Resource Model Calibration at Neal Hot Springs, Oregon, USA

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ABSTRACT

Neal Hot Springs is a robust low-temperature resource in the northern Basin and Range geologic province that currently supplies a 26 MW_e (net) binary power plant. Production of this field has been reliable and stable since the commissioning of this plant in 2012. Since acquiring the field in 2018, Ormat has collected an array of data to facilitate the understanding of the reservoir. Of importance is the quantification of an order-of-magnitude increase in injection capacity in one of the utilized injection wells (NHS-11). This evolution of permeability in the reservoir has been linked to a decrease in injection return times to the production field and a deflection in the predicted cooling trend of the system. This paper presents the conceptual resource model and an updated numerical model for Neal Hot Springs and serves a case study to highlight the advantages of iterative interdisciplinary workflow in a 3D modelling environment.

1. INTRODUCTION

The Neal Hot Springs (NHS) geothermal field in Malheur County, Oregon is owned and operated by Ormat. Chevron Minerals first discovered the resource during natural gas exploration drilling efforts in the late 1970's. Decades later in 2006, the field was leased by US Geothermal and drilling efforts commenced in 2008. A 26 MW_e (net) binary-cycle power plant was commissioned in 2012 and has been in operation ever since, with generation periodically exceeding 30 MW_e in the winter months (when the air-cooled condensers are the most efficient). Ormat obtained control for the project in 2018 with the acquisition of US Geothermal. Since that time, an array of new datasets (described further below) have been collected to help characterize the reservoir. Geologic and reservoir data have been assimilated into Leapfrog software to visualize and interpret them in a 3D environment. This visualization was used to update the numerical reservoir model, honoring newly gathered data for the field.

2. CONCEPTUAL RESOURCE MODEL

The structural environment and subsurface geology of the NHS geothermal system is detailed by the work of Edwards and Faulds (2012) and Edwards (2013). The subsurface geology of NHS and is comprised of a 1.3 to 1.6 km-thick sequence of Middle Miocene flood basalts that non-conformably overlies a Jurassic granitic/metamorphic basement (intersected at 2051 m in NHS-11). Overlying the flood basalts are 300 to 450 m of bimodal Middle Miocene volcanics and volcaniclastics, which are themselves covered by a similarly thick sequence of Late Miocene to Quaternary (3 to 0.8 Ma) volcanics.

NHS is situated within a region of elevated heat flow in eastern Oregon, attributed to an area of anomalously thin continental crust (Idaho National Laboratory, 2006; Eager et al., 2011). Elevated helium isotope values of 2.25 Rc/Ra from NHS are at the higher-end of the range that are present in thermal fluids from non-magmatic/non-volcanic systems in the Basin and Range geologic province (e.g., Kennedy and van Soest, 2006). These elevated values are explained by the percolation of mantle-derived volatiles along deeply-penetrating structures in a region of elevated crustal extension; there is no perceived magmatic heat or volatile source at NHS.

The dominant local structural control of the system is interpreted to be an extensional left step (and potential relay ramp) between the SSE-striking, west-dipping Neal Fault and Sugarloaf Butte Fault. The Neal Fault and an associated splay are the main permeability features intersected by all of the production wells (NHS-1, -2, -5, and -8) and three of four utilized injection wells (NHS-4, -11, and -13). The controls of permeability in the NHS-10 are not as well understood but may be related to a west-dipping structure that represents the southern extension of the Sugarloaf Butte Fault.

Surface manifestations at NHS include extinct hot springs, hard opaline sinter terrace, fossil silicified alluvial sands and outcrops of the silicified and brecciated Neal Hot Springs fault zone.

The primary reservoir liquid at NHS is a 140-150°C, neutral pH, Na-HCO_3-Cl fluid with a low TDS of 800-900 mg/kg and a low dissolved NCG concentration of <0.1 wt.%. The low chloride (~160 ppm) chemistry of the fluid likely relates to the equilibration of deeply-circulating meteoric water with dominantly basaltic host rock (i.e., rock with a low proportion of Cl in associated volcanic glass). Equally low Cl concentrations are found in other basalt-hosted geothermal systems in widely ranging geologic environments, e.g., Beowawe in Nevada and the fresh-water dominated geothermal systems of the Neo-Volcanic Zone in Iceland (e.g., Nesjavellir, Krafla, and Hellisheidi; Stefánsson et al., 2011).

Upflow of the geothermal system is concentrated along the Neal Hot Spring Fault within the step-over zone to the Sugar Loaf Butte Fault. Outflow characteristics of the system are not fully characterized, however, it is apparent that some outflow is channeled along the NW-striking Cottonwood Creek Fault as evidenced by the presence of warm artesian water wells at a farm that is 1.5 km to the west of the NHS power plant.
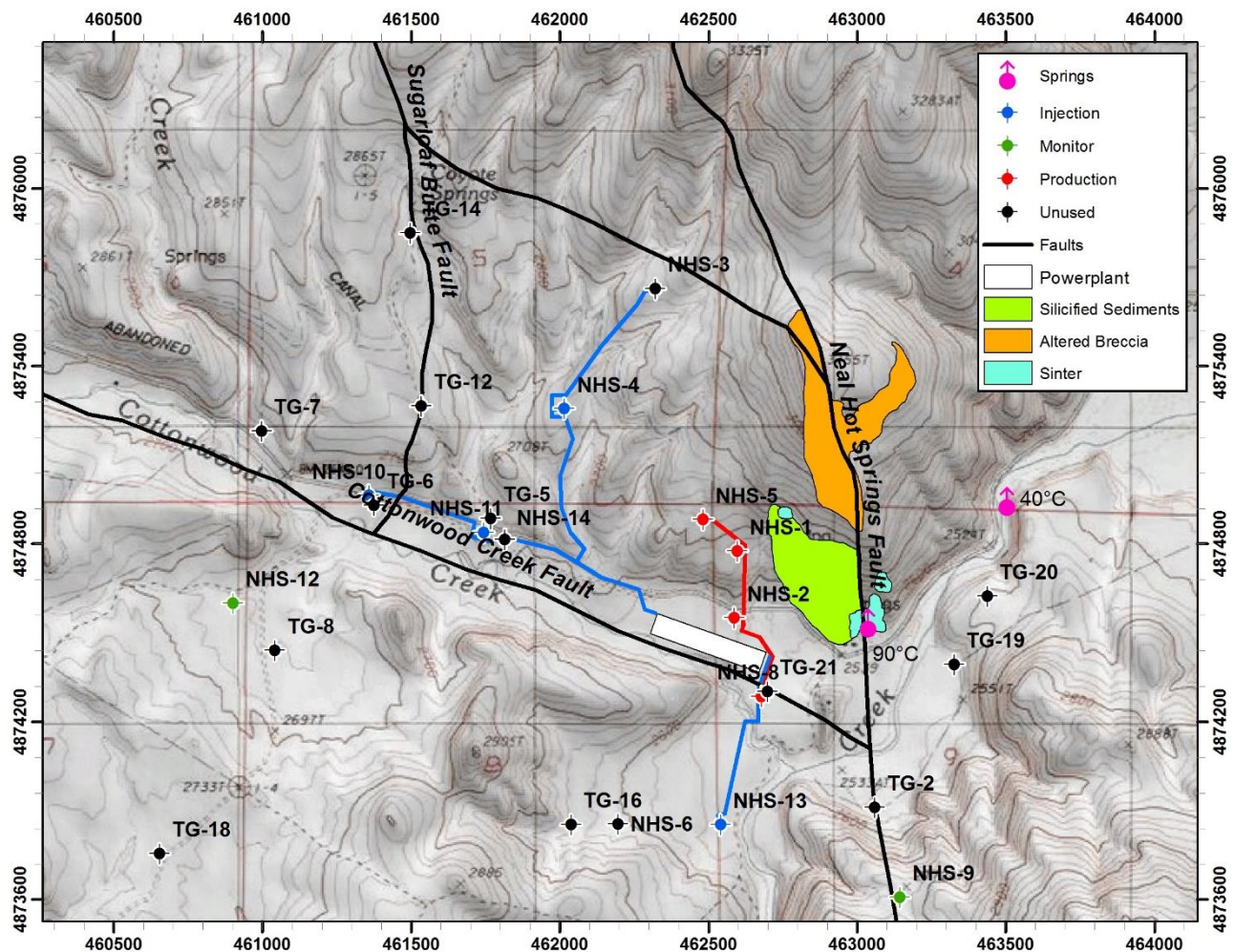
Figure 1. Neal Hot Springs summary map. Faults and geological features adapted from Edwards (2013). Coordinates in WGS84 UTM Zone 11 north.

3. NUMERICAL MODEL

3.1 Previous Numerical Model

The initial numerical reservoir model for Neal Hot Springs was developed by Geothermal Science, Inc. using the TETRAD reservoir simulator (Vinsome and Shook, 1993) This model was calibrated to initial state temperatures, long-term flow testing, and a tracer test performed in 2013 (Holt, 2018). The model closely matched the stable temperatures which were observed at startup and the gradual, acceptable decline in reservoir pressures. The geologic conceptual model for this numerical model was integrated with the reservoir with a close collaboration with the geoscience team at US Geothermal, Inc.

One of the important aspects of the geologic and numerical models was the reliance on very deep feedzones in injectors NHS-4 and NHS-13, which allowed for reinjection with sufficient pressure support but no initial impact on production temperatures. There is approximately 2000 meters total separation between injection and production zones, and 1300 meters vertical separation.

After plant startup, cooling was immediately observed due to injection in shallow injector NHS-3, a well with only around 1000 meters separation from production and no vertical separation. Following a tracer test to confirm the shallow injectors as the source of cooling, fluid was diverted from the shallow injectors NHS-3 and NHS-6 to deep injectors NHS-4 and NHS-13. This reconfiguration was very successful, and total field temperature changed less than 0.5 °F between 2013 and 2017.

3.2 New Reservoir Data

Following the Ormat acquisition of US Geothermal in 2018, additional reservoir data were gathered, which were used to update the numerical model calibration in conjunction with the refinement of the 3D geologic conceptual model. These data include:

- A tracer test performed in 2018 under the established injection and production configuration
- Downhole injection surveys on all injection wells with pressure, temperature, and spinner
- Direct ultrasonic measurements of flow rate at NHS-10 and NHS-11 to identify individual well flow rates
- Continued monitoring of reservoir temperature and pressure. Beginning in 2017, a minor temperature decline trend was observed (1.1 °F/year) that indicated the onset of injection related cooling occurring earlier than predicted by the numerical model.
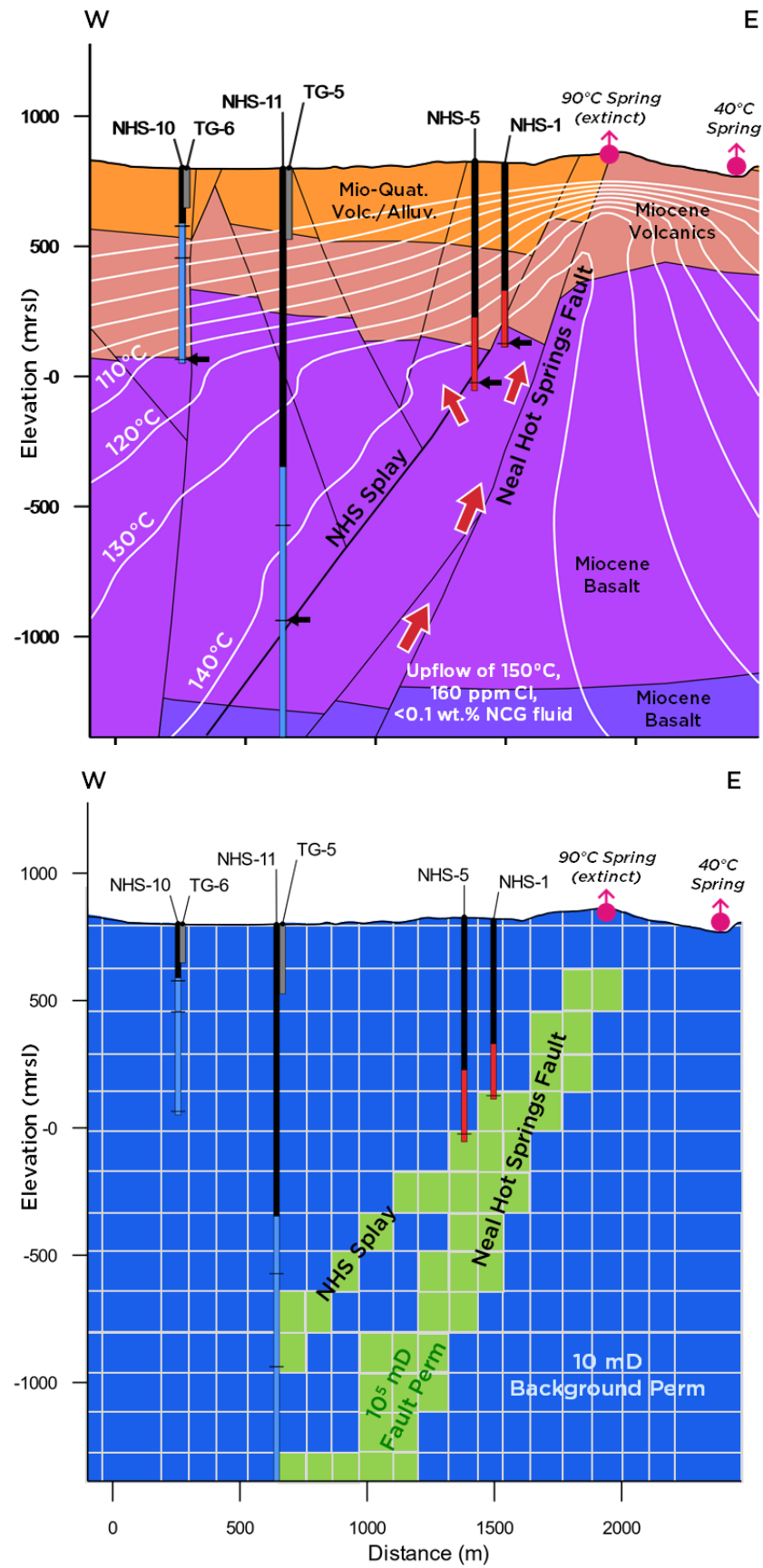
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Figure 2. (Upper) Cross-section through 3D geologic model with conceptual model annotations. Small black arrows denote main feed zones in the displayed wells. Westward outflow channeled along Cottonwood Creek Fault. (Lower) Cross-section of permeability structure for updated NHS numerical model.

Notable among the new field data was the development of new injection zones in NHS-11 and NHS-13. Correspondingly, high tracer returns were recovered from NHS-11 and moderate returns were recovered from NHS-13 (Figure 3). The development of these zones is hypothesized to be the source of the minor temperature decline at Neal Hot Springs.

NHS-11 was originally known to be a very low permeability well, injecting at rates less than 100 GPM. NHS-10 injected around 1000 GPM but shared a pipeline and flow meter with NHS-11. Between field startup and 2018, NHS-11 experienced a significant increase in permeability, likely due to long-term injection at low rates. Ultrasonic flow rate measurements recorded 1000 GPM injection at NHS-11, a tenfold increase in injection rate since plant startup. Utilizing a dowhole spinner survey, the injection zone was determined to be at a depth of 5700 feet measured depth, consistent with the downward extension of a splay in the Neal fault.

NHS-13 has been injected at rates around 4500 GPM since the reconfiguration in 2013. During drilling and testing, very low permeability was encountered until the final well deepening, when a major injection was encountered around 6950 feet measured depth. This injection zone is consistent with the intersection with the Neal Fault in the 3D geologic conceptual model. A downhole injection survey performed in 2018 identified a shallower injection zone accepting significant fluid at 5000 feet measured depth, at a zone that may intersect the Neal fault. During the 2018 survey the injection rate was curtailed from the total 4500 GPM to 2000 GPM at the discretion of the wireline operator. Using the 2018 downhole survey, it is expected that the shallow zone is capable of accepting nearly all the injection fluid at normal operating injection pressure. A subsequent injection survey is planned at full operating pressures to identify the distribution of injection zones downhole in NHS-13.

Both the 1000 GPM injection into NHS-11 and the existence of a major shallow injection zone at NHS-13 were significant changes to the reservoir configuration. This change occurred solely due to long term injection into those wells. This likely temperature-controlled stimulation has been documented in geothermal wells in a volcanic setting and a wide-range of reservoir temperatures in New Zealand, Iceland, and Japan (Grant et. al., 2013) and at the Southern Negros Geothermal Field, Philippines (Aqui and Zarrouk, 2011). It has also been observed in fault-hosted fields with similar geologic and temperature settings to Neal. For example, it has occurred under concerted efforts to utilize high-pressure injection at Desert Peak, Nevada (Zemach et. al., 2017) and also under normal operations on low-injectivity, low-pressure injectors at Blue Mountain, Nevada (Swyer et. al., 2016). At Raft River, a field with temperatures similar to Neal Hot Springs, high pressure stimulation of RRG-9 successfully increased the injectivity index by of factor of 2 and subsequent long-term injection has increased the injectivity index by an order of magnitude (Bradford 2018, Internal Data).

The mechanism at Southern Negros was hypothesized to be rock dissolution resulting in an increase in permeability, whereas at Neal Hot Springs the mechanism is likely a thermal effect. At Desert Peak, the stimulation of low-permeability zones was a favorable outcome to increase injection capacity in an area with less risk of cooling. At Neal Hot Springs, these new zones are hypothesized to contribute to the minor change in temperature decline.
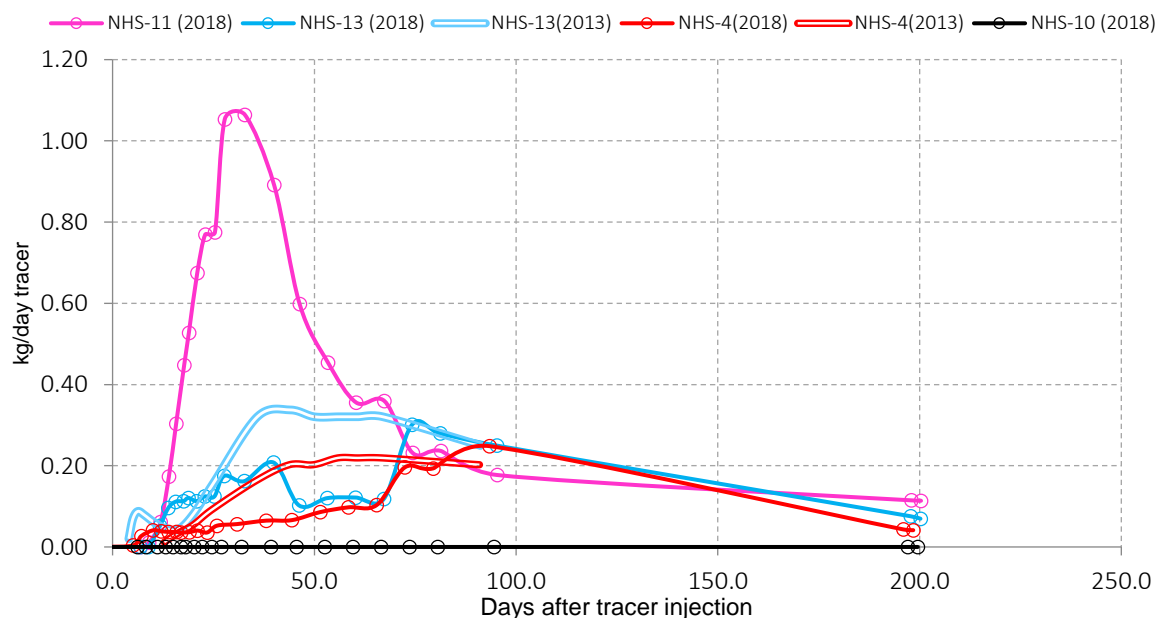

Figure 3. Tracer returns in NHS-2 from tests conducted in 2013 and 2018.

3.3 Numerical Model Recalibration

The primary goal of the updated numerical model calibration was to identify the source of the minor cooling and to guide field optimization to maximize generation and with acceptable long term temperature declines. Utilizing the updated field data and the 3D geologic conceptual model, the development of stimulated shallow injection zones was identified as the likely source of minor cooling.

Figure 2 shows the updated numerical model permeability structure alongside the 3D geologic model. One notable change from previous models is production partially from a splay from the Neal Fault. This splay is also the injection zone in NHS-11, which

was originally impermeable at depth but was stimulated over several years of injection to exhibit moderate permeability and accept 1000 GPM injection. High tracer returns from NHS-11 to production indicate that this is a direct pathway along the splay fault. Numerical modeling indicates that NHS-11 is contributing to cooling, and the injection configuration is being reconsidered in light of identifying this stimulated zone.

Figure 4 shows a comparison of total field temperature between the 2018 model and the 2019 recalibration. With the benefit of the additional reservoir data, multiple subsurface datasets, and an iterative resource evaluation using a 3D geologic conceptual model, the match to total field temperature has been improved . The numerical model recalibration corroborates the hypothesis that the development of shallow feedzones in NHS-13 and NHS-11 is the source of minor cooling. Despite these reservoir changes, Neal Hot Springs remains an extremely robust resource, with the opportunity to further optimize by adjusting the injection allocation to account for changes in injection zones.

4. CONCLUSION

Neal Hot Springs is a robust low-temperature, fault-controlled geothermal resource that has been stably producing electricity from a 26 MW$_e$ air-cooled binary plant since 2012. Long term injection into NHS-11 has stimulated the permeability of the feed zone at 5700 ft, which correlated with the down-dip trace of the splay of the Neal Hot Springs Fault (the main production structure at NHS). Stimulation of this feed zone has resulted in an increase in the rate of injection returns to the production field, and there has been a corresponding increase in the cooling trend of the field; it is important to note that this cooling trend of 1.1 °F/year is still considered small in comparison with other developed Basin and Range geothermal fields. This case study emphasizes the benefit of cross-disciplinary data interrogation in a 3D model environment.
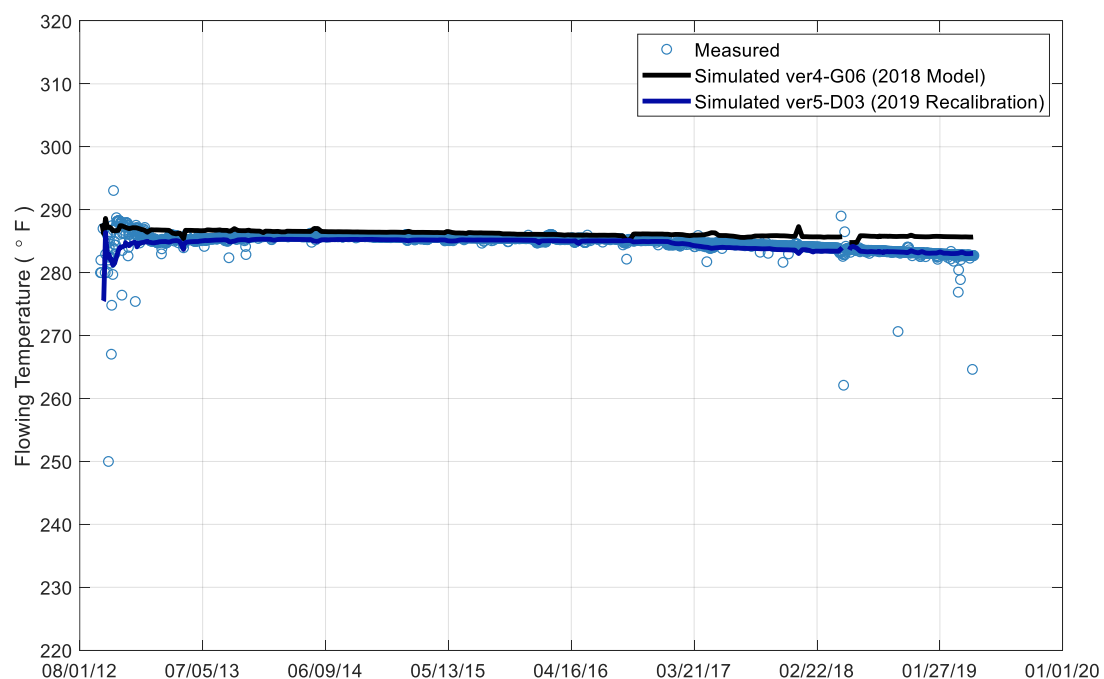

Figure 4: Total Field Measured and Simulated Temperature

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