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From Exploration to Utilization, Hoffell Low Geothermal Field, Southeastern Iceland

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ABSTRACT

A good progress has been achieved in recent years in drilling of exploration/production wells in Hoffell/Miðfell in Hornafjörður, SE-Iceland. Low-temperature geothermal exploration began in the county of Austur-Skaftafellssýsla at the initiative of the municipalities in 1992. A noticeable heat anomaly was observed in Hoffell with a geothermal gradient of 186°C/km. Chemical analysis indicated that the temperature in the geothermal system might reach 70-80°C. Exploration in Hoffell was under the supervision of Jarðfræðistofan Stapi until 2012 when Iceland State Electricity (RARIK) got the geothermal utilization right in the area. Thereafter, Iceland GeoSurvey (ÍSOR) started the exploration of the area. Lithological measurements were conducted in selected boreholes as well as acoustic televiewer logging. Interpretation of these logs changed the previous ideas, which experts had, about the geothermal system and results showed that it was more complicated than initially considered.

Five deep explorations/production wells have been drilled in Hoffell from 2012 and several gradient wells, the outcome of this drilling and the processing of imaging with acoustic televiewer among other lithological measurements in these wells have strengthen the hypothesis that the main convection of water is in northeasterly striking fractures and that the geothermal system is much larger than previously anticipated. Information derived from acoustic televiewer images have been crucial in locating production wells with greater accuracy and thus increasing the likelihood that the wells will intercept open fractures at the right depth.

Today four of the five deep wells are productive: HF-1, HF-3, HF-4, and HF-5. Well HF-2 did not prove to be usable as a production well. But it did turn out to be an excellent monitoring well for the system. A lumped reservoir model for the water table of well HF-2 was calibrated using production data from wells HF-1, HF-3, and HF-4. Predictions for the future water table of well HF-2 was made from and including the year 2018. Two production scenarios were considered, 35 L/s and 45 L/s, and each production scenario included predictions with and without reinjection. Predictions for the water tables of wells HF-3 and HF-4 was extrapolated from the water table of well HF-2. The main result is that the system can withstand 35 L/s and 45 L/s production for 20 years. It is though recommended that reinjection starts within 10 years of production to minimize drawdown in the system.

1. INTRODUCTION

The Hoffell low-temperature geothermal field is located in the region of Austur-Skaftafellssýsla in Southeast Iceland, in the upper Hornafjörður region. Bedrock in the area is mostly composed of basaltic plateau lavas with thin sediment layers intermittently and intrusions widely intercalated, although layers of felsic rocks and sedimentary agglomerate are also found. The volcanic pile is of Tertiary age and was deeply eroded by glaciers during the Pleistocene. The area is at the edge of a monoclinal flexure which runs from Breiðamerkurjökull in the Southwest, along the Vatnajökull ice-sheet cone some 250 km north to Vopnafjörður. Intercalated with the lava pile is an extinct Tertiary central volcano, named the Geitafell volcano (Friðleifsson, 1983), which is exposed because of deep glacial erosion (Figure 1). The volcano was formed within a rift zone in central Iceland, and was active for about 1 m.y., between 5 and 6 Ma (Friðleifsson, 1983), slightly predating the SE-Icelandic flexure zone. According to studies of infilling sequences of mineral veins and amygdales and their associated wall-rock alteration (Friðleifsson, 1983), the Geitafell volcano has experienced three major structural events, (i) uplift of the central region, (ii) caldera subsidence, and (iii) regional flexuring.

Heat is still preserved in the crust at the Hoffell low-temperature field, which has been explored discontinuously over the last two decades or so in the purpose of finding hot water for a heating utility in Höfn, the main town of the region some 20 km away. Geothermal prospecting commenced in the region of Austur-Skaftafellssýsla in 1992 with the drilling of shallow research wells which were employed to accomplish a survey of geothermal gradient (Smárason, Stapi – Jarðfræðistofa, 1993). An anomaly was soon detected in the geothermal gradient data near the farms at Hoffell ("Hoffell" and "Midfell" in Figure 1), which are located at the periphery of the Geitafell volcano, and this area accordingly became the main focus of interest. Drilling was hence continued in the Hoffell field (Smárason, Stapi – Jarðfræðistofa, 1992; 1993; 1994; 2002; 2005; 2006), totaling in 33 vertical research wells, most of them less than 60 m deep. Highest measured temperature was 61.1°C at 505 m depth in the deepest well in the area (ASK-86). Based on the geothermal gradient data, combined with further research, a model was constructed of the geothermal system which exhibited two predominant Árnadóttir et al (2013) 2 fracture trends, ENE-WSW and approximately N-S, which appeared to be related to the geothermal gradient maximum (Sæmundsson, 1995; 1996; Stapi – Jarðfræðistofa, 1992; 1993; 1994; 2002; 2005; 2006). Figure 1. Friðleifsson's (2004) geological map of the Geitafell volcano. Location of the mapped area is shown to the left. In terms of the model of the geothermal system it was recommended that further research would involve drilling of an approximately 1000-1200 m deep exploration well (Smárason, Stapi – Jarðfræðistofa, 2006; Árni Hjartarson et al., 2012), which originally was intended to intersect the ~N-S trending fracture below 800 m depth.

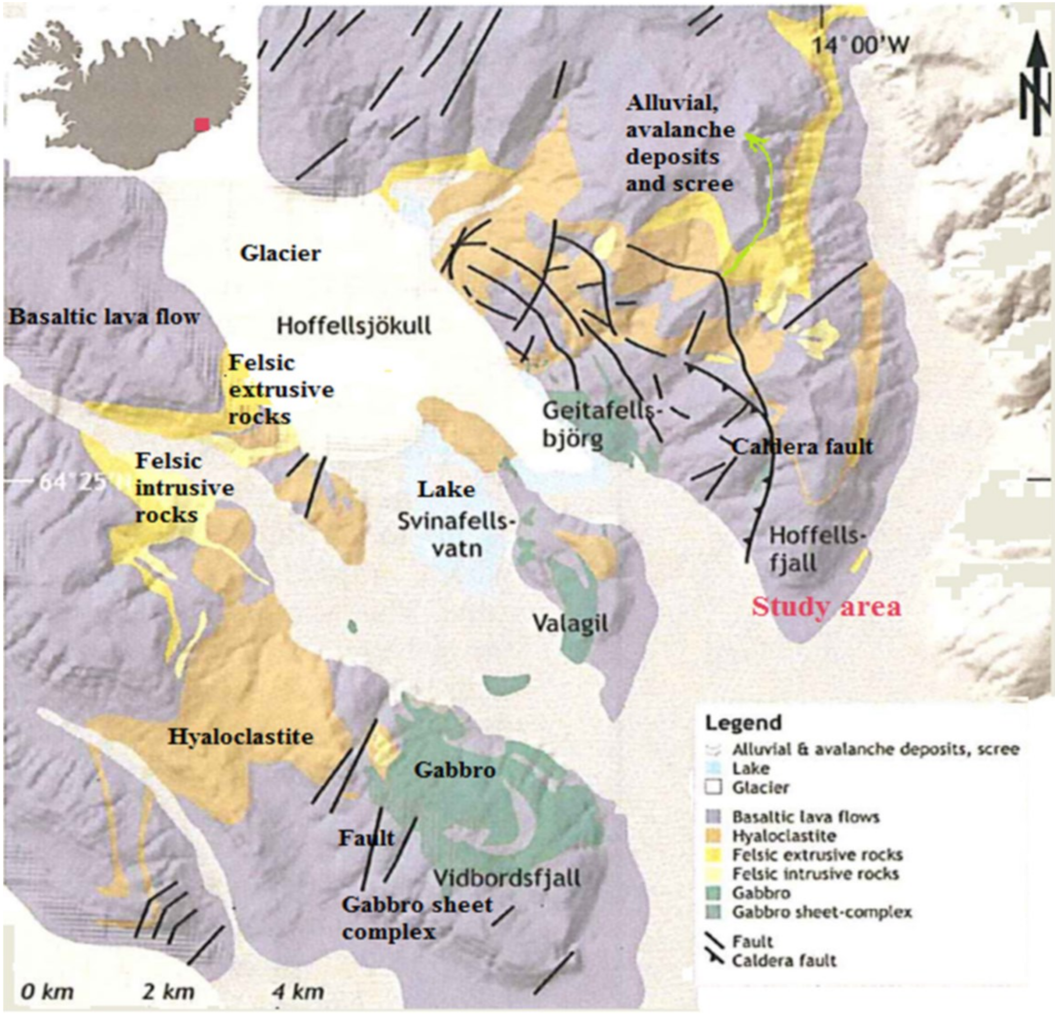

Figure 1: Geological map of the study area (modified from Fridleifsson, 1983a)

2. EXPLORATION FROM 2012-2018

In 2012, lithological measurements were conducted in selected boreholes as well as acoustic televiewer logging. Interpretation of these logs changed the previous ideas, which experts had, about the geothermal system and results showed that it was more complicated than initially considered. On the basis of these measurements, production well HF-1 (1608 m deep) was drilled south-east of the N-S heat anomaly with acceptable results (Kristinsson et al 2013, Axelsson and Kristinsson 2015), but more water was still needed for the district heating of Höfn, the main town in the area.

A production well HF-2 (1684 m deep) was drilled in late 2014. The location of the well was decided in a similar manner as customary in Iceland, taking into account the temperature gradients in shallow exploration wells and then drilling straight into the area with the maximum thermal gradient. The result of that drilling did not meet expectations since any water-bearing fractures weren´t intercepted.

Based on that, all assumptions were thoroughly reconsidered. A heat anomaly seen to the east with quite a flat peak was taken into further investigation and as a result, several shallow exploration wells were drilled to better determine the orientation of this anomaly. The hypothesis is that the main convection of geothermal water in the system is connected with NE-SW striking fractures dipping to the SE and extending NE from where production wells HF-1 and HF-2 were drilled (Figure 2).

Several exploration wells were drilled in 2015 and 2016 in the northeast part of the area to further explore the inner part of the geothermal system. Imaging with acoustic televiewer among other lithological measurements in these wells have strengthen the hypothesis that the main convection of water is in northeasterly striking fractures (Figure 3) and that the geothermal system is larger than previously anticipated. Information derived from acoustic televiewer images have been crucial in locating production wells with greater accuracy and thus increasing the likelihood that the wells will intercept open fractures at the right depth. Production well HF-3 (1084 m deep) was drilled in early 2016 (Kristinsson et,al 2016) and drilling of HF-4 (1750 m deep) was finished in middle of July 2017 (Kristinsson et,al 2017). Both of them were very successful and have increased the possibility that sufficient water for the district heating in Höfn can be obtained. Well HF-4 is the easternmost production well in the area and is showing the highest temperature which indicates that it is closer to the main convection in the system (Fig. 5). In 2018 the exploration was taken even further to the east, several new shallow wells were drilled to see if the area extended so far. On the bases of this new wells a production well HF-5 was set 250 m northeast of HF-4. Temperature logs show that the geothermal system extends at least this far (Figure 2). HF-5 successful and showed that the geothermal system extends further to the northeast (Kristinsson et al 2018).

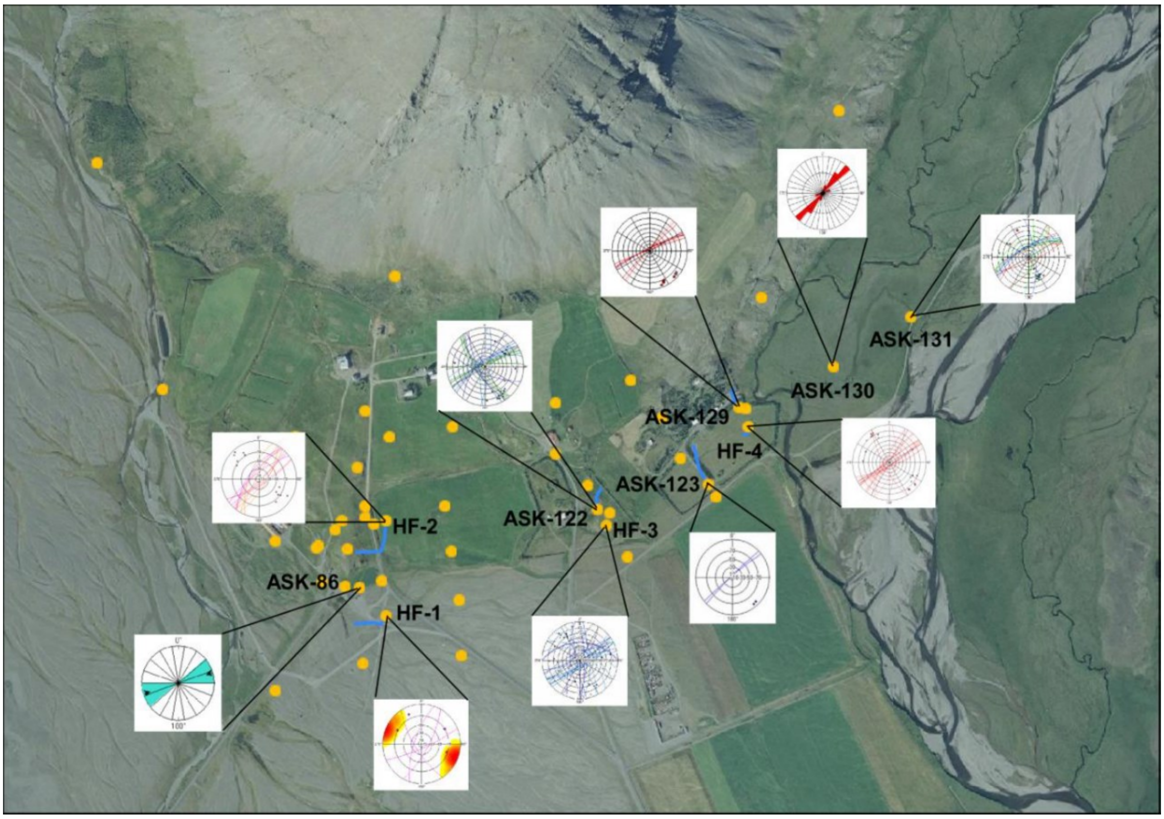

Figure 2: Strike of open fractures that exploration/production wells have intercepted (Wulff plots). These fractures were analysed from acoustic televiewer data. As can be seen, the main striking of fractures is NE-SW which supports the main convection of geothermal water in the system.

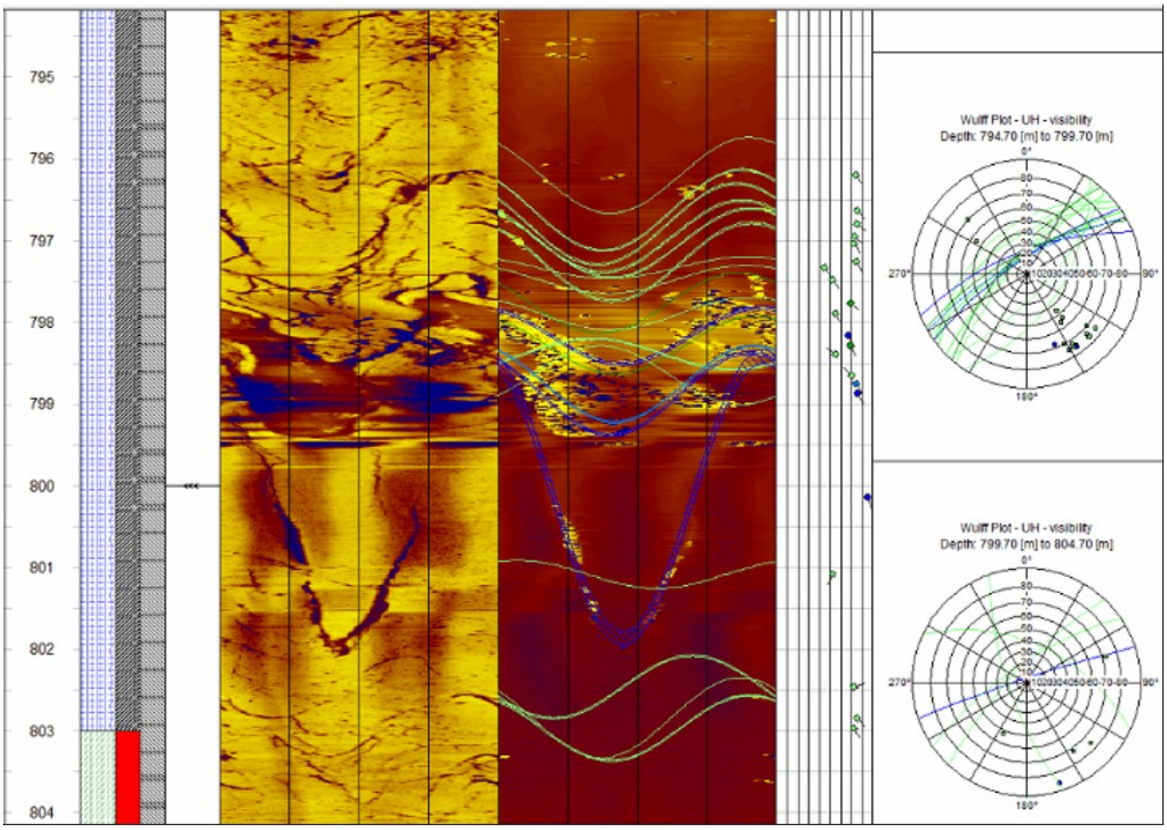

Figure 3: Example of a open fracture at 800 m depth in well HF-3, seen with acoustic televiewer. The left televiewer image shows the amplitude (north) and the right image shows the travel time (north). The wulff-plots to the right show the strike and dip of the fracture.

3. LITHOLOGY IN THE DEEPER WELLS

In general, the lithology of deep wells in the Hoffell area reflects a bimodal suite of basaltic and rhyolitic/granophyric rock (Figure 4), whereas the evolved rocks (rhyolites/granophyre) are appear as intrusions within the basalt pile. The uppermost 600- 800 m consist of a sequence of basaltic lava flows, intercalated by sedimentary interbeds that where formed during the volcanic hiatus. Within this basaltic pile several thin (< 10 m) rhyolitic/granophyric intrusions crosscutting the lava pile. Some minor mafic intrusion are present as well within the uppermost 600 – 800 m. At about 600 - 800 m depth a change from effusive to intrusive formation is observed. Between 600 and about 1100 m the lithological inventory is dominated by basaltic intrusions, whereas acidic rocks of minor thicknesses (< 10 m) are present. The basaltic intrusion shows a high variability and indicate rather thin intrusive bodies. Within the depth range from 1000 to about 1590 m a thick granophyre body is very homogenous and only intercalated/crosscut by some thin basaltic units (<10 m). Below a depth of 1590 m in well HF-5 the lithology changes to a basaltic dominated intrusive complex, intercalated by some thin acidic intrusions. The appearance of acidic units observe by cutting analysis are also observed within the natural gamma log, which fits quite well the geochemical characteristics observed during cutting analysis. The role of this intrusive bodies to the geothermal system is not quite clear but wells HF-4 and HF-5 show changes in temperature (Figure 5) at similar depth as changes in lithology (Kristinsson et.al.2018).

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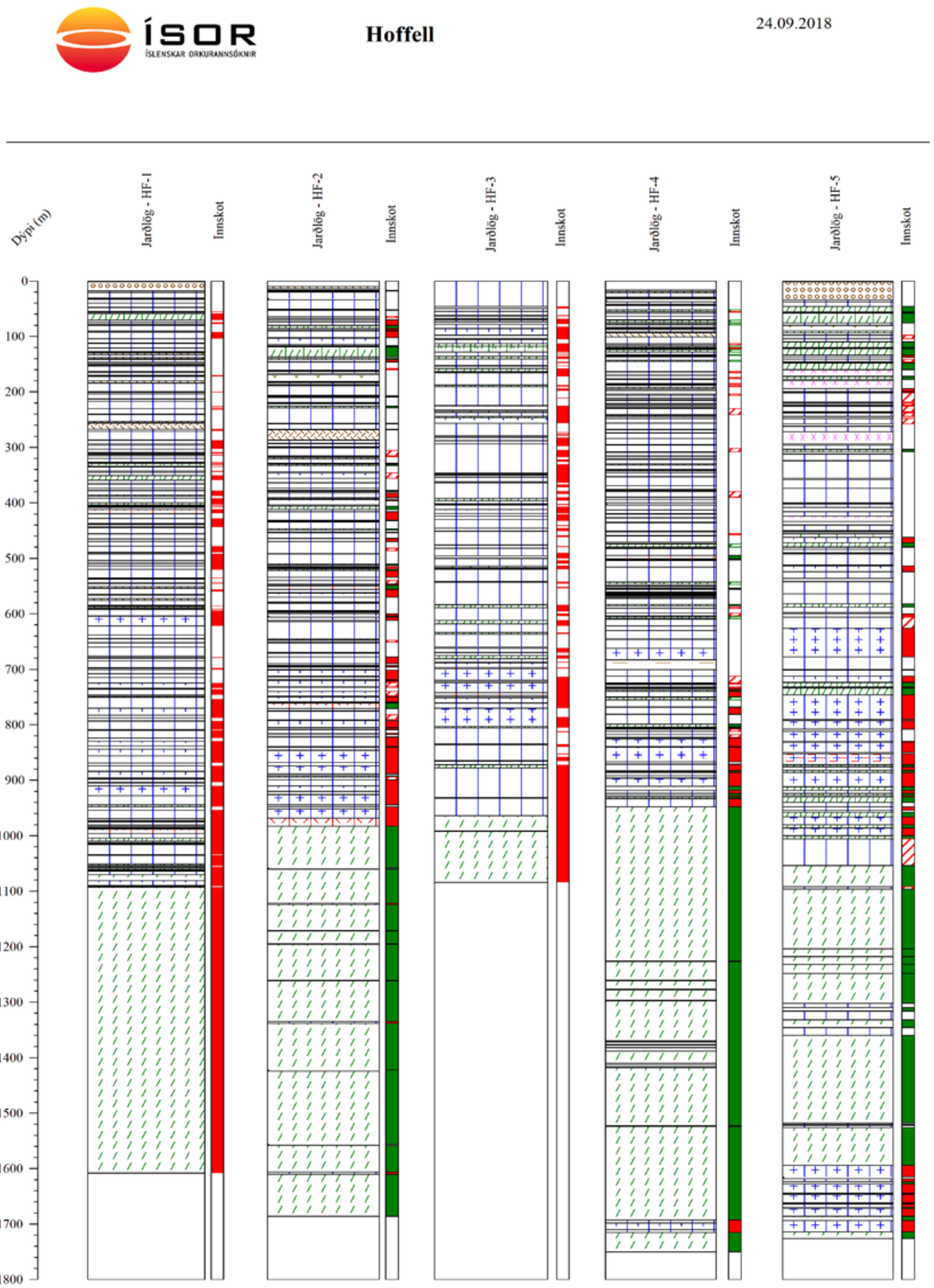

Figure 4: Comparison of lithological logs in the 5 deep wells drilled in Hoffell.

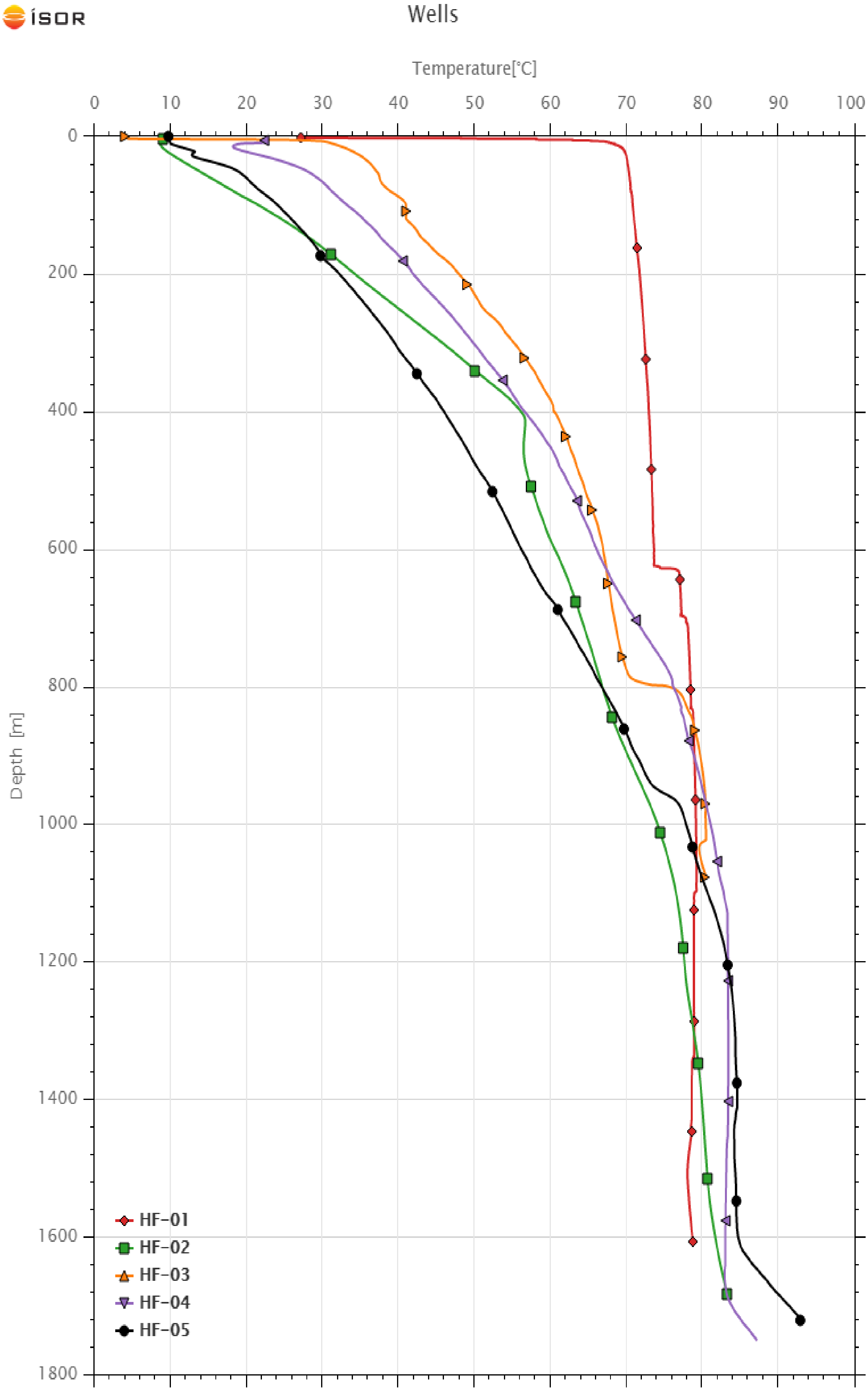

Figure 5: Temperature logs in wells HF-2, HF-3 and HF-4. The temperature log in HF-4 is most likely showing the formation temperature of the system.

4. RESERVOIR

Production and water table data have been compiled for wells HF-1, HF-2, HF-3, HF-4 and HF-5 in Hoffelli, Nesjum, from the end of March 2013 to the end of February 2019. The data were used to calibrate a closed and an open two tanks lumped model and a closed and an open three tankslumped model of the Hoffell geothermal system. The water table data that was used in the calibration was collected in well HF-2. Data from that well is considered to best reflect the production changes in other wells in the area and water levels in the geothermal system. Water level data from well HF-2 during the period from the 23rd of January 2018 to end of February 2019 needed to be shifted by 3.5 m due to discrepancies in automatic water table data and manual measurements. Well HF-2 is very poor production well but is well suited for the monitoring water level of the geothermal system during production in other wells. In the model calibration, the total production from wells HF-1, HF-3, HF-4, and HF-5 was used along with estimates of water losses from the system due to air rated drilling in well HF-4 the summer of 2017 and in well HF-5 the summer 2018.

The results of the model calibration were two two-tank models, one closed and the other open, with a standard error of 2.0 m for the closed model and 1.7 m for the open model, and two three-tank models, open and closed, both with a standard error of 1.5 m. The comparison of the waterlevel calculated by the models to measured water levels can be seen in Figure 6 for the two tank models and in Figure 7 for the three tank models. The calibration gave effectively the same model for the closed and open three-tank models, since the only difference was a very weak connection to the infinite reservoir in the open-model. This indicates that the geothermal system is closed rather than open.

The open two-tank model and the closed three-tank model were used to calculate water level forecasts in well HF-2 for a 20 year period, as of September 2020, for eight different future production cases. Four cases account for 35 L/s average production , which is an estimated current hot water requirement for Höfn in Hornafjörður. The other four cases allow for 45 L / s average production. For each set of cases, the following four different scenarios of injection are considered: No injection, injection starts after 10 years, 5 years or at the beginning of the planned operation (0 years). Seasonal fluctuations in the total production are also accounted for and we assume that half of the production will find its way back to the reservoir via reinjection. (Þorgilsson et.al. 2018)

Figures 8–11 show water level predictions for the 35 L / s average production (equivalent to 34 kg / s of 80 ° C hot water) with peak production of 44.2 L / s (42.9 kg / s) and base production of 26.0 L / s (25.2 kg / s). This amount of production corresponds to the estimated hot water demand for Höfn in Hornafjörður. The upper part of the figures show the water level forecast according to the open two-tank model and the closed two-tank model. The lower part of the figures show measured production up to 2019 and estimated net production as of 2019. The difference between figures is whether water is reinjected into the geothermal system, and if so, when the reinjection begins. The amount of reinjection is always half of the total production and the net production is then equal to half of the total production.

Average production equivalent to 35 L / s is considered sufficient to meet the current need for hot water for Höfn in Hornafjörður. In order to test the tolerance of the geothermal system for increased production predictions where production is in excess of projected need were made. Figures 12-15 show water level prediction for 45 L / s average production (equivalent to 44 kg / s of 80 ° C hot water) with a peak production of 56.8 L /s (55.2 kg / s) and base production of 33.4 L / s (32.5 kg / s). Arrangement of figures 12-15 and reinjection is as in Figures 10–13 for the 35 L / s average production.

Measured water table data in HF-3, HF-4 and HF-5 were compared with the measured water table in HF-2 for different operating conditions of wells HF-3, HF-4 and HF-5. From the comparison, water level prediction in hole HF-2 can be transferred to water level in holes HF-3, HF-4 and HF-5. Comparable comparisons for well HF-1 could not be made because there are no simultaneous water level measurements in the well and in the other wells.

The forecast assumes production will be from wells HF-3, HF-4 and HF-5. The HF-4 well is expected to provide the base production and either well HF-3 or well HF-5 to provide the seasonal variation in production.

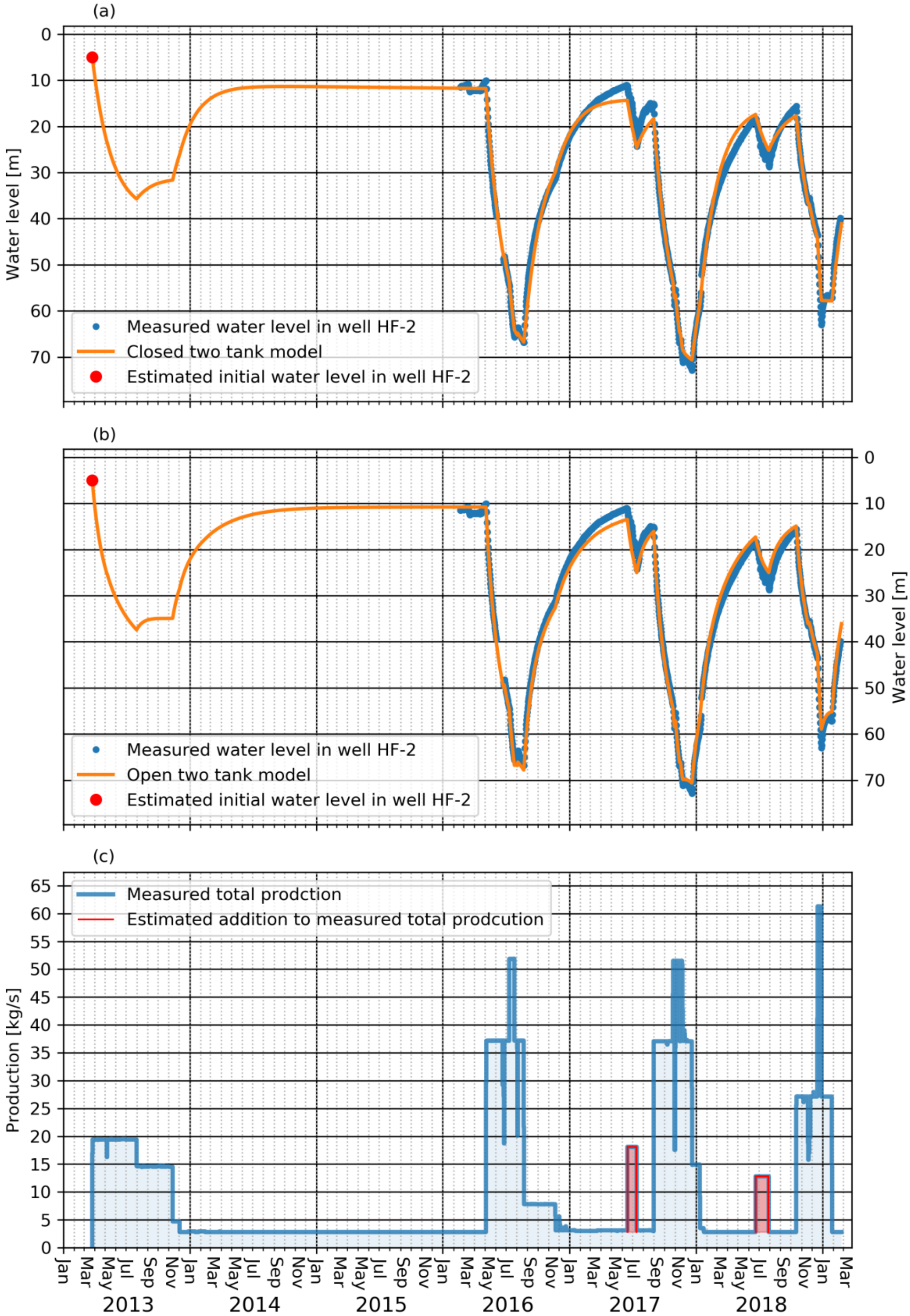

Figure 6: Figure (a) shows a water table calculated with a new, calibrated closed two-tank model compared to the measured water level together with the estimated starting water level. The same can be seen in Figure (b) a new, open two-tank model. Figure (c) shows the total processing all used in the calibration. Estimated auxiliary flow from the geothermal system due to air rated drilling of wells HF-4 and HF-5 is shown with a red color.

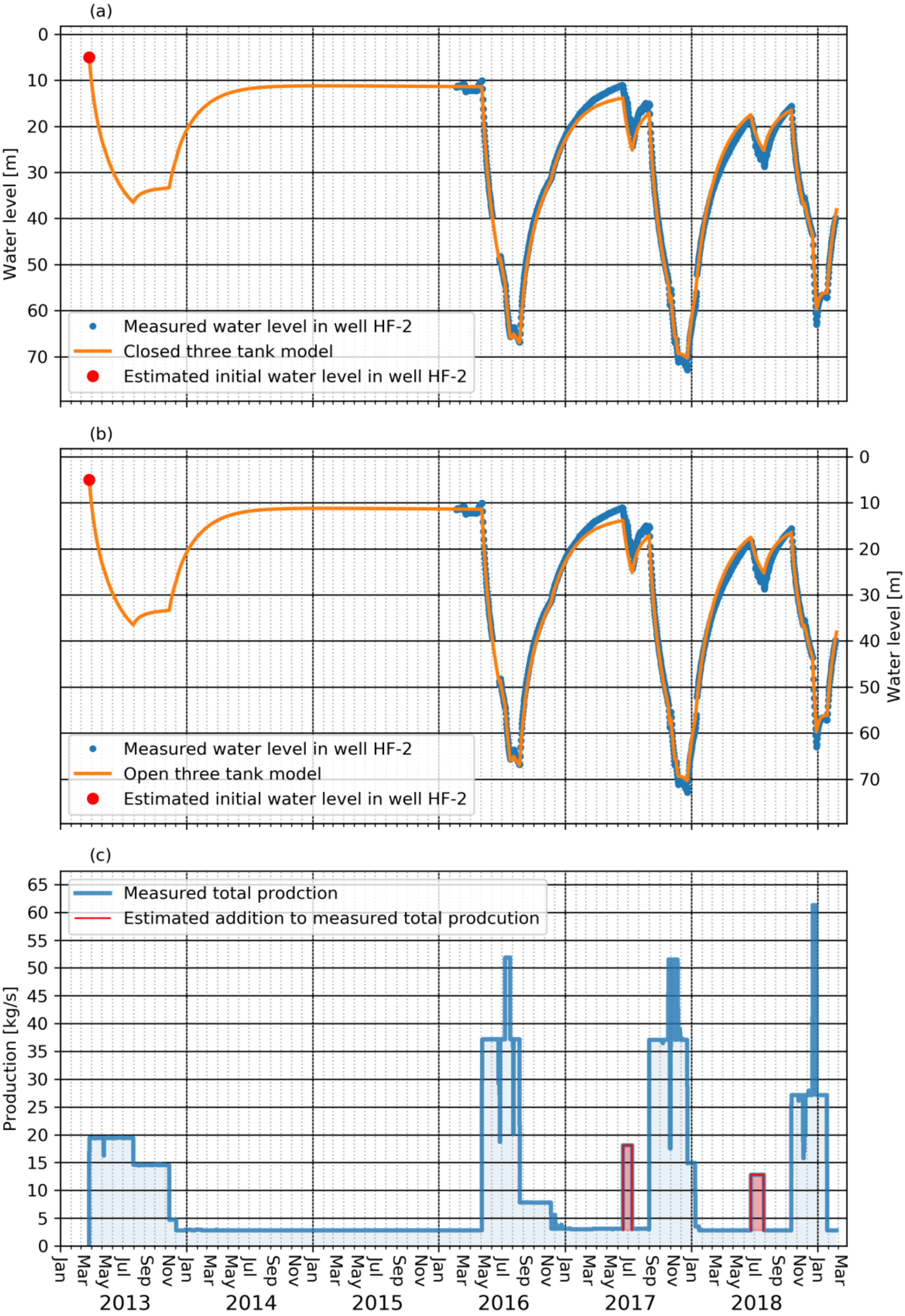

Figure 7: Figure (a) shows a water table calculated with a new, calibrated closed three-tank model compared to the measured water level together with the estimated starting water level. The same can be seen in Figure (b) a new, open three-tank model. Figure (c) shows the total processing all used in the calibration. Estimated auxiliary flow from the geothermal system due to air rated drilling of wells HF-4 and HF-5 is shown with a red color

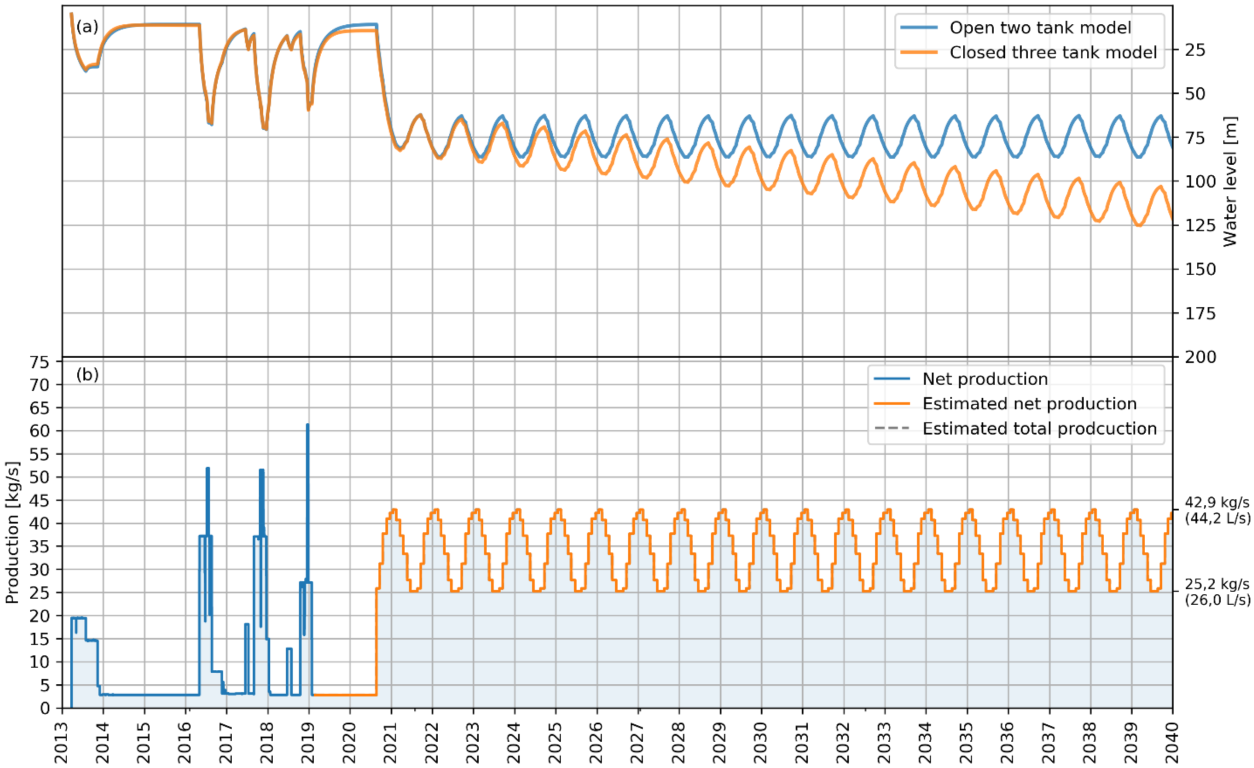

Figure 8: Water level prediction with closed and open model for 35 L / s average production (equivalent to 34 kg / s of 80 ° C hot water) and no reinjection. Estimated top and basic production are marked the right axis of the graph.

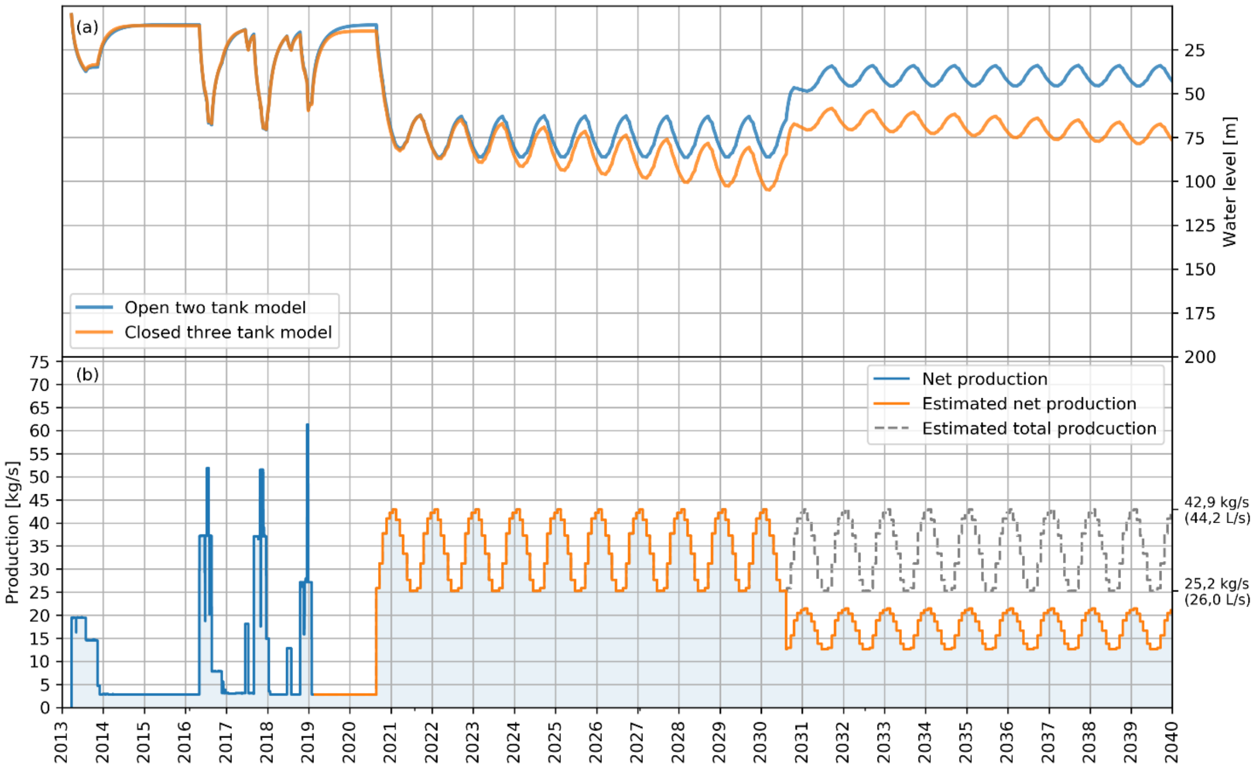

Figure 9: Water level prediction with closed and open model for 35 L / s average processing (equivalent to 34 kg / s of 80 ° C hot water) and a reinjection starting in the fall of 2030, or 10 years from the start of production. Estimated peak and basic production are marked on the right axis of the graph.

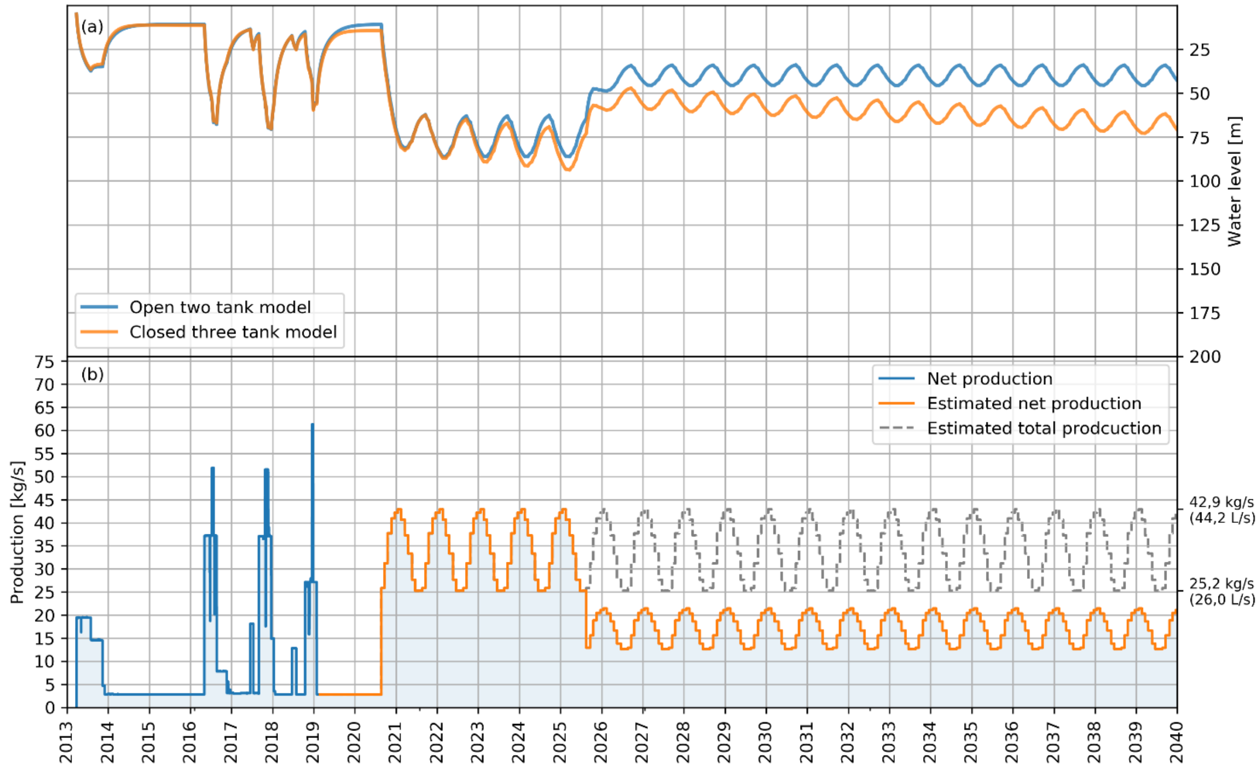

Figure 10: Water level prediction with closed and open model for 35 L / s average processing (equivalent to 34 kg / s of 80 ° C hot water) and a reinjection starting in the fall of 2025, or 5 years from the start of production. Estimated peak and basic production are marked on the right axis of the graph.

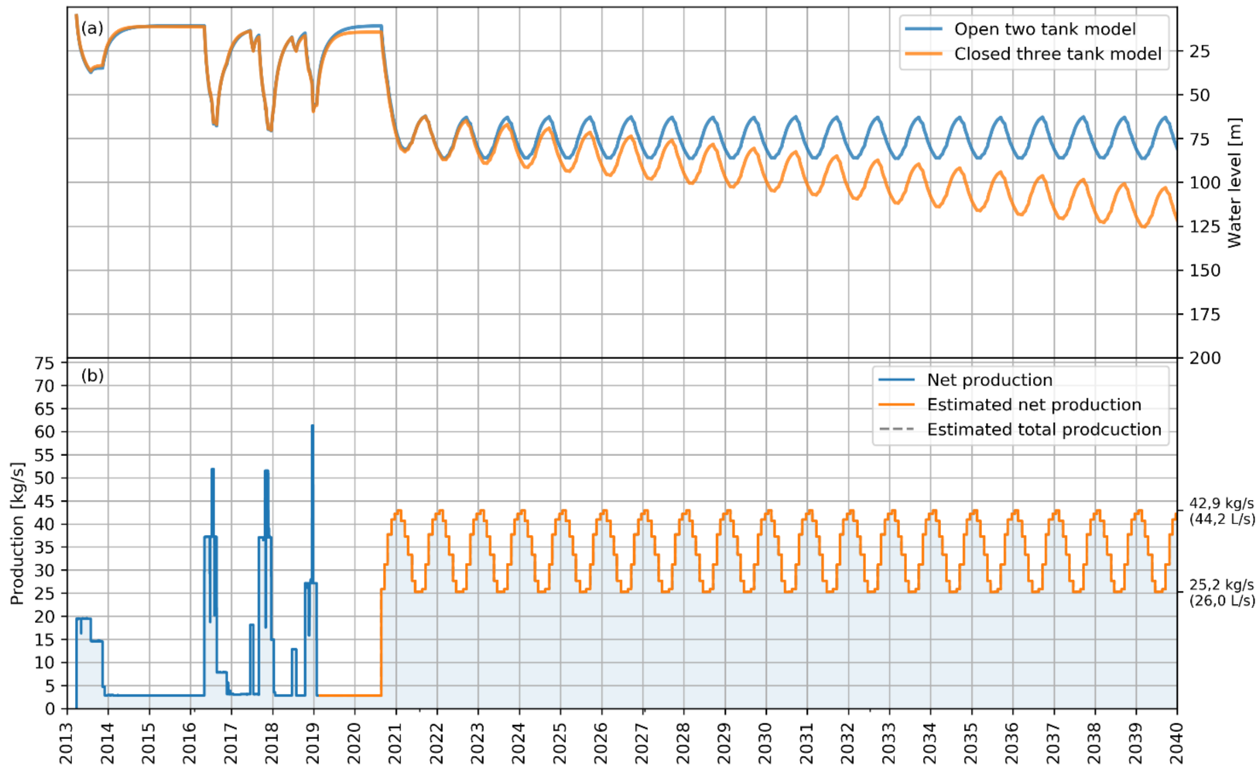

Figure 11: Water level prediction for closed and open model for 35 L / s average production (equivalent to 34 kg / s of 80 ° C hot water) and reinjection starting in the fall of 2020, or at the start of production. Estimated top and basic production is marked on the right axis of the graph.

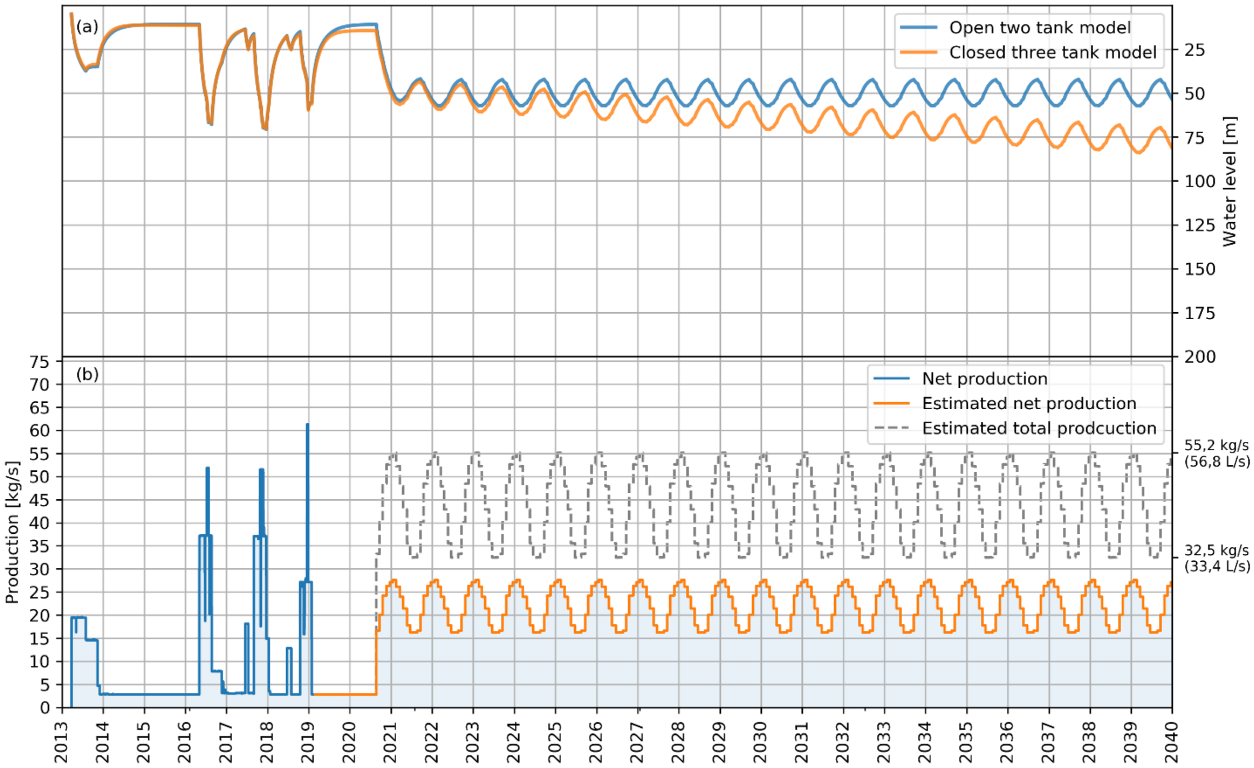

Figure 12: Water level prediction with closed and open model for 45 L /s average production (equivalent to 44 kg /s off 80 ° C hot water) and no reinjection. Estimated top and bottom are marked on the right axis of graph.

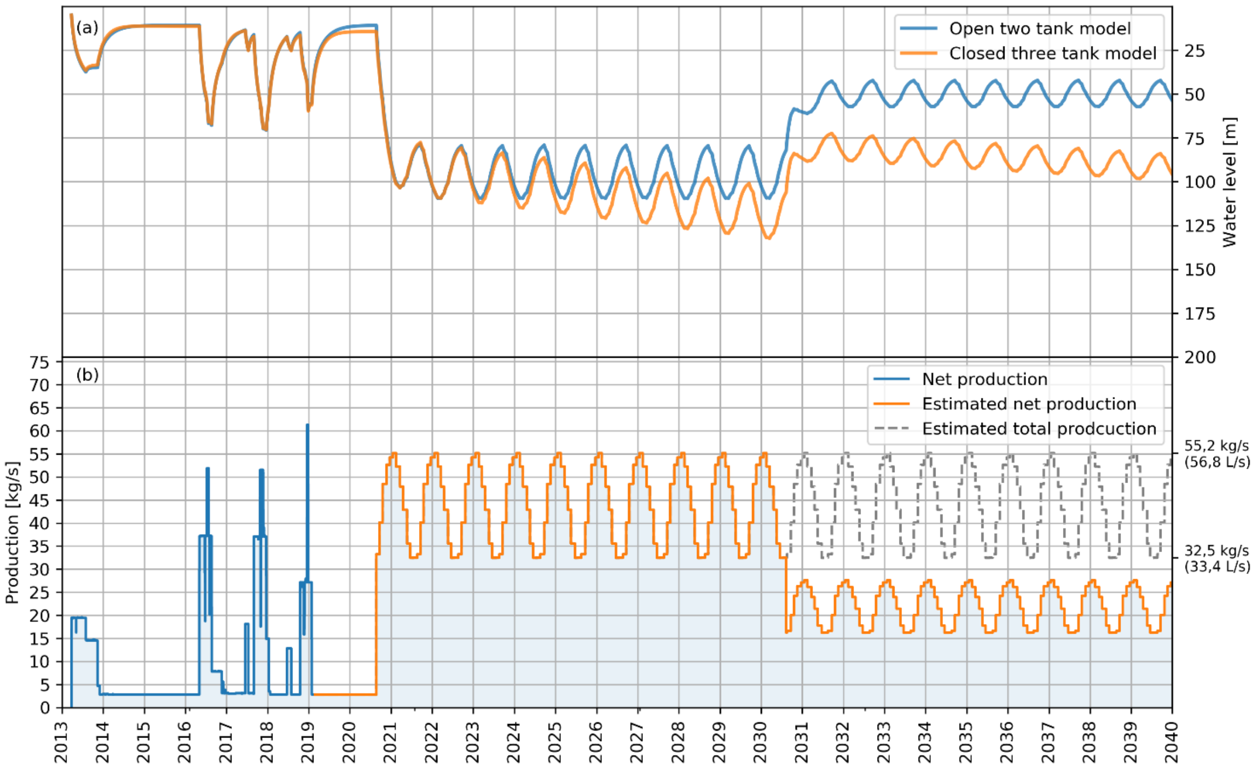

Figure 13: Water level prediction with closed and open model for 45 L / s average processing (equivalent to 44 kg / s off 80 ° C hot water) and a re-injection beginning in the fall of 2030, or 10 years from the start of processing. Estimated peak and basic processing are marked on the right axis of the processing graph.

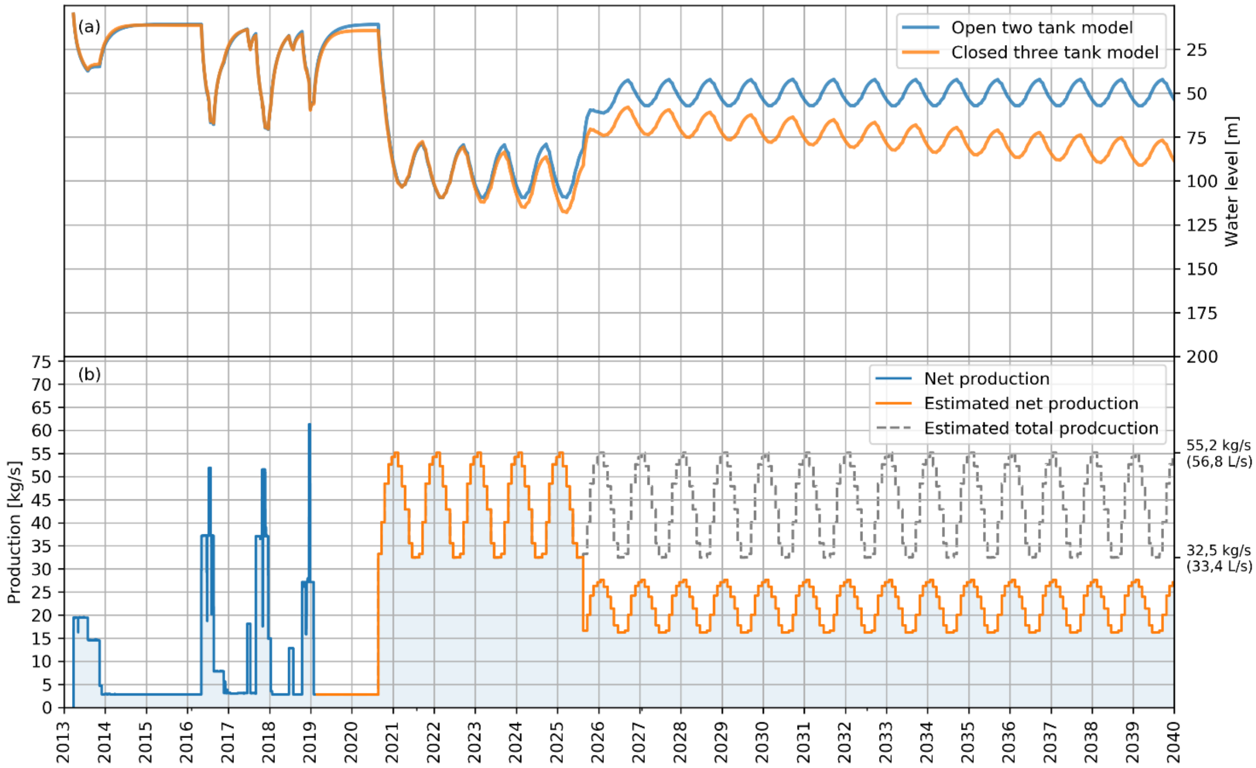

Figure 14: Water level prediction with closed and open model for 45 L /s average production (equivalent to 44 kg / s off 80 ° C hot water) and a reinjection starting in the fall of 2025, or 5 years from the start of production. Estimated peak and basic production are marked on the right axis of the graph.

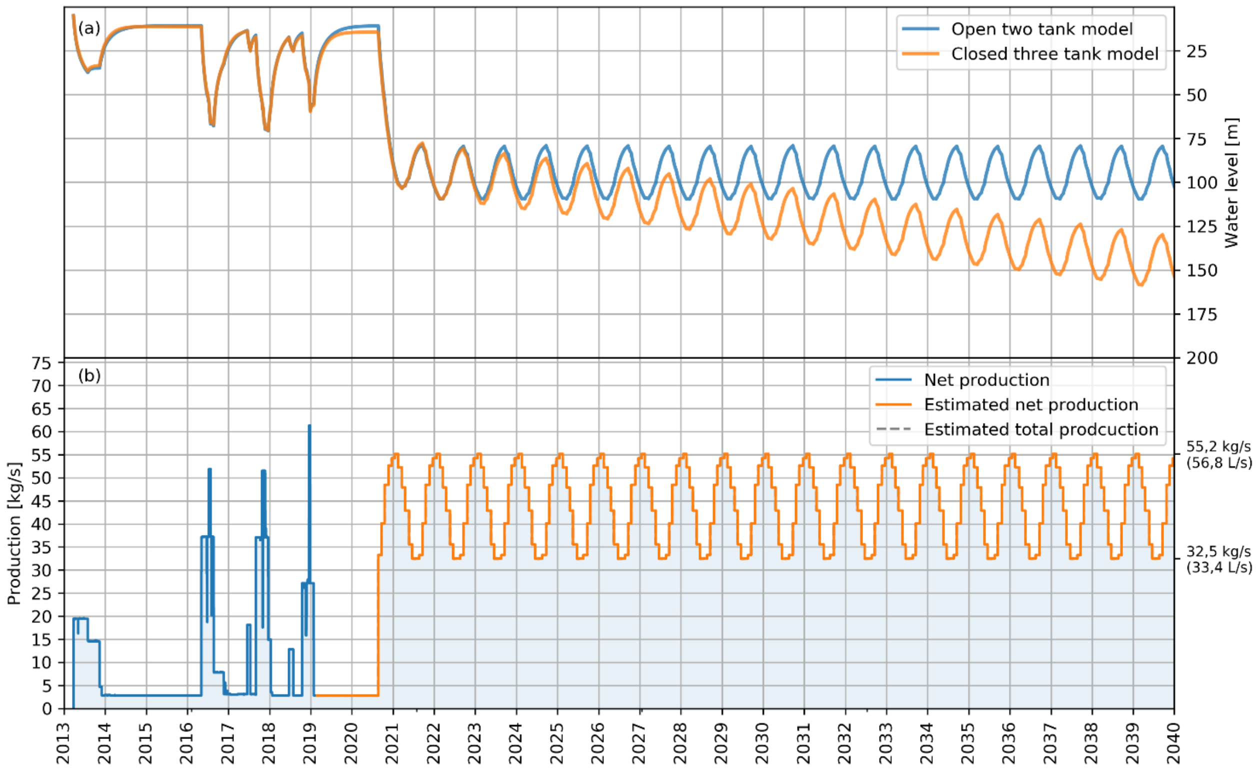

Figure 15: Water level prediction with closed and open model for 45 L / s average production (equivalent to 44 kg / s off 80 ° C hot water) and reinjection starting in the fall of 2020, or at the start of production. Estimated top and basic production are marked on the right axis of the graph.

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