# Optimization of Non-Paved Drainage Area Configurations for SAGD

John G. Manchuk and Clayton V. Deutsch

*Placement of SAGD surface production pads and subsurface drainage areas in the McMurray formation to maximize the economic potential of an area is a challenging problem. The location of surface pads and drainage areas have a large impact on their production performance due to several factors including variation of bitumen in place, variation of the reservoir base surface, vertical conformance, areal conformance, interaction between different drainage areas and pads, and surface hazards. An optimization algorithm is presented to determine the positions and orientations of surface pads and drainage areas over a reservoir area so that the potential for economically recoverable bitumen is maximized. The optimization considers either a deterministic model of the relevant properties or multiple realizations to account for uncertainty. Optimization considers all drainage areas simultaneously to ensure joint optimality of an entire set. Drainage areas are not restricted to a predefined paved layout, but are permitted to take on any orientation independent of other drainage areas.*

## Introduction

A significant percentage of the McMurray formation oil sands are planned to be recovered using unconventional methods such as steam assisted gravity drainage (SAGD). There are a number of producing projects and more under construction and being proposed in Alberta. Several companies are involved such as Cenovus Energy, ConocoPhillips, Husky Energy, Shell, Statoil and Suncor, among others (ERCB, 2012). SAGD production generally requires three components: a surface pad (SP) that includes the required facilities and from which wells are drilled; a subsurface drainage area (DA) consisting of a set of horizontal well pairs; and the individual well pairs with a steam injector drilled above a producer. The aerial extent of a SAGD project can be extensive, requiring potentially hundreds of DAs to achieve target production rates over the lifetime of the project. Designing the layout of the set of DAs to maximize recovery or net present value (NPV) of an operation is a complex optimization problem that has largely been unexplored. Optimization should consider all DAs simultaneously to converge to a global optimum.

This paper focuses on optimizing the configuration of a set of DAs to maximize the potential recovery of the set. Unlike the paved version (see Paper 206 of this report), DAs are not restricted to be joined in a pre-defined pattern, but are permitted to take on different orientations. This adds to the complexity of the optimization problem due to the increased degrees of freedom (Papadimitriou and Steiglitz, 1998). Finding the optimal position of a single DA within an area is challenging because the optimal trajectory of wells is a function of the position and orientation of the DA. The problem is also highly multi-modal having many local maxima due to the variation in the base, thickness and quality of the reservoir and due to the spatial constraints from surface culture such as existing infrastructure, lease boundaries, and topographic hazards like escarpments and bodies of water among others.

Devising an optimization approach that finds the global maximum of the objective function is non-trivial. In this work, the objective function is expressed in barrels of bitumen. It is calculated as recovered bitumen less capital and operating costs that have been scaled to barrels of bitumen. The optimization problem was approached using granular flow theory, where DAs are considered the individual grains that interact with one another and flow gradients are derived from the various surfaces involved. Like the paved version, it is possible to optimize the configuration using a single deterministic model of the required properties or using a set of realizations. A synthetic example is provided to demonstrate the effectiveness of the optimization procedure, as well as identify some of its limitations.

## Problem Description

DA geometry defines the area, usually rectangular, that will be drained by a set of nearly horizontal well pairs. Wells are drilled from the SP located near the heel of the DA (Figure 3). The optimization problem is to determine the spatial configuration of DA's and SP's and the depth of wells for a field to be produced such that the economic potential is maximized. Three variables that describe the reservoir are required and include a reservoir quality variable, a base surface, and gross thickness. In this work, reservoir quality is summarized using net continuous bitumen (NCB) that is the total thickness of recoverable bitumen above the base surface (Figure 4). Net reservoir is often determined based on facies and cut-offs for porosity, permeability and water saturation. The base surface is a base of continuous bitumen (BCB) that defines the lowest elevation a horizontal well could retain while still being able to recover bitumen from above. Well length below the BCB is considered ineffective, that is, bitumen cannot flow into that length of the well. Gross thickness or gross continuous bitumen (GCB) includes all recoverable net and non-net intervals above the BCB.

The BCB, NCB and GCB surfaces would often be derived from a 3D reservoir model although these variables could be mapped directly. They are deterministic if a single reservoir model is available or stochastic if the reservoir is modeled by a set of realizations. In the latter case, the optimization problem is solved in a probabilistic sense, accounting for the uncertainty that is quantified by the set of realizations. In either case, the objective function of the optimization problem is measured in barrels of bitumen and defines the economic value of a specified SP-DA configuration. Variables involved in calculating the objective of a single DA are: the number of well pairs, $m$; the elevation of each well, $z_j, j = 1, \dots, m$; and the barrels of bitumen recovered from each well pair, $R_j, j = 1, \dots, m$. $R_j$ is a function of the position of the well relative to the BCB, NCB and GCB surfaces and of $z_j$ and the well spacing defined by Eq. 1, where $u$ and $v$ are coordinates that span the area of influence of the well, $\theta$ is an angle that defines the limit of drainage between adjacent well pairs, $v_j$ is the location of the well in the $v$ coordinate, and $z_{TCB} = z_{BCB} + h_{GCB}$ is the top of continuous bitumen:

$$R_j = \iint_{u,v} h_{NCB}(u,v) \cdot \frac{z_{TCB}(u,v) - z_j(u) + |v - v_j| \tan(\theta)}{h_{GCB}(u,v)} dvdu \qquad (1)$$

This equation is applicable in areas where $z_j(u) > z_{BCB}(u,v)$. There are two cases where the integrand evaluates to zero: when the GCB is less than a minimum producible thickness and when the injection well intersects the TCB. A case that requires a slightly different integrand is when a segment of the well is ineffective and its length exceeds the limit of steam chamber growth. The stranded volume of bitumen left behind is assumed to be of a similar geometry as that between neighbouring well pairs, where wedge wells are being used to recover it (Jaremko, 2010). If the length of ineffective well is small enough, denoted $l_{\min}$, all of the bitumen above that portion is assumed to drain; however, in longer segments the thermal and pressure gradients to drive flow are assumed inadequate (Figure 5) based on the theory of steam chamber growth proposed by Butler (1991).

Theoretically, it is possible to drain the stranded bitumen in both cases shown in Figure 5; however, as the height of the volume of stranded bitumen above the producer decreases with time, the flow rate also decreases, eventually to a point where it is uneconomic to sustain (Butler, 1994). This type of behaviour is difficult to incorporate into Eq. 1 analytically. Numerically, the stranded oil volume due to ineffective well length can be approximated using a cone emanating from the point of intersection between the production well and the BCB surface. The angle of the cone relates to the time a DA has been producing, with high angles being representative of early production and low angles of late production. Assuming such a point exists along a well, the recovery equation is modified to involve a distance function, $d(u,v)$, in Eq. 2. Along effective length of a producer, $d(u,v) = |v - v_j|$, and along ineffective length $> l_{\min}$ , it is the distance to the nearest effective portion.

$$R_j = \iint_{u,v} h_{NCB}(u,v) \cdot \frac{z_{TCB}(u,v) - z_j(u) + d(u,v)\tan(\theta)}{h_{GCB}(u,v)} dvdu \qquad (2)$$

The efficiency of recovery is also affected by irregularity in the height of the DA in cross section along a well pair. Under ideal conditions, the steam chamber should rise uniformly along an injection well, assuming injection rates are uniform along the entire length; therefore, the recovery rate could be decomposed into the product of recovery in a cross section perpendicular to the well with the length of the well. If the DA is non-uniform, the shape of the steam chamber and DA will not conform, thus having some negative influence on recovery rates. To account for this activity in DA optimization, the potential recoverable volume of bitumen above a well pair is augmented based on the distribution function, $F(h)$, of the thickness, $h$, between the producer and the TCB (Figure 6). In Eq. 2, $z_{TCB}$ is replaced by $z'_{TCB}$ that is defined by Eq. 3, where $h(q)$ is the thickness as a function of the probability, $q$, such that $F\big(h(q)\big) = q$.

$$z'_{TCB}(u,v) = \min\left( z_{TCB}(u,v), h(q) + z_j(u) \right) \tag{3}$$

Selecting a low value for $q$ will lead to a potential recovery that is closer to the thin portions of a DA. As $q$ increases, potential recovery increases. The more uniform the thickness is above a well, the less impact the choice of $q$ has on results.

Recovery of a DA is approximated by the sum of the recovery of the set of $m$ wells. To evaluate Eq. 2, the trajectory of the horizontal portion of the producer well, $z_j(u)$, must be defined. Solving for the trajectory is another optimization problem, related to but independent of the DA configuration optimization problem, that is applied to each well pair in a DA. In this work, horizontal wells are used so that $z_j(u) = z_j$; however, the final well trajectory will be permitted to vary along $u$ within some design constraints. For the purpose of DA optimization it is reasonable to use horizontal wells. Solving for $z_j$ is straightforward and is accomplished using a line search algorithm. Minimum and maximum values for $z_j$ are equal to the corresponding elevations of the BCB surface along the producer. The optimal producer elevation exists somewhere in between.

Using wells that are exactly horizontal was chosen for simplicity, but also because their potential recovery will be dependent on the BCB geometry along it. If the base is very non-uniform relative to the producer, the well is placed higher to minimize stranded oil due to ineffective length, leading to increased stranded oil below the well in effective portions. At a different orientation, if the BCB is nearly horizontal, losses due to stranded oil are minimal. The dependency between horizontal wells and BCB uniformity will influence the SP – DA optimization process so that DAs are generally oriented where base conformance is good.

The objective function for optimization also accounts for costs, including: fixed capital costs for items such as surface facilities and land; supply costs that also included operating costs and royalties; and costs associated with horizontal wells that are not of a target design length (Fisher and Gill, 1999). The last cost assumes that if wells are too long or short, surface facilities or operating practices result in additional cost compared to wells that are approximately of the designed length. Capital cost is assumed to be a function of the number of well pairs in a DA in addition to a base cost and supply costs are expressed as a function of recoverable bitumen. The objective function is expressed by Eq. 4, where $c_j$ is the cost associated with unordinary well length, $C(m)$ is the capital cost varying by the number of well pairs, and $S$ is the supply cost.

$$F = \sum_{j=1}^{m} \left( R_j (1-S) - c_j \right) - C(m) \tag{4}$$

Capital cost is expressed as Eq. 5, where $C_0$ is a base cost incurred independent of the number of well pairs, and $C_j$ is the cost of a well pair (different from $c_j$):

$$C(m) = m \cdot C_j + C_0 \tag{5}$$

Units of recovery and costs are in barrels of bitumen, except for supply cost that is in barrels per barrel of bitumen recovered. The sum of the objective of all DAs in a set is the function used in the optimization problem given by Eq. 6, where $n$ is the number of DAs.

$$P = \sum_{k=1}^{n} F_k \tag{6}$$

In the case of multiple realizations, the objective is the expected recovery over all realizations from a DA configuration defined by Eq. 7, where $L$ is the number of realizations:

$$\overline{P} = \frac{1}{L} \sum_{l=1}^{L} \sum_{k=1}^{n} F_{lk} \tag{7}$$

For optimizing the DA configuration, evaluating the recovery of all well pairs within each DA must be efficient and fast computationally as it will be done potentially thousands of times for tens to hundreds of DAs involved in a configuration.

### Optimization Strategy

Optimizing a configuration of DAs involves searching for the layout of DA locations, orientations, and sizes that maximizes economic value. The objective function described previously is intended to provide a measure of potential economic value in barrels of bitumen based solely on the geometric attributes of the problem; therefore it is dependent on the location and orientation of each DA. The objective function will ensure that good DA configurations are found, where our concept of goodness is based on specific properties of each DA. One of the properties is base conformance. Because horizontal wells are involved, recovery will tend to be higher in orientations where the base is flat or dipping perpendicular to the well pair orientation, with flatness measured on a length scale larger than $l_{\min}$. In such orientations, the volume of stranded oil is less. Another property is steam chamber uniformity for low choices of $q$ from the thickness distribution function. Recovery will tend to be higher in locations and orientations where the volume for steam chamber expansion is uniform.

In this version, DAs are not constrained to a pre-defined paved pattern. Instead, they are permitted to take on any orientation independent of the other DAs with the constraint that more than one DA cannot exist in the same space, that is, they cannot overlap. An example of such a configuration (termed a free configuration from here on) is shown in Figure 8. Two optimization strategies were utilized to optimize free configurations: gradient ascent and space packing. The gradient is required to define where to move and rotate DAs so that their objective function increases and space packing is required to cover the recoverable resource as efficiently as possible with DAs. Traditional space packing algorithms do not apply to this case because they typically deal with objects oriented with the axes of the problem. Methods dealing with random packings of various shapes were more applicable (Finney, 1970). In this work a random packing of rectangular DAs is generated and updated using gradient ascent. During the update process, DAs are moved and rotated simultaneously leading to a significant amount of interaction between DAs. By treating the DAs as individual grains in a larger system, the movement and interaction of DAs can be considered a granular flow problem (Kesava Rao and Nott, 2008), where the flow of grains is directed by the gradient.

The gradient is derived from a response surface that is initially defined by the NCB surface prior to the generation of any free DA configurations. Translation and rotation gradients that define how a DA is to be moved so that its value increases are computed numerically based on the spatial position and geometry of the DA. As DAs are moved, they interact via collisions because they are treated as solid grains, preventing overlaps and allowing the DAs to gradually organize into an economic configuration. As DAs are moved, the gradients are updated based on the different region of the response surface they are on. When handling collisions, the value of each DA, which is approximated as the integral of the response surface within the DA, is treated as mass for computing momentum transfer. Since more valuable DAs have more mass, they are affected less by collisions and maintain precedence along their path to higher valued positions and orientations.

The space packing component of the optimization process is initialized by randomly placing a set of DAs over a region of interest so that their centers are approximately equally spaced. The DAs start with a size that is significantly smaller (1 %) than the intended size and they are slowly grown to the targeted size. This is done for three reasons: 1 – the initial random configuration is straightforward to generate since there is no chance of interaction; 2 – the growth process allows time for DAs to move and orient themselves to beneficial locations based on the gradient information, and; 3 – it is straightforward to define a stopping criteria, that is when the growth process reaches the targeted DA size. A few iterations of this process are shown in Figure 9.

Additional control is incorporated into the space packing process to ensure that the majority of DAs are positioned in feasible locations, that is, in areas where it will be possible to create a SP. For each iteration of the growth process, a feasibility check is done whereby an attempt to place an SP at one of the ends of each DA is made. If it is not possible to create an SP for a particular DA, then the gradient is overridden by a force that pulls the DA towards the nearest feasible position. When the space packing process is finished, DAs that are infeasible are deleted from the configuration. The resulting configuration is then used for creating and optimizing wells and evaluating the objective function. The objective function for each DA is used to update the response surface so that the algorithm learns the positions and orientations of high valued and low valued DAs. After many configurations are generated and the response surface is updated, DAs tend to be placed in a consistent configuration and the process can be stopped. The stopping process is not instant; rather, DAs are slowly frozen in place starting with the highest valued DA. After each DA is frozen, further space packing and response surface update iterations are done to account for their impact on surrounding DAs. Once all DAs are frozen, the optimization process is complete and an optimal configuration has been found.

## Example

Synthetic surfaces were generated for demonstrating the optimization algorithm (Figure 10). Surfaces were defined on a 400 by 400 cell grid with 20 by 20 m cells. Surface culture consists of rivers and isolated pools that were placed to interfere with high pay regions. Surface culture polygons were generated with a setback of 100 m from the actual rivers. Wells were given a target length of 1000 m and a spacing of 100 m. Minimum and maximum well length was 500 m and 1500 m respectively. The target number of wells was 7 and this was permitted to range from 3 to 8. A minimum net thickness of 10 m was defined for development.

Optimization over the whole area took 112 minutes and resulted in an increase in value from 165 M barrels for an initial random configuration to 186 M barrels for the configuration shown in Figure 11. Recovery for the configuration was 296 M barrels and the aerial and vertical conformance were 80 % and 93 % respectively. Aerial conformance was calculated as the ratio of the area of the 10 m NCB thickness contour inside DAs to the total area of the same contour. Vertical conformance was calculated as the ratio of NCB above production wells to total NCB along the wells. Compared to the paved optimization used in Paper 206, the aerial conformance is lower, hence the recovery is lower. This is primarily due to the lack of a cleaning stage in the algorithm that would resolve gaps between DAs in high pay regions, which is currently done manually after the optimization algorithm is executed. A slight improvement in vertical conformance is observed due to the increased flexibility in aligning DAs with the base and pay zones.

## Conclusions

Optimization can be utilized to automatically design the preliminary layout of drainage areas and surface pads for SAGD applications. Optimization is done to maximize the economic potential or recovery from a set of drainage areas for deterministic models or multiple realizations. The optimization problem was defined with an objective function and set of rules so that viable DA configurations are found. Resulting configurations were shown to yield significantly higher values than naive configurations. Considering the complexity of the problem, optimization executes in a reasonable amount of time; however, a deterministic model was used in the examples and longer times are incurred with multiple realizations. As problem complexity increases, the optimal configuration will not be intuitive and optimization techniques will provide a much more in depth search of the parameter space. The non-paved or free configuration version developed in this work is applicable to resources that are more discontinuous or non-stationary and that involve complex surface culture. Paved layouts would have significant difficulty in conforming to non-linear high pay contours while resolving conflicts with such surface culture.

Development of the algorithm is ongoing and future work includes: incorporating recovery factors as well as porosity and oil saturation surfaces for a more accurate computation of recovery; space packing using more variation in DA geometry since the current algorithm uses fixed sizes for each space packing iteration; improving local aerial conformance to remove gaps over high pay regions, and; optimization of SP positions for added flexibility around complex surface culture.

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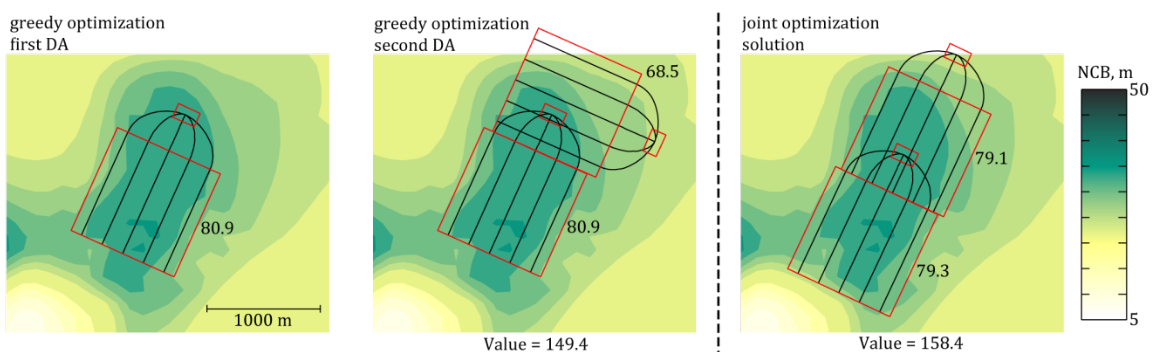


**Figure 1:** Greedy versus joint optimization techniques for maximizing recovery. Values are relative and were calculated by integrating the area of contour polygons inside the DAs.

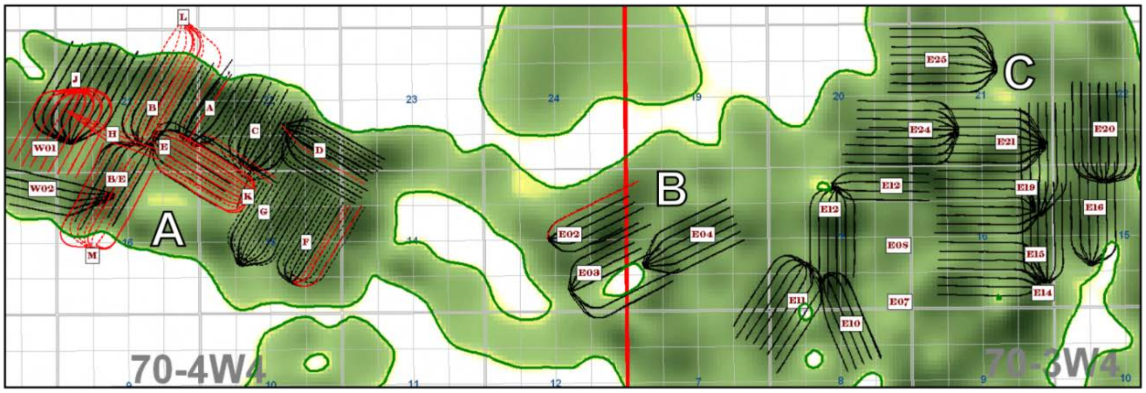


**Figure 2:** Aerial view of three compact sets of DAs (marked A, B, C) in the Cenovus Foster Creek area (Cenovus Energy, 2011, page 38). Black lines indicate well trajectories. The lower left portion of set C appears more disconnected.

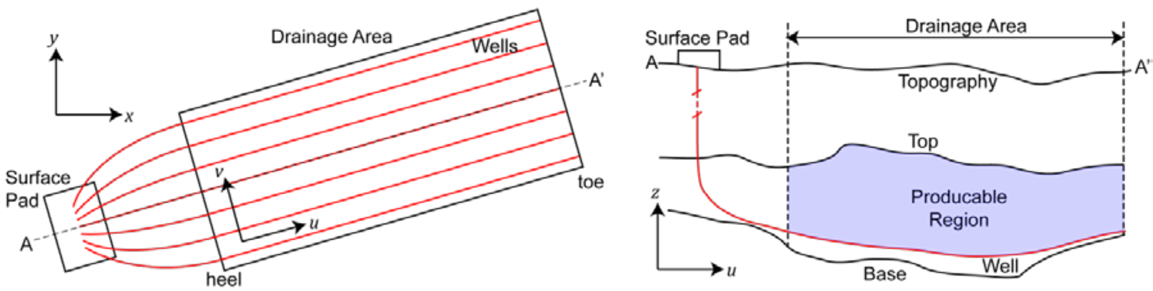


**Figure 3:** Top view of DA and SP layout (left) and cross section showing deviated well and producible region (right). Steam injector not shown.

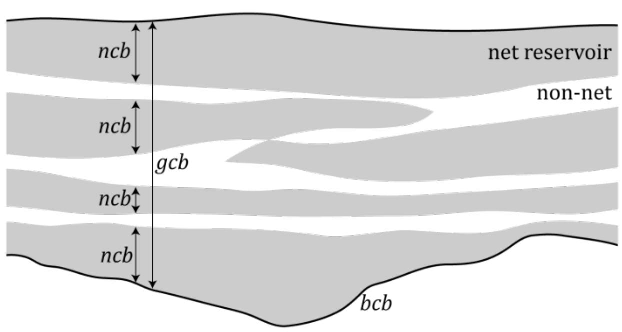


**Figure 4:** Schematic of NCB, BCB and GCB.

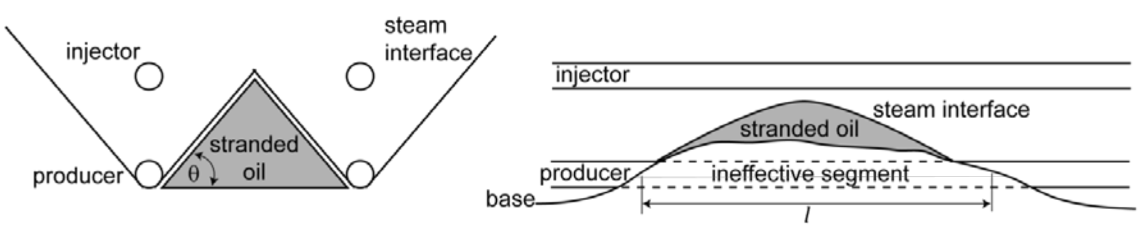


**Figure 5:** Idealized cases of stranded oil (bitumen) between neighbouring well pairs (left) and above a length, $l$, of ineffective production well. When $l$ is small enough, the stranded oil is assumed zero.

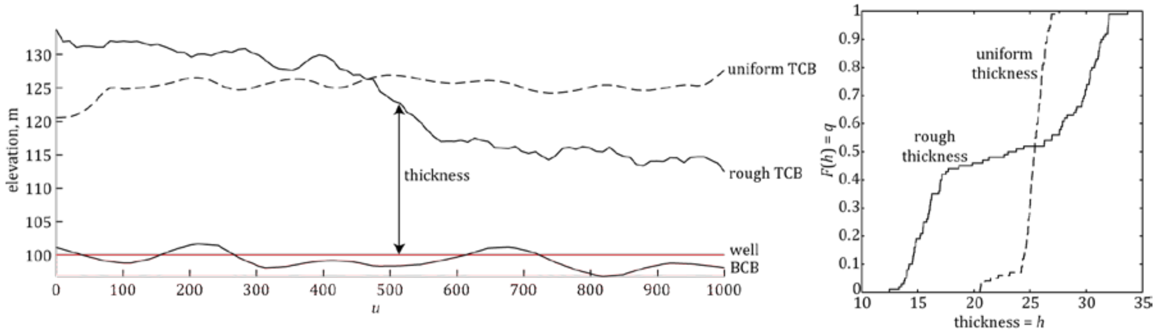


**Figure 6:** Examples of distribution functions of thickness for a rough TCB and uniform TCB used to augment recovery for a DA.

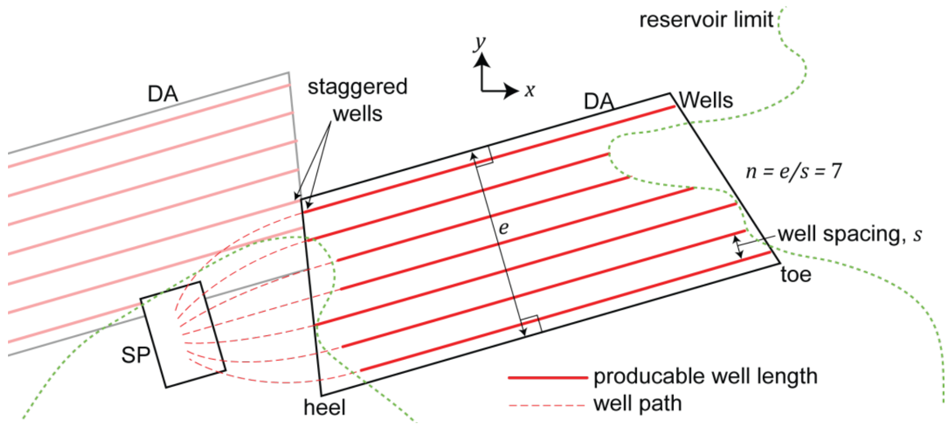


**Figure 7:** DA geometry, also showing well spacing, variable well length and staggered wells for DAs joined from toe to heel.

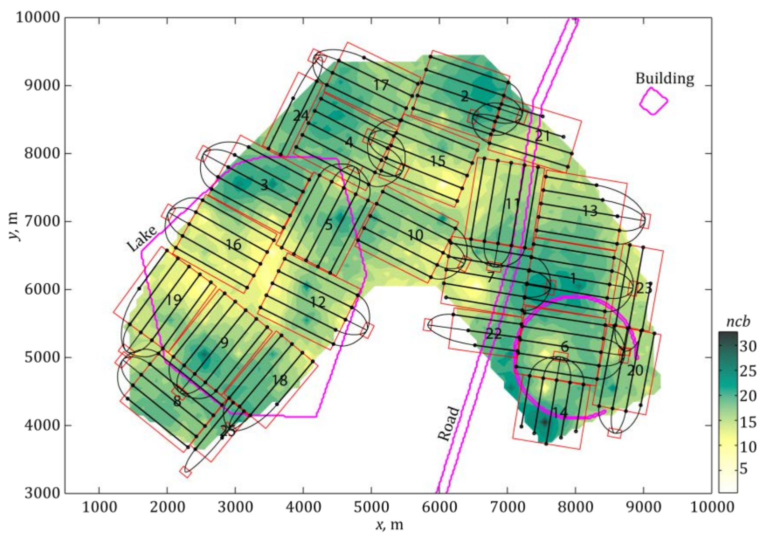


**Figure 8:** Example of a non-paved DA configuration, also showing surface culture.

Space

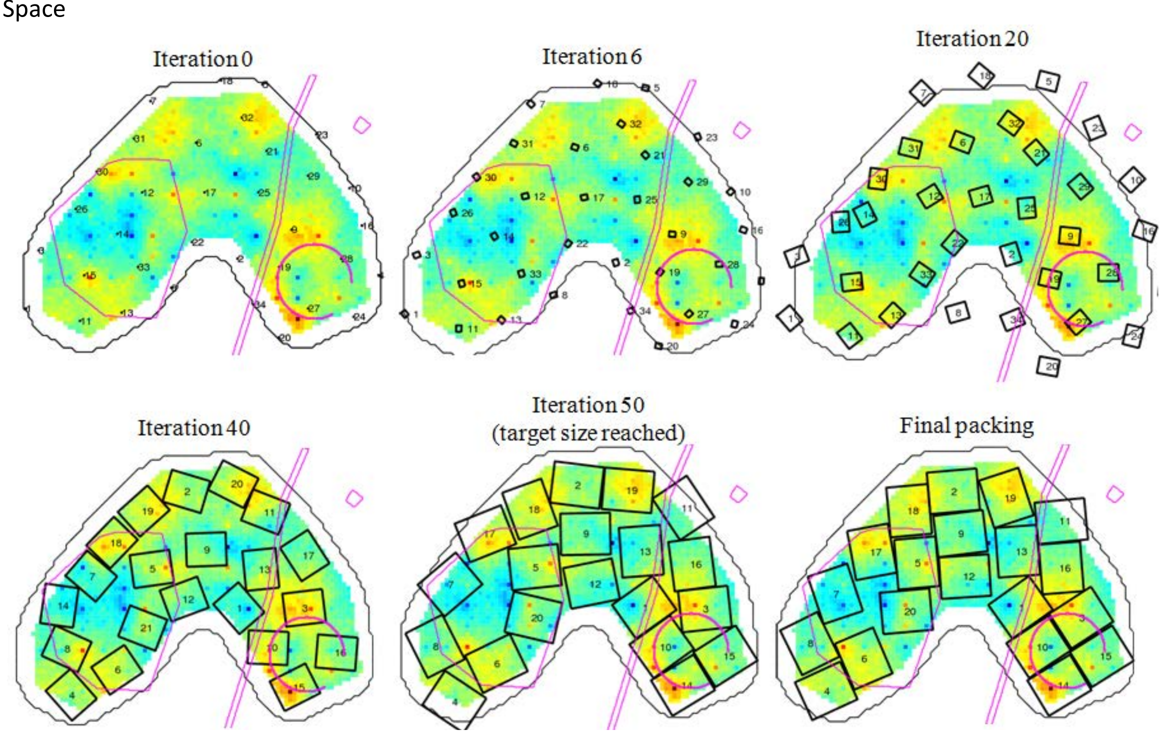


**Figure 9:** Space packing progress showing growth of DAs from 1 % of their targeted size (Iteration 0) to the targeted size. The shaded surface is the response surface used for gradient computations. The same surface culture as in Figure 8 is also present.

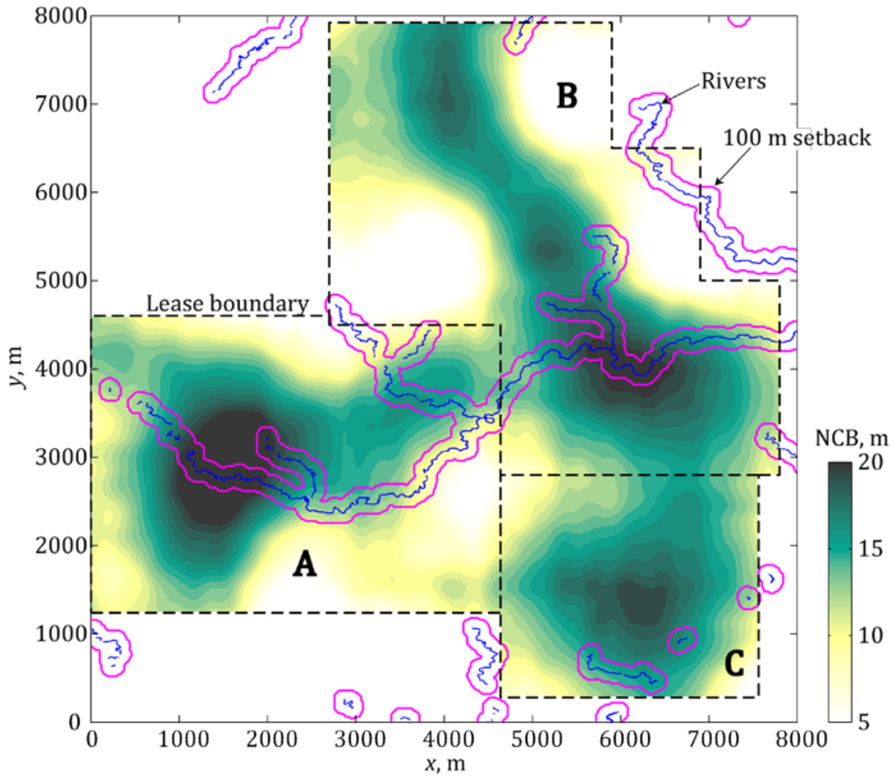


**Figure 10:** NCB and surface culture for the example. Areas A, B and C were combined for optimization.

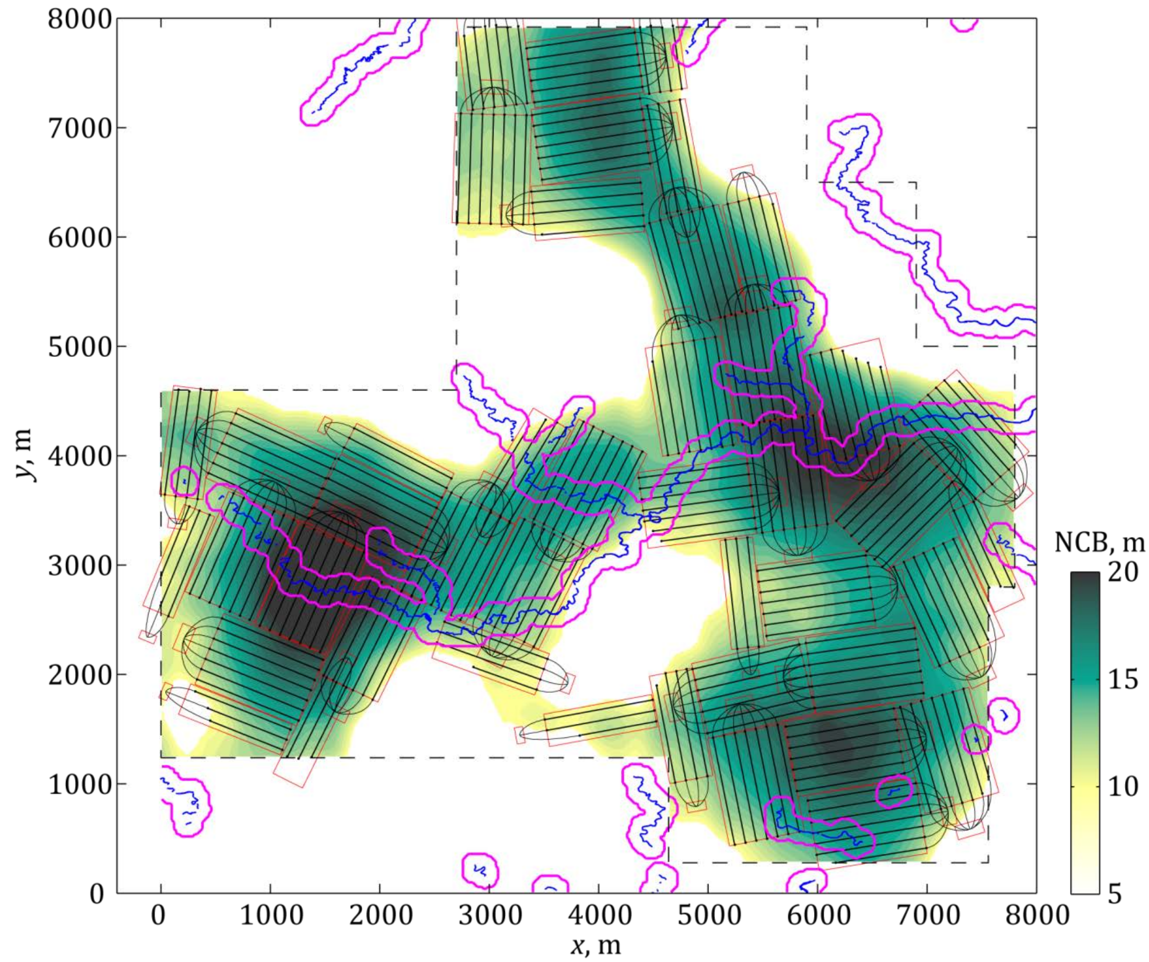


**Figure 11:** DA configuration from optimization over the entire area.