METHODOLOGY FOR GENERATING QUALITY MAPS WITH APPLICATION IN THE SELECTION AND OPTIMIZATION OF DRAINAGE STRATEGIES OF OIL RESERVOIRS

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Abstract. *Quality maps are important decision making tools capable of representing various reservoir properties which influence field production; therefore, such maps are important for the definition and optimization process of drainage strategies. These maps integrate geological and fluid inherent variables, allowing for the identification of regions with greater or lower production potential, whether one is analyzing reservoirs in the development phase or mature fields. The most commonly used method to generate a quality map uses several reservoir numerical simulations considering a unique production well, operating for enough time to extract as much oil as possible. The well position is changed in each simulation run in order to cover all the reservoir grid area; as a consequence, this method is time-consuming and requires high computational effort, which could render the process unfeasible depending on the problem features. This work presents two reservoir models, one with homogeneous characteristics and the other with heterogeneous features. In order to reduce the time and computational effort requirements of the map generation by numerical simulation, various quality map generation schemes have been tested: using a single well, a group of four wells covering the reservoir grid in different ways and the simultaneous operation start of many wells distributed around the reservoir grid area; injector wells were also used. The kriging interpolation method was used for the missing points in all cases. Each method generated different maps, therefore a methodology was developed to compare them and to determine the best generation technique.*

Keywords*: quality map, drainage strategy, numerical simulation, petroleum fields.*

1. Introduction

Exploration, evaluation, development and production management are sequential stages of a reservoir life cycle. First, in the exploration phase, a long and thorough study of geophysical and geologic data of the sedimentary basins is done, in order to confirm, to a certain degree of uncertainty, the presence of oil. After this exhausting study, the perforation of a exploratory well can be considered, stage that demands great capital investment to prove the existence and to study the viability of hydrocarbon production. If this exploratory well confirms the production viability, the evaluation phase starts, when other delimiter wells are perforated to diminish the relative uncertainty regarding the real reservoir area. The next step is the elaboration of a technical-economic feasibility study, which, in the case of positive results, can stimulate investors to initiate the development phase. In this stage, an exploitation plan of the field is developed to optimize the production and to maximize the profits during the useful life of the petroleum field.

In the elaboration of this exploitation plan, different production strategies can be simulated and analyzed in order to define the best position of wells, maximizing an objective function that can be a physical property, e.g. the cumulative oil production, or an economic parameter, such as the net present value (Mezzomo and Schiozer, 2003). Determining the best position for wells is a difficult task because it depends on several parameters, including pressure, saturation, permeability, porosity, etc. The quality map, defined as a two-dimensional representation of the regions with greater and lower production potential in the reservoir area, is used at this stage to help in the allocation process and the determination of the ideal number of production and injection wells. The quality map tries to concentrate all the information provided by saturation, permeability and porosity matrices and other reservoir properties in just one map.

Cruz *et al.* (2004) generated the quality map using a numerical simulator, integrating all the parameters that affect the fluid flow in heterogeneous reservoirs and guaranteeing that all the dynamic interactions were taken into account. The authors also affirmed that, by modeling the geologic uncertainty by the elaboration of multiple scenarios and building a quality map to each one, the uncertainty can be integrated in the decision process.

There are a few works in the literature that use the concept of quality map to help in the optimization process of production strategies. Badru (2003) studied the well allocation using the quality map tool integrated with an optimization algorithm that used concepts of hybrid genetic algorithms and the polytope method (also known as simplex method).

Ierapetritou (1999) also used the quality concept. With information from a field, such as the quality and the geo-object (that express, respectively, productivity and connectivity of the points) he formulated a problem to select the location of vertical wells using MILP (Mixed-Integer Linear Programming) optimization.

Nakajima *et al.* (2004), working with the optimization process of production strategies, analyzed the performance of wells based on technical and economic parameters; they also studied the influence of defining different priorities to the analyzed parameters and showed how the choices define the way that the optimization process follows and how they affect the final result. The quality map was used to define the initial production strategy, in order to guarantee a good initial configuration.

Despite the limited number of works on this topic, some researchers have proposed different ways of generating the quality maps. As mentioned before, Cruz *et al.* (2004) developed a method that uses a numerical simulator to generate the map; it consists basically in simulating one producer well in each block of the grid. The well has to be completed in all layers and the simulation time needs to be long enough to allow the reservoir to produce as much as possible. After all the simulations, an objective-function representing the quality of the block, e.g. Np (cumulative oil production), is calculated for each point, thus generating a two-dimensional map. The main disadvantage of this method is the often long time taken to simulate all the points (locations) of the reservoir grid.

Another method, proposed by Nakajima (2003), used concepts of artificial intelligence to generate the map. Some variables were determined as the most important to be used as input data according to their influence on the productivity of horizontal wells; the parameters used by Nakajima were porosity, porous thickness, horizontal and vertical permeability, aquifer and gas cap distance to the well and oil saturation. Heuristic rules were created from a sensitivity analysis involving these variables, and a database with such rules was built to assist in the generation of quality maps.

Nakajima and Schiozer (2003) made a comparative study of quality maps generated with three different methods: numerical simulation, fuzzy logic and analytical. To validate the maps, a production strategy was defined and optimized using each map; the main parameter used in their analysis was the field Net Present Value. The maps generated using fuzzy logic and the analytical methods were considered more flexible; however, it was observed that the fuzzy logic method presented a better relation between accuracy and speed.

The main goal of this paper is to analyze different quality map generation methods derived from numerical simulation, which was initially proposed by Cruz *et al.* (2004), in order to make this process faster (requiring fewer simulations), while still maintaining a reasonable degree of reliability. Another generation technique, using injectors between the producers, was also tested to verify the suitability of this method for reservoirs which are considered for water flooding.

2. Methodology of quality map generation

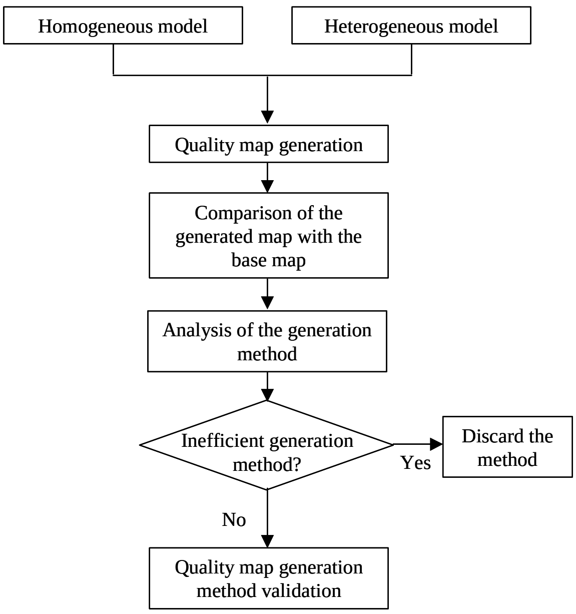


Figure 1. Methodology flowchart

A methodology flowchart, Fig. 1, was developed to help in the analysis and classification of the generated maps. It allows one to identify, analyze and seek solutions for the problems encountered in the proposed methods. The method can also be eliminated if its solution is not considered sufficiently precise.

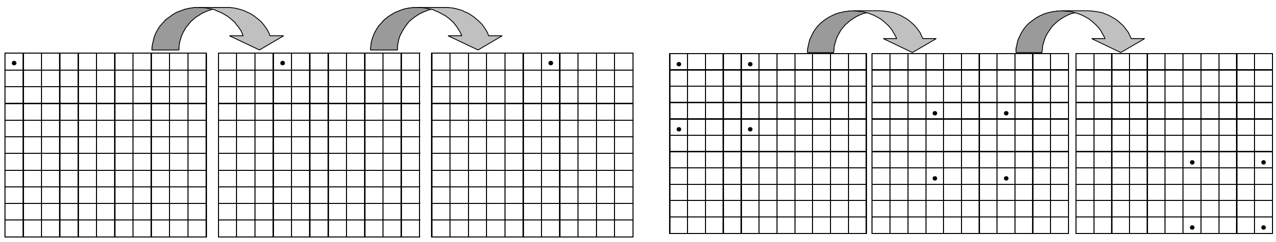
2.1. Numerical simulation method

The methods elaborated and studied in this work make use of numerical simulation; some variations of the methodology proposed by Cruz *et al.* (2004) were tested in order to develop an efficient technique that required fewer simulations, thus spending less time. The numerical simulation methods presented in this work are classified as "sweep", "fixed producers" and "fixed producers and injectors", as detailed next.

2.1.1. Sweep

The first method is the same one proposed by Cruz *et al.* (2004); it was considered as the reference case to which the other results were compared. As mentioned before, in this case the well position is changed in each simulation over the entire reservoir grid; the well is completed in all layers and the simulation time is long enough to guarantee high production.

The next procedure tested in this case is the generation of the map skipping some blocks of the grid, so that a lesser number of simulations would be necessary. Another variation of this method is the use of a group of wells instead of a unique well. Figure 2 shows examples of the variation of well position for cases using a single well and a group.



Sweep with one producer well (•) Sweep with a group of four producers wells (•)

Figure 2. Representation of the sweep method

2.1.2. Fixed producers (FP)

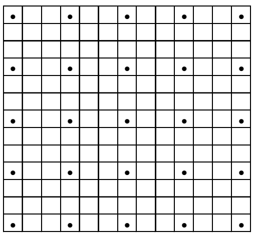


Figure 3. Group of producers (•) distributed uniformly over the reservoir grid

In this method, the wells are distributed uniformly over the grid, aiming to cover all the reservoir area. The map is constructed with only one simulation, as all wells start to operate at the same time under the same conditions. Figure 3 represents the uniform distribution of the producers over the reservoir grid. A problem with this method is the rapid pressure drop that takes place due to the opening of a great number of wells at the same time. To diminish, or even eliminate, this problem, another method is tested in which injectors are added between the producers, as shown in the next topic.

2.1.3. Fixed producers and injectors (FPI)

Besides the producers, some injectors are added in the reservoir grid in order to better maintain the pressure. Another good reason for adding injectors in the generation method is the fact that, in practice, when an engineer is designing a production strategy of a petroleum field, water flooding is the usual process adopted to maintain the pressure and improve the reservoir production. Figure 4 shows producers and injectors uniformly distributed over the reservoir grid, using the five-spot configuration.

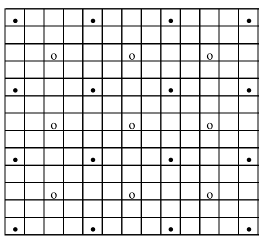


Figure 4. Group of producers (•) and injectors (o) distributed uniformly over the reservoir grid in a five-spot configuration

A geoestatistical method, known as ordinary kriging, was used to estimate the skipped points of the mesh. Journel and Huijbregts (1978) defined this local interpolation technique as the best linear unbiased estimator of the unknown properties of a study.

2.2. Comparison of the generated map with the base map

The generated maps are visually compared to the base map, to check their reliability; a difference function was defined in order to assist with this comparison; it is shown in Eq. (1),

$$difference(\%) = \frac{\sum_{i=1}^{n} \frac{\left| M_{reference_i} - M_{generated_i} \right|}{M_{reference_i}}}{n} \times 100 \qquad (1)$$

where $M_{reference}$ and $M_{generated}$ mean, respectively, the quality of the reference and of the generated maps in block i and n is the total number of blocks.

This difference function gives the mean difference of all generated map blocks relative to the reference map blocks.

2.3. Analysis of the generation method

The analysis of the generation method is made by taking some wells simulated by the method under study and comparing their behavior with the wells simulated by the reference case method. Some graphics plotted for the analysis are the oil and water production, water cut and field pressure versus time.

If the method does not give results coherent with the reservoir reality or if the calculated difference is too big, yielding a map with low precision, the method can be discarded.

2.4. Validation of the quality map generation method

After the analysis of the generation methods results, the advantages and the disadvantages of each one are listed and the maps are validated. The validation of the methods that did not use injectors (sweep and FP) is only based on the relative differences and on their well analyses. For the methods with injectors (FPI) the validation is made in two stages: first, an initial drainage strategy is defined for this method and for the FP method, in order to compare and decide which one presents the best result. This strategy is set with the same number of producers and injectors to each map. After this, producers were eliminated keeping the number of injectors constant in order to obtain the number of producers that yield the higher NPV. In the elaboration of each strategy some simulations were made to assist the strategy construction, in order to guarantee a coherent behavior between wells. The rules used to assist the strategy elaboration were:

1. The producers were positioned in the location with high quality and the injectors in the low quality ones;
2. The producers with lower NPV were closed or had their position changed;
3. The injectors without a high water injection rate were closed or had their position changed;
4. The oil saturation map was observed in order to reallocate the wells during the simulations, but the most important factor to define the position of the wells was the quality map;
5. The producer and injector ratio was maintained as close to one as possible; and,
6. The minimum distance between wells was three hundred (300) meters.

With this strategy, both models are simulated and the NPV (net present value) of each one is calculated, so that the analysis can be made comparing this parameter and the position of the wells over the quality map. The second stage aims to double-check this analysis by simulating some variations of the initial strategy, always totally based on the quality map; in this stage, their Np and NPV are compared to describe the efficiency of each map.

3. Application

Two models were developed to study the methods proposed by this paper: a homogeneous one, having the same permeability all over the reservoir, and a heterogeneous one, containing the presence of a channel and two barriers of permeability, both shown in Fig. 5. A Fetckovich aquifer was used to maintain the pressure in the reservoir.

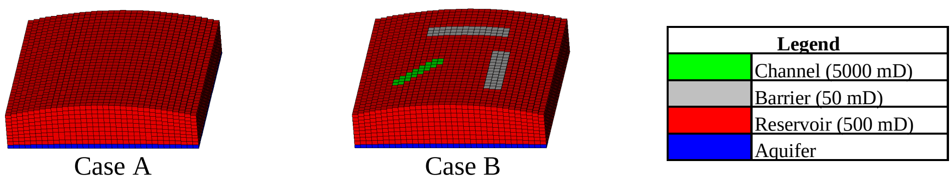


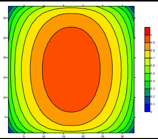
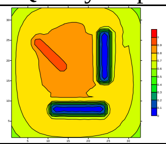
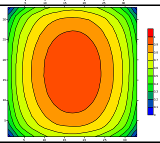
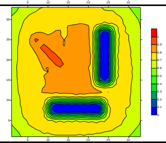
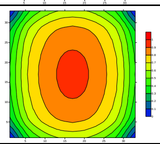
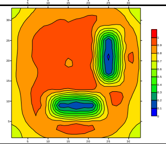
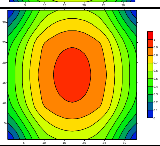
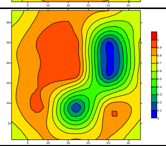
Figure 5. Homogeneous cases (1A and 1B), showing the position of the aquifers

4. Results and discussion

4.1 Sweep Method

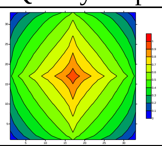
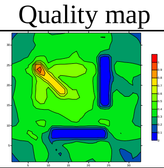
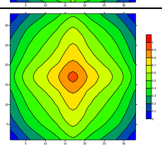
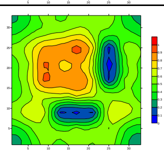
Table 1 shows the quality maps generated by the different procedures of the sweep method: well being allocated from one block to the next, then jumping two in two, three in three, four in four and eight in eight blocks (to reduce the number of simulations). It can be observed that, as more blocks are skipped, the relative difference of the map increases, at the same time that the number of simulations needed to generate the map is reduced. By visually analyzing the maps for case B (heterogeneous reservoir), one can see that with fewer simulations (simulated points) the permeability channel and the barriers start to disappear because the influence of the interpolating method is increased; the same effect cannot be seen in case A (homogeneous). The more simulated points, the better the definitions of the greater and lower regions of the reservoir; however, the simulation time increases considerably, sometimes rendering the process unfeasible. The reservoir engineer can, depending of the complexity of the problem, choose a method with more or fewer simulated points in order to balance the generation time against the required precision.

Table 1. Quality maps and differences for the sweep method with a unique well

	Simulations	Case A		Case B	
		Quality map	Difference	Quality map	Difference
Reference case 1 in 1	1089		0%		0%
2 in 2	289		1%		8%
4 in 4	81		3%		46%
8 in 8	25		11%		46%

The maps generated with the sweep method and a group of four wells are shown in Tab. 2. The distance between the wells has to be sufficient to avoid the mutual influence of the wells; however, despite the precautions that can be taken to avoid this influence, the simultaneous opening of four wells results in a pressure distribution significantly different when compared to the opening of a single well; this effect alone can increase the difference value. As can be seen, for both cases the maps presented high difference values and an accentuated visual difference relative to the reference map. The permeability barriers and channel in Case 1B are well recognizable and the tendencies of the greater regions are coherent, but the deviation is big because there is a difference between the mean values of the maps (noticeable by the difference in the color of the larger area, which is mostly orange in the base map and green in the maps of Case 1B).

Table 2. Quality maps and differences for the sweep method using a group of wells

	Simulations	Case A		Case 1B	
		Quality Map	Difference	Quality map	Difference
1 in 1	289		37%		52%
4 in 4	25		37%		45%

4.2 Fixed Wells Method

Table 3 shows the maps generated with fixed producers (FP). As can be seen for the homogeneous models, the maps constructed with fixed producers presented a tendency completely contrary to the reference map, as a consequence of the big pressure drop at the very beginning of the simulation. Some wells are closed as a result of the large pressure drop observed in regions where the aquifer effect on reservoir pressure cannot be readily felt (thickest areas), making this generation method not trustworthy. For the heterogeneous models, the fixed producers method resulted in a map with a large difference function (close to the difference of the homogeneous case), but the tendency is the same of the reference map, with the channel and the barriers also being identified, which indicates that the presence of heterogeneities diminished the effect of pressure drop.

Table 3. Quality maps and differences for the fixed producers (FP)

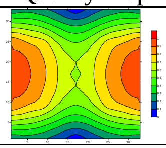
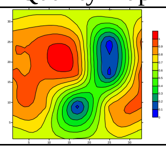
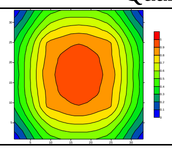
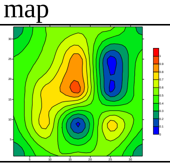
	Simulations	Case A		Case B	
		Quality map	Difference	Quality map	Difference
25p	1		41%		44%

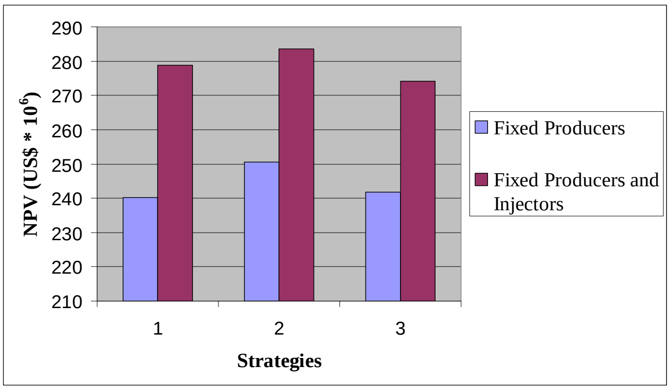
Table 4 shows the maps generated with the fixed producers and injectors method (FPI). Using injection in the homogeneous model the quality map presented a better visual result, with a tendency of the region of higher production potential being located in the middle of the reservoir, just like in the reference case. For the heterogeneous model the map seems to be coherent with the reservoir reality. The difference relative to the reference case was not calculated because it is not appropriate to compare a map generated by a method that uses injection directly to another that did not use it; thus, the drainage strategies described in section 2.4 were used to compare the maps generated by the FP and FPI methods.

Table 4. Quality maps for the fixed producers and injectors (FPI)

	Simulations	Case A	Case B
		Quality map	
Five-spot 25p 16i	1		

The use of injection eliminated the pressure drop problem; however, since the maps cannot be compared to the reference ones, another technique was used to validate them - two drainage strategies were set for the heterogeneous case, one for the FP method and another for the FPI method, and the results were compared to verify which map yields the best results.

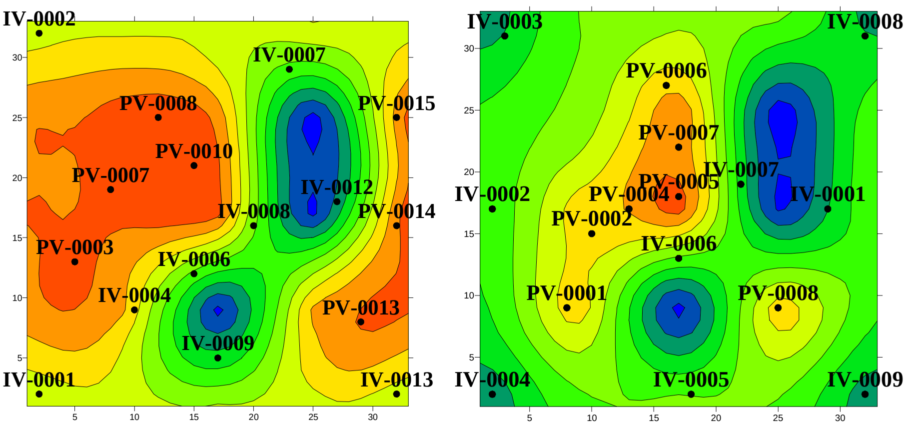
Figure 6 shows the NPV values for each strategy simulated. The FPI map presented better results, but the ideal number of producers was the same for both maps (7 producers and 9 injectors). In Fig. 7, the drainage strategy number 2, generated using each map and following the rules exposed in the methodology (Item 2.4), is shown. As one can observe, the strategy made using the FPI map resulted in a well configuration with most of the producers located pretty close to each other over the region of higher quality. This can be explained by the fact that, in the FPI method, the higher quality region is smaller than in the FP map.



Strategies	Number of Wells
1	8p9i*
2	7p9i*
3	6p9i*

*p means producers and
i means injectors

Figure 6. NPV of the simulated initial strategies



FP method
Number of producers (PV): 7
Number of injectors (IV): 9

FPI method
Number of producers (PV): 7
Number of injectors (IV): 9

Figure 7. Drainage strategies generated using the FP quality map generation method and the FPI quality map generation method

Some variations to the initial strategy were made in order to confirm the validation method of these maps. Figure 8 shows a comparison between the NPV and the Np of the resulting strategies made according to each map. As one can see, Np results from the strategies set with the FPI map were always greater, but the NPV of some strategies were very close for both cases. One of the strategies of the FP map presented NPV bigger than 2 of those based on the FPI map, what can be a consequence of the costs related to water flooding.

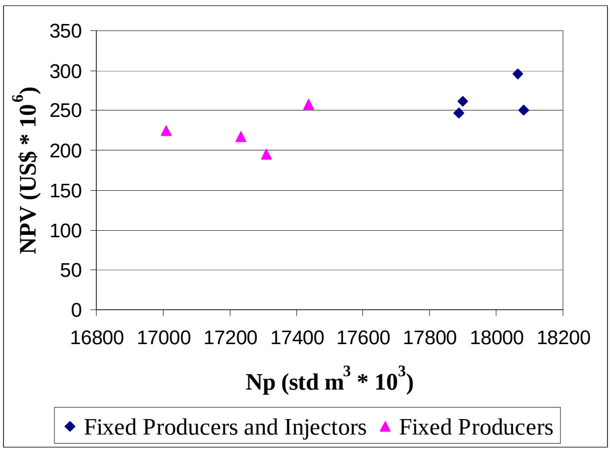


Figure 8. Comparison of some variations of strategy number 2, based on the respective quality map

5. Conclusion

1. The maps generated with the sweep method, using a unique well, presented trustworthy results, although the map lost precision when fewer points were simulated.
2. The number of skipped blocks between each simulation depends on the complexity of the model and of the studied problem, being a task of the reservoir engineer to define the precision of the required map and how much time can be spent in its generation.
3. When generating a map with a group of four wells, an important factor is the distance between them, which has to be sufficient to avoid any kind of mutual influence. Although the maps presented the same tendency of the reference case, the calculated relative difference values were too high, what indicated low precision.
4. When using the FP method for the homogeneous case, the maps generated presented high deviation and a tendency completely contrary to the reference case as a consequence of the large pressure drop that happens when many producers are opened at the same time through the reservoir.
5. In the heterogeneous case, the pressure drop was smaller and the map presented a good tendency identifying the two barriers and the high quality region near the permeability channel.
6. In the FPI method, the water injection eliminated the pressure drop problem and the generated maps presented more coherent results compared to the reality of the reservoir (the high quality region was located in the thickest region of the reservoir).
7. To validate the map generated by the FPI method, it was compared with the FP method by the construction of variations of the initial drainage strategy based on both maps; the first method presented better results, with higher values of Np for all strategies, although the NPV was, in some cases, higher for the FP map.
8. More studies need to be made to improve the quality map generation method using injectors and to validate it.

6. Acknowledgements

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