Technical Memorandum

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SUBJECT: **SUBTASK 4.3 MODEL OBJECTIVES AND SELECTION EAST BAY PLAIN SUBBASIN GROUNDWATER SUSTAINABILITY PLAN**

Luhdorff & Scalmanini Consulting Engineers (LSCE) and a team of subconsultants (the LSCE Team) are working with the East Bay Municipal Utility District (EBMUD) and the City of Hayward (Hayward) to develop a groundwater sustainability plan (GSP) for the East Bay Plain (EBP) Subbasin, in compliance with the requirements of the California Sustainable Groundwater Management Act (SGMA) and the Groundwater Sustainability Plan regulations. Based on a preliminary compilation and review of the hydrogeological data, and SGMA requirements for development of the GSP for the EBP Subbasin, the LSCE Team has prepared this technical memorandum that summarizes the groundwater model purpose, model objectives, and recommended model framework to meet the identified objectives. This technical memorandum was prepared in accordance with Subtask 4.3 of Exhibit A-1 (Description of the Consultant Services) of the Master Agreement dated January 25, 2019.

1 MODEL OBJECTIVES

Sustainable management of the EBP Subbasin will require a numerical groundwater flow model capable of simulating groundwater and surface water interaction. In accordance with the Best Management Practices (BMP) guidance document for modeling published by the California Department of Water Resources (DWR, 2016), the EBP Subbasin groundwater model will provide an important framework that brings together conceptual understanding, available data, and science. The model will be used to support the development of the GSP by providing a tool to help meet the following objectives:

- Quantify annual water budgets and sustainable yield;
- Evaluate potential projects and management actions needed to maintain sustainability of the EBP Subbasin, including consideration of changing climate conditions;
- Analyze groundwater-surface water interactions including recharge areas and groundwater dependent ecosystems; and

- Define undesirable results and sustainable management criteria (particularly minimum thresholds and measurable objectives) to comply with GSP regulations and ensure groundwater sustainability.
- Support development of a monitoring network

Based on these objectives, compilation and review of hydrogeological data for the EBP Subbasin, and identification of the main processes influencing groundwater flow and water budgets, the numerical model needs to include capabilities to represent and/or help address the following:

1) Porous media heterogeneity and anisotropy in three dimensions;
2) Confined and unconfined aquifers;
3) Groundwater pumping and injection (well hydraulics);
4) Aquifer storage capacity and temporal change in storage;
5) Fault structures;
6) Groundwater - surface water interactions (e.g., streams, lakes, springs, etc.);
7) Areal precipitation and recharge;
8) Evapotranspiration;
9) Comparison between modeled and observed data to facilitate model calibration; also, conducting sensitivity analyses that may include evaluation of historical pumping rates/water levels from the late 1950s to early 1970s;
10) Groundwater fluxes and water budget;
11) Potential changes in groundwater quality, including seawater intrusion; and
12) Potential subsidence from declining groundwater levels associated with groundwater pumping.

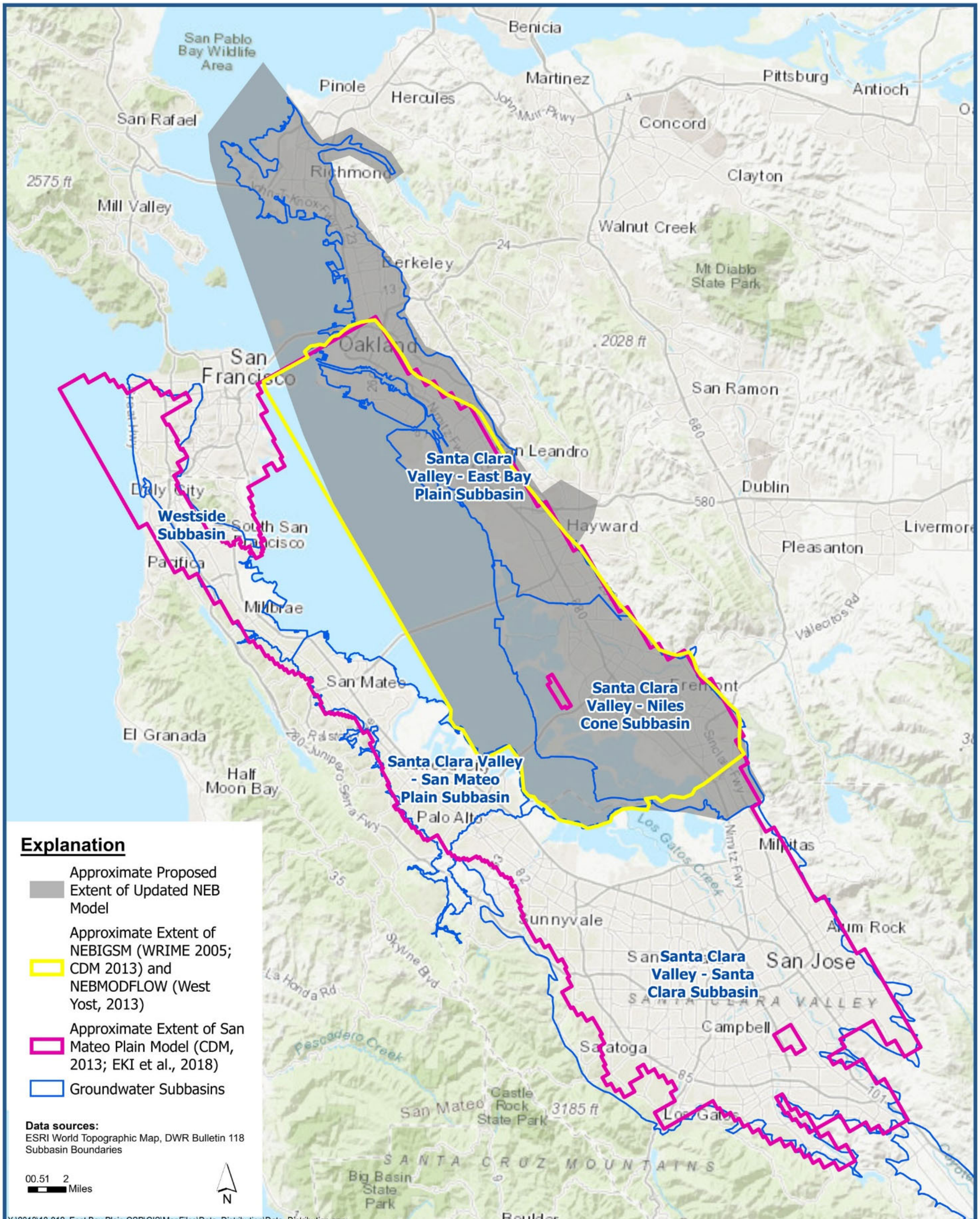
2 EXISTING MODELS IN PROJECT VICINITY

The LSCE Team has reviewed regional numerical groundwater models prepared by others in the EBP Subbasin and other nearby groundwater basins. Previously developed groundwater models that overlap or partially overlap the EBP Subbasin area include:

1) the Niles Cone and South East Bay Plain Integrated Groundwater and Surface Water Model (NEBIGSM),
2) the Niles Cone and South East Bay Plain MODFLOW Model (NEB MODFLOW), and

3) the San Mateo Plain Groundwater MODFLOW Model (SMPGM).

Figure 1 below shows the extent of these three model domains that include the EBP and the approximate proposed domain for the new EBP Subbasin model. **Figure 2** below shows the extent of two additional regional models in the SF Bay Region that are also used as tools for management of groundwater resources: Westside Basin MODFLOW model and Santa Clara Valley MODFLOW Model. **Table 2-1** provides a summary of the software used for each basin, the objectives of the modeling effort, and timing; more detailed discussion of each follows. As shown in **Table 2-1**, nearly all groundwater modeling in the project vicinity since the early 2000s uses MODFLOW.



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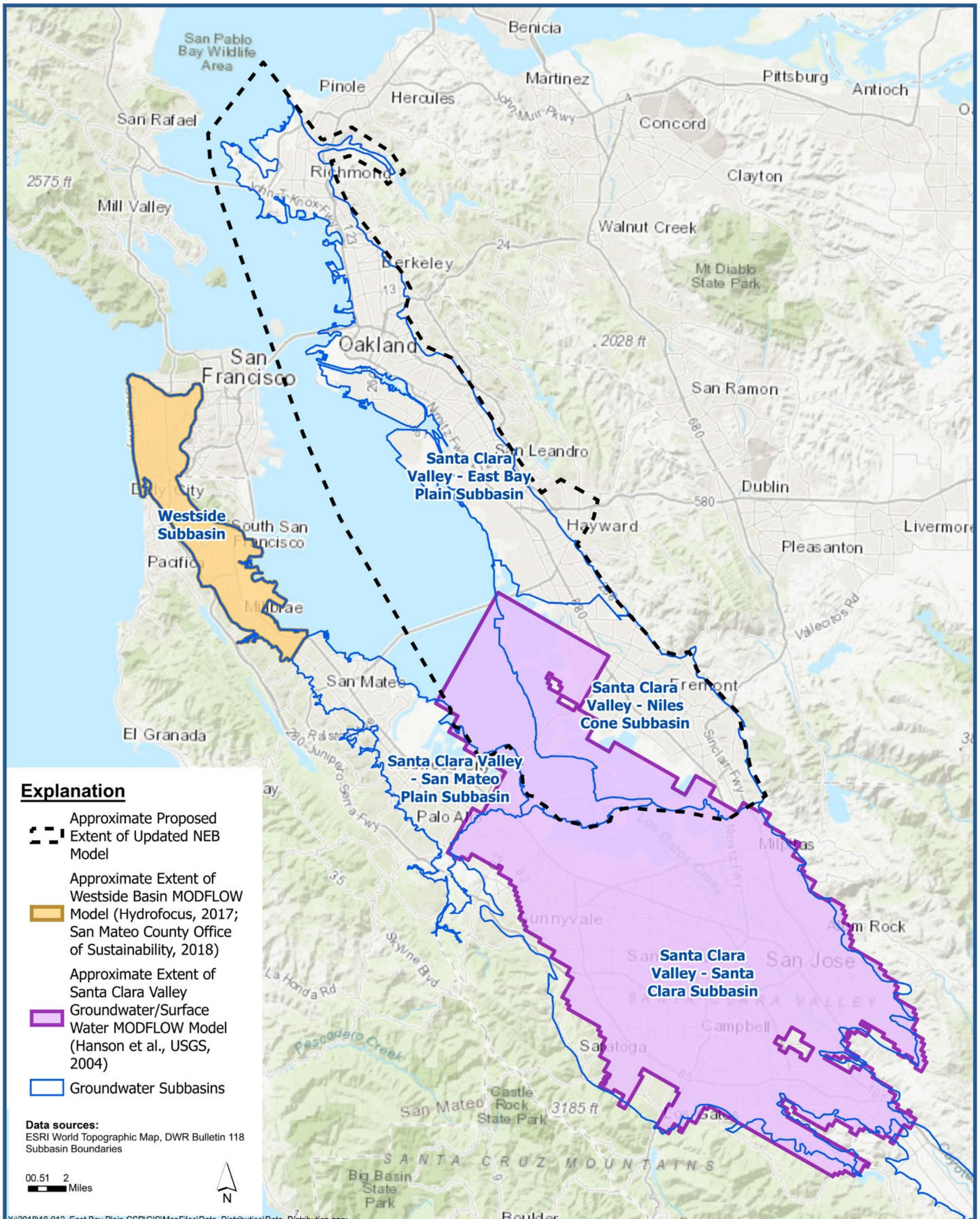
Groundwater Model Domains that Include the East Bay Plain

East Bay Plain Subbasin
Groundwater Sustainability Plan

Figure 1



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Additional Regional Models in the San Francisco Bay Area

East Bay Plain Subbasin
Groundwater Sustainability Plan

Figure 2

Table 2-1: Summary of Groundwater Modeling Software used in the Project Vicinity

Software	Locations	Year	Key Objectives
IGSM	Niles Cone; southern East Bay Plain	1991; 2005	Primarily for management of Niles Cone Groundwater Basin; secondary purpose for application to EBMUD Bayside ASR Well EIR.
MODFLOW	Southern East Bay Plain	2001	Used for evaluation of EBMUD Bayside ASR project
MODFLOW	San Mateo Plain	2018	General basin management
MODFLOW	Santa Clara Valley	1990s; periodically updated	General basin management
MODFLOW	Westside Basin – San Francisco/San Mateo Counties	2007; periodically updated	General basin management

2.1 Niles Cone and South East Bay Plain Models

In 2004/2005, EBMUD, Alameda County Water District (ACWD), and Hayward developed a model for the South East Bay Plain and Niles Cone groundwater basins in the southeastern portion of the San Francisco Bay Area (WRIME, 2005). This model was based on previous models developed by ACWD and EBMUD for the southern portion of the East Bay Plain and the Niles Cone Subbasins. The NEBIGSM was developed using the Integrated Groundwater Surface Water Model version 6 (IGSM). IGSM is a proprietary, finite-element-based software developed in the 1970s (Montgomery Watson, 1995). The NEBIGSM consists of four layers representing the four main aquifers, and indirectly simulates overlying aquitards in each aquifer model layer.

Review of the IGSM (version 5) software revealed some fundamental problems with computation techniques and potential significant inaccuracies that raise questions about the validity of IGSM-based model applications (e.g., LaBolle et al., 2002). While some of the problems with the software have been corrected in more recent versions, IGSM is not listed by DWR in their Modeling BMP document (DWR, 2016) as one of the commonly used groundwater model codes appropriate for developing GSPs for sustainable groundwater management. The upgraded version of the NEBIGSM is used by ACWD as a tool for management of groundwater resources. We understand that ACWD is considering further upgrades and conversion of their model from the proprietary IGSM modeling code to IWFM (Integrated Water Flow Model)[1], which is public-domain software supported by the DWR.

[1] https://water.ca.gov/Library/Modeling-and-Analysis/Modeling-Platforms/Integrated-Water-Flow-Model

In 2013, EBMUD converted the NEBIGSM from the IGSM modeling code to the public-domain MODFLOW modeling code (e.g., Harbaugh, 2005), which is a modular, finite-difference software platform that is widely used, formally validated, and supported by the United States Geological Survey (USGS). Like the NEBIGSM, the NEB MODFLOW model represents three primary hydrogeologic units:

- Shallow Aquifer Zone (from the ground surface to depths ranging up to approximately 200 feet);
- Intermediate Aquifer Zone (at depths ranging from approximately 200 to as much as 500 feet below ground surface [bgs]); and
- Deep Aquifer Zone (at depths ranging from approximately from 400 to 500 feet to more than 660 feet bgs).

The NEB MODFLOW model consists of seven layers that represent these aquifers and intervening aquitards, and it includes some refinement of hydraulic properties in the southern portion of the EBP Subbasin based on additional data compilation (EBMUD, 2013).

2.2 San Mateo Plain Model

The San Mateo Plain Groundwater Model (SMPGM) was developed using MODFLOW by the Bay Area Water Supply Conservation Agency (BAWSCA) and San Mateo County to support the evaluation of options for brackish groundwater desalination and the development of groundwater management strategies for the San Mateo Plain Groundwater Subbasin (CDM, 2013, 2015; EKI et al., 2017, 2018). The model domain covers the majority of San Francisco Bay and the surrounding coastal plains and includes the portion of the EBP Subbasin from Hayward to Oakland. (**Figure 1**).

2.3 Westside Basin Model

Westside Basin (DWR Basin 2-35) extends along western portion of San Francisco and southeast into San Mateo County to San Francisco Bay. The portions of the basin in San Francisco and San Mateo Counties are referred to as the North and South Westside Basins, respectively. A MODLOW model of the Westside Basin originally developed in 2003 has been updated several times (Hydrofocus, 2017) and is used a tool for groundwater management for both the North Westside Basin (SFPUC, 2005; LSCE, 2010) the South Westside Basin (WRIME, 2012). The Westside Basin MODFLOW model has been an important tool for planning development of groundwater resources and building consensus among stakeholders that include the SFPUC, Daly City, City of San Bruno, and California Water Service[2]. The extent of the West Basin Groundwater Model is shown on **Figure 2**.

2.4 Santa Clara Valley Model

The Santa Clara Valley Model extends approximately 20 miles southeast of the southern end of San Francisco Bay. The regional alluvial aquifer system of the Santa Clara Valley is an important source of

[2] https://www.smcsustainability.org/download/energy-water/groundwater/Westside-Basin-Groundwater-Modeling.pdf

groundwater that has supported agricultural and urban development. In 2004, an updated regional groundwater/surface water MODFLOW Santa Clara Valley model (SCVM) was developed by the USGS (Hanson et al., 2004) in collaboration with the Santa Clara Valley Water District (now Valley Water) as a tool for water resources management. The 2004 model builds on the original Santa Clara Valley MODFLOW model (CH2M Hill, 1991). The most recent modeling efforts include additional model refinements and recalibration for indirect potable reuse studies in the southern Santa Clara Plain Groundwater Basin (Todd, 2017a and 2017b) and in the Palo Alto area (Todd, 2018). The extent of the SCVM is shown on **Figure 2**. The northern portion of the SCVM overlaps with the Niles Cone and South East Bay Plain models (NEBIGSM and NEB MODFLOW) and the San Mateo Plain Model (CDM, 2013, 2015; EKI et al., 2017, 2018).

3 RECOMMENDED MODELING SOFTWARE

The LSCE Team recommends using MODFLOW for simulating groundwater flow and interaction between surface water and groundwater. MODFLOW is widely used in the project vicinity and, therefore, familiar to potential stakeholders associated with the EBP Subbasin GSP, and MODFLOW can simulate the necessary hydrogeological processes and features required for the EBP Subbasin model as outlined in Section 1 and as discussed in Section 4 below. MODFLOW is well-suited for a robust numerical groundwater flow model that fulfills the objectives defined above.

With MODFLOW as the modeling code, the Department of Defense Groundwater Modeling System (GMS, Aquaveo, 2018) and Arc Hydro Groundwater (AHGW, Jones and Strassberg, 2008) are planned to be used as the graphical user interface (GUI) for pre-and post-processing of MODFLOW files and storing the fundamental information that comprises the conceptual model, including databases of aquifer properties, groundwater levels, pumping rates, and sources (i.e., inflows) and sinks (i.e., outflows). GMS will be used primarily for pre-and post-processing of data and AHGW will be used for managing, visualizing, and storing groundwater data within an ArcGIS environment. GMS and AHGW were selected for various reasons including seamless integration of the 3-D geologic model being developed for the project with MODFLOW and because they provide an excellent interface for mapping files/data in ArcGIS (which is also the GIS system used by Hayward and EBMUD). As further discussed in Section 4, both GMS and AHGW will facilitate the development of tables and graphics necessary for achieving the model objectives and communicating with potential EBP Subbasin stakeholders.

MODFLOW (e.g., Harbaugh et al., 2000; Harbaugh, 2005; Niswonger, et. al., 2011) and related programs such as MODPATH (USGS, 2012) are the most widely used software for simulating groundwater flow, particularly in the San Francisco Bay Area (see **Table 2-1**). MODFLOW meets the SGMA guidelines (DWR, 2016) for model software transparency and documentation:

- Documentation is publicly available at no cost from the website maintained by the USGS[3].
- The mathematical foundation of physical processes simulated by MODFLOW and related programs have been subjected to the rigorous USGS review process and also have been independently peer-reviewed and validated, and their limitations are well documented.

Moreover, DWR reports in the Modeling BMP for the Sustainable Management of Groundwater (DWR, 2016) that MODFLOW is appropriate software for developing GSPs.

MODFLOW uses a finite-difference method to solve the governing groundwater flow equation. This method represents a system of discrete locations, which are the finite difference grid cells. The size of the finite-difference grid cells determines the model resolution and influences practical aspects, including size of model files and computational run time.

MODFLOW can simulate a series of transient (time-varying) conditions where inflow and outflow components of the groundwater system change with time, or steady-state (equilibrium) conditions for which inflow and outflow components are in balance so there is no change in storage and groundwater levels are constant with time. Both steady-state and transient model simulations will be used with MODFLOW in developing the EBP Subbasin GSP.

Steady-state models are useful for simulation of groundwater conditions for different average pumping and/or recharge rates, which is useful for evaluating hypothetical groundwater pumping and/or recharge quantities, or determining the sustainability of potential pumping without considering the time required to achieve an equilibrium condition. Steady-state models also are commonly used to represent baseline conditions that are subsequently used to establish starting conditions for transient runs.

Transient model simulations of groundwater conditions simulate varying inflow and outflow conditions and the associated change in hydraulic gradients and change in groundwater storage with time. In MODFLOW, simulation time is partitioned into stress periods during which the specified inputs or outputs (pumping rates, recharge, etc.) for the model remain constant. Time steps are specified for a transient MODFLOW model to achieve the desired precision in the mass-balance and resolution of change in conditions with time during stress periods.

4 SUITABILITY OF MODFLOW FOR EBP SUBBASIN MODELING NEEDS

This section presents discussion of the suitability of MODFLOW, GMS, and AHGW to meet the modeling needs for the EBP Subbasin.

[3] https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs?qt-science_center_objects=3#qt-science_center_objects
https://www.usgs.gov/software/modflow-2005-usgs-three-dimensional-finite-difference-ground-water-model

4.1 Porous Media Heterogeneity and Anisotropy

The model will need to represent the hydrogeologic parameters associated with a range of lithologies and soil types within the EBP Subbasin. Moreover, the model will need to represent the location-dependent relationships between differing media.

The attributes of the three-dimensional geological model developed as part of the hydrogeologic conceptual model (HCM) can be seamlessly incorporated in the multi-layer grid structure of MODFLOW. In addition, GMS is integrated with ArcGIS and AHGW, which will be used to develop the HCM and three-dimensional geological model, and includes automated refinement options and geoprocessing tools that offer flexibility and efficiency to design the model layers and interpolate heterogeneous properties to the numerical model grid.

4.2 Confined and Unconfined Aquifers

MODFLOW has several options for specifying properties that control flow between cells, including the Block Center Flow (BCF), Layer Property Flow (LPF), Hydrogeologic Unit Flow Package (HUF2), or Upstream Weighting Package (UPW) packages. All versions of MODFLOW facilitate simulation of confined and unconfined (phreatic) groundwater conditions and allow transition between confined and unconfined conditions and vice-versa.

4.3 Groundwater Pumping and Injection/Well Hydraulics

Withdrawal or injection is most commonly represented in MODFLOW as specified flux using the well (WEL) package. The Multi-Node Well Package (MNW2) or Multi-Aquifer Well Package (MAW) can also be used to simulate wells that include more than one node of the grid; both allow better representation of wells that partially penetrate a layer, non-vertical wells, and head losses within wells. The MAW package relates the contribution to total discharge from each layer penetrated by a multi-aquifer well to the hydraulic conductance and the head difference between the well and the aquifer (Langevin et al., 2017; Neville and Tonkin, 2004). The WEL and MNW2 (Konikow et al., 2009) packages are supported by all standard current versions of MODFLOW, and the MAW package is supported by MODFLOW 6 (Langevin, et al., 2017).

4.4 Aquifer Storage Capacity and Temporal Change in Storage

Transient model simulations with MODFLOW can represent groundwater being removed or added to storage within aquifers. The two physical mechanisms of aquifer storage (specific storage or pressurization under confined conditions and filling of pore space in the vadose zone under phreatic conditions) can both be simulated with MODFLOW.

4.5 Fault Structures

Faults and other potential barriers to groundwater flow can be represented with MODFLOW using the horizontal-flow barrier (HFB) package, or by local variation in assigned hydraulic conductivity distribution.

4.6 Groundwater/Surface Water Interaction and Surface Water Routing

The EBP Subbasin includes San Lorenzo, San Leandro, and Alameda, and other creeks that have gaining and losing reaches, and recharge ponds in the vicinity of Hayward near Alameda Creek.

MODFLOW has several options to simulate surface water flow, and flow between groundwater and surface water:

- The drain (DRN) package simulates the withdrawal of groundwater by a drain (only outflow from groundwater to the drain);
- The river (RIV) package simulates head-dependent inflow/outflow between a river and the underlying groundwater;
- The lake (LAK) and reservoir (RES) packages simulate flux between groundwater and surface water bodies with a uniform surface water elevation;
- The Streamflow Routing Package (SFR2, Niswonger and Prudic, 2005), which is an update to the STR and SFR1 Packages, simulates inflow/outflow between surface and groundwater, and one- dimensional unidirectional surface water flow for conditions where the flow rate is a function of the slope of the channel. In addition to simulating streams and rivers, the SFR2 Package can be used to simulate groundwater discharge to springs and drains, and groundwater interactions with canals. For streams with reaches that are hydraulically disconnected from underlying aquifers, SFR2 includes the ability to simulate unsaturated flow beneath streams. SFR2 also provides options for addition or subtraction of water from stream reaches at user-specified rates.
- The Surface Water Routing Process (SWR1, Hughes et al., 2012) was developed for MODFLOW– 2005 to supplement the SFR package capabilities. The SFR2 Package and the SWR1 Process both route surface water based on a solution to the continuity equation. However, the SWR1 Process has the added capability to account for backwater (tailwater) effects, bidirectional surface-water flow, and management of surface water using control structures.
- Specified head boundaries assigned in MODFLOW can also be used to simulate flux between groundwater and surface water.

Although the primary water source in the EBP Subbasin service areas is surface water imported from outside the basin, the application of surface water for irrigation (golf courses, parks, lawns, etc.) and other means of surface water recharge (e.g., reservoirs and leaking pipes) will be evaluated outside of the groundwater model via a water balance analysis and represented in the MODFLOW model as appropriate. Simulation of variably saturated flow within the vadose zone will not be conducted and is not necessary for the purpose of the GSP and future groundwater management in the EBP Subbasin where the water table is generally shallow. Readily available MODLOW packages can provide more than adequate simulation of interaction between surface water and groundwater in the EBP Subbasin for GSP purposes.

4.7 Areal Recharge and Evapotranspiration

Geographic information for spatially varying properties such as precipitation, land use, and surficial soil distribution will be interpolated to the MODFLOW grid. The HCM will provide an initial estimate of the spatial distribution of the ratio between precipitation and recharge to groundwater. The recharge flux will be simulated within MODFLOW using the recharge (RCH) package.

Evapotranspiration from the unsaturated zone will be evaluated in a water balance outside the model and will be subsequently integrated with the recharge component. Existing geographic data from past potential evapotranspiration (PET) studies as well as vegetation distribution data can be assigned to the model grid to represent evapotranspiration (ET) from the shallow water table within the EBP Subbasin. The evapotranspiration (EVT) package in MODFLOW (Harbaugh et al., 2000) simulates ET and accounts for maximum ET rate, which can vary seasonally, and maximum ET depth (i.e., extinction depth), which depends on vegetation type. Typically, shallow groundwater is associated with higher ET rates.

4.8 Comparison between Simulations and Observations to Facilitate Calibration

Groundwater models are calibrated by iteratively modifying assigned parameter values to reduce the discrepancies between model-generated and observed values such as groundwater head or flux rates. Calibration can be performed manually and using automated parameter estimation software such as PEST (Doherty, 2015) and UCODE (Banta, 2011; Hill and Tiedman, 2000; Hill et al., 2000a,b; Poeter et al., 2014).

GMS allows efficient integration of automated calibration software with MODFLOW. Observed water levels and observed flows will be incorporated directly into the model and used to calibrate the model simulated values to observed values in accordance with the GSP Regulations (§352.4(f)(2)) and with consideration of other groundwater modeling guidance documents (e.g. Reilly and Harbaugh, 2004; ASTM, 1998; Middlemis, 2000; DWR, 2016). GMS provides an efficient method for graphically representing quantiles and residual error at observation locations, which facilitates communicating the results and comparing observed and model-predicted head values. GMS also includes automated methods for generating calibration metrics, including summary statistics, scatter plots, and time-series hydrographs to compare observed and model-simulated groundwater levels.

Sensitivity analyses will be used to evaluate the influence of parameter uncertainty on model predictions and design a range of predictive scenarios. The sensitivity analyses will also provide the basis for understanding uncertainty when estimating sustainable yield and developing groundwater management strategies. In addition, if sufficient data are available, other sensitivity analyses that may be conducted such as evaluation of cumulative groundwater pumping rates in the southern portion of the EBP Subbasin in comparison to available groundwater level data from the late 1950s to early 1970s.

4.9 Quantifying Groundwater Fluxes and Water Budget

MODFLOW calculates water budgets for the entire model domain for each time step, and the user can specify the frequency (or specific time steps) for water budget output. The water budget output is provided as a text file for the entire model domain and as a binary file for each model cell. The text file can be read with any word processor, spreadsheet such as Excel, or a database. GMS and other pre- and post-software for MODFLOW include options for efficient zone budget accounting to facilitate calculation of fluxes between subsets of the model domain, including:

- Groundwater flow between aquifers;
- Flow to and from boundary conditions and source/sink terms (e.g., streams, lakes, San Francisco Bay, wells, recharge, evapotranspiration);
- Flow between individual or groups of model grid cells; and
- Change in storage.

4.10 Seawater Intrusion

The proposed western boundary of the model is near the middle of the bay. Representation of the bay as either a lake or as a portion of an added upper layer with constant water level will facilitate computation of rate of influx of water from the bay to the interfacing aquifers. A water budget approach will be used initially to evaluate the potential for seawater intrusion for different groundwater pumping scenarios because, in most cases, the influence of density variation (seawater vs. groundwater) is negligible compared to the hydraulic gradient caused by pumping. Additionally, for the EBP Subbasin GSP purposes, uncertainties in hydraulic conductivity, which varies by orders of magnitude, are relatively more important than variable density with salinity because seawater is only approximately 2.5% more dense than freshwater.

If necessary, potential options for simulating seawater intrusion associated with density variation in a MODFLOW model include the Seawater Intrusion Package for MODFLOW (SWI2, Bakker et al., 2013), the solute transport code MT3DMS, or a SEAWAT model.

The SWI2 package facilitates simulation of vertically integrated variable-density groundwater flow within individual MODFLOW layers. Density zones are separated by interfaces or density isosurfaces. Density within each zone can be uniform or linearly vertically varying between the interfaces. After the groundwater flow equation is solved, a separate solution is required to simulate horizontal and vertical movement of surfaces separating zones of different densities. SWI2 makes it possible to simulate vertically integrated variable-density groundwater flow using one model layer per aquifer. Seawater intrusion can be simulated in existing MODFLOW-2005, MODFLOW-NWT, and MODFLOW 6 models with limited modifications. The solute transport code MT3DMS can be used to estimate changing chloride concentration with time in the aquifers. A SEAWAT model, which explicitly simulates variable-density groundwater flow and dispersive solute transport, can also be developed from the MODFLOW model.

Although it may be unnecessary for the EBP Subbasin, another option is to preliminarily assess the influence of variable density from salinity on potential seawater intrusion by developing a separate relatively simple analytical or cross-sectional SEAWAT model based on the three-dimensional MODFLOW model.

4.11 Subsidence

An initial assessment of subsidence and compilation of subsidence data/studies in the EBP Subbasin will be conducted in Subtask 4.2 as part of HCM development. Subsidence is the gradual lowering of ground surface elevation due to compaction of underlying geologic materials. Subsidence in California has been associated with groundwater pumping (Sneed et al., 2018; Brandt et al., 2017), which lowers hydrostatic pressure in the aquifer. Hydrostatic pressure in an aquifer counteracts the gravitational force of overlying sediments in aquifers, so when it is lowered, the result is both elastic and inelastic compaction of sediments, which can result in subsidence of the land surface.

Assessment of historical groundwater levels, occurrence (or lack thereof) of historical subsidence, available extensometer data, and soil/sediment properties will be reviewed. Available lithologic data and geologic cross sections will be used to cross check the occurrence and physical properties of clay layers that may cause inelastic (i.e., irreversible) subsidence. Groundwater elevation data from wells in areas where land subsidence could be a future concern will be used to determine historical groundwater level lows, the exceedance of which has the potential to cause compaction of inelastic clay layers. An initial screening level evaluation of the potential for subsidence will be conducted based on geotechnical properties of the soil and aquifer materials and model simulations of change in groundwater levels. The LSCE Team plans to review data from the USGS Bayside Groundwater Project extensometers in evaluating the potential for compaction and subsidence.

Based on the screening level assessment of potential for subsidence using water levels and geotechnical properties of the soil, model simulations will be run using the subsidence module of MODFLOW to further evaluate the potential for both elastic and inelastic subsidence as appropriate. MODFLOW includes the ability to simulate clay interbeds with time-delayed subsidence, a phenomenon observed in thicker clay beds, in addition to simulating instantaneous compaction, which can occur in thinner clay beds (e.g. Harter and Hubert, 2013).

4.12 Simulation of Agricultural Irrigation Processes Not Needed for EBP

The Integrated Water Flow Model[4] (IWFM), which is supported by DWR, and One-Water Hydrologic Model (MODFLOW OWHM, Hanson et al., 2014), which is supported by the USGS, are both integrated hydrologic models that simulate agricultural crop demands and irrigation supplies in addition to groundwater flow (Dogrul et al., 2011; Harter and Hubert, 2013; USGS, 2017). These integrated hydrologic modeling programs were developed for agricultural groundwater basins such as the Central Valley and Salinas Valley to predict agricultural water demands and dynamically simulate acquisition and routing of available water supplies in terms of surface water diversions and groundwater pumping, and irrigation of crops to meet demands. However, simulation of surface water routing and model determination of water demands for different crop types is not needed for the EBP Subbasin where the setting is mostly suburban and urban.

[4] https://water.ca.gov/Library/Modeling-and-Analysis/Modeling-Platforms/Integrated-Water-Flow-Model

The LSCE Team will estimate irrigation demands for the EBP Subbasin using available data for golf courses, parks, and suburban neighborhoods. Crop water-demand models, such as the IWFM Demand Calculator developed by DWR (2017), will also be utilized as appropriate to evaluate irrigation needs for the EBP Subbasin.

4.13 Other Advantages of MODFLOW

In addition to being able to efficiently meet the modeling objectives for the EBP Subbasin, MODFLOW has other advantages for this project, several of which are discussed below.

4.13.1 Accessibility to Stakeholders

Multiple stakeholders are involved in the development of the EBP Subbasin GSP. MODFLOW is developed and maintained by the USGS, it is publicly available, and the model files can be shared easily and used with other commercial software for MODFLOW as well as standard USGS public domain software.

The files for a MODFLOW model comprise a series of files, or packages. Many of the files are written in American Standard Code for Information Interchange (ASCII) and some are in binary format. Both public domain and commercial GUIs are readily available for pre- and post-processing of MODFLOW ASCII and binary input and output files. GMS facilitates the generation of standard MODFLOW files that can be used with the public domain MODFLOW software or imported into other MODFLOW GUIs.

In addition, MODFLOW meets the GSP regulation §352.4(f)(3), which specifies that the model developed in support of a GSP after the effective date of the regulations shall consist of public domain open-source software.

4.13.2 Stable Estimate of Water Budget

The calculated groundwater flow budget and subset zone budget accounting are critical components for estimating groundwater sustainability and a key component of the EBP Subbasin groundwater flow model. Finite-difference models like MODFLOW can more readily achieve a stable "closed water budget" than finite-element models, because finite-difference calculations are better able to quantify cell-by-cell flow (e.g., Kumar, 2019).

4.13.3 Modeling for Regional Groundwater Management in Project Vicinity

MODFLOW has a long history of use for groundwater management in California (USGS, 2018), including the San Francisco Bay Area. Previous models developed with MODFLOW for this purpose include NEB MODFLOW used to support the South East Bay Plain Basin Groundwater Management Plan and SMPGM used to support the development of groundwater management strategies for the San Mateo Plain Groundwater Subbasin (Section 2). Thus, MODFLOW was used for two of the existing models that overlap the EBP Subbasin. In addition, other models within the general San Francisco Bay Area have been developed with MODFLOW, including the Sonoma Valley Area Model (USGS, 2006), Santa Clara Valley Regional Ground-Water/Surface-Water Flow Model (USGS, 2004), and Westside Basin Groundwater-Flow

Model (Hydrofocus, 2017). In addition, MODFLOW can simulate the processes included in the IGSM model previously developed for the Nile Cones and South East Bay Plain.

4.13.4 Post Processing and Visualization

GMS and AHGW smoothly integrate with GIS and facilitate efficient visualization with two- and three-dimensional mapping using programs like ArcGIS and ArcScene.

4.13.5 Incorporation of Other Processes

MODFLOW can also simulate other processes such as subsidence (SUB and/or SWT package), particle tracking (MODPATH), solute transport (MT3DMS or MT3D-USGS), geochemical reactions (RT3D, in conjunction with PHREEQC, or PHT3D), and variable-density groundwater flow (SWI2 package for MODFLOW-2005; SEAWAT).

MODFLOW files can be readily adapted in the future (as needed) to run with MODFLOW-SURFACT[5], which can simulate variably saturated flow within the vadose zone. However, because groundwater is generally shallow in the NEB area, the primary objectives of the EBP Subbasin model do not include variably saturated flow processes and residence time of water flowing within the vadose zone between surface water and groundwater.

5 SUMMARY

The LSCE Team recommends MODFLOW for simulating groundwater flow and interaction between surface water and groundwater for the EBP Subbasin. We also recommend GMS as the GUI for pre-and post-processing of MODFLOW files and data, and AHGW for managing, visualizing, and storing groundwater data within an ArcGIS environment.

MODFLOW is the most versatile and widely used software for groundwater modeling and is well-suited for simulating groundwater flow and developing the EBP Subbasin GSP. Moreover, MODFLOW is public-domain software supported and extensively documented by the USGS. GMS and AHGW are powerful pre-and post-processing platforms for MODFLOW that can efficiently couple the numerical groundwater flow model with the three-dimensional geologic model and available data. The MODFLOW model will also serve as an important tool for planning of future groundwater development and management in the EBP Subbasin.

[5] https://www.hgl.com/softwareproducts-new/modflow-surfact/
https://www.waterloohydrogeologic.com/modflow-surfact-flow/

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