University of Alberta

Optimal Drainage Area and Surface Pad Positioning for SAGD Development

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mining Engineering

Department of Civil and Environmental Engineering

Spring 2011
Edmonton, Alberta

Abstract

The optimal allocation of drainage areas and surface pads for SAGD development is challenging because of several surface and subsurface constraints. It becomes more complex due to uncertainty in reservoir properties. This Thesis presents a heuristic methodology to maximize the recovery of bitumen by optimal placement of drainage areas and surface pads. Multiple realizations of reservoir variables are used to quantify the uncertainty. The optimization problem can be seen as space packing and optimal allocation of well pairs. Space packing ensures the maximum access to available resource and optimal allocation of well pairs guarantees the maximum combined recovery over the field. A DASP (drainage area surface pad) software tool is developed and examples are presented to explain the optimization steps. Optimization considers the compact and non overlapping arrangements of drainage areas. Problem is converted into unconstrained optimization one by including penalties for different constraints.

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Nomenclature

List of Symbols

ϕ	Porosity, in proportions.
S_w	Water saturation, in proportions.
L_{DA}	Length of drainage area (m).
W_{DA}	Width of drainage area (m).
n_{well}	Total number of well pairs in a drainage area.
r_{SP}	Radius of circular surface pad (m)
d_0	Ideal distance of surface pad from drainage area (m).
d_l	Distance tolerance of SP from its ideal position (m).
d_p	Distance tolerance of SP from its ideal position (m).
(x_i, y_i, θ_i)	Location (x_i, y_i) and orientation (θ_i) of DA.
WS	Well Spacing, horizontal distance between adjacent well pairs of SAGD.
$R_{i,j}^{aval}$	Mean NCB thickness (m) over jth well pair of ith DA.
$R_{i,j}^{recov}$	Mean NCB thickness (m) of recoverable bitumen for jth well pair of ithDA.
ar_c	Fractional areal of cth cell inside polygon.
$pen_{i,j}^{base}$	Base penalty factor for jth well pair of ithDA.
Pen_i^{SP}	Surface pad penalty factor for ith SP.
Pen_i^{tz}	Thief zone penalty factor for ith DA.
$Pen_{i,j}^{out}$	ROI penalty for jth well pair of ithDA.
N_{DA}	Total number of DAs used in the optimization.

f_i^{obj}	Objective function value of ith DA.
F^{obj}	Total objective function over all DAs.
T_{opt}	Translational optimization step. Translate entire group of DA for maximum objective function.
S_{opt}	Sliding Optimization step. Slide individual rows for maximum objective function.
R_{opt}	Rotational optimization step. Rotate entire group of DA at its centre for maximum objective function.
R_{θ}	Rotate entire group of DA at its centre by an angle θ in counter clockwise direction.
n_{eff}	Total number of well pairs affected by thief zone.
λ	Base penalty factor.
ft	Thief zone penalty factor.

Acronyms

BCB	Bottom Continuous Bitumen, Elevation in meters.
DA	Drainage Area, Collection of grouped SAGD well pairs
GCB	Gross Continuous Bitumen, thickness in meters.
NCB	Net continuous Bitumen, thickness in meters.
ROI	Region of Interest, A part of reservoir planned for SAGD development.
SAGD	Steam Assisted Gravity Drainage, in situ method of bitumen recovery.
SOR	Steam to Oil Ratio (m3/m^3).
SP	Surface Pad, a surface facility for drilling SAGD well pairs.
TCB	Top continuous Bitumen, elevation in meters.
TZ	Thief zone, A part of reservoir containing underground water. Different operating pressure is required to operate wells in these regions.

Chapter 1 - Introduction

Alberta's deposits of heavy oil are the world's second largest proven reserve of oil [12]. The current estimate of crude oil reserve is 27 billion cubic meters [11]. Alberta's heavy oil deposits are divided into three regions based on their geographic and geologic setting - Athabasca, Cold Lake and Peace River. Only 20% of this reserve is recoverable by mining [12]. The remaining 80% will be recovered by in situ production methodologies [12]. Currently, the two main potential methods of in situ production are cyclic steam simulation and steam assisted gravity drainage process (SAGD) [10]. SAGD is the most common and effective for in situ production of bitumen. Several SAGD projects including Surmont, Christina Lake, Sunrise, and Hangingstone are in the development stage. Additional wells are being planned and drilled every year for production. Almost USD $170 billion of investment is under way or proposed in heavy oil development [12].

SAGD well pairs are drilled in areas of economically recoverable bitumen deposit where deposit is too deep for mining. A SAGD developable area is determined on the basis of several technical and economical factors. An important economic factor is the anticipated steam to oil ratio (SOR) [12]. Several reservoir properties such as porosity, horizontal and vertical permeability, and deposit thickness are considered together to determine if an area is suitable for SAGD development. A region is considered profitable for SAGD development if the net pay thickness of good reservoir exceeds some minimum value. The minimum net pay thickness for economic recovery depends on the permeability of reservoir. A less thick deposit with good permeability can be better than a relatively thicker one with bad permeability. The current practice of SAGD development ([8] and [9]) suggests that a SAGD developable area will have several well pairs connected to the same surface facility. A collection of well pairs tied to the same surface facility will be called a drainage area (DA). Generally compact layouts of DAs are used to access all the reserve in a developable area. Gaps between DAs result in a loss of resource. One challenge is that the boundaries of the developable area may expand or shrink with time based on oil price and/or technological advancement. Additional information about the reservoir properties will be gained as time goes on and this may also affect the span of area for development. An important engineering challenge is to locate the positions of surface pads for the facilities and drainage areas (DAs) inside a developable region. The production rate and recovery factor of bitumen is highly affected by the areal and vertical positioning of the well pairs among other factors [12]. Moreover, the uncertainty in the reservoir properties must be considered in the development plan since exploratory wells are relatively widely spaced prior to development.

The problem of optimal positioning of surface pads and drainage areas for maximum recovery is new in academia. There are no papers on the optimization of the positioning of DAs and related facilities. There is research related to optimization of elevation of individual wells [14]; however, the optimal elevation can only be determined after the DA has been located. The industry standard approach is to layout the DAs and surface facilities by hand. Although the judgment of a qualified engineer (and the entire subsurface characterization team) will surely lead to good results, there is a hope that a more rigorous and automatic optimization will add some incremental improvement.

The optimization problem can be divided in two parts. The first part is a space packing problem that insures the maximum accessibility of available resources. And the second part is to find the optimal positions of well pairs to maximize the recovery. This thesis will present a methodology for optimal positioning of drainage areas for SAGD development. Different constraints associated with drainage area placement are considered in the optimization. An objective function will be formulated to capture the deemed important constraints. A heuristic optimization methodology will be discussed to get a near optimal solution. The developed optimization tool will be discussed with synthetic examples and realistic case studies to validate the methodology. Optimization is performed to maximize the primary reservoir variable which is measure of resource expressed in net bitumen thickness (NCB) or original oil in place (OOIP). NCB has been considered as primary variable for optimization in this thesis.

1.1 Background

1.1.1 Bitumen deposit

A bitumen deposit is characterized by several reservoir variables that will be reviewed here. Bitumen is found in a porous medium such as sand stone and covered with impermeable rock types such as shale. The surface defining the top limit of the bitumen deposit will be referred to as the top continuous bitumen (TCB) and the lower surface will be referred to as the bottom continuous bitumen (BCB). Determining the locations of these bounding surfaces is not simple in practice. Well log data are available from exploratory drilling. The most common way to pick boundary limit for TCB and BCB is by analyzing the permeability and saturation of oil and water. Sometimes there is no clear indication of location of BCB and TCB. The BCB and TCB picks are chosen either manually or by some automatic algorithm. The difference between TCB and BCB will be referred to as gross continuous bitumen (GCB). The net continuous bitumen (NCB) is the total thickness of within the GCB that meets some minimum criteria of reservoir quality. NCB can be calculated from GCB by removing the thickness that has very low permeability and oil saturation (no bitumen content). **Figure 1.1** shows a schematic representation of BCB, TCB, GCB, and NCB variables for a bitumen deposit. The most important variable for technical and economic evaluation is NCB; the quality of the reservoir can be represented in terms of NCB. A higher value of NCB indicates more bitumen volume in deposit. The well logs also provide the water saturation for different vertical intervals. The vertical and horizontal permeability are inferred from core data and well logs. Permeability is another important measure of reservoir quality. A highly permeable region will likely have high recovery of bitumen.

The quality of a bitumen deposit can be determined by four primary variables- NCB, porosity, water saturation and permeability. NCB gives the thickness of deposit; porosity is the void volume of rock filled with water and bitumen. A deposit with less water saturation has higher bitumen content. Permeability determines the flow quality of bitumen deposit. The volume of original oil in place (OOIP) is expressed in terms of net thickness, porosity and water saturation (**Equation 1.1**). V is the volume of bitumen deposit in consideration (in cubic meters for an arbitrary volume), ϕ is the porosity (in percentage), and S_w is the fractional water saturation of the void volume.

$$OOIP = V \cdot \phi \cdot (1 - S_w) \tag{1.1}$$

Different variables are calculated at well locations based on the well log data. Numerical models of different reservoir variables are generated over entire region. A single estimate or several realizations can be modeled by standard geostatistical methods. Either 2D or 3D models can be generated. This thesis considers only 2D models of reservoir properties in the optimization process. Methodology based on 3D models can be developed in future. To get 2D models, values of GCB, NCB, TCB, BCB, water saturation and permeability values are determined at well locations. A single map of estimate of each variable can be generated using kriging. The uncertainty in the estimate is given by the kriging error variance. Results based on a single map can be misleading since uncertainty is not accounted for. Several realizations of reservoir variables are used to quantify the uncertainty; there are standard geostatistical procedures for this purpose.

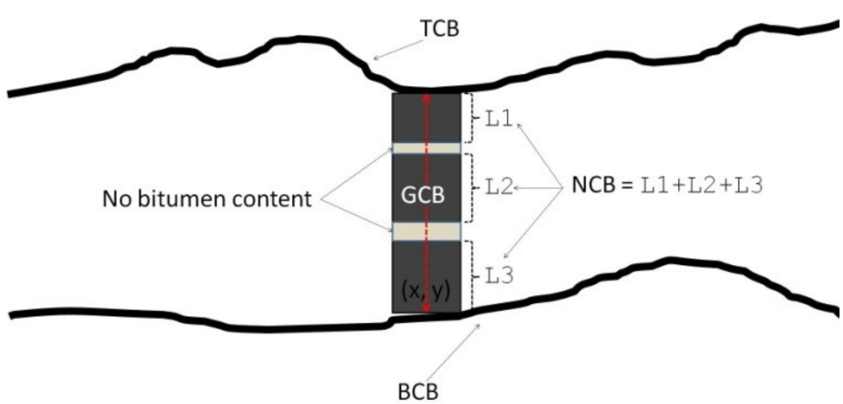

Figure 1.1 - Characterizing a bitumen deposit, not to scale.

1.1.2 Steam Assisted Gravity Drainage Process (SAGD)

SAGD is an in situ enhanced oil recovery method. It is suitable for relatively thick bitumen deposits at greater depth than can be mined economically. The basic idea of SAGD [2] is to reduce the viscosity of thick bitumen by injecting super heated steam into the deposit. Thermal energy from the steam melts the bitumen which recovered by a producing well. The basic idea of SAGD is illustrated in **Figure 1.2**. Two horizontal wells are drilled into the deposit. The vertical span between the two wells is nearly constant throughout the well length and is about 4 to 6 meters ([12], [13]). The start of the horizontal well is called the heel and the end is the toe. The upper well is used to inject the steam into the deposit (injector well) and the lower well (production well) collects the melted bitumen and transports it to the surface [3]. At the very beginning both wells are used to inject steam to form a steam chamber. Then, after a certain period the upper and lower wells are used for injection and production, respectively. SAGD is a gravity drainage process in which bitumen is recovered by means of gravity flow to the production well. Generally SAGD is a low pressure recovery [7]. The in-situ pressure of the bitumen deposit may change because of steam injection. SAGD is a slow but continuous recovery process. Different lengths of well pairs and different reservoir conditions may require different operating pressure. A 1200m long well pair is often operated at a higher pressure than a 800m well pair. Generally wells are drilled horizontally. The elevation differences between the heel and toe of the well are avoided. If a well is inclined upwards then a pressure loss in steam may result as a cost of overcoming gravity. Some thermal energy will be used to overcome the gravitational potential and the process will be suboptimal. If the wells are declined from heel to toe then a constant pressure cannot be maintained and the process is suboptimal.

1.1.3 Surface Pad and Drainage Area

Several well pairs can be drilled from a single surface facility. The surface area covered by surface facility can amount to 10 percent of the bitumen deposit accessed underground [12]. Surface facilities are developed on the surface and used to inject steam and collect bitumen from well pairs. These surface facilities are referred to as a surface pad (SP). A SP is used as a working station for SAGD production. Superheated steam is produced at a single surface facility sometimes called a central processing plant (CPF). Steam is transported to surface pads by pipe lines. A number of parallel well pairs are drilled from a single SP, referred to as a drainage area (DA). Generally all well pairs in a DA have the same length. Drainage areas can either be rectangular or square in shape. The well spacing (WS) is the horizontal distance between two adjacent well pairs. The well spacing is a function of operating pressure. A large well spacing is selected for higher operating pressure. The steam chamber of two adjacent wells should not interact with each other early in production. At the same time, similar pressures should be maintained in two adjacent steam chambers to avoid the collapse of one steam chamber. **Figure 1.3** illustrates the spatial arrangement of a DA and SP. It is possible to have different lengths of well pairs within a SAGD development area. But it is generally avoided to maintain operational simplicity. A shorter well pair is more common at the boundary of the deposit to allow flexible access to remaining resources. **Figure 1.4** shows some of the future plans of drainage areas and surface pads locations. These plans are published in resource management report of ERCB, Canada ([8] and [9]). It can be seen that all the well pairs (and drainage area) are of the same length. Also, there are no gaps between adjacent drainage areas which suggests a compact pattern of drainage areas are used to maximize the accessibility of available resources.

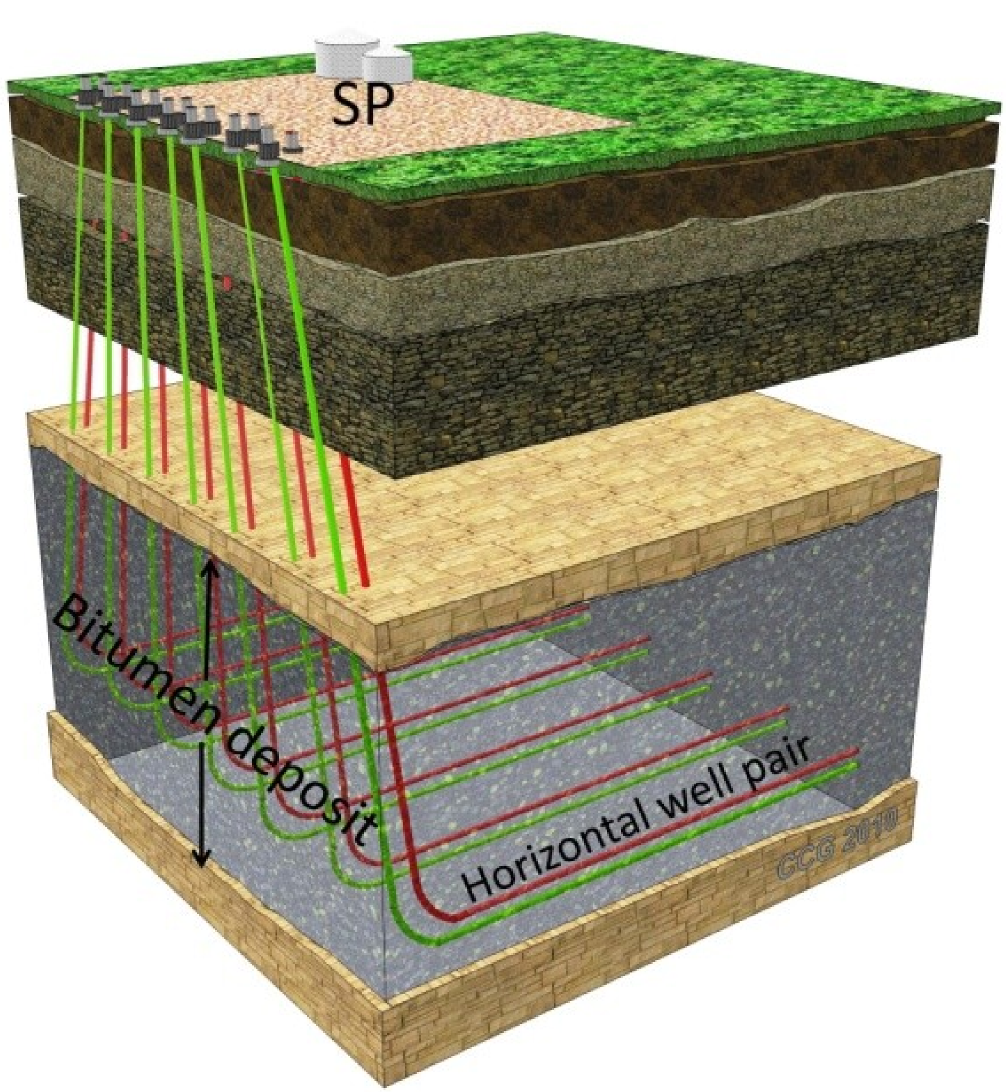

Figure 1.2 – Schematic representation of SAGD methodology, not to scale.

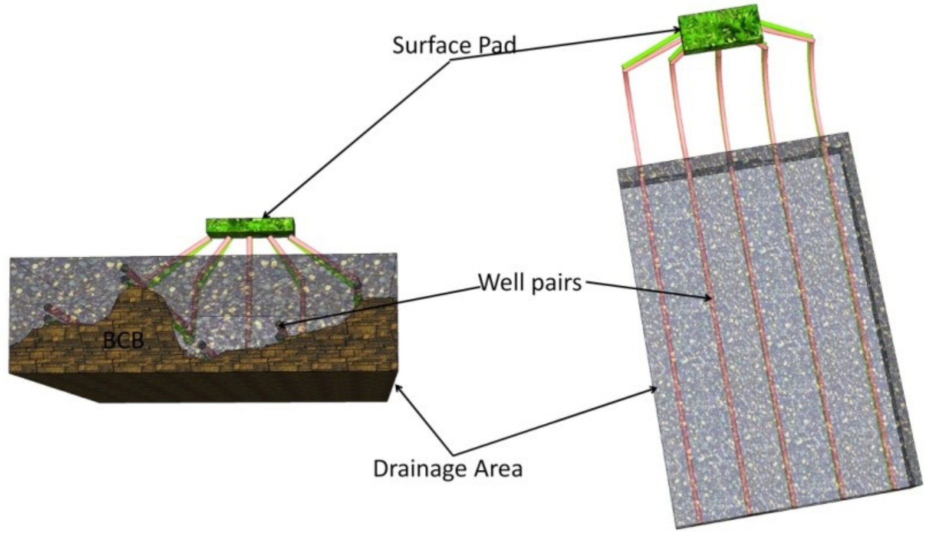

Figure 1.3 – Schematic representation of surface pad and drainage area, not to scale.

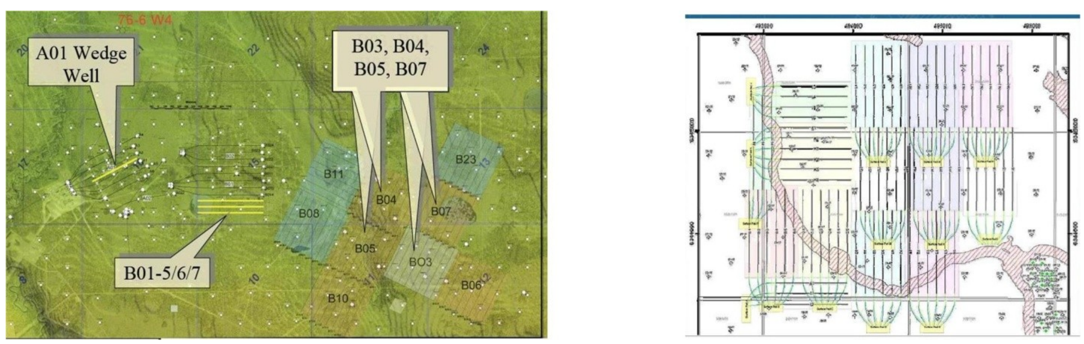

Figure 1.4 - Future plans for Drainage area locations. Christina Lake project, Encana, 2009 (left); Sunrise project, Husky Energy, 2006 (right); Taken from RMR reports, Canada, not to scale.

1.2 Problem Definition

The main objective is to maximize the profit and satisfy a number of constraints. The profit for a SAGD project can be quantified in terms of bitumen production. Maximizing net present value and minimizing steam to oil ratio can be criteria for the optimization but only recovery in terms of bitumen thickness is considered here. The objective is to maximize the recovery of bitumen by selecting optimal locations of drainage areas and associated surface pads. Maximization of recovery of bitumen can be achieved by considering two main decision factors- (1) the arrangement of drainage areas should be in a compact and non-overlapping form as shown in the RMR reports (**Figure 1.4**). The idea is similar as “space packing” to maximize the access to a SAGD developable area. A SAGD developable area can be of any shape. Drainage areas are of a rectangular shape. Filling any arbitrary polygon with rectangular shapes is itself an optimization problem of space packing. (2) Second objective is to locate drainage areas for maximum bitumen recovery. Different constraints are associated with drainage area positioning- Placement of surface pads at unobstructed surface locations, control the crossing of well pairs at boundary, base conformance of well pairs, and thief zone effect.

1.2.1 Base Conformance of Well Pair

Since SAGD is a gravity assisted process; any resource below the producer well is not accessible **(Figure 1.5).** The vertical positions of well pairs are crucial for maximizing the recovery. Placing a well pair at a deeper depth increases the amount of accessible resource, but if some part of well passes below the BCB surface then that part of the well will be ineffective and resource will be lost. There are two negative impacts on the production because of ineffective well length. First, a loss of steam in the regions where there is no bitumen content. The steam injected in ineffective regions is not utilized in the production and can be considered as a cost with no revenue generation. The second negative factor is loss of bitumen production above ineffective well length. The bitumen will not be produced since the steam is not going into the bitumen deposit above the ineffective well length. This unrecovered bitumen is a loss in terms of money. If BCB surface is very rough then losing some resource in ineffective regions can be balanced by access of additional resource in the other parts. If BCB surface is smooth then placing a well below BCB surface is not profitable. The volume of recoverable bitumen for a particular elevation can be calculated with some simple assumptions. Selecting a vertical elevation of wells based on single estimate can be misleading if the uncertainty in BCB surface is high. Vertical placement of wells is another optimization problem. The optimal positioning of DAs comes first.

1.2.2 Optimum Well Positions

The inter relationship between adjacent well pairs is illustrated in **Figure 1.6**. The optimum configuration of all well pairs for maximum production is different from the optimum position of individual well pairs. Optimizing the position of a single well does not guarantee maximum recovery across the field since an optimum position for a single well can affect the positions of neighbouring wells and may force them to be located in non favourable positions, which does not maximize the recovery over all pairs; the example in **Figure 1.6** highlights this in a simple two pair 2D configuration. First, well A is placed at a location which is optimum for A, i.e., maximum recovery from well A is achieved. Then placement of well B is done from the available remaining positions. Wells A and B are placed side by side with no gap between them to maximize space packing. But this configuration is not optimum in terms of combined production from both wells A and B together. The last figure shows a position of well A which is not maximum for well A, but has the maximum overall recovery.

1.2.3 Other Constraints

Complexity is introduced because of surface locations where it is not possible to develop surface pads. Surface obstructions such as roads, rivers, lakes and structures restrict the area available for development. It might be possible that there is no unrestricted surface available for development of a surface pad for a potentially good drainage area location. If possible, a different location and orientation could be developed away from any surface restrictions; however, there is a distance limitation between the surface pad and corresponding drainage area. Both surface and subsurface factors must be considered together for a feasible surface pad location and drainage area position for optimum recovery of bitumen. Considering two different but inter-related objectives makes drainage area and surface pad allocation a multi-objective optimization problem. One part of objective is to find the best positions of surface pads and the other part of the objective is to find the best location and orientation of associated DAs for maximum recovery of bitumen. Another constraint is thief zones. Thief zones are regions where subsurface water may be in contact with the bitumen zone. A different kind of operating pressure and temperature is required if a well passes through these regions. The layout of wells should be considered to minimize the total number of wells affected by thief zones.

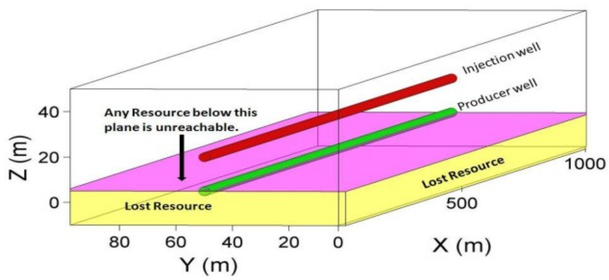

Figure 1.5 - Any resource below producer is unreachable.

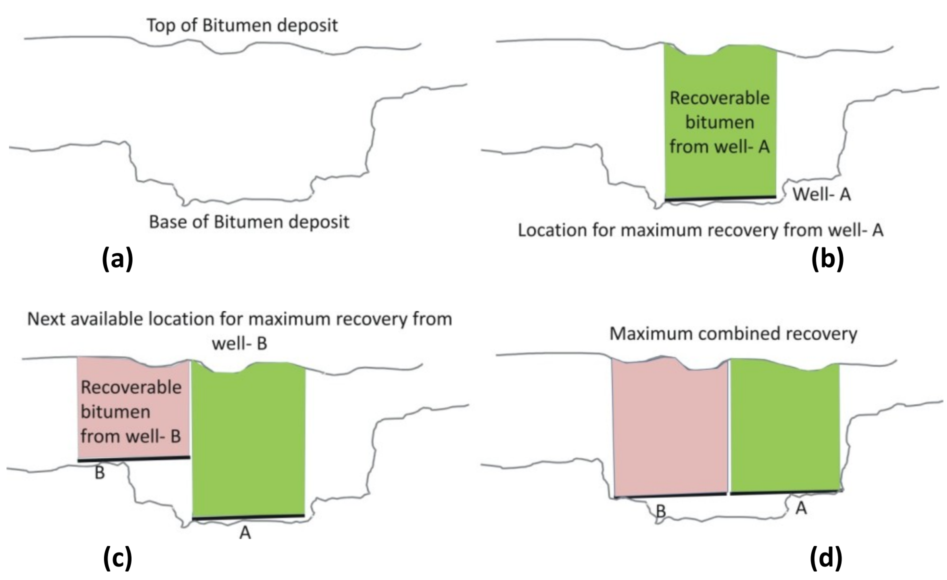

Figure 1.6 – **(a)** An example of bitumen deposit to illustrate the necessity of optimization; **(b)** placing well 'A' at a location which gives maximum recovery for well 'A'; **(c)** then placing well 'B' at a location which gives maximum recovery for 'B'; **(d)** Not an optimal location for well A but the combined recovery is maximum. Figures are not to scale.

1.3 Literature Review

SAGD is relatively new methodology and there is no direct research work available on drainage area and surface pad optimization. Work has been done in the areas of individual well pairs using 3D geostatistical models [14]. This work is limited to a single well pair with fixed areal location. The objective of methodology discussed in [14] is to find the optimum well elevation for maximum bitumen recovery. Volume of recoverable bitumen is calculated for all possible elevations and the one that has maximum recovery is selected. The risk involved in the vertical position of well pair is addressed by computing the objective function over several realizations.

The polygon packing problem is not new in the area of manufacture engineering. This problem can be stated as- finding the optimal arrangements of given 2D shaped polygons on a given 2D metal sheet so that the loss of sheet material is minimum. Several papers ([1] and [6]) are available on space packing algorithms. The space packing algorithms are NP hard problems and therefore there is no efficient algorithm in general. Often, dynamic or mixed integer programming is used for the polygon packing problems. These algorithms are guaranteed to give the optimal result, but the computer run time is not guaranteed. Computer run time depends on the nature of the problem and is highly effected by size of the problem [1]. Optimization based on evolutionary algorithms is available [1] and [6]. [6] often use the bottom left strategy for polygon packing in conjunction with a genetic algorithm. This algorithm is limited and can be applied only when the material sheet is rectangular in shape. [1] overcomes the limitation of rectangular sheet and works for polynomial with any shape and sizes. The methodology described in [1] uses genetic algorithm in conjunction with bottom left fill strategy. The main limitation of this algorithm is the CPU time and it gives gaps between adjacent polygons on a sheet. Most of the methods described in the polygon packing problem literature assume a continuous metal sheet with equal metal quality over the entire sheet. The problem of optimal positioning of SPs and DAs has varying quality in the regions. The optimal allocation of DA and SP is a more advanced space packing problem. The rectangular shaped drainage areas make the problem a little simpler. Space packing can be maintained if drainage areas are placed side by side with no gap between them.

1.4 Outline

This thesis will first go through the problem formulation for drainage area and surface pad optimization (Chapter-2). Chapter-2 formulates and discusses the objective function. Decision variables of the objective function are the locations and orientations of drainage areas. Locations of surface pads are functions of the location of their corresponding drainage area. Different constraints are included in the objective function as penalty factors. Chapter-3 gives the details about the developed tool for optimizing the locations. The optimization algorithm is discussed and presented with help of examples. Special cases are tested to validate the developed methodology. Chapter-4 is a case study. Each and every step for drainage area and surface pad optimization is explained with help of examples. The case study is discussed form the very beginning well-log data. The main emphasis is the set-up for the optimization and running the developed optimization approach. Geostatistical modeling is not presented in detail. The details of different methodologies for geostatistical modeling can be found in [16]. Chapter-5 discusses future work. Possibility of additional features in the developed tool is discussed. An appendix contains the structure of different parameter files for programs.

Chapter 2 – Problem Formulation and Optimization

For any optimization strategy the formulation of the problem is very important. The main key in finding the optimal solution is the way the problem is approached. The mathematical representation of objectives gives the idea about which optimization algorithm is best in finding the global and/or local minimum or maximum. Once the objective function is formulated and constraints are represented mathematically, then the nature of these mathematical functions is investigated. Each optimization algorithm has its strength and weakness. A particular optimization algorithm can be best for one kind of problem but may not be suitable for another. For example any direct search methods such as gradient method, steepest decent method, or conjugate method are practical when the objective function is not highly multimodal in nature. These direct search algorithms may converge to a local minimum or maximum. Evolutionary algorithms may be able to get out of local optimum and look for other possible maxima or minima. Different kinds of evolutionary algorithms are available in the literature including genetic algorithms, simulated annealing, and particle swarm optimization. The applicability and success of evolutionary algorithms are problem dependent. The difference between evolutionary algorithms and direct search algorithms are that evolutionary algorithms consider some component of a "random search". If direct search methods find local optima then the algorithm converges to it and stops. Evolutionary algorithms can be generalized based on search direction as- direct search and random search. To search for an optimum point, an evolutionary algorithm does some direct search to converge towards local optimum point and at the same time uses random search to look for other nearby optimum values (**Figure 2.1**). Some evolutionary algorithms have more direct search part than random search. For example- simulated annealing starts with large and random search space; Genetic algorithm controls the direct search by selecting the better parents for cross over; and particle swarm optimization controls direct and random search by inertial weight and acceleration parameters. Selection of an evolutionary algorithm for a particular problem is based on the requirement of random search and direct search. If the nature of the problem suggests a very high multimodal nature of the objective function then random search should be given more weight than direct search. This chapter will provide details about formulation of objective function, nature of objective function, and the way to approach the problem.

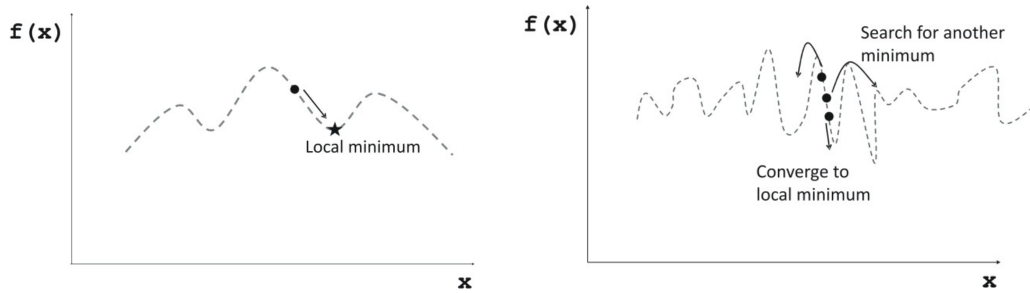

Figure 2.1- Schematic representation of direct search (left), direct and random search (right) for evolutionary algorithms. Not to scale.

2.1 DA and SP Placement Considerations

The main objective of positioning of drainage areas and surface pads is to maximize the feasible recovery of bitumen subject to a number of important constraints. Variables considered in the objective function formulation are discussed below.

Subsurface reservoir properties-include deterministic estimate or multiple realizations of reservoir variables such as NCB, BCB, GCB, porosity (ϕ) and thief zones (Tz). NCB is an important variable and represents the quality of reservoir. Reservoir variables are available at well-locations. These variables are modeled over the entire region of interest at a specific grid size. 2D modeling is often considered. Several correlated realizations of the reservoir properties are used to capture the inevitable geologic uncertainty and minimize the risk involved in DA and SP placement.

Drainage area specifications- Rectangular shaped drainage area are assumed. L_{DA} and W_{DA} are the length and width of a drainage area, respectively. WS is the spacing between two adjacent wells within a drainage area. **Figure 2.2** represents the schematic diagram of a DA and its specification. The dimension of the side of the rectangle in the orientation of the well pair is L_{DA} . The well spacing and number of well pairs (n_{well}) in a drainage area are related:

$$n_{well} = \frac{W_{DA}}{WS}$$

Surface pad specifications- In practice, surface pads are rectangular in shape. But for calculation simplicity circular surface pads are assumed. Rectangular surface pads can be easily included but at additional calculation time. Another advantage of a circular shape is that it is independent of orientation. An assumption is that a feasible circular surface pad will also lead to a feasible rectangular surface pad in the close vicinity. r_{SP} is the radius of a surface pad SP. d_0 is the ideal distance between the surface pad and its corresponding drainage area. A surface pad can be located within some offset distance from its ideal position. **Figure 2.2** shows the offset distances d_l and d_p - along the direction of well pairs and in perpendicular direction respectively. If it is not possible to locate a surface pad at its ideal position then it can be located anywhere in the rectangle ABCD but as close as possible to its ideal position. The allocation scheme of surface pads is explained in future sections.

SP location with respect to DA- If a DA is rectangular then there are two possibilities of for the SP location and there are 4 possibilities of the SP position if the DA is square. **Figure 2.3** shows the possible positions of SP in case of a square shaped DA. The orientation of the wells is always in the direction of SP.

Region of interest (**ROI**)- is a region which is SAGD developable and is considered for drainage area and surface pad placement. The optimization of drainage area locations is inside a region of interest. The objective is to access as much resource as possible in the region of interest. The region of interest can be of any shape. Instances where well pairs cross the boundary of the ROI are avoided or minimized.

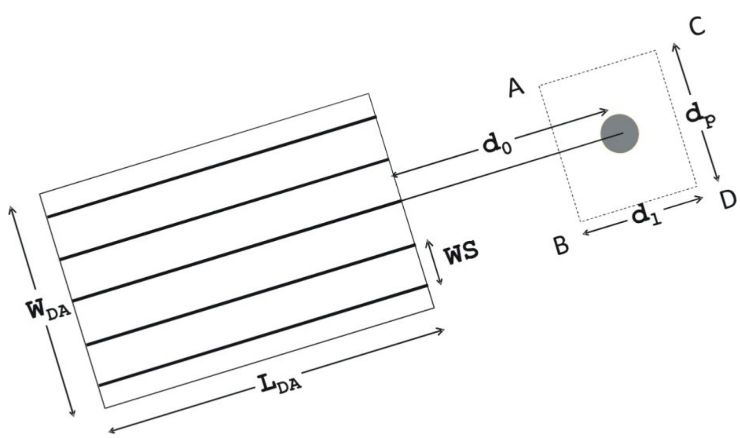

Figure 2.2- Schematic representation of drainage area and surface pad specifications.

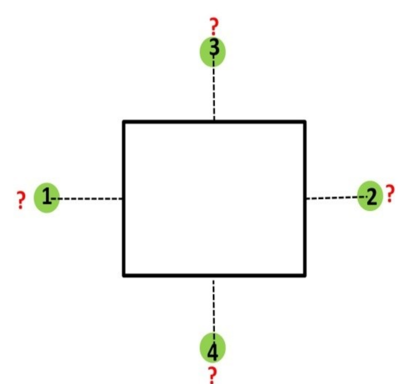

Figure 2.3- Location of SP with respect to DA. There are 4 possible locations if a DA is square shaped.

2.2 Objective Function

The objective of optimization is to find the locations of drainage areas for maximum recovery of bitumen. Therefore, the decision variables are the locations and orientations of drainage areas- (x_i, y_i, θ_i) for i^th^ drainage area (**Figure 2.4**). Where (x_i, y_i) is the centre of i^th^ drainage area and θ_i is the orientation of this drainage area measured in counter clockwise direction from x-axis. Constraints associated with drainage area are included in the objective function by means of different penalty factors. The most important Part of the objective function- “available/recoverable bitumen” is discussed. Expressions used in the mathematical representation of objective function are discussed briefly below and calculation details are explained in the next chapter.

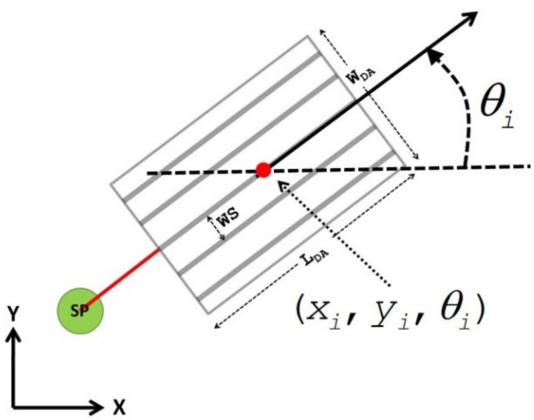

Figure 2.4- Schematic representation of decision variable for optimization.

2.2.1 Available Bitumen

Available bitumen of a well pair is the quantity of bitumen available for production along the trajectory of the well pair. Available bitumen is represented by $R_{i,j}^{aval}$ for j^th^ well pair of i^th^ drainage area. It is represented in terms of thickness (in units of meters) of NCB in this thesis. $R_{i,j}^{aval}$ is calculated by taking the NCB value of all cells inside rectangle (polygon ABCD in **Figure 2.5**) of well pair over all realizations. As the location and orientation of the well pair changes, the mean thickness of NCB inside well pair rectangle changes. Therefore $R_{i,j}^{aval}$ is the function of DA co-ordinates and orientation: (x_i, y_i, θ_i). Equation 2.1 gives expression for $R_{i,j}^{aval}$ calculation.

$$R_{i,j}^{aval} = \sum_{isim}^{nsim} \left(\frac{\sum_{c \in well_{i,j}} NCB_c \cdot ar_c}{\sum_{c \in well_{i,j}} ar_c} \right) \tag{2.1}$$

Where, c is the index of cell inside ith DA rectangle.
ar_c =fraction of area of cell c inside DA rectangle.
NCB_c =NCB value (in meters) of cth cell.
$isim$ is the index of realization number and $nsim$ is total number of realizations into consideration.

Calculating the average NCB weighted by the fraction of the cell area inside the well pair rectangle gives a precise calculation of the available resource for a given decision variable. This calculation is precise even if the modeling of reservoir variables is done at a coarse grid compared to the drainage area size. Calculating the available resource is fast once the cell indices inside the DA polygon are found. $R_{i,j}^{aval}$ represents the overall quality of for this well pair.

2.2.2 Recoverable Bitumen

Available bitumen is not a complete representation of DA quality at a given location. It is possible to have two locations with the same available resource but different recoverable quantities of bitumen. A location with a flat BCB surface inside a DA rectangle suggests high recovery of bitumen. A rough BCB surface inside a DA rectangle will incur higher losses of bitumen volume. Recoverable bitumen is a more realistic representation of reservoir quality for a DA location. A location with more recoverable bitumen should be selected irrespective of available bitumen. For a given location of a well pair there will be different values of recoverable bitumen for different elevations of well pair. One way to calculate recoverable bitumen is by placing well pairs at maximum elevation of BCB surface along the well. Then recoverable thickness can be calculated by removing any resource below well elevation. For the time being it is assumed that recoverable bitumen representation for a drainage area is a better representation than available bitumen. Recoverable bitumen for jth well pair of ith drainage area, $R_{i,j}^{recov}$ calculation is done for each well pair after determining the maximum BCB elevation along the well pair and requires lot more computer time than $R_{i,j}^{aval}$ available bitumen calculation. But then, there is no need to compute the base penalty (explained later) in case of recoverable bitumen because the base surface is already included in the recoverable bitumen calculation.

2.2.3 Base Penalty

$pen_{i,j}^{base}$ is the base penalty value for jth well of ith drainage area. The value of base penalty is 0 in case of fully penalized base surface and 1 is for non-penalized base surface. The penalty is calculated based on the roughness of BCB surface along well pair. A transfer function is used to convert roughness of BCB surface between 0 and 1. Calculation details are explained in the next chapter.

2.2.4 Surface Penalty

Pen_i^{SP} is the penalty for surface pad of ith drainage area. It is either 0 or 1. A 0 value is assigned for a surface pad when it is over a surface restriction. A value of 1 for surface penalty represents that the development of surface facility is possible for corresponding drainage area. There could be two possibility of SP for a rectangular shaped DA and four for square shaped DA. A location which gives the maximum numerical value of objective function is considered. Distance tolerances of SP are considered in the SP location calculation.

2.2.5 Thief zone Penalty

Pen_i^{tz} is thief zone penalty value (between 0 and 1) for the ith drainage area. A penalty value of 1 indicates no penalty- none of the well pairs of drainage area are crosses through thief zone. The thief zone penalty is assigned based on the number of well pairs affected by thief zone. If a certain minimum length of a well pair passes through thief zone then it is considered as effected by the thief zone region. The location of drainage areas that gives the minimum number of affected well pairs is preferred. The effect of thief zone in determining the drainage area location is explained in **Figure 2.5**. It shows two drainage areas- DA-I and DA-II. DA-I has all of its well pairs affected by the thief zone and DA-II has only two of its well pairs affected by the thief zone. Therefore, the DA-II location is preferred over the DA-I location if the other factors such as available/recoverable bitumen, base penalty, surface penalty are same.

2.2.6 ROI Penalty

$Pen_{i,j}^{out}$ is the penalty of jth well pair of ith drainage area when some part well pairs crosses the region of interest. The idea behind introducing this penalty is to minimize instances where a well pair crosses the boundary of the ROI and reaches lease limits, economically unfavourable regions or regions that have already been developed. A drainage area with some of its well pairs completely outside ROI is preferred over a drainage area with all of its well pairs crossing the boundary of region of interest. A well pair completely outside ROI is considered as undevelopable. **Figure 2.6** DA-II is preferred over DA-I because the entire well pairs of DA-I crosses the ROI boundary. Also, DA-II has one of its well pair completely outside the ROI which suggests that this well pair can't be developed and must not be included in the objective function calculation. But DA-I has all of its well pairs crossing the boundary. If well pairs of DA-I are not going to be developed then the resource in between DA-I and ROI is not going to be recovered. On the other hand if well pairs of DA-I are going to be developed then almost half of the well lengths are in unproductive regions. Cases similar to DA-I location must be minimized. This can be easily achieved by penalizing quality part of well pair by the amount it crosses over unproductive regions.

2.2.7 Objective Function Formulation

After combining the available bitumen and the penalties related to different constraints described above, the overall objective function for optimization problem can be expressed mathematically as an unconstrained optimization problem (**Equation 2.2a**). Different constraints are penalized according to their effect on the recovery of bitumen.

$$F^{obj} = \sum_{i=1}^{N_{DA}} f_i^{obj},$$
$$f_i^{obj} = \frac{1}{n_{pair}} \left[\sum_{j=1}^{n_{pair}} \left(R_{i,j}^{aval} * pen_{i,j}^{base} * pen_{i,j}^{out} \right) \right] * pen_i^{SP} * pen_i^{tz} \tag{2.2a}$$

Where F^{obj} is sum of objective function value of all drainage areas N_{DA}. f_i^{obj} is objective function of i[th] drainage area. n_{pair} is total number of well pairs inside a drainage area. It is assumed that all pairs and drainage areas are of same dimension.

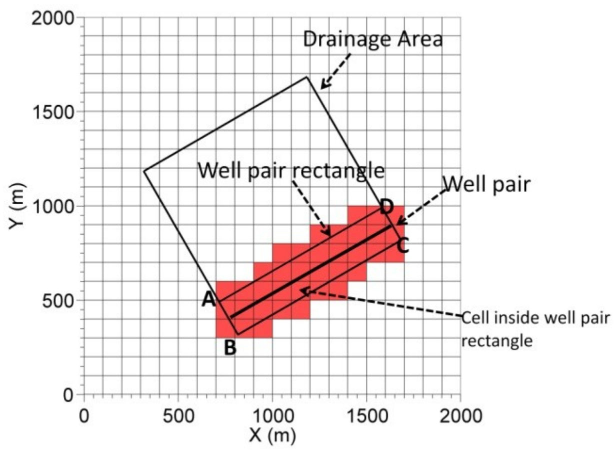

Figure 2.5- Defining well pair rectangle. Influence area of a well pair.

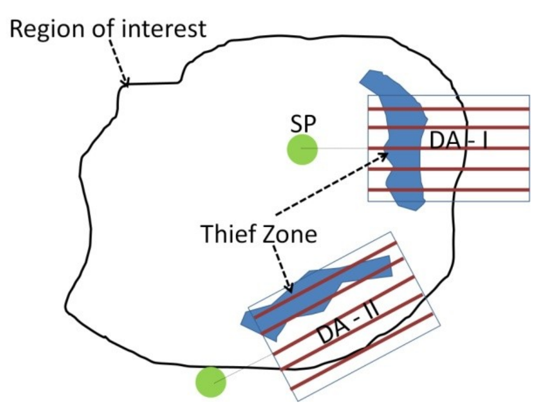

Figure 2.6- Schematic representation of effect of thief zone and ROI penalty.

Different penalty factors are introduced to guide the objective function to allocate drainage areas at locations where constraints have the least effect. The base penalty indicates the amount of roughness of BCB surface along well pair. More resource is lost in an area of rough BCB surface. Higher penalty is given for an irregular and curvy BCB surface. Thief zone penalty is assigned based on the number of well pairs affected inside a DA because of passing through a thief zone area. Surface penalty indicates the availability of a surface pad, it is either 0 or 1. 0 being the case where it is not possible to locate a surface pad for corresponding drainage area and therefore making the objective function value 0 for corresponding drainage area (i.e. not possible to develop a drainage area). Value 1 of surface pad penalty indicates the availability of surface pad for corresponding drainage area location. The nature of optimization is the maximization of objective function by means of improving different penalty values for each well pair and drainage area. It should be noted that the sum of all available resource over ROI is constant but the multiplication with different penalty values and then summing over entire region is different for different positions of drainage area.

Another way to express objective function is by eliminating the base penalty factor from objective function equation. An improper choice of base penalty value might be misleading in the optimization process. Implementation of other penalty factors: pen_i^{tz} $pen_{i,j}^{out}$ and pen_i^{SP} are straightforward. Selection of the thief zone penalty value is relatively simple. The objective function is penalized with a high penalty value based on the number of affected well pairs. A high penalty for thief zone ensures that the minimum number of affected wells irrespective of the available resource. Also, thief zones are not present everywhere in the area. A large penalty to the base will force the objective function to allocate drainage areas in an orientation that has a smoother BCB surface. For example it is possible to have a rough base in high resource area, and then a high penalty for base will decrease the value of objective function for the corresponding drainage area; however, a smooth BCB surface in a low R^{aval} will have a larger objective function value. This can be misleading in the optimization process if a low reservoir quality is selected over a higher one. Removal of the base penalty can be done by considering of the recoverable resource of each well pair inside the drainage area. The calculation of the recoverable reserve for a well pair is done by placing the well at maximum BCB elevation. This maximum BCB elevation is calculated from the elevation of BCB surface along the well pair. This way no well part lost inside BCB surface. Even if a rough BCB surface is present in an area of thick reserve then the value of objective function will be still higher. This way of expressing the objective function is:

$$f_i^{obj} = \frac{1}{n_{pair}} \left[\sum_{j=1}^{n_{pair}} \left(R_{i,j}^{recov} * pen_{i,j}^{out} \right) \right] * pen_i^{SP} * pen_i^{tz} \qquad (2.2b)$$

$R_{i,j}^{recov}$ =Amount of recoverable resource by j^th well pair of i^th drainage area. The recovery from a drainage area can be given as

$$R_i^{DA} = \frac{1}{n_{well}} \sum_{j=1}^{n_{well}} R_{i,j}^{recov} \tag{2.3}$$

All the factors included in the objective function are functions of the location and orientation of the DAs. The optimization problem can be expressed as an unconstrained optimization by means of of penalty functions.

$$\begin{aligned} &Find\ (x_i, y_i, \theta_i)\ , i = 1, ...N_{DA} \\ &to\ Maximize: \ \sum_{i=1}^{N_{DA}} f_i^{obj}(x_i, y_i, \theta_i), \end{aligned} \tag{2.4}$$

(X_i, Y_i) is location, θ_i is the orientation of i^th drainage area.

N_{DA} is the total number of drainage areas for optimization. The number of drainage area in consideration is fixed. This number should be higher so that the entire ROI can be covered with drainage areas. The value of the objective function for a drainage area outside the ROI is zero and therefore does not have any contribution into the optimization.

2.3 Comment on the Choice of an Optimization Algorithm

Even though the objective function is expressed as an unconstrained optimization problem it is hard to apply any general optimization algorithms because of the large dimension of the solution space and high multimodal nature of the objective function (see example below). The dimension of the problem increases as the number of drainage areas considered for optimization increases. For N_{DA} number of drainage areas across the region of interest the dimension of the optimization problem is 3 times the number of DA ($x_i, y_i, \theta_i,\ i = 1 \text{ to } N_{DA}$). The dimension of the solution space also increases with the size of the region of interest. Even if the dimension is tractable, it is the multimodal nature of objective function that makes it very difficult to solve by any gradient or direct search algorithms. Additionally, the numerical calculation of gradient might be challenging because of large dimension of the problem. The multimodal nature of objective function can be easily understood by considering even a single drainage area. Consider a single drainage area across the field with the continuous reservoir quality as shown in **Figure 2.7**. There are numerous increases and decreases in reservoir quality as the DA is moved from left to right i.e. in the direction of x-axis. Let us simplify the problem further by assuming that there are no surface obstructions across the field along with no penalty for base and thief zone. Therefore every location has the objective function value equal to the quality of reservoir. The change in the value of objective function when moving the DA from point A to point C is shown at the bottom of the figure. There is a continuous increase and decrease in the value of objective function for a single variable. The single variable for this example is the value of x-coordinate since y-coordinate and orientation of DA are fixed. The example discussed here is a very simple example. For a typical DA and SP optimization there will be many DAs with x and y co-ordinates and orientations as variables in addition with surface obstructions and other penalties. The spatial distribution of the reservoir quality may be much more complex with frequent increases and decreases with location.

Direct search methods for optimization are not appropriate because of the multimodal nature of the objective function. A direct search algorithm will likely get stuck in a local maximum. Evolutionary algorithms ([5]) are another area where the optimization is possible by means of including random search to get out from local maximum. A long list of literature is available on optimal polygon packing problems. References such as [6] and [1] describe the use of the bottom left strategy, no fit polygon and genetic algorithms to pack a given area optimally using polygons. The main limitations of these approaches are that they either work on rectangular regions ([6]) or have a very high CPU time ([1]) and are specially designed only for space packing with uniform quality across the field. Adding non-uniform space quality into the optimization makes the objective function complex and more multimodal; it may be impossible to get a global optimum with an evolutionary algorithm. Packing a rectangular sheet with different sizes of rectangles is NP-complete problem [15]. Although all Das are of same size but the ROI can be of any shape and non- uniform quality throughout the area. Formulating the objective function in a different way with lower dimension and/or less of a multimodal nature will encourage the use of evolutionary algorithms. Optimizing drainage area locations with special grid coding ([1]) was investigated using particle swarm optimization and functional stretching ([17]). The whole area is divided into grids and coded with binary values (0 or 1). All grids within the DA polygon are coded as 0. grids outside the DA polygon are set to 1. The purpose of binary grid coding is to avoid the overlap of two DAs. The results are shown in **Figure 2.8.** A random configuration was selected as the starting point for optimization. Results after optimizations had gaps between adjacent DAs. This happens because of working on discretized region (grids) rather than continuous one. The gaps can be reduced by using higher resolution of grid at the cost of higher computation time. Handling large number of DAs are not possible with high resolution of grids.

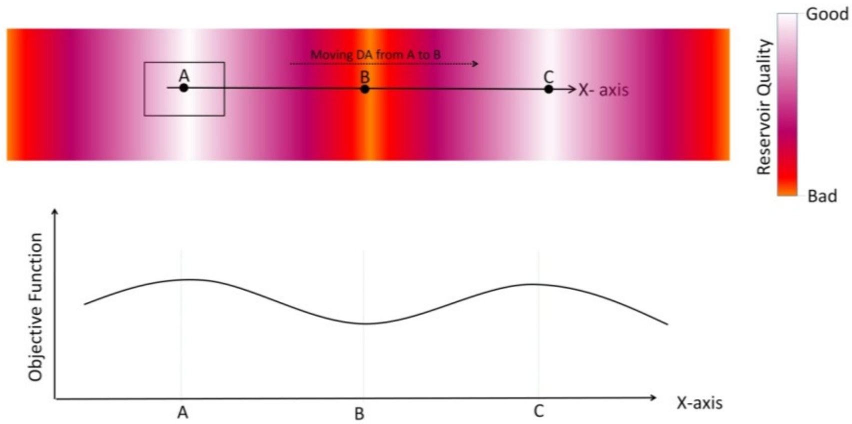

Figure 2.7- A schematic representation of high multimodal nature of objective function

Figure 2.8- Particle swarm optimization applied to DA locations. The final result after optimization shows gaps between adjacent DAs. May not be practical for SAGD application.

2.4 Optimization Methodology

The current practice of SAGD (**Figure 1.4**) suggests a compact pattern of drainage areas over a developable region. A pattern with few gaps between adjacent drainage areas guarantees the maximum areal conformance. Space packing can be achieved if a compact pattern is maintained during the optimization process. A layout of drainage areas as shown in **Figure 2.9** is an example of compact and non-overlapping drainage areas. The optimization starts with a compact arrangement like the one shown in **Figure 2.9a**. Then, optimization is approached in a heuristic way. The locations of the drainage areas are changed by means of four optimization steps:

1. Optimization by translation ($\mathbf{T_{opt}}$)- The entire group of DA is translated to maximize the objective function.

2. Rotation (**R**)- The entire group of DA is rotated at its centre at a given angle.
3. Optimization by Sliding ($\mathbf{S_{opt}}$)- Each row of DA is made to slide to maximize the value of objective function.
4. Breaking- A row of DAs can be broken by creating space between adjacent DAs. Breaking is performed to increase the number of unrestricted surface pads and applied only once when optimization by different combinations of translation, rotation and sliding is done.

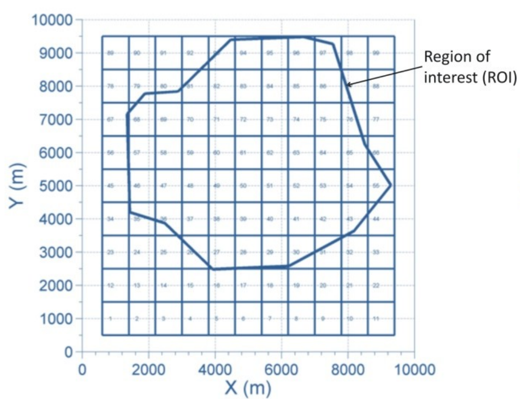

Figure 2.9 (a)

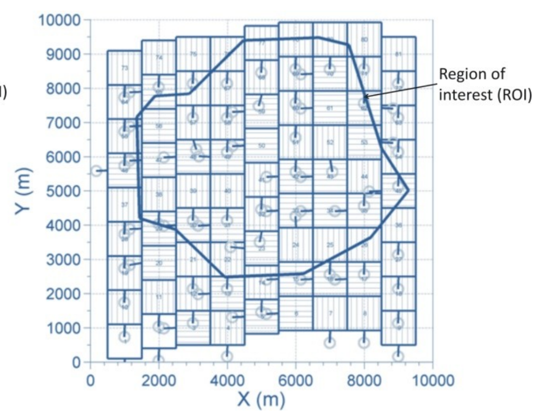

Figure 2.9 (b)

Figure 2.9- An example of DA and SP optimization approach. (a) Starts with a compact and non-overlapping pattern of DA. (b) Tries to maximize the value of objective function heuristically.

A sequence of optimization steps is applied on the initial configuration of drainage area by different permutations of rotation, translation and sliding. The compact pattern of drainage areas is maintained during all of the optimization steps. The optimum translation is determined by selecting the maximum objective function from all possible translations. The value of the objective function is calculated by translating the entire group with small increments in x and y directions. The maximum translation distance is limited by the dimension of drainage area. This distance is equal to the maximum dimension of drainage area (length or width whichever is maximum). The maximum translation distance is discretized by small increments in x and y direction. The value of the objective function is calculated by translating the entire group of drainage area at all permutations of points (x,y). The translation distance with the maximum value of objective function is the optimum one. **Figure 2.10** shows one such translation.

An example of sliding optimization is shown in **Figure 2.11**. Sliding is done in the orientation of paved drainage areas. The individual rows of the paved configuration are translated by small increments. Again the maximum sliding limit is equal to the length or width of drainage area whichever is greater. The optimum sliding of row is determined by a sliding distance that has the maximum objective function value. After sliding one row (**Figure 2.11**) drainage areas cover the high reservoir quality and they are completely inside the region of interest

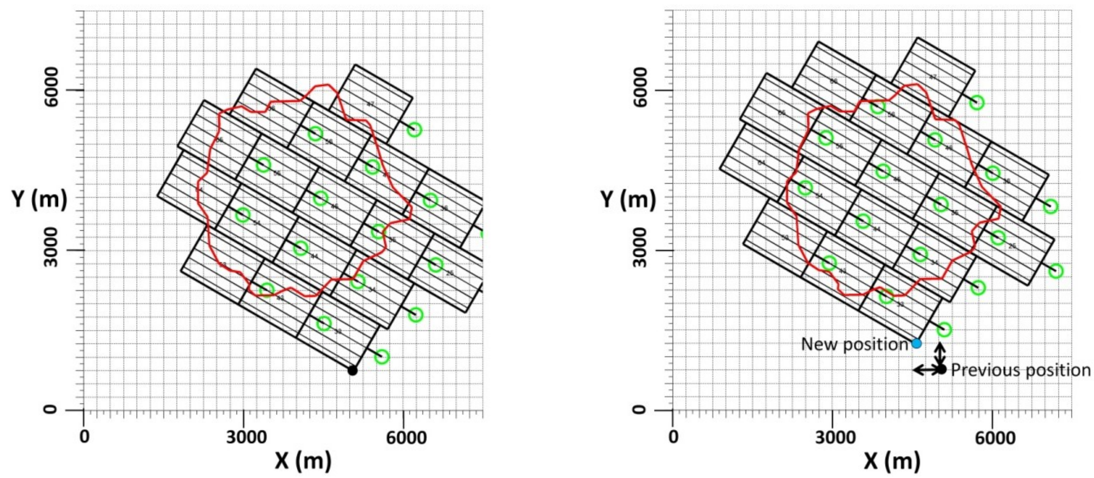

Figure 2.10- Finding optimal positions by Translation.

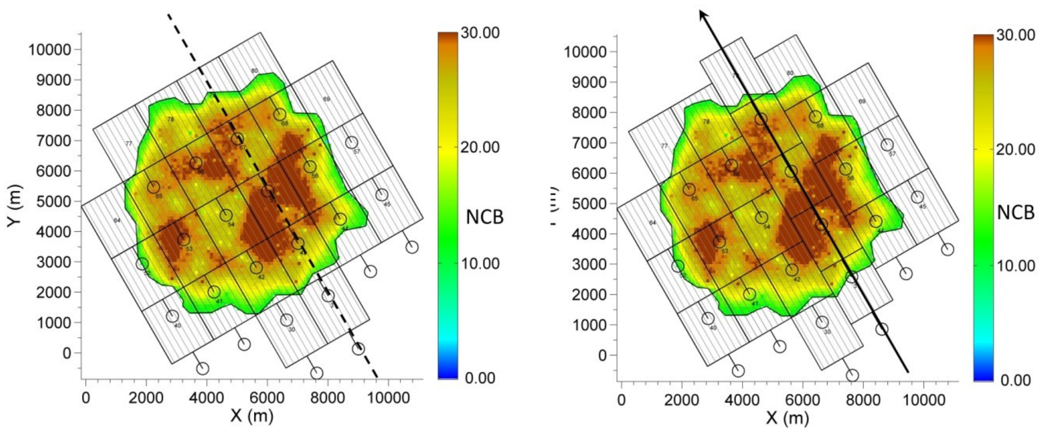

Figure 2.11- Optimization by sliding a single row.

Rotation- Rotation is an important aspect of optimization. Combinations of sliding and translation optimization can generate the optimal configuration for a fixed orientation. Optimization using rotation has two types- (i) Rotational optimization, and (ii) Just rotation. Rotational optimization is same as translational or sliding optimization, where the entire paved group of drainage areas is tested by rotation around its centre; the orientation that gives the maximum value of the objective function is selected. The upper and lower limits for the angle can be set as per requirement or can be between 0 to 180 degrees to check against full rotation. Then, a second type of rotation is to rotate the entire group by a given angle regardless of increase or decrease in the value of objective function. The importance of rotation is explained by the following example. Consider an optimization sequence $R^{opt}_{-45to45} - T^{opt} - S^{opt}$ which is a 3 step optimization- Step 1- Rotate initial configuration of entire group of DA between angles of -45 to 45 degrees and determine the optimal rotation which gives the maximum value of objective function, step 2- Translate entire group of the optimal arrangement obtained from previous step (rotation) and find the optimal translation value, step 3- After finding the optimal from 2nd step, slide individual rows to maximize the objective function. Suppose 7 degrees is the optimum angle of rotation for the first step of $R^{opt}_{-45to45} - T^{opt} - S^{opt}$ pattern. After 7 degrees of rotation, translation and sliding optimization is done which increases the value of objective function further. But it is possible that a global maximum exists for a pattern with a different angle of rotation, translation and sliding. This can be illustrated as below:

	Initial Guess-	$R^{opt=07}_{-45to45} -$	$T^{opt} -$	S^{opt}
Obj. fun. =	100 -	110 -	115 -	120

	Initial Guess-	$R_{30} -$	$T^{opt} -$	S^{opt}
Obj. fun. =	100 -	105 -	110 -	125

The global optimum can be searched by trying all possible permutations of rotation (R), sliding (S), and Translation (T) steps. It checks for all possible rotations from 1 to 180 degrees. There are total 3x2x2=12 arrangements of T (translation), S (sliding), and R (rotation) with no consecutive repetitions of T, S or R. Single T is achieved in only one way (selecting only optional translation for entire group) and similarly one S can be achieved in one way (selecting optimum sliding for each row). R can have 180 values (1 to 180 degrees of rotation option). A simple permutation calculation gives a total of 66,242 patterns of optimization involving 3 steps. For example one such pattern can be $T^{opt} - R_7 - S^{opt}$ i.e. first translate the entire group and find the optimum translation, then rotate the entire group by 7 degrees (in counter clockwise direction) and then slide individual rows and find the optimal sliding for each rows. A global maximum is selected after testing against all the optimization patterns. Another benefit of testing against all possible permutations is that all permutations can be sorted as per their objective function value and top patterns can be analyzed. Then it is possible to select an angle that is more favourable in technical terms and have local maximum value or close to the global maximum.

This chapter establishes the concept of optimization methodology along with the mathematical expression of objective function. Objective function is expressed in the units of reservoir thickness (meters) which is result of reservoir quality penalized by unit less penalties for different constraints. Thus, converting a constrained optimization problem into an unconstrained one. Four penalty factors are included in the expression of objective function- penalty for base, surface pad, thief zone, and region of interest. A detailed methodology for calculation of penalties are explained in the next chapter. A heuristic optimization strategy is going to be used for the optimization. This methodology maintains the compact arrangement of drainage areas to maintain the space packing criteria. Optimization is done by different combinations of- rotation, translation and sliding. A more detailed calculation methodology for optimization is described in the next chapter.

Chapter 3 – Implementation

An important engineering requirement is that the optimization tool generates results that make practical sense within a reasonable run time. Different computer languages are available to deploy the methodology for numerical problems. Some of the most common languages used in numerical calculations are C, C++, C#, FORTRAN, and MATLAB. Each language has its own style of syntax. An optimization algorithm can be implemented in any of the languages. FORTRAN is one of the oldest computer languages and there is a huge collection of already existing efficient codes for numerical calculations. On the other hand, C languages are structured for more general purposes and have many advanced features as compared to FORTRAN. But as far as numerical calculation is considered either FORTRAN or C can be used to implement the underlying idea. MATLAB is fourth generation language which itself has collection of several routines written in FORTRAN, C, and C++. It is easy to implement and requires minimal effort in writing and running the code. The graphics tools available in MATLAB make visualization of results very easy. A drawback of MATLAB is the necessity of the MATLAB compiler to run a MATLAB code. Executable files can be generates by C and FORTRAN codes and can be executed easily on almost any operating system.

This chapter describes the developed code along with details of testing and validating it against special cases. FORTRAN language is used to develop the optimization calculation. Standard GSLIB format ([4]) is used to provide the input files and parameters. Visualization of results can be done either with a FORTRAN program or MATLAB. The semi-transparent plots in MATLAB make it easy to visualize subsurface quality and surface restrictions on a single figure. MATLAB is not necessary to run the code or visualize the results, but MATLAB is used for advanced visualization purposes. The optimization routine of drainage area and surface pad location is included in a tool box named **DASP** (drainage area and surface pad). The DASP tool has 4 programs– **`clipdata`**, **`setpen`**, **`dapave`**, and **`DASPopt`**. A flowchart of the program sequence and interrelationships is shown in **Figure 3.1**. The steps for optimization are: (1.) Clip data inside region of interest (optional), (2.) Model the surface penalty map, (3.) Generate initial paved arrangements of drainage areas, and (4.) Run optimization. Each step is explained with some examples. The parameters for the optimization program DASPopt are explained in detail. Parameter files for the other programs are shown in an Appendix. The DASP tool is validated with special examples. These special examples are designed to check the results of the optimization tool for positioning of drainage areas, effectiveness of well pairs, base conformance, positioning of surface pads, and thief zone effect. Validation is presented after discussing the details of programs.

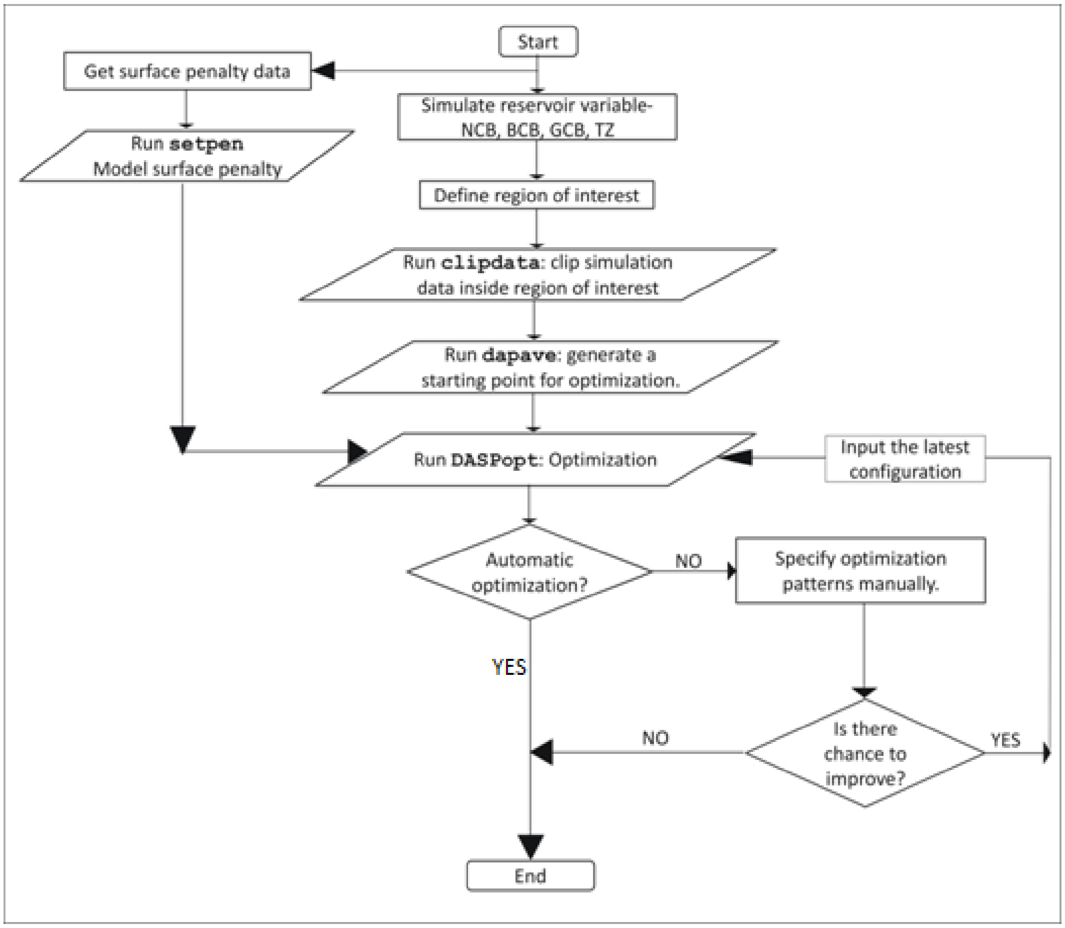

Figure 3.1- Flow chart for running DASP tool.

3.1 Program Flow

The optimization of drainage areas and surface pads starts after preparing the input data and initial paving arrangement of drainage areas. Surface and subsurface data is prepared first. The surface data is optional to the optimization program. If surface data is absent then all locations in the model area are considered for developing the surface facilities. The **`setpen`** program is used to prepare the surface data. After preparing the surface penalty data, the geostatistical realizations of reservoir variables are generated. Any standard geostatistical software can be used to generate these realizations. It is possible to run the optimization based on a single realization or deterministic model. A single estimate of the reservoir variable can be used to run the optimization. Four reservoir variables are included in the optimization program- NCB, BCB, GCB, Thief zone. Except NCB, the other three variables are optional for running the optimization program. If BCB and/or GCB data is provided then base penalty or recoverable reserve calculations are included in the objective function. Instead of using NCB, one can use any other variable against which drainage area and surface pad locations can be optimized. For example, OOIP can be used as primary data for optimization. The examples discussed here are based on NCB data.

If positioning of drainage areas is constrained within a polygon (region of interest), then an additional step is required before running the optimization. The **clipdata** program is used to clip the primary reservoir data inside the polygon defining region of interest. During the optimization, well pair locations are restricted inside the region of interest. After preparing the data for input reservoir variables, the **dapave** program is used to generate the initial paved arrangement of drainage areas. The parameter files for `dapave` and `clipdata` are shown in Appendix-C and Appendix-D respectively.

The necessary data are- (i) reservoir variable- data for one primary variable must be present. (ii) Data for surface penalty- optional. (iii) An initial location for all drainage areas. The optimization program `DASPopt` can be run after completing the previous steps. The optimization program will implement a full optimization by selecting the automatic optimization option. The automatic optimization option tells the program to check for all possible orientations of drainage areas and generates a report with value of the objective function for each orientation. The optimization program can also be operated by providing the optimization steps manually. This mode of optimization can impose constraints such as forcing the DAs to a particular direction.

3.1.1 Clipping Reservoir Variables Inside ROI

This is the first step towards optimization after modeling the reservoir variables. A program `clipdata` is developed for this purpose. This program is for clipping subsurface realizations (not the surface penalty map) inside a polygon defining the development area for drainage area placement. If required, the same program can be used to clip data outside a polygon. Generally, clipping outside a polygon is done when there is already some drainage areas present in the development area. Clipping realizations outside an already developed area forces the optimization program to not place drainage areas that overlap with existing drainage areas.

Figure 3.2 shows an example of clipped NCB. A development area polygon is used to clip NCB realizations. It is not necessary to clip the other reservoir variables since the other reservoir variables are not included in the calculation wherever primary variable is not available. The primary variable can be clipped outside already existing drainage area. Then the objective function for a drainage area is penalized if it overlaps with an existing drainage area. The same logic is applicable if data are clipped outside the region of interest. Any cell outside the development area polygon is assigned a -999 value. If a well pair or drainage area overlaps with an area with -999 value then the objective function is penalized with the amount of overlap. This forces the optimization algorithm to allocate complete drainage areas and well pairs inside the development area as much possible.

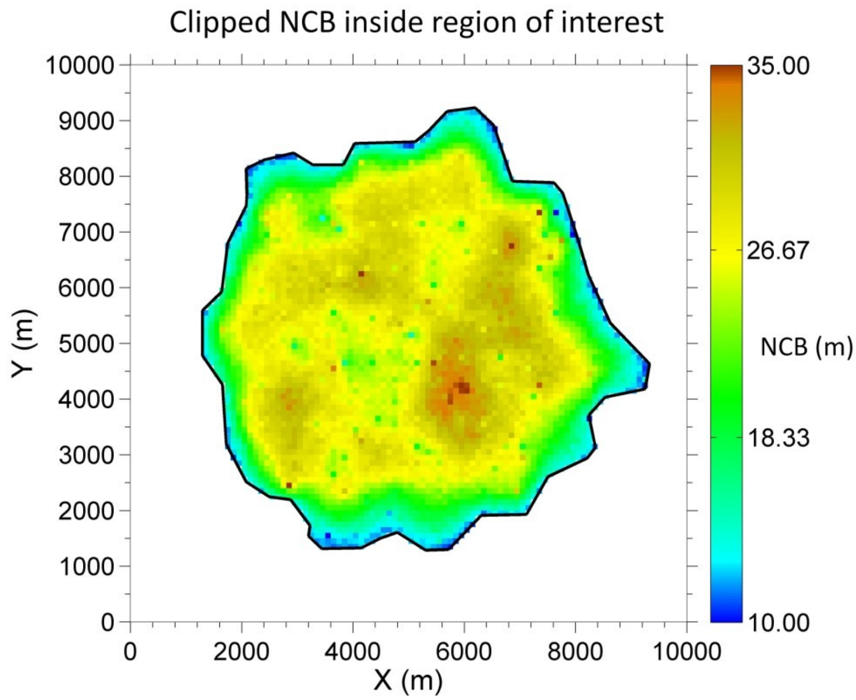

Figure 3.2- Clipped NCB (one realization) inside region of interest

3.1.2 Modeling Surface Penalty Map

The program `setpen` calculates the penalty map for any grid definition. Any grid cell over a surface obstruction is assigned with a 0, otherwise the location is accessible and is assigned a 1. A surface obstruction can be any types of restriction over which development of surface facilities are restricted, such as rivers, highway, lake, historical sites and parks. The resolution of the surface penalty map is specified in the parameter file (see Appendix). The resolution of the surface penalty map can be different from the resolution of maps of the subsurface variables. Generally, a high resolution is used for the surface penalty map to ensure a precise calculation for SP allocation. This calculation is not CPU intensive. Another reason for modeling at a high resolution is the certainty of surface obstructions; in general, the location of rivers, roads and other surface obstructions are precisely known. Reservoir variables have higher uncertainty and a high resolution for reservoir maps increases computational time. Each cell inside the surface pad polygon is checked for 0 values. If any of these cells have 0 values then the corresponding location of SP is not considered for the development.

An input file is provided with the coordinates of surface restrictions. This file follows a special format in order to identify the shape of surface restriction. The `setpen` program considers 4 different shapes: line, polygon, circle and arc. The format of input file for `setpen` program is shown in Appendix-B. A setback distance value is used to calculate the surface penalty map. The setback value is the minimum distance limit of a surface pad from the surface obstruction. For example if a setback value is 100 meters for roads then any part of surface pad must be at least 100 meters away from roads. The value of the setback must be greater than or equal to 0. The program automatically determines a new polygon (a bigger one based on the setback value) for an input polygon, a polygon for a line, a bigger circle (or arc) for input circle (or arc). If the setback value is set to zero then the surface only inside and on the surface obstruction is penalized. The program could be run multiple times for different setback values. The results can be combined to generate a single surface penalty map when both types of surface constraints are satisfied. **Figure 3.3** shows the map of surface penalty for a lake and road used in the example. A 0 value for setback has been used for both the lake and the road. A grid size of 25m x 25m has been used for the penalty map.

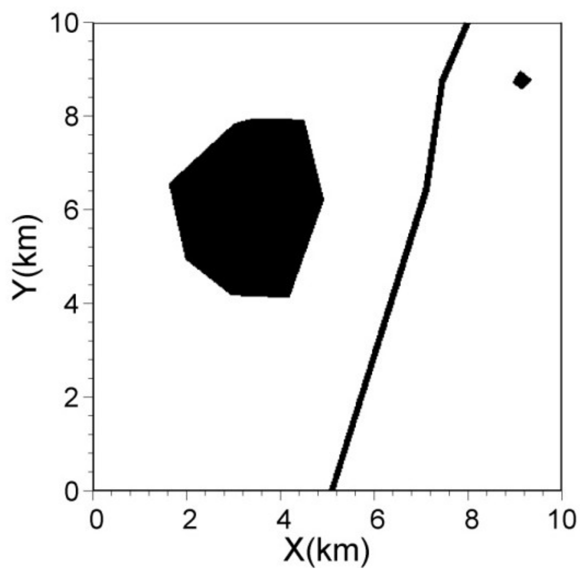

Figure 3.3- Surface penalty map.

3.1.3 Generating Initial Input

The program `dapave` is developed for the purpose of generating initial input for the main optimization program. A group of drainage areas are generated with no spacing between them. One example of input layout of DA's is shown in **Figure 3.4** for DAs of size 1000m x 800m. The individual rows of layout are shown with numbers. These lines are numbered from 1 to 15. The name of the lines can be used in the optimization program to provide an option to slide or freeze individual lines. The names of the DA's are indicated at their centers. There are a total of 180 drainage areas in the paved arrangement. The initial paving of drainage areas should cover the entire region of interest from all directions. Covering the entire region of interest completely with drainage area is important when full optimization is performed because when the entire group of paved drainage areas are rotated at its centre then no part of region of interest should be left uncovered. The uncovered parts are not included in the objective function calculation therefore that specifc rotation angle will be penalized. After running the optimization, drainage areas outside the region of interest can be removed. For the objective function calculation, the value of the objective function for a drainage area outside the region of interest is always 0 and thus makes no contribution in the optimization process. It is possible that some outside drainage areas can be inside the region of interest after rotation and some inside ones can go outside.

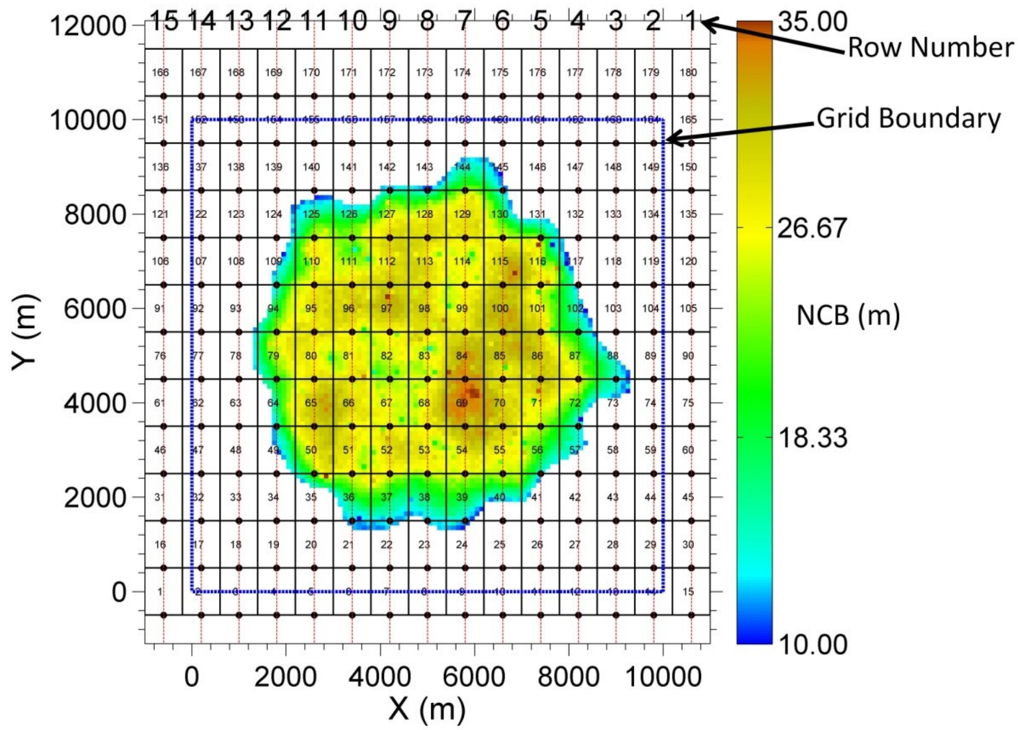

Figure 3.4- Result from `dapave` program. Paved configuration covers the region of interest from all directions.

3.1.4 Optimizing DA and SP Positioning and Orientations

The objective of optimization is to locate drainage areas inside the region of interest and maximize the value of the objective function. The objective function (**Equations 2.2a and 2.2b**) is expressed in a single mathematical expression after combining different constraints by means of penalty functions. The overall objective function is the sum of objective function values of each drainage area across the field. The objective function value of a single drainage area depends on its location and orientation. The main part of the objective function is reservoir quality expressed in average thickness of NCB over a DA (**Equation 2.2a**) or recoverable bitumen thickness (**Equation 2.2b**). Both types of objective functions are available in the tool and can be selected to guide the optimization. Recall that the objectives of optimization are:

1. Maximizing reservoir quality over entire configuration of drainage area.
2. Minimizing the placement of surface pads over surface restrictions.
3. Optimize the base conformance along well pairs.
4. Minimize the number of well pairs affected by thief zones.
5. Minimize the number of well pairs crossing the region of interest and minimize the instances where a drainage area crosses the region of interest.

There are two forms of objective function- one is with base penalty and one is with recoverable bitumen. Both forms are designed to maximize the base conformance along well pairs. The penalty for the base is calculated based on the roughness along the well pair. The BCB values of cells along the well pairs are used to determine the measure of roughness, r :

$$r = \frac{1}{n}\sum_{i}\left|bcb_i - bcb_{mean}\right|, \tag{3.1}$$

$$\text{where i} \in \text{cell along well,}$$

$$\text{bcb}_{mean} = \frac{1}{n}\sum_{i} bcb_i$$

The penalty is more if the numerical value of the penalty function is less. The penalty function is restricted between 0 and 1. The penalty function for the base is shown in **Figure 8**. Increasing the value of λ will increase the importance of the base surface.

$$pen_{base} = e^{(-\lambda * r)} \tag{3.2}$$

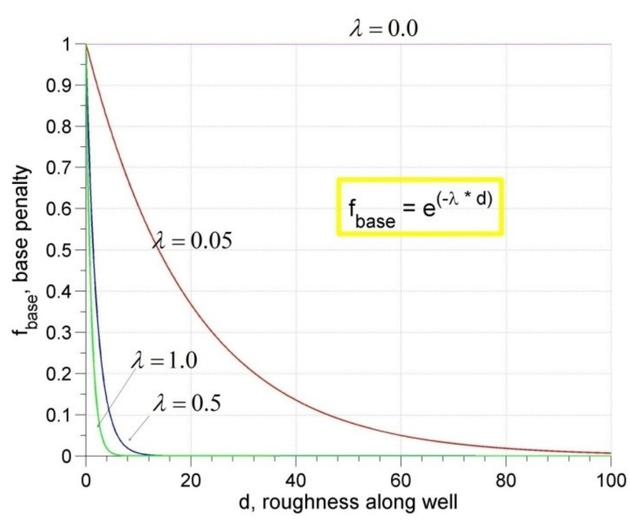

Figure 3.5: Penalty function for base. Penalty increases as roughness of base surface along well pair increases.

The second form of the objective function is based on recoverable bitumen calculation. Recoverable bitumen is calculated by considering three reservoir variables: NCB, BCB and TCB. Recoverable bitumen is calculated over all well pairs inside the DA, and then it is averaged for the DA. All calculations are done at the 2-D grid level. All cells inside the polygon defined by well pair are included in the calculation

The recoverable resource of a DA is the mean of the resource recoverable by individual well pairs (r_j^i). r_j^i is the thickness of recoverable reserve by the j^{th} well of the i^{th} DA. To calculate the recoverable resource of a well pair: first a well pair polygon ABCD (**Figure 3.6**) is established. Sides AB and CD are parallel to well pairs and points A and B are at a midpoint between wells 3 and 4. Similarly points C and D are in the middle of wells 2 and 3. A maximum BCB elevation value $bcb_{\max}$ is determined from all the cells located along well 3. For the calculation of recoverable reserves, well 3 is assumed to be placed at $bcb_{\max}$ elevation. Value of r_j^i is calculated from all the cells inside polygon ABCD as:

$$r_j^i = \left(\frac{\sum_{k \in inside\, ABCD} \mathrm{recov}_k * \mathrm{Ar}_k}{\sum_{k \in inside\, ABCD} \mathrm{Ar}_k} \right)$$

where recov_k is recovery form k^{th} cell.

Ar_k is fraction of area of cell 'k' inside polygon ABCD

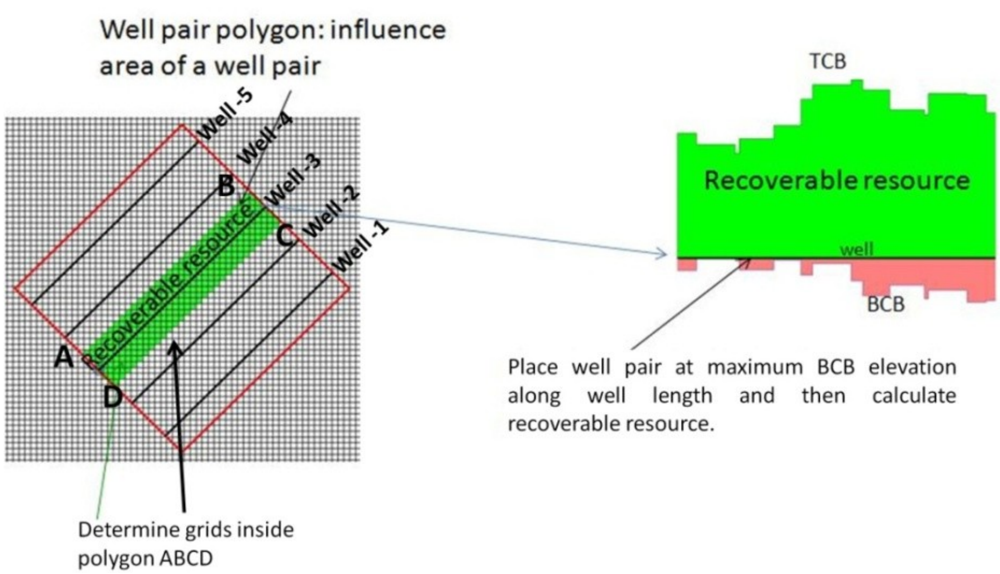

Figure 3.6 Calculation of recoverable bitumen

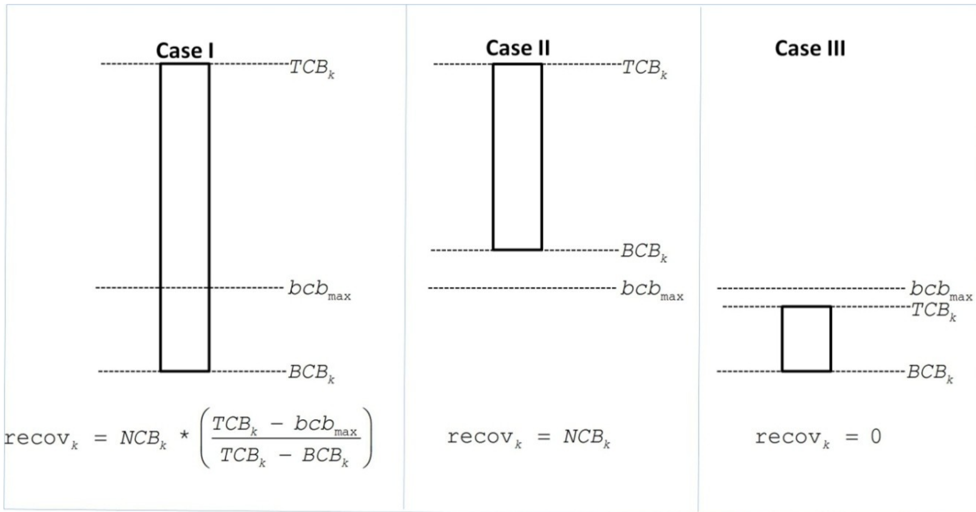

Figure 3.7- An illustration of different cases in recoverable bitumen calculation

recov_k for each cell is calculated as: There are 3 possibilities for a cell 'k' which is inside well pair polygon ABCD (**Figure 3.7**). Case I is typical. Case II is the situation when elevation of well is less than the BCB surface elevation at k^{th} cell. Note that this k^{th} cell of case II will never lie along well pair, because for any cell along the well the value of BCB is less than $bcb_{\max}$. For case II all the resource at k^{th} cell is recoverable. Case III is a rare case when the thickness of a bitumen deposit is so low at k^{th} cell doesn't even crosses the well pair elevation.

A thief zone penalty pen_{tz} is also calculated over each drainage area. The thief zone penalty is a function of the number of well pairs affected by thief zones n_{eff} . A well is considered affected if it passes through thief zone area. The penalty function (Equation 3.3) is explained in Figure 3.8.

$$pen_z = ft + (1-ft) * \left(1 - \frac{n_{eff}}{n_{well}}\right)^{wt} \tag{3.3}$$

The fifth and final constraint is to force well pairs inside the region of interest. It is possible in some situations that well pairs must reach beyond the region of interest. Then good well pairs (located in high reservoir quality) are made to fit inside at the cost of losing some well pairs located in low reservoir quality. The same logic is used for locating the drainage areas completely inside the region of interest. The penalty for crossing well pairs and drainage areas is proportional to the non effective area which is outside the region of interest.

The surface pad penalty for a drainage area is a 0 (not possible to develop a SP), a 1 (possible to develop a SP) or somewhere in between 0 and 1 (possible to develop SP but at additional cost). There are 4 main parameters used for checking the possibility of SP. (i) radius of SP (r_{SP}). (ii) Ideal distance of SP from its DA (d_{ideal}). (iii) Search direction of

SP: There can be 1, 2, 3, or 4 search directions. For a rectangular DA it can be either direction 1 or 2 and for a square shaped DA it can be maximum up to 4 (Figure 2.3), surface pad can be located in any one of these directions. (iv) Distance tolerances (`dis1, dis2`): are the values of distance tolerances in the direction of DA (`dis1`) and in the perpendicular direction (`dis2`) (Figure 3.9(a)). All possible directions for development of surface pads are checked for the possibility of unrestricted surface area. Checking the possibility of surface pad in one direction is shown in Figure 3.9(b). First a surface pad is placed at its ideal position. This ideal position is assumed to be the centre of the cell of the surface penalty map which falls at a distance d_{ideal} from drainage area. The surface pad is placed at this location and checked whether it is overlapping with any penalized cells or not? If it overlaps then this location is not available to develop surface facility and surface pad penalty value pen_{SP} is set to 0. If it is not possible to place SP at its ideal location, then the next nearest cell is checked for the possibility of a SP location. This checking process continues until all cells inside rectangle ABCD are used or a cell is found for the SP location. The surface penalty value is assigned for all search directions. If all 4 positions are available for the surface pad then one is selected that gives the maximum value of objective function for this drainage area. It should be noted that there are 2 different values of available/recoverable bitumen for a DA when all four directions are available for surface pad placement. One value is when wells are drilled either from directions 1 or 2 and other is when wells are drilled either from directions 3 or 4 (Figure 2.3).

The optimization program tries to locate surface pads over non penalized locations. If surface pads cannot be located in non penalized regions then surface pads for better drainage areas are kept at the cost of sacrificing some of surface pads for poor drainage areas. The selection of better drainage areas and well pairs is applied for all penalties-thief zone, base conformance, and crossing well pairs and drainage areas.

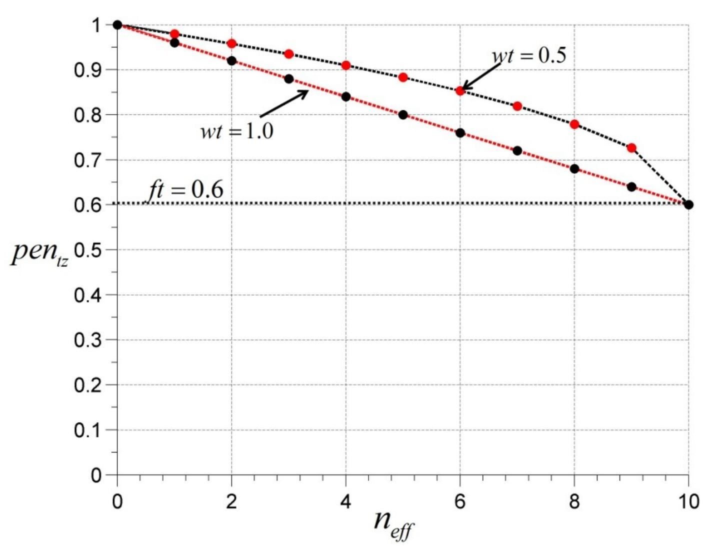

Figure 3.8: Penalty function for thief zone with different parameters.

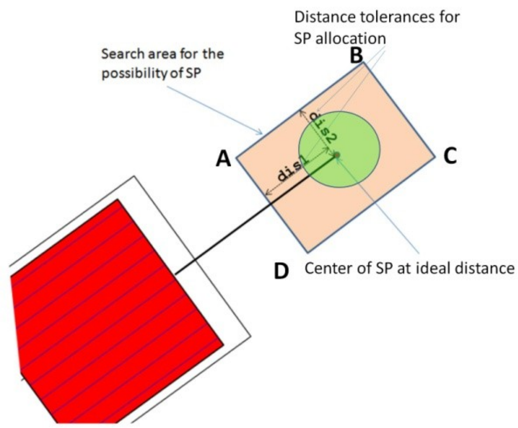

Figure 3.9(a)

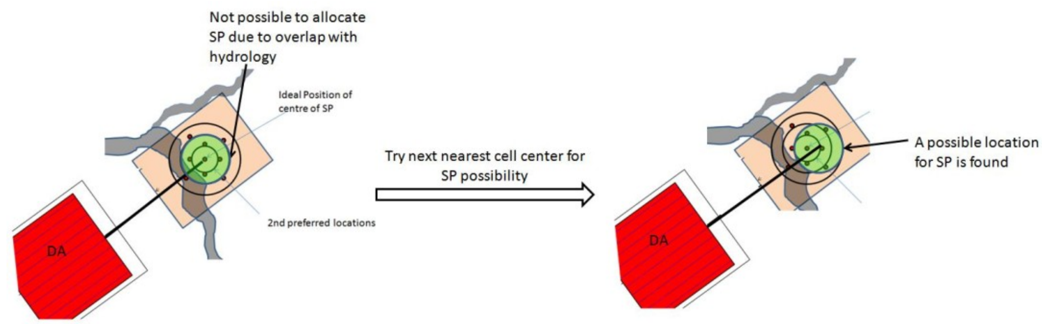

Figure 3.9(b)

Figure 3.9: (a) Distance tolerances in search for SP. (b) Searching of SP location by gradually moving away from the ideal position of SP.

3.2 Parameter File

The parameter file of the optimization program DASPopt is explained here. The input data files and parameters for optimization are provided in a text formatted file. **Table 3.1** shows the different parameters listed in the parameter file. The first line of the parameter file specifies the length and width of drainage area. The length is the dimension along the direction of well pairs. Line 2 specifies well spacing and pad radius. Number of well pairs in drainage area is width divided by well spacing. Therefore width of drainage area should be completely divisible by well spacing. Circular shaped surface pads are considered. Line 3 specifies different parameters for surface pad positioning for a drainage area. This first parameter is the ideal distance between surface pad and drainage area. Second and third parameters are dis1 and dis2 values as discussed in previous section. Line 4 has flag parameters for surface pad search directions (**Figure 2.3**). Line 5 and 6 specifies the input file and column numbers for realizations of reservoir variables- Primary variable (e.g. - NCB), BCB, GCB and TZ. Primary variable is required to run the optimization. Other variables ate optional. The quality part drainage area is based on primary variable. If Column number of BCB is specified then only base penalty or recoverable reserve calculation can be done. If GCB is supplied then TCB is determined by adding GCB value to BCB value and used in recoverable reserve calculation. If GCB value is not supplied then a kind of TCB is calculated by adding NCB/primary variable to BCB. If thief zone column number is nonzero then only thief zone calculation are included in objective function. Line 7 has parameter to choose the optimization option based on base penalty or recoverable reserve calculation (if BCB data is supplied). 0 is for recoverable reserve calculation and 1 is for base penalty calculation. The second parameter is the λ factor of base penalty function. Line 8 specifies parameters for thief zone penalty function. The first and second values are ft and wt parameters (**Equation 3.3**). The last value is the cut-off value for thief zone consideration. If thief zone thickness is more than cut-off then only it is considered as thief zone.

Lines 9, 10, 11 and 12 specifies the input file for surface penalty data, column number of surface penalty value, and grid definition for surface penalty data. Line 13 specifies the input file with initial drainage area configuration. This file is generally the output of dapave program. The optimization program is designed to take input from either dapave or the output of DASPopt itself. In this way the optimization can be rerun on the output of DASPopt. Line 14, 15, and 16 specifies different types of output file. Line 16 specifies the main output file with drainage area and surface pad locations along with surface pad penalty and recovery and elevation for each well pair. Line 17 specifies the output plotting file with map of quality of reservoir against drainage area locations. The first parameter is the name of output file; second parameter is selection flag for variable to show in map, third parameter is the realization number of selected variable to plot. If the third parameter is equal to -1 then the mean value from all realizations are plotted as a map. Fourth and fifth parameters are the color limit of the map. The last parameter is cut-off value of objective function of a drainage area. A drainage area (after running the optimization) is plotted over the map of reservoir variable if value of objective function for this drainage area is greater than specified cut-off. Line 18 specifies the output file with plots of drainage areas and surface pads against surface penalty map. Lines 19 and 20 specify the grid of input data for reservoir variables.

Line 21 specifies flag for optimization by breaking rows of drainage area configuration. Breaking of rows is performed after running all optimization steps either in manual or automatic options. It checks for the improvement in objective function value by breaking individual rows. Breaking helps to locate the surface pads for those drainage areas which are impossible to develop because of surface pad location over restricted area. Line 22 specifies the flag for automatic optimization. If automatic optimization flag is set to 1 then full automatic optimization is performed. If this flag is set to 0 then the next parameter specifies the number of optimization steps provided manually.

Table 3.1- Parameter file for optimization program

```
                                      Parameters for DASPopt
                                      **********************
   START OF PARAMETERS:
1  1000  1000                  -length and width of DA

2  125  100                    -well spacing, pad radius

3  350  50  50                 -Ideal distance of SP from DA, dis1, dis2

4  1  1  0  0                  -search direction for SP (1-yes, 0-no) for 2 directions

5  DATA.dat                    -Input data file, column number for DRSC, dis-
                                reser,BCB,NCB,GCB,Phie,Sw,Tz
6  1  3   0  2                 -Column numbers for Primary variable,BCB,TZ,GCB

7  1   0.8                     -Penalize base:1- yes, 0-recoverable reserve calc; if 1 then
                                f10 factor
8  0.6 0.5 0.5                 -0: ft, wt, thickmax for thief zones

9  Scpen.dat                   -Input surface penalty map (optional)
10 1                           -column number for surface penalty data
11 400   12.5  25.0            - nx,xmn,xsz for surface penalty
12 400   12.5  25.0            - ny,ymn,ysz for surface penalty

13 dapave.csv                  -input file with initial configuration of DA
14 DASPreal.out                -output by realization and DA
15 DASPsumm.out                -summary output file
16 DASPopt.csv                 -Output file with final result of optimization
17 DASP.ps 1 1 8 30 0.1        -plot variable(1=NCB,2=GCB,3=BCB,4=TZ),realz# (-
                                1=mean),cmin,cmax.qual_cut
18 DASP_SP1_b.ps               -Plot DA/SP locations against surface culture

19 73   505550   100.0         -input size: nx,xmn,xsiz
20 94   6225650   100.0        -            ny,ymn,ysiz

21 0                           -Optimization by breaking lines
22 1         1                 -automatic optimization (1-yes, 0-user specified), nopt
23 -1 database.dat             -if automatic, -1:write database, 1-read from file, 0-
                                nothing, filename
24 DASPobj.out                 -output file with maximum obj.
25 DASPobj.ps                  -file for plotting objective function

26 4  0  1                     - Rotate:    minimum and maximum angle
.  3     1000  1000            -  Optimization by sliding:     max distance in 2 directions
.  nofile                      -  file (optional) with order of lines to slide (or not)
.
.
```

line 23 specifies the option to read or write the database on a binary file. Database of calculation can be saved when optimization is ran for the first time and can be read running next time without changing parameters used in objective function calculation. IT saves lots of time for next runs. Parameters in lines 24 and 25 are exercised only when the automatic optimization flag is set to 1. Line 24 specifies the output file with report on best possible configuration of drainage areas and surface pads for each orientation form 0 degrees to 179 degrees at unit intervals. It also lists the optimization steps for each orientation. Optimization steps for one orientation are combination of sliding optimization, translational optimization, and just rotation. If one such optimization sequence is performed on starting drainage area configuration then the optimum configuration for respective orientation is achieved. Line 25 specifies the name of the output file with plot of value of maximum objective function against each orientation. This plot is important in analyzing the different orientations with objective function value. For example two different orientations might have almost same objective function value then the direction which makes more practical sense can be selected for development.

Line 26 and onwards specify the parameters for manual optimization. A single optimization step is entered on each line. There are total four different optimization options- optimization by sliding, optimization by translation, optimization by rotation, and just rotation. Any optimization step requires 3 parameters. The sliding optimization requires one additional parameter with input file name with indexes of line to slide. The input file name is optional. If this file is not present then sliding optimization is performed on all lines. If this file is present then optimization by sliding is performed only for those lines whose indexes are mentioned in the file. Manual optimization steps can be performed after running the full optimization. To get the optimum drainage area and surface pad configuration for a particular orientation, the manual steps are taken from the report generated by automatic optimization. Any manual input for optimization step has three parameters. First parameter indicates the type of optimization: 1 is for optimization by translation, 2 for optimization by rotation, 3 for optimization by sliding individual rows, and 4 for just rotation. Meanings of next two parameters are listed in **Table 3.2**.

3.3 Validating Optimization Methodology

This section provides series of examples to check the results of optimizations. Examples are simple in nature and the optimum orientation and location can be guessed easily. There are 4 examples presented here for checking results against- (i) orientation of well pairs for best base conformance, (ii) orientation of well pairs to minimize the effect of thief zone, (iii) orientation of well pairs to minimize the number of well pairs outside region of interest, and (iv) improving the locations of drainage areas by breaking rows.

Table 3.2: Details of optimization parameters.

Optimization step	Example of par2, par3	Description
1- translation optimization	300, 100	Translate entire group of DA by 100m step size in x and y direction up to the limit of -300 to 300.
2-rotation optimization	-30, 45	Rotate entire group of DA about its centre of arrangement. Rotation is done at one degree interval up to 30 degrees in clockwise direction and 45 degrees in counter clockwise direction. A rotation with maximum objective value is optimal rotation.
3-sliding optimization	800, 1000	Slide all DAs on a line in the direction of line up to -800m in one direction and 1000m in another direction. First direction is the direction making positive angle with x axis and second direction is one which makes negative angle with x axis (figure 14). Select a sliding distance which gives the maximum objective function value.
	Line_to_slide.dat (optional)	This file includes the index of lines for sliding. If this file is not present then all lines are checked for sliding optimization.
4- rotation	30, 1	The first parameter 30 specifies the rotation angle, the second parameter specifies the direction 1- counter clockwise, -1 clockwise direction. No optimization is done in this step. Entire configuration is rotated regardless of improvement in the objective function.

3.3.1. Testing Base Conformance Along Well

To test base conformance of well pairs an example data for BCB is created (**Figure 3.10**). The BCB surface is a plane with a north-west strike direction. To minimize the variability of the BCB surface along the well pairs, the orientation of drainage areas must align in the strike direction. This example is simple and the anticipated well orientation is confirmed by the output of DASP tool. Running the optimization either with base penalty or with recoverable reserve calculation produces the same result. **Figure 3.11** shows the optimization results with and without base penalty. Values of the objective function for the optimum configuration for each orientation is also plotted. A factor of 1.0 was used for the base penalty function, which is very high therefore the change in the objective function is smooth with angle. **Figure 3.12** shows effect of base penalty factor (λ) on the objective function. An optimization with λ equal to 0 is the same as no base penalty at all. The higher the value of λ is, the larger the base penalty. Figure 3.12 illustrates that as λ increases, the local optima vanish. A very high base penalty will force the drainage areas in an orientation with the smoothest BCB surface, regardless of reservoir quality. Optimization based on recoverable reserve calculation eliminates the use of a base penalty factor. The example used here is very simple. The BCB surface is a plane with a constant dip direction. A more complex surface can be sensitive to the base penalty factor and can produce different optimum orientations with different base penalty factor.

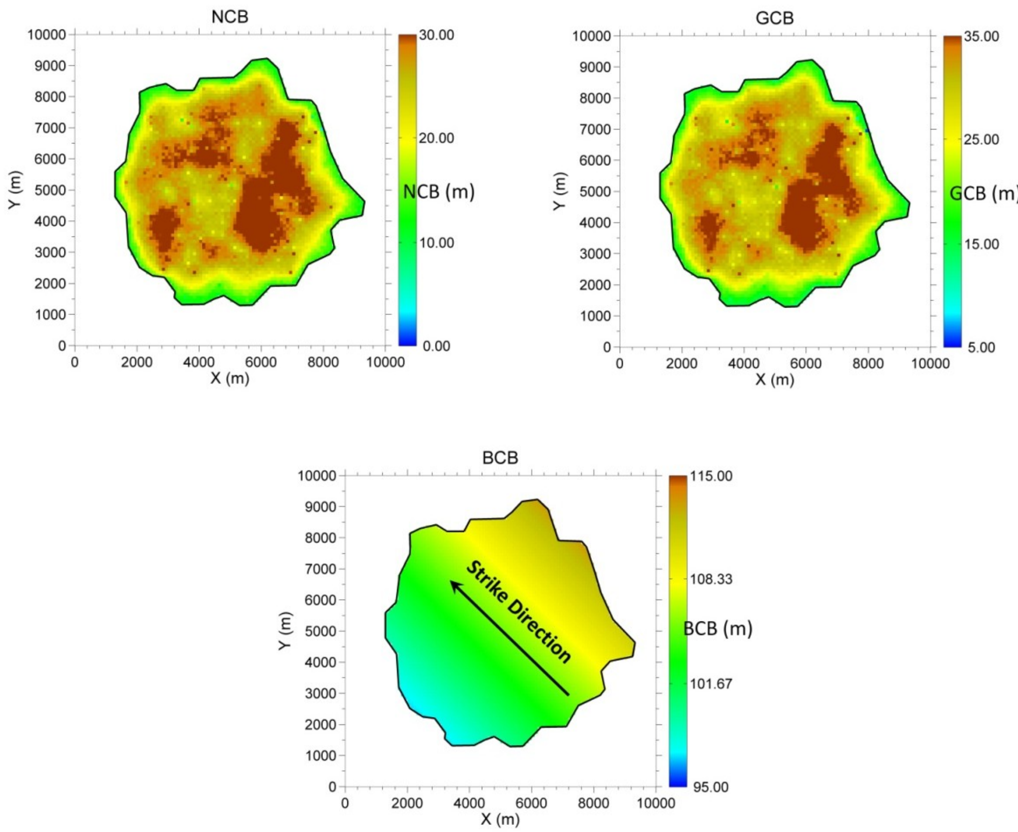

Figure 3.10: Input data for testing base conformance. clipped maps of NCB (thickness in meters), GCB (thickness in meters), and BCB (elevation in meters).

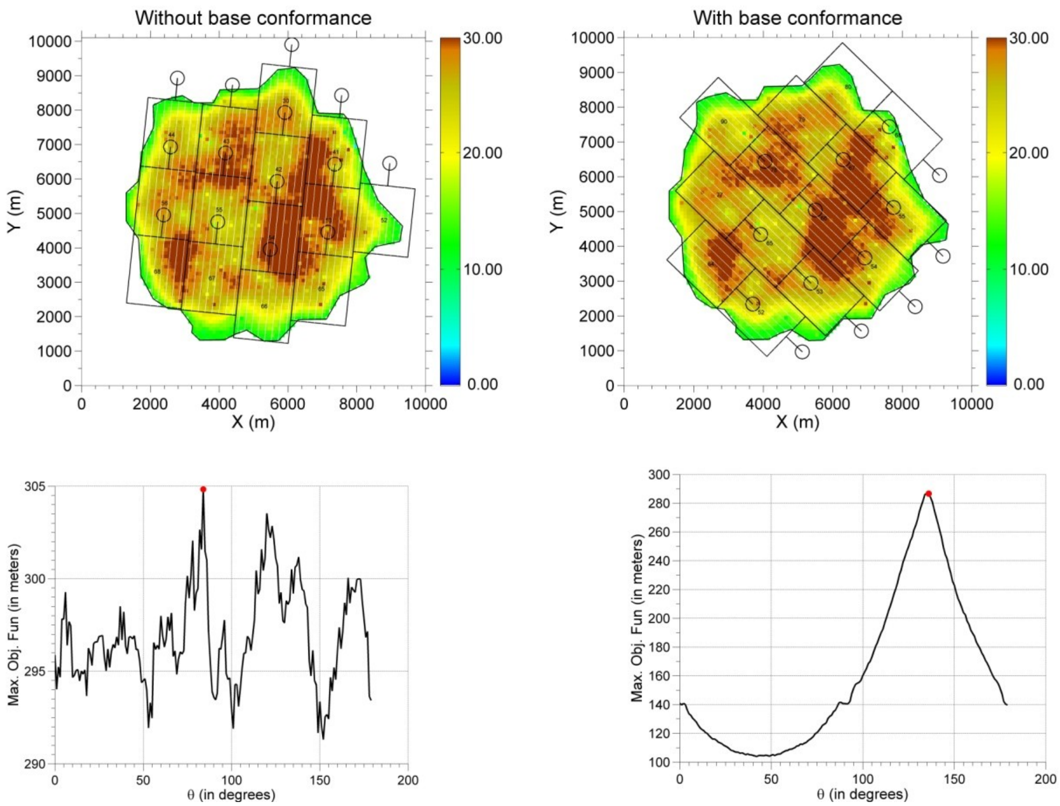

Figure 3.11: Testing base conformance- Optimization results with and without base conformance. Figures in right show results with base conformance. Optimum objective function value for different orientations is shown at bottom. A base conformance factor of 1.0 was used.

3.3.2 Testing Effect of Thief Zone

The test data used to check the effect of the thief zone is the same as used for checking base conformance. Base conformation is not used in the optimization in order to make the example simple**. Figure 3.13(a)** shows the thief zone data. A nonzero thief zone thickness was considered as an effective thief zone. The optimum well configuration based on the thief zone is one that minimizes the total number of well pairs affected by the thief zone area. **Figure 3.13(b)** is the result after optimization which suggests the minimum number of well pairs affected by thief zone because well pairs are aligned parallel to the direction of thief zone. Using the base penalty in conjunction with the thief zone penalty will produce different results.

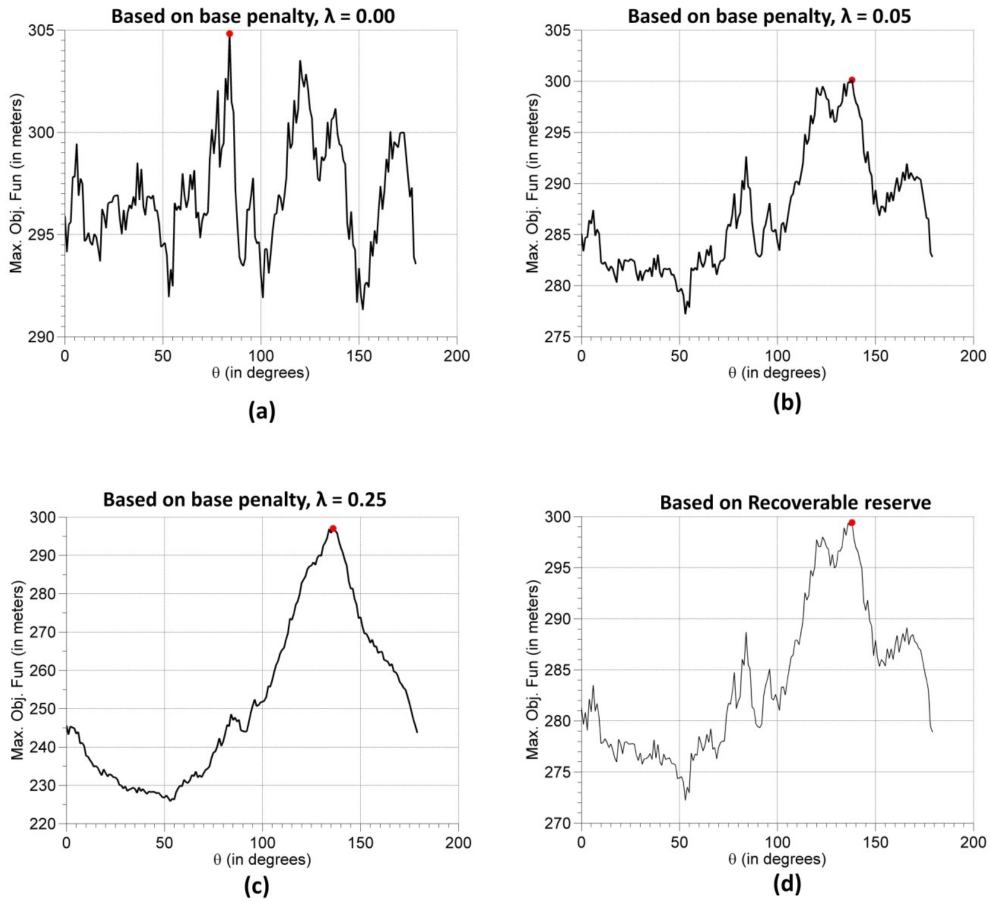

Figure 3.12: Optimum objective function for different orientations. Different results with base penalty and recoverable reserve calculation. A higher base penalty forces orientation of drainage area in smoother base regardless of effect of orientation on reservoir quality

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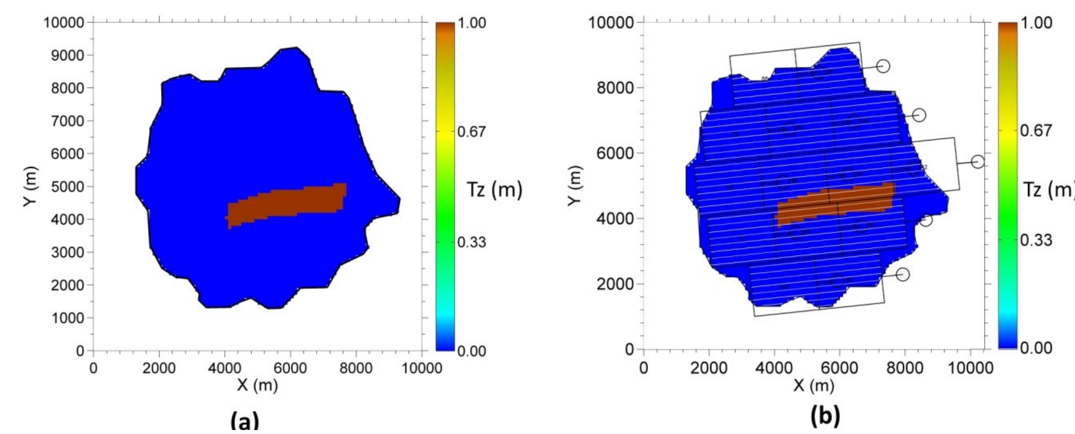

Figure 3.13: Testing for thief zone. (a) Thief zone map. (b) Optimization based on thief zone penalty.

3.3.3 Testing Orientation of Well Pairs

Changing the polygon defining the region of interest can change the orientation of the drainage The objective function value of a well pair/drainage area is penalized by the amount it is outside the region of interest. **Figure 3.14** shows different regions of interest and the resulting optimum configurations. Base conformance was considered in the optimization. This result shows the fitting of drainage areas inside the region of interest. Drainage areas are fitted inside the region of interest and satisfy the space packing constraint. Results were tested against different starting configurations. All of them produced the same locations and orientations of drainage areas as when the full optimization was run.

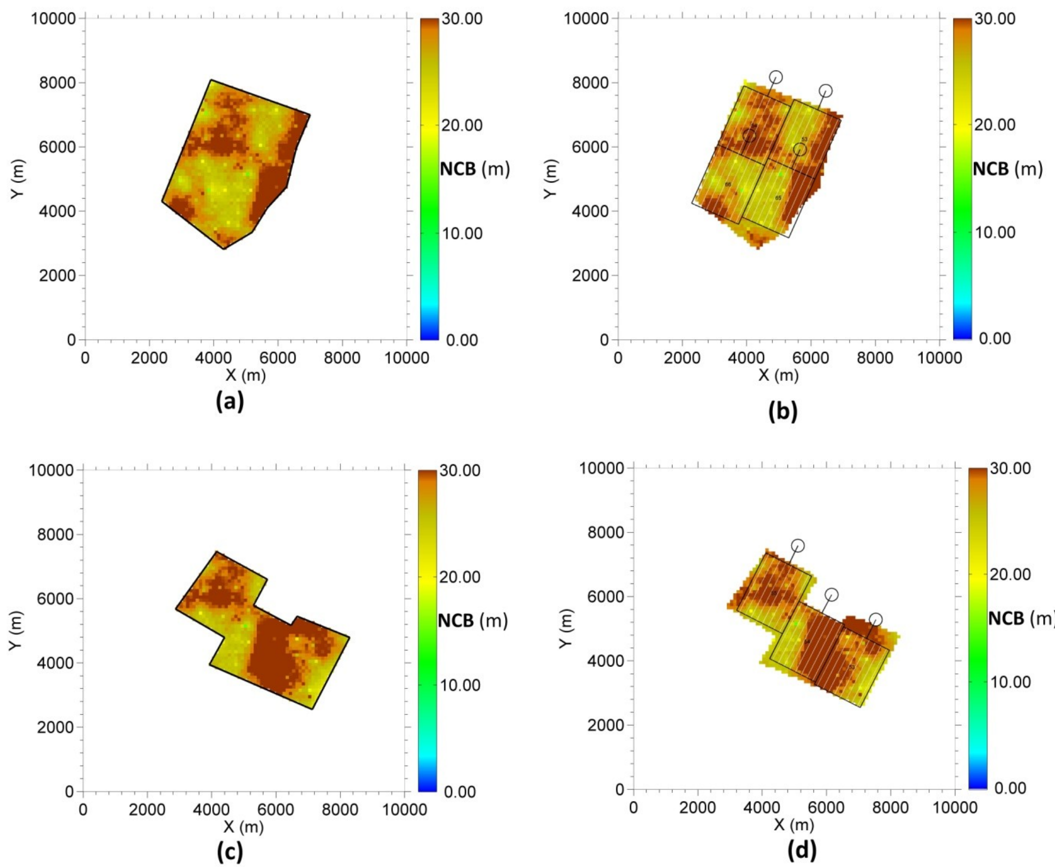

Figure 3.14: Testing well orientation. Example 1- (a) region of interest, (b) optimum well locations. Example 2 – (c) region of interest, (d) optimum well orientation.

3.3.4 Testing Optimization of Surface Pad Locations

All the examples discussed in previous sections were without any surface penalty data. Finding the optimum location of surface pads is very important to SAGD projects. The optimization algorithm first tries to place surface pads at the ideal distance from drainage area. If the ideal position is obstructed by some surface obstruction then surface pads are positioned as near to the ideal position as much possible. **Figure 3.15** shows the optimization of surface pad positions. First, optimization was without surface penalty (with no surface data). The optimum positions of drainage area and surface pad is shown in **Figure 3.15(a)**. The ideal distance of the surface pad from the drainage area was set to 650 meters. Next, a surface penalty data was included to obstruct the development of one drainage area. Optimization was rerun with surface penalty data but surface pads were restricted to their ideal position; no search window was assigned to look for the possibility of surface pad near to its ideal position. This result is shown in **Figure 3.15 (b)**. Then, optimization was done by introducing a 400m x 400m search window. After running the optimization surface pad is located at a position which is nearest to ideal position and within search window. The other optimization for surface pad positioning, which is not shown here is looking surface pad in the other direction (see parameter file specifications).

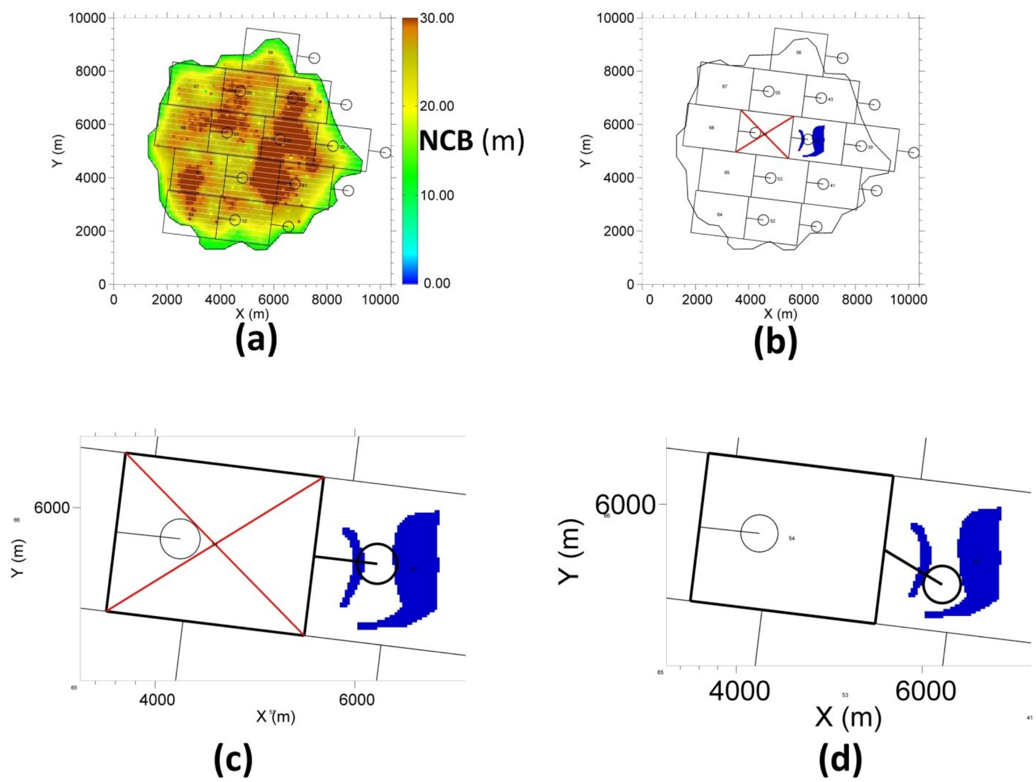

Figure 3.15: (a) Optimum result without surface penalty, (b) surface obstruction is added, (c) not possible to develop drainage area because surface pad is over an obstruction, (d) result after optimizing surface pad location. Surface pad is located at nearest available position.

Chapter 4: Case Study

This chapter documents the implementation details of the DASP optimization tool developed in previous chapter. Several special cases were presented and tested in Chapter 3. The case study presented here is a synthetic example fashioned after a realistic scenario for the McMurray formation. The objective is to present a step-by-step implementation of the optimization methodology so that others could use the developed tools on real life data. The test case starts from drill hole data and finishes with drainage area and surface pad positioning for a development area. The test data are presented. Several drill hole data are available with BCB, GCB, TCB and NCB values. Sequential Gaussian Simulation (SGS) is used to generate multiple realizations of the reservoir variables on a specified grid. After this, the DASP tool is used to generated surface penalty maps, make an initial guess and perform optimization.

4.1 Drill-hole Data

A model area of 10Km by 10Km is selected**. Figure 4.1** shows the drill-hole locations and values of NCB, GCB and BCB at different locations. There are a total 259 drill-hole locations. The mean value for NCB is 17.14m and the standard deviation is 11.04m. The mean for GCB is 21.07m with a standard deviation is 11.42m. The correlation between NCB and GCB are very high (0.96). The BCB mean is 102.07m with a standard deviation of 11.20m. BCB values are in elevation relative to mean sea level; therefore 100m BCB value is deeper than 120m BCB value. Histograms of the reservoir variables are shown in **Figure 4.2**.

4.2 Simulation of Reservoir Variables

Sequential Gaussian Simulation (SGS) is used to generate 10 realizations of each reservoir variable at a 100m x 100m grid scale. **Figure 4.3** shows the first realization of each variable. All realizations are used in the calculation of drainage area and surface pad locations. **Figure 4.4** shows the mean value of NCB obtained from all 10 realizations. A polygon is defined (thick black line) to cover SAGD developable region. A SAGD developable region is assumed everywhere when the thickness of NCB is greater than 15 meters. The polygon defining developable region is region of interest (ROI). Drainage areas will be located inside the ROI.

4.3 Surface Data

Figure 4.5 shows the surface restrictions inside the model area. Two types of surface restrictions are present- road and lake. A surface pad cannot be located over these surface restrictions. But a surface pad can be located just beside the restrictions. A surface penalty map is generated using the `setpen` program over a 25m x 25m grid. The resolution of the surface penalty map is 4 times higher than the subsurface realization maps. A penalty value of zero is assigned for a cell over a surface restriction. Any cell with dark color (**Figure 4.5**) is penalized and positioning of surface pad is not possible over it. The region of interest is also shown along with surface restrictions.

4.4 Clipping Reservoir Variables and Generating Initial Input

The next step is to clip the subsurface data inside the ROI. Clipping reservoir properties inside a polygon forces the drainage area placement to stay within the polygon. Clipping helps to locate a DA with most of its well pairs inside the ROI. Only reservoir variables are clipped inside the polygon; the surface penalty is not. It is assumed that surface pads can be located anywhere inside the model area. Locations of surface pads are not restricted within the ROI only.

An initial arrangement of drainage areas is generated by the `dapave` program. All drainage areas are oriented in the north south direction. **Figure 4.6** shows the initial pattern. 1000m long and 1000m wide drainage areas are used to generate initial arrangement. Different rows of DA pattern are indicated in the figure. Numbering of rows can be used in the optimization. It provides the option to freeze or slide individual rows. Index of drainage areas are shown at the centre.

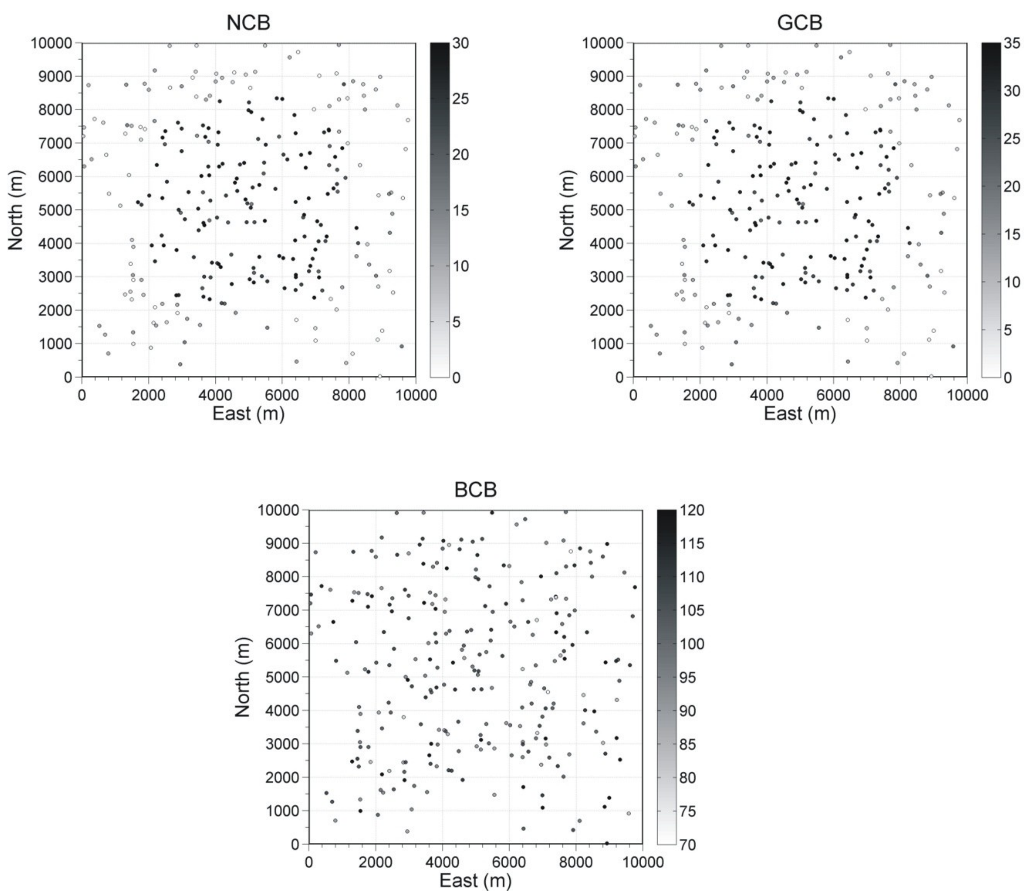

Figure 4.1- Drill-hole data for NCB, GCB, and BCB (chosen randomly for the example study)

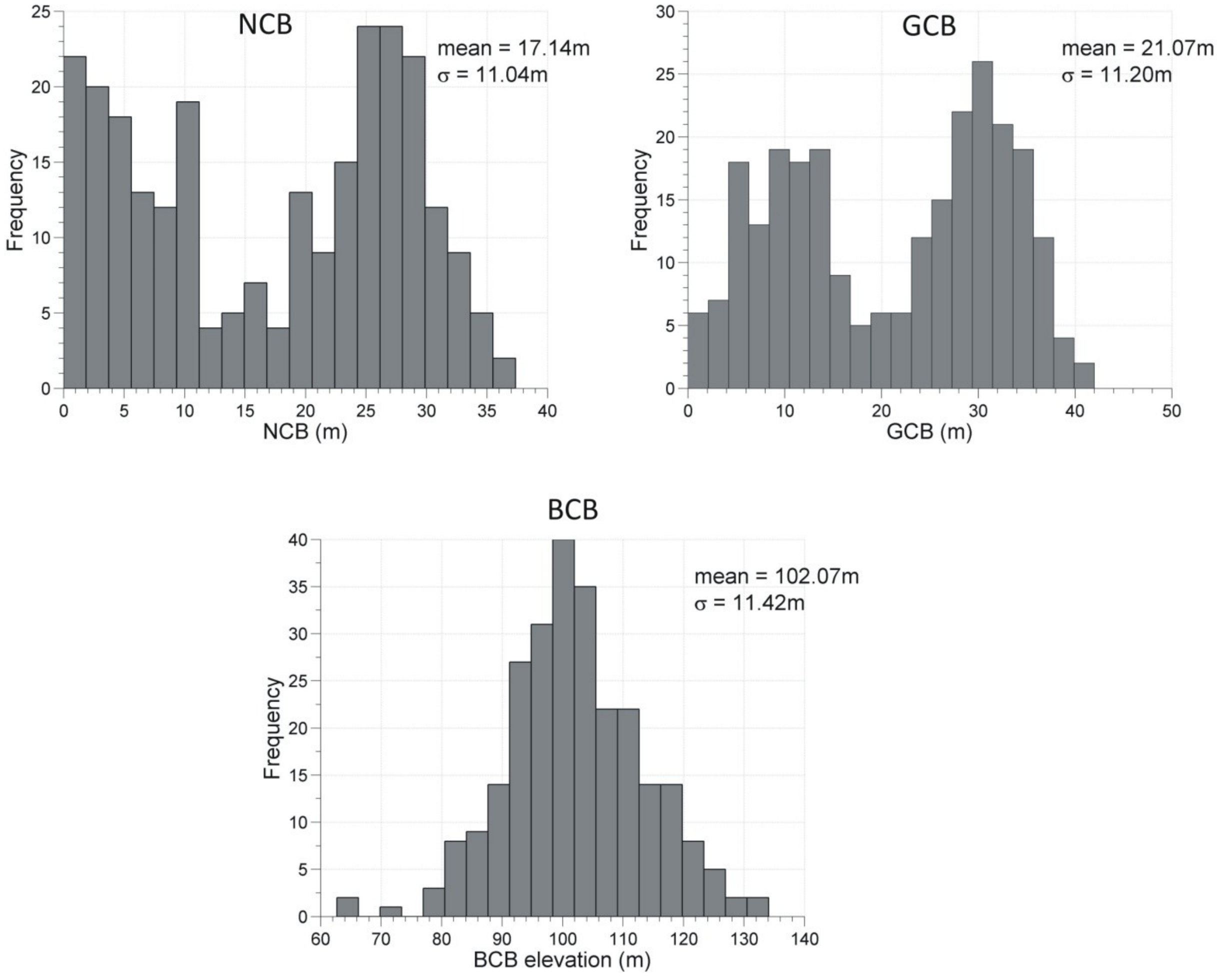

Figure 4.2- Histograms for NCB, GCB and BCB

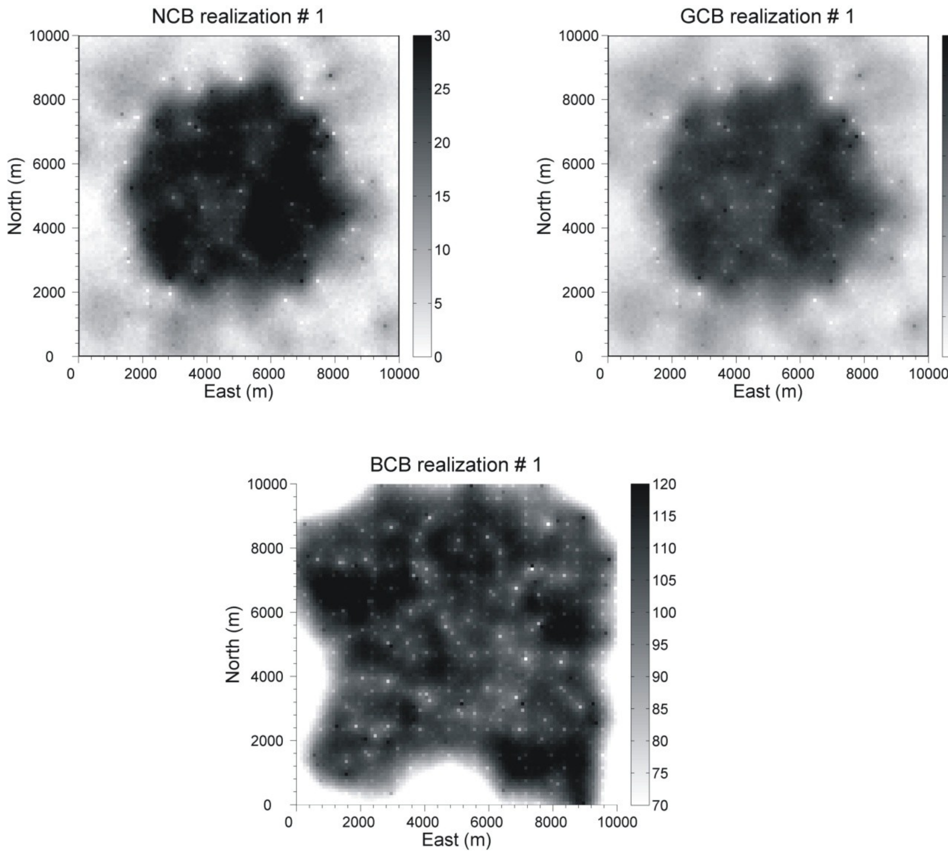

Figure 4.3- First realizations of reservoir variable.

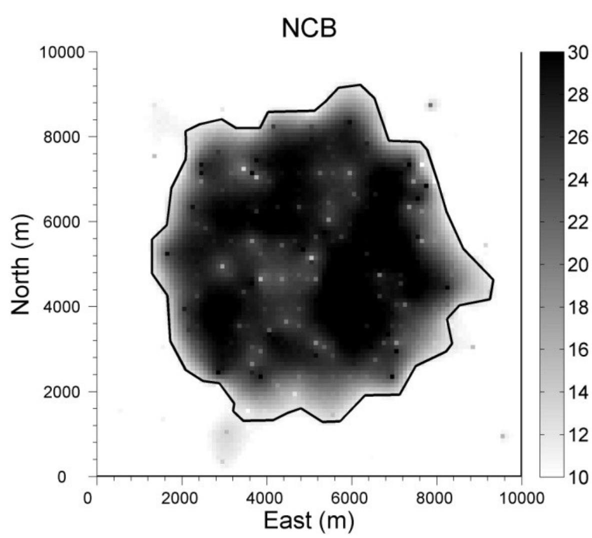

Figure 4.4- Defining Region of Interest (ROI)

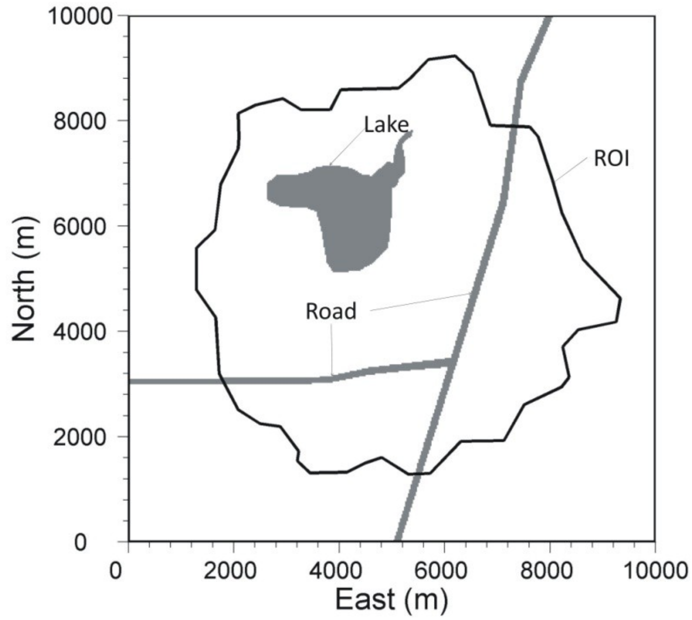

Figure 4.5- Surface penalty map over 25m x 25m grid.

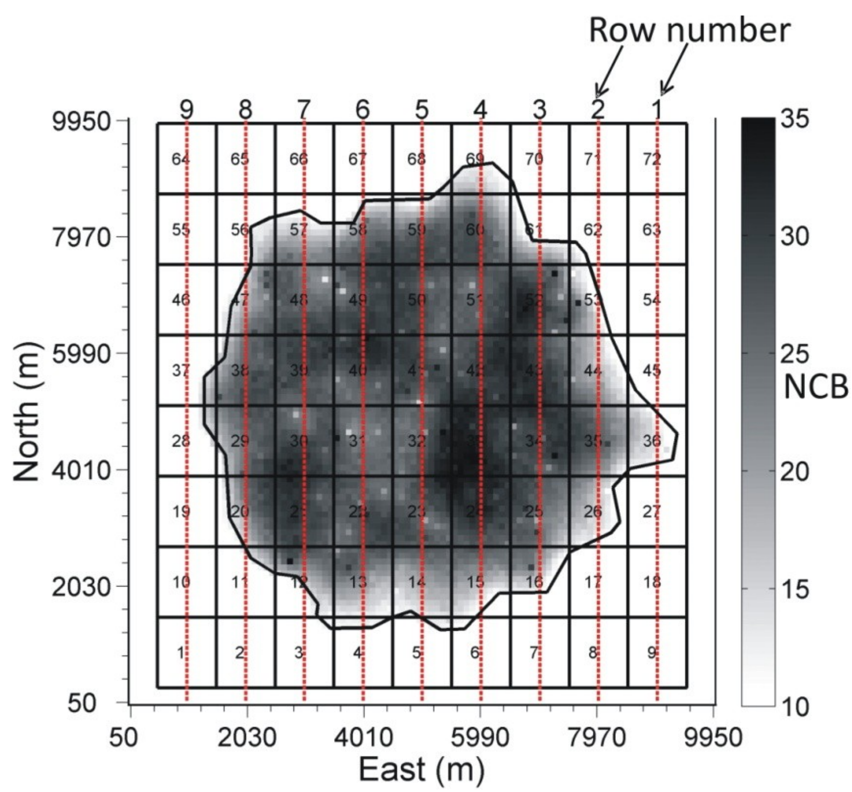

Figure 4.6- Initial arrangement of drainage areas.

4.5 Running the Optimization

All input variables required for optimization is provided in the previous steps. The surface penalty map will be used to check the availability of surface pads. The clipped subsurface reservoir variables will be used to calculate the recoverable bitumen for entire drainage area and each individual well pair. A well pair/DA outside ROI is penalized as per the amount they are outside the ROI.

Surface pads are idealized as circular in shape with a radius of 150 meters. The ideal distance between each SP and the corresponding DA is 350 meters. The distance tolerances for SP positions are: dis1 = 100m, dis2= 100 (see Section 3.4 and Figure 3.9 for details about tolerances). The well spacing is 125 meters; therefore there are 8 well pairs in a single DA. Since each DA is rectangular in shape there are 2 possibilities for the SP locations for a given DA. **Figure 4.7** shows the initial arrangement of DA. Locations of DA are same as of generated from `dapave` program. The locations of the SPs are optimized with respect to the DA locations. The total objective function value was 1009.8m with recoverable bitumen quality equal to 1057.4m. Units of objective function and recoverable bitumen are expressed in meters as total thickness, volume (cubic meters) can be calculated by multiplying with DA area ($10^6 m^2$). Recoverable quality is higher than objective function because objective function is in terms of quality but penalized for surface restrictions, thief zones, base penalty etc. DA number 60 is not possible to develop because of surface restrictions. **Figure 4.7** has two transparent maps over one another. The map with the color scale is the quality of reservoir (NCB). Another gray color map can be seen below the quality map. This is the surface penalty map. Combining quality and penalty in a single map helps to analyse the quality of drainage area and surface pad possibility together.

Next, optimization is done by sliding individual rows of drainage area pattern to compare the improvement in the DA and SP locations with respect to initial arrangement. It helps to understand the objective function and optimization methodology. **Figure 4.8** shows the optimal pattern of DA obtained after sliding only. Each individual row is translated until it maximizes the objective function. The improvement in patterns can be easily seen. Row-1 has one effective DA (number- 55). In **Figure 4.7** none of wells of this DA are completely inside ROI, but after sliding three well pairs are completely inside ROI. This kind of improvement can be seen in other rows too. For example in row-8 DA-81 is completely inside ROI after sliding optimization. One major improvement other than well-pair quality was in the surface pad allocation. After sliding, all drainage areas are accessible where as there was one DA not possible to develop before sliding. Value of objective function was improved from 1009.8m to 1084.8m. The quality part of the objective function increased from 1057.4m to 1102.0m. The difference between quality and objective function value is decreased because of activating one DA which was not possible to develop before sliding. Now, the difference between quality and objective function value after sliding is because of penalty due to some of well pairs are still crossing the ROI.

Sometimes the value of the objective function can be improved by sliding optimization. But it is possible to improve objective function by rotating or translating the entire group of DAs and then applying the sliding optimization. It is often desirable to automate the sequence of optimization, that is, consider all possible combinations and take the best result.

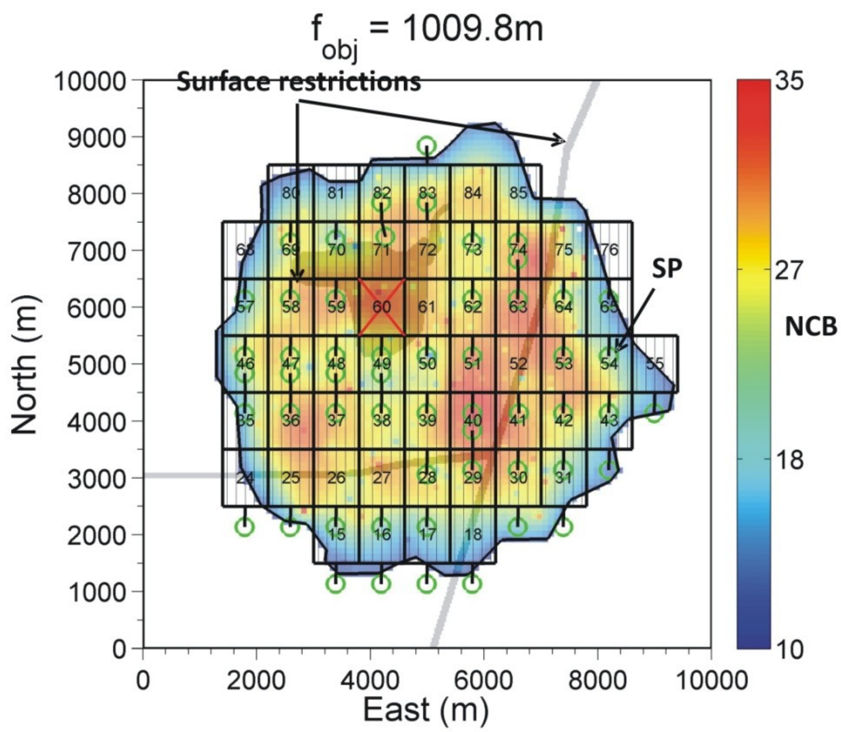

Figure 4.7- Initial optimization- the optimal locations of SP for initial guess of DA.

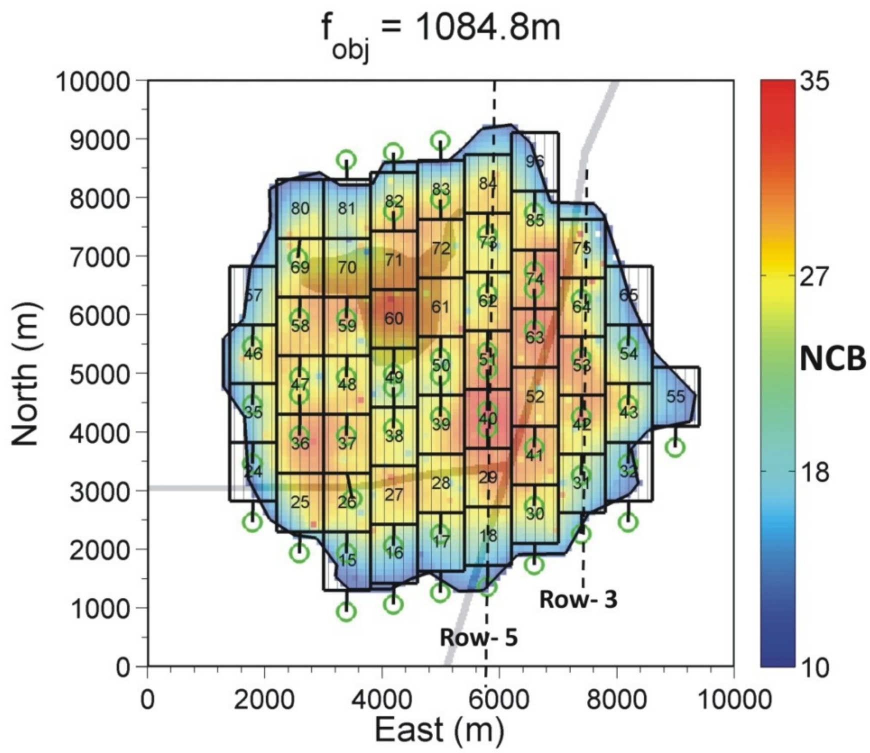

Figure 4.8- Optimization by sliding. DA quality in different rows is improved.

Even if there are restrictions on the rotation or translation, the results of the objective function obtained from automatic optimization can be interesting. For example, consider that the orientation of the DAs is restricted to north-south. The optimal pattern for DA and SP for north-south orientation can be obtained semi automatically by combination of translation and sliding optimization if the initial DA configuration has north-south orientation. If initial configuration doesn't have north-south orientation then a rotation step can be added in the optimization pattern to make them north-south. Now let's assume that the global orientation is in some other direction than north-south. The improvement in the optimal direction is useful information. Or we can investigate about how different directions are better in terms of objective function value. **Figure 4.9** shows the value of maximum objective function as a function of direction. The directions are measured in counter-clockwise from x-axis (east). Therefore 90 degrees represents north-south direction. The maximum objective function value for north-south direction is 1100.8m which is obtained by translation and sliding. **Figure 4.10** shows the locations of DA and SP for global maximum. After running the automatic optimization DASP tool generates a file with details of maximum objective function for each direction. It also includes the detail of how to reach this maximum objective function for each direction starting from initial configuration. Figure 4.9 shows a noisy nature of the objective function. It is mainly because of the grid resolution and number of realizations used in the optimizations. Noise is reduced when cell size is reduced and number of realizations are increased (Different example, **Figure 4.11**).

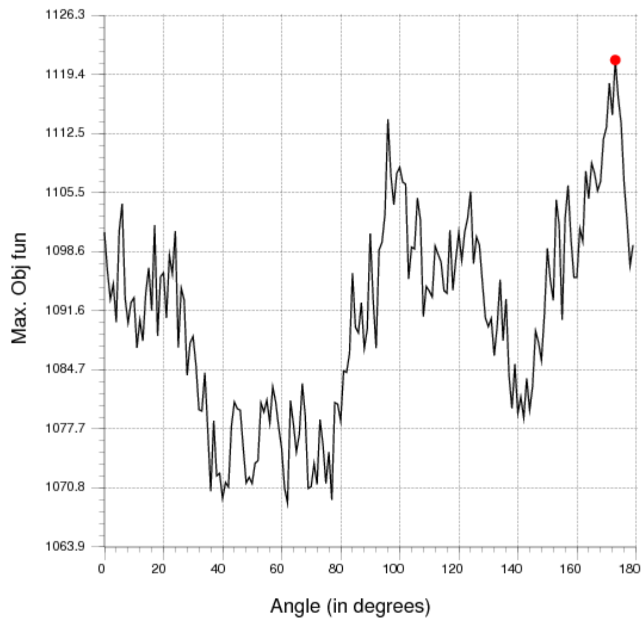

Figure 4.9- Maximum objective function value for each direction. The noise is because of grid size. A smaller cell size with more realizations will have less noise.

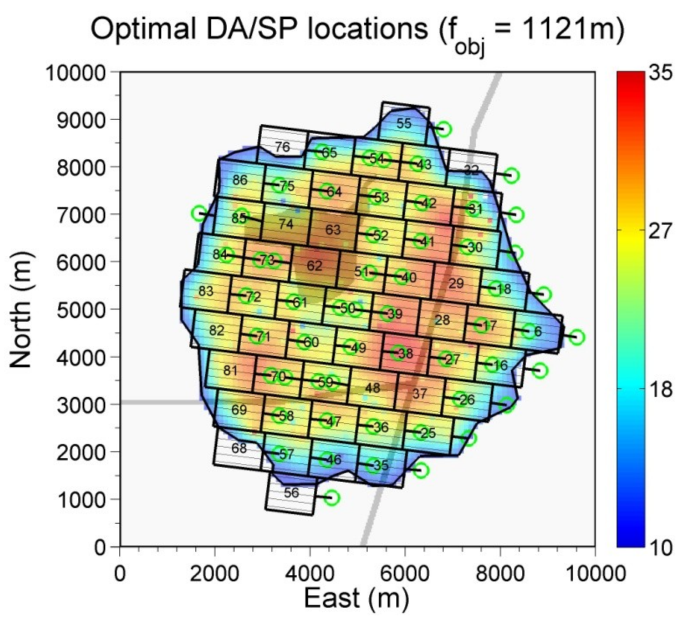

Figure 4.10- Overall optimum configuration of DA and SP. Giving maximum objective function value.

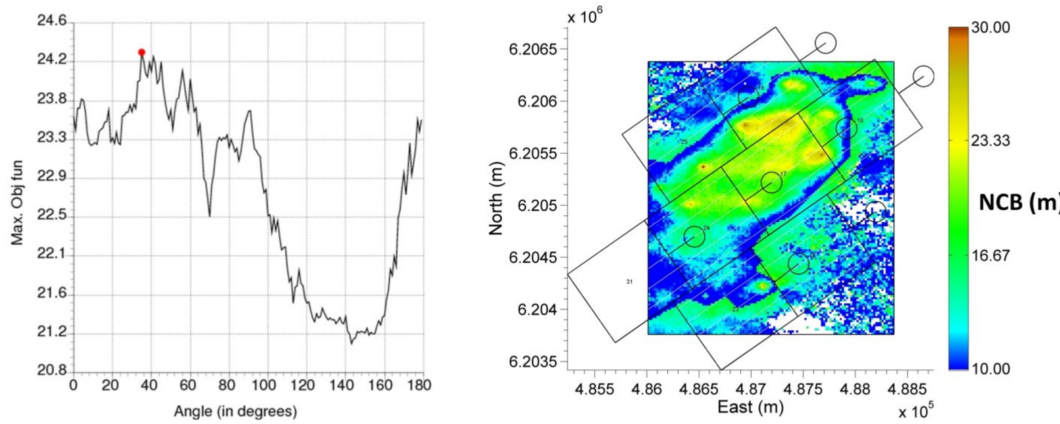

Figure 4.11- A different example; Noise in objective function is reduced for cell size of 20m x 20m, and for 100 realizations.

Breaking is another optimization method when it is not possible to develop a SP for some DA. For the same problem if the possibility of a SP is assumed in only one direction for a DA, then the optimum pattern is shown in **Figure 4.12**. The optimization after breaking is also shown in the same figure. Comparing them row wise suggests that the DA configuration has improved further. There is no change in row-1. But row-2 has one additional well pair in DA-76. Row-2 is broken between DA-76 and DA-85 and DA-76 is moved so that a complete well pair can be developed. Row-3 and row-4 are unchanged. In row-4 it is not possible to improve the objective function by breaking rows at locations where DA is not possible to develop because of surface restrictions. Row-5 breaks between DA-62 and DA-73. DA-73 is developable because of breaking at the cost of loosing DA-84. DA-84 was not completely covering the high quality reservoir. DA-73 is completely covering a reservoir with better quality. In practical sense DA-73 (after breaking) is preferred over DA-84 (before breaking) because of continuous good quality of reservoir. All DA in row-6 was developable even though breaking of row took place for this row. DA-83 comes completely inside ROI. DA-83 had all its wells crossing ROI before breaking. Also, DA-39 is now covers a continuous good quality of reservoir inside it. The other important factor for breaking is the nature of the BCB surface inside DA which affects the well's vertical positioning. The value of objective function increased from 1029m to 1041m because of breaking optimization.

4.6 Already Existing Drainage Area

All the methods and case studies covered previously assume that there are no drainage areas already present inside the ROI. It is possible to have some already developed drainage areas inside the ROI prior to perform optimization. The same optimization tool can be used in this case. **Figure 4.13 (a)** have a drainage area inside the developable area. The trick is to clip the realizations of reservoir variable outside the DA polygon. After that each step is similar as used in normal case. **Figure 4.13 (b)** shows the clipped data for optimization, starting configuration for optimization is shown in (c) and (d) shows the final optimization result. All DA in neighbourhood of clipped DA polygon fit exactly with it. If the shape and size of clipped polygon is different from DA then optimization result will not have compact pattern around clipped DA polygon. Optimization with breaking can improve the objective function further in this case.

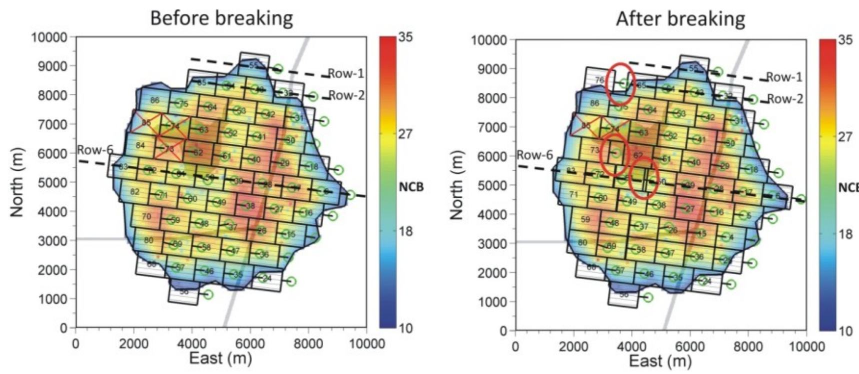

Figure 4.12- Optimization by breaking.

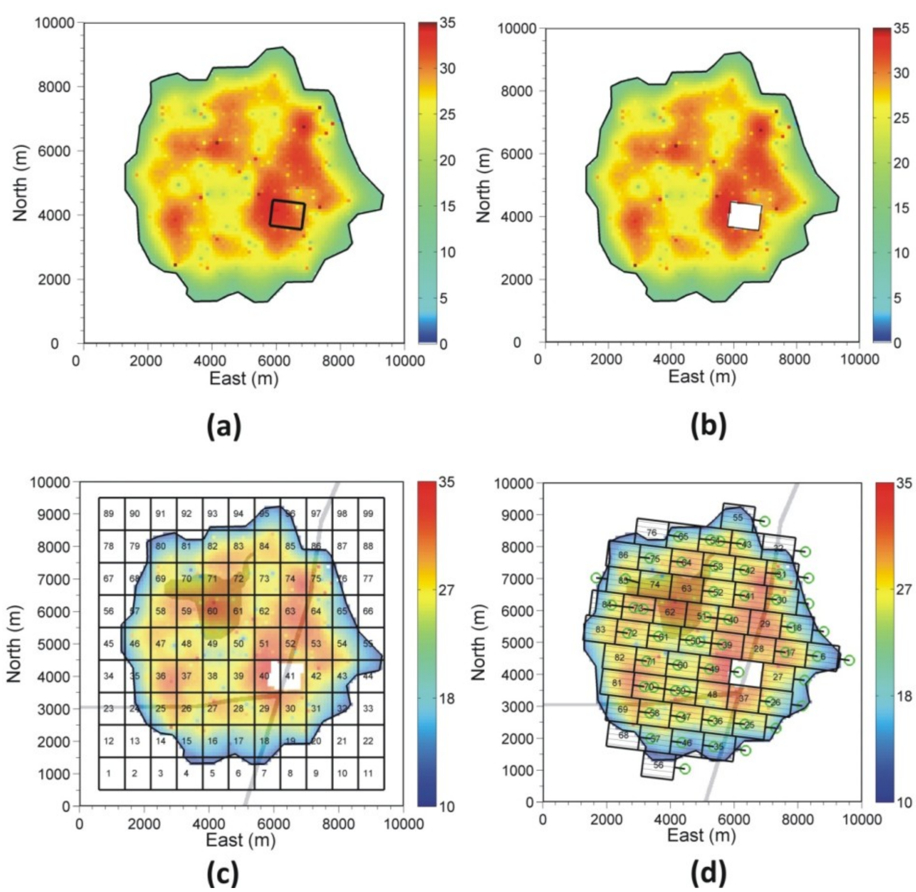

Figure 4.13- Optimization in case of existing DA. (a) A DA is already developed in ROI. (b) Clipping data outside DA polygon. (c) Starting configuration for optimization. (d) Final result after optimization.

Chapter 5 – Conclusions and Future Work

Placement of well pairs and surface facilities for SAGD development is a complex engineering optimization problem. Many technical parameters must be considered. The uncertainty in the reservoir variables makes the optimization even more challenging. Maximum profit is an important aspect in a commercial project. Therefore the objective is not only maximum recovery, but also the optimization of economic values such as NPV and CSOR. To get the maximum profit well placement should be as deep as possible to allow access to most of resource above. At the same time most part of well should pass through permeable regions. The problem of allocating several well pairs over a large bitumen deposit is achieved by positioning drainage areas.

An optimization methodology has been presented in this thesis along with implementation of developed tool and case studies. The main objective of optimization is to maximize the recovery of bitumen by finding the optimal locations of drainage areas and surface pads. The objective function calculation is summed over individual well pairs so that the optimization process generates optimal positions of well pairs and drainage areas. The reservoir uncertainty is handled by considering multiple realizations of reservoir variables. A single value of the objective function is calculated over all realizations by averaging the individual objective function for each realization. The objective function is defined in a single mathematical expression leading to an unconstrained optimization problem by including several penalty factors including a surface penalty, base conformance along well pair, thief zone penalty and crossing of well pair in unproductive regions.

The optimization of drainage area locations for maximum recovery is achieved by satisfying two main objectives- optimal space packing and access to the maximum resource over all well pairs throughout the field. A compact pattern of drainage areas is maintained throughout the optimization process. A part of reservoir area is left undeveloped and without well pairs only when there are surface restrictions on the placement of surface pads of the associated drainage area. The locations of drainage areas and surface pads are optimized to minimize the total undeveloped reservoir area. Another important aspect of the optimization is to minimize different penalty factors by improving the positions of drainage areas and surface pads. A best "packing pattern" of drainage area might give the maximum access to available resource but it cannot guarantee the minimization of penalties. Different parameters are included in the objective functions formulation to control the amount of penalty for respective constraints. Optimization is done based on the input parameters specified by user.

An optimization tool kit is developed to work on 2-D realizations of reservoir variables. The optimization methodology is a heuristic one. The use of standard optimization algorithms both direct and random search types are not straightforward to implement because of the multimodal nature of objective function .The dimension of the problem is also very large. A different way to express the objective function could be promising for standard optimization algorithm. The heuristic methodology is made from four optimization processes- sliding, translation, rotation and breaking. Optimization starts with an initial input of a compact and non-overlapping pattern of drainage areas. Optimization is achieved by combination of three main optimization steps- rotation, translation and sliding. Breaking is the fourth optimization step which is performed after trying many different permutations of rotation, translation and sliding. Rectangular shaped drainage areas are considered with fixed well spacing and fixed drainage area geometry. The shape of the surface pads are approximated by a circle. The distance of the surface pad from the drainage area is controlled by different distance parameters that allow flexibility of allocating surface pads at an offset different from its ideal position. A surface pad can be located on two sides of a rectangular drainage area and on four sides of square shaped drainage area. The user can control the number of possible locations of surface pads by modifying the input parameters of optimization. The optimization tool is designed to handle different grid sizes for geological realizations of sub surface data and 2D data of surface penalty. Also, the optimization can be performed with or without surface data so that results can be compared. The optimization can be done with or without base penalty. The objective function is expressed in two different forms- one is with base penalty and other is with recoverable reserve calculation. The base penalty is quick and robust whereas recoverable resource calculations are more time consuming but more realistic.

Different permutations of optimization steps- translation, rotation, and sliding can be given as input. Any number of optimization steps can be included. Automatic optimization or full optimization is also included into the tool if user does want to run the optimization for all possible orientations. The automatic optimization option generates an important summary with the best pattern of DAs and SPs for all orientations. Different orientations can be compared and optimal pattern for any orientation can be generated.

5.1 Limitations and Future Work

There are several limitations of the developed tool. Actual engineering process of drilling well pairs and drainage areas can have many technical and economical factors and all of them are not considered in this tool. The technical factors can change with reservoir types or operating strategy. The methodology and the developed tool presented in this thesis can be seen as an initial assessment tool for SAGD well placement. Different orientations can be compared in terms of a quantitative objective function value. Expert engineering knowledge can be applied after running the tool. It is very difficult to manually consider the optimization of recovery/economy by keeping all constraints satisfied. In future, this tool could be developed further to include specific parameters into optimization. Some limitations of the current tool are mentioned here. Some of the modifications can be easily implemented, but others might be difficult and may require a different optimization approach or objective function formulation.

5.1.1 Different Shapes of Drainage Areas

A fixed drainage area specification such as fixed shape and size and fixed well spacing is not necessarily practical. Changing the well spacing and well length as a function of depth may be needed. A smaller size of drainage area with fewer well pairs could be located at the boundary of the region of interest. A different number of well pairs could be achieved in the current version at boundaries only (**Figure 5.1**). Wells outside the region of interest can be removed. **Figure 5.2** illustrates the concept of varying length and well spacing. Different shapes of drainage areas can be used at the boundary of region of interest (**Figure 5.3**). Another important modification could be the distance between the surface pads and drainage areas as a function of well depth.

5.1.2 Rectangular Shaped Surface Pads

Circular shaped surface pads are considered in this thesis. A rectangular shaped surface pad would be more realistic. Rotating a circle at its centre has no effect on the penalty, but rotating a rectangle can change the enclosed surface penalty. **Figure 5.4** illustrates the placement of a rectangle shaped surface pad in a narrow region of the surface. The size of the surface pad could also be a function of the number of well pairs in the drainage area. A rectangular surface pad may not be parallel to drainage area. The rotational feature of rectangle can be used to locate surface pad in restricted areas (**Figure 5.4**).

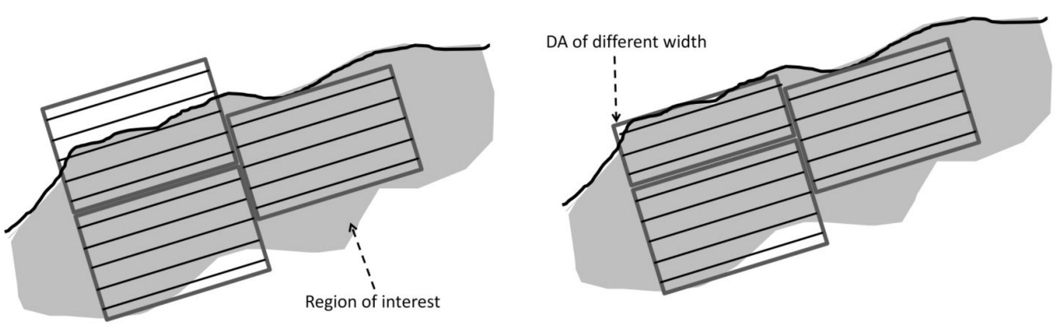

Figure 5.1- Schematic representation of drainage areas of different sizes.

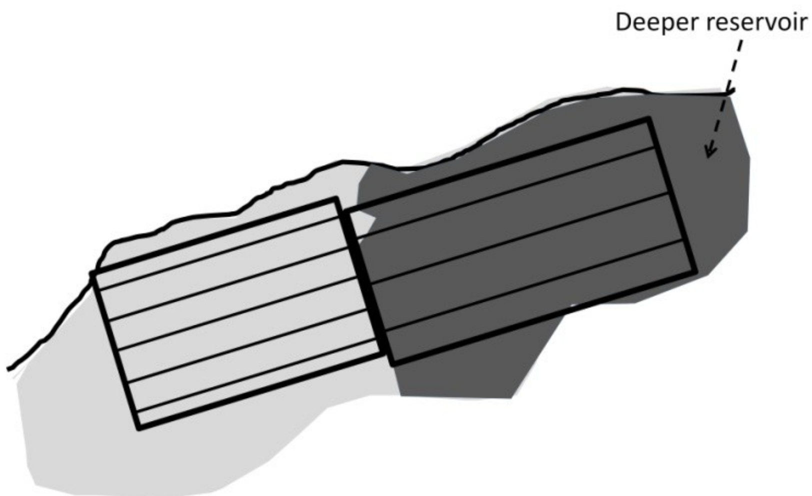

Figure 5.2- Schematic representation of varying well length and well spacing.

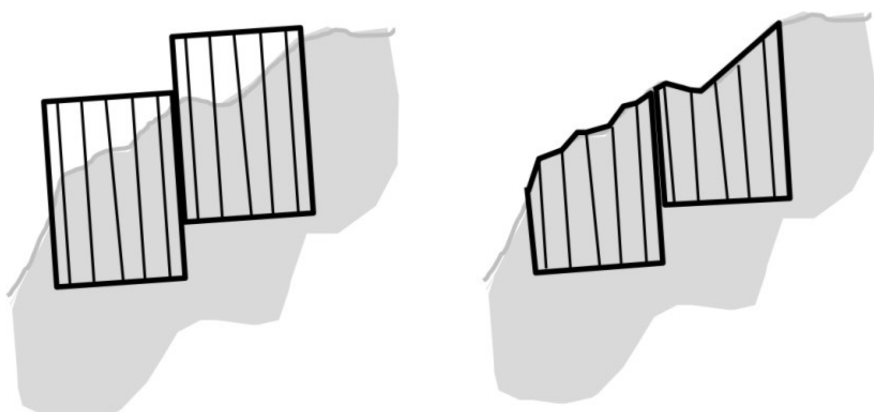

Figure 5.3- Schematic representation of different shapes of drainage area.

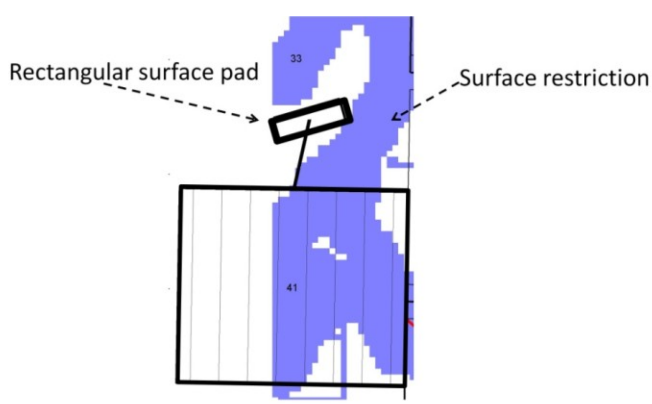

Figure 5.4- Schematic representation of placement of a rectangular surface pad.

5.1.3 Run Time

The run time for full optimization depends on two main factors- (1) the grid resolution for the surface and subsurface data. The cell size of the subsurface data with respect to the size of drainage area has a large influence. (2) The number of realizations of subsurface reservoir variables. Running full optimization with 20m x 20m cell for subsurface data, against 1000m x 1000m DA size and over 100 realizations takes approximately 4 hours 30 minutes on an Intel Core i7 2.80GHz processor. 110 drainage areas were used for the entire optimization process. The run time with 100m x 100m cell was less than 10 minutes (for same DA size and same number of realizations). The run time is highly affected by the cell size of subsurface data because calculations are done after determining the cells inside well pair polygon. Also, calculations are done by considering the fractional area of cells inside polygon. The full optimization is done by selecting all possible permutations of rotation, sliding and translation for up to 3 optimization steps. Approximately 66,242 permutations are tested for full optimization. The objective function calculation for one input of DA coordinates is very fast, but it is possible to have thousands of objective function calculations for one translational optimization step or even more for sliding optimization. The run time can be highly improved if testing for all possible permutations is avoided or if the objective function is modeled in different way to avoid the highly multimodal nature of it.

5.1.4 Optimization of Economic Factors

The methodology and tool presented in this thesis is based on a single objective which is maximization of recovery of bitumen. The units of the objective function is expressed in terms of thickness of the deposit (meters). The applicability could be improved by including optimization of economic factors such as net present value and cumulative steam to oil ratio. A single objective function can be defined with both recovery and economic factors connected by appropriate weights by using suitable conversion factors for different units.

5.1.5 More Realistic Well Planning

Calculations are based on flat horizontal well-pairs. Also there is no restriction in elevation difference of adjacent well pairs. The tool could be improved by allowing inclined well pairs or slight curvature to the well pattern. Figure 5.4 shows an example of a curved well trajectory. Another modification is possible by controlling the elevation difference between the producer of one well pair and injector of an adjacent well pair.

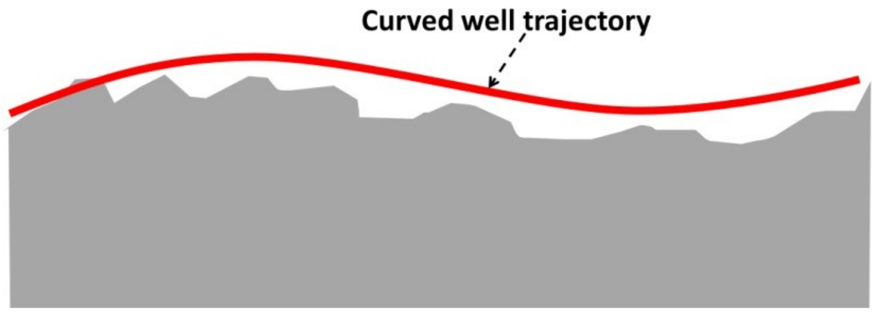

Figure 5.5- Schematic illustration of a curved well trajectory.

5.1.6 Additional Future Work

2D reservoir variables are considered in the optimization. A more detailed calculation could be based on 3D reservoir models. The calculation time for 3D models could be challenging, but detailed well planning and vertical positioning could only be achieved with the help of 3D models. Another area of improvement is to include the pipeline lay out. Surface pads can be positioned in such a way that the total cost of installing pipe lines for transpiration of steam and bitumen is minimized. Additional constraints can be added into the optimization to minimize the risk of well collisions. A buffer distance can be included between adjacent drainage areas to allow some space for error in well-pair drilling and to separate the steam chamber of one drainage area from an adjacent drainage area.

The applicability of the tool could be improved greatly by these proposed improvements. The basic framework for drainage area and surface pad placement has been developed and deployed in a tool.

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Appendix

A. Parameter file for **`setpen`**

Parameter file for program **`stepen`**. This program generates the map of surface penalty with 0 and 1 values. 0 represents the area with surface obstructions and development of SP is not possible over it. 1 is for non penalized surface area. The grid resolution of surface penalty map is specified in the parameter file. the coordinates of surface obstructions are provided in a special format (see **Appendix B**). Four different shapes can be provided as surface obstruction- polygon, line, circle and arc. The setback value can be also provided in the parameter. Surface penalty map is written on an output file in a single column and follows standard GSLIB format ([3]).

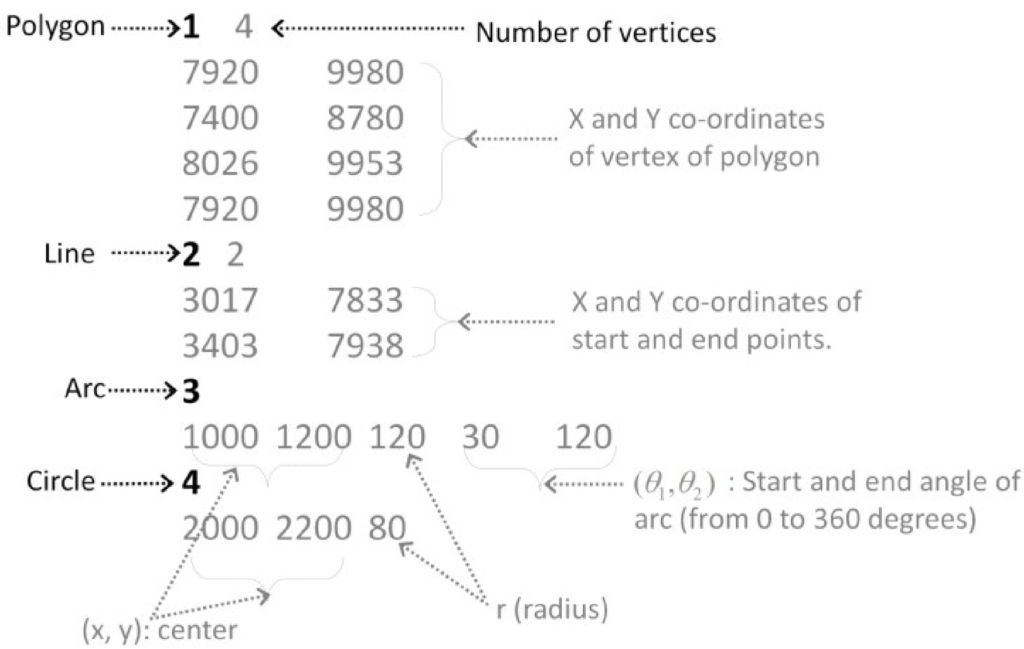
```
                                        Parameters for SETPEN
                                        *********************
  START OF PARAMETERS:
1 sc.dat                             -infl: input file with surface obstructions
2 1 2 3 4  10                        -code for POLYGON, LINE, ARC, CIRCLE, NOT_IMPORTANT
3 100                                -setback value
4 400   12.5    25                   -nx,xmn,xsiz
5 400   12.5   25                    -ny,ymn,ysiz
6 sc_pen.out                         -outfl: (1-good,0-penalized)
```

Variables in parameter file

1. **`infl`**- is name of the input file with shape and co-ordinate details of surface restrictions. The format of this file is illustrated in Appendix B.
2. **`code`**- shape identification codes in infl. 1- polygon, 2-line, 3- arc, 4- circle, 10- not important. These codes are used to identify the shape of surface restrictions.
3. **`setback`**- No surface facility should be located by this distance nearest to surface restrictions. Must be greater than or equal to zero.
4. **`nx, xmn, xsiz`**- x grid specifications for output surface penalty map.
5. **`ny, ymn, ysiz`**- y grid specifications for output surface penalty map.

B. Structure of surface restriction file

The format of surface obstruction input file. Four different shapes can be mentioned- line, polygon, circle, arc. Any number of surface restrictions can be mentioned in the input file. For example there can be 100 lines and 10 polygons, 20 circles in the same file in any order. Here is a simple example of format of surface obstruction. Codes 1, 2, 3, and 4 are used for polygon, line, arc, and circle respectively. For line, number of vertices which is 2 must be specified along with line code, then next two lines are start and end points of line co-ordinates. One separate line must be used for one point/vertex only. x co-ordinate and then y co-ordinate should be mentioned. Same pattern is followed for polygon. Vertices of polygon must be ordered continuously either in clockwise or counter-clockwise direction. If surface restriction is in form of closed polygon then the first and last vertex must be identical otherwise program treats it as an open polygon and surface penalty is generated as an open polygon. The format for circle and arc are self explanatory. Angle used for arc are standard mathematical angle- measured counter clockwise from x-axis.



C. Parameter file for `clipdata`

The purpose of clipdata program is to clip an input data inside given polygon(s). The input data is provided in a file with single column which must be in standard GSLIB format. The grid resolution of data is mentioned in the parameter file. Any number of realization can be used for input. Any number of polygons can be specified in the parameter file. polygon co-ordinates must be continuous (clockwise or counter clockwise). Polygon can be closed or open. If input polygon is open then calculation is done by closing the polygon.

```
                                 Parameters for CLIPDATA
                                 ***********************
  START OF PARAMETERS:
1 data.dat                    -infl: input data file
2 outfl.out                   -outfl: clipped data file
3 400   12.5    25            -nx,xmn,xsiz
4 400   12.5   25             -ny,ymn,ysiz
5 10                          -nreal, number of realizations
6 1   5                       -npoly, maxv
7 4   1                       -invert, iclip (1-outside, 0- inside)
. 6666        9486             -x,y verices
. 4466        9406
  2880        7846
```

Variables in parameter file

1. **`infl`**- is name of input file with gridded data.
2. **`outfl-`** output file with clipped data.
3. **`nx, xmn, xsiz`**- x grid specifications for output surface penalty map.
4. **`ny, ymn, ysiz`**- y grid specifications for output surface penalty map.
5. **`nreal`**- number of realizations of input data
6. **`npoly, maxv`**- Number of polygons, maximum number of vertices.
7. **`invert, iclip`**- number of vertices, clip option (1- outside, 0- inside)

D. Parameter file for **dapave**

dapve program is used for generating the initial input for main optimization program. DAs are populated based on the input location and orientation of DA. First, a group of compact and non-overlapping drainage areas are generated throughout the grid boundary. The extent of generated DAs can be controlled by parameter **frac**. The best input for optimization is to take all DAs without removing a single DA. Although the parameter file provides the flexibility to remove some DAs based on the average quality inside DA polygon. But it is highly recommended that no DA should be removed from the pattern if full/automatic optimization is being performed. Automatic optimization will automatically remove unproductive DAs. Some DAs can be removed based on quality (**smin, smax**) if optimization steps are provided manually.

```
                                    Parameters for DAPAVE
                                    *********************
   START OF PARAMETERS:
1  data.dat                         -infl: input data file
2  1  0  1000                       -coln, tmin, tmax
3  -1e21  1e21                      -smin, smax
4  0.25                             -frac: extent of paved DAs
5  400   12.5   25                  -nx, xmn, xsiz
6  400   12.5   25                  -ny, ymn, ysiz
7  2562  2456                       -x0, y0: origin of a DA
8  0                                -ang: azimuth of DA centre line
9  1                                -istart: starting number of DA
10 1000  800                        -len, wid: size of DA
11 dapave.csv                       -outfl: output DA file
12 dapave.ps                        -psfl: output plotting file
13 0  25                            -cmin, cmax: color limits for map
```

Variables in parameter file

1. **infl**- is name of input file with gridded data.
2. **coln, tmin, tmax-** column number for input data, minimum value, max value.
3. **smin, smax**- selection criteria for a DA. A DA is selected if average value of input data is between `smin` and `smax`.
4. **frac**- Controls the extent of DA outside grid. 0- inside grid boundaries. 0.25- extend is 0.25 times the area covered by grid.
5. **nx, xmn, xsiz**- x grid specifications for output surface penalty map.
6. **ny, ymn, ysiz**- y grid specifications for output surface penalty map.

7. **`x0, y0`**- centre of one DA. All other DAs are populated based on this DA.
8. **`ang`**- azimuth of paved DA orientation.
9. **`istart`**- numbering index of DA.
10. **`len, wid`**- length and width of drainage area
11. **`outfl`**- output file with DA co-ordinates.
12. **`psfl`**- output file with plot of DAs over input data map.
13. **`cmin, cmax`**- color limit for plotting input data map.