Technical Evaluation of the Report titled – “Characterization of Brackish Groundwater Resources in Victoria County” by S. Young and R. Kushnereit, Intera Inc.

By

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Contents

Executive Summary

The purpose of this document is to provide a detailed evaluation of a study conducted by Intera Inc. titled - "*Characterization of Brackish Groundwater Resources in Victoria County*" authored by Dr. Steve Young and Mr. Ross Kushnereit. The document presents delineation of brackish groundwater zones and certain details of a groundwater flow model developed to study fresh and saline groundwater formations within Victoria County Groundwater Conservation District (VCGCD). The model is then used to evaluate drawdowns associated with pumping in saline groundwater formations within VCGCD. The methods adopted are generally reasonable for the purposes of developing groundwater policies and rules related to the management of groundwater resources within these aquifer formations. However, the developed model is an idealized representation of the aquifer system and appears to make certain assumptions that do not err on the side of conservatism. As written, the report has certain weaknesses, which can be addressed to improve its usefulness and accessibility to a broad range of stakeholders. Major recommendations in this regard include – 1) Cleaning up the report so Figure titles and captions match the charts and figures presented; 2) Highlighting major assumptions within the developed modeling framework and discussing them in the context of developing saline groundwater policies; 3) Correcting fundamental flaws in presentation, identified as part of this evaluation; 4) Providing necessary geostatistical information used to develop salinity maps; 5) Recognizing all sources of uncertainties associated with studying brackish groundwater formations and conducting a more comprehensive sensitivity analysis that can guide further data collection activities. A detailed review of the report is presented to help authors address the above-mentioned recommendations.

Introduction – Purpose of the Study

This report presents a technical evaluation of a modeling-based study conducted by Intera Inc. to characterize brackish groundwater resources within Victoria County Groundwater Conservation District (VCGCD). The modeling study is documented in a report titled – "*Characterization of Brackish Groundwater Resources in Victoria County*" (referred to as model report or report from hereon for brevity). The study was conducted by Intera Inc. and authored by Dr. Steve Young and Mr. Ross Kushnereit. The report is dated December 2018.

The technical review provided here is based on the abovementioned report alone and does not include an evaluation of associated modeling files. Proper documentation of modeling results is important not only to provide information about the modeling effort to a broad range of stakeholders but also to evaluate assumptions and reasonableness associated with any policy formulations that are developed using the modeling results. The present modeling study aims to support the policies and rules of the VCGCD with regards to the production of brackish and saline groundwater resources.

The importance of proper documentation and dissemination of groundwater modeling results has been recognized in the groundwater industry. Guidelines for effective model calibration (e.g., Hill 2000), as well as presentation and documentation of final reports, have been standardized and documented in the literature (Gass and Thompson, 1980; ASTM, 2013). These guidelines, in conjunction with other literature, was used here as the basis for the evaluation of the groundwater modeling report. The evaluation focused on whether pertinent information necessary for model development such as the underlying conceptual model, model architecture (e.g., discretization, boundary conditions), input parameters, calibration, sensitivity analysis, discussion of assumptions, and other model limitations are properly discussed and documented within the report. The model evaluation is carried out in a systematic manner covering each section of the report. The findings of the model evaluation are presented next.

Model Evaluation

Modeling Goals and Objectives:

Groundwater models are developed to address specific questions. Understanding the goals and objectives of the model is, therefore, an important first step in model evaluation. The objectives of the study are stated in the report as:

- Improve the characterization of brackish groundwater in Victoria County,
- Develop and apply a methodology for predicting impacts to groundwater resources caused by pumping brackish groundwater, and
- Investigate management goals and criteria that are suitable for VCGCD to use for developing rules to regulate the development of brackish groundwater.

Model Domain:

The groundwater model (VCGFM) domain extends approximately 50 miles around Victoria County. As the focus is on VCGCD, the extension of the model over a larger domain to avoid boundary effects appears reasonable. It is, however, unclear if the extension was to a natural boundary or was arbitrarily defined. If latter, a justification for doing so would be useful.

The VCGFM includes fifteen model layers to represent nine of the formations that comprise the Gulf Coast Aquifer System. The vertical extent of the model domain is also reasonable for the study. However, it is unclear how the 15 model layers delineated within the 9 formations. Clarification would be appropriate.

The grid size or the range of grid sizes used in the study appears reasonable.

Characterization of the Gulf Coast Aquifer System Stratigraphy, Lithology, and Water Quality

The report claims that the lithology of the aquifer was based on 251 geophysical logs of which 97 were from previous TWDB brackish study and 154 were from this study. Where were the new logs obtained? Did the logs improve the coverage in areas with previous data gaps? Did the logs provide better coverage at shallower depths? What QA/QC protocols were used to ensure the reasonableness of these logs?

Some discussion on these new logs would be useful, especially highlighting similarities and differences from other logs they were combined with. Figure 2-3 shows the locations of new and old logs and can be referenced on Page 4 to make it easier for the reader to see where the logs were added. However, the Figure does not provide additional details such as the logging interval and geophysical methods used.

The definition of salinity used in the study is reasonable. The definition of brackish water - TDS > 1000 mg/L but less than 10,000 mg/L is relegated to the footnote and easy to miss. Perhaps it can be moved to the main text as the term brackish groundwater is used widely in Texas and with different definitions.

The authors claim that the definition of TDS is consistent with both the definition of the Texas Administrative Code (TCEQ website) and the Texas Water Development Board (TWDB) groundwater database. The definitions provided in the report (pages 5 and 6) are not the same. The TCEQ definition includes all inorganic salts (not just of the major ions) and some organic material. The TWDB definition is limited to Major ions and silica and does not include the salts of infrequent inorganic ions and organic compounds. While the two definitions may yield TDS values that are close to one another (when infrequent and organic salts are low) they are not the same definition wise. <u>The authors must clarify which definition was adopted in this study.</u> It is also unclear as to why a TDS value based on the summation of major ions was adopted over direct gravimetric measurements of TDS. Presentation of STORET codes for the TDS data used will further clarify the discussion.

Where were the TDS values used with the mean R_o obtained from? Please clarify. There are significantly more EC values available (e.g., in TWDB database) as they are easy to measure and it is common to convert EC to TDS values. Is to be assumed that these EC measurements were not converted to TDS and used in Figure 2-10? (A clarification would be useful). EC based TDS values can provide additional validation to the TDS calculations here if not used in the calculations. Figure 2-10 shows a consistent over-estimation of TDS by the regression line at higher R_o mean levels (shallow depths). In a similar vein, the regression model under-estimates TDS at higher levels. The limitation of the model to properly model the salinity extremes must be acknowledged as a limitation along with the fact that the model is only explaining about 60% of the observed variance in the data. The addition of a regression equation would also be useful in addition to R^2. A weighted regression or log-transformed regression perhaps would have been better choices to pull the extreme values in rather than the untransformed regression adopted here.

The R_{ws} calculation is based on regional-scale values for cementation exponent and the conversion factor of EC to TDS ratio (0.57). It would have been better had these values been recalibrated for the model domain. The regional values are likely to be conditioned by measurements along the coast more so than inland high TDS values which are of greater relevance in VCGCD.

Additional details with regards to contouring of the salinity zones must be provided. Are the contours in this report the same as the ones presented in the previous regional study (Young and Others, 2016)? If this is the case, the new logs would not be used in the study and their purpose is unclear. If the contours were redrawn using all the logs in this study, then additional details with regards to the geostatistical models used (variograms) must be presented here. Assumptions and choices made with regards to contouring play a significant role in the delineation of salinity zones. Not providing necessary information hampers the scientific reproducibility of the report. This information is particularly important if the delineation of salinity zones are to be contested.

This same comment also holds for sand percentages maps shown in the report as this information is vital for mapping of the salinity zones.

The Titles of the Figures 2-13 – 2-20 must be consistent with the legend presented in Figure 2-12. The word Dip is used in Figure 2-12 but abbreviated to D in the titles of the Figures. Similarly, D-A, D-B, and D-C are used for strikes but are not labeled so in Figure 2-12.

Figure captions for Figure 2-13 – 2-20 refer to Figure 2-9. They should be referring to Figure 2-12 instead?

As the logs are not marked in Figure 2-12, it is best to add a statement to the Figure Captions 2-13 – 2-20 that the logs are arranged sequentially moving along a specific direction on the transect. Or mark the lines in Figure 2-12 as A-B, C-D, etc. (which appears to be the intent with the labeling but is not shown properly).

There is no legend provided for colors used in Figures 2-21 through 2-25. The use of red lines for contours is difficult to read. I recommend that the color (filled contours) be removed to make it easier to interpret the Figure or add an appropriate legend for the filled contours. While some colors can be inferred from contours, not all can be.

What is the reference location (origin) of the downdip in Figures 2-27 through 2-30? Please specify with the Figure and identify it in Figure 2-26.

What is the distance of the buffer drawn in Figure 2-26? Please specify and discuss why this buffer was chosen?

Figures 2-27 through 2-30 are confusing to interpret. Recommend adding the names of the stratigraphic layers within the Figure rather than use different colored lines to show the upper and lower boundaries. As the same dashed line is used, the colors are difficult to interpret due to the size of the chart.

I recommend that all charts be placed closer to where they are discussed rather than all in one location to improve the readability of the report.

Characterization of the Hydraulic Properties of the Aquifer System

The use of specific capacity tests for estimating hydraulic conductivity is certainly pragmatic but perhaps is not the best method to obtain K values. In addition, there are very few tests in Victoria County for the Upper Goliad formation and most tests are in neighboring De Witt and Goliad counties. The representativeness of these tests which are all likely in the unconfined portions of the formation to areas within VCGCD where the upper Goliad may be confined must be discussed and perhaps listed as a possible limitation of this study. Based on Figures 3-4 through 3-9, the same comment holds for other deeper (older) formations which exist as confined formations within VCGCD but specific capacity test analysis appears to be mostly to be in outcrop (unconfined) portions of the formation. Please clarify.

On page 37, Out of the 14 plots of hydraulic conductivity versus screen size, 13 confirm the expected result of decreasing hydraulic conductivity values with increasing screen size for both the arithmetic and geometric mean. Please explain why one group did not confirm to this expected result and whether those values not confirming to the expected result were used in the study.

The scaling of hydraulic conductivity-sand percent relationships for formations older than lower Goliad, based on the relationship in lower Goliad is a major assumption in this study. While the pragmatism of such scaling can be recognized, it cannot be justified on hydrogeological grounds. A better approach would be to scale the "permeability" (an intrinsic geological property) based on sand percentages but use the properties of the fluid (density and viscosity) that is consistent with the solution chemistry in these formations. In this manner at least the fluid part of the K is more descriptive of the formation.

Comparison of specific capacity based K and pumping tests based K is a good one. However, the limitation of whether these tests are representative of aquifer conditions within VCGCD remains.

Figure 3-14 is mislabeled. It shows specific storage but the caption talks about hydraulic conductivity.

Consideration of depth variation of porosity and specific storage is also good. However, the regression line presented in Figure 3-14 shows a rather poor fit with likely heteroskedastic error structure (variance increasing with depth). Please provide the equation and R^2 on the graph for proper interpretation. A weighted or log-transformed regression would be more appropriate in this case as well.

Figure 3-15 is mislabeled. The caption refers to specific storage but plots porosity.

Development and Application of the Groundwater Flow Model for the Victoria County

Construction of Groundwater Flow Model

The use of groundwater flow simulator MODFLOW which does not explicitly consider density variations or mixing effects of fresh and saline water is perhaps the biggest limitation of this study. The use of this simulator must be justified and the limitations arising from using a freshwater simulator in a variable density flow system must be addressed to place the modeling results in proper context.

The modeling study essentially ignores the variable density regime in the study area and essentially treats it as essentially a system of uniform water density. The hydraulic heads in the freshwater and saline zones are not the same due to density differences and, at a minimum, it might be best to convert them all to "pressure" by correctly compensating for differing densities. At a very minimum, the assumption of constant density used in representing heads must be explicitly acknowledged.

The model does not include key processes such as saltwater upconing and dispersion of brackish water due to pumping. For higher production rates these factors may be important. Also, many deeper wells tend to be partially penetrated to minimize the costs of construction of such wells. This aspect is not included in the model and must be clarified.

The temperature correction presented in Equations 4-1 and 4-2 assume linear (continuous) change while the model layers are discretized vertically. What values were used to represent hydraulic conductivity? - Was the K averaged over the depth of the vertical layer? Please clarify

Recommend using ft/d or ft/day instead of ft/dy in Table 4-1 and be consistent elsewhere in the report.

Vertical hydraulic conductivity is clearly a difficult parameter to obtain but nonetheless an important parameter for modeling mixing between brackish and freshwater formations. The use of harmonic mean of sand and clay permeabilities as a representation of Kv is a practical choice. The authors are essentially stating that horizontal hydraulic conductivity is primarily driven by interconnected sands but the vertical hydraulic conductivity is affected by both sands and clays in the formation (i.e., clays impede the vertical movement of water to a greater degree than horizontal movement). As fine and coarse grains are being treated separately, the choice of reducing the permeability of sands by a factor of 10 makes little sense and is simply an arbitrary choice. Please justify this choice with a suitable non self-citation or reference (i.e., something other than - it was used in LCRA model which was developed by the same author/group or any other study carried by the same author. Self-citation essentially implies justifying this hypothesis on the grounds that the same hypothesis being made elsewhere by the same authors/group).

As the model is being used to delineate brackish groundwater zones with conceivably higher production rates, a reduced vertical hydraulic conductivity value would render the model less conservative (i.e., allows for greater pumping without causing upconing or mixing of saline water with freshwater. These effects are not explicitly modeled here and implicitly controlled by vertical hydraulic conductivity).

The delineation of brackish zones within each formation is another very critical component of any brackish groundwater study. Unfortunately, the report falls short in explaining the geostatistical methods that were used in delineation of these zones once again referring to self-citation of procedures in another report by the author. It is recommended that the geostatistical models (variograms) used, their cross-validation be presented here. In addition, kriging also allows the creation of error maps which will be very helpful in delineating uncertainty associated with the delineation of brackish groundwater zones and its spatial characteristics. As mentioned previously, the delineation of brackish zones over regional-scales to understand the extent of brackish groundwater availability is of different scope than local enactment of policies and production rules which allocate these resources to landowners.

It appears the use of porosity (specific storage?) is simply for estimation of saline groundwater volumes. As the developed model is "Steady State" this information is not explicitly included in the modeling that is performed. A clarification here would be helpful.

Do numbers in Table 4-2 and 4-3 represent total groundwater volumes (saturated thickness multiplied by porosity) or an estimate of extractable groundwater volume (saturated thickness multiplied by storage coefficient). Please clarify. If the estimates are based on porosity then a statement indicating that not all of this volume can be extracted would be beneficial to help place these numbers in proper context.

Please recheck the total for Freshwater in Table 4-2. I believe the freshwater in Beaumont formation is incorrectly presented as 1 (1000 ac-ft) instead of 8590 (1000 ac-ft). As written the column total should be 232079 instead of 240669 (1000 ac-ft) and the row total should be 1 (1000 ac-ft). Numbers in other columns appear to match with +/- 1 (1000 ac-ft) representing roundoff errors.

Development of a Steady-state Flow Model

The discretization and vertical layering seem reasonable. Please specify whether the layers were modeled as convertible or "confined".

Selection of Flow Boundary Conditions

The use of General Head Boundary (GHB) conditions to model recharge and discharge features can be problematic in that these boundary cells can act as an infinite source within the model. A better description of what surface water features present within the model domain are represented within the model needs to be presented to place the conceptual model in proper perspective. In addition, the proximity of pumping wells to these GHB features must also be evaluated to ensure there are no artifacts in the predicted drawdowns.

The basis for initial choice for GHB parameters seems rather arbitrary. It is hard to evaluate these numbers as the location of GHB cells used for rivers and coast are not depicted. Recharge GHBs are present in each cell. It is also unclear what the authors mean by the GHB head was set "close to" land surface elevation. Please quantify "close to". Depending upon the elevation of the water table, the head difference could be considerable at many locations causing a considerable driving force for water to enter the aquifer.

The model does not account for any pumping that is currently in place within the model domain. While such pumping is presumably confined to upper (freshwater) layers, their non-inclusion is not realistic in terms of the vertical movement of the water from lower zones. This modeling assumption in conjunction with lower vertical hydraulic conductivity values and the lack of processes pertinent to the movement of water in variable density environments makes the model non-conservative in terms of simulating the effects of vertical movement of groundwater. While data on vertical migration is extremely limited and perhaps non-existent, it is important that the model be based on conservative assumptions (i.e., err on the side of caution) until data proves otherwise.

The authors should clarify that the drawdowns and heads calculated with the model represent drawdowns in addition to that caused by any additional pumping that may already be occuring in the aquifer formation.

The purpose of the model is not clearly explained. Why was a steady-state model developed? How does the said development help with the objectives of the study which are stated early on in the report (and repeated here for convenience)?

- Improve the characterization of brackish groundwater in Victoria County,
- Develop and apply a methodology for predicting impacts to groundwater resources caused by pumping brackish groundwater, and
- Investigate management goals and criteria that are suitable for VCGCD to use for developing rules to regulate the development of brackish groundwater.

Tying the presentation of the modeling methodology with broader goals of the study will greatly help with the readability of the report and help understand some of the assumptions made in the study.

Selection of Water Levels for Calibration Targets

The selection of calibration targets carried out here is tantamount to cherry-picking the data. The procedure systematically removed observations with relatively high drawdowns (presumably caused by pumping) and further removed wells that led to localized depression (caused by pumping). While, the need to do so to simulate pseudo-steady-state conditions can be noted, doing so makes the model lack fidelity to actual conditions within the district and will again be less conservative (i.e., predict smaller drawdowns within the district) in terms of predicting overall drawdowns. At the very least, the authors should clarify that the drawdowns produced by the model are in addition to those caused by existing pumping.

The calibration is limited to comparisons in 9 of the 15 layers within the model and 4 of these 9 had less than 10 calibration targets. 5 of the 9 layers had no calibration targets within VCGCD. As stated previously, some of the layers exist under confined conditions within VCGCD but outcrop in other counties. The location of the calibration targets with respect to the aquifer formation type (confined/unconfined) must be presented to place the results in the proper context.

The location of GHB cells used to simulate rivers and discharge boundaries relative to the calibration targets should be presented. Furthermore, it would be good to show which layers have GHB cells. I am assuming GHB is limited to shallowest layer at any given location.

The use of artificial boundary condition (GHB) precludes its evaluation independently with field observed data. However, comparison of GHB fluxes with likely recharge values and stream discharges would be informative to evaluate the reasonableness of the model. The conductance values, in particular, can also be informative to evaluate whether these cells are likely to act as infinite sources of water.

I did not see any water budgets being presented within the model. The inclusion of water budgets is recommended to further evaluate the working of the model. In particular, the model prediction of vertical exchange between fresh and saline layers would be useful for policy formulation studies.

There appears to be no independent evaluation of calibrated model. All 150 wells with hydraulic head data were used as part of the calibration process without holding out some for independent verification of the calibrated model, neither was k-fold cross-validation performed. Given the large number of GHB cells (each with 2 adjustable parameters), it should come as no surprise that the calibration would yield reasonable RMSE values as the number of adjustable parameters >> the number of calibration targets. It is incorrect to rely on the statistical evaluation of calibration alone. The non-uniqueness of the calibration and the lack of independent evaluation of calibrated inputs must be acknowledged to place the results in proper perspective. It would be illustrative to see how well the model did within VCGCD where is will be applied (in addition to its performance over the entire model domain). Adding an error surface or at the very least computing the RMSE for wells within VCGCD would be beneficial to place the model results in proper context.

It would be useful to present the datum used for the hydraulic heads (are they all above MSL?) Please clarify. It is technically incorrect to plot heads from different formations on the same graph unless they are all measured from the same datum. The presence of only positive values for heads seem to indicate that they are probably not being measured with reference to MSL.

In addition to presenting the average value of recharge over the model domain (0.07 inches/year), it will be better to show the map of recharge. This will provide a better spatial representation of how the model captured the recharge spatially and evaluate if it is reasonable across the model domain. The presentation of average value without variance bounds can be misleading.

Applications of the Victoria County Groundwater Flow Model to Predict Drawdown from Pumping

What was the basis for selecting the 5 well locations within the district? It appears to be an arbitrary choice, please explain.

If the developed model is steady state ($t \rightarrow \infty$ or time-invariant), I am unclear how the simulation was carried out for a period of 30 years? Please explain.

The comparison of VCGFM and CGC-GAM is tantamount to comparing “apples” to “oranges”, given the differences between the two models (e.g., steady-state versus transient, 4 layers versus 15 layers, other differences in calibration and process parameterizations). Given these differences, how were the drawdowns compared? - Averaged over common hydrogeologic units? If so, presenting comparisons for different units would be better. Further explanation is necessary to place the comparison in proper context. A cautionary note on why such a comparison is difficult to make is also necessary for proper evaluation.

The sensitivity analysis shown in Figure 4-58 and 4-59 refer to sensitivity associated with calibration runs. These figures indicate that GHB have different impacts at different locations of the aquifer. Therefore, the sensitivity will likely be different within different formations and at different locations within the district. While the sensitivity analysis as presented is useful for calibration purposes, it adds little to any subsequent policy discussion. While the sensitivity is only performed for GHB for recharge, but GHBs were also used and calibrated to represent streams and discharge boundaries. It is unclear as to why sensitivities were not evaluated for these GHBs.

Please see the earlier comment on the datum used to measure hydraulic heads and clarify if the same datum was used for all layers and what that datum was.

I am not sure how 30-year time-frame drawdowns were obtained with a steady-state model. This needs some explanation. See Table 4.8 and 4.9. Time-variant results from a time-invariant model make the results in these tables highly suspicious.

Please denote the datum used for the midpoint of depth in Table 4.8 and 4.9

The sensitivity analysis appears to imply that the GHBs used for recharge are the only uncertain parameters in the model. While the Kh and Kv values were fixed, there should be no mistake that these input parameters are also highly uncertain and there are no real measurements in many formations modeled here. A more detailed sensitivity analysis that includes plausible ranges of horizontal and vertical hydraulic conductivities will be more illuminating, intuitively these parameters are likely to have a greater influence on the simulated heads, particularly in the deeper layers where the effects of recharge and surficial boundaries are minimal. Also, the sensitivity of the input parameters at the five selected locations will highlight the spatial variation in sensitivity. Such a sensitivity analysis would be extremely useful for future data collection efforts.

Closing Remarks

Overall the developed model may be reasonable for the intended purpose of the study and given the data limitations within the study area. However, the report does not provide the limitations and assumptions of the model. The presentation is sloppy and/or flawed at times and must be rectified. The uncertainties in the model are poorly discussed, if at all. There are several assumptions in the model that do not appear to be conservative. There should be an explicit acknowledgment that the modeling effort is a first-cut approach and does not include pertinent processes that affect the movement of saline groundwater. Caution must, therefore, be exercised when translating the model results to policy formulations as there is very little field data available for key model parameters.

References:

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Gass, S. I., & Thompson, B. W. (1980). Letter to the Editor—Guidelines for Model Evaluation: An Abridged Version of the US General Accounting Office Exposure Draft. *Operations Research*, *28*(2), 431-439.