be easy. The centerline often becomes erratic and shows features that should not appear in real channels. It is hard to control the sinuosity of the centerline generated by Equation 2.1. The parameters in the equation honor many aspects at the same time while the sinuosity is a dependent variable resulted from the combination of those parameters in the equation.

$$\theta(s) + \frac{2h}{k}\frac{d\theta(s)}{ds} + \frac{1}{k^2}\frac{d^2\theta(s)}{ds^2} = \epsilon(s) \tag{2.1}$$

Where $\theta(s)$ is the channel direction, s is the distance going along the channel. h is a damping factor ($0 < h < 1$). The undamped limiting case h=0 is the randomized sine-generated curve, but as h increases an ever greater degree of damping is introduced until with h=1 no trace of oscillatory behavior remains (Ferguson, 1976). $\epsilon(s)$ is a random disturbance function, which causes the center line move randomly during the procedure. k is a scale parameter, i.e. a parameter related to the wavelength λ along the channel ($k = 2\pi/\lambda$). And the equation has a maximum deviation ω being the initial condition, i.e. $\theta(0) = \omega$.

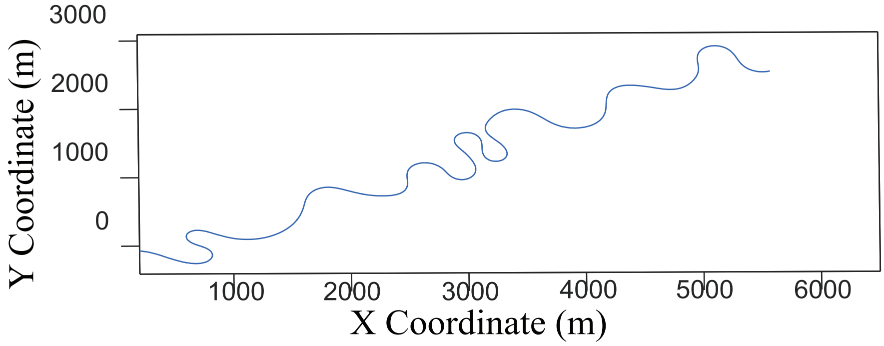


Figure 2.6: A channel center line from the disturbed periodic model.

The basic idea of the simple stepped cosine model is to concatenate segments truncated from cosine function curve. If the selected cosine segment for connecting is always with phase from 0 to 2π, the model will be a regular cosine function curve. If using partial segments whose phase starts randomly between 0 and π and ends at 2π, the centerline appears more like natural river channels (Figure 2.7). Each segment can be treated as a bend of the channel. The wavelength and amplitude of each bend can be set independently. By adjusting the ratio between wavelength and amplitude, the sinuosity of the channel can be controlled. The method is capable of generating Ω-shaped sinuous bends, which are commonly seen in rivers.

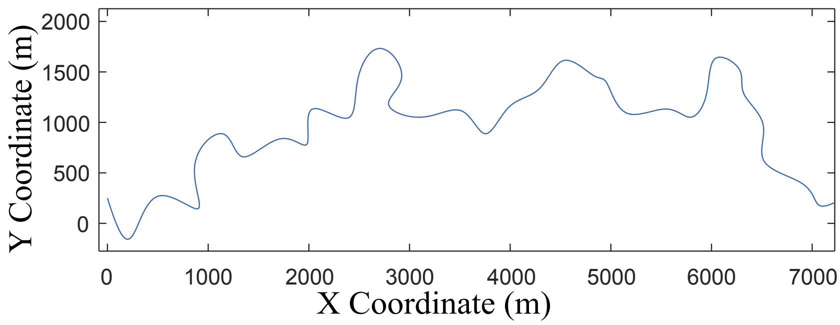


Figure 2.7: A center line from a simple stepped cosine model.

Feature points

The storage of centerlines is another problem in modeling. A centerline consists of an infinite number of points. Simple lines or curves can be described by certain functions. However, most other complicated curves cannot be expressed by a single function. One approach is to segment the centerline into pieces and use discrete points for the calculation. This may still require a large number of parameters, considering that every point is moved repeatedly during the optimization procedure. Therefore, only feature points are captured and stored as object parameters. The rest of the points are reproduced according to these key control nodes through a spline function. The number of total points for a centerline should be chosen carefully. If it is too small, objects appear blocky. If it is too high, computational time increases significantly. The value should be assigned according to the well spacing, equipment size, etc. so that the size of one area dominated by one centerline point is smaller than the size of a production block.

For example, Figure 2.8 shows the procedures of a centerline reproduction by control nodes extracted from a simple stepped cosine model. There are two centerlines in the figure. First, the colorful segments represent the centerline generated by combining truncated cosine function lines. The extrema and inflection points of the cosine function on truncated segments are extracted and selected as control nodes. The selection deletes the points that are too close to each other. Local varying densities of control nodes could cause distortion in centerline reproduction when applying the spline interpolation. The blue circles represent the control nodes and the blue line is the reproduced centerline. The reproduced centerline captures most features of the original centerline.

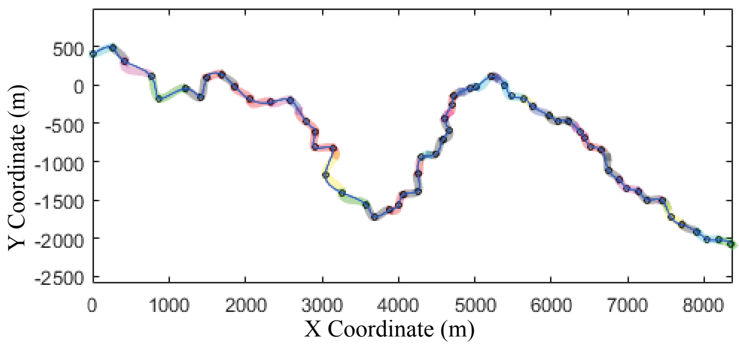


Figure 2.8: A centerline (the blue line) reproduced by interpolation of control nodes. In comparison, the colorful lines are the original centerline.

2.2.2 Channel sinuosity

Channels are classified into four categories according to sinuosity: low sinuosity, meandering, braided and anastomosed. Braided channels are more often connected than other types. This may lead to higher hydrocarbon recovery in the reservoir. Reservoirs with straight channels are more monotonic while meandering channels often have a stacking feature together with crevasse, avulsion and cut-off channels. Sinuosity must be addressed in reservoir modeling.

The sinuosity of a centerline from the stepped cosine model can be controlled by the amplitude and wavelength of the cosine functions. The higher the amplitude:wavelength ratio, the more sinuous a centerline is. Figure 2.9 displays a set of centerlines with the ratio being from 4:100 to 60:100. One issue is that the ratio can only control local sinuosity. The variation of local flowing direction resulted from each newly added segment is not controlled by the parameters. Thus the global sinuosity may differ significantly with the same amplitude:wavelength ratio.

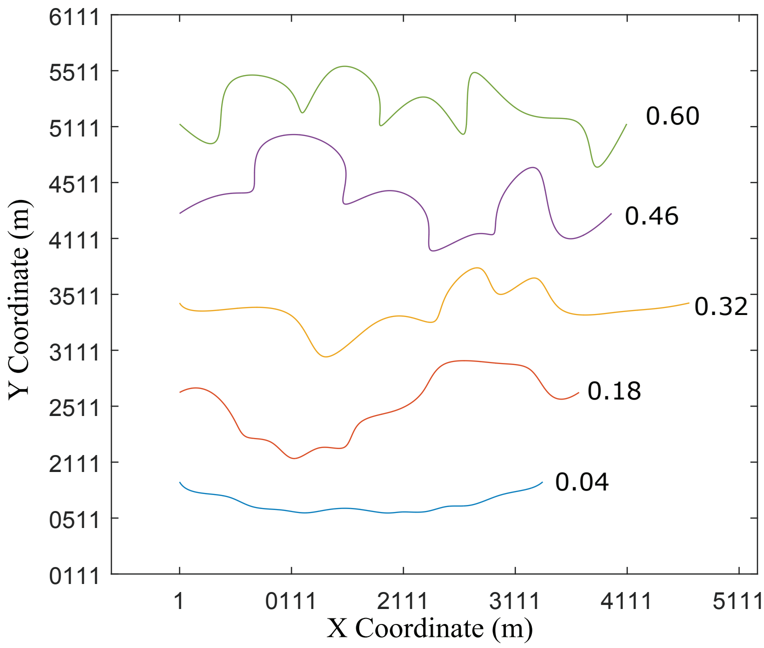


Figure 2.9: Centerlines generated with different amplitude:wavelength ratios, being 0.04, 0.18, 0.32, 0.46 and 0.6 respectively from bottom to top.

2.2.3 Channel profile

In object-base modeling, various channel profiles have been used such as a rectangle (Holden et al., 1998), a parabola (Shmaryan and Deutsch, 1999) and an asymmetric section (Deutsch and Wang, 1996). Here, channel profile (Figure 2.10 and Figure 2.5) honors the shape of a channel model, including the width, depth, curvature of bottom surface and asymmetry. The cross section consists of a straight line as the top boundary and two parabolas as the edges. The cross sections are asymmetric. The asymmetry rate depends on the location of the cross section on centerline. A deviation rate is given to represent the ratio between the offset distance on plan view (Figure 2.5) and the channel cross section thalweg deviation from the control spline (d_center on Figure 2.10). The deviation (d_center) between thalweg, i.e. the lowest point on the cross section, and control spline can be calculated through the deviation rate and the equation in Figure 2.10. Then the parameters of two parabolas can be calculated. For the parameterization of a cross section, seven variables including channel width, ratio of width to depth, deviation rate, elevation of channel and three coordinates for shifting, are required.

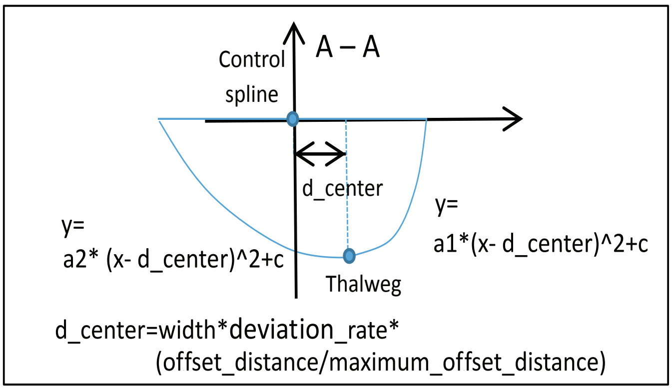


Figure 2.10: A channel profile (NTS) illustrating the parameterization.

According to Gibling (2006), the width of channel fill can vary from below 10 m to larger than 10 km and channel depth can vary from 1 m to thicker than 50 m. Width:depth ratio can be less than 5 or larger than 1000. The large widths and depths are from channel belts. For an individual channel element, some outcrop data from turbidite channel reservoirs (McHargue et al., 2011) show that the width typically falls between 100 and 300 m. The same data gives an average depth around 13 m. The width:depth ratio of a single channel element is set between 10:1 and 30:1 according to the summarization by Milliken et al. (2012). The above numbers give an idea about the magnitude of the parameters that should be used in modeling.

2.2.4 Levee profile

There are numerous studies into the morphology of a natural levee. Cazanacli and Smith (1998) and Adams et al. (2004) depicted the levee shapes with cross sections using the modern Saskatchewan River as example. Brierley et al. (1997) summarized characteristics of both modern and ancient levees according to published rock records. Table 2.1 lists width, thickness and geometry of levees as well as the associated channel dimensions from the examples summarized by Brierley et al. Here, the geometry of levee profile uses the shape of

Table 2.1: Levee characteristics in literatures summarized by Brierley et al. (1997).

Levee geometry	Levee width	Levee thickness	Associated channel width	Associated channel depth
primary dips 2-4°, up to 10°	$\leq$ 10 km	<15-20 m	$\leq$ 10 km	$\leq$ 15-20 m
variable; some broad brows, thins distally	500 m	10 m	200-250 m	$\leq$ 10 m
elongate belt, tapers out distally	>2 km	$\leq$ 10 m	average 1-2 km	10-30 m
5° bed. dip away from channel	450 m	$\leq$ 12 m	$\geq$ 2 km	>17 m
dips away from channel at 10°	150-3200 m	1.5-9 m	300-8000 m	4-23 m
thins distally	100s m	$\leq$ 7 m	150-300 m	$\leq$ 20 m
inclined sheet-like bodies	> 1500 m	1-4 m	50-100s m	1-5 m

wedge. The levee dimension differs according to channel style but one common rule is that levee size is related to channel size (Brierley et al., 1997).

In nature, levees are often missing on one side of the channel or even on both sides. The objects are discontinuous. To simplify and generalize the model, in this work the levees are always attached on both sides of channel cross section, referred as the inner bend levee and outer bend levee (Figure 2.11). Levees could be omitted. The levee cross section is a four-edge configuration. The levee bottom surface is flat. The straight edge connected to the channel top surface has a constant slope. The levee outer bend height is proportional to the channel depth. The levee inner bend height is proportional to the outer bend height. The later proportion is decided according to the position on the centerline with the same rule of deciding the channel asymmetry. Both inner and outer levees have the same depth from the channel surface to the levee bottom. With the design above, there are three extra parameters for modeling, levee width, levee depth and levee height. The width and heights of levees are proportion to channel depth.

2.2.5 Stacking pattern

Another goal is to reproduce the stacking feature of models, which is common in a channel system (Abreu et al., 2003; Sylvester et al., 2011; Deptuck et al., 2003; Deptuck et al., 2007; McHargue et al., 2011; Macauley and Hubbard, 2013). Typically, channels migrate and aggrade/degrade with time and leave a series

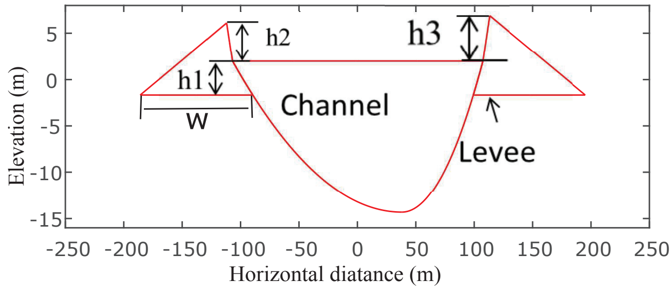


Figure 2.11: A cross section of a levee illustrating the parameterization. The X axis represents the horizontal distance on the cross section.

of channel fill bodies, creating a stacking pattern. The distance between each element in the stacking pattern dependents on the aggradation/degradation rate and horizontal erosion speed. Since the modeling of objects in fluvial systems is less mature (with respect to object-based characterization), the channel stacking model here is based on deepwater fill models.

Depending on the stage of the deepwater fill, the stacking model could be organized or disorganized (McHargue et al., 2011). For an organized stacking pattern the center line of each element in a stacking model is constant and a constant shift is added (Figure 2.13 left). A uniform shift with meander loop expansion (swing) and meander loop down-system migration (sweep) could be added to the stacking model (Alpak et al., 2013).

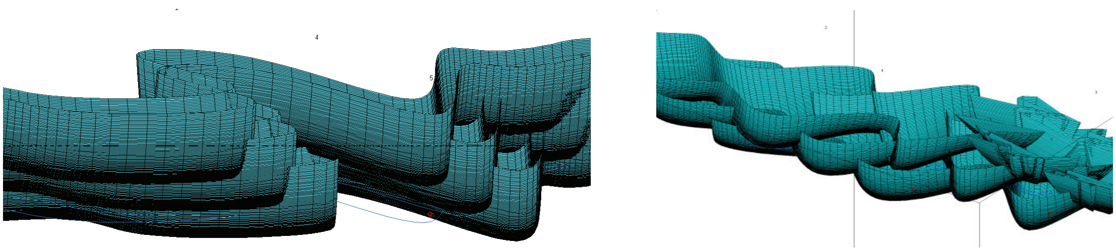


Figure 2.12: Organized stacking channel (left) and disorganized stacking channel (right).

In a disorganized stacking model, besides the uniform shift, there are also a set of random shifts between each element. When generating shifts representing local randomness, control nodes of the center line move along or perpendicular to the basin ward direction. A distribution of deviation distance is used to randomly assign how much each node moves for the local shift. The distribution for this shift may be considered to follow a Gaussian distribution (Leuangthong et al., 2011). When the stacking is somewhere between a disorganized and organized stage, a control variable, D, between 0 and 1 is used to adjust the organization level. The shift vector for each node is based on the equation below:

$$shift = [1(1 - D) + R * D] * H \tag{2.2}$$

Where H is the movement amount for a node, D is the control variable, and R is a random number between 0 and 1 from a distribution. $D = 0$ is completely organized and $D = 1$ indicates disorganized. With the shift amount for each control node assigned based on Equation 2.2, a series of center lines for a stacking pattern, arranged from organized to disorganized are presented (Figure 2.13). From left to right and top to bottom, the control variable is increasing from 0 to 1.

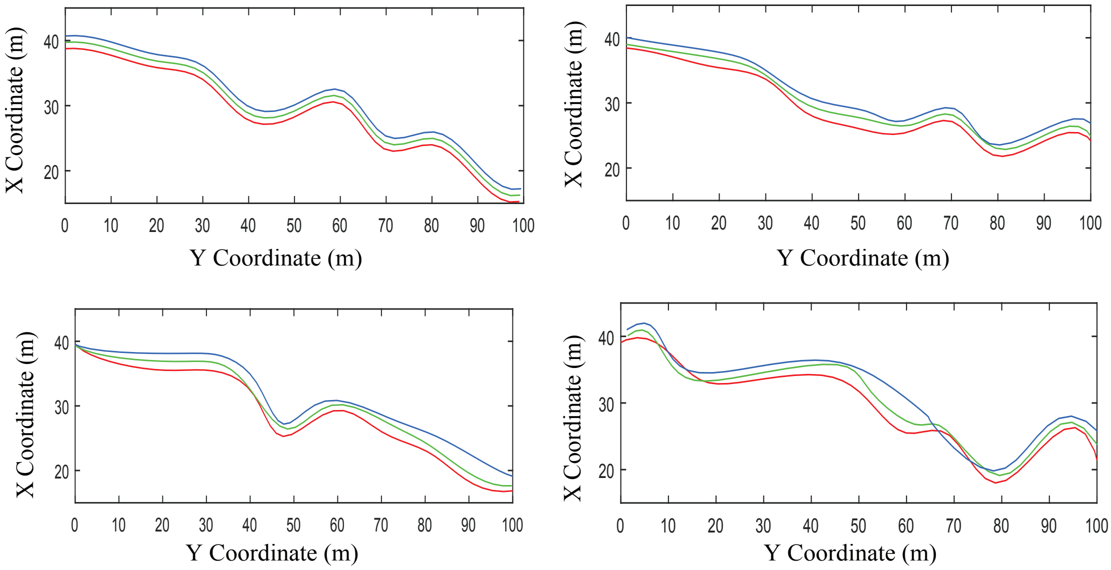


Figure 2.13: Center lines of stacking patterns (three elements represented by three colors). From left to right, top to bottom, the level of disorganization is increasing. The control variable is 0, 1/3, 2/3 and 1 respectively.

The drawback of stacking in this way is that the control variable is the same for each element but the elements have different sinuosity. The change to sinuosity due to shifting may not be expected. An alternative method would be to generate another channel model with the same parameters as the original channel element. To generate a disorganized three elements stacking channel model, three independent channels could be generated and treated as three elements of one stacking pattern.

2.3 Geology and parameterization of crevasse splays

There is research on crevasse splays from modern fluvial region such as the Lower Mississippi Valley (Gouw and Berendsen, 2007; Arco et al., 2006; Smith, 1996; Rittenour et al., 2007). Although ancient fluvial systems might be different from modern ones, this research offers analogues for object parameterization.

The crevasse splay is parameterized by a centerline and cross sections. It is assumed that, when a crevasse is present, the materials in the channel flow out of an avulsion point as if generating a new channel, based on the researches done by Li and Bristow (2015) and Stouthamer (2001). The first step is to find the breakthrough point. A crevasse is more likely at a sinuous section of the channel and is always on the outer bend.

Crevasse features are shown in plain view (Figure 2.14). According to Li and Bristow (2015), the crevasse splay consists of one to three main courses, starting at the same avulsion point. Each course has a corresponding radiation area. Here each radiation area is modeled as a high eccentricity ellipse. Thus a radiation area is small at the proximal end close to the avulsion point and becomes wider when the course moves forward, shrinking again at the distal end. At the avulsion point, outbursts of material expands the crevasse splay volume. With the momentum being lost, the radiation area of the course shrinks till the distal end. Selecting an ellipse as the geometry is convenient for conditioning to well data.

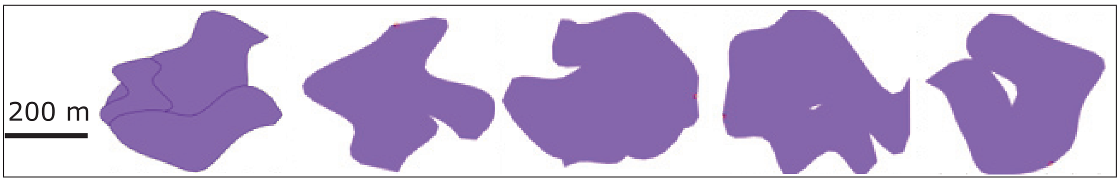


Figure 2.14: Examples of crevasse splay plan views.

Initially, each crevasse splay consists of two or three ellipses. The ellipses transforms and becomes sinuous so that the crevasse splay appears more vivid. Certain points on the long axis of the ellipses are selected as control nodes. Theses nodes can be vertically shifted a small distance away from the long axis. Each node controls a segment of ellipse and the segment shifts perpendicular to the long axis corresponding to control node movement. The shifts make the crevasse splay course sinuous and more natural.

As for the cross section of the crevasse splay, it is detached into cross sections identical to the channels.

The parameterization variables for a single course includes two coordinates of the avulsion point, two coordinates for an end point, the width of the course and five ratios measuring how the control nodes shift away from the long axis. The width to depth ratio is fixed.

2.4 Geology and parameterization of oxbow lakes

The oxbow lake is another important basic structure for petroleum sediments. An oxbow lake is part of an abandoned meander channel (Dieras et al., 2013). A sinuous-channel inner bend is frequently filled by point bars (Arco et al., 2006). Inclined heterolithic stratification is the product of point bars lateral accretion beside meandering channels (Thomas et al., 1987). It is one of the main facies of interest in the Fort McMurray, Alberta area.

The shape of an oxbow lake is set the same as a channel. But the centerline is more sinuous (Li and Fang, 2011). The thalweg on the cross section will therefore deviate further from the center line. The plan view of an oxbow lake can be either a crescent shaped bend or a straight course left isolated because of being replaced by a new course. The crescent shaped bend generated by a cut off is more prevalent. There are many oxbow lake examples around the Mississippi river area (Smith, 1996; Arco et al., 2006). Google maps show that the layout pattern can be very different between each oxbow lake. The only obvious common feature is that inner bend of oxbow lake is usually facing the center line of a channel. With this constraint, oxbow lakes are simulated (Figure 2.15) along channels. The cross section of the oxbow lake is taken from the channel parameterization. In this work an oxbow lake requires $2n_2$ variables for control nodes coordinates.

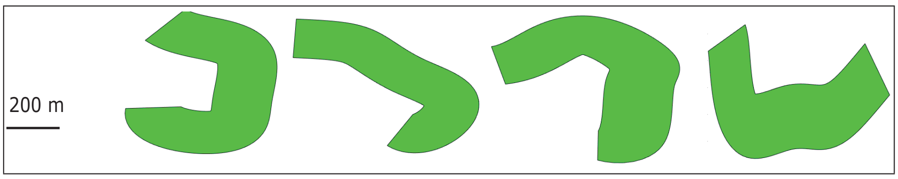


Figure 2.15: Examples of oxbow lake plan views.

2.5 Parameter summary

In summary, the parameters used for fluvial object based modeling are listed in Table 2.2. These parameters can be assigned by users prior to modeling. Some parameters like the control node coordinates require many values.

Table 2.2: Parameters in fluvial objects modeling.

Object	Num.	Parameter
Channel	1	channel width:depth ratio
	2	channel shift in X direction
	3	channel shift in Y direction
	4	channel shift in Z direction
	5	surface elevation
	6	channel width
	7	asymmetric rate of channel profiles
	8	X/Y coordinates of a set of control nodes for a centerline
Levee	9	a ratio of levee height (above surface) to channel depth
	10	a ratio of levee depth (below surface) to channel depth
	11	a ratio of levee width to channel depth
Stacking	12	the number of elements in a stacking pattern
	13	one set of control node shifts for each element in stacks
	14	a control number for organized level of stacking pattern
Crevasse splay	15	X/Y coordinates of a crevasse point
	16	X/Y coordinates of the distal end of the crevasse course
	17	width of the crevasse course
	18	a set of shifts for crevasse course control nodes
	19	a ratio of crevasse course depth to channel depth
Oxbow lake	20	X/Y coordinates of a set of control node for a centerline

Given the parameterization discussed, objects including crevasse splays, levees and oxbow lakes can be modeled together with channels. Figure 2.16 shows a highly sinuous channel with consecutive levees around it. Three crevasse splays break out from the outer bend levees at the curvy parts of the channel while several oxbow lakes scatter along the channel.

2.6 Stratigraphy

Stratigraphic interpretation is undertaken before modeling and divides the reservoir into sub-layers. The well data in each sub-layer are conditioned by the objects proposed but have a constant elevation. Even though two wells at different sub-layers can be conditioned by one channel in the program using a stacking pattern, it is not encouraged. The two wells are more likely from different stratifications and should not be conditioned by the same channel. A channel should

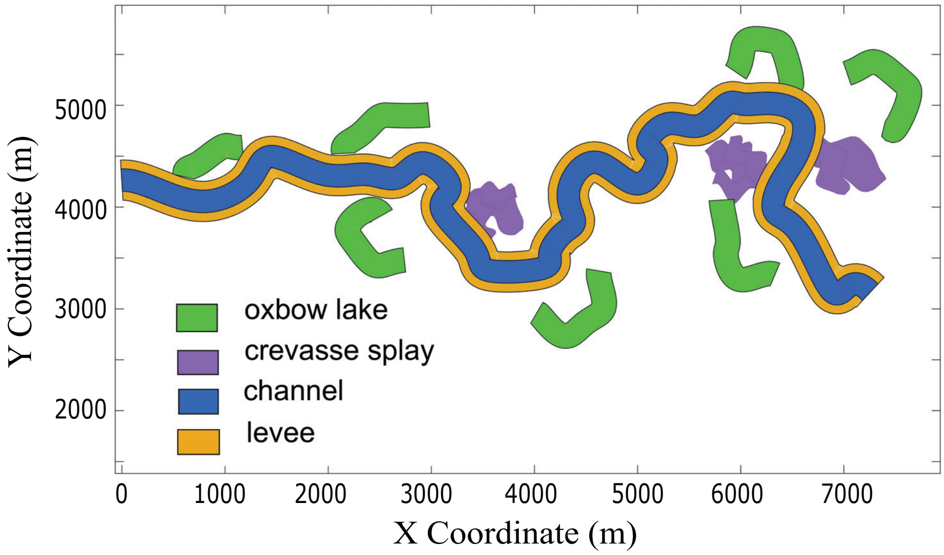


Figure 2.16: Examples of all modeled objects (plan view).

not fluctuate between stratifications for the purpose of conditioning. A reservoir model is constructed layer by layer so that the conditioning to data is more realistic. The elevations of well data in each layer are transformed into separate local coordinate systems with constant top elevations. After modeling in each layer, the coordinates of channels are back transformed to the reservoir original coordinate systems. With a model of every layer stacked together, the entire reservoir model is constructed.

If a reservoir does not have high resolution stratification surface data and it consists of many channel complexes rather than single channels, layers will be divided according to the statistics of the available data. For example, a segment of elevation with relatively more channel facies is assigned into one layer. Layer division differs for each reservoir and should be addressed accordingly before modeling. Examples are given in case studies later.

Chapter 3

Conditioning OBM

After the objects have been digitized and represented by parameters, OBM objects are conditioned to available data. First, a modeling domain is divided into sub-layers according to geological stratigraphic interpretation. Within each sub-layer, objects are populated to cover corresponding facies observed at well data. Trend models obtained from seismic data can constrain the proportion of each object type. The construction of conditioned models for an entire reservoir with multiple layers is the focus of Chapter 4. This chapter illustrates the conditioning procedure for an individual sub-layer.

The conditioning procedure for one layer of channels and levees is shown in Figure 3.1. More objects can be added thereafter with the work flow in Figure 3.2.

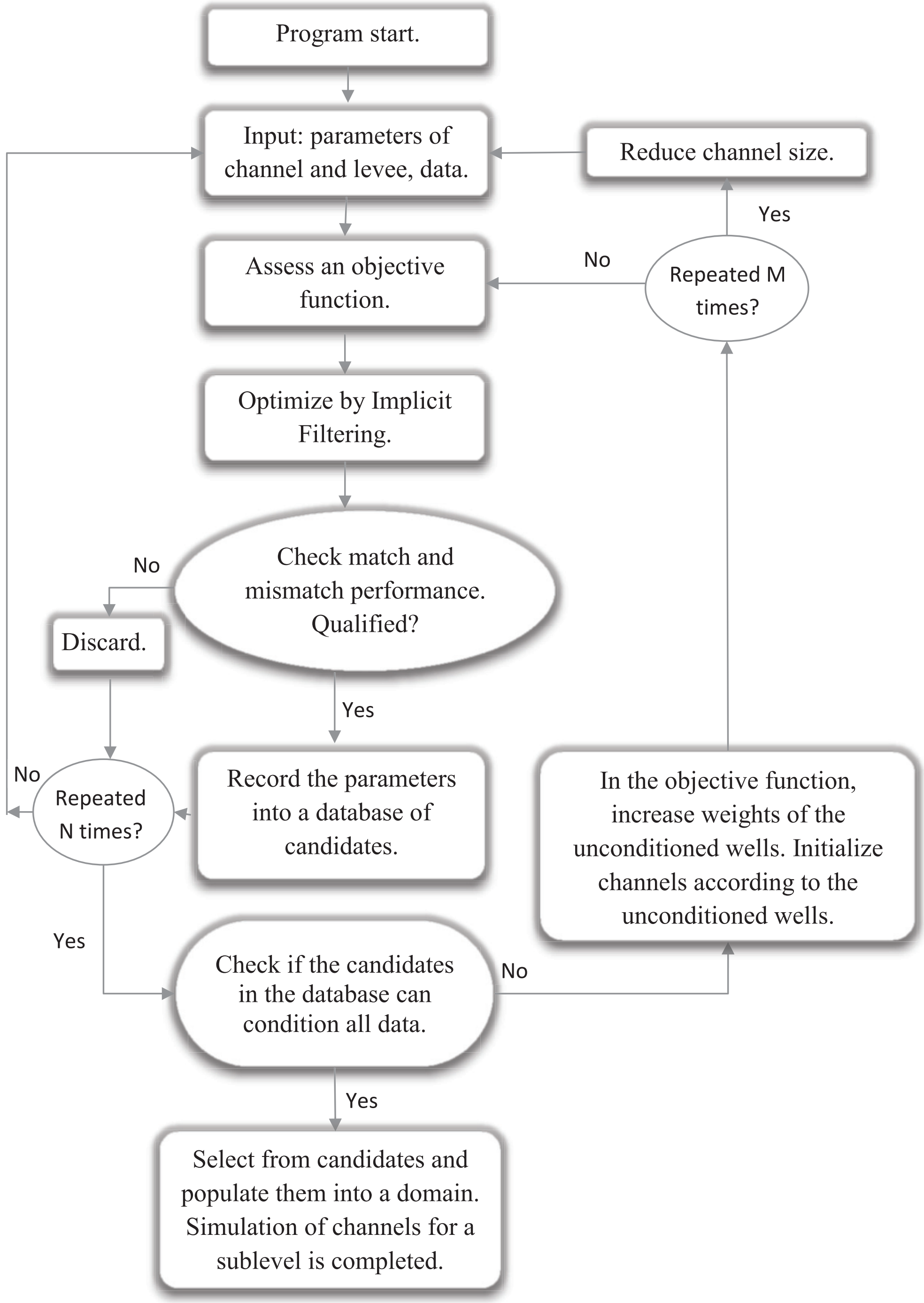


Figure 3.1: The work flow for simulation of single-type objects.

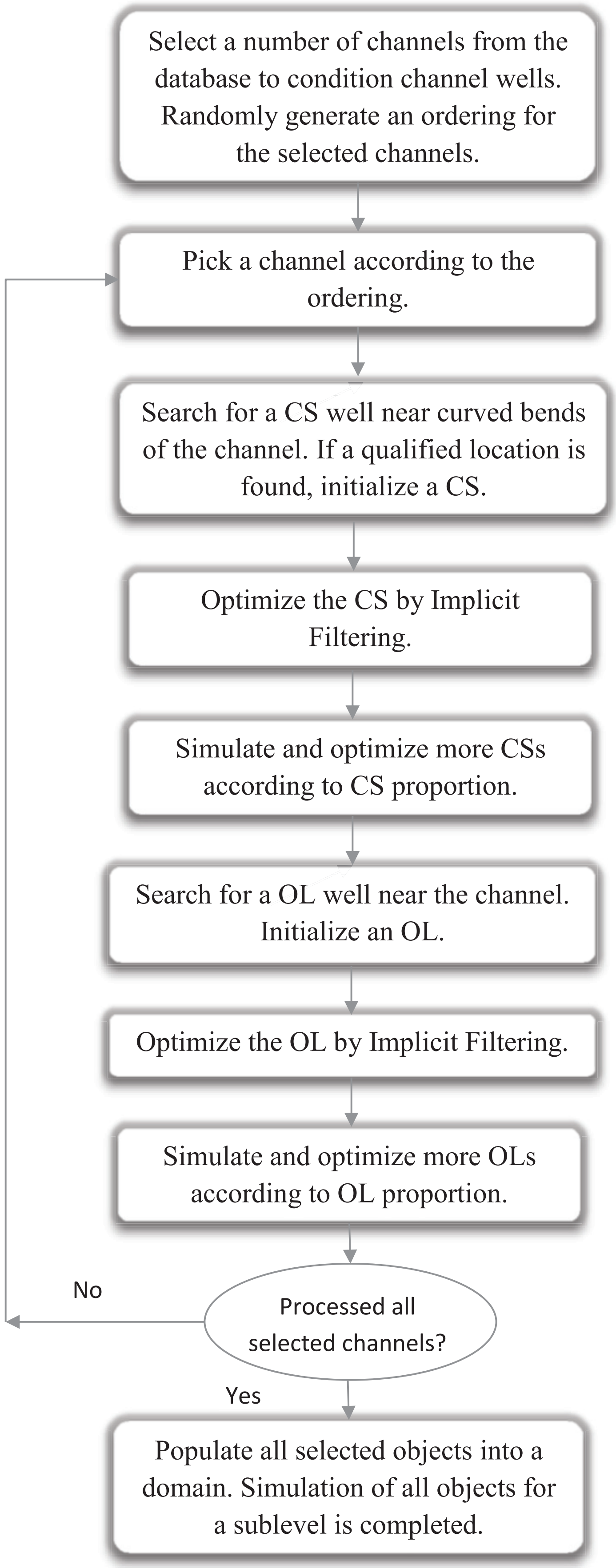


Figure 3.2: The work flow for simulation of one realization with all types of objects.

3.1 Conditioning data

Two data types are discussed: well data is used for exact conditioning; seismic data is used to infer a 3D facies proportion model.

3.1.1 Well logs and core data

Well log data is most commonly used to infer facies along the well. Equipment drills down into the earth and sensors measure rock properties which are converted to facies data. After analysis of lithological constituents, physical and biological structures etc. (Walker, 1990), the core samples can be assigned a corresponding facies. Facies data and corresponding coordinates are available. Objects models should be conditioned to these data.

Well data is preprocessed to invalidate a segment of facies shorter than a limit or to combine two segments of identical facies separated by a short segment to improve conditioning. After data formating, each well consists of three segments including top, middle and bottom. The facies of a middle segment can be any object while the facies of top and middle segments is flood plain (Figure 3.3). When using this sandwich-type design of well data in modeling, an object simply passing the location of a well is insufficient to claim the well is conditioned. The object has to be at right elevation with appropriate sizes that it conditions the middle segment and escapes top and bottom segments. Under such setting, the modeling of the objects are considered as 3D modeling.

The wells maybe non-vertical because it is possible that in reality wells decline slightly. The objects are digitized in a grid-free manner so that well lengths are arbitrary values rather than a multiple of the grid size used.

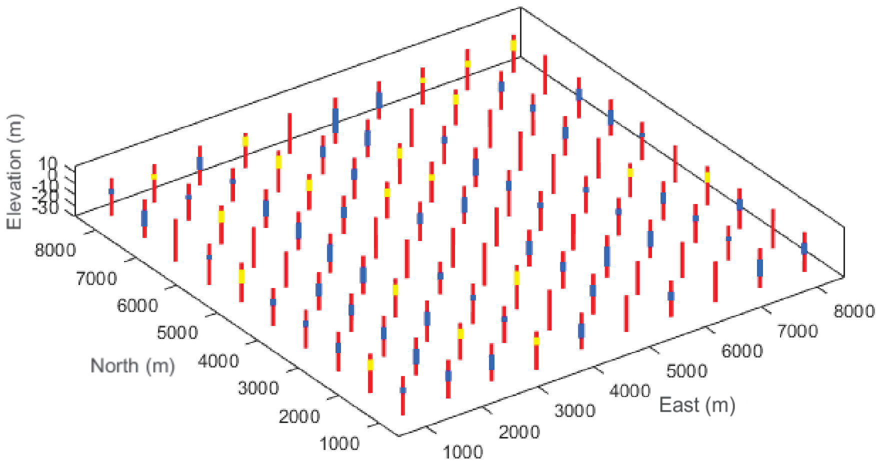


Figure 3.3: An example of well data. Red indicates floodplain facies, blue indicates channel and yellow indicates levee.

3.1.2 Seismic data

Seismic data is obtained by sending seismic waves to a target location. Partial waves are reflected after they reach different layers of rocks. The reflected waves from different rock structures vary and can help identify the structures. Due to the reflection mechanism of waves, only large scale structures can be distinguished. As a result, seismic data is an effective data resource for stratigraphic interpretation, boundary confinement and trend modeling. These trend models are matched in the proposed object conditioning.

3.2 Conditioning a single object to facies data

The objects are conditioned to well data through optimization. For each individual object, the optimization procedure is as below:

1. Parameterize the desired object by a set of parameters $(x_1, x_2, \ldots, x_n)$.
2. Define an objective function to minimize based on conditioning data and reducing bias.
3. Start with an initial set of parameters for the object. Apply the Implicit Filtering (Kelley, 2011) to adjust the parameters. The only inputs are the object parameters (step 1) and the objective function value (step 2).

The parameterization (step 1) is described in Chapter 2 using a fluvial system as an example. Here, steps 2 and 3 are explained through a modeling example of channels. Optimization of other objects would be identical. Note, after the optimization procedure, each object is locally optimized, i.e. it is only conditioned to those well data near its location. Sometimes an object is only partially conditioned to well data and violates some data. These problems are addressed by rejection sampling and are discussed further.

3.2.1 Objective function

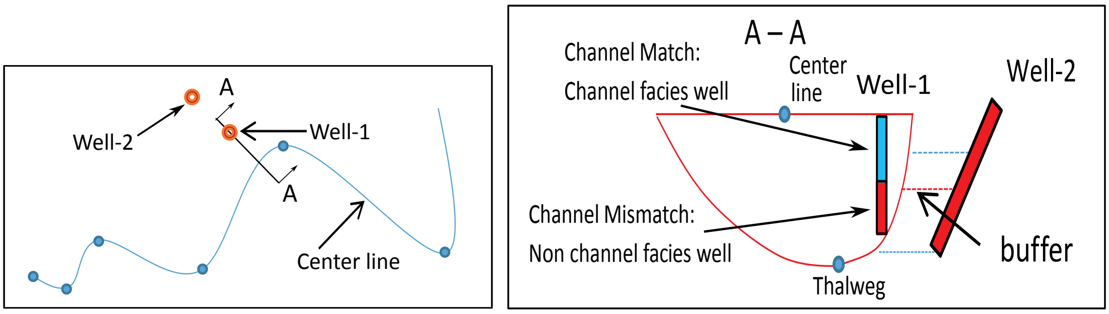
The goal of the optimization is to alter the parameters of an object such that the object better fits the data. The following objective function (Equation 3.1) is used to assess how well an object fits the available conditioning data:

$$\begin{aligned} Obj = \omega_1 * \sum_{i=1}^{n} L_i^1 + \omega_2 * \sum_{i=1}^{n} L_i^2 \\ + \omega_3 * \sum_{i=1}^{n} L_i^3 + M * S \end{aligned} \tag{3.1}$$

Where L_i^1 is the channel mismatch length of well i, L_i^2 is the channel match length of well i, L_i^3 is the buffer length of well i, and ω_1, ω_2 and ω_3 are the corresponding weights for mismatch, match and buffer. The M is a large number (see Big M Method, Griva et al., 2009) and S is a binary variable, indicating violation of hard constraints.

The objective function can be seen as comprising two parts. The first two components L_i^1 and L_i^2 measure how well the channel is conditioned to data while the latter two component L_i^3 and S help channels achieve realistic configurations.

The match and mismatch length calculation steps are indicated in Figure 3.4. For each well near the center line, the closest point on the center line is found (Figure 3.4-a). A cross section A-A going through the well and the closest point will be captured (Figure 3.4-b). The mismatch length L_i^1 and match length L_i^2 can be obtained by calculating intersecting points of the well and the boundary on the cross section. The L_i^1 and L_i^2 for every well is calculated to determine the first component of the objective function.



(a) (b)

Figure 3.4: The calculation of the variables in the objective function. (a) A plan view displaying a well building its cross section view. (b) A cross section (NTS) showing the definition of variables in the objective function. The functions representing object boundary are already parameterized (Figure 2.10).

An objective function with only L_i^1 and L_i^2 will move a channel until it is once outside the non-channel well data. As a result, a conditioned channel exists close to non-channel data after optimization. This is an obvious bias. The buffer variable L_i^3 adjusts channels away from the non-channel wells.

L_i^3 is calculated only when an entire well i is not intersecting the channel. Otherwise the buffer L_i^3 is 0. The shortest distance between the well and the channel is calculated. Here the shortest horizontal distance is searched instead of 3D distance (Figure 3.4-b). A limit is set as the closest distance allowed between a purely non-channel facies well and a channel. Currently it is set to half a channel width. However, the push-away distance for each well should be different according to the statistical rules. The magnitude of the push-away distance could be determined by simulating an unconditioned model of channels and randomly drilling synthetic wells in the domain. The distribution of distances between purely non-channel wells and channels can be calculated and used to infer the expected distribution in the conditional models.

S is a binary variable that keeps the channel centerline plausible. The value of S is decided by a function considering all parameters. If the center line moves in an awkward behavior such as crossing over itself, outreaching the domain or turning sharply, then the S variable becomes one. Through trial and error, a channel center line is prone to overlap when the angle limit is set to larger than 150 degree. The big M (Griva et al., 2009) is a large penalty and the extreme center line is discarded through the optimization procedure. Since the optimization algorithm changes the parameters without considering their physical meaning, undesirable features are unavoidable. These undesirable features are eliminated by setting S to one.

To be more specific, the program judges the fitness of a centerline by checking every segment of the centerline. Every four points on te centerline, A, B, C and D are assessed. The coordinates of the points are known. With the law of cosines, it is easy to judge whether the angle ABC is larger then 150 degree. If ∠ABC>150 then S=1. Besides, to check whether the line segment AB crosses CD, one way is to find the point E where line AB and CD intersect. If E is on both line segments AB and CD then it means line segment AB crosses CD and S=1. To find the point E, a linear equation system needs to be solved. Expressing the line segments in parametric equations (Equation 3.2) is suitable for this case. t_1 and t_2 are the parameters for the corresponding line equations. The results for the linear equations are as Equation 3.3. Whether the line segments cross each other can be told from whether the values of t_1 and t_2 are both within zero to one.

$$\begin{cases} X_E = (1-t_1)X_A + t_1 X_B \\ X_E = (1-t_2)X_C + t_2 X_D \\ Y_E = (1-t_1)Y_A + t_1 Y_B \\ Y_E = (1-t_2)Y_C + t_2 Y_D \end{cases} \tag{3.2}$$

$$
\begin{cases}
t_1 = \dfrac{\dfrac{X_D - X_C}{Y_D - Y_C} - \dfrac{X_A - X_C}{Y_A - Y_C}}{\dfrac{X_D - X_C}{Y_D - Y_C} - \dfrac{X_B - X_A}{Y_B - Y_A}} * \dfrac{Y_C - Y_A}{Y_B - Y_A} \\[2em]
t_2 = \dfrac{\dfrac{X_B - X_A}{Y_B - Y_A} - \dfrac{X_C - X_A}{Y_C - Y_A}}{\dfrac{X_B - X_A}{Y_B - Y_A} - \dfrac{X_D - X_C}{Y_D - Y_C}} * \dfrac{Y_A - Y_C}{Y_D - Y_C}
\end{cases}
\tag{3.3}
$$

3.2.2 Object optimization

The optimization begins with an initial set of parameters given by the users or is randomly generated by the algorithm. In reality, a full set of data is often conditioned by a set of objects rather than one object, because the data are often widely spread in the domain. When the objects are generated, their initial locations are changed so that some of them can match well locations. Thus, the well data has a better chance to be conditioned.

The objective function value (Equation 3.1) of each initialized object is calculated, measuring the conditioning level of the object. The objective function value is minimized by implicit filtering (Kelley, 2011). Any object that can be parameterized can be optimized. The algorithm uses coordinate searches as well as gradient approximation to generate parameters with a lower objective function value. The interested reader can find more details in Kelley (2011). Note other optimization algorithms were tested and implicit filtering was found to be superior (Boisvert and Pyrcz, 2014).

After the optimization, the objective function is locally minimized and the conditioning for the object is locally optimum. This means the object intersects a well segment of corresponding facies and conditions the maximum length of the well data, and avoids well segments with other facies. However, it is possible that some data are not conditioned and some data are violated by the locally optimized object. Therefore the algorithm is repeated to build a large number of optimized objects. To condition all well data with the object facies, multiple objects are selected simultaneously from among the remaining locally optimum objects.

3.3 Realization construction

The proposed optimization method using the implicit filtering algorithm only conditions individual objects to well data. Realizations are created by combining multiple locally optimized objects to match all available conditioning data. For the simulation of one realization, the main construction procedure is:

1. Build a model database with a sufficient number of optimized channels.
2. Check match performance and whether every well with channel facies has been conditioned by at least one channel model from the database. Build channel models particularly for the unconditioned wells if there is any.
3. Select the channel models from the database in a way that all the channel wells in the domain will be conditioned.

The steps are expanded upon below.

3.3.1 Step 1: Building an object database

The optimization (Section 3.2) is repeated N times to build a database of locally optimized channel objects. N is a number between 20 and 2000 according to conditioning difficulty and channel proportion. During every run, different locations in the domain are selected as the starting point of the channels. These locations are spread within the domain so that every well has a chance to be conditioned by one of the channels.

After each optimization, the match and mismatch performance at every well and the optimized parameters are stored. The selection of channels for the single-layer realization is based on these two measures of performance. First, channels with a large mismatch performance are removed. For any well intersected by a channel, if the mismatch at the well is larger than a user defined threshold, say five percent (of the channel-facies segment), the channel is rejected from the database. The remaining channels are used when populating the domain for the construction of realizations.

3.3.2 Step 2: Enforcement of channels for difficult data

After building N channels there may still be insufficient channels condition to all data (examples in Section 3.3.4). This usually occurs when a channel well is surrounded by non-channel wells. Three additional measures are taken when the above situation occurs.

First, more weight is given to the unconditioned channel wells in the objective function. If a channel conditions to a segment of channel lithofacies on the unconditioned well, the objective function value gets reduced by ten times the amount that the match length normally reduces. This gives the unconditioned wells first priority over other data during optimization.

Second, after the program initializes a channel it moves the channel to an unconditioned well. As the initial channel already goes through an unconditioned well, what remains for the optimization algorithm to do is to honor other non-channel wells. This movement increases the chance that the unconditioned well is conditioned after the optimization.

Third, if there is data still not conditioned, the total length of the designed channels is reduced and the shorter-length channels is used to match the well data. Shorter channels are easier to match to data without violating surrounding wells.

The three steps above do not guarantee conditioning a channel to all the unconditioned wells. The algorithm randomly orders the unconditioned wells and deals with them sequentially. Each problem data is matched by several new channels before the algorithm gradually lowers the conditioning criteria on this well. The new channels that happen to condition any unconditioned data are added to the database if they satisfy the mismatch threshold and geologic realism.

3.3.3 Step 3: Channel selection

Finally the channels are selected from the database so that all channel wells in the domain are conditioned. The selection can be formulated as an integer linear programing problem (Equation 3.4 and). For a qualified channel model from the database, the match length at every well is checked.

It is difficult to match a channel 100% to a specific segment on a tilted well while avoiding other segments on the well (see the format of well data in Figure 3.3). Not only does the channel location need to be controlled, but also the channel size, elevation, locally flowing direction and profile geometry need to be adjusted so that the boundary of the channel encloses the channel-facies segment and excludes non-channel-facies segment on wells. The two types of segments are connected, which means the boundary needs to be located at the exact points connecting two types of segments. Furthermore, the channel needs to condition multiple such wells. When modifying the channel parameters to condition one well, the conditioning at previously conditioned wells might be jeopardized and the parameters need to be modified again. The profiles of a channel at different locations interact with each other because the asymmetric rate of a profile is related to channel sinuosity.

Therefore, the conditioning requirement is compromised (Equation 3.5a). If channel i conditions the majority (say 90-95%) of well j, it is regard as matched. If a channel i and well j are matched, the algorithm sets $a_{ij} = 1$, otherwise $a_{ij} = 0$. The coefficient matrix $A_{(1:n,1:m)}$ representing the matching relationship between n wells and m channels is calculated based on the assumption above. The variable of the linear programing problem is xs. If the channel i is selected then $xs_i = 1$, otherwise $xs_i = 0$.

The only mandatory constraint is that every well must be matched by at least one object (Equation 3.5a). In order to achieve case specific requirements, additional constraints are added. For example, if the preference is that the channel objects have minimum overlap within one layer then a corresponding constraint can be added. The overlap length between each pair of channel objects i and j is calculated and recorded in matrix O_{ij}. If o_{ij} is greater than a limit, the program forbids this pair of objects, i and j, from being selected together (Equation 3.5c). Equation 3.5d forbids the selection of certain objects. For example when building a second realization, the objects selected in the first realization are preferably not to be used again.

An objective function is required for the linear programing problem (Equation 3.4). The objective is to minimize the total number of channels selected for conditioning. The result represents the lowest proportion of channels in one layer that the program can reach while conditioning all the data. If the global proportion is higher, this is achieved by placing additional channels in the domain.

$$Obj = \sum_{i=1}^{m} xs_i \tag{3.4}$$

$$S.T. \begin{cases} \sum_{i=1}^{m} xs_i * a_{ij} \geq 1, & \forall j \in J_n \quad (3.5a) \\ xs_i \in \{0, 1\}, & \forall i \in I_m \quad (3.5b) \\ xs_i + xs_j \leq 1, & \forall i, j \in \{I, J | o_{ij} \geq limit\} \quad (3.5c) \\ xs_i = 0, & \forall i \in \{I | customized\} \quad (3.5d) \end{cases}$$

After solving the linear problem, the selected channels have been populated in the domain. By using Equation 3.5d and forbidding the objects that were used in the first realization, a second realization can be generated. This is repeated for the desired number of realizations.

3.3.4 Synthetic 3D single-layer case study #1

The first example is a braided channel reservoir similar to reservoirs in the Gulf of Mexico (Shmaryan and Deutsch, 1999). There are a hundred wells evenly located in the domain. 25% of the wells are non-channel. The data spacing is about three to five times the channel width. The wells may be up to ten degrees deviated in the vertical direction. The elevations of the channel wells have been processed, and all have the same top elevation. The mismatch tolerance selected is 5% for a single well, and that a channel i must match at least 95% length of a channel well j to claim it matches the well ($a_{ij} = 1$). 2000 channels are generated for the database and more than 90% of them satisfy the criteria to become candidate objects.

Being surrounded by pure non-channel wells increases the difficulty of conditioning certain wells. After randomly building the database with thousands of channels, five wells that are rarely conditioned by channels remain (Figure 3.5).

Specific channels are designed (as discussed in Section 3.3.2) for these five wells to build a full realization (Figure 3.6-a). The cross sections of well data are presented in Figure 3.7. The channel proportion (<20% in Figure 3.6) does not match the proportion of channel well data (about 40% in Figure 3.6). All the simulations in this case study create the conditioned models with the least channel proportions. If a higher proportion is preferred, it can be achieved by adding more channels in the domain or by increasing channel width. The conditioning results are good. The final conditioned percentage of the channel well reaches 99.43%. The total mismatch length is 1.98% of the total match length.

Although the conditioning is not 100%, it is quite close. Considering the measuring error of the data and approximations in stratigraphic processes, the error in conditioning results can be neglected. If a 100% conditioning is necessary, it can be achieved by dilution or erosion procedures in gridded models (Pyrcz et al., 2009).

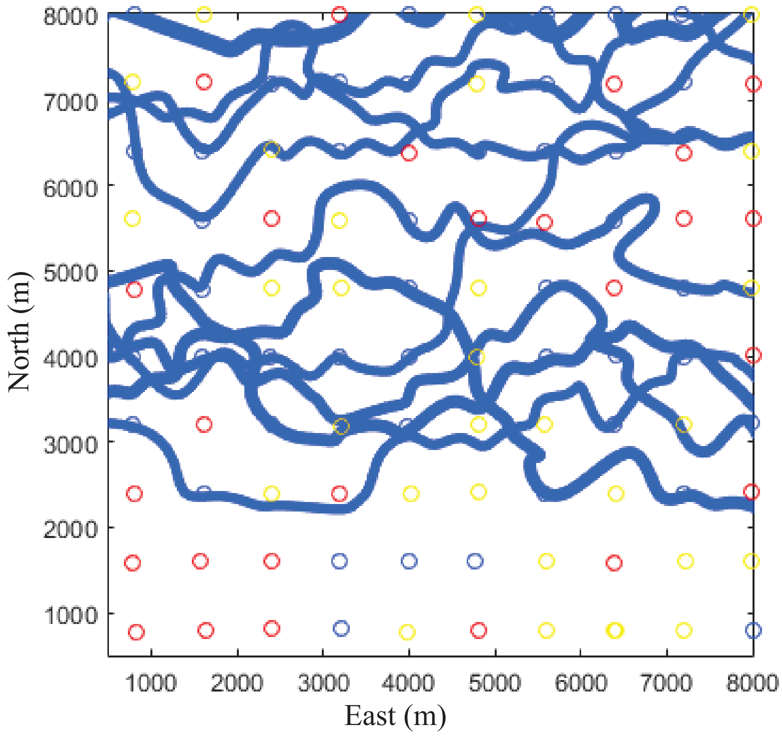
A second realization is shown in Figure 3.6-b. The cross sections of well data are presented in Figure 3.8. The final conditioned percentage of the channel well reaches 99.1%. The total mismatch length is 2% of the total match length.

The methodology works well for more dense data. The relative-density here refers to the ratio of the well density to the channel width. Instead of decreasing the well data spacing, the case study increases the channel size so that the ratio of well data spacing to channel width decrease, which is equivalent to a higher relative-density. In this case study the well data spacing is approximately 1.3 to 2 times the channel width while the number is 3 to 5 in last case. The relative-density doubles.

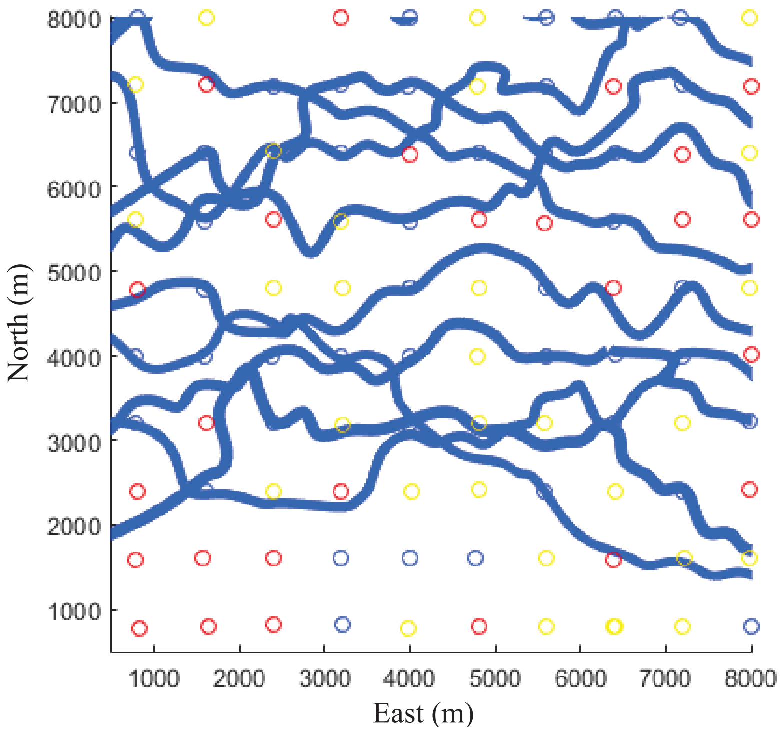
Given the higher relative-density, the conditioning difficulty rises. About 60% of the 2000 objects satisfy the selection requirement to enter the database and become candidate objects. The program then selects from the available objects and builds the realization. The simulation results are shown in Figure 3.9. In this case, the channel proportion is close to the proportion of channel facies well. The final conditioned percentage of the channel well reaches 99.47%. The total mismatch length is 6.00% of the total match length. The mismatch is a little high as the raised relative-density of data increases the conditioning difficulty. To reduce the mismatch, one method is to generate more candidate objects in the database.

3.3.5 Synthetic 3D single-layer case study #2

This model is designed for fragmented channel reservoirs such as the ones in Fort McMurray (Andriashek, 2007). The channels are truncated by each other during the geological periods. Similarly to the model above, given channel width, depth, sinuosity, general flowing direction, and other parameters, a set of locally conditioned channels are generated and selected. The program randomly truncates the continuous channels into broken pieces that are about $1/6$ to $1/4$ of the original length. Fragmented channels are then populated in the domain, as shown in Figure 3.10. There is a total match percentage of 97.78% and a total mismatch percentage of 2.49%.

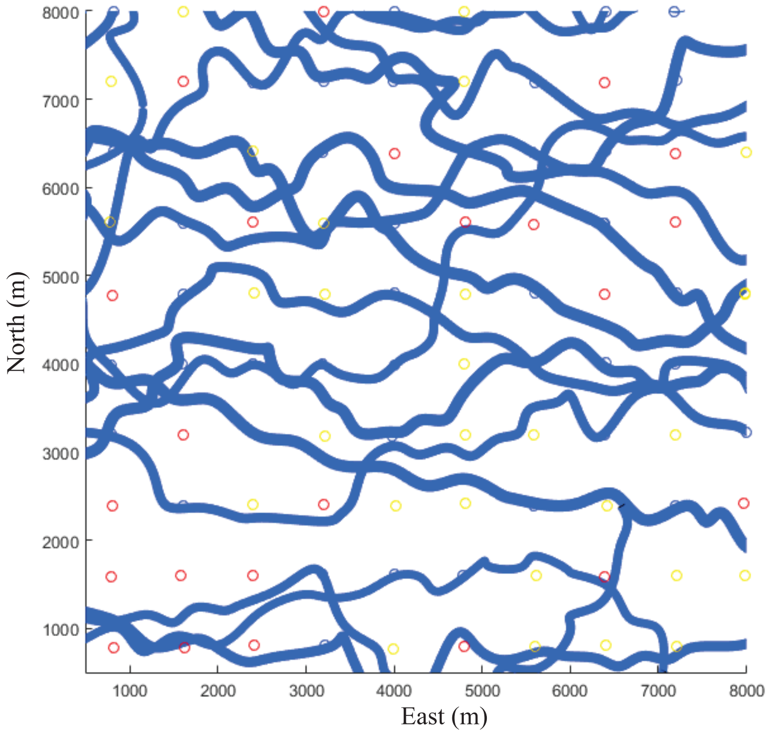


(a)

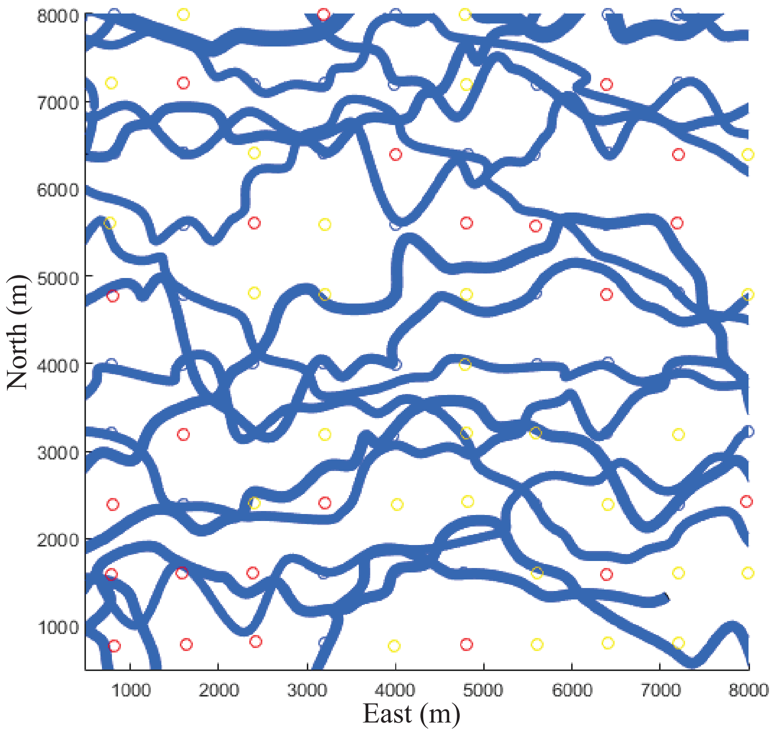


(b)

Figure 3.5: Plan views of fluvial channels together with wells. (a) is realization one and (b) is realization two. Both are partially conditioned. Channel wells are in blue. Yellow and red wells are non-channel wells. Channel wells at bottom of the maps are not conditioned due to conditioning difficulty.



(a)



(b)

Figure 3.6: Plan views of two channel realizations. Channel wells are shown in blue, levee wells are indicated in yellow and the floodplain wells are depicted in red. All channel wells are conditioned. Levee wells are not conditioned in this example.

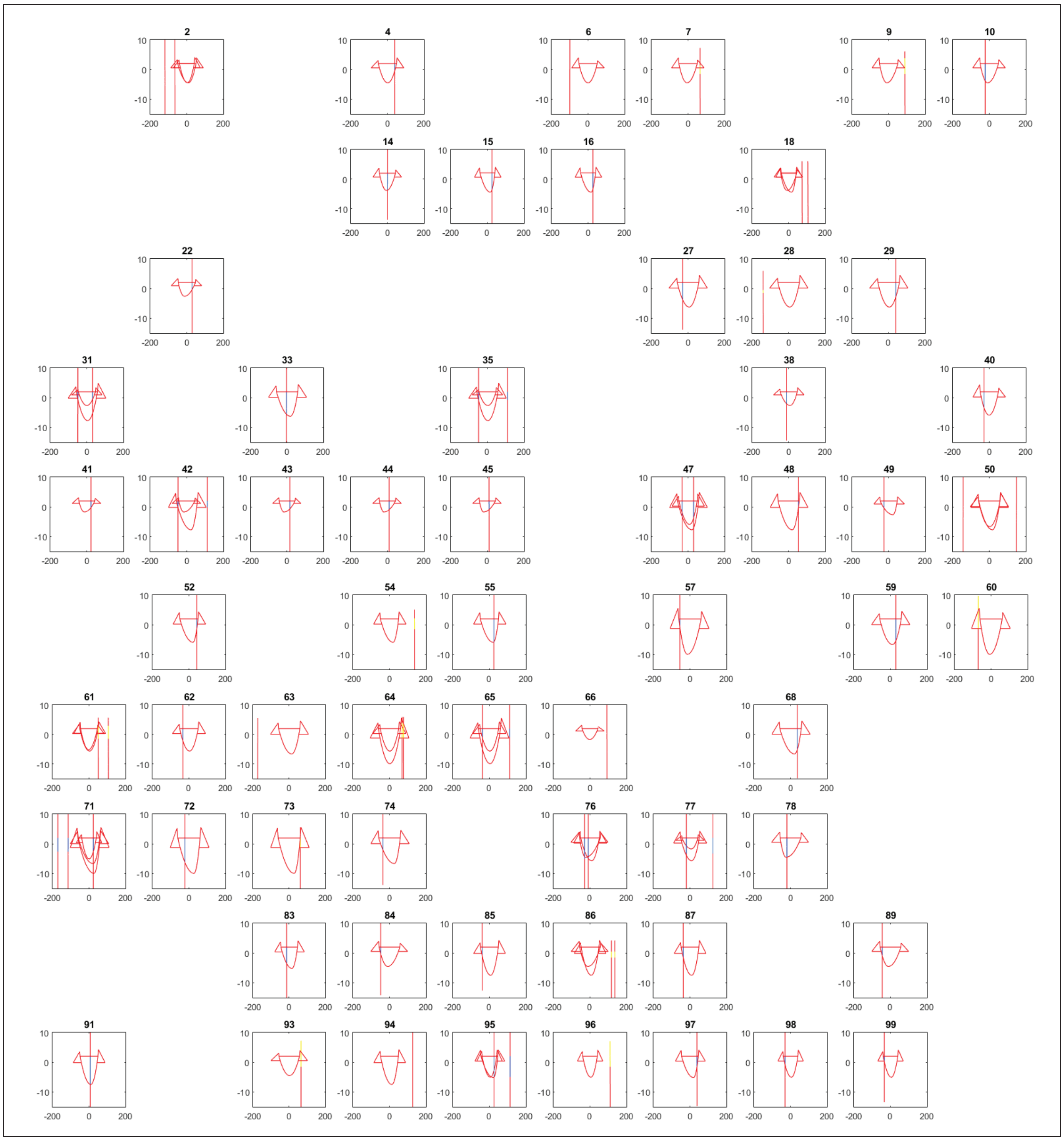


Figure 3.7: Cross sections of wells for realization one. The distance unit is meter. The cross sections are listed sequentially according to the well ordering. There might be multiple channel profiles for one well because several channels intersect this well. The missing wells of cross sections mean there is no channel passing nearby these non-channel wells. Zoom in to see the precise conditioning results.

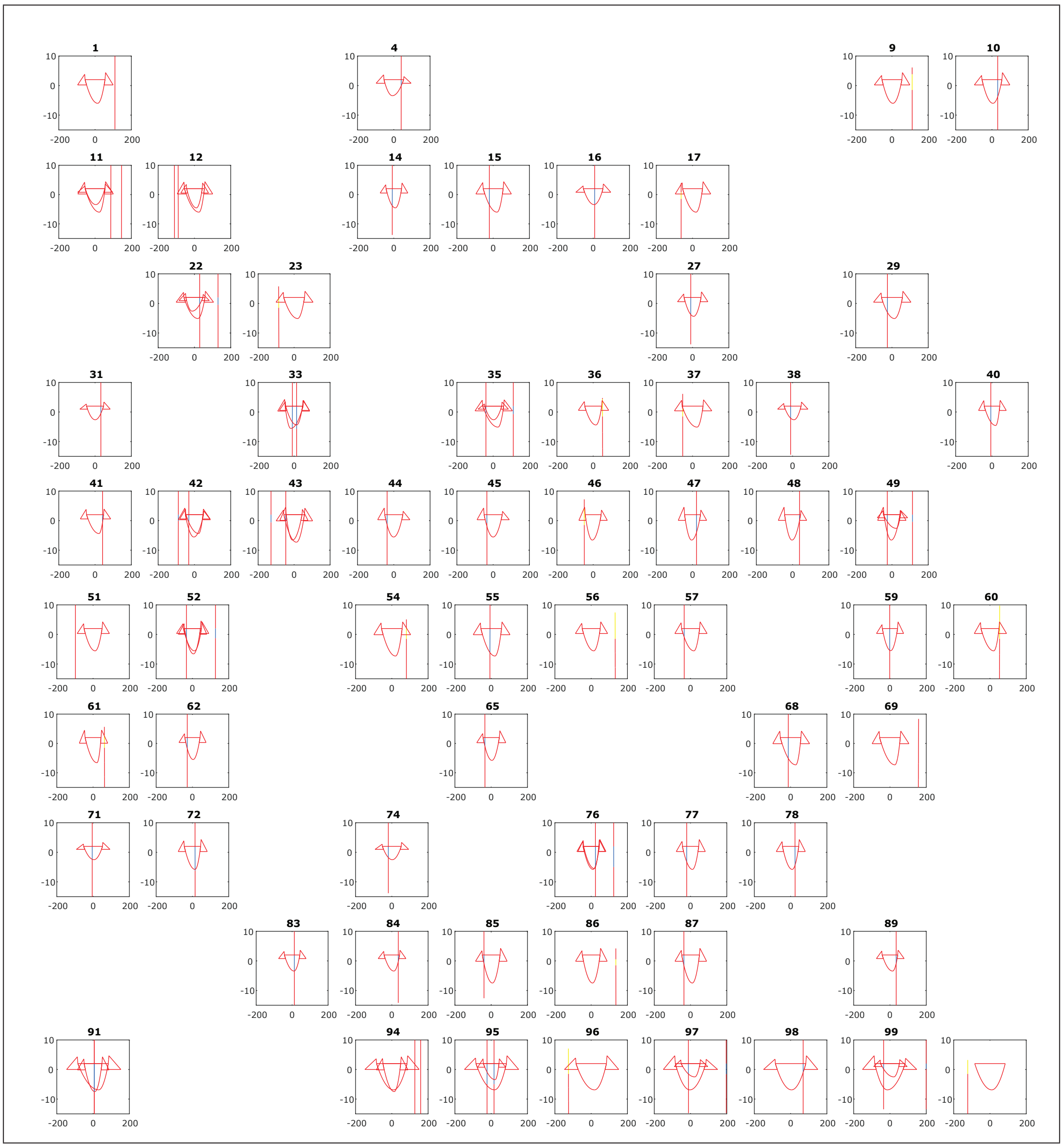


Figure 3.8: Cross sections of wells for realization two.

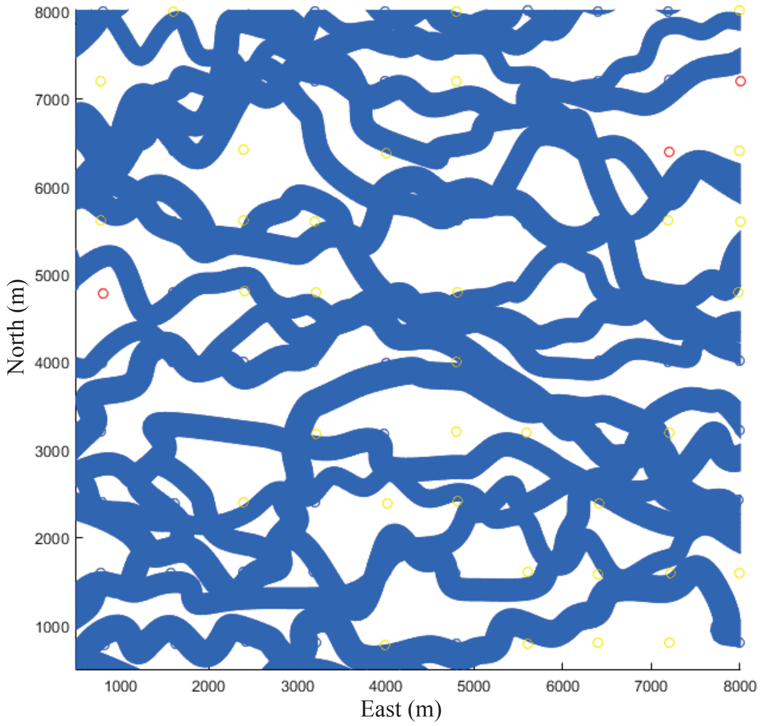
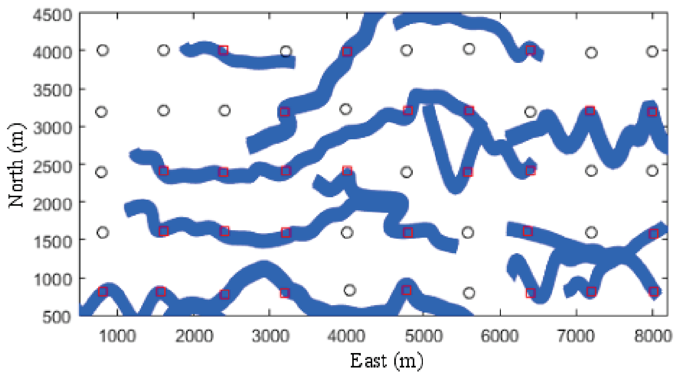
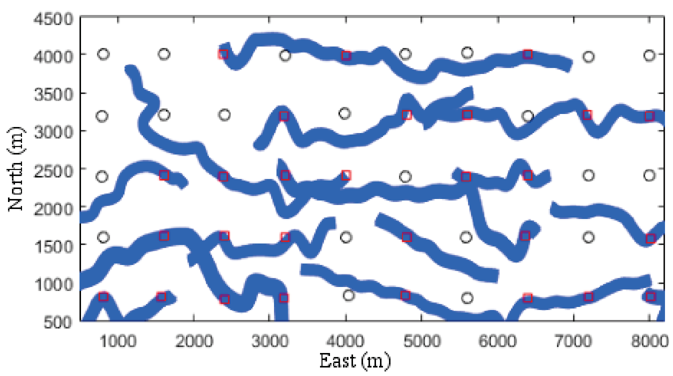


Figure 3.9: A plan view for a realization with relatively-dense data. Channel wells are in blue and are covered by channels. Non-channel wells are in red and are avoided by channels. Yellow levee wells are not conditioned in this example.



(a)



(b)

Figure 3.10: Two realizations of fragmented channels.

3.4 Conditioned realizations with multiple objects

Additional types of objects besides channels can be added using the same optimization method. Extra processes are added to honor the correlation between objects. Generally speaking, channels and levees are the main objects. They are optimized first using implicit filtering algorithm. After the optimization, the algorithm attaches crevasse splays and oxbow lakes to the channels. Each attached-object has an anchor point so that the object relative positions are constrained. The initial parameterization of crevasse splays and oxbow lakes is discussed in Chapter 2.

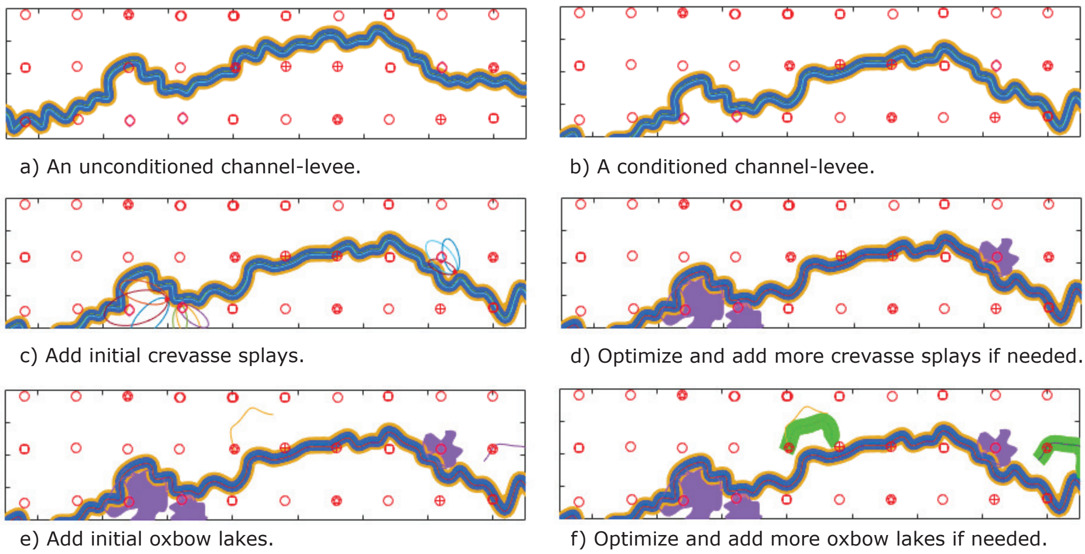


Figure 3.11: Steps to condition multiple objects.

Figure 3.11 depicts each of the modeling steps for five types of objects. First, the channel and the levee are optimized simultaneously. After the centerline layout, width and depth of the channel and levee are fixed, crevasse-splay wells near the channel are identified. For each identified well, a curved bend of a channel nearby is searched from the channel database. If the bend is more curved than a limit and the well is located at the outer bend side, a crevasse point is allocated along the outer bend of levee. If the direction from the crevasse point to the well is at an appropriate angle, i.e. between 50 and 110 degrees, relative to the water flow direction at the crevasse point, one major course of the crevasse passing through the well is placed. Accessory courses are simulated beside the major course. The area dominated by the major course, an ellipse, rotates around the crevasse point to escape non-crevasse-splay facies wells if needed. The area of accessory courses also rotates or shrinks for the same purpose.

The procedure of simulating all objects together is subject to many restrictions. Not every initial model can condition the crevasse-splay wells after the optimization. The conditioning of a particular crevasse-splay well might require multiple optimization iterations. More crevasse-splay objects are added to match global proportions if needed.

Oxbow lakes are generated after the crevasse splays. Similarly, wells containing oxbow lake facies near a conditioned channel are identified. An oxbow lake is simulated and placed at the well. When initializing, the location of the oxbow lake is random except for the requirement that the well be located somewhere on the centerline of the oxbow lake. The locations of the previously simulated crevasse splays are checked and avoided by new objects. If there is conflicting well data within the object, the oxbow lake will be rotated slightly. After the optimization, oxbow lakes may overlap with channels and levees slightly. The overlapped parts of the oxbow lake are truncated.

Figure 3.12-a shows a synthetic example of a fluvial system with multiple types of objects. Corresponding cross sections of conditioning results are shown in Figure 3.12-b.

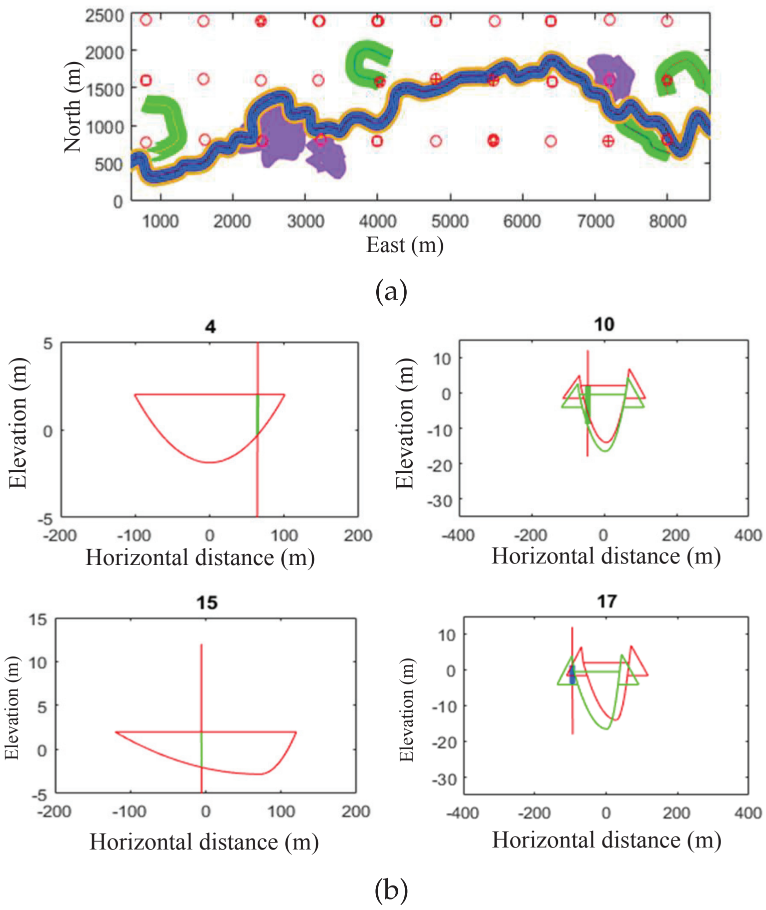


Figure 3.12: An example of all objects conditioning together. (a) A plan view of a model with all objects conditioned. A square represents channel facies and a cross represents levee facies. The circles indicate floodplain facies. The crevasse splay and oxbow lake facies are represented by diamonds and stars respectively. (b) Cross sections of objects intersecting wells. Only one cross section for each type of object is drawn. The top left is a plot for a single course of a crevasse splay, the top right for the channel, the bottom left for an oxbow lake and the bottom right for the levee. The wells are non-vertical and segmented.

3.4.1 Synthetic 3D single-layer case study #3

A simulation of a full domain can be built with the fluvial system discussed previously. Over time, the fluvial system changes location, boundary, etc. It is common to have several fluvial systems from different geological periods (Assine et al., 2014) gathered in one domain. Figure 3.13 shows a realization of multiple types of objects. A representative fluvial reservoir similar to this model can be found in the Uinta-Piceance Basin (Dubiel, 1992).

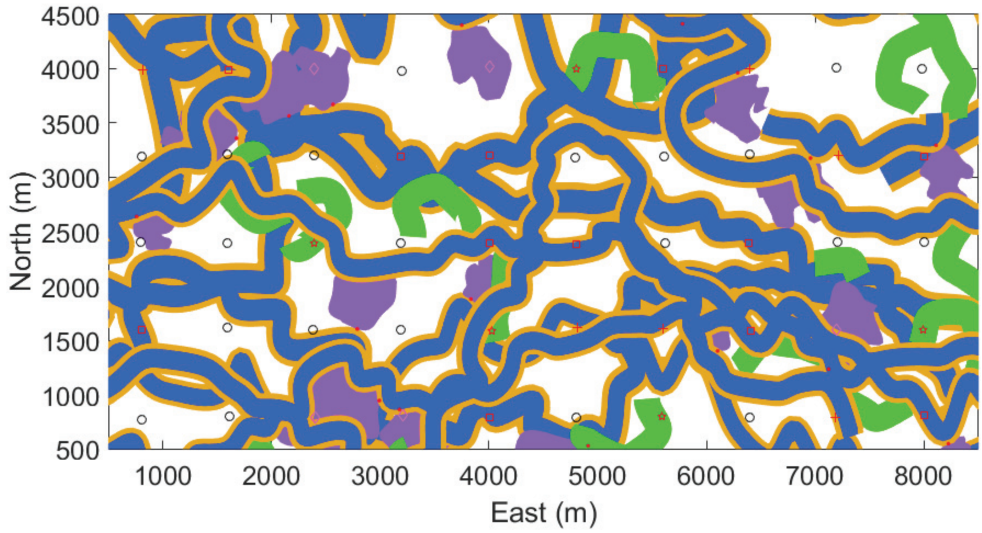


Figure 3.13: A simulation with all objects conditioned to well data. The square, cross, circle, diamond and star represent channel, levee, floodplain, crevasse splay and oxbow lake facies well respectively.

Channels and levees are the main modeling objects in this domain. Crevasse splays and oxbow lakes are small objects, only five wells each are added for these two types of objects. Six levee wells and twelve channel wells are included. A thousand channels and levees are generated for the candidate database. The requirement for object selection is that a object violating a single well data more than 5% (of the conditioning segment) is abandoned and the object needs to cover more than 95% (of the conditioning segment) to claim it matches the well. The total match and mismatch percentage per facies is shown in Table 3.1. The percentage is calculated as the total match length (or total mismatch length) of a particular facies divided by the total well length of that facies. The total matching and mismatching results perform better than the requirement. To pursue a even higher performance, one way is by increasing the number of objects in candidate database. The conditioning of crevasse splays and oxbow lakes are easier.

Table 3.1: Conditioning performance of each facies.

Facies	Match percentage	Mismatch percentage
Channel	98.81%	0.95%
Levee	99.07%	2.78%
Crevasse splay	99.89%	0%
Oxbow lake	99.99%	0.12%

Chapter 4

Reservoir simulation

The channels simulated using the method in Chapter 3 assume a stratigraphic coordinate transformation and, therefore, have a constant top elevation in each realization. Different locations along a channel should not fluctuate within one domain after a stratigraphic transform. The well data is preprocessed before modeling. It is divided into multiple layers so that all the segments with the channel facies in one layer share the same top elevation. Bottom elevations of the segments vary. The stratigraphic transformation accounts for any post deposition elevation changes of the top of the channel.

The layers can be divided according to stratigraphic data, if there is detailed geological interpretations of the reservoir. Otherwise, a reservoir can be stratified into sub-layers by setting elevation thresholds. By conditioning each layer independently, the reservoir model is conditioned to all available well data. This chapter illustrates the simultaneous modeling of multiple layers through two cases using different stratification methodologies.

4.1 Simulation with sparse data

Some projects only have few data in early stage and the strata in the reservoir are flat and simple. In this case, a set of elevation thresholds are assigned to vertically divide the reservoir into layers.

4.1.1 Reservoir geology

Different geological environments generate different styles of reservoir (Figure 4.1). The geometry of OBMs in reservoirs vary accordingly. Therefore, modeling should be customized based on the geologic style of a given reservoir. According to the slope gradient and relative discharge rate, channels form into different styles of reservoirs. Hartley et al. (2010) roughly categorized channels into six types including braided bifurcating, single braided, braided to meandering, single sinuous bifurcating, multiple sinuous and single sinuous (Figure 4.1). Each branch of a reservoir may be from different time periods and the elevation may differ.

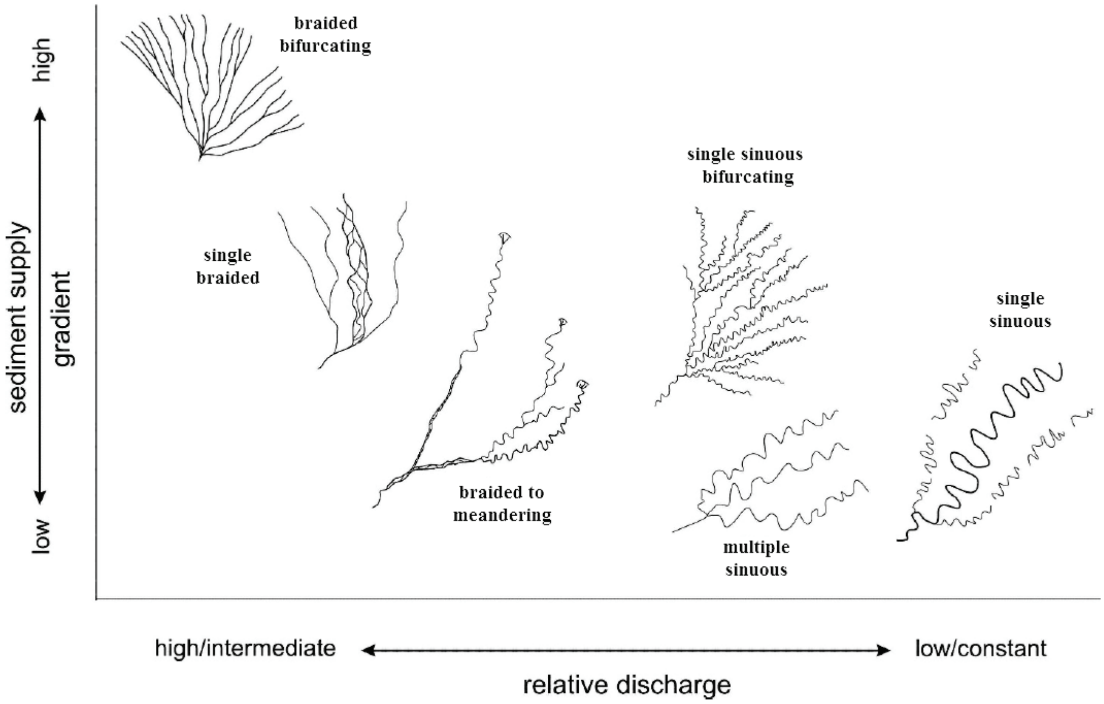


Figure 4.1: Reservoirs with different continuum and sinuosity style in relation to gradient and discharge rate (Hartley et al., 2010).

Sinuosity and continuum degree are modeled in regard to honoring the appearance of different reservoir styles (Figure 4.1). Meanwhile, avulsion rate and sediment aggradation rate are accounted for the appearance difference in reservoir types. Avulsion rate decides the number of channels in the domain. Sediment aggradation rate determines the elevation of each channel element and the number of elements in each stacking. A higher aggradation rate indicates that more elements gather in one stacking within the same sedimentary length of the surrounding formation.

In this example, the reservoir is customized for a bifurcating style river. One typical example of bifurcating style channels is Koshi River (Davidson et al., 2013). Modeling focuses on the location and proportion of channels (Figure 4.2). Avulsion behavior (the location where avulsion happens) is not modeled.

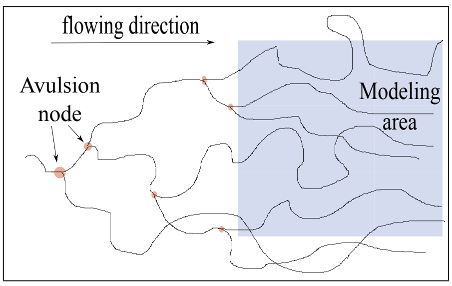


Figure 4.2: A sketch depicting the modeling area.

4.1.2 Synthetic example

The domain is divided into sub-layers for modeling. The thickness of each sub-layer differs according to well data. Each sub-layer is divided into several cuboids (Figure 4.3). The modeling goal here is that data located in each cuboid is individually taken care of by one channel stacking. Traversing a cuboid and entering the neighborhood cuboids without violating their data is allowed.

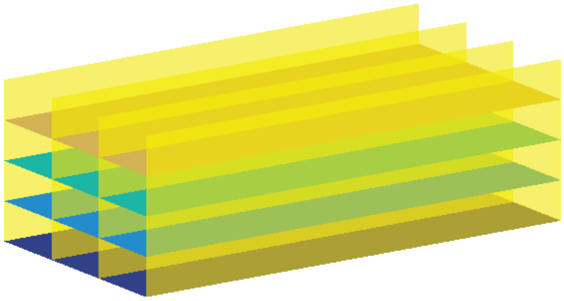


Figure 4.3: A domain divided into cuboids.

Channels are built and conditioned to well data independently within a cuboid. When working on one cuboid, the channel facies wells in other cuboids are shut off to prevent these wells from being counted in the calculation of objective function value; thus the conditioning of channel wells inside the cuboid are given first priority. The non-channel facies wells outside the cuboid remain effective to prevent channels from violating conditioning data. In each cuboid, a channel is repeatedly generated and optimized until it is conditioned to all related data or until a fixed number of iterations is reached. In the later case, the standard of acceptance is gradually lowered (i.e. the acceptance value of the objective function for minimizing is increased). The best model generated is selected for one realization.

A synthetic example together with the data used is displayed in Figure 4.4. The data is stratified and trimmed before modeling. In each layer the channel lithofacies segments on wells start from the same top elevation and have varying bottom elevations. The initial centerlines of the channels are simulated randomly using the stepped cosine model.

If a cuboid has many wells, the well data can seldom be fully conditioned with a single channel initialized randomly. As illustrated in Figure 4.4, the blue circles indicate channel well data that is not conditioned. To achieve better conditioning under such geologic settings, the optimization is modified to initialize channels preferentially near well data.

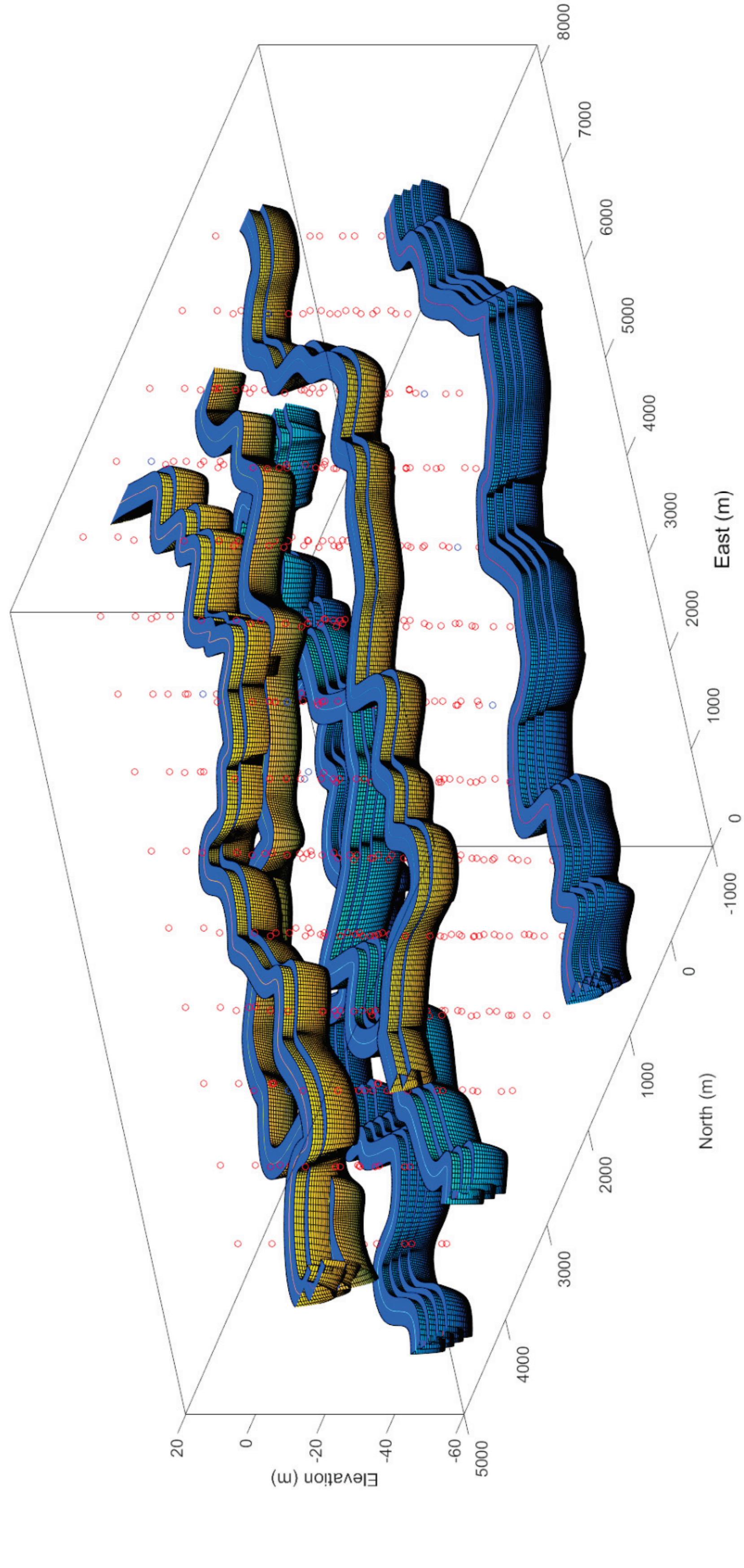


Figure 4.4: A reservoir constructed cuboid by cuboid using the centerlines based on stepped cosine models.

4.1.3 Centerline initialized to problematic well data

An appropriately located centerline can significantly alleviate difficulty in conditioning. The procedure of conditioning includes moving the channel to the points near the wells and then changing the channel size and shape to fit the well data. If the initial channel begins near wells, the optimization to achieve conditioning is simplified.

In this example, the centerline is generated piecewise from well to well (Figure 4.5). When interpolating a centerline between two close wells by concatenating truncated cosine lines, the centerline is prone to be a straight line. To handle this problem, the distance between the two wells is measured and when concatenating truncated cosine segments, the algorithm generates a curve with its accumulated length being triple the measured well distance. A segment is then truncated from the concatenated curve to connect the two wells. The direct distance between two ends of the segment equals the measured well distance but the accumulated distance can be much longer. Thus the segments of centerline are capable of "circuiting" backward. The above procedure is repeated for every pair of adjacent wells. The feature points and the well locations are extracted as control nodes. A centerline moving through the well locations is generated and parameterized.

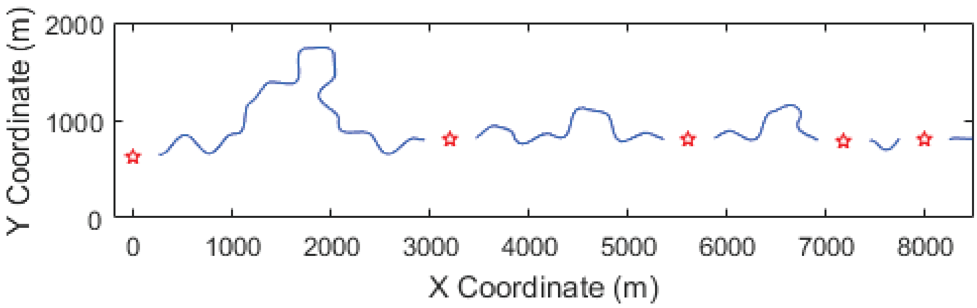


Figure 4.5: A centerline initialized according to well data. Red stars indicate the wells and blue lines are the centerline segments passing near the wells.

A synthetic example (Figure 4.6) conditioning channels to all well data is simulated using the centerlines initialized near well data. All the channel wells (in blue) are conditioned by the channels, regardless of the density of well data. There are slight errors (within 5%) but in general the conditioning result is satisfying.

Besides the conditioning, the bias (i.e. channel being attached to non-channel wells) is prevented in the modeling. The buffer variable in the objective function (Equation 3.1) is also assigned a weight in this modeling example. As Figure 4.6 shows, the channels are pushed a distance away from the pure non-channel wells. Currently the distance is half a width of the channel but the value can be assigned from a distribution based on further studies.

The avulsion rate and sediment aggradation rate are honored through the number of channels in the domain. Some stacking patterns have two elements and some have four (Figure 4.6). The number of elements is decided by the aggradation rate. If there is related data, the number of elements for each stratum can be explicitly specified.

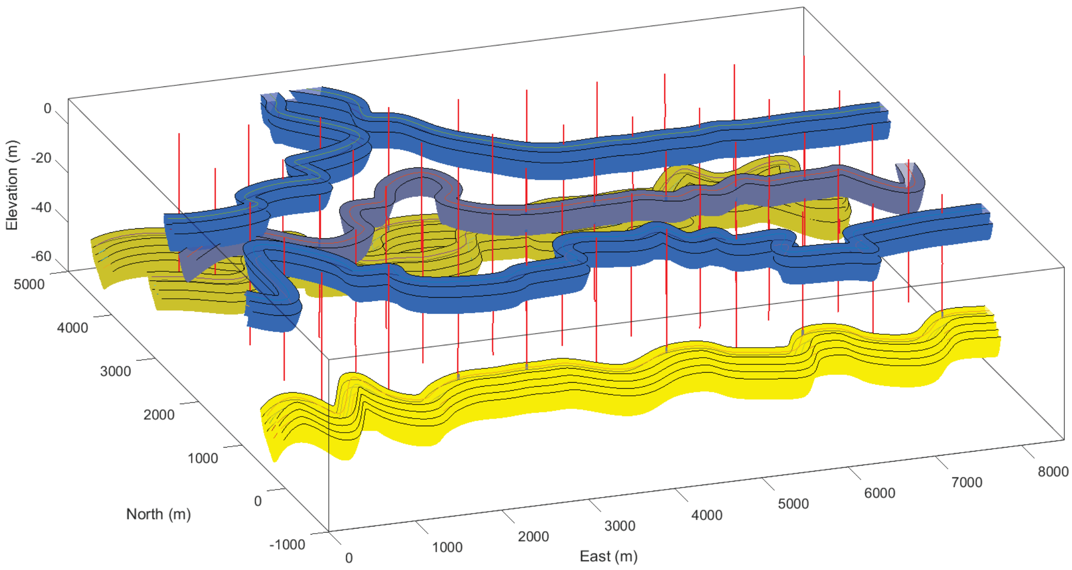


Figure 4.6: A reservoir constructed using the centerlines initialized according to well data. The non-channel wells (in red) are avoided by the channels. The channels are half transparent. The red wells transferring into blue wells can be seen at the top surface of channels. The blue wells transfer back to red wells at the bottom surface of the channels.

4.1.4 Results

The conditioning results of the two examples using data-driven centerlines are summarized in Table 4.1. Conditioning all well data in one region using one randomly generated channel is difficult. Only 75.73% of the well segments with channel facies are conditioned and a total mismatch of 23.63% of the total length of wells segments with channel facies is generated. If using the channels initialized according to well locations, the match and mismatch is 95.67% and 1.37% respectively. The model using channels initialized to well locations obtains a better conditioning result.

Table 4.1: Channel wells conditioning results.

Modeling method	Well data conditioned	Mismatch
Random channels	75.73%	23.62%
Channels initialized according to data	95.76%	1.37%

The conditioning details of the data-initialized modeling are summarized in Table 4.2. Six channels are generated to handle the six regions containing wells with channel facies. The first to sixth region have four, six, six, three, five and seven channel wells respectively. Many wells are fully conditioned. The lowest conditioning percentage of a single well is 66.08%. The low match percentage means that either this well has a short segment of channel facies or the data is difficult, i.e. to match more of the segment will cause more mismatch. The optimization considers one channel as a unit and compromises the conditioning of one well for the conditioning of others. Most wells have more than 90% being conditioned.

Table 4.2: The number of wells conditioned by each channel and the conditioning performance of each channel at each of its conditioned well location.

	1_{st} well	2_{nd} well	3_{rd} well	4_{th} well	5_{th} well	6_{th} well	7_{th} well
1_{st} channel	100%	99.59%	88.04%	100%	NA	NA	NA
2_{nd} channel	66.08%	87.37%	100%	98.13%	90.22%	100%	NA
3_{rd} channel	100%	92.90%	99.77%	100%	93.32%	100%	NA
4_{th} channel	100%	98.99%	100%	NA	NA	NA	NA
5_{th} channel	99.85%	98.45%	96.02%	96.16%	75.23%	NA	NA
6_{th} channel	97.59%	97.67%	94.14%	100%	98.44%	96.47%	98.34%

To condition all data in one region with one channel is challenging. The function to initialize centerlines according to well data alleviates the difficulty. It also allows the modeling to consider known connectivity between wells. All the correlated wells can be connected by one channel regardless of the data density.

4.2 Simulation with dense data

4.2.1 Reservoir geology

In this case study, a braided-channel reservoir similar to those encountered in the Gulf of Mexico (Shmaryan and Deutsch, 1999) is considered. Multiple branches of channels coexist. When considering each branch as an independent channel, the modeling task becomes the simulation of a set of channels that, considered together conditions all the well data. A set of facies data observed at 29 wells from a reservoir in west Africa is used to illustrate the conditioning. The hydrocarbons are trapped in a structure comprised of fault seals, structural closure and stratigraphic pinch-outs. Within the structure, there are stacked and amalgamated channels. Seismic data and well data are available.

Stratigraphy

The stratigraphy of the reservoir has been interpreted thoroughly. Initially the interpretation relied on a combination of 2D and 3D seismic data and a few well data. The resolution was at a magnitude of a channel complex. A later interpretation using sequence stratigraphic principles recognized more channel complexes. Then the reservoir was divided into three main geobodies. As the production continued, more wells were drilled and the quality of 3D seismic data was improved. Detailed structures were recognized within the geobodies.

If the stratigraphic interpretation is integrated into the modeling, the layout of each channel can be confined inside corresponding channel complex; as a result, conditioning models have a higher accuracy regarding proportions and trends. They are two of the key parameters simulated in the facies modeling as inputs to the following property modeling. Due to confidentiality issues, stratigraphic surfaces are not available. The well data is roughly divided into separate strata according to the statistics of the well data and several stratigraphic sketches. The horizontal range of channels in each stratum is also roughly confined according to the sketches.

The elevation of channel facies in the well data is analyzed to find common stratigraphic channel tops (Figure 4.7). Elevations within the same spike can be categorized into one layer. In this example, the elevations are divided into eighteen layers.

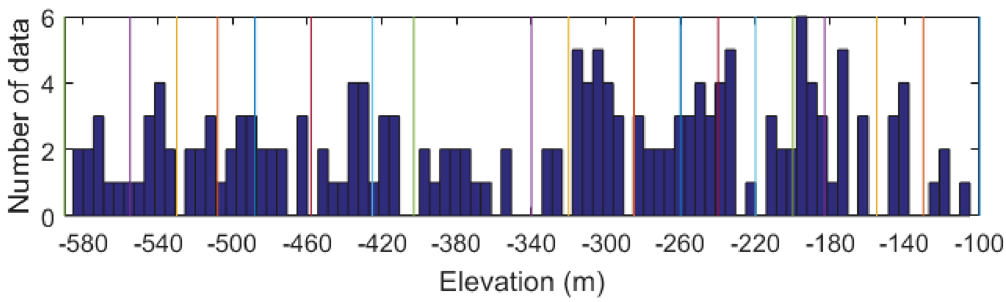


Figure 4.7: The histogram of the elevations. The elevations are divided into 18 groups. A few data at the bottom of the reservoir are eliminated.

Processing data

There are four types of rocks in the core samples including massive sandstone, laminated sandstone, thin-bedded mud and debris. They are interpreted as channels, levees and floodplains by geologists considering net-to-gross ratios. The facies data is shown in Figure 4.8. The data used in this example is actually from a gridded model. The wells are non-vertical. When a tilted well crosses the domain of a block, its X/Y coordinates abruptly increase or decrease the value of the block size. Geological modeling as proposed in this thesis is grid-free and does not have this issue but the well data considered does. For simplicity, the wells are transformed to be vertical but non-vertical wells can be considered.

The low NTG facies is treated as flood plain; the high NTG facies is defined as channel; the medium NTG facies can be treated as levee or flood plain. The layout of the data is consistent with the geological interpretation.

It is more complicated to format data that has both channel and levee facies. In one stratum, all segments of channel facies share the same top elevation while all segments of levee facies share the bottom elevation, according to the design of the objects; a

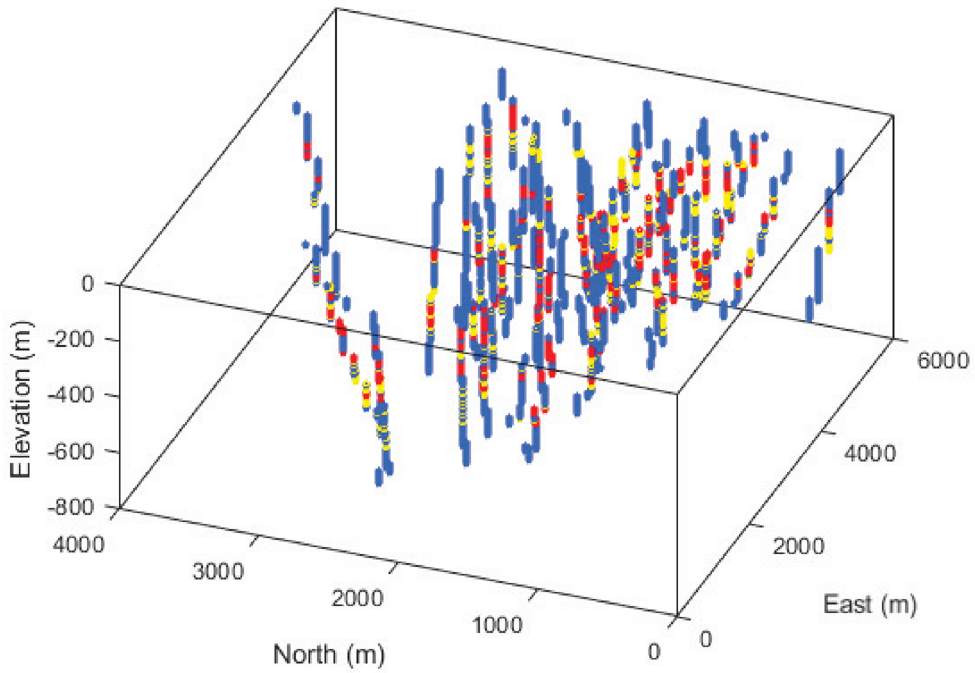


Figure 4.8: The data set of the project. The blue wells indicate low net-to-gross (NTG) facies; yellow represents medium NTG facies and high NTG facies wells are in red.

channel and its attached levee are at different elevations. The elevation difference adds significant difficulty to the data processing. At a same elevation, it is possible that a segment of channel facies belongs to one stratum while if it is a segment of levee facies, it should be assigned to another stratum above. Other information is required to determine which layer this elevation belongs to. Since there is insufficient stratigraphic data supporting the stratification, the medium NTG facies is treated as flood plain rather than levee.

The well data is formated so that in each layer a well contains only one segment of channel facies. If there are multiple segments of channel facies, they will be combined into one; or some of the segments will be invalidated and the rest will be combined into one. If one segment spans two layers, it will be cut into two segments and be conditioned separately in the modeling of the two layers. When dealing with one of the two segments, the other segment is assigned as in neutral facies, rather than floodplain facies. When optimizing objects, the objective function does not get a match length nor a mismatch length from the segments with the neutral facies. This strategy significantly relaxes the conditioning constraints and alleviates the conditioning difficulty. Besides, if the elevation of a combined/truncated segment starts from the middle of a layer, the segment will be shifted so that it starts from the top of the layer. After preprocessing, all segments in one layer have identical top elevations with varying bottom elevations.

4.2.2 Modeling the case study

Modeling is conducted independently by layer. In each layer, the methodology illustrated in Section 3.3 is used. Additional constraints, such as trends, are optional and considered.

Vertical trend

After the reservoir is divided into separate layers, the vertical trend can be modeled by controlling the proportion of channels in each layer. A higher proportion indicates more channels in one layer and vice verse. To illustrate how trends would be incorporated if available, three strata with low, medium and high proportions are selected. The trend is based on the statistics of the data in that layer. The models with corresponding proportions are shown in Figure 4.9 and Figure 4.10.

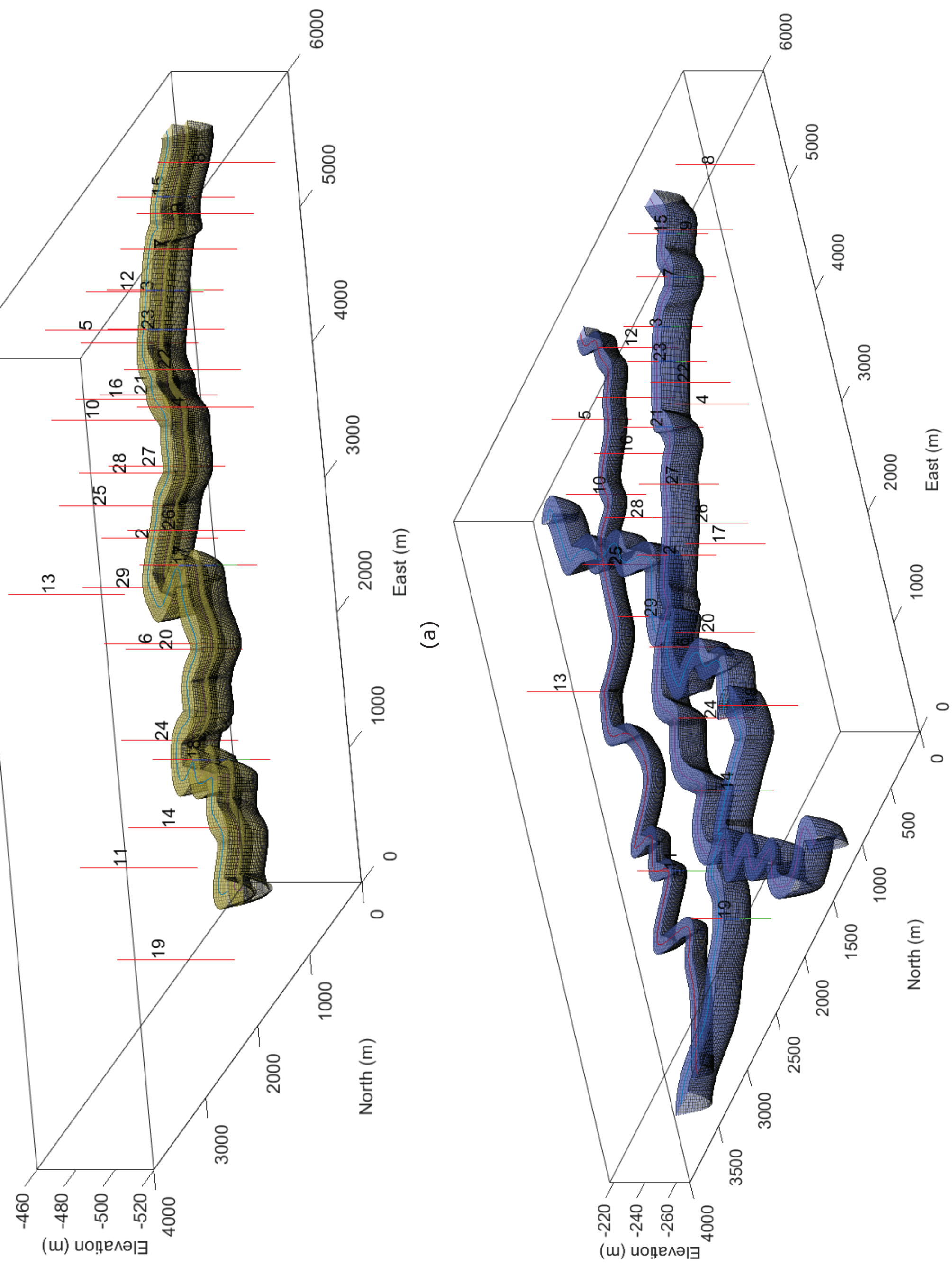
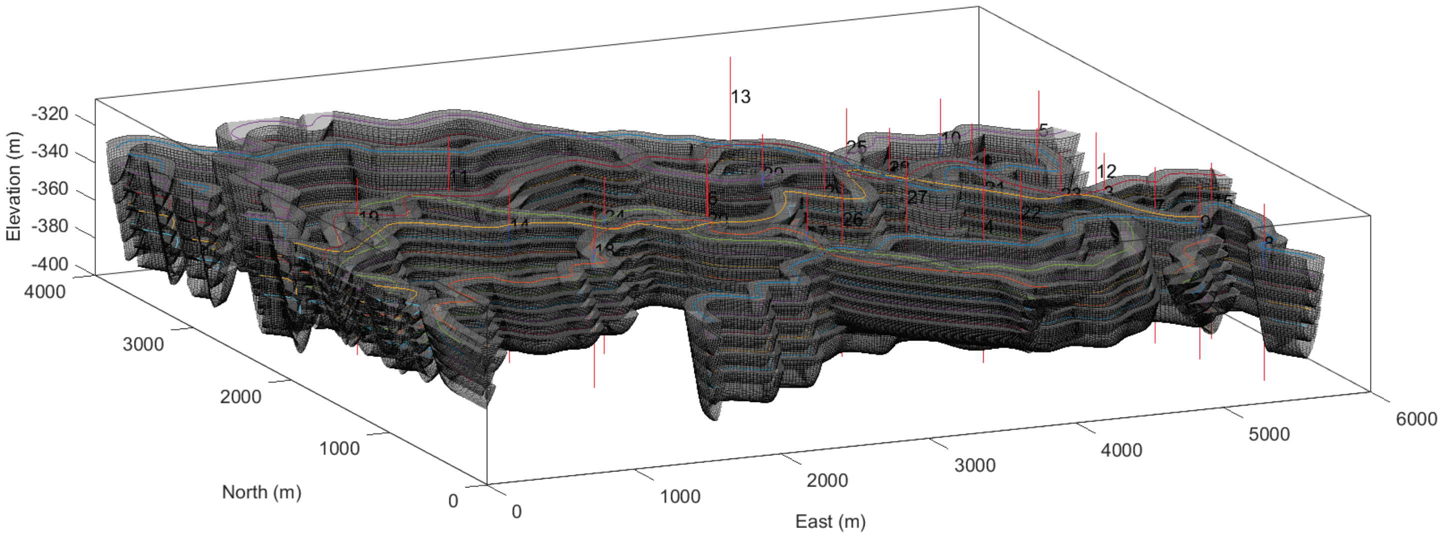


Figure 4.9: Modeling of the reservoir at different layers with low (a) and medium (b) proportions. This figure is continued to Figure 4.10.



(c)

Figure 4.10: Modeling of the reservoir at different layers with high proportions. The well segments colored in blue represent channel facies. Floodplain facies is represented by red. The segments in green means they are channel facies but that they are assigned to the next layer. Channels do not get credit from conditioning the green segments. Neither do channels get penalty.

There is no hard control on the final proportion of channels. The proportion value is determined by the channel parameters with randomness. It may not strictly obey the given proportion requirement. The number of channel stacking patterns has the largest influence on the proportions. The low, medium and high proportion models have two, three and five channels respectively. The number of channel elements in each channel stacking pattern is the second most significant parameter to proportions. For example, there are five elements in the stacking pattern in the high proportion model and the channel stacking pattern appears wider and thicker than that in the low proportion model where each stacking pattern has two elements. Besides, sinuosity, channel width and depth also alter the proportions.

Areal trend

An areal proportion map is used to impact a horizontal trend in conventional reservoir modeling. However, intact channels are long and continuous objects. The channel proportion in the domain does not frequently switch between low and high and is usually gradual. Considering the intrinsic property of the reservoir, a trend in one dimension rather than an areal map is modeled.

In this example, the proportion trend along the flow direction is modeled. It is achieved by controlling the range of the channels at different locations along the flowing direction. The width of the range is increased at high proportion areas and decreased at low proportion areas. The range of channels is defined considering the 1D proportion trend (Figure 4.11). When optimizing the channels, if a channel moves outside the range, the objective function value will be assigned a penalty value. Thus the channels tend to move within the range after optimization. At narrow-range locations, channels overlap more and the proportion of channels reduces. The result of the 1D proportion trend modeling is shown in Figure 4.12.

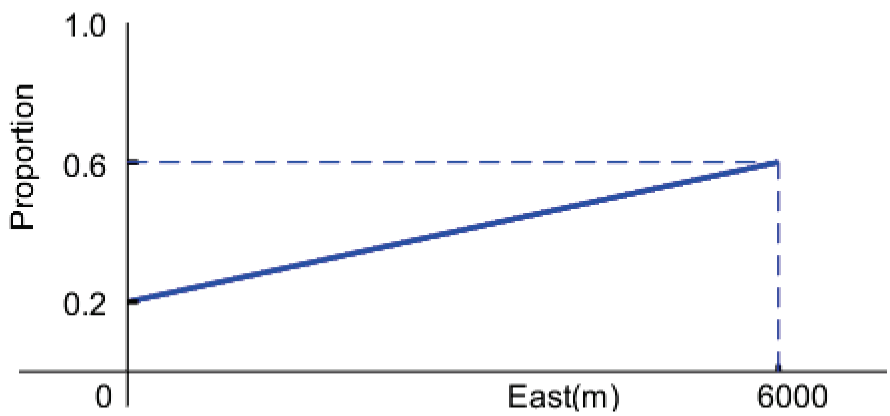


Figure 4.11: 1D horizontal trend for one layer of the reservoir.

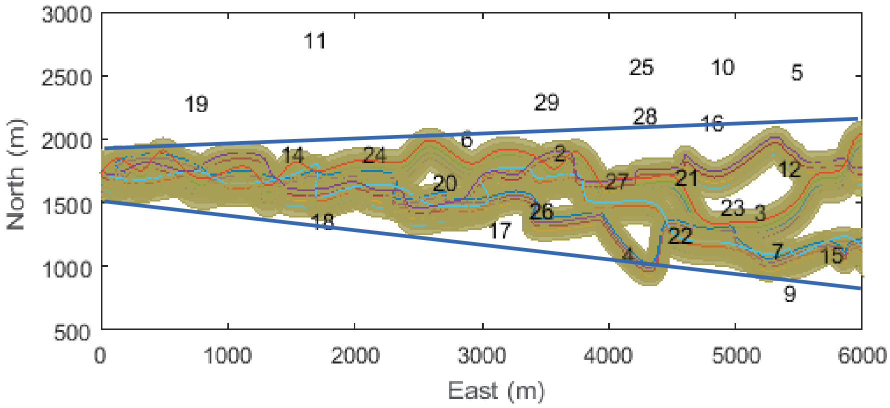


Figure 4.12: Modeling of 1D horizontal trend. The two blue lines represent the range of channels. There is an obvious proportion trend from left to right. Each number in the middle of the figure represents a well. Every channel well is conditioned.

Combining layers

Before modeling, the coordinates of channel well segments in the local coordinate system of a layer are transformed so that every segment has a consistent top elevation. Channels are simulated in the local coordinate system. After modeling, the local coordinates are back transformed to the global coordinate system. All layers are combined to obtain the final reservoir model. The elevations of well segments do not have identical values in the original coordinate system. If a channel only conditions one well, the channel will be assigned an elevation the same as the well in the global coordinate system. A channel conditioning multiple wells needs to fluctuate its elevations according to the wells it matches.

Figure 4.13 shows an example of a final realization. The channels are selected from a database of channel candidates independently by layer. The selection method in Section 3.3 is used. The number of channels selected in each layer is based on the well data density and vertical proportion. The number of elements in each stacking pattern differs between layers. The aggradation (vertical) shift of each element is controlled by the layer thickness and desired number of elements in one stacking.

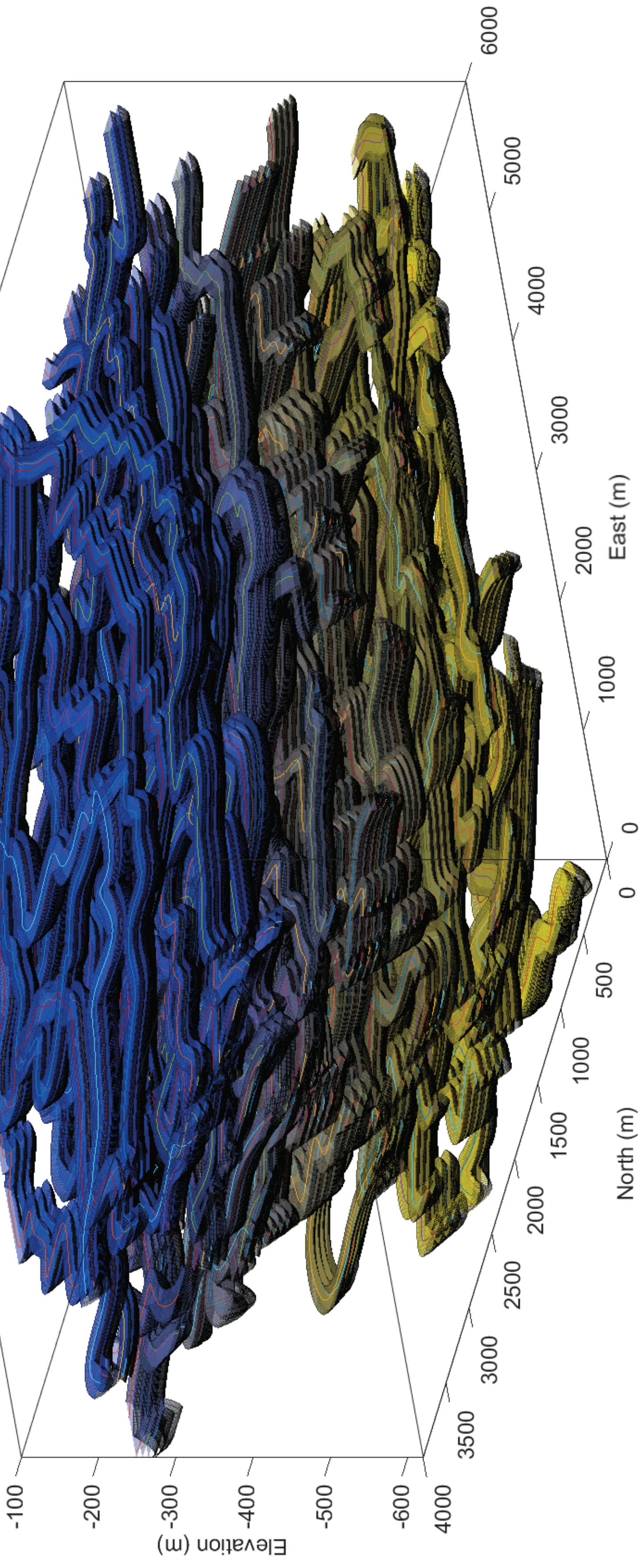


Figure 4.13: One final realization. The changing color represents the channel elevations. The lines in the channels are the centerlines.

4.2.3 Results

The reservoir is divided into 18 layers and the data match results of all 18 layers are summarized in Table 4.3. The percentage is the total match length of every channel well segment divided by the total length of channel well segments in the corresponding layer. Every layer has a match percentage higher than 95%.

Table 4.3: Well data conditioned in each layer.

	1_{st} layer	2_{nd} layer	3_{rd} layer	4_{th} layer	5_{th} layer	6_{th} layer
Conditioned well data	100%	95.40%	99.95%	99.91%	100%	98.49%
	7_{th} layer	8_{th} layer	9_{th} layer	10_{th} layer	11_{th} layer	12_{th} layer
Conditioned well data	98.67%	98.48%	99.58%	100%	98.15%	98.54%
	13_{th} layer	14_{th} layer	15_{th} layer	16_{th} layer	17_{th} layer	18_{th} layer
Conditioned well data	95.30%	99.91%	96.43%	99.42%	100%	98.24%

The mismatch results are summarized in Table 4.4. The mismatch percentage is the total mismatch length of every non-channel well segment divided by the total length of channel well segments in the corresponding layer. Most of the mismatch percentages are less than 5% except the last layer. The notable mismatch in last layer is because the proportion of channel facies is low at the bottom of the reservoir and the total length of channel well segments in last layer is very short, which leads to a higher mismatch percentage with the same mismatch length.

Table 4.4: Mismatch of well data in each layer.

	1_{st} layer	2_{nd} layer	3_{rd} layer	4_{th} layer	5_{th} layer	6_{th} layer
Mismatch	0.00%	0.00%	0.00%	0.35%	0.56%	0%
	7_{th} layer	8_{th} layer	9_{th} layer	10_{th} layer	11_{th} layer	12_{th} layer
Mismatch	1.79%	1.24%	0.52%	4.09%	4.49%	1.80%
	13_{th} layer	14_{th} layer	15_{th} layer	16_{th} layer	17_{th} layer	18_{th} layer
Mismatch	2.78%	0.00%	0.85%	0.18%	3.73%	8.60%

To assess the quality of conditioning, it is compared with conditioning results from a conventional gridded modeling method (e.g. MPS), where the size of objects are rounded to the multiple of grid size. When considering the size of production equipment, the depth of a channel can normally be as long as two or three cells. It is common to have a round-off error about a quarter of a grid size, i.e. 10% conditioning error of either less match or more mismatch. In comparison, the conditioning error after the proposed optimization is small and acceptable.

Chapter 5

Conclusion

Geostatistical modeling using classic two point statistics such as sequential Gaussian simulation simulates conditioned models but fails to reproduce known geometries in certain reservoir types. Object-based modeling reproduces the geometry of objects in the reservoir but have trouble conditioning to data. There are a number of existing conditioning methods but either the geologic features are too simplistic or the conditioning is not convincing.

In this thesis, a new methodology is adapted for conditioning. Conditioned OBM is customized for fluvial reservoirs containing channels, levees, oxbow lakes, crevasse splays and flood plains. The modeling is conducted in a grid-free way and channels are visualized in 3D coordinate system. Reasonable geologic complexity is reproduced in the conditioned models. In addition to that, the methodology can be easily applied to the modeling of other objects.

5.1 Summary of contributions

The main contributions of the thesis include: (1) the parameterization of complicated objects and the correlation between objects, (2) the development of an algorithm to optimize objects for the purpose of conditioning, (3) the work flow to simulate a conditioned single-layered model of multiple types of objects and (4) two work flows to simulate a channelized reservoir comprised of multiple layers.

5.1.1 Parameterization of fluvial objects

Four types of objects are parameterized including channels, levees, oxbow lakes and crevasse splays. Channel and levee models can be sinuous and are capable of wandering backward. Their profiles are asymmetric and vary in different locations. Moreover, a stacking feature is optional for channels and levees. Oxbow lakes are mostly crescent in shape. A crevasse splay is modeled as a composition of several crevasse courses.

The boundaries of these 3D objects are fully described in their parameter sets. The objects can deform according to how the values of parameters are changed. In the simultaneous modeling of the four types of objects, they are located together subject to simple physical and geologic rules. The parameterizations of objects have the complexity to honor geologic realism while the calculational burden in optimizations remains reasonable.

5.1.2 Conditioning objects

Implicit filtering is used to help achieve conditioning and can locally minimize the value of any objective function under the constraints of parameter value. In the area of this research, the objective function measures the conditioning level and geologic realism. The contribution of this work is the design of the specific objective function that incentivizes the geologic realism of objects during the optimization procedure. Not every run of optimization generates qualified objects and unqualified ones are eliminated. Objective functions for several types of objects are built separately. Sinuous channels and levees shift locations and change their sizes while not crossing over themselves after optimization. Oxbow lakes resemble channels. Since a crevasse splay is detached into crevasse courses, the objective function is also separately assessed for crevasse courses. Crevasse courses rotate around crevasse points and shrink to avoid passing wells of mismatching facies. The courses twist so that the crevasse splays mimic natural appearances.

5.1.3 Work flow for single-layer simulation

Well data of four types of facies including channel, levee, crevasse splay and oxbow lake are conditioned sequentially. For each type of facies, a large number of conditioned objects are generated and stored in a library. A set of objects are selected from the library, which condition all well data of that facies in one layer of the modeling domain. The selection of objects to jointly form a realization is formulated as an integer linear programing problem. Channels and levees are selected first. Based on that, crevasse splays and oxbow lakes are simulated and selected so that they are attached to channels at suitable locations. The proportions of objects are controlled through the number of the objects.

5.1.4 Simulation of channelized reservoirs

Two case studies are presented. Channelized reservoirs comprised of multiple layers are modeled considering the geology. One case study is customized for bifurcating style channels and the other is for braided style channels. Different work flows are set up for the modeling of the two reservoirs. Enforcing well continuity is possible if known. The proportions of channels are controlled through the number of channels in each layer. The constraints of a 1D trend and the location range of channels can be added. More than 95% of channel facies well data can be conditioned in the simulations.

Conditioning performance can be improved by simulating more candidates objects in the library.

5.2 Future work

Even though a number of geologic features have been integrated, others are possible. To advocate the application of the proposed modeling methodology, further studies in the following aspects may be helpful.

5.2.1 Proportion

The proportions of channels in modeling domains are controlled through the number of channels. It is easy for programming but the proportion cannot be changed in a gradual manner. Every additional channel populated into the domain increases a large number of proportion, especially for long continuous channels.

To increase the channel proportion gradually, one idea is to partially change the size of channels at locations without well data. Currently a channel has the constant width and depth. In reality, these values varies at different locations along the river due to the different topography. If the width and depth parameters are set independently for each segment on a channel, they can be easily modified after the optimization so that the proportion requirement is satisfied without causing violation of well data.

Another methodology to control the proportion in a realization is rejection sampling. The method designs an objective function measuring the proportion of channels in the realization. When using different sets of channels selected from the candidate library, the proportion changes and the objective function value changes accordingly. The set of channels that obtain the best objective function, i.e. the proportion of the model being the closest to the proportion requirement, are selected for the final realization.

5.2.2 Stratification and data formating

Stratification can add strong constraints on channel complexes such as the thickness, location range and proportion to support the modeling of channelized reservoirs. The stratification divides a reservoir into thinner layers and alleviates the conditioning difficulty. However, the case studies in this thesis do not get the stratigraphic surface data for channel complexes. The layer thickness in the modeling is assigned according to the statistics of the data samples and a little surmise. If the channel complexes data is available, it can be integrated into the proposed modeling procedure easily but significantly improves the geologic realism of the modeling. Besides, well data can be vertically divided into layers according to the stratigraphic surface data. The data formating about combination or invalidation of well segments can have more supporting information.

5.2.3 Other reservoir types

This thesis only considers the modeling of channelized reservoirs. However the environment for the application of the proposed methodology is not restricted to fluvial reservoirs. It can be applied on any type of object with known geometry such as lobes in deep-water reservoirs and veins within rock mass. After a slight modification to the objective function, a new type of object can be conditioned. As illustrated in this thesis, the modeling is customized for a wide range of reservoir styles. The practitioner needs to have knowledge of the type of objects in the modeling reservoir. The simulation work flow can be applied to many different geologic settings.

Bibliography

Abreu, V., Sullivan, M., Pirmez, C. & Mohrig, D. (2003). Lateral accretion packages (LAPs): an important reservoir element in deep water sinuous channels. *Marine and Petroleum Geology* 20(6), 631–648.

Adams, P. N., Slingerland, R. L. & Smith, N. D. (2004). Variations in natural levee morphology in anastomosed channel flood plain complexes. *Geomorphology* 61(1), 127–142.

Allen, J. R. (1965). A review of the origin and characteristics of recent alluvial sediments. *Sedimentology* 5(2), 89–191.

Alpak, F. O., Barton, M. D. & Naruk, S. J. (2013). The impact of fine-scale turbidite channel architecture on deep-water reservoir performance. *AAPG bulletin* 97(2), 251–284.

Arco, L. J., Adelsberger, K. A., Hung, L. & Kidder1, T. (2006). Alluvial geoarchaeology of a Middle Archaic mound complex in the lower Mississippi valley, USA. *Geoarchaeology New York* 21(6), 591.

Assine, M. L., Corradini, F. A., Nascimento Pupim, F. do & McGlue, M. M. (2014). Channel arrangements and depositional styles in the São Lourenço fluvial megafan, Brazilian Pantanal wetland. *Sedimentary Geology* 301, 172–184.

Babonneau, N., Savoye, B., Cremer, M. & Bez, M. (2010). Sedimentary architecture in meanders of a submarine channel: detailed study of the present Congo turbidite channel (Zaiango project). *Journal of Sedimentary Research* 80(10), 852–866.

Bertoncello, A. (2011). Conditioning Surface-based Models to Well and Thickness Data. PhD thesis. Stanford University.

Bertoncello, A., Sun, T., Li, H., Mariethoz, G. & Caers, J. (2013). Conditioning surface-based geological models to well and thickness data. *Mathematical Geosciences* 45(7), 873–893.

Boisvert, J. B. & Pyrcz, M. J. (2014). Conditioning 3D Object Based Models to a Large Number of Wells: A Channel Example. In: *Mathematics of Planet Earth*. Springer, 575–579.

Boisvert, J. B., Pyrcz, M. J. & Deutsch, C. V. (2007). Multiple-point statistics for training image selection. *Natural Resources Research* 16(4), 313–321.

Bridge, J. S. (2009). *Rivers and floodplains: forms, processes, and sedimentary record*. John Wiley & Sons.

Brierley, G. J., Ferguson, R. J. & Woolfe, K. J. (1997). What is a fluvial levee? *Sedimentary Geology* 114(1), 1–9.

Cazanacli, D. & Smith, N. D. (1998). A study of morphology and texture of natural levees Cumberland Marshes, Saskatchewan, Canada. *Geomorphology* 25(1), 43–55.

Chan, A. H. & So, D. K. (2006). Measurement and quantification of visual lobe shape characteristics. *International Journal of Industrial Ergonomics* 36(6), 541–552.

Cressie, N. (1993). Statistics for spatial data: Wiley series in probability and statistics. *Wiley-Interscience New York* 15, 16.

Davidson, S. K., Hartley, A. J., Weissmann, G. S., Nichols, G. J. & Scuderi, L. A. (2013). Geomorphic elements on modern distributive fluvial systems. *Geomorphology* 180, 82–95.

Deptuck, M. E., Steffens, G. S., Barton, M. & Pirmez, C. (2003). Architecture and evolution of upper fan channel-belts on the Niger Delta slope and in the Arabian Sea. *Marine and Petroleum Geology* 20(6), 649–676.

Deptuck, M. E., Sylvester, Z., Pirmez, C. & OByrne, C. (2007). Migration–aggradation history and 3-D seismic geomorphology of submarine channels in the Pleistocene Benin-major Canyon, western Niger Delta slope. *Marine and Petroleum Geology* 24(6), 406–433.

Deutsch, C. V. & Tran, T. T. (2002). FLUVSIM: a program for object-based stochastic modeling of fluvial depositional systems. *Computers & Geosciences* 28(4), 525–535.

Deutsch, C. V. (2006). A sequential indicator simulation program for categorical variables with point and block data: BlockSIS. *Computers & Geosciences* 32(10), 1669–1681.

Deutsch, C. V. & Wang, L. (1996). Hierarchical object-based stochastic modeling of fluvial reservoirs. *Mathematical Geology* 28(7), 857–880.

Dieras, P. L., Constantine, J. A., Hales, T., Piégay, H. & Riquier, J. (2013). The role of oxbow lakes in the off-channel storage of bed material along the Ain River, France. *Geomorphology* 188, 110–119.

Dubiel, R. F. (1992). *Sedimentology and depositional history of the Upper Triassic Chinle Formation in the Uinta, Piceance, and Eagle basins, northwestern Colorado and northeastern Utah*. 1787. US Department of the Interior, US Geological Survey.

Ferguson, R. I. (1976). Disturbed periodic model for river meanders. *Earth Surface Processes* 1(4), 337–347.

Gibling, M. R. (2006). Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. *Journal of sedimentary Research* 76(5), 731–770.

Gouw, M. J. & Berendsen, H. J. (2007). Variability of channel-belt dimensions and the consequences for alluvial architecture: observations from the Holocene Rhine–Meuse Delta (the Netherlands) and Lower Mississippi Valley (USA). *Journal of Sedimentary Research* 77(2), 124–138.

Griva, I., Nash, S. G. & Sofer, A. (2009). *Linear and nonlinear optimization*. Siam.

Guardiano, F. B. & Srivastava, R. M. (1993). Multivariate geostatistics: beyond bivariate moments. In: *Geostatistics Troia92*. Springer, 133–144.

Hartley, A. J., Weissmann, G. S., Nichols, G. J. & Warwick, G. L. (2010). Large distributive fluvial systems: characteristics, distribution, and controls on development. *Journal of Sedimentary Research* 80(2), 167–183.

Hassanpour, M. M., Pyrcz, M. J. & Deutsch, C. V. (2013). Improved geostatistical models of inclined heterolithic strata for McMurray Formation, Alberta, Canada. *AAPG bulletin* 97(7), 1209–1224.

Hauge, R., Holden, L. & Syversveen, A. R. (2007). Well conditioning in object models. *Mathematical Geology* 39(4), 383–398.

Henrion, V., Caumon, G. & Cherpeau, N. (2010). ODSIM: an object-distance simulation method for conditioning complex natural structures. *Mathematical Geosciences* 42(8), 911–924.

Holden, L., Hauge, R., Skare, Ø. & Skorstad, A. (1998). Modeling of fluvial reservoirs with object models. *Mathematical Geology* 30(5), 473–496.

Journel, A. B. & Alabert, F. G. (1989a). Focusing on spatial connectivity of extreme-valued attributes: Stochastic indicator models of reservoir heterogeneities. *AAPG Bull.;(United States)* 73(CONF-890404-).

Journel, A. G. & Alabert, F. (1989b). Non-Gaussian data expansion in the earth sciences. *Terra Nova* 1(2), 123–134.

Journel, A. G. (1983). Nonparametric estimation of spatial distributions. *Journal of the International Association for Mathematical Geology* 15(3), 445–468.

Journel, A. G., Alabert, F. G., et al. (1990). New method for reservoir mapping. *Journal of Petroleum technology* 42(02), 212–218.

Kelley, C. T. (2011). *Implicit filtering*. Vol. 23. SIAM.

Le Loch, G. & Galli, A. (1997). Truncated plurigaussian method: theoretical and practical points of view. *Geostatistics Wollongong* 96(1), 211–222.

Leuangthong, O., Khan, K. D. & Deutsch, C. V. (2011). *Solved problems in geostatistics*. John Wiley & Sons.

Li, J. & Bristow, C. S. (2015). Crevasse splay morphodynamics in a dryland river terminus: Río Colorado in Salar de Uyuni Bolivia. *Quaternary International*.

Li, Z. & Fang, C. (2011). Limit sinuosity for river bends. *Journal of China Institute of Water Resources and Hydropower Research* 3, 3.

Macauley, R. V. & Hubbard, S. M. (2013). Slope channel sedimentary processes and stratigraphic stacking, Cretaceous Tres Pasos Formation slope system, Chilean Patagonia. *Marine and Petroleum Geology* 41, 146–162.

Mackey, S. D. & Bridge, J. S. (1995). Three-dimensional model of alluvial stratigraphy: theory and application. *Journal of Sedimentary Research* 65(1).

Matheron, G., Beucher, H., De Fouquet, C., Galli, A., Guerillot, D., Ravenne, C., et al. (1987). Conditional simulation of the geometry of fluvio-deltaic reservoirs. In: *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

McHargue, T. et al. (2011). Architecture of turbidite channel systems on the continental slope: patterns and predictions. *Marine and Petroleum Geology* 28(3), 728–743.

Miall, A. D. (1996). *The geology of fluvial deposits:...* Springer Verlag Berlín.

Miall, A. D. (2014). *Fluvial depositional systems*. Springer.

Miller, J. K., Sun, T., Li, H., Stewart, J., Genty, C., Li, D., Lyttle, C., et al. (2008). Direct modeling of reservoirs through forward process-based models: Can we get there? In: *International petroleum technology conference*. International Petroleum Technology Conference.

Milliken, K., Blum, M. & Martin, J. (2012). *Scaling Relationships in Fluvial Depostional Systems*. URL: http://www.searchanddiscovery.com/documents/2012/30245milliken/ndx_milliken.pdf (visited on 04/01/2016).

Mutti, E. & Normark, W. R. (1991). An integrated approach to the study of turbidite systems. In: *Seismic facies and sedimentary processes of submarine fans and turbidite systems*. Springer, 75–106.

Nanz Jr, R. H. (1954). Genesis of Oligocene Sandstone Reservoir, Seeligson Field, Jim Wells and Kleberg Counties, Texas. *AAPG Bulletin* 38(1), 96–117.

Oliver, D. S. (2002). Conditioning channel meanders to well observations. *Mathematical Geology* 34(2), 185–201.

Posamentier, H. W. (2003). Depositional elements associated with a basin floor channel-levee system: case study from the Gulf of Mexico. *Marine and Petroleum Geology* 20(6), 677–690.

Pyrcz, M. J. & Deutsch, C. V. (2005). Conditioning event-based fluvial models. In: *Geostatistics Banff 2004*. Springer, 135–144.

Pyrcz, M. J. & Deutsch, C. V. (2014). *Geostatistical reservoir modeling*. Oxford university press.

Pyrcz, M. J., McHargue, T., Clark, J., Sullivan, M. & Strebelle, S. (2012). Event-based geostatistical modeling: description and applications. In: *Geostatistics Oslo 2012*. Springer, 27–38.

Pyrcz, M. J. (2005). Integration of geologic information into geostatistical models. PhD thesis. University of Alberta.

Pyrcz, M. J., Boisvert, J. B. & Deutsch, C. V. (2009). ALLUVSIM: A program for event-based stochastic modeling of fluvial depositional systems. *Computers & Geosciences* 35(8), 1671–1685.

Ringrose, P. & Bentley, M. (2015). *Reservoir model design*. Springer.

Rittenour, T. M., Blum, M. D. & Goble, R. J. (2007). Fluvial evolution of the lower Mississippi River valley during the last 100 ky glacial cycle: Response to glaciation and sea-level change. *Geological Society of America Bulletin* 119(5-6), 586–608.

Sadeghi, S. & Boisvert, J. B. (2015). Optimization of variograms used for truncated plurigaussian simulation. *Bulletin of Canadian Petroleum Geology* 63(4), 345–357.

Shmaryan, L. E. & Deutsch, C. V. (1999). Object-based modeling of fluvial/deepwater reservoirs with fast data conditioning: methodology and case studies. In: *SPE annual technical conference*, 877–886.

Smith, L. M. (1996). Fluvial geomorphic features of the Lower Mississippi alluvial valley. *Engineering Geology* 45(1), 139–165.

Stouthamer, E. (2001). Sedimentary products of avulsions in the Holocene Rhine–Meuse Delta, the Netherlands. *Sedimentary Geology* 145(1), 73–92.

Strebelle, S. (2002). Conditional simulation of complex geological structures using multiple-point statistics. *Mathematical Geology* 34(1), 1–21.

Strébelle, S. & Journel, A. G. (2000). Sequential simulation drawing structures from training images.

Sylvester, Z., Pirmez, C. & Cantelli, A. (2011). A model of submarine channel-levee evolution based on channel trajectories: Implications for stratigraphic architecture. *Marine and Petroleum Geology* 28(3), 716–727.

Thomas, R. G., Smith, D. G., Wood, J. M., Visser, J., Calverley-Range, E. A. & Koster, E. H. (1987). Inclined heterolithic stratificationterminology, description, interpretation and significance. *Sedimentary Geology* 53(1-2), 123–179.

Viseur, S., Shtuka, A., Mallet, J.-L., et al. (1998). New Fast, Stochastic, Boolean Simulation of Fluvial Deposits. In: *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers.

Walker, R. G. (1990). Facies modeling and sequence stratigraphy: perspective. *Journal of Sedimentary Research* 60(5).

Weimer, P. & Slatt, R. M. (2004). *Petroleum systems of deepwater settings*. Society of Exploration Geophysicists.

Wietzerbin, L. J., Mallet, J. L., et al. (1994). Parameterization of complex 3D heterogeneities: a new CAD approach. *SPE Computer Applications* 6(3), 11–18.

Wingate, D., Kane, J., Wolinsky, M. & Sylvester, Z. (2015). A New Approach for Conditioning Process-Based Geologic Models to Well Data. *Mathematical Geosciences*, 1–27.

Appendix A

Implicit filtering

The optimization algorithm used in the modeling programs is implicit filtering, a deterministic sampling method for bound-constrained optimization. It is designed to minimize functions which are noisy, non-smooth, possibly discontinuous or random, and which may not even be defined at all points in design space (Kelley, 2011).

This optimization algorithm uses the sampling and interpolation methods. In sampling methods, the objective function is evaluated at a set of separate feasible solutions. A new set of feasible solutions are sampled around the current optimal solution. The sampling solutions are decided through the iterations and do not require gradient information, therefore sampling methods can be used on discontinuous functions. Interpolatory method calculate the first (and possibly second) derivative for the variables based on sampling by interpolation. The obtained gradient can speed up the convergence.

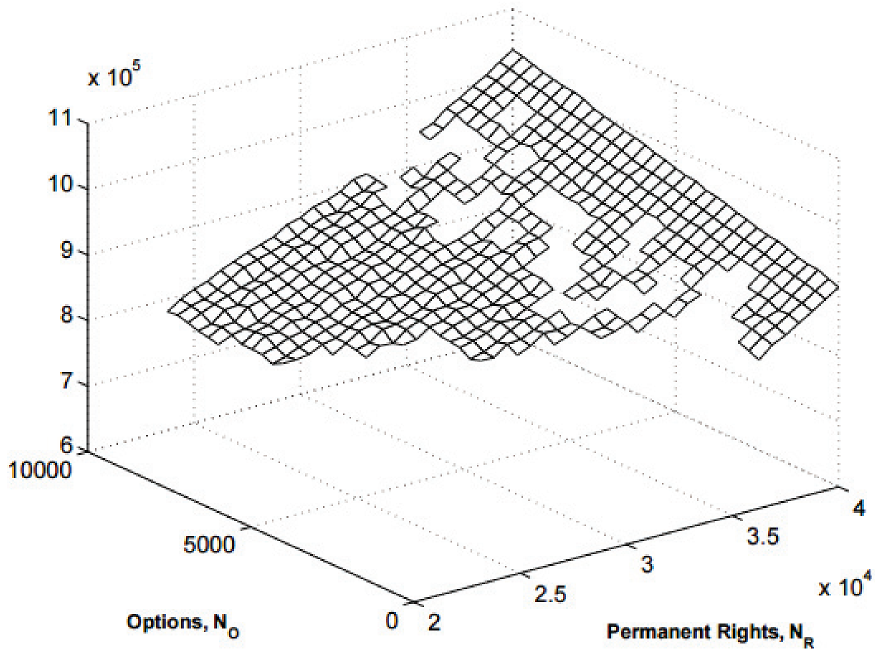


Figure A.1: A typical problem that can be solved by Implicit filtering (Kelley, 2011).

Figure A.1 describes the optimization landscape of the problems applicable to implicit filtering. A landscape is a plot of a function against two of the independent variables, (Kelley, 2011). There are gaps on the landscape. Regions near the optimum are oscillatory. The coordinate search algorithm in sampling methods can step over the gaps and the local minima near the global optimum.

In MATLAB, the program calls the implicit filtering function through the keyword $imfil$ (Equation A.1). The first input of the function, $x0$, is a vector of parameters that need to be optimized. In this thesis, $x0$ is a set of parameters that fully describes a fluvial object. The optimized values are given out in x. f is the objective function with adapted form of Equation A.2. It evaluates the conditioning level and the geologic realism in the modeling. The evaluation value is given in $fout$. The program stops the computations during the optimization when $budget$ is exceeded. $bounds$ are the constraints on parameters $x0$, including upper bound values and lower bound values. $hisout$ gives the optimized values of $f(x)$ with corresponding $x0$. It also records the values of $f(x)$ obtained during the optimization.

$$[x, histout] = imfil(x0, f, budget, bounds) \tag{A.1}$$

$$[fout, ifail, icount] = f(x) \tag{A.2}$$

Equation A.1 optimizes one object each time. The program loops over the function hundreds or thousands of times to generate enough candidate objects. The optimization using Equation A.1 is totally independent for each object, except the channel stacking pattern. Although a pattern contains multiple elements, they are regarded as one object. The interaction between different objects are achieved through other algorithms.

In this thesis, $f(x)$ in A.2 is different for each type of object. The conditioning level and the geologic realism are assessed in the function. The conditioning level of an object is based on match and mismatch with facies data interpreted from the available wells. The part of $f(x)$ measuring the geologic realism really depends on the type of the object.

Appendix B

Programs

B.1 Conditioned single-layer simulation of a reservoir consisting of full-size channels

Table B.1: Parameters for the program condichan.

Num.	Parameter
1	channel width:depth ratio
2	channel shift in X direction
3	channel shift in Y direction
4	channel shift in Z direction
5	surface elevation
6	channel width
7	asymmetric rate of channel profiles
8	X/Y coordinates of a set of control nodes for centerline
9	weight of match in the objective function
10	weight of mismatch in the objective function
11	weight of buffer in the objective function
12	the number of elements in a stacking pattern
13	the organized level of a stacking pattern
14	average aggradation distance between each stacked element
15	average migration distance between each stacked element
16	wavelength and amplitude for channel sinuosity
17	maximum length of a channel
18	minimum length of a channel
19	whether or not to plot cross sections for well data
20	the number of segments of a channel controlling the modeling precision
21	a percentage as conditioning requirement of a single well
22	a percentage as violation limit on a single well
23	the desired number of channels in the domain

Parameter No. 1 is used to calculate channel depth from channel width. No. 5 is the top surface elevation for channels. No. 7 is used to calculate the deviation on channel profiles (Figure 2.10). No. 8 is a set of coordinates of points as in Figure 2.8. Information for No. 9-10 can be found in Equation 3.1. No. 13 is used in Equation 2.2. No. 14-15 describe the relative location between elements in a stacking pattern. No. 18 is used when conditioning is difficult and the object size is reduced to alleviate the difficulty. No. 19 controls the display of conditioning results, i.e. plot in 3D or 2D cross sections, to plot conditioned channels separately or to plot a simulation of the entire domain. No. 20 controls the precision in the optimization. A channel is discretized into segments. A channel appears blocky when the number of segments is low. If the number is too high, the amount of calculation in optimization increases significantly. No.21-22 are described in Section 3.3.3. No. 23 controls the proportion of channels in the domain.

The program, condichan, assigns default values for all the parameters (Table B.1). If users have a specific domain, the parameters can be constrained. Users can provide fixed values for parameters No. 9 to No. 23 and the program does not change the values. For parameters No. 1 to No. 8, users can provide ranges for the parameters and the program adjusts their values within the ranges to find an optimized object.

B.2 Conditioned single-layer simulation of a reservoir consisting of fragmented channels

This program, condifrag, generates the model based on the modeling result of Program B.1. Many of the parameters are the same, except a length range for the fragmented channels is added.

B.3 Conditioned single-layer simulation of a reservoir consisting of multiple types of objects

Parameters No. 1-3 are used to calculate levee size in Figure 2.11. No. 4-8 are parameters for crevasse splay (Figure 2.14). No. 4-5 decide the location of a crevasse splay. No. 5-6 decide the shape and sinuosity of a crevasse splay. No. 12 controls the relative distance between oxbow lakes and crevasse splays so that in the same system (the minimum modeling unit in the conditioning program) they do not overlap.

This program, condimultype, generates objects other than channels. Besides the parameters of channels in Program B.1, some more parameters (Table B.2) are used for the modeling of other objects. The parameters No. 1 to No. 9 in Table B.2 are optimized through the optimization. The parameters No. 10 to No. 13 have fixed value during the optimization.

Table B.2: Additional parameters for the program condimultype besides those in Table B.1.

Num.	Parameter
1	a ratio of levee height (above surface) to channel depth
2	a ratio of levee depth (below surface) to channel depth
3	a ratio of levee width to channel depth
4	X/Y coordinates of a crevasse point
5	X/Y coordinates of the distal end of the crevasse course
6	width of the crevasse course
7	a set of ratios for the shifts of crevasse course control node
8	a ratio of crevasse course depth to channel depth
9	X/Y coordinates of a set of control nodes for centerlines of oxbow lakes
10	the number of crevasse splays in the domain
11	the number of oxbow lakes in the domain
12	the desired distance between oxbow lakes and crevasse splays
13	the curve requirement of a channel bend to generate crevasse splays

B.4 Conditioned simulation of a reservoir of bifurcating channels

Parameters No. 1-16 and 19-20 are similar to variables in Table B.1 and are described there. No. 17 controls the stopping criteria of objective function value in the optimization. When exact conditioning can not be achieved, the optimization requirement in the objective function is relaxed. The relaxation amount per iteration and the total relaxation amount allowed are controlled. No. 18 controls the consideration of the locations of well data when initializing the center line of a channel. No. 22 controls the width of the cuboids (Figure 4.3) for each channel.

This program, condibifur, simulates a reservoir with a style of bifurcating channels. The parameters modeled are listed in Table B.3. Parameters No. 1 to No. 9 are optimized with their values between given ranges. The values of parameters No. 10 to No. 20 are fixed during the modeling.

B.5 Conditioned simulation of a reservoir of braided channels

This program, condireser, generates simulation consisting of multiple layers of the simulation from Program B.1. The parameters are the same, except that a set of elevations are added to divide the reservoir and that a boundary of channel complex is added for

Table B.3: Parameters for the program condibifur.

Num.	Parameter
1	channel width:depth ratio
2	channel shift in X direction
3	channel shift in Y direction
4	channel shift in Z direction
5	surface elevation for each layer
6	channel width
7	asymmetric rate of channel profiles
8	X/Y coordinates of a set of control nodes for a channel centerline
9	weight of match in the objective function
10	weight of mismatch in the objective function
11	weight of buffer in the objective function
12	the number of elements in a stacking pattern in each layer
13	the organized level of a the stacking pattern
14	average aggradation distance between each stacked element
15	average migration distance between each stacked element
16	wavelength and amplitude for channel sinuosity
17	the relaxation level when the modeling can not be fully conditioned
18	whether or not to use data-driven centerlines
19	whether or not to plot cross sections for well data
20	the number of segments of a channel controlling the modeling precision
21	a set of wells that show connectivity between each other
22	the activity range of a bifurcating channel

trend control. Users can choose to plot model in a 3D coordinate system or show the conditioning results on 2D cross sections.