Numerical model as a decision-making tool for drills in the low enthalpy geothermal context of Martinique

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ABSTRACT

In the context of the volcanic Island arc of the Lesser Antilles, low enthalpy Geothermal Energy is available in the "Plaine du Lamentin" in Martinique. Its exploitation could be effective within a few years but additional studies are necessary to evaluate it and to acquire a better understanding of its behaviour. This is one of the reasons why 3D numerical modelling is essential in order to enrich the exploratory phase, which would eventually culminate in a successful exploitation of this energy source.

In view of assessing the practicability of an exploitation of the geothermal resource, we thus build a numerical model which employs the groundwater software Processing Modflow in order to obtain a tool for the determination of the most promising sites for drilling, as well as assess the expected flows. Some assumptions are proposed for inflows and outflows that have meteoric and marine origins.

Finally, we will show that this model could prove a useful tool in terms of the risk management connected to the exploitation. Our numerical tool, simple and fast, allows one to form rapid decisions in the eventuality of an urgent problem, when, for instance, one is confronted to the difficulty of accessing some location, in order to appraise the consequences of the opening and closure of a well on the neighbouring ones.

1. INTRODUCTION

In most Caribbean countries, the energy needs depend on the costly importation of oil, resulting in a disproportionately expensive production of electricity. Due to its remarkable potential in the Lesser Antilles (GEA 2014), geothermal power tends to be regarded as a possible solution for cheaper energy. Indeed, volcanism – due to the subduction of the Atlantic Plate under the Caribbean one (Poux and Brophy 2012, Joseph et al 2013) – is largely responsible for the formation of these islands and remains currently active.

Ever since the early 60ies, the geothermal properties of the "Plaine du Lamentin" have raised much interest in the scientific community. The hydrothermal activity is well documented locally, e.g. by the presence of springs of hot water, siliceous travertine or the observation of hydrothermal alterations (Cormy 1970). This convinced the company Eufrarep to engage a campaign of geothermal prospections in all this area, which has been pursued until now by the French National Institute of Geology, BRGM.

An intermediate geothermal field has been identified with a temperature of about 90°C (CFG 2001, Gadalia et al 2014). In this case, the production of electricity does not appear as a realistic option. However, the large concentration of industrial, commercial and economic activities in the "Plaine du Lamentin" suggests the possibility of employing geothermal energy for heating and cooling production. Currently, neither the origin nor the extension of the geothermal reservoir are precisely known, despite many studies on the Lamentin site (Gadalia et al 2014, Boy et al 2013, Sanjuan et al 2002).

The software Modflow has already been employed as a tool to form rapid decisions, e.g. for the problem of the deep-water horizon blow out into the Gulf of Mexico in 2010 (Hsieh 2011), or in order to study the sensitivity of some hydrogeological parameters (Panagopoulos 2012). This tool thus appears appropriate for applications in the geothermal context. As a first approach, that more precise tools would complete, this numerical model would help one take preliminary decisions.

In the following, we will explain how to construct our model via Modflow. In particular we will analyse the assumed values for various input parameters. In the third part, we will show that although Modflow does not take into account thermal effects, it may prove an interesting tool not only in the exploitation phase but also in the final exploration phase of the geothermal resources, in order to select the best drilling locations, the optimal depth of wells, the optimal flow and indirectly the capacity of the geothermal reservoir. Then, we will discuss our results.

2. MODEL PARAMETERS

2.1 Processing Modflow

Processing Modflow is a 3D-model of groundwater and pollutant transport. It is based on the method of finite difference (Chiang and Kinzelbach 1998). So one can thus describe and forecast the behaviour of hydrogeological systems for “simple” geometries. Several independent modules are available and use the output of Modflow.

PMPATH is a pollutant advection and transport module, which can represent streamline flows, velocity fields, and calculation of trajectories and times of transport.

MT3D is a pollutant transport module that uses a mixed Eulerian-Lagrangian approach and approximates a 3D solution of the transport equation, taking into account advection, dispersion and reaction phenomena. This module uses calculated hydraulic heads and considers the distribution of the concentration of pollutants and simple chemical reactions (linear and non-linear sorption, first order irreversible decay, biodegradation).

MT3DMS is an adjusted version of **MT3D**, which can compute dispersion, sink or source and reaction terms without any stability constraints. Three major classes of technical solutions of transport are included in this module, the classical model of finite differences, the track of particles using Eulerian-Lagrangian methods and the finite volume methods with high order.

MOC3D is a transport model that estimates variations of the concentration of a chemical component due to advection, mixing and dilution in the water host.

Lastly, **PEST** and **UCODE** are two calibration modules that help for the interpretation of data. From available and known data, these modules adjust the parameters while paying attention to reduce the gap between available measures and generated model.

These modules have not been employed in our simulations but one could consider applying modules like **PMPATH** or **MOC3D**, which would give us an idea of the conditions of flow into the geothermal reservoir. Following the variations of concentration of a tracer, one could detect areas of concentration or form an idea of the anisotropy of hydrogeological parameters. The modules **PEST** and **UCODE** could be employed to consider elements of validation of our results.

Although it is possible to use the **Recharge** package and the **Evapotranspiration** package into Modflow, we will not apply these packages in this simulation for two reasons. First, it is not the purpose of the present paper to study the behaviour of a water table but that of a geothermal reservoir with a deep origin, and we can assume that meteoric water does not influence significantly the level of the geothermal reservoir. On the other hand, the contribution of meteoric water is indirectly included in the flow that models the supply of the reservoir. We will discuss this contribution in the Input and output part.

For the same reasons as above, we have decided to simulate our geothermal system in the steady-state mode, knowing that, in the case of simulations over a one-year period, when the exploitation of the resource becomes an effective possibility, the transient mode would have to be considered.

It is also possible to use the **Reservoir** package (Fenske et al 1997) into Modflow but we will not employ it in this simulation because of the structure of our simplified model, as we shall discuss in the following section.

2.2 Defining the numerical model

The geological and geochemical data, given the distribution of several hot springs, the geochemical anomalies (He, CO2, Rn…) and data from the deep drills, seem to indicate a lateral flow of fluid along the NW-SE trending faults of the ditch of Lamentin. Moreover, the origin of the geothermal fluids under the “Plaine du Lamentin” may be researched northward, probably in the direction of the nearby “Pitons du Carbet” volcano (Traineau 2012, Gadalia et al 2014).

Nevertheless, in this paper we take into account the orientation of the prospect for the sake of emphasizing the possible global effects of hydrogeological parameters on the capacities of production and their optimization. This is the reason why we have built a homogeneous two layers rectangular model (6050 x 3050m with 121 columns and 61 rows) with the bottom of the first upper layer, representing our reservoir, which evolves from a depth of 1000m to a depth of 342m by steps of 10m, 5m, and then 2m from NW to SE. We must keep in mind that the second, deeper layer is regarded as impermeable. The model is divided into cells of 2500 m^2 (50m x 50m) in order to stay close to the order of magnitude probed by drill pipes. The size of the grid could be refined of course.

In Fig.1, we show the grid described above overlapping the map of the "Plaine du Lamentin".

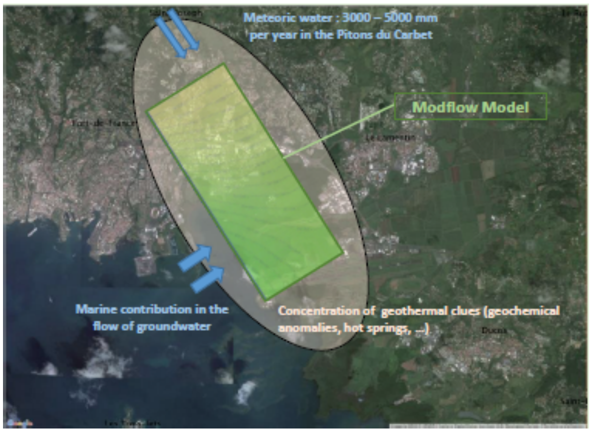

Figure 1: grid of the Modflow model-overlapping map of the "Plaine du Lamentin".

In a future work, we intend to refine the correlation between our numerical model and the real situation**,** considering the real coordinates, a more constrained geometry, as well as up-to-date data.

2.3 Input and output

In the following, we present some of the Modflow parameters in the input (Initial hydraulic head, Horizontal and vertical conductivity, Specific yield, Recharge rate, Localization and flow in wells, Reservoir's parameters…) or output (drawdown, calculated hydraulic head, flow cell by cell, compaction, subsidence, Darcy's velocities, concentration, mass…).

In particular, among the possible input of the software, we have considered the hydraulic heads, horizontal and vertical hydraulic conductivities, specific yield, flows and distribution of wells. As far as the output of the model is concerned, we have only studied the calculated hydraulic heads but we intend to take into account the drawdowns flow cell by cell in a future work**,** where our reservoir will be further constrained by data.

Initial hydraulic heads

Despite the scarcity of the available data, we were able to specify the initial hydraulic head and the conditions of flow at different boundaries; these boundary conditions will probably be supplemented by data to come. We can point out that it is not the first time that Modflow has ever been used with very restricted data (Comeaga and Dassargues 1997).

The distribution of the isotherms at 40°C and 80°C, obtained by thermal gradient wells, reported on a vertical cut in the prospect area along the NW-SE direction, tends to evidence a flow of fluid in the same area from a depth of 400m at the well of Californie to a depth of 200 m at the LA 101 well, increasing up to a depth of about 10m (CFG 2001, Gadalia et al 2014). Thus, we impose the initial hydraulic head from a depth of 400m to a depth of 100m, by steps of 50m then 25m (from right to left of the numerical model), which helps Modflow to compute the hydraulic head.

The hydraulic head at the left boundary (see Fig.1 and 2) has been fixed at a depth of 400m**,** unlike the other depths. This hydraulic head includes the contribution of flows from the "Pitons du Carbet", from the NW direction, corresponding to the left boundary of Fig.2. Here we make the hypothesis of a constant contribution of meteoric water and marine water. Actually, we assume that the contributions of meteoric water and marine water do not vary significantly on the timescale of the possible exploitation; indeed annual precipitations remain stable year after year (Gadalia et al 2014, Vittecoq et al 2012), and average about 3000 to 5000mm per year.

Marine contribution

As one observes on Fig.1, we have only considered the marine contribution flowing from the bay of Fort-de-France, i.e. from the SW direction, which corresponds to the lower part of the rectangular numerical model on Fig.2. We can point out that the contribution of the sea becomes increasingly relevant when we move towards the SE border (in the lower right-hand corner of the rectangular model).

In order to model the marine contribution, given that this contribution should represent about 30% of the total input flow in the prospect (Gadalia et al 2014), the condition of flow is also considered at the lower boundary of Fig.2.

We have used the package **Well** to represent the marine contribution**,** keeping the same level of flow for each cell where we imposed it. These cells do not have the same depth (the corresponding depths decrease from left to right, i.e. from NW to SE), thus the marine contribution becomes increasingly important when one moves to the right of the prospect, i.e. in the SE direction. The marine contribution is considered more relevant in the upper layers of the model, which is consistent with the concrete situation. The value of the flow, which represents the marine contribution, has been chosen such that a certain amount of water keeps above the bottom of the first layer, which represents our reservoir.

Hydrogeological parameters

We have been confronted with the difficulty to collect hydrogeological information, particularly concerning the deep formation; neither production tests nor deep hydrogeological surveys have been carried out in Martinique.

In this work, we have used data gathered by hydrogeological surveys performed at the surface as well as typical values found in almost the same context in Guadeloupe. Based on such sources, we have chosen the following values (Cottez and Deneufbourg 1970, Cottez 1971, Dörfliger et al 2011):

- Horizontal conductivity: $K_h = 1.10^{-6}$ m.s^{-1},
- Vertical conductivity: $K_v = 1.10^{-7}$ m.s^{-1},

- Specific yield: ω = 0.20.

Moreover, we must consider the actual difficulty to account for the hydraulic conductivity at the site of interest. It is true that the “Plaine du Lamentin” is severely fractured with many faults. This implies a high anisotropy. Yet, the numerical model that we employ is based in particular on the hypothesis of a flow in the horizontal direction. Consequently, we will address this parameter as soon as additional data becomes available.

The influence of the values of the hydraulic conductivities on the output of the model may prove a worthy focus of interest. We can show that the horizontal hydraulic conductivity has a larger impact on this output. In this way, we can try to optimize the position and the production of the wells.

In view of improving the production, the flow in the vicinity of the production wells could also turn out as an interesting object to study.

3. POSITIONS OF PRODUCTION AND REINJECTION WELLS

The first endeavour of this part consists in recovering the extension of the geothermal field (Gadalia et al 2014) under simple assumptions. Then, based on the simulation**,** we have studied the influence of the position of a production well and/or a reinjection well on the flow.

3.1 Recovering the Lamentin prospect

In the next figure, we show that we are able to recover the general form of the prospect (Gadalia et al 2014) under minimal assumptions. Indeed, the upper piezometric height ranges from 400m under sea level on the left, to about 10m under sea level on the right.

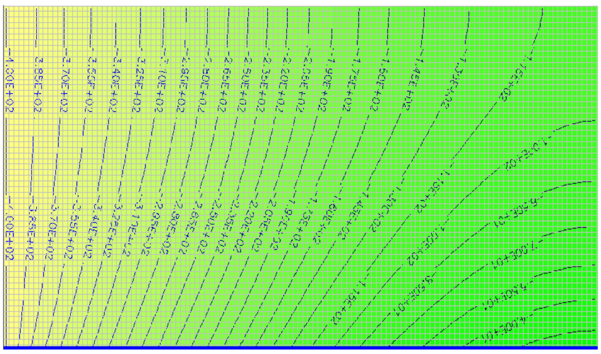

Figure 2: marine flow contribution +0.001m^3/s.

It was necessary to assume a marine contribution of +0.001 m^3/s to recover the form of the prospect of the Lamentin plain in Fig.2.

We remind the reader that keeping a constant value for the marine contribution in the lower part of Fig.2**,** knowing that the depth decreases from the left (NW direction from “Pitons du Carbet”) to the right (SE direction) is relevant in order to establish a model for the actual impact of this contribution.

The chosen value for the marine contribution seems to be consistent with the estimate obtained with data concerning the seepage in the prospect. Indeed, the total seepage at the “Pitons du Carbet” can be estimated at 25 Mm^3/year (0.79 m^3/s) on average (Gadalia et al 2014) and**,** considering that about 10% of this seepage flows in the direction of the Lamentin, we obtain an estimate of 0.08 m^3/s there. Finally, we know that the marine contribution corresponds to 30-35% of the waters in the zone of interest and the sea penetrates in a transverse direction to the main supposed direction of flow. Consequently we can state that the contribution of the sea is limited.

In the following, we assume that the marine contribution represents less than 10% of the flow from the “Pitons du Carbet”. Finally, we consider a value of +0.001m^3/s in our simulation, in order to mirror the geometry of the prospect.

This value of the marine flow contribution indicates that the meteoric contribution flow is possibly smaller than the previous estimate.

3.2 Impact of the marine contribution

In a second step, we study the influence of the marine contribution. For instance, we reduce the marine contribution by a factor ten, i.e. assume a marine flow of +0.0001 m^3/s.

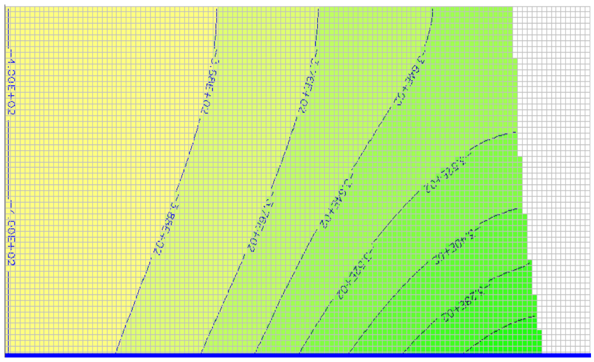

Figure 3: marine flow contribution +0.0001m^3/s.

We can see here that the cells on the right, i.e. in the SE, are dry.

On the other hand, the chosen value for the marine contribution should not be too large because of the level of the hydraulic head, which would evolve above the topographic surface in our numerical model for large values of the marine contribution.

Similarly to the marine contribution, we wish to study the impact of the waters from the “Pitons du Carbet”, varying the value of its flow. But, as we have fixed the hydraulic head on the left boundary, we cannot observe significant modifications when fixing a flow at this same location (left boundary). Thus, we assumed that the value of the flow of waters from the “Pitons du Carbet” is fixed.

3.3 Influence of the production wells

In the following, we keep a marine contribution of +0.001 m^3/s.

In this part, we place a production well on the right part of Fig.4. Here, our goal is to determine the magnitude of the production flow, which dries up the cell of the well.

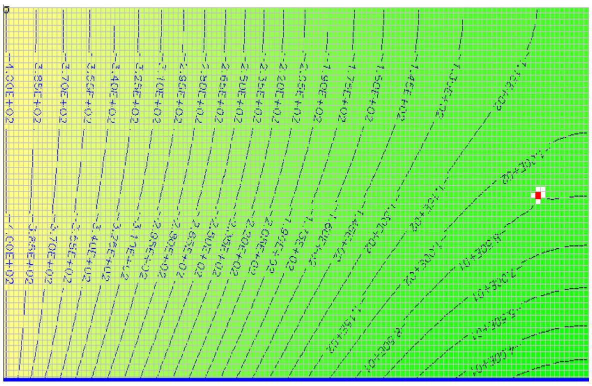

Figure 4: marine flow contribution +0.001m^3/s and production well flow -0.03m^3/s.

We can see in Fig.4 that the maximal production flow is -0.03 m^3/s. From this value upwards, the cell of the well would be dry.

Figure 5 confirms that a lower production flow, here -0.02 m^3/s, does not induce any draining of the cells.

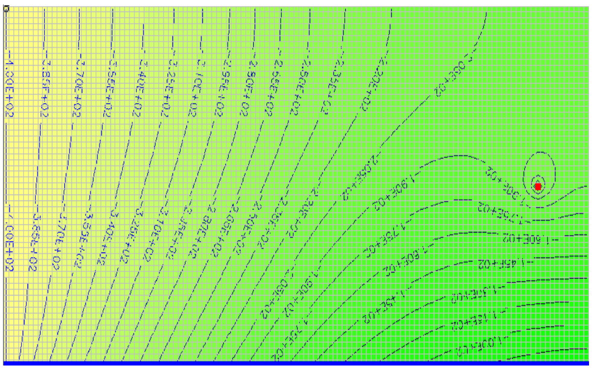

Figure 5: marine flow contribution +0.001m^3/s and production well flow -0.02m^3/s.

We observe, in the case of a lower production, a modification of the piezometric lines in the vicinity of the production well, which persists at 1300m on the left of the production cell. This area of influence might be less extended when the production decreases, since the value of -0.02m^3/s corresponds to the critical production flow for which absolutely no cell dries out.

3.4 With a reinjection well

In this part, we maintain the marine contribution at +0.001 m^3/s again. In Fig.6, we consider the production flow of -0.03 m^3/s, in which case, the results of the previous paragraph show that the cell of the well is dry. However, we now also include a reinjection well with the inverse flow +0.03 m^3/s.

Our goal in this part is to determine the maximal distance between the two wells that keeps the production cell wet.

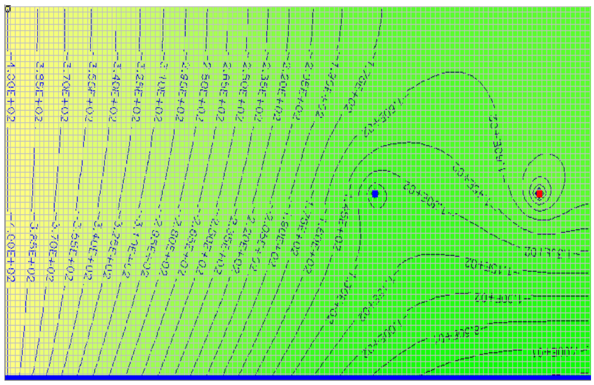

Figure 6: marine flow contribution +0.001m^3/s, production well flow -0.03m^3/s and reinjection well flow +0.03 m^3/s, d = 1700m.

We find that the cell of the production well would dry up if the reinjection well were placed at a distance of more than 1700m of the production one. Of course, at this maximal distance of 1700m, the reinjection flow would have to reach its maximal value of +0.03m^3/s.

In Fig.7, considering the presence of the reinjection well, we increase (in absolute value) the production flow at -0.04 m^3/s. The inverse reinjection flow +0.04 m^3/s would then have to be placed closer to avoid the depletion of the production cell: 700m.

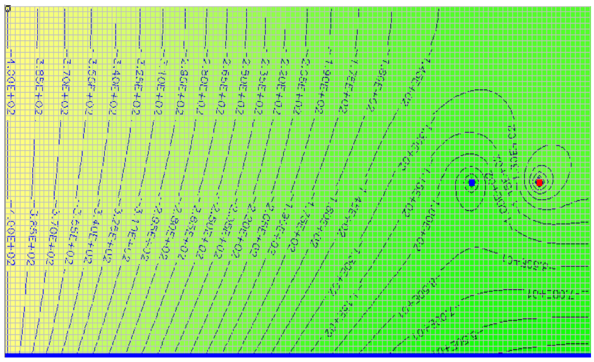

Figure 7: marine flow contribution +0.001m^3/s, production well flow -0.04m^3/s and reinjection well flow +0.04 m^3/s, d = 700m.

3.5 Influence of the hydraulic conductivity

In this part, we still maintain the marine contribution at +0.001m^3/s, and keep the production and reinjection flows at +/-0.03m^3/s. We only increase the value of the horizontal hydraulic conductivity K_h, from 1.10^{-6} to 2.10^{-6} $m.s^{-1}$.

In Fig.8, we show that the piezometric heights are very sensitive on the horizontal hydraulic conductivity. We also checked that the vertical hydraulic conductivity has no impact on the considered output.

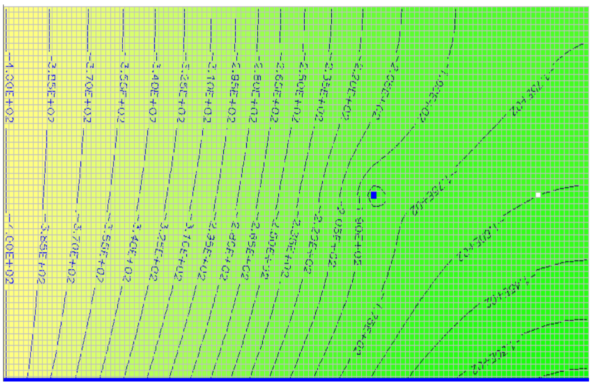

Figure 8: marine flow contribution +0.001m^3/s, production well flow -0.03m^3/s and reinjection well flow +0.03 m^3/s with K_h = 2.10^{-6} m.s^{-1}, d = 1700m.

In Fig.8, for a distance of 1700m between the two wells (which kept the production cell wet in Fig.6 for a lower hydraulic conductivity), we observe that the production cell is drained for this higher conductivity.

Then we have determined in this case the position of the reinjection well, which would keep the production cell "wet". Fig.9 shows that the reinjection well could be placed at the position (100, 31), i.e. at 550m from the production well.

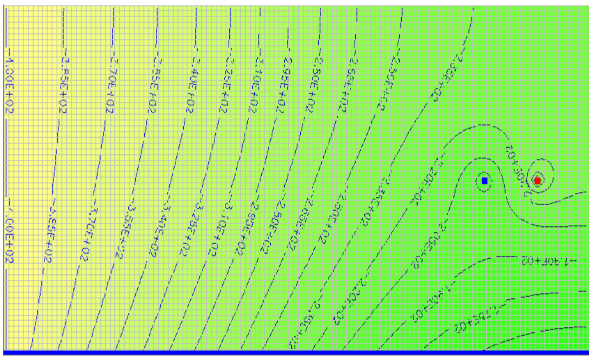

Figure 9: marine flow contribution +0.001m^3/s, production well flow -0.03m^3/s and reinjection well flow +0.03 m^3/s with K_h = 2.10^{-6} m.s^{-1}, d = 550m.

We insist on the relation that exists between the flows, the optimal distance between the two wells and the horizontal hydraulic conductivity of the medium.

3.6 Discussion

In this work, we have chosen to place the production well in the southeast area, on the right-hand side of the rectangular model. The limited depth of the reservoir justifies this choice. It would also be possible to consider a drill in the northwest area, at least from a technical point of view; in practice, this would prove rather difficult to perform because of the high concentration of population and industrial installations in this area, though not impossible of course.

Therefore, keeping these constraints in mind, one understands why, in the hypothesis of a reinjection well, we have chosen to place the latter on the left-hand side of the production well. This choice is consistent with the idea of a lateral flow in the geothermal reservoir from the "Pitons du Carbet" volcano to the "Plaine du Lamentin".

To increase the viability of our numerical model, it will be necessary to use the calibration models **UCODE** or/and **PEST** of Modflow to validate some of the results (hydraulic head at the position of deep drills). The numerous fractures and faults would have to be considered later on, in order to define the relevant geometry of the reservoir more precisely.

Finally, the question of the anisotropy will remain as the most difficult one to solve. In a future work, we will continue with our observation of the high influence of the horizontal hydraulic conductivity on the optimal position of the wells. In this case the maximal distances determined between the production well and the reinjection well will be complemented with additional estimates of the relevant distances. These additional estimates will depend on the anisotropy of the medium, which will be studied.

4. CONCLUSIONS

The development of geothermal energy in the Caribbean could reduce the energy dependence, hence the energy budget of these territories. The geothermal potential of these regions seems such that self-sufficiency and even exportations could be achieved.

In Martinique, the very active "Montagne Pelée" volcano comprises an obvious locus for high enthalpy geothermal resources and in the southwest of the island, in the area of "Anses d'Arlet", geochemistry analyses also indicate a high enthalpy geothermal potential. Unfortunately, the accessibility of the first prospect and the limited recharge of the second one raise concerns as to their exploitation.

At the moment, the most accessible area from a geothermal point of view is the "Plaine du Lamentin". The temperature of the Fort-de-France - Le Lamentin geothermal field is about 90°C. It is not enough to produce electricity but cooling or heating production would be possible. As we discussed early on, the location of this geothermal resource is adapted to its direct uses.

In this work, we have highlighted the importance of the position of the production and reinjection wells. The corresponding flows also play a critical role.

Moreover we have been confronted with the lack of available data and the difficulty to take into account the anisotropic character of the hydraulic conductivity, so that this scarcity of information justifies further studies and exploration before the geothermal exploitation. But owing to the use of Modflow as a simple numerical tool, we have managed to obtain a few orders of magnitude for some parameters such as the position of the wells, the distance between them, the appropriate fluxes. More involved numerical models could admittedly provide more precise results but our goal rests also in the production of a simple tool, which could address emergency situations, for instance.

Finally, all the results that we have produced with Modflow demonstrate the relevance of a fast numerical tool for the incoming steps: in the management phase, or in the opening of a geothermal site for example.

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