PACIFIC groundwater GROUP

SITKA SEDGE NATURAL AREA
HYDROLOGICAL ANALYSIS
FINAL REPORT (DRAFT)

98% Review Draft – Subject to Revision

June 4, 2019

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98% REVIEW DRAFT - SUBJECT TO REVISION

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SIGNATURE

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1.0 INTRODUCTION

The Oregon Parks and Recreation Department (OPRD) is interested in investigating the feasibility of responsible restoration of the Sand Lake Estuary (Figure 1-1). One component of the restoration scoping effort is deciding how to address a failing tide gate in the Beltz dike. Options range from repair or replacement of the tide gate to removal of a portion of the dike. These modifications will alter the flushing processes in 12 acres of marsh area south of the dike, potentially improving habitat quality and benefitting federally listed salmonids in the marsh and upstream creek areas. The existing tide gate is currently malfunctioning such that it allows limited tidal inundation of the marsh area.

The effects of increased tide water in the marsh on groundwater and stormwater drainage to the south in Tierra Del Mar (TDM) have not previously been fully understood. The Tierra Del Mar community has raised concerns that marsh restoration could exacerbate historically problematic groundwater flooding. Groundwater flooding occurs regularly in the rainy season and causes standing water and impairment of septic system function. Thus, while the overarching objective of the project is to investigate the potential for restoration, the immediate goal of this study is to understand how changes at the dike and tide gate may influence the groundwater flooding issues in TDM, and how a range of marsh restoration scenarios may alleviate or exacerbate those impacts now and in the future.

In Oregon, approximately 70% of estuarine wetlands have been lost to conversion. Sand Lake Estuary is perhaps one of the most intact for the entire coast. Native hydrology of the estuary has been altered by past human use, including construction of Beltz Dike that separates two estuarine communities: one open salt water and saltmarsh, the other a combination of saltwater and salt marsh, freshwater marsh, scrub-shrub wetland, and forested wetland.

There is a potential opportunity to return Beltz Marsh to a more naturally functioning state, by allowing tidal exchange in the estuary south of the dike. This habitat restoration may benefit federally listed coho salmon and optimize native fish passage to Beltz and Reneke Creeks. OPRD hopes to collaborate with stakeholders from the local community and conservation organizations to identify potential restoration concepts, investigate and understand the risks and benefits of each potential restoration concept, and find a solution that enhances fish passage and habitat, while not adversely impacting adjacent property.

A preliminary study, conducted under a separate contract, consisted of the installation of three groundwater monitoring wells within the northern portion of TDM and a surface water elevation recorder within the Beltz Marsh (Marsh), west of Sand Lake Road (Waterways, 2017). Following completion of a draft Summary Report, OPRD determined that a more comprehensive evaluation was warranted. The work in this report is an expanded study to understand existing conditions and a range of alternatives for modification of the Beltz Dike with the ultimate goal of improving fish passage at the Beltz Dike and improving habitat for listed coho salmon in the upstream watershed

1.1 SCOPE OF SERVICES

This DRAFT final report is completed under project Task 4. The following tasks are included in PGG's Scope of Work:

- *Task 1: Data Review and Scope Refinement* includes: reviewing existing and new data, and refining the originally proposed scope as needed.

- *Task 2: Site Characterization* includes: installation of monitoring wells, collection of surface and groundwater level measurements, estimation of hydraulic conductivity from grain size analysis and hydraulic tests, and surface water hydrologic characterization.
- *Task 3: Model Development & Calibration* includes: Attending a site characterization and modeling kickoff meeting, development of the surface-water and ground-water models, and model calibration to existing conditions.
- *Task 4: Evaluate Future Conditions Scenarios* includes: model evaluation of extreme-case future-condition scenarios, developing partial draft report #2, attending a meeting to present model results and choose directions, evaluating supplemental future conditions scenarios (if needed), developing a final draft report, attending a meeting regarding draft report revision (scheduled for June 2019), and finalizing the report.

As noted in the scope, this is a final draft to facilitate discussion of modeling results for the first phase of modeling. All sections of this report may be revised on the basis of subsequent discussions and technical work.

1.2 REPORT ORGANIZATION

This final draft report supplements prior versions by documenting additional predictive analyses performed with the calibrated surface-water and groundwater models, identified based on prior recommendations from the consulting team and public input. It also includes qualitative and semi-quantitative analyses performed to address public comment.

1.3 AUTHORIZATION AND WARRANTY

This work is being completed under Contract 7952 with the State of Oregon Parks and Recreation Department. PGG and ESA's work was performed, and this report prepared, using generally accepted hydrogeologic and hydrologic practices used at this time and in this vicinity, for exclusive application to the Sitka Sedge Natural Area, and for the exclusive use by Oregon Parks and Recreation Department. This is in lieu of other warranties, express or implied.

2.0 SUMMARY OF FINDINGS & RECOMMENDATIONS

This section provides a summary of the key features of the study area that control surface and groundwater flow, modeling methods, and key findings of the study. .

2.1 SURFACE-WATER HYDROLOGY

- Surface water hydrology in Beltz Marsh and adjacent areas is influenced by tides in the Sand Lake Estuary, freshwater input from Reneke Creek and Beltz Creek, and local drainage features. Tides are the primary driver of regular surface-water level fluctuations in Beltz marsh. Tidal fluctuations in the Pacific Ocean are transmitted to the marsh via the shallow Sand Lake Estuary and communicated through Beltz dike via an existing culvert and tide gate.
- Beltz Marsh is separated from Sand Lake by the Beltz dike. The dike has an approximate crest elevation of 12 feet. The FEMA base flood elevation in this area is 11.8 feet. FEMA floodplain

mapping shows the Beltz dike but does not consider it a barrier that prevents flooding from Sand Lake.

- High tides in Sand Lake are amplified (higher) compared to ocean conditions. Daily low tides in Sand Lake and Beltz Marsh are severely muted and never fall below 5.3 feet due to a controlling bed elevation in Sand lake.
- The existing tide gate is a leaky, wooden, top-hinged gate that allows significant water to enter the marsh during high tides. The tide gate has limited capacity to drain water out of the marsh. During heavy rainfall events, water accumulates behind the dike leading to elevated water surface elevations in Beltz Marsh that are not fully released during outgoing tide. It takes multiple low tide cycles for accumulated water to drain and water levels in the marsh to equilibrate with Sand Lake. This water retention can impact adjacent groundwater levels beneath TDM.
- Areas within the marsh below 5.0 feet remain inundated most of the time, while areas with elevations above 8.0 feet are rarely inundated. The low point in Sand Lake Road is approximately 11.6 feet. Residential areas within TDM have ground elevations generally ranging from 14.0 to 22.0 feet, or higher. TDM has installed a drainage ditch and culvert network that flows north and discharges into the marsh above the direct influence of the tide.
- An existing beaver dam at the south end of Beltz Marsh impounds water and creates a backwater condition. The beaver dam elevation is approximately 7.0 to 7.5 feet, and water levels south/upstream of the beaver dam typically do not fall below 7.0 to 7.5 feet. The East Marsh is affected by the backwater from the beaver dam and is subject to tidal fluctuations during extreme high tides. Backwater from the beaver dam can lead to water surface elevations of 7.5 to 8.0 feet at the culvert connecting the East Marsh to Beltz Marsh across Sand Lake Road. There is a slope to surface water between TDM and the beaver dam.
- The upland drainage network installed at TDM has limited capability to drain TDM following intense rainfall events due to a combination of local topographic depressions with a lack of positive surface-water drainage, absence of a drainage network along residential roads, and limited capacity of the culverts along Sand Lake Road to transmit flows. The two drainage ditches intercept shallow groundwater and convey it to Beltz Marsh.

2.2 HYDROGEOLOGIC CONDITIONS

PGG installed seven wells at four locations at TDM. There are two layered aquifers beneath TDM: a shallow unconfined aquifer and a deeper confined aquifer. PGG's wells were completed in both aquifers to track and compare their relative water level elevations WLE's). Both aquifers are composed of sandy sediments and are separated by a clay layer (aquitard). The clay layer appears to be present throughout the study area and extends from bedrock on the east towards the beach areas west of the foredune. The layer appears to thin to the west and is inferred to pinch out and end under the foredune or beach.

PGG and OPRD measured water levels in new and selected existing monitoring wells completed above and below the clay layer over a 38-day monitoring period from February 16, 2018 to March 26, 2018. Additional water-level snapshots were taken in May and August 2018, with the former including water-level measurement at a temporary piezometer installed between existing monitoring wells to document the presence of a groundwater divide. Groundwater levels indicated:

- There is a persistent downward vertical gradient between the Shallow and Deep Aquifers with a head differential of up to 4.25 feet across the clay layer. No upwelling from the deeper aquifer was observed beneath TDM, but likely occurs offsite where the deep aquifer discharges to surface-water features.

- The groundwater beneath TDM flows towards surrounding discharge points. A groundwater flow divide (high point in water level elevations) separates flow to the northwest (towards the beach) from flow to the north (towards Beltz Marsh) from flow to the northeast (towards the ditch along Sand Lake Road and the east marsh).
- There is no tidal signature in the shallow aquifer and a muted tidal signature in the Deep Aquifer. This is consistent with unconfined conditions in the shallow aquifer and confined conditions in the Deep Aquifer unit, as suggested by geologic observations during drilling.
- The water levels in the deeper aquifer unit suggest that the clay layer is absent, discontinuous or leaky near the bedrock contact east of TDM at the toe of the hillslope east of the east marsh, thus allowing groundwater discharge into the east marsh area via the shallow aquifer.

Groundwater flooding issues at TDM occur when the water table rises above the ground surface. This is most common during winter months and is qualitatively observed to occur with precipitation events greater than one inch in 24 hours. This flooding covers roads, driveways and yards, and can also impact septic system function with the water table near, but not above, the ground surface. After a groundwater flooding event, subsequent decline of the shallow water table is limited by rates of groundwater flow towards discharge features (constructed drainage ditches and nearby surface-water features).

2.3 MODELING

Both surface-water and groundwater modeling were used to evaluate how changing the tide-gate configuration on the Beltz Dike would affect depth to groundwater in the shallow aquifer beneath TDM. The surface-water model was used to estimate how different tide-gate configurations (existing tide gate, modern tide gate, and dike breach engineered for fish passage) affects the extent and duration of inundation in Beltz Marsh due to tides and stream inflows. The groundwater model was used to compare how shallow groundwater beneath TDM responds to the three inundation regimes predicted by the surface-water model. After presenting the three initial modeling runs to stakeholders, PGG and ESA performed a set of supplemental analyses to respond to questions and suggestions that were received. The questions and suggestions that led to these supplemental analyses are detailed in Appendix H. Supplemental analyses included both surface-water and groundwater assessment.

2.3.1 Surface-Water model

An existing surface water balance (“bucket”) model was updated for this study. The water balance model captures the essential hydrologic characteristics of the surface-water system and provides a time series of surface water levels (stages) as input to the groundwater model. The bucket model was modified to improve the stage-storage relationships in Beltz Marsh based on new topographic and bathymetric information provided by OPRD and incorporate water inputs from TDM, the East Marsh, and direct precipitation on the marsh.

The bucket model was calibrated to a 7-month record of water level data collected inside and outside of the dike (November 2016 thru June 2017), which includes wet periods, dry periods and at least 5 intense rainfall events. Calibration was performed by adjusting the friction in the modeled tide-gate culvert opening and by assuming that the gate remained slightly open during rising tides (driving ‘leaky tide gate’ conditions). Calibration achieved a high level of agreement between modeled and observed water levels inside the marsh.

To understand how water levels in Beltz Marsh would be affected by alternatives to the existing tide gate, we developed an initial "worst case" hydrology scenario to use for predictive modeling scenarios. OPRD and the PGG/ESA team agreed on a 38-day hydrology scenario that incorporates: (1) a 28-day "wind-up period" with typical winter tide and runoff conditions from January 7th to February 4th, and (2) a 10-day 'storm' period from February 5th to February 14th based on precipitation and runoff scaled to approximate a 50-year flood-flow condition and king tide conditions in Sand Lake Estuary.

The bucket model was configured to address three different tide-gate configurations in the Beltz dike. Besides the existing tide-gate configuration, two alternative configurations (both likely to meet fish passage criteria) included:

- Breached Dike – excavating a portion of the dike to create an open "breach" or tidal channel inlet, sized based on Design Guidelines for Tidal Channels in Coastal Wetlands (Philip Williams & Associates, 1995). The modeled breach extends to 0 feet elevation and ranges from 37 feet wide at the base to 53 feet wide at Mean Higher High Water.
- Modern Tide Gate System – replacing the existing culvert and tide gate with a modern tide gate system designed to meet fish passage criteria, while allowing the water level in the marsh to be controlled at a set elevation. Preliminary sizing is based on a Muted Tidal Regulator system that limits the surface water elevation to 7.0 feet; the tide gates shut when the interior water surface elevation reaches 7.0 feet and the tide gates re-open when the water level in Sand Lake falls below the interior water level allowing Beltz Marsh to drain. The preliminary tide gate sizing includes two, side-by-side tide gates, each 8 feet tall and 10 feet wide.
- Under the supplemental analyses (Section 8), an alternate tide gate closure setting of 8.0 feet was also modeled, using the same tide gate dimensions.

Use of the model to simulate the 38-day hydrology scenario under all three tide-gate configurations was considered to provide a range of "bookend scenarios" that bound the predicted effects of various tide-gate configurations over a range of hydrologic conditions. The modeled scenarios are expected to reflect the greatest range in tidal stage in Beltz Marsh.

Surface-water modeling results for the three scenarios include:

- Existing Conditions (existing culvert and tide gate through dike):
  - During the 28-day wind up period, water levels inside marsh ranged from 5.5 to 8.3 feet.
  - During the 10-day storm period, water levels peaked at 12-12.5 feet.
  - Flood levels in the marsh remained above 9 feet for more than 3 days because the existing tide gate is inefficient at draining Beltz Marsh.
- Breached Dike:
  - The breach is an efficient conveyance and water levels inside the marsh closely matched the water levels in Sand Lake at all times.
  - During the 28-day wind up period, water levels inside marsh ranged from 5.5 to 11.2 feet.
  - During the 10-day storm period, water levels briefly exceeded 12.0 feet.
  - The much larger opening allows water to freely drain out of the marsh, so elevated water levels quickly fell as the tide receded and were not impounded behind the dike.

- Modern Tide Gate:
  - Peak daily water levels were lower than both the breached-dike and existing-tide-gate configurations because the tide gate closes when water levels inside the marsh reach 7.0 feet on a rising tide.
  - During the 28-day wind up period, water levels inside marsh ranged from 5.5 to 7.5 feet.
  - During storm conditions, water levels in the marsh were lower than both the breached-dike and existing-tide-gate configurations because of the limited tidal inflow and the efficient flow of water out of the marsh.
  - During the 10-day storm period, water levels briefly exceeded 10.0 feet, but quickly fell as the tide receded.

Based on recommendations from PGG/ESA team members and public comment, OPRD decided to have the consulting team run a variety of supplemental analyses. The comments and suggestions received, paired with study response and action are detailed in Appendix H. Supplemental surface-water modeling and analyses included:

- Evaluating the feasibility of constructing a setback dike located south of Reneke and Beltz Creeks that would allow for full tidal reconnection of the majority of Beltz Marsh while maintaining flood protection for TDM;
- Characterizing the effect of surface water "backing up" upstream of the Sand Lake Road culvert in the East Marsh, or in the TDM east ditch along Sand Lake Road;
- Characterizing the protective value of an overtopped dike for its ability to reduce peak water levels or delay rising water levels upstream of Beltz Dike;
- Assessing how inclusion (or exclusion) of inundation accumulated behind the beaver dam affects surface-water model results (i.e., if substantial additional storage volume could be achieved by removing the beaver dam);
- Simulating the modern tide gate with an 8-foot closure setting (rather than a 7-foot closure setting) during the same time 38-day prediction period as used in the previous model. Appendix H refers to modeling both 7.5 and 8-foot closure settings; however, in completing the 8-foot setting and finding insignificant storm-scenario differences from the 7.0 closure setting (in terms of both surface water and groundwater effects), it was decided that additional modeling effort and expense to complete the intermediate 7.5-foot closure setting was not necessary.

2.3.2 Groundwater Model

The groundwater model covers 442 acres over a domain that extends west-to-east from the beach to the bedrock uplands and north-to-south from Beltz Marsh to Sears Lake. The model divides up the subsurface into interconnected cube-like "cells", which are further grouped into three "layers". The top layer represents the shallow aquifer, the middle layer represents the clay aquitard, and the bottom layer represents the Deep Aquifer. The top of the model is the land surface, and the bottom is the estimated bedrock surface that underlies the sedimentary aquifers.

The groundwater model represents key elements of the groundwater and surface-water flow systems, including:

- The hydraulic properties of the shallow aquifer, the clay aquitard and the Deep Aquifer;

- The role of exposed and buried bedrock in constraining groundwater flow;
- Groundwater levels within aquifer units and the hydraulic gradients between aquifer units;
- Hydrologic interactions between aquifers and key surface-water features including Beltz Marsh, the East Marsh, the Pacific Ocean, and drainage ditches excavated at TDM;
- Tidal influence and inundation along the coastline and within Beltz Marsh; and
- Groundwater recharge from precipitation and septic-system effluent.

The groundwater model was calibrated in steady-state (time-averaged) and transient (time-varying) modes. Steady-state calibration focused on matching average groundwater elevations observed during the 38-day wet season monitoring period (2/16/18-3/26/18), and transient calibration focused on matching the groundwater level variations observed during the monitoring period. Calibration also considered water-level differences between the Shallow and Deep Aquifers, predicted areas of groundwater flooding, and discharge to TDM drainage ditches. Two versions ("realizations") of the model were developed during calibration which reflect different magnitudes and timing of groundwater recharge based on precipitation records from the two nearest weather stations with published data (Tillamook and Cloverdale). These stations are assumed to represent the potential range of precipitation in TDM, as they provide different precipitation values (Tillamook is wetter on average, and Cloverdale is drier on average). The dual realization approach was chosen to bracket a range of precipitation uncertainty, and (via model calibration) yield a range of aquifer properties that provides a range of model predictions of groundwater-level response to changes in Beltz Marsh inundation. Additional model configurations can be considered to further explore predictive uncertainties associated with hydrogeologic uncertainty.

Model calibration provided good matches to both average groundwater elevations and groundwater-level responses to precipitation and tidal variation. Calibration also included a "sensitivity analysis", which quantified the sensitivity of steady-state model calibration to ranges of key model parameters. The parameters that had the most effect on calibration matches between observed and predicted groundwater elevations included: rates of groundwater recharge, horizontal hydraulic conductivity of the sandy sediments that comprise both the Shallow and Deep Aquifers, and vertical hydraulic conductivity of the clay aquitard. Model calibration was not very sensitive to the hydraulic conductivity of the finer-grained sediments that have accumulated on the bottom of Beltz Marsh. Supplemental sensitivity analysis with both the steady-state and the transient models showed that experimentally increasing the hydraulic connectivity between the marsh and the Shallow Aquifer beneath TDM did not significantly affect predictions of Shallow Aquifer groundwater responses to Beltz Marsh inundation. Lastly, groundwater levels beneath TDM were not sensitive to whether channels behind the beaver dam were represented as permanently inundated (dam functioning) or open to tidal variation (dam removed). For this reason, the beaver dam was not represented in final versions of the groundwater model.

2.3.3 Model Predictions of Groundwater Level Changes

Both realizations of the groundwater model were used to predict how the three Beltz Dike configurations would affect groundwater levels in the Shallow Aquifer beneath TDM. The predictive simulations included 28 days of average wet-season precipitation and winter tidal variation followed by a ten-day long "storm event" that included extreme (King) tides, high onshore winds, and high precipitation recharge.

- Relative to current tide gate configuration, the model predicted that a modern tide gate would reduce wet-season shallow groundwater elevations beneath TDM by very small amounts (<0.01 feet = <1/8inch) during average conditions. During flood conditions, the model predicted water-level reduction of up to 0.17 feet (about 2 inches) in monitoring well PGG-1i (located in the Shallow Aquifer adjacent to Beltz Marsh). This effect rapidly diminishes with distance from the marsh, and is not predicted for any other Shallow-Aquifer monitoring wells referenced in this report. Predicted reductions in groundwater elevations occur due to propagation of reduced surface-water elevations in Beltz Marsh that result from both: 1) more efficient drainage achieved by the modern tide gate, and 2) the tide gate design's prevention of incoming tide after water surface elevation outside the dike exceeds 7.5feet. Model simulations originally assumed a tide-gate shutoff of 7 feet NAVD88; however, supplemental simulations with an 8-foot shutoff did not significantly change predictions of Shallow Aquifer responses beneath TDM.

- Relative to existing conditions, the dike-breach simulations predicted insignificant change in shallow groundwater elevations beneath TDM during average conditions and reduced groundwater elevations during the storm event. During average conditions, water levels in Shallow-Aquifer monitoring well PGG-1i (located adjacent to Beltz Marsh) were predicted to exhibit increases up to 0.02 feet (or, 1/4inch) . This minor increase occurs because the breached dike allows more tidal exchange and supports higher peak surface-water elevations in Beltz Marsh. The increase is predicted to decay rapidly with distance from Beltz Marsh, and is not predicted for any other Shallow-Aquifer monitoring wells referenced in this report. During storm conditions, Shallow-Aquifer groundwater level reductions are predicted to range from a maximum of 0.14 feet (1.7 inches) in Well PGG-1i (near Beltz Marsh), diminishing rapidly in monitoring wells located farther south. Reduced groundwater elevations during storm conditions arise because better drainage through the dike breach reduces the accumulation of stream inflows behind the dike causing less prolonged inundation.
- Model predictions for the Deep Aquifer exhibit the same trends as noted above for the Shallow Aquifer, but water-level changes are predicted to be larger than for the Shallow Aquifer. This difference occurs due to the confined nature of the Deep Aquifer, which results in enhanced propagation of water-surface elevation changes in Beltz Marsh back into the adjacent groundwater system. The clay confining layer between the Shallow and Deep Aquifers constrains the influence of predicted changes in the Deep Aquifer on water levels in the Shallow Aquifer. The model therefore predicts that water-level changes in the Deep Aquifer will have minimal impact on the Shallow Aquifer.

3.0 SITE OVERVIEW AND CLIMATE

In 2014, OPRD acquired property north of Pacific City, including and adjacent to portions of Sand Lake Estuary. The property consists of approximately 87 acres of marsh (including approximately 42 acres of tidal marsh, sand, and mudflats and approximately 12 acres of estuary altered by the half-mile long Beltz Dike which runs east/west across the property.)

Tierra Del Mar (TDM) is a residential community located immediately south of Beltz Marsh (Figure 1-1). Relative to surrounding areas, TDM is flat, with elevations ranging from around 18 to 23 feet NAVD88. TDM is triangular in shape, pinching out to the south. It is surrounded by the Pacific Ocean (and associated foredune) to the west, additional dunes (with scrubby vegetation) and Beltz Marsh to the north, and forested bedrock hills to the east. A marshy swale ("East Marsh") occurs between TDM and the bedrock hills.

Climatic conditions in the Beltz Marsh/TDM vicinity are moderated by the Pacific Ocean. Winter conditions are generally warmer and wetter than more interior portions of Oregon, whereas summer conditions are cooler and wetter. Temperatures seldom drop much below freezing in winter. When summer temperatures in the Willamette Valley reach 80-90 degrees F, it is common for the coast to remain near 60 degrees F. Annual precipitation along the immediate coast is generally lower than in the rising elevations to the east (depending on local topography). Precipitation over the ocean is between 30 and 50 inches per year, and increases up to 200 inches per year in the highest coastal mountains where topography forces moisture to condense. The majority of annual precipitation falls as rain and occurs primarily from November to March. A fog belt occurs along the coast which is characterized by fog, low clouds, and moist marine air. Coastal fog often persists when areas outside the belt are cloud-free.

Climatic conditions in the Beltz Marsh/TDM vicinity are characterized by published data from weather stations at Tillamook (15.3 miles to the northeast) and Cloverdale (5 miles to the southeast) (Figure 1-1). Table 3-1 summarizes monthly climate data from both stations and shows that average annual precipitation at Tillamook (88 in/yr) is 10 percent higher than average annual precipitation at Cloverdale (80 in/yr). PGG also reviewed published precipitation from both stations for the months of February and March 2018 – assumed to be representative of conditions influencing the period of water-level monitoring conducted in the study area. The daily precipitation time-series is shown on Figure 3-1 and shows that Tillamook precipitation over the 2-month period was 37% higher than Cloverdale precipitation.

PGG was also provided with climate data from a private weather station (PWS) at TDM. However, precipitation measured at the PWS was lower than either of the two published stations and was therefore inconsistent with the expected geographic trend. The accuracy of PWS climate data is typically not as rigorous as for published weather stations, as evidenced by a high degree of variability noted by PGG for 6 PWS's in the Cloverdale vicinity. For this reason, PGG did not utilize the TDM PWS data for this investigation.

4.0 SURFACE-WATER HYDROLOGY

Surface water hydrology in Beltz Marsh and adjacent areas is influenced by tides in the Sand Lake Estuary, freshwater input from Reneke Creek and Beltz Creek, and local drainage features. This section characterizes existing surface water hydrology based on observations and studies conducted by ESA, PGG, and others. This characterization and associated conceptual model will inform the basis for surface-water modeling of existing and future conditions being considered by OPRD.

4.1 PREVIOUS STUDIES

The Federal Emergency Management Agency (FEMA) includes surface water flooding of the project area in the effective FIS and preliminary Flood Maps for unincorporated Tillamook County, OR (FEMA 2002, FEMA 2015). Preliminary flood maps (FEMA 2015) indicate an "Zone AE" with base flood elevation of 11.8 ft NAVD88 within Sand Lake Estuary and Sitka Sedge. Zone AE are areas that have a 1% probability of flooding, also known as the 100-year floodplain, where flood water elevations have been established.

Preliminary maps also indicated flooding across the low spot in Sand Lake Road for base flood conditions. The basis for flood elevations depicted in the preliminary FEMA maps is documented in the Oregon Department of Geology and Mineral Industries (DOGAMI) coastal flood hazard study for Tillamook County (DOGAMI 2015). Flooding sources are described coastal backwater effects from the Pacific Ocean and do not include the influence of river or stream inputs into Sand Lake. ESA notes that the FEMA maps show the Beltz Dike but do not consider it a barrier that prevents flooding from Sand Lake for the purpose of flood insurance.

Tillamook Estuary Partnership collected 6-weeks of water surface elevation data and other water quality parameters during the summer of 2015.

OPRD's botanical assessment (OPRD 2017a), wildlife assessment (OPRD 2016a), and master plan (OPRD 2016b) collectively describe site history, existing habitat types, fish use and fish passage concerns, surface-water quality measurements (salinity, temperature, dissolved oxygen) within the marsh and adjacent to the existing dike and tide gate. These reports also present alternative management measures and information regarding modifications to the existing dike and tide gate similar to that presented in Waterways (2017).

Waterways Consulting, Inc. (Waterways) previously conducted a feasibility study for OPRD to investigate potential changes to water surface elevations and inundation frequency within the marsh for a range of restoration alternatives. The Waterways (2017) summary report describes topographic and bathymetric data, hydrologic background, preliminary "bucket" inundation model calibration and application to evaluate alternatives, fish passage evaluation, and limited groundwater analysis. The "bucket" model was calibrated to limited water level measurements made in the summer of 2015 and then used simulated water surface elevation within the marsh at 15-minute intervals from 2005 to 2015 by considering tidal flux from Sand Lake, freshwater input from two tributary creeks, and storage within the marsh. Waterways (2017) indicates that modifications to the existing tide gate may result in slightly better drainage at low tide and a moderate increase in the frequency of tidal inundation in the high marsh and adjacent areas. The report recommends incorporation of drainage from the marsh east of Sand Lake Road and suggests that an expansion of the modeling effort may be required to answer questions in a subsequent phase of work.

Waterways subsequently collected water level data at twelve locations in 2016 through June 2017. Surface water measurements included locations inside and outside the existing dike at the tide gate, within Beltz marsh upstream of the existing beaver dam, and within the marsh on the east side of Sand Lake Road.

OPRD has conducted supplemental survey of monitoring wells and topographic survey points and made adjustments to provide correct survey information. OPRD-corrected elevations have been applied to water level and topographic data collected in 2016 to 2017, as possible, to support the current hydrologic study effort.

4.2 TOPOGRAPHIC CONDITIONS

Prior to diking, Beltz marsh was formerly a shallow embayment fully connected to the Sand Lake Estuary via tidal channels and mudflats. Topographic modifications including construction of the Beltz dike, ditching in the marsh, construction of Sand Lake Road, quarry activities, and development of Tierra Del Mar community continue to affect site hydrology. Primary sources of data are available to describe site and adjacent topography and bathymetry include:

- OPRD Combined LiDAR and Photogrammetric (PhoDAR) DEM (various dates)
- Waterways RTK and Total Station survey (2016)
- NOAA LiDAR (2016)
- OPRD Survey (2017 & 2018)

In general, limited bathymetric data are available to describe the elevations of channels and low-lying mudflats within the study area and adjacent Sand Lake Estuary.

Figure 4-1 depicts an annotated site topography map derived from OPRD DEM (various dates). Appendix A includes a series of photographs of key site features taken during ESA's field reconnaissance. Key features include the Beltz Dike, tide gate, remnant tidal channel and ditch network, beaver dam in the marsh, Sand Lake Road prism, Tierra Del Mar community ditches, east marsh complex, and dunes to the west of the marsh. Note that areas within the marsh having elevations below 5.0 ft NAVD88 remain inundated most of the time, while areas with elevations above 8.0 ft NAVD88 are rarely inundated. The low point in Sand Lake Road has an elevation of approximately 11.6 ft NAVD88. Residential areas within Tierra Del Mar (TDM) have ground elevations generally ranging from 14.0 to 22.0 ft, or higher. The TDM ditch and culvert network that flows north and discharges into the marsh above the direct influence of the tide.

4.3 TIDES

Tides are the primary driver of surface water level fluctuations in Beltz marsh. Tidal fluctuations in the Pacific Ocean are transmitted to the marsh via the shallow Sand Lake Estuary and communicated through the existing tide gate. Pacific Ocean tides are influenced by both astronomical (sun & moon) and meteorological factors (storms). Storms and other large-scale atmospheric phenomenon, such as El Niño, tend to elevate the tides above predicted levels during the winter season. These same storm events are also responsible for delivering heavy rain to the area that frequently correspond with high tide events. Measurement of ocean tides in the immediate vicinity of Sand Lake Estuary are not available. Long term measurements at South Beach in Newport, OR, and Garibaldi, OR (within Tillamook Bay), provide a representative ocean tides offshore of Sand Lake Estuary.

As ocean tides enter the Sand Lake Estuary they are affected by the shallow nature of the estuary and complex tidal channel network, resulting in a situation where water levels in the estuary near the Beltz marsh are elevated above the ocean tides almost all of the time. Measurements consistently show that tides at the outside of the Beltz Dike are transformed such that daily low tides are severely muted and never fall below elevation 5.3 ft NAVD88 (for reference mean sea level in the ocean is about 3.7 ft). Water levels at high tide outside the dike are elevated approximately 0.5 to 1.0 ft above the ocean tides. The precise mechanism resulting in higher tides at the dike can likely be explained by shallow-water overtide harmonic phenomenon.

Fluctuations behind the dike in Beltz marsh are primarily controlled by the interaction of tides in Sand Lake with the tide gate, and secondarily by inflow from creeks and local drainages. Measurements show that for existing conditions, the tide gate leaks and allows some limited tidal flux to gradually enter the marsh on rising tides. Water passes through the leaky tide gate and water levels behind the dike rise more slowly and lag behind those in Sand Lake due to the limited flow through the tide gate. Tides in Sand Lake peak and begin to fall before the marsh completely fills and as water levels equilibrate on the ebb tide the flow reverses and the tide gate opens to release water from behind the dike. Compared to Sand Lake, the daily higher high tide elevation behind the dike is about 1.0 to 2.0 ft lower. In the absence of significant freshwater input, low tides behind the dike tend to be similar to those in Sand Lake but are slightly elevated (a few inches) and of longer duration as the marsh slowly drains. Freshwater inputs from creeks and local drainages that arrive on a rising tide accumulate within the marsh and contribute to elevated water levels behind the dike. Following heavy rainfall events, it can take multiple tidal cycles for accumulated freshwater to be discharged through the existing tide gate. The existing leaky tide gate does not appear to function for any specific purpose, though it does limit flux through the dike and thereby cause lower water levels than in Sand Lake at high tide, and higher water levels than in Sand Lake at low tide and following intense rainfall events.

Existing tidal fluctuations in the south end of the marsh are impeded by the existing beaver dam that impounds water in the ditches and wetlands near Sand Lake Road. Water levels remain relatively constant in time at about elevation 8.0 ft NAVD88 during the wet season and drop down to elevation 7.0 ft during summer low flow period. The beaver dam is approximately 3.0 ft high, based on observations by ESA staff in February 2018.

Figure 4-2 depicts typical water level fluctuations in the project vicinity during winter (rainfall) and Figure 4-3 depicts typical summer (no rainfall) conditions.

Sea level rise will cause future tidal fluctuations in the ocean, within Sand Lake, and in Beltz Marsh to rise in elevation relative to the land. The precise amount of sea level rise that will be experienced at the project site in the future is unknown and depends upon many factors. Additional future conditions modeling could, if warranted, explore a range of future sea level rise scenarios. It is important to note, however, that the current dike would be overtopped with only inches of sea level rise, and modeling of overtopping dynamics, dike erosion, etc. is extremely complex and outside of the scope of the current contract

4.4 FRESHWATER

Frequent and intense rainfall is common along the Oregon coast, and in the vicinity of the project site. Mean annual rainfall is on the order of 80 inches per year, with 2-year peak 24-hour rainfall intensity of about 3 inches (USGS 2018). Measurements of local rainfall collected by Buck Miller (pers. com) are available from 2009 to present. Other rainfall records are available at Tillmook and Cloverdale, OR. Periods of intense rainfall correspond to both elevated water levels in Beltz marsh and photographs of flooding provided by the TDM community from 2016-2017 (pers. com). Given the size of Beltz marsh, direct rainfall in the marsh may contribute meaningful surface water inflow during high intensity events.

Beltz Creek (0.5 square mile drainage) and Reneke Creek (0.9 square mile drainage) are the primary freshwater sources that discharge into Beltz marsh under existing conditions. As reported by Waterways (2017) neither of the creeks has been gaged and few streamflow measurements are available to describe the response of the creek drainages to rainfall events. Therefore, the current understanding of creek hydrology relies on limited observations, comparisons with nearby gaged steams (Tucca Creek), and scaling to approximate discharge from Beltz and Reneke Creeks.

Reneke Creek flows west towards Sand Lake Road, where it encounters a blocked culvert and then diverts southwest along Sand Lake Road. The creek then flows into a partially blocked 38-ft long, 2-ft diameter, culvert that passes beneath Sand Lake Road into Beltz marsh. The culvert invert elevations are low enough to be subject to tidal fluctuations in the marsh during extreme high tides and ESA observed what appeared to be salmonid fish in the pool immediately downstream of the culvert. Upon entering the riparian area west of Sand Lake Road, the creek channel meanders through wetlands and then bifurcates into multiple smaller braided channels that separately discharge into the marsh. Signs of erosion and road overtopping indicate that the existing culvert is undersized and does not pass all creek flows beneath the road. Historic photos and ground observations indicate that Reneke Creek was formerly routed through the blocked culvert and then to the north along what is currently a dry swale

Beltz Creek arrives at Sand Lake Road at a higher elevation than Reneke Creek and passes beneath Sand Lake Road through an angled 80-ft long, approximately 3-ft diameter, culvert. The downstream end of the culvert is perched about 2.5 ft above the adjacent creek channel and well above the influence of the tide.

The creek channel then flows through the former rock quarry and splits into at least two smaller channels before entering the marsh and ditch network.

The primary drainage ditch from TDM (identified as the East Ditch) flows north through a series of small culverts that parallel Sand Lake Road. The final culvert beneath Roma Ave. consists of a 40-foot long 12-inch diameter corrugated smooth interior wall HDPE pipe with an outlet invert elevation of 11.7 ft NAVD88. The ditch continues north and connects with other ditch networks upstream of the existing beaver dam within the marsh. Flows through the ditch along Sand Lake Road are limited by the capacity of the culverts and condition of the ditch.

A secondary drainage swale within TDM (identified as the North Ditch on Figure 4-1) runs parallel to the dune line and flows northeast through TDM, including beneath roads and structures, before turning in an east-northeast direction north of the trail at the end of Roma Ave. Culverts were located that pass flow beneath Jasmine and Pollock Ave., however no culvert north of Pollock was located. Therefore, it is unclear how water within the swale reaches the marsh. Surface water ponding is a common problem in as evidenced by photographs provided by property owners to OPRD. ESA reviewed these photos and LiDAR topography and found that much of this ponding can be attributed in part to topographic depressions that lack positive drainage. Such ponding likely is exacerbated when the soil becomes saturated with groundwater following heavy rains. Figure 4-4 illustrates ESA's conceptual understanding of frequently ponded areas based upon review of topographic depressions that correlate well with site photographs following intense rainfall events. Ponding depths may vary from a few inches to more than one foot, depending upon local topographic conditions.

Finally, drainage from the East Marsh located on the east side of Sand Lake Road and across from TDM, flows into the south end of Beltz marsh via a 2-ft diameter culvert beneath Sand Lake Road. The drainage basin for this marsh is not well delineated, but likely is on the order of 0.1 to 0.2 square miles. Limited measurements in this marsh by OPRD in 2018 indicate that water levels in the immediate vicinity of Sand Lake Road are controlled by the backwater created by the beaver dam in Beltz Marsh. Ground levels and surface water levels in the East Marsh continue to rise to the south likely impounded by relic beaver dams and/or emergent vegetation. Observations by ORPD in spring of 2018 indicated water ponded approximately 1 ft above the ground surface throughout this marsh, with deeper water closer to the Sand Lake Road culvert.

ESA suspects that groundwater baseflow also contribute surface water inputs to the marsh, particularly during the wet season. Groundwater hydrogeology is discussed in the following sections.

4.5 HYDROLOGIC CHARACTERIZATION

- The Beltz dike tide gate does not function properly and allows water to flow into the marsh when water levels are higher in Sand Lake. Still, water levels at high tide are lower on the inside of the dike under existing conditions due to limited flux allowed in and out by the tide gate.
- The existing tide gate is not sufficient to drain accumulated freshwater within the marsh following intense rainfall events and thus it currently takes multiple low tide cycles for water levels in Beltz Marsh to equilibrate with Sand Lake.
- The existing beaver dam at the south end of Beltz Marsh impounds water and creates a backwater area that causes water to pond on the east side of Sand Lake Road within the East Marsh.

- The Reneke Creek culvert is partially buried and cannot convey the flow of the stream during peak flow conditions. Beltz Creek culvert is perched above the downstream channel and well above the influence of the tide.
- The upland drainage network in TDM has limited capability to drain TDM following intense rainfall events due to a combination of local topographic depressions with a lack of positive drainage, absence of a drainage network along residential roads, and limited capacity of the culverts along Sand Lake Road to transmit flows.
- The East Marsh is affected by the backwater of the beaver dam in Beltz Marsh and is subject to tidal fluctuations during extreme high tides. Ponded water has been observed in the East Marsh well above the influence of the backwater from Beltz Marsh.
- Figure 4-5 shows and describes the major hydraulic control features affecting surface water movement into, out of, and within Beltz Marsh, including the Beltz Dike, culvert and tide gate and the main beaver dam in the marsh's interior.
- Figure 4-6 summarizes elevations of key site features and water levels

5.0 GROUNDWATER HYDROLOGY

This section describes groundwater and associated surface-water observations from investigations conducted by PGG in cooperation with OPRD in February and March 2018. Appendix A includes photographs of the hydrogeologic investigations, and site observations and features of interest.

5.1 PREVIOUS STUDIES

Previous studies have installed monitoring wells and measured surface water and groundwater in the Sitka Sedge and TDM areas. These studies include:

- Waterways hydrogeologic characterization (Waterways, 2017)
- TDM water level monitoring (ongoing)

Waterways installed multiple monitoring wells, conducted preliminary surface water hydrologic characterization of the Beltz marsh and tributaries, and preliminary evaluation of fish passage with dike modification alternatives. Water level monitoring and boring logs in the Waterways report indicated the presence of a clay layer in the project area, but due to well designs that penetrated the clay layer, water levels recorded at the majority of the wells were not useful for evaluating the hydraulic significance of the clay layer

TDM has a network of shallow wells (TDM-1s through TDM-4s) located south of Bilyeu Avenue. Water levels are monitored by TDM residents. TDM residents also have useful anecdotal understanding of how groundwater flooding issues relate to changes in site hydrologic features, especially the ditch along Sand Lake Road.

5.2 EXPLORATORY BORINGS AND HYDROSTRATIGRAPHY

Exploratory borings and well construction were completed in February 2018 to characterize the extent of hydrostratigraphic units identified in previous reports, and to improve the water-level monitoring network in the shallow aquifer (Waterways, 2017). Observations from exploratory borings were used to select screen intervals for well construction above and below the regional confining clay layer.

Five exploratory borings were advanced by direct push in the TDM neighborhood concurrent with well installation (Figure 5-1; Appendix B). Monitoring wells were completed at four of these sites, as discussed in Section 5.3. Malia Kupillas, Registered Geologist and TDM resident, also observed drilling and archived soil cores after sampling and logging. A boring was advanced at each new well location to investigate the site-specific geology and provide a basis for well construction screen intervals. An additional boring ("PGG-Boring") was advanced at the Community Center on Bilyeu Avenue to provide additional lateral coverage of the extent of subsurface units. Boring logs are included in Appendix B. At each location, continuous soil cores were collected to a depth of 20 feet below ground surface (bgs). Soil cores were described in the field with observations of soil type by depth. At location PGG-Boring, drill rods were advanced below 20 feet without collecting soil cores to tag the bedrock contact. The rods hit refusal at approximately 54 feet, which was interpreted to be a contact with underlying weathered bedrock.

Two hand-auger locations were also advanced to depths of 1 ft bgs at the edge of the marsh area north of Roma Avenue to look for shallow, low-permeability soils that could act as a barrier to groundwater exchange with surface water (Figure 5-1). This is referred to as a "skin-effect". Low-permeability sediments that would form a hydraulic skin were not observed at hand auger locations. Whereas a low-permeability skin might limit groundwater discharge to the marsh floor, there was no evidence that surficial sediments prevented groundwater discharge to the marsh. PGG observed orange bacterial mats on the marsh floor (and in other surface-water features) that suggests groundwater discharge; iron- and manganese-metabolizing bacteria live on the chemical gradient between the water types and cause the accumulation of these colored mats.

The following generalized geology is inferred from the soil core borings, and shown conceptually in the geologic cross sections in Figures 5-2a,b. The subsurface is dominated by fine sands nearly identical to the modern beach and dune sands. The sands exhibited textures consistent with both dune (wind) and shallow coastal (marine) depositional environments. Subsurface sediments show a shallow and deep zone, separated by a clay and silt layer. This fine-grained confining layer was observed in all borings at approximately 12 feet bgs, including at an equivalent depth in a boring advanced to the north on Whalen Island (Waterways 2017). The layer likely forms a regional aquitard between the Shallow and Deep Aquifer units. The clay layer thins and become more silty/peaty to the west which may locally influence effective leakance through the layer. The clay layer is often underlain by an interval of peat and roots extending into the underlying sand unit. The clay layer is also described in the boring log for the well installed on Whalen Island, suggesting that the clay layer extends north under the Beltz Dike and marsh area. Based on this observed geology, we divide the subsurface into three aquifers:

- **Shallow Aquifer**: this is the unconfined water table aquifer above the clay layer
- **Clay Unit (or clay layer)**: this is a thin aquitard separating the Shallow and Deep Aquifers
- **Deep Aquifer**: this is the confined or semi-confined aquifer below the clay layer.

5.3 WELL CONSTRUCTION

Nine wells were installed at four of the exploratory boring sites on February 14 and 15, 2017 (Figure 5-1). Between one- and three-wells were installed adjacent to the exploratory borings using a direct push drill rig. Completion intervals were selected based on the geologic observations from co-located exploratory borings to collect water levels immediately above and below the clay layer. At sites PGG-2 and PGG-3, additional wells were completed near the water table to investigate if vertical gradients were present *within* the shallow aquifer. Wells were constructed of 1-inch flush threaded schedule 40 PVC, 2-foot long pre-packed screens, and additional 20/40 sand pack in the annular space to 1-foot above the screen. A bentonite seal was then placed to the base of the concrete that the flush-mount monument was set in. Wells were screened at three depth intervals, with the following well name suffixes:

- **Shallow (-s)**: well screened at the February 2018 water table in the Shallow Aquifer and above the clay layer; these wells may be dry in summer months (e.g., PGG-2s).
- **Intermediate (-i)**: Well screened immediately above the clay layer in the Shallow Aquifer (e.g., PGG-2i).
- **Deep (-d)**: well screened just below the clay layer in the Deep Aquifer (e.g., PGG-2d).

Well construction and survey information are summarized in Table 5-1. OPRD survey crews measured top of casing elevations to the nearest 0.01 ft, concurrent with survey of other site features in March and April 2018 (Figure 5-1, Table 5-1, Appendix B). Top of casing elevations are approximately 0.3 feet bgs inside the flush mount monuments.

5.4 AQUIFER PROPERTIES

Soil grain size analyses, slug hydraulic tests, and field descriptions from borings were used to estimate the hydraulic conductivity (K) of the deep and Shallow Aquifer unit and clay layer. The hydraulic conductivity is a measure of the soil permeability and is an important input to the groundwater numerical model.

Four soil samples from exploratory borings were submitted to Krazan Associates for grain size analysis (Appendix B). Two samples were submitted from the shallow sand unit (PGG-2 and PGG-4), one sample was submitted from the deep sand unit (PGG-2), and one sample was submitted from a sandy peat (PGG-4). Table 5-5 summarizes sample descriptions, locations and laboratory results. K was estimated from grain size distributions by multiple calculation methods following the procedure in Rosa (et al, 2014). K estimates from the different calculation methods showed good agreement and the average of the estimates for each unit are used in subsequent calculations. K estimates ranged from a maximum of 1.2×10^{-2} cm/s to 6.7×10^{-3} cm/s with an overall standard deviation of 1.7×10^{-3} cm/s.

Slug hydraulic tests were conducted at wells PGG-4i and PGG-4d, completed in the Shallow and Deep Aquifer units, respectively (Appendix C). Slug test water level measurements were analyzed by the Bouwer-Rice method in a USGS spreadsheet tool for analysis of slug tests (Halford, 2002; Appendix D). Due to the rapid water level recovery from slug insertion and removal, the results have low precision. Slug test analyses indicate K values of approximately 1.6×10^{-2} cm/s at PGG-4i and 4.6×10^{-3} cm/s at PGG-4d, which is consistent with and brackets grain size analysis estimates discussed below. Due to the scatter in the slug test results, K-estimates from grain size data are considered more representative than the slug test results.

Grain size analyses and hydraulic testing were not conducted on the clay layer that separates the Shallow and Deep Aquifer units. This layer is assigned a preliminary value of 1×10^{-6} to 1×10^{-9} cm/s based on standard literature values for silts and clays (Freeze and Cherry, 1979).

In summary, the following hydraulic conductivity values are derived from PGG's data collection and review, with the understanding that there may be local variations in aquifer properties and that values may be adjusted during model calibration (Table 5-5):

- Shallow Aquifer: 1.2×10^{-2} cm/s to 6.7×10^{-3} cm/s

- Clay Layer: $1x10^{-6}$ to $1x10^{-9}$cm/s
- Deep Aquifer: $1.2x10^{-2}$ cm/s to $6.7x\ 10^{-3}$ cm/s

The similarity between the Shallow and Deep Aquifer units is consistent with the field observation that the units both appear to be constituted of beach and dune sands similar to the modern dunes and beach. The lower permeability of the clay unit is consistent with the strong vertical hydraulic gradients observed across it (Section 5.5). The cross-layer effective permeability of the unit may be variable across the site based on the observation in boring logs that they layer thins to the west.

During public review of interim project deliverables, a question was posed regarding whether compaction of soils beneath Sand Lake Road is likely to affect the transmissivity of the underlying Shallow Aquifer. Based on a review of geotechnical literature and discussions with professionals familiar with this question, PGG found that compaction beneath the road is unlikely to significantly affect aquifer transmissivity. Sand Lake Road elevations range from 15-22 feet MSL along TDM, whereas the bottom of the Shallow Aquifer (top of clay layer) generally occurs at an elevation of around 4-5 feet MSL. Assuming that the road was installed directly on native materials or on a built upon a base of crushed rock positioned on top of native materials, the thickness of sandy materials beneath the road is expected to range from about 10-18 feet. Compaction depth for loose sand is generally not expected to exceed 4-5 feet, and the affected zone can be *significantly* less if the sand is already wave-compacted or if the road does not have a (heavy) fill base. Within the affected zone, compaction also diminishes as a function of depth. Saturation in the Shallow Aquifer is generally expected to occur at least several feet below the road. Applying these concepts to conditions at Sand Lake Road suggests that compaction will not significantly affect groundwater flow beneath the road.

5.5 GROUNDWATER LEVELS

PGG and OPRD measured water levels in monitoring wells locations to investigate the response of the deep and Shallow Aquifers to precipitation events and tidal influence. Groundwater levels are compared to concurrent measurements at surface-water points inside and outside of the tide gate at Beltz dike, and selected marsh locations.

5.5.1 Water-Level Monitoring

Groundwater levels were measured manually at 10 locations and with pressure transducers and data loggers at 10 locations (Table 5-1)[1]. OPRD staff measured water levels approximately weekly from February 19 through March 26, 2018. Solinst Levelogger transducers were suspended from well caps and set to record every half-hour. A barometric transducer (Solinst Barologger) was left at TDM for the duration of the water level study and set to record on the same interval. Transducers were installed on February 15 and 16, 2018 and removed on March 26, 2018. Transducer data were barometrically corrected and converted to water-level elevation (WLE) using the OPRD-survey data in Table 5-1. Figure 5-3 is a hydrograph of WLE data from the transducers.

Several important characteristics of the groundwater are shown in the hydrograph, including:

- Wells completed below the clay ("-d" wells, presented as solid lines) show tidal influence, while those completed above the clay ("-s" and "-i" wells, presented as dotted lines) do not show tidal influence. The amount of tidal influence is measured as the tidal efficiency, the ratio of the tidal variation in the controlling feature (Pacific Ocean) to the periodic water-level

[1] Water levels are expected to be provided by Tierra Del Mar for wells TDM-1s through -4s in late May 2018.

variation observed in the well. Tidal efficiency is typically highest at the shoreline and diminishes with inland distance due to aquifer storage effects. The lack of tidal influence in Shallow Aquifer well completions is likely due to aquifer storage properties that significantly attenuate tidal variations in unconfined aquifers. The tidal efficiency in the Deep Aquifer is an expression of confined conditions in the aquifer and associated lower storage coefficients. As noted in Section 6, the tidal efficiencies in the Deep Aquifer do not smoothly decay with distance from the shore, and well PGG-2d (farther from the coast) exhibits a higher tidal efficiency than PGG-4d (closer to the coast). This heterogeneous tidal efficiency response in the Deep Aquifer likely reflects heterogeneity in the Deep Aquifer and/or the overlying clay layer, and may also be influenced by the subsurface topography of the top of bedrock. Supporting calculations of tidal effect damping are included in Appendix E.

- At locations where a well pair supports comparison of WLE's above and below the clay unit, there is a consistent 2- to 4-foot downward head differential across the unit. Based on measurements at PGG-2, there is no significant vertical gradient *within* the Shallow Aquifer.
- Responses to precipitation for wells completed above the clay unit are rapid, suggesting efficient infiltration and recharge. Recharge responses may differ during the summer months when the water table is lower and evapotranspiration captures more available precipitation from the root zone.
- The response of deep wells to precipitation events is slower, suggesting a damped flowpath to regions below the clay layer. This damped flowpath may reflect either leakage through the clay layer or a roundabout flowpath between the Shallow Aquifer and the Deep Aquifer (via distant areas where the clay layer pinches out).

Beaver dams in Beltz Marsh locally buffer the impacts of tidal inundation. In the present configuration, it appears that tidal inundation in Beltz Marsh does not overtop the beaver dam during normal tidal cycles. However, because the beaver dam acts as a storage area maintaining higher water levels in the upstream areas, removal (or natural degradation) of a beaver dam would allow better drainage and lower the average water level in the upstream area. The effect of the beaver dam on shallow groundwater levels beneath TDM is expected to be insignificant based on simulations with the groundwater flow model (Section 6.2.5).

5.5.2 Groundwater Flow Directions

Groundwater flow directions are controlled by differences in WLE, with flow from areas of higher WLE to lower WLE. Higher WLE's occur in areas dominated by groundwater recharge, whereas lower heads occur near discharge areas. Groundwater beneath TDM receives recharge from over 80 inches/year of average annual precipitation. In the TDM groundwater system, groundwater flow is expected to discharge to features such as the ocean, Beltz Marsh, the East Ditch and the East Marsh. Higher WLE's are expected to occur in areas between these discharge features, with local groundwater "divides" (areas where groundwater flow is in difference directions on difference sides of the divide) separating areas where groundwater flows towards different discharge features.

Estimation of groundwater flow direction is constrained by the spatial and temporal distribution of WLE measurements discussed earlier in this section. Water-level snapshots from this data set reflect winter conditions when the water table is high. Three-day average WLE "snapshots" were calculated for each well in periods centered on March 2, 2018 and March 20, 2018. These dates respectively capture conditions immediately after a 2-inch precipitation event and after a period of lower rainfall (Table 5-4, Figures 5-4a-c).. Key observations include:

- The geographic distribution of available WLE data was too sparse to fully capture the groundwater flow directions anticipated beneath TDM. Specifically, data from the 6 Shallow-Aquifer wells did not demonstrate occurrence of the groundwater divide that separates flow to the aforementioned discharge features. For this reason, on May 21, 2018 PGG installed a temporary piezometer in east of well PGG-2s and performed a supplemental WLE snapshot for all actively monitored wells. The snapshot is presented in Table 5-2 and Figure 5-4c, and confirms occurrence of the expected water-table divide. This divide supports PGG's expected interpretation that groundwater beneath TDM flow to the west (towards the coast), to the north (towards Beltz Marsh), and to the east (towards the East Ditch and the East Marsh.
- Downward vertical gradients between the Shallow and Deep Aquifer suggest downward flow of groundwater across the clay layer. The significance of this flux within the overall site groundwater flow is likely small due to the low permeability of the clay unit despite the persistence of downward vertical gradients over time.
- Groundwater flow direction in the Deep Aquifer is interpreted as generally to the east, similarly towards the Sand Lake Road Ditch and the East Marsh swale located at the foot of bedrock topography. A discharge point to the east may indicate that the clay layer is discontinuous near the contact with bedrock, thus allowing upwelling and discharge near the toe of the slope. Similar to the Shallow Aquifer, a groundwater divide is expected to exist in the Deep Aquifer beneath TDM. However, such a divide would have little influence on flooding considerations in the Shallow Aquifer.
- The Marsh Stake is located between the Sand Lake Road Ditch and the East Marsh. Surface-water elevations at the Marsh Stake and Sand Lake Road Ditch are consistent with groundwater flow in the Shallow Aquifer towards the East Marsh, which has lower water level elevations. Both the Sand Lake Road Ditch and the East Marsh are expected to be important groundwater discharge features based on their position and elevations relative to the shallow water table.

6.0 NUMERICAL MODELING APPROACH

This section describes the numerical modeling approach. Surface water and groundwater modeling are discussed separately for clarity.

6.1 SURFACE-WATER MODEL

The hydrologic characterization forms the basis for modifications to the prior surface-water "bucket" water balance modeling performed by Waterways (2017). The water balance model is intended to capture the essential hydrologic characteristics for incorporation into the surface water balance model and will serve primarily as input to the groundwater model.

6.1.1 Surface-Water Conceptual Model

For the Beltz Marsh and TDM areas, the key features of the existing conditions surface-water model will include:

- High tides in Sand Lake are amplified (higher) compared to ocean conditions.
- Daily low tides in Sand Lake and Beltz Marsh are severely muted and never fall below 5.3 feet due to a controlling bed elevation in Sand lake. Muted flux through the existing tide gate and dike system on both the flood and ebb tidal cycle.

- Freshwater input from the blocked culvert at Reneke Creek and perched culvert at Beltz Creek.
- Freshwater input from the East Marsh drainage basin.
- Discharge from the ditch and swale system that drains TDM along Sand Lake Road.
- Direct rainfall into the marsh during intense events.

6.1.2 Adequacy of Previous "Bucket" Model and Proposed Modifications

The previous water balance model developed by Waterways (2017) is considered adequate to be adapted for use in the modeling phase of this project with some modifications. Key modifications include:

- Performing model calculations in the computational program Matlab, rather than MS Excel.
- Utilizing a 7-month record of actual water level data outboard of the dike/culvert, which captures the influence of the estuary on tidal amplification.
- Updating of the stage-storage relationships in the Beltz Marsh to account for new topographic/bathymetric information using LiDAR/PhoDAR DEM provided by OPRD.
- Incorporating conceptualized flows from East Marsh into Beltz Marsh using direct rainfall applied to the watershed area. No subtraction was made for infiltration, as some of that water may also enter the marsh as groundwater.
- Incorporating conceptualized TDM East Ditch and North Ditch flow contributions to Beltz Marsh using direct rainfall applied to the watershed area. No subtraction was made for infiltration, as some of that water may also enter the marsh as groundwater.
- Recalibrating the existing conditions surface-water model to water level data measured in both wet and dry periods, including intense rainfall events, from November 2016 to June 2017. An important advancement since the prior phase is the availability of seven months of continuous water level data inside and outside of the dike.

6.1.3 Existing Conditions Model Calibration

The surface-water model was run from November 20th, 2016 to June 28th, 2017, spanning wet and dry seasonal conditions and capturing at least 5 significant rainfall-runoff events. Rainfall records were obtained from the National Weather Service Tillamook station (#358494), and these were used with the surface area of the Marsh, subwatershed areas of the Sand Lake Ditch and East Marsh to estimate direct rainfall contributions to the marsh and approximate storm hydrographs from the subwatersheds to the marsh. Tides in Sand Lake Estuary immediately outside of the existing culvert were used to drive the tidal boundary conditions in the model, and tides in the Marsh were used to check model predictions inside the gate. The model was calibrated by adjusting the friction in the culvert opening and by assuming that the gate remained slightly open by a certain cross-sectional area during rising tides (i.e. driving 'leaky tide gate' conditions).

Figure 6-1 illustrates the time series of modeled and observed water levels in the Marsh for the 6.5-month calibration period. The lower segment of the plot illustrates the scaled flows from Reneke and Beltz Creeks and the additional subwatershed areas supplying surface water to the Marsh. In general, the surface-water model closely matches observations in the marsh. Figure 6-2 compares the water level exceedance curves for the model and observations in the Marsh, as well as a plot showing the level of agreement for all time steps. The root-mean-squared error (RMSE) was 0.13 feet.

6.1.4 Hydrologic Scenarios/Boundary Conditions for Surface-Water Model

To understand how surface water levels would be affected by alternatives to the existing tide gate, we developed an initial "worst case" hydrology scenario to use for the bookend model scenarios. This concept and the combination of hydrology inputs was developed and agreed upon between OPRD, PGG, and ESA.

The team agreed on a 38-day hydrology scenario that incorporates (1) a 28-day wind-up period with typical winter conditions from January 7th to February 4th (applying measured tides in Sand Lake Estuary from 2017 and long-term average rainfall and runoff conditions for these dates), and (2) a 10-day 'storm' period from February 5th to February 14th. The storm period applied the following conditions:

- Scaled precipitation and runoff to approximate 50-year flood flow conditions, and
- King tide conditions in Sand Lake Estuary.

King tide conditions were achieved by applying a measured king tide event from the NOAA Garibaldi gauge and applying a vertical shift to account for the time-varying difference between the measured tides in Sand Lake and at Garibaldi from February 5th to 14th, 2017. This was an important step, since it accounts for differences in tidal amplitude and wind setup between the two sites, which result in higher water levels at the project site than at the coast. Scenarios 1-3 were run for the above 38-day period.

The hydrology and boundary conditions for the surface-water model are summarized below in Table 6-1.

6.1.5 Alternative Configurations for Modifying the Existing Dike/Tide Gate System

OPRD is interested in improving fish passage and habitat conditions in Beltz Marsh. Furthermore, if the existing tide gate fails or requires maintenance, ODFW and NMFS may require the tide gate connection to the marsh to be upgraded to meet current fish passage criteria. For this reason, we developed two possible alternatives for modifying the tide gate/dike system that would be likely to meet fish passage criteria:

- Removing the existing tide gate and breaching the dike with a large tidal channel connection to allow full tidal reconnection between Beltz Marsh and the Sand Lake estuary
- Replacing the existing tide gate with a modern tide gate system sized and specifically designed for improved fish passage conditions and to allow a muted tidal connection between Beltz Marsh and the Sand Lake estuary

Existing Conditions Configuration

The existing, baseline conditions includes an earthen dike with an approximate crest elevation of 12 feet. A 48-inch diameter culvert drains water from Beltz Marsh into the Sand Lake Estuary. The culvert is fitted with a top-hinged wooden tide gate that leaks, allowing a muted tidal signal to enter the marsh.

Alternative Configuration #1 – Breached Dike

This configuration assumes that a portion of the dike would be excavated, creating an open "breach" that would function as a permanently open tidal channel passing flows into and out of the marsh. The breach was sized based on the published Design Guidelines for Tidal Channels in Coastal Wetlands (Philip Williams & Associates, 1995) and considers the equilibrium cross-sectional area that would be expected to form given the tidal prism volume that would enter and exit the marsh between MHHW and MLLW. A channel inlet sized using this method would also be expected to meet fish passage velocity criteria, as it mimics natural tidal channel inlet dimensions based on empirical measurements in unaltered tidal systems. The exact dimensions, side slopes, associated scour protection, and interaction with other site features (trail/future bridge) would be further refined in a subsequent design phase.

The breach dimensions for this modeling scenario has a bottom width of 37 feet, with side slopes of 1H:1V. The channel has a top width of approximately 53 feet (at MHHW). The total width at the top of the existing dike would be about 61 feet. The invert elevation of this channel was set at 0.0 feet NAVD88. This appropriately sized breach would be expected to meet fish passage velocity criteria of less than 2 feet per second, 90% of the time. A detailed fish passage analysis would be required in a subsequent design phase.

Alternative Configuration #2 – Modern Tide Gate System

This configuration assumes the existing culvert and tide gate would be replaced by a modern tide gate system design to meet fish passage criteria while allowing the water level upstream of the tide gate to be controlled at a set elevation.

Preliminary tide gate sizing is based on a Muted Tidal Regulator system, with the ability to allow tidal water levels inside the marsh up to a selected elevation and close when that water level is reached. If the tide gate is closed during storm events, runoff flowing into the marsh would accumulate behind the dike. When water levels in Sand Lake fall below water levels in the marsh, the tide gate would open allowing the marsh to drain.

We performed a preliminary fish passage analysis to estimate the average velocity through the tide gate/culvert system. We estimated the tidal prism volume that would enter and exit the site between MHHW and MLLW, and calculated the velocity required to pass that volume of water through the structure over a tide cycle. The proposed tide gates are sized to prevent the velocity of water passing through the structure from exceeding 2 feet per second for more than 50% of the time the gate is open, in accordance with ODFW state fish passage guidelines. A detailed fish passage analysis would be required in a subsequent design phase.

The tide gate system is modeled using the following dimensions and operating parameters.

- Two, side-by-side, 8' tall x 10' wide, side-hinged tide gates.
- Interior Water Surface Elevation limited to 7.0 feet NAVD88
    - Tide gates would shut when interior water surface elevation reaches 7.0'.
    - Tide gates would re-open when water level in Sand Lake falls below the interior water level, creating a head differential to open the gate.

6.2 GROUNDWATER MODEL

The conceptual site model (CSM) forms the basis for the design, calibration and application of a groundwater model that will be used to predict the impact of various tide-gate modification scenarios. The groundwater model incorporates and simulates essential hydrogeologic features of the CSM, including:

- Shallow and Deep Aquifer units separated by the clay layer – including associated hydraulic properties;
- Exposed and buried bedrock constraining groundwater flow in the adjacent Shallow and Deep Aquifers;

- Hydraulic connectivity between aquifers and surface-water features, including ditches, the ocean, Beltz Marsh and the East Marsh;
- Tidal influence and inundation along the coastline and within Beltz Marsh;
- Groundwater recharge from precipitation and septic-system effluent; and,
- Groundwater levels *within* aquifer units and the hydraulic gradients *between* aquifer units.

6.2.1 Model Interface, Code, Solver, Timestepping & Realizations

PGG developed the groundwater model using the USGS public domain software "MODFLOW 2005" (Harbaugh, 2005). We also used the graphical user's interface "Groundwater Vistas Version 7" (ESI, 2018) as a platform to organize input data, run the model, and view results. The model was run with MODFLOW's "PCGn" numerical solver, which consistently provided acceptable mass balance errors (significantly less than 1 percent).

The model was run in both steady-state and transient modes. During steady-state simulation, all hydrologic conditions (e.g. recharge, tidal inundation) are held constant, and the model simulates hydrologic equilibrium to these conditions. During transient simulation, hydrologic conditions are allowed to vary over time. PGG performed calibration to both steady-state and transient simulations, and used transient simulations for predictive analysis. The model was calibrated to conditions observed during the 2018 monitoring period (February 16 – March 26), with averaged WLE's (groundwater-level elevations) used for steady-state calibration and observed WLE trends used for transient calibration. During transient calibration, simulation of conditions during the monitoring period was preceded by a steady-state condition (representing average preceding conditions) followed by a 7-day "warmup" period (February 9-15). Model simulations used to predict the impact of alternative tide-gate configurations were run in transient mode over a 38-day simulation period which included 28 days of average winter conditions followed by a 10-day "perfect storm" event (high tides plus high precipitation recharge). All transient simulations employed an hourly stress period with a single timestep per stress period[2].

During model calibration, it became apparent that publicly available climatic datasets used to define precipitation recharge are not perfectly representative of conditions at TDM. Comparison of the precipitation records suggested variability in the amount and timing of rainfall both over single storm events, seasonally, and based on long-term statistics. Precipitation recharge is an important input to the model, and these differences relate to how the water table rises and falls in response to storm events. Therefore, PGG used recharge estimated from both these datasets to develop two "realizations" of the model. Calibration between time-series WLE records (targets) and two precipitation inputs resulted in different sets of aquifer-property values for each realization. The suitability of more than one model realization, a phenomenon termed "non-uniqueness", occurs because model parameters are seldom known precisely everywhere and more than one combination of parameters can yield similarly acceptable calibration results. While parameter values can be constrained within reasonable limits, some degree of uncertainty is common in hydrogeologic characterization due to natural variation (heterogeneity) and insufficient data to fully describe the natural variation. Besides the differences between model realizations resulting from different recharge specification, other uncertainties can cause non-uniqueness. Using both model realizations for predictive simulations provides a range of predicted impacts of proposed tide-gate modification, thus providing some indication of model uncertainty. Additional uncertainty analysis can be performed for subsequent model simulations if warranted.

[2] Variations in tidal inundation were represented based on hourly predictions, whereas groundwater recharge was based on daily precipitation records with recharge rates held constant for each day in the model simulation.

6.2.2 Model Domain and Discretization

The model domain occupies an area of 442 acres (3,500 by 5,500 feet) that extends from offshore to the west (about 1,200 feet east of the dune) to the bedrock upland slope to the east, to Sears Lake to the south, to within Beltz Marsh to the north (Figure 6-3). Extending the northern model boundary all the way to the dike was unnecessary because model predictions (particle tracking) confirms that groundwater discharge from TDM occurs in the far southern portion of Beltz Marsh.

The model domain was discretized into a 3-layer, variable-spacing grid with 109 rows and 84 columns creating 27,468 cells. Cells in the eastern model domain coincident with the bedrock upland are specified as “inactive”, reducing the number of active cells to 22,245. Column and row spacings range from 112.5 feet near the outer boundaries of the model to 25 feet in the transition area that slopes downward from TDM to Beltz Marsh (Figure 6-4). The model grid is rotated 8^{o} clockwise so that its Y axis roughly aligns with the Pacific coastline.

Model layers were defined based on the hydrostratigraphic units discussed in Section 5. The top layer (L1) represents the Shallow Aquifer, the middle layer (L2) represents the clay aquitard, and the bottom layer (L3) represents the Deep Aquifer. HSU’s generally extend across the entire active model domain within their associated layers; however, along the coast where wave action has likely eroded through the clay aquitard, L2 was assigned similar properties to the sandy overlying and underlying aquifers.

Model layer elevations were set using the following procedure:

- The top of L1 is equivalent to the land surface and was set using 2009 LiDAR elevation data averaged for each model cell (Figure 6-5). LiDAR data refined to better depict channel features using PhoDAR were supplied by OPRD and later used to define surface-water feature elevations in Beltz Marsh. Among active model cells, L1 top elevations range from 39 feet NAVD88 (along the edge of the bedrock upland) to -4.9 feet NAVD88 (submerged area coincident with western model boundary).
- L1 top elevations (L1-Top) were simplified for the portion of the beach that experiences tidal inundation. L1-Top was depicted as a plane with downward slope perpendicular to the dune (along the direction of model rows). The modified slope extends downward from an elevation of 9.0 feet NAVD88 (representative high tide) to -4.9 feet NAVD88 (along the western model boundary). Portraying this portion of the beach with a uniform slope simplified simulation of tidal inundation and was justified by the fact that beach elevations are (subtly) ever changing with storm events.
- L1 bottom elevations (L1-Bot) are equivalent to the top of the clay aquitard. The top of the clay aquitard was defined by interpolation between 11 control points where the clay aquitard was encountered during drilling. Nine of these control points are shown on Figure 6-6, whereas the other two were outside the model domain. L1-Bot values generally ranged from 3 to 6 feet NAVD88, except along the coast, where the sloping seafloor required that all layer elevations be “pushed down” to achieve a minimum layer thickness of 0.5 feet.
- L2 represents the clay aquitard, and was assigned a constant thickness of 0.5 feet. While the actual observed thickness varied from 0.3 to 1.6 feet (Section 5.2), the modeled value can be somewhat arbitrary because the hydraulic role of the aquitard is dictated by its conductance (proportional to vertical hydraulic conductivity divided by thickness). The conductance of the clay in L2 was adjusted during calibration to simulate the hydraulic gradient across the aquitard. It should be noted that the clay occupied L2 everywhere in the model except along the beach where L1-Bot elevations fell below 4 feet NAVD88. Below this elevation, PGG assumed

that wave action had eroded the clay layer and replaced it with beach sand via the process of littoral drift.

- The bottom of L3 (L3-Bot) was assumed equivalent to the top of bedrock, and was approximated based on surface bedrock exposures, bedrock encountered in Well "PGG Boring", and approximation based on typical bedrock topography of wave-cut shorelines. The bedrock surface likely has considerable variability that is not reflected in the model. Figure 6-7 shows the modeled thickness of Layer 3, which ranges from a minimum of 0.5 feet along the edge of the bedrock upland to 51 feet in the northwest model domain. The actual thickness of L3 is unknown due to lack of subsurface bedrock control; however, the modeled thickness is incorporated into the L3 transmissivity term during calibration. Aquifer properties for L3 (Deep Aquifer) are not critical because the Deep Aquifer plays little role in the TDM shallow groundwater flooding issues due to hydraulic separation from the Shallow Aquifer by the clay aquitard.

6.2.3 Boundary Conditions

PGG used a variety of MODFLOW boundary conditions to represent geologic and hydrologic features within the model domain. Boundary conditions in the model include:

- Bedrock was represented as a "no-flow" boundary using MODFLOW's *inactive* model cells.
- Sears Lake was represented using MODFLOW's *constant-head* model cells.
- Recharge to the uppermost model layer from precipitation and septic return flows was represented with MODFLOW's *recharge* boundary condition.
- Drainage ditches constructed in northern and eastern TDM were represented using MODFLOW's *stream* cells.
- Periodic tidal inundation of Beltz Marsh and the beach was represented with MODFLOW's *river* cells. River cells were also used to represent inundated water stored behind the beaver dam during model sensitivity analysis.
- Select areas, where potential groundwater flooding is expected to be maintained at or near the average land-surface elevation, were assigned MODFLOW's drain cells. Drain cells were also used to represent the East Marsh, including the stream that flows along the toe of the slope along the bedrock upland in the eastern model domain.

The geographic distribution of boundary-condition cells is shown on Figure 6-8. All boundary conditions are simulated in model layer 1 except bedrock, which is simulated in all model layers. Transient model simulations supported time-variation of recharge, tidal water level, and water level in drainage ditches.

Bedrock

PGG represented bedrock associated with uplands east of TDM and Beltz Marsh with "no-flow" (inactive) model cells. Inactive cells associated with bedrock are the same in each model layer.

Sears Lake

PGG represented Sears Lake, near the southern edge of the model domain, with MODFLOW's constant head (CH) cells. The CH feature was set to an elevation of 20 feet NAVD88. It should be noted that the lake is largely isolated from the main (TDM) portion of the model domain by a bedrock protrusion that extends from the uplands towards the coast.

Recharge

Primary sources of recharge include precipitation and infiltration of septic effluent. PGG used a proprietary recharge calculation spreadsheet that employs the algorithm of the USGS Deep Percolation Model (Bauer & Vaccarro, 1987) to estimate long-term average monthly and early-2018 daily precipitation recharge. The algorithm employs the following data:

- Long-term monthly and 2018 daily precipitation from the Tillamook and Cloverdale weather stations;
- Long-term monthly temperature from the Tillamook and Cloverdale weather stations;
- Soil available water capacity (AWC) reported for Waldport Fine Sand in a Natural Resources Conservation Service soil report for TDM (NRCS, 2018).
- Potential evapotranspiration (PET) associated with coniferous trees using the method of Blainey-Criddle (FAO, 1986).;

Deep Percolation Model (DPM) predictions of recharge and the associated monthly water balance are presented on Table 6-2. On an annual basis, recharge based on Tillamook precipitation is predicted to be 70 inches (relative to 88 inches precipitation) and recharge based on Cloverdale precipitation is predicted to be 61 inches (relative to 80 inches precipitation). The majority of recharge is predicted to occur during the months of December thru March. Given the sandy texture of TDM soils, most of the difference between precipitation and recharge is attributed to water lost to the atmosphere by evapotranspiration.

Figure 6-9 shows daily recharge predicted using the DPM algorithm during the 2018 data collection period using Tillamook and Cloverdale precipitation. Immediately apparent is that Tillamook (15.3 miles northeast of TDM) experiences higher intensity precipitation events than Cloverdale, (6.5 miles south of TDM) and that notable precipitation events do not necessarily occur on the same precipitation monitoring 24-hour period. This variability suggests that actual precipitation at TDM is not perfectly represented by either weather station, and some level of uncertainty remains regarding the recharge time series used to calibrate the model.

Recharge was applied uniformly across the model domain. Precipitation recharge was slightly augmented by septic-system recharge for TDM – which was estimated to be 0.007 in/day during winter months based on TDM reported average November-April water use (~9,000 gallons per day) and a TDM area of 46 acres. Estimated septic-system recharge amounts to only 2 percent of estimated precipitation recharge and plays a relatively minor role in the water budget. The daily recharge values shown on Figure 6-9 include septic-system recharge, which provide a (slightly greater than zero) baseline during days with no precipitation recharge.

It should also be noted that the assumption of uniform recharge is a simplification, and departures are expected – particularly in TDM where development has created impervious and compacted areas which route water accordingly. Resulting variations in the spatial distribution of recharge may affect the calibration process, if WLE trends in monitoring wells used for calibration are affected by localized variations in recharge.

Tidally Inundated Areas

Areas that experience periodic tidal inundation were simulated with MODFLOW's river package. River cells allow exchange between groundwater and a surface-water feature based on the water-level difference between groundwater elevation (h_{gw}) and surface-water elevation (h_{sw}) as well as a conductance term (C). C is defined as the footprint area of the surface-water feature within the model cell times the hydraulic conductivity of a riverbed (K_s) divided by the riverbed thickness (b_s). When conductance is low relative to the ability of the aquifer to conduct water, the riverbed functions as a hydraulic "skin" that restricts the exchange between groundwater and surface water.

Flow in river calls can occur from groundwater to surface water or in the opposite direction. The flow direction follows the direction of the hydraulic gradient (from higher to lower WLE). The user also specifies a "river bottom elevation" (h_b) which, among other functions, can limit the directionality of flow. When river elevation (h_r) > h_b, exchange can occur in *either* direction. However, when $h_r = h_b$, exchange can only occur *from* groundwater *to* surface water. In this case, the river cell functions equivalently to MODFLOW's drain boundary condition (one-way transfer). For all versions of the Sitka-Sedge models, the *only* relevance of h_b is to dictate whether exchange is one-way or two-way.

Because river cells defined for Beltz Marsh and the beach alternate between inundated and dry conditions, PGG used the $h_r > h_b$ configuration to represent the inundated condition and the $h_r = h_b$ to represent the dry condition. For defining C, PGG set the footprint area to the area of the model cell, set b_s to a nominal value of 1-foot, and adjusted K_s during calibration (see discussion of hydraulic property values in Section 6.2.4). Values of h_r and h_b were set for each model stress period (and for each steady-state condition) using the following algorithm:

- For each model river cell and for each model stress period, reference values of land-surface elevation (h_{ls}) were defined for comparison with predictions of tidal elevation (h_t) to identify "inundated" versus "dry" river cells.
    - Reference h_{ls} values for cells associated with the beach (including areas below low tide) were specified as discussed in Section 6.2.2.
    - Reference h_{ls} values for Beltz Marsh were generated using LiDAR/PhoDAR (L/P) coverage developed by OPRD. The L/P coverage is superior to the 2009 LiDAR coverage for representing marsh floor elevations because PhoDAR modification were performed from photographs taken at a lower tidal inundation elevation (6.0 feet rather than 7.3 feet) and therefore better define the channel occurrence. Further refinement was required to apply the L/P coverage, and the refinement algorithm is documented in Appendix F.
- Time-series and average h_t values for Beltz Marsh were derived from actual data from the "inside dike" stage gage collected during the monitoring period and used for model calibration. Time-series h_t values for predictive simulation were derived from surface-water model predictions developed by ESA (Section 7.2).
- Time-series and average tidal ocean h_t values for the beach were derived from tidal predictions at Garibaldi for the model calibration period. For the 38-day predictive simulation period, h_t values were developed by ESA as documented in Section 7.2.
- For each stress period in the transient model simulations, and for the average conditions portrayed in steady-state simulations, PGG assigned of h_r and h_b as follows:
    - Dry river cells – where the boundary condition functions as a groundwater drain" – were identified as cells where $h_t \leq h_{ls}$. For these cells, both h_r and h_b were set equal to h_{ls}. Note that both actual observations and surface-water model predictions dictate that h_t is always ≥ 5.38 feet NAVD88.
    - Inundated river cells – where exchange between groundwater and tidal inundation can occur in either direction – were identified as cells where $h_t \leq h_{ls}$. For these cells, h_r was set equal to h_t, and h_b was set to h_t-0.1 feet.

During steady-state model sensitivity analysis, PGG assessed how representing water in channels behind the existing beaver dam affected predicted Shallow-Aquifer WLE's beneath TDM. We represented the channels behind the dam both at a WLE set by the dam crest and at an average WLE associated with free tidal exchange. Model predictions showed no difference in Shallow-Aquifer WLE's beneath TDM, as further discussed in Section 6.2.5). Therefore, for consistency with all other portions of Beltz Marsh, PGG portrayed the channels behind the beaver dam as freely responding to tidal exchange for all simulations.

Drainage Ditches

Drainage ditches constructed on the east and north sides of TDM intercept local groundwater when the water table is sufficiently high. PGG used MODFLOW's "stream" boundary condition to simulate exchange between the Shallow Aquifer and the "North" and "East" ditches. The stream package is similar to the river package, except:

- It tracks cumulative flow in the surface-water feature from upstream to downstream, adding groundwater inflows and subtracting seepage losses.
- Rather than simulating stage (h_r) as a value specified by the user, it allows h_r to be calculated as a function of flow based on a simple function (Manning's Equation).

PGG elected to use the steam package because both flow and stage in the ditches are expected to vary both spatially and temporarily. Unlike the h_t values for the marsh and the beach that are *approximately known* and specified by the user, stage in the ditches is *unknown* and must be calculated by the model. PGG applied the stream package in a simplified manner which allowed stage to vary from 0 to 1.3 feet over an associated flow range of 0 to 1.2 cfs (Figure 6-10). No attempt was made to calibrate the stage vs. flow relationship, as related field data were unavailable. Nevertheless, the added capability of the model to track wet and dry reaches in the ditches and to allow variation in stage as a function of flow was seen as an advantage over using MODFLOW's river or drain packages. The following parameters were used to set up stream cells for both ditches:

- Calculation of stage as a function of flow requires that the user specify the ditch-bottom elevation for each model cell.
    - For the East Ditch, bottom elevations were interpolated between surveyed invert elevations or were based on minimum LiDAR LSE's below the invert at Roma Avenue.
    - For the North Ditch, bottom elevations were develop based on fitting a smoothed curve to a plot of minimum LiDAR elevation per model cell as a function of downstream distance.
- Stream width was specified as 4 feet, and streambed thickness was specified as 1 foot for both ditches.
- Stream length (per model cell) was set to the length of the ditch crossing that cell.
- PGG specified uniform values of Manning's parameters (streambed roughness, streambed slope) for all cells to achieve the stage/flow relationship described above.
- Streambed hydraulic conductivity (K_s) was adjusted during calibration.

Drainage of Groundwater Flooding

In some areas of the model domain, high water-table elevations cause groundwater flooding by accumulation of standing water in closed depressions. In other areas, sloped topography is expected to allow groundwater that reaches the land surface to flow towards lower LSE's and/or surface-water features.

MODFLOW's drain package was used to simulate drainage from selected areas of groundwater flooding during high water-table events. Although similar to MODFLOW's river package, the drain package only allows one-way exchange from groundwater to drainage features. Drain cells were positioned in areas where topography is likely to support drainage (Figure 6-8). For the purpose of discussion, such cells will be referred to as "land-surface drains", and include:

- Areas of the beach above high tide;
- The wetland areas east of Sand Lake Road, which lead down to the stream that runs along the base of the bedrock upland;
- The northern edge of TDM, as it slopes down to Beltz Marsh; and,
- Other areas bordering Beltz Marsh expected to slope down to the marsh.

Similar to the river cells discussed above, PGG specified drain areas as equivalent to model-cell footprints along with a drain-bed (skin) thickness of 1 foot. Drain elevations (h_d) were derived from minimum Li-DAR elevations for each model cell. Hydraulic conductivities for the drain "skin" were adjusted during calibration.

The overall effect of including drain cells in the model is to not allow modeled groundwater elevations to exceed LSE's in specified areas. Where drain cells are not specified, the model will predict groundwater levels to rise above the land surface and linger (without drainage) until the water-table recedes. This condition is shown as "flooded model cells" in portrayal of model results later in this report.

6.2.4 Hydraulic Properties of Aquifers, Aquitards and Substrate Sediments

The hydraulic properties of aquifers and aquitards are specified in the model using hydraulic conductivity (K), specific storage (S_s), and specific yield (S_y). Hydraulic conductivity can be further separated into its horizontal and vertical components (K_h and K_v). Groundwater Vistas calculates the transmissivity of a model layer based on its thickness (b) and its K_h. PGG used a method of zonation, where zones of like aquifer properties are distributed over continuous regions of active model cells.

In defining the distribution of aquifer-property zones, PGG used the simplest distribution possible that yielded acceptable calibration results. PGG did not attempt to further improve calibration results by adding complexity (e.g. spatial variation or "heterogeneity") beyond what is supported by available data or what was needed to adequately calibrate the model. As hydraulic testing of the onsite aquifer materials is limited to slug tests at PGG-4i and PGG-4d, adding further heterogeneity predominantly follows observations of textural variation. Also, since the thickness of the clay aquitard is represented as constant (0.5 feet) but actually varies slightly between borings (Sections 5.2 and 5.4), variation of L2 K_v was used to embody variations in thickness.

Substrates that underlie surface-water features and land-surface drains can affect the hydraulic connection between groundwater and surface water. Where surface-water features are underlain by deposits of finer-grained sediments, or where surficial soils are less permeable than underlying aquifer materials, these finer-grained sediments can form a hydraulic "skin" that restricts groundwater/surface-water exchange. Finer-grained sediments are expected to accumulate in features that have relatively low flow velocities and suspended sediment in source water. MODFLOW represents these fine-grained skins with a hydraulic conductivity value (K_s). Similar to our approach with aquifer properties, PGG attempted to use simple K_s distributions for calibration by assigning uniform K_s values for each surface-water feature or grouping of land-surface drains.

Figures 6-11, 6-12 and 6-13 show the geographic distribution of aquifer property zones in model layers 1, 2 and 3 (respectively). Figure 6-8 shows the geographic distribution of boundary conditions that include K_s values for substrate sediments or surficial soils (rivers, streams and drains). Table 6-3 summarizes the hydraulic property ranges employed during calibration along with final calibrated model values.

Aquifer Hydraulic Conductivity

During field exploration, PGG observed very little textural variation within the sandy sediments that comprise the Shallow and Deep Aquifers. For that reason, PGG permitted no geographic variation of K (K_h or K_v) within model layers representing sandy aquifers. We did allow K values to differ between L1 and L3 because the thickness (b) of L3 is more uncertain, and model calibration to L3 responds to transmissivity (T) as opposed to K (T = K*b). Allowing L3 K to vary from L1 K is a means of compensating for uncertainty in L3 thickness.

L1 and L3 aquifer property zones on Figures 6-11 and 6-13 show a single zone over most of the model domain except for a “ribbon” zone along the toe of the bedrock uplands. During calibration, it was deemed necessary to allow a hydraulic connection between the Shallow and Deep Aquifers along the edge of the bedrock, consistent with a higher-energy environment where stream activity may have eroded through the clay aquitard or prevented its deposition entirely. Acceptable calibration could not be achieved without this connective feature. The same aquifer property zone (Zone 4) also occurs in L2.

Besides the connective “ribbon zone”, L2 includes three other aquifer property zones (Figure 6-12). Zone 1 is the same as the sandy aquifer sediments in L1, and occurs in the western model domain where wave action was assumed to have cut through the clay layer. Zones 2 and 5 divide the clay layer into two simple regions with higher K_v in the western region based on observation of sedimentary texture and aquitard thickness. During exploration, PGG noted that the clay aquitard was more peaty and thinner towards the west and more clayey and thicker towards the east (Section 5.2). PGG represented this variation the simplest manner (2 zones) rather than adding more complexity to the modeled variation in aquitard properties.

PGG identified reasonable K ranges to be used during calibration based on aquifer test data, observations of sedimentary texture, published representative ranges of hydraulic parameters, and best professional judgement. As summarized on Table 6-3:

- Freeze & Cherry (1979) report a K range for clean sand of 0.5 to 3,000 ft/d. PGG expects a Kh range of 3 to 60 ft/d for sediments with a typical beach-sand texture. Calibrated values ranged from 15 to 32 ft/d. K_v was assumed to be 10% of K_h.
- Freeze & Cherry report a K range for marine clay of $1x10^{-7}$ to $2x10^{-4}$ ft/d. Calibrated values of K_v ranged from $3.4x10^{-4}$ for more clayey portions of the aquitard to $3.4x10^{-3}$ for more peaty portions of the aquitard. Aquitard K_h values have little effect on groundwater flow, and both units were assigned a value of 1 ft/d.

Aquifer Storage Parameters

Transient calibration of the model focused largely on water-level variations, which are sensitive to aquifer storativity (S). For unconfined aquifers, S is equivalent to S_y, and was expected to range from 0.1 to 0.38[3]. Calibrated values of S_y ranged from 0.12 to 0.34.

[3] Morris and Johnson (1967) report an Sy for dune sand of 0.38.

PGG employed a feature in Groundwater Vistas that allowed S_y to increase to 1.0 when WLE's in layer-1 model cells rose above the land surface. This specification is consistent with effective storage for water ponded upon the land surface. For model cells without land-surface drains, the model will not simulate removal of ponded water via runoff pathways, and *all* groundwater flooding will be simulated as remaining on the land surface.

For confined aquifers, S is calculated based on the product of aquifer thickness (b) and specific storage (S_s), with S_s values expected to range from $1x10^{-6}$ to $1x10^{-4}$. The model employed a calibrated S_s value of $2x10^{-5}$.

Hydraulic Conductivity of Substrate Sediments

Substrate sediments for surface-water features (MODFLOW rivers and streams) and surficial soils associated with land-surface drains, were assigned skin hydraulic conductivity (K_s) values based on soil mapping by NRCS (2018) or expected K values based on sedimentary texture:

- Soil mapping of the Beltz Marsh shows a dominant soil type of fluvaquents-Histosols with a reported minimum K_v of 0.4 to 4 ft/d. The calibrated K_s for Beltz Marsh surficial sediments was 0.4 ft/d.
- Soil mapping of beach sediments shows a dominant soil type of Waldorf fine sand, with a reported minimum K_v of 12 to 40 ft/d. The calibrated K_s for beach sediments associated with MODFLOW river and drain cells was 12 ft/d.
- Mapping of surficial soils in the vicinity of TDM and east of Sand Lake Road shows a dominant soil type of Klootchie-Necanicum with a reported minimum K_v of 1.2 to 4 ft/d. The calibrated K_s for MODFLOW "land-surface drains" in these areas was 2 ft/d.
- K_s values for substrate materials in the East Ditch and North Ditch were expected to be consistent with silty to sandy sediments, ranging from around 0.6 to 60 ft/d. Calibrated values ranged from 3 ft/d (North Ditch) to 40 ft/d (East Ditch).

6.2.5 Steady-State Model Calibration

Calibration is the process of adjusting model parameters (Kh, Kv, Ks, Ss, Sy) within acceptable, representative ranges to achieve the best match between model predictions and observations from the hydrologic system ("calibration targets"). During steady-state calibration, targets included average monitoring-period WLE's measured in six Shallow-Aquifer and four Deep-Aquifer monitoring wells at TDM. Other observations considered during calibration included: distribution of predicted groundwater flooding, WLE difference between the Shallow and Deep Aquifers, and predicted flow in the East and North drainage ditches.

Calibration was performed on both realizations of the model: one with recharge based on Tillamook precipitation and one with recharge based on Cloverdale precipitation. Multiple versions of each realization were developed during calibration. The names of the calibrated steady-state realizations are "Sitka-SS-v12" (Tillamook) and "Sitka-SS-v21" (Cloverdale).

Steady-State Targets

The average monitoring-period WLE's used for calibration are shown on Table 6-4. During calibration, PGG viewed model results to assess how well they represent other field observations, including:

- WLE's in the Shallow Aquifer are several feet higher than the Deep Aquifer. Average WLE differences observed during the monitoring period ranged from about 2 to 4 feet (Section 5.5).

- Groundwater flooding is expected between the dunes north of TDM and at selected locations within TDM. However, since the steady-state calibration represents *average* conditions over the 38-day monitoring period (rather than conditions specific to a high-precipitation event), areas of modeled groundwater flooding will not match those observed during storm events.
- Groundwater discharge to the land surface is expected to occur in observed wetland areas.
- Groundwater discharge to the East and North ditches will (optimally) exhibit a similar geographic distribution to observed conditions, and monitoring-period average predicted ditch flow should be less than 0.3 cfs[4].

It should be noted that PGG considers departures from some of the more qualitative targets listed above to be acceptable as long as the groundwater model replicates the key features of the groundwater flow system beneath TDM. Success in replicating these key features is assessed based on the results of both the steady-state and transient model calibrations.

Sensitivity Analysis

PGG performed sensitivity analysis on key model parameters by varying the parameter over a range (0.01x thru 100x) and noting the effect on the squared sum of target WLE residuals (SSR). A "residual" is herein defined as the difference between the observed and the predicted WLE, such that positive residuals indicate that the observed WLE was higher than the predicted WLE. SSR provides a measure of the overall departure from observed WLE's, regardless of whether the residual is positive or negative. A model is "sensitive" to parameters that substantially affect the SSR, and insensitive to parameters that have little effect on SSR.

Figures 6-14 and 6-15 present results of the sensitivity analyses for both steady-state model realizations. In both cases:

- Both realizations show the highest sensitivity to K_h of the Shallow and Deep Aquifers (zones 1 and 3), and to K_v of the more permeable portion of the clay layer (zone 2, towards the west side of the model domain).
- Both realizations are not very sensitive to variations in K_v for the eastern portion of the clay layer (zone 5) or the "connective" zone along the toe the bedrock upland (zone 4).
- Both realizations are not very sensitive to variations in K_s hydraulic connections to Beltz Marsh, the beach, or either of the ditches. One exception occurs for the east ditch, where increasing K_s by 100x does have a notable effect on SSR.

As expected, the model also proved to be highly sensitive to groundwater recharge. Recharge and hydraulic conductivity are directly correlated (e.g. a two-fold increase in recharge requires a two-fold increase in hydraulic conductivity to obtain the same predicted WLE's). Recharge is not shown on Figures 6-14 or 6-15 because the range of applicable multipliers (0.5x to 2x) differs from the multipliers used for all other parameters.

Despite the fact that some of the model is minimally sensitive to some of the parameters discussed above, varying the K_v and K_s properties still has some effect on local calibration targets, and PGG optimized the

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[4] Although actual ditch flows have not been measured, it should be noted that the average monitoring-period recharge to TDM is estimated to range from 0.50 to 0.64 cfs between model realizations. About half of this recharge expected to flow towards the beach and a portion of the remainder is expected to flow towards the marsh and other wetlands.

parameter values accordingly. For low sensitivity parameters, it is best to stay close to published values (such as NRCS K_v estimates) but to recognize that uncertainty exists around these parameter values. Parameter estimates for high-sensitivity parameters have less uncertainty because model results “force” convergence to parameter values that fit the calibration targets.

Furthermore, although a parameter may be defined as “low sensitivity” in the analysis discussed above, it can still affect model predictions of a different phenomenon of interest. For instance, while the sensitivity analysis was indexed to SSR, variation of a low-sensitivity parameter could still affect predictions of groundwater-level response to changes in tidal inundation. Associated uncertainties can be addressed by performing “uncertainty analysis”, where low-sensitivity parameters are varied as part of model predictive simulations.

PGG’s sensitivity analysis also assessed how representation of water levels in the channels behind the beaver dam affect predicted WLE’s in the Shallow Aquifer beneath TDM. Using realization “Sitka-SS-v12” (Tillamook), PGG compared representation of the channels behind the beaver dam as either:

- Maintaining a standing WLE set to the estimated crest elevation of the dam (8.0 feet NAVD88); and,
- Allowing free tidal exchange, such that the steady-state WLE was set to the average marsh WLE measured during the calibration period (6.07 feet NAVD88).

Figure 6-16 shows the predicted difference in Shallow-Aquifer WLE’s resulting from the 1.93-foot WLE difference represented in the channels behind the dam. The predicted difference is localized to the channels behind the dam and is less than 0.01 feet beneath TDM. The model therefore exhibits low sensitivity to representation of standing water behind the beaver dam for Shallow-Aquifer WLE’s beneath TDM. Factors that limit the propagation of inundated WLE’s behind the Beaver Dam into TDM include: the hydraulic properties of the Shallow Aquifer and the fact that adjacent model cells in Beltz Marsh likely provide “pressure relief” for higher WLE’s in the channels behind the dam.

After simulation of extreme scenarios (documented in Section 7-3), PGG performed supplemental analysis to evaluate the sensitivity of increasing hydraulic connectivity between Beltz Marsh and the Shallow Aquifer beneath TDM. This was accomplished by increasing both K_s of the “skin” sediments beneath the marsh and the transmissivity of Shallow-Aquifer immediately underlying the marsh. Both parameters were increased together, and the simulated increase in connectivity had no significant effect on model predictions (Section 8.6).

Steady-State Calibration Results

Figures 6-17 and 6-18 show the distribution of steady-state calibration residuals along with predicted WLE contours for the Shallow and Deep Aquifers (respectively). Steady-state calibration results and statistics are summarized on Table 6-4, and water budgets for the steady-state calibration runs are summarized on Table 6-5. In general:

- Calibration residuals in the Shallow Aquifer are predominantly less than 0.8 feet and do not show significant geographic bias between overestimates and underestimates. It should be noted that WLE’s are expected to be very sensitive to the actual geographic distribution of groundwater recharge, and patterns of development within TDM (e.g. impervious surfaces, rooftops) not represented in the groundwater model may affect *actual* observed WLE’s.
- WLE contours predicted for the Shallow Aquifer show the expected pattern of groundwater gradients and flow directions (discussed in Section 5.5). The contours show that a groundwater

divide occurs beneath TDM, and that groundwater discharges to the beach, the marsh, the drainage ditches and the wetlands east of Sand Lake Road.

- Calibration residuals in the Deep Aquifer are less than 1.5 feet and are larger than for the Shallow Aquifer. A geographic bias is noted, with model underpredictions beneath western TDM and overpredictions beneath eastern TDM. Calibration to WLE's in the Deep Aquifer was more difficult than for the Shallow Aquifer because observed WLE's show more variation from expected groundwater flow patterns. This departure from expected WLE's is also noted for tidal efficiency as a function of distance from the beach (Section 5.5.1; Appendix E).
- A key calibration statistic used to judge calibration success is the "scaled root-mean-squared (RMS) error". This statistic is calculated by dividing the square root of the SSR by the range of target WLE's (maximum minus minimum). In general, a scaled RMS error of 10% or less is considered to be acceptable. For the L2 targets, this statistic ranges from 8.8% to 11.4% (Table 6-4), and is therefore considered to be of reasonable magnitude. When calculated for both L1 and L3 targets, this statistic is slightly larger due to the larger influence of L3 residuals.

Regarding the less-quantitative calibration observations discussed above, the following results further support the quality of the calibration achieved by both steady-state model realizations:

- Figure 6-17 shows predicted areas of standing, wet-season groundwater flooding between the remnant dunes west of Beltz Marsh. It also shows a small area of standing wet-season groundwater flooding in northern TDM.
- Estimates of groundwater discharge to the East and North ditches (Table 6-5) are consistent with the magnitude of groundwater recharge predicted for TDM.
- Figure 6-19 shows model predictions of WLE difference between the Shallow and Deep Aquifers. WLE differences beneath TDM generally range from 2 to 5 feet, and are therefore consistent with the scale of observations discussed in Section 5.5.
- Figure 6-20 shows the L1 grid cells for which the model predicted groundwater discharge to surface-water features. Both portions of the model predict discharge to: the beach; Beltz Marsh; wetlands east of Sand Lake Road and north of TDM; and both drainage ditches. Discharge is predicted along most of the length of the East Ditch, but only to the lower portions of the North Ditch.

Overall, considering both the WLE-target residuals and the calibration observations discussed above, PGG considers the steady-state calibration to be successful. PGG accepts the fact that calibration residuals were not as good for the Deep Aquifer because actual departures from expected hydrogeologic conditions in the Deep Aquifer suggest greater complexity in this hydrogeologic unit, and because the Deep Aquifer has significantly less influence on Shallow-Aquifer WLE's and their connection with Beltz Marsh.

6.2.6 Transient Model Calibration

The steady-state calibration described above strives to adjust model parameters so that monitoring-period average conditions are well represented in the model. A transient calibration, on the other hand, strives to adjust model parameters so that time varying stresses (precipitation recharge or fluctuating tidal inundation) and corresponding WLE responses in the aquifer system are well represented in the model. Calibration targets used for transient calibration included WLE trends measured in TDM monitoring wells over the 38-day monitoring period (head changes over time). WLE trends in the Shallow Aquifer were dominated by responses to precipitation recharge, whereas WLE trends in the Deep Aquifer showed more muted response to precipitation events but also responded to tidal variations at the beach. Along with the less-quantitative observations discussed above, PGG considered modeled flow hydrographs in the East and North drainage ditches.

Transient calibration was performed for both model realizations and included iterative feedback between the transient and steady-state models. This iterative approach led to adjustments in aquifer K values; however, storage properties (S_y, S_s) were the most prominent parameters adjusted during transient calibration. Final hydraulic property values are discussed in Section 6.2.4 and summarized on Table 6-3.

PGG judged the success of transient calibration based on graphical comparison between observed vs. predicted hydrographs TDM monitoring wells over the monitoring period. Our calibration focused on the timing and magnitude of transient responses to precipitation and tides expressed as WLE change over time. The graphical comparisons, developed for all 10 monitoring wells, are shown on Figures 6-21 thru 6-30. The hydrographs show average daily WLE's, so do not indicate model predictions of tidal variation. Each figure also lists a value of offset (ΔH) between the observed hydrograph and the predicted hydrograph. The ΔH value is similar to the steady-state residual, except that it was developed graphically by adjusting the Y-axis for the predicted hydrograph to obtain the best match between the observed and predicted WLE trends. A positive ΔH means that observed heads were higher than predicted, and a negative ΔH means that observed heads were lower than predicted. In addition, PGG compared model predictions of tidal variation in the monitoring wells to observed values. Values of ΔH and observed vs. predicted tidal variation are summarized on Table 6-4.

The following observations are noted in reviewing the transient hydrographs and calibration statistics:

- Predicted WLE trends generally show good agreement with observed trends. Differences in timing associated with predicted WLE responses to the precipitation-recharge events (shown on Figure 6-9) are attributed to variations in the timing and magnitude of precipitation events at Tillamook and Cloverdale. This observed variability suggests similar variability with TDM, and associated departures from either recharge time series. As noted above, patterns of land-use development may affect patterns of recharge and magnitude of predicted transient WLE response.
- Similar to steady-state residuals in the Shallow Aquifer, absolute values of ΔH for Shallow-Aquifer transient targets are predominantly $\leq$ 1 foot (Table 6-4). In contrast, absolute ΔH values for the Deep Aquifer range from 0.5 to 2.2 feet.
- Ranges of tidal variation for transient calibration targets were determined by viewing predicted hydrographs with Groundwater Vistas (displayed based on hourly stress periods). Observed and predicted ranges are summarized on Table 6-4. The range of tidal variation predicted for transient targets is generally consistent with the *magnitude* of responses observed in TDM monitoring wells.
    - Both the model and the monitoring data show no tidal response in the Shallow-Aquifer wells.
    - Observed tidal responses in the Deep Aquifer monitoring wells are on the order of 0.1 to 0.3 feet, whereas predicted target responses range from 0.01 to 0.5 feet.
    - Although the range of Deep-Aquifer responses shows good agreement, the model does not reproduce the distribution of tidal efficiencies observed in wells. The model predictions show decreasing tidal efficiency with distance from the beach, as expected based on the geometry of the groundwater flow system. However, hydrographs measured in monitoring wells show poor geographic correlation with distance from the

beach (Section 5.5.1; Figure 5-2). Tidal efficiency can be reduced by lateral variations in the degree of aquifer confinement (change in aquifer storage coefficient), variations in aquifer thickness (due to variations in buried bedrock topography), or the presence of low-permeability zones between the monitoring well and the coast. Model calibration and field observations suggest that the clay layer (L2) has some lateral variability and thins to the west. Variations in the vertical hydraulic conductivity of L2, variations in depth to bedrock, or differences in the lateral extent of L2 under the foredune and beach areas could account for the variable tidal efficiency observed in the well hydrographs. At the model scale, this variability is adequately accounted for in the calibration process because the magnitude of tidal variations is generally in agreement, and unresolved variability is unlikely to significantly affect the water-level responses in L1.

Along with model calibration to WLE trends, PGG extracted model predictions of groundwater-fed baseflow in the East Ditch and the North Ditch (Figure 6-31). Predicted ditch flows respond to rising WLE's caused by precipitation events and provide reasonable estimates of groundwater discharge to the two ditches. Measured ditch flow data were unavailable for model calibration.

Overall, the results of transient calibration are considered very good. The relatively higher values of ΔH predicted in the Deep Aquifer, along with the lack of *actual* correlation between tidal variations and distance from the beach, suggests heterogeneity in the Deep Aquifer beyond what can be supported by observations made during exploratory drilling. As discussed above, PGG views the level of calibration success in the Deep Aquifer as sufficient to support the primary purpose of the model application: predicting WLE changes in the Shallow Aquifer in response to changes in inundation in Beltz Marsh. Differences in time-series precipitation recharge applied to the two realizations effects the predicted timing of WLE variations, and neither of the two precipitation time-series is expected to perfectly capture conditions at TDM. Nevertheless, the model does a good job in simulating the magnitude and timing of transient WLE responses to precipitation and tidal events (expressed as WLE *changes* over time). Accurate prediction of WLE responses is key for the predictive simulations, which focus on WLE responses to changes in Beltz Marsh inundation regimes resulting from possible replacement of the existing tide gate.

7.0 MODEL PREDICTIVE RESULTS AND DISCUSSION

This section presents predictions of Beltz Marsh tidal inundation for three tide gate configurations developed with the surface-water model and predicted effects on groundwater levels in the Shallow Aquifer beneath TDM associated with the tidal predictions.

7.1 BOOKEND MODEL SCENARIOS

The surface-water model was configured to address three different scenarios. These scenarios apply the hydrologic conditions described in Table 6-1 to the existing conditions configuration, as well as two alternative configurations to the existing culvert and tide gate draining through the dike. These bookend scenarios would be expected to have the greatest affect in changing the tidal exchange between Beltz Marsh and the Sand Lake Estuary, and the two alternative configurations are expected to meet fish passage criteria.

The bookend model scenarios were developed to estimate how the existing and alternative configurations perform under extreme hydrologic conditions, and whether modifications to the existing tide gate configuration would have any effect on groundwater levels in Tierra Del Mar. Based on the outcome of these bookend scenarios, the project team will assess the need to perform additional modeling of refined scenarios.

7.2 SURFACE-WATER MODEL RESULTS

The existing configuration and the two alternative configurations were modeled under the 38-day hydrology scenario described in Table 6-1. Figure 7-1 shows the model-predicted tidal water levels for all three predictive scenarios, during the full 38-day model simulation, including the 28-day period of average conditions and the 10-day storm event. Figure 7-2 shows the model-predicted tidal water levels for all three predictive scenarios, focusing on the 10-day storm period.

Figure 7-3 illustrates the water level and velocity exceedances for the each of the three scenarios, showing a significant improvement in flood water levels for each of the alternatives.

Results for each of the three predictive scenarios are described in more detail below.

7.2.1 Predictive Scenario 1: Existing Conditions

During the initial 28-day period, predicted water levels inside the dike ranged from 5.5 to 8.3 feet NAVD88. During the 10-day storm period, the combined king tide and 50-year runoff event resulted in peak water levels at 12-12.5 feet in the Marsh on February 10th. Since the gate is inefficient at passing flow (as calibrated in the existing conditions run), flood levels in the Marsh remained persistently high, and the period from February 9th to February 12th experienced levels consistently above 9 feet NAVD88.

7.2.2 Predictive Scenario 2: Breached Dike (Alt. Configuration #1)

With the breached dike, water levels in the Marsh closely matched tides in Sand Lake Estuary. During the 28-day initial period, predicted tides ranged from 5.5 to 11.2 feet NAVD88. During the entire simulation, water-level setup due to runoff was minimal, as the size of the breach efficiently drains water from the marsh to the estuary. During the early portion of the 10-day storm period, peak daily water levels were sometimes higher than with the existing tide gate (Figure 7-2), since the existing gate mutes the estuary tides, but high levels were short-lived, as they essentially rose and fell with the tidal signal in the estuary. Peak water levels during the 10-day storm period in the estuary and in the breach scenario briefly exceeded 12.0 feet NAVD88, but water levels quickly fell as the tide receded. In contrast, during the later portion of the 10 day storm cycle (when freshwater inputs exceeded the ability of the tide gate to pass accumulating water before the next incoming tide), high water levels predicted under the existing conditions scenario were similar to the maxima under the breach scenario, but persisted for 3-4 days due to poor drainage of accumulated runoff through the existing tide gate rather than quickly receding with the outgoing tide.

7.2.3 Predictive Scenario 3: Modern Tide Gate System (Alt. Configuration #2)

With the modern tide gate replacement (Scenario 3), peak daily water levels were lower than both the breach and existing gate scenarios during both the 28-day period of average conditions and the 10-day storm period. During average conditions, predicted peaks were lower than both the existing condition and the breach condition because the new gates were assumed to prevent tides above 7.0 feet NAVD88 from entering the Marsh. During storm conditions, water levels in the marsh were lower than both the existing conditions and the breach condition because of the limited tidal inflow and because the larger tide gate system is more efficient than the existing tide gate at passing flows out of the Marsh. During the 10-day storm period, peak daily water levels occurred when flood runoff was impounded by the gates during rising estuary tides (when the gates were assumed to be closed). The peak water level under Scenario 3 reached an elevation of 10.5 feet NAVD88, but water levels fell quickly as the tide receded.

When adjusting the model to use an 8-foot tide gate closure setting, instead of the 7-foot closure setting, the predicted peak water levels were similar. Peak water levels during typical tidal conditions and moderate storm conditions were about 1 foot higher when using the higher tide gate closure setting. However, during the height of the 10-day storm scenario, peak water levels were nearly identical, maxing out at 10.5 feet. See the supplemental analyses in Section 8 for more detail on the alternate tide gate closure setting.

7.3 GROUNDWATER MODEL RESULTS

PGG's analysis of WLE changes beneath TDM finds no evidence for significant Shallow-Aquifer WLE rise due to changing the dike configuration from the current tide gate to either a modern tide gate or a breach engineered to promote fish passage. The basis for this finding, along with discussion of additional possible uncertainty analysis, is presented below.

7.3.1 Bookend Scenarios Addressed with the Groundwater Model

Both realizations of the groundwater model were run over the same 38-day period simulated by the surface-water model. The groundwater model employed the same values of precipitation input to the surface-water model to estimate daily groundwater recharge, hourly tidal water levels in Beltz Marsh tides predicted by the surface-water model, and hourly values of ocean tide based on predictions for the Garibaldi gauge. The 10-day period of "storm conditions" (days 29-38) was considered to provide a "bookend" for hydrologic conditions (groundwater recharge, tides) that could potentially cause higher groundwater elevations in the Shallow Aquifer beneath TDM.

Beltz Marsh WLE's predicted for the existing tide gate were used as a "base-case" against which other scenarios (modern tide gate and dike breach) were compared. For the modern tide gate scenario, the surface-water model predicted that daily maximum Beltz Marsh WLE's are consistently less than for the existing tide gate. Based on this relationship, the groundwater model was used to assess the magnitude of expected WLE reductions in the Shallow Aquifer. For the dike breach scenario, the surface-water model predicted higher Beltz Marsh WLE's during the 28-day period of average conditions but lower sustained WLE's during the 10-day storm period. For this scenario, the groundwater model was used to assess whether higher marsh WLE's would cause significant WLE increases during average conditions or significant WLE decreases during storm conditions.

7.3.2 Predictive Modeling Methodology

Model simulations were run in transient mode similar to the transient calibration runs discussed above. The model employed hourly transient stress periods over the 38-day simulation period (912 stress periods total), preceded by a single steady-state stress period to provide an initial condition for the transient simulation. Relative to calibration versions of the model, the following inputs were changed for the predictive model runs:

- Daily recharge was estimated with PGG's proprietary version of the Deep Percolation Model using the same long-term average daily precipitation values from Tillamook as the surface-water model. Figure 7-4 shows both the precipitation and recharge time-series associated with the predictive model runs.
- Hourly WLE's in Beltz Marsh generated by the surface-water model were assigned to the MODFLOW river cells associated with Beltz Marsh.

- Hourly WLE's for the Garibaldi gage were assigned to the MODFLOW river cells associated with beach (ocean) conditions west of TDM.
- Values of recharge, Beltz Marsh tidal elevation, and ocean tidal elevation specified over the initial 28 days of the transient simulation period were averaged and assigned to the preceding steady-state stress period.

It should be noted that applying recharge based on Tillamook precipitation to the model realization calibrated to recharge from Cloverdale precipitation (v21) results in overestimating groundwater levels beneath TDM. PGG elected to use the same recharge values for predictive simulations performed with both realizations of the groundwater model to maintain consistency with the surface-water model and because this overprediction will not significantly alter the ability to compare model results regarding how different dike configurations change in Shallow-Aquifer WLE's. Neither recharge nor ocean tides are changed between any of the predictive groundwater model simulations. The only element changed between simulations is the WLE hydrograph for Beltz Marsh. Therefore, even if WLE's are overpredicted by using Tillamook-based recharge in v21, comparison of model versions *that differ only in specified Beltz Marsh WLE's* should reveal associated *changes* in Shallow-Aquifer WLE's.

7.3.3 Predicted Change in Groundwater Levels

Figures 7-5 thru 7-14 show the predicted WLE's for each of the 10 monitoring wells referenced during model calibration. Each figure provides a hydrograph of predicted average daily groundwater elevations under the existing tide gate, the modern tide gate and the dike breach generated with both realizations of the groundwater model (v12 and v21). Figure 7-15 provides a comparison of predicted flows in the East Ditch and North Ditch under all 3dike configurations for both model realizations. Table 7-1 summarizes predicted Shallow-Aquifer WLE differences between dike configurations for both the 28-day average condition and the 10-day storm condition.

Modern Tide Gate Scenario

The model predicted average daily WLE's during the 28-day average-condition period are virtually the same between the existing and the modern tide-gate configurations. In all cases, predicted WLE's for the modern tide gate were lower than for the current tide gate. Lower WLE's occur because the modern tide gate provides superior exclusion of inflow to the marsh at high tides and superior drainage of marsh storage at low tide (Figure 7-1).

Model results for the 10-day storm condition do show a difference between the current tide gate and the modern tide gate for some monitoring locations, predominantly for the Deep Aquifer. Where present, this difference shows slightly lower WLE's for the modern tide gate relative to the current tide gate. This difference is caused by reduction of prolonged inundation in Beltz Marsh predicted by the surface-water model due to improved drainage provided by the modern tide (Figure 7-2). Among the Deep-Aquifer monitoring wells, the most notable difference (0.95 feet) occurs in PGG-1d (Figure 7-6). Among Shallow-Aquifer monitoring wells, a very small WLE reduction is predicted closest to the marsh with no change predicted at greater distance. The model predicts that PGG-1i (located closest to the marsh) would experience a 0.01-foot WLE reduction during the storm condition (relative to the current condition) due to improved drainage associated with the modern tide gate.

Similar to WLE's predicted in the Shallow Aquifer, model ditch flows show no significant change between the current tide gate and the modern tide gate during the 28-day average period (Figure 7-15). Predicted ditch flows are slightly higher during the tail end of the 10-day storm period under current conditions, presumably due to the proximity of the lower reaches of the ditches to Beltz Marsh.

Dike Breach Scenario

Similar to the modern tide-gate scenario, the breach scenario predicted average daily WLE's during the 28-day average-condition period are virtually the same between the current tide-gate and the dike-breach configurations. The only exception occurs in Deep-Aquifer monitoring well PGG-1d, which is closest to the marsh (Figure 5-1). In PGG-1d, the higher peak WLE's in Beltz Marsh associated with the dike-breach configuration appear to cause a small (~0.1 foot) rise in Deep-Aquifer WLE, presumably due to the higher average daily WLE in Beltz Marsh and the proximity of the well to the marsh[5]. Table 7-1 reports model-predicted WLE difference down to a significant digit of 0.01 feet, and shows that model predictions of Shallow-Aquifer WLE changes during average conditions are typically less 0.005 feet. Minor WLE increases associated with the dike-breach configuration are predicted in the Shallow Aquifer close to Beltz Marsh under average conditions, as reflected by the 0.02-foot increase at PGG-1i.

Model results for the 10-day storm condition do show a difference between the current tide gate and the dike breach for some monitoring locations, predominantly for the Deep Aquifer. Where present, this difference shows slightly lower WLE's for the dike-breach configuration relative to the current tide gate configuration. This difference is caused by reduced prolonged inundation in Beltz Marsh predicted by the surface-water model due to improved drainage provided by the dike breach (Figure 7-2). Among the Deep-Aquifer monitoring wells, the most notable difference (0.95 feet) occurs in PGG-1d (Figure 7-6). Among Shallow-Aquifer monitoring wells, a small WLE reduction is predicted closest to the marsh, but decays sharply with distance from the marsh. The model predicts that PGG-1i (located closest to the marsh) would experience a 0.2-foot WLE reduction during the storm condition (relative to the current condition) due to breaching the dike.

Similar to WLE's predicted in the Shallow Aquifer, model ditch flows show no significant change between the current tide gate and the dike-breach configurations during the 28-day average period (Figure 7-15). Predicted ditch flows are slightly higher during the tail end of the 10-day storm period under current conditions, presumably due to the proximity of the lower reaches of the ditches to Beltz Marsh.

The predictive hydrographs show that groundwater level rises caused by prolonged inundation during the 10-day storm period remain relatively high through the end of the period. A longer model duration would be needed for modeled water levels to recover back down to average conditions; however, the critical time is during peaks in the hydrograph and extending the model duration is not needed for the intended modeling purpose. As noted above, Shallow-Aquifer WLE's are overpredicted by using Tillamook-based recharge values to realization v21 calibrated with Cloverdale-based recharge. Again, this WLE overprediction has no significant effect on v21 prediction of WLE changes between the current tide gate and the breached-dike configurations.

7.4 MODEL LIMITATIONS

The following limitations are noted for the surface-water and groundwater models:

7.4.1 Surface-Water Model Limitations

The adapted surface-water "bucket model" remains, in essence, a basic accounting of flows into and out of the Beltz Marsh that drive water level fluctuations computed from stage-storage relationships. The

[5] It should also be noted that, similar to model predictions during calibration, WLE's in the Deep Aquifer show diurnal variations due to tidal influence that are predicted to be absent in the Shallow Aquifer (even under the dike-breach configuration).

model's primary purpose is to provide input to the groundwater model. Therefore, model application limitations include the following:

- The model cannot be reformulated within the existing scope and budget to account for complex phenomenon such as roadway overtopping, dike overtopping, and complex hydraulics in stormwater drainage systems. Inputs can be turned on, turned off, or reasonably scaled using simple theoretical methods.
- The model relies upon an accurate stage-storage relationship computed from PhoDAR/LiDAR supplemented by topographic survey. Due to the complex topography of emergent marsh systems, and the practical difficulty of surveying them, some inherent error in the stage-storage relationship must be acknowledged and accepted. Survey coverage is limited within the lower-lying, permanently inundated areas of the marsh.
- The topography of the beaver dam is incorporated in the stage-storage relationship, but the storage area upstream of the beaver dam is not evaluated as a separate "bucket" in the model. The entire marsh is evaluated as a single "bucket". Simulation of beaver dam's influence on water levels at the edge of TDM would be incorporated as a static water level that never drops below 7.5 feet.
- The modeling relies upon watershed scaling based on the nearby gaged stream Tucca Creek to define freshwater input from the two creeks; a detailed hydrology study of the two creeks drainages is outside the scope of this study. The model does not replace detailed studies of surface water flooding and hydraulics that might be required by local or federal flood authorities to implement changes to site conditions.

7.4.2 Groundwater Model Limitations

- The groundwater model was calibrated average (steady-state) and time-series (transient) WLE's recorded during the wet-season monitoring period. Successful calibration indicates that the model is suitable for simulation of wet-season conditions. The model has not been calibrated to dry-season conditions or to seasonal variations over a representative annual cycle. In order to confidently apply the groundwater model to year-round conditions, additional dry-season WLE data would need to be collected from project monitoring wells[6], and the model would need to be recalibrated based on the full set of available data. PGG does not recommend using the current model to simulate dry-season conditions until realizations are calibrated to both wet-season *and* dry-season data.

- Although the groundwater model was calibrated to both Tillamook and Cloverdale wet-season precipitation datasets, predictive simulations for both model realizations employed a hypothetical precipitation dataset based on Tillamook data (Section 7.3.2). Applying Tillamook-based precipitation data to the Cloverdale predictive model realization tends to overestimate groundwater elevations and WLE responses to precipitation. While the predictive Cloverdale realization was useful for constraining the expected WLE response to modifying the tide gate, associated overestimates of WLE's and WLE responses do not represent *absolute* WLE's associated with the predictive scenario. A separate recharge time series, based on Cloverdale rather than Tillamook precipitation, would need to be developed and utilized in the Cloverdale model realization to estimate the (lower) absolute WLE's during the hypothetical flooding event.

[6] A single WLE snapshot was collected in August 2018.

8.0 SUPPLEMENTAL ANALYSES

Based on recommendations from PGG/ESA team members and public comment, OPRD decided to have the consulting team run a variety of supplemental analyses. The comments and suggestions received, paired with study response and action are detailed in Appendix H. Supplemental analyses included:

- Evaluating the feasibility of constructing a setback dike located south of Reneke and Beltz Creeks that would allow for full tidal reconnection of the majority of Beltz Marsh while maintaining flood protection for TDM;
- Characterizing the effect of surface water "backing up" upstream of the Sand Lake Road culvert in the East Marsh, or in the TDM east ditch along Sand Lake Road;
- Characterizing the protective value of an overtopped dike for its ability to reduce peak water levels or delay rising water levels upstream of Beltz Dike;
- Assessing how inclusion (or exclusion) of inundation accumulated behind the beaver dam affects surface-water model results (i.e., if substantial additional storage volume could be achieved by removing the beaver dam);
- Surface-water modeling for an 8-foot modern tide gate closure set point during the same time 38-day prediction period as used in the previous model;
- Groundwater modeling for an 8-foot modern tide gate closure set point during the same time 38-day prediction period as used in the previous model.
- Groundwater model sensitivity analysis to hydraulic connectivity between the Shallow Aquifer beneath TDM and Beltz Marsh, achieved by increasing the transmissivity of the Shallow Aquifer beneath Beltz Marsh and the hydraulic conductivity of the "skin" sediments on the marsh floor.

The first three items were addressed by ESA using engineering calculations and hydrologic assumptions. The last four simulations were addressed by ESA and PGG using the surface-water and groundwater models (respectively).

8.1 SETBACK DIKE PRELIMINARY FEASIBILITY ASSESSMENT

Another potential alternative for reconnecting Beltz Marsh to tidal processes (breaching Beltz Dike), while maintaining flood protection at the south end of the marsh/TDM, would be to construct a setback dike near the south end of the Marsh. A setback dike constructed near the location of the existing beaver dam would allow Beltz Creek and Reneke Creek to drain directly to the restored tidal marsh, while No Name Creek (East Marsh) and the TDM ditches would drain into the area upstream of the setback dike. Therefore, the storage volume behind the setback dike would need to be sufficient to contain flood flows from No Name Creek, stormwater runoff from TDM, and direct precipitation.

The setback dike would prevent or limit tidal fluctuation at the south end of the marsh and isolate TDM from the reconnected Beltz Marsh. Accumulated freshwater behind the setback dike would drain out to Beltz Marsh through a culvert, and a tide gate would prevent high water in Beltz Marsh from flowing in to the area behind the setback dike. The new tide gate would likely need to meet fish passage criteria. This tide gate would be significantly smaller than the modern tide gate in Alternative Configuration #2, because the upstream/inundated area is much smaller.

We performed a preliminary assessment to determine if a setback dike could be a feasible alternative. We selected a setback dike location cutting east-to-west across the wetland near the existing beaver dam. This results in an upstream wetland/storage area of approximately 10 acres, between the setback dike and the edge of TDM. The area behind this setback dike would have a stage-storage relationship is shown in Figure 8-1. For this assessment we neglected any potential storage volume below 8'. Much of the area below 8.0' is currently impounded by the beaver dam and could be designed to hold water under future conditions with the setback dike in place. When upstream water levels reached 10.0', 17 acre-feet of water would be stored. The low point in Sand Lake Road, near the East Marsh culvert is 11.6'. Approximately 35 acre-feet could be stored upstream of the setback dike before water started to overtop the roadway.

Water would accumulate behind the setback dike when the tide gate is closed. For this assessment, we assumed the tide gate would close when outboard water levels reached 8.0' and reopen when the tide dropped below 8.0'. Reviewing the available Sand Lake water level data and the Ocean tides at Garibaldi, we estimate the maximum duration this tide gate would stay shut would be 8 hours. We developed 50-yr and 100-yr event hydrographs for the combined inflows including the East Marsh, TDM runoff, and direct precipitation.

Under the 100-year flood event, the maximum water accumulation in any 8-hour period is 21 acre-feet. This water stored behind the setback dike would result in water levels near 10.4' NAVD88.

In order to evaluate when the storage capacity of the setback dike would be exceeded, we considered a theoretical worse-case extreme condition, where the tide gate stayed shut for 18 hours. With a sustained inflow at the 100-year peak flow rate of 32 cfs, approximately 48 acre-feet would accumulate, resulting in water levels near 12.4'. In some river systems, such as the Nehalem River, tide gates may stay shut for multiple tide cycles due to elevated water levels during high flow events. However, due to Sand Lake's proximity and direct connection to the Ocean, combined with the lack of large river inputs, this condition is not likely to occur.

This preliminary assessment indicates a setback dike alternative is feasible and could result in:

- Lower peak and sustained water levels than the existing configuration
- Lower peak water levels than the breached dike configuration
- Similar peak water levels to the modern tide gate configuration

This preliminary feasibility assessment was performed with limited time and budget, and was therefore based on coarsely estimated storage volume, hydrology, and operational assumptions. We would recommend a more-detailed analysis and modeling to further evaluate the ability of a setback dike to meet the project goals if later scoping indicates that this alternative is desirable in the context of wider environmental effects analysis.

8.2 EFFECT OF SURFACE WATER "BACKING UP" IN EAST MARSH OR EAST DITCH

During the stakeholder review and comment period, OPRD received questions about how the Sand Lake Road culvert draining the East Marsh would be affected by elevated water levels in Beltz Marsh, and if these elevated water levels could cause water to "back-up" in the East Marsh or in the East Ditch along Sand Lake Road. In order to characterize these scenarios, ESA developed a series of culvert capacity calculations based on elevated water levels in Beltz marsh and compared them to peak flow estimates contributing to these locations.

8.2.1 Effect of Elevated Water Levels and Sand Lake Road Culvert on East Marsh Water Levels

The flows from the East Marsh (No Name Creek) are conveyed across Sand Lake Road in a 24-inch corrugated metal pipe. The culvert is nearly flat, with a slight negative slope (invert elevation on the east side of the road was surveyed as lower than the invert elevation on the downstream/west side of the road). With an invert elevation below 5' NAVD88, and backwater effect from the downstream beaver dam, this culvert is typically submerged on both ends. The capacity of a culvert in under these conditions is driven by the size of the pipe, roughness/friction factor, and the relative difference in water levels on each side of the culvert.

We used spreadsheet calculations and HY-8, a culvert hydraulic analysis program developed by the Federal Highways Administration, to estimate the capacity of the culvert under Sand Lake Road. The estimated culvert capacity ranges from 7 cfs (with 0.5' of water level difference) to a maximum of 18 cfs (with 4 feet of water level difference, just before the roadway overtops). The limited pipe capacity would provide resistance to water moving in either direction (to or from the East Marsh).

When stormwater runoff/stream flow from the East Marsh exceeds the capacity of the culvert, impounded water would accumulate upstream of the culvert, increasing water levels in the East Marsh. The East Marsh 50-year storm hydrograph developed for the predictive model scenarios includes several peak flows above 14 cfs, with a maximum peak flow of 23 cfs. We developed an estimated 100-year storm hydrograph for the East Marsh drainage, which includes peak flows above 16 cfs, with a maximum peak flow of 27 cfs. During both the 50-year and 100-year event, stream flows from the East Marsh watershed would exceed the capacity of the culvert, resulting in stormwater backing up in the East Marsh.

When water levels in Beltz Marsh are elevated (up to 12' NAVD88 under some modeled conditions), water levels in the East Marsh would rise to equilibrate to water levels in Beltz Marsh. The limited culvert capacity would slow down the equilibration process. While the capacity of this culvert connecting the East Marsh to Beltz Marsh was not incorporated in the surface-water model, the existing groundwater model does assume this equilibration and water level propagation of Beltz Marsh tidewater back into the East Marsh.

Incorporating these culvert capacity limitations into the surface water model could have a minor effect on the timing of flows reaching Beltz Marsh, but this factor is unlikely to have a noticeable effect on modeled surface-water levels or groundwater levels. The proposed dike modifications could influence the capacity of this culvert, in that, the higher the water level is in Beltz Marsh, there is less potential difference in water levels driving flows out of the East Marsh. However, the most prolonged, elevated modeled water levels are observed under the existing culvert/tide gate configuration. Both alternative dike configurations result in less prolonged high water levels in Beltz Marsh, and therefore could stand to increase the average capacity of culvert draining the East Marsh.

8.2.2 Effect of Elevated Water Levels in East Ditch

In the east ditch along Sand Lake Road, elevated water levels in Beltz Marsh would propagate up the ditch at approximately the same elevation of the water in Beltz Marsh. The lowest/northernmost culvert in this ditch (under Roma Ave.) has an invert elevation of 11.72', and a 12-inch diameter (top elevation of 12.72'). The HDPE pipe has an approximate slope of 3 percent, with an estimated capacity of 8 cfs.

If water levels in Beltz Marsh exceed 11.72’, tailwater conditions would begin to influence culvert capacity, and if water levels exceeded 12.72’, the culvert would exhibit full outlet controlled hydraulic conditions which can reduce capacity of water to pass through (potentially backing water up in the ditch upstream of the Roma Ave culvert.

50-year peak runoff rates from TDM that could contribute to this ditch are approximately 8cfs, with 100-year peak runoff rates of up to 10 cfs. These peak runoff rates are conservatively estimated based on an assumption of 100% runoff (no infiltration). Actual peak runoff rates are likely much less, and would probably rarely exceed the culvert capacity. However, deposited sediment and debris blockages could significantly reduce the drainage capacity if the culverts are not maintained. A more detailed assessment of the capacities and condition of all of the east ditch culverts could be undertaken to identify potential blockages and sources of water backing up in the east ditch along Sand Lake Road. This detailed assessment is beyond the scope of the current modeling effort.

8.3 PROTECTIVE VALUE OF OVERTOPPED DIKE

The hydrologic boundary conditions developed for the predictive model scenarios included 50-year storm stream flows and king tide water levels in Sand Lake. These conditions nearly overtop Beltz Dike. More extreme high tide conditions resulting from a storm surge or sea level rise would overtop Beltz Dike, and water levels within Beltz Marsh would eventually equilibrate to the water levels in Sand Lake. During tidal events that overtop Beltz Dike, the dike may still provide some flood protection, or have a buffering effect by slowing water down as it fills Beltz Marsh.

Under a full breach scenario, the water levels in Beltz Marsh would rise along with the water levels in Sand Lake, and the remaining dike would not provide any protection or delay rising water levels. Under a modern tide gate scenario, where the Beltz Dike is still intact, the dike could slow down an incoming tide event in the short term.

To estimate the duration of this delay, we developed a series of weir flow calculations to determine the flow rate of water entering Beltz Marsh when the water level in Sand Lake overtops the dike by 0.5’ and 1’ of water. Beltz Marsh has a total storage volume behind the dike of about 300 acre-feet.

When the dike is overtopped by 0.5 feet (approximately 12.6’ water level), water would overflow into Beltz Marsh at a rate of approximately 1,000 cfs, and it would take about 3.5 hours to fill in/equilibrate. When the dike is overtopped by 1.0 feet (approximately 13.1’ water level), water would flow into Beltz Marsh at a rate of approximately 6,500 cfs. At this rate, it would take only 30 minutes to completely fill in/equilibrate.

Depending on the depth of water overtopping the dike, the overtopped dike can provide some flood protection value by delaying rising water levels. However, overflowing water could cause erosion along the embankment which could lead to dike failure or an un-planned dike breach. To counteract this potential failure, low spots in the dike could be identified and rock armoring could be installed to protect the embankment from erosion during overflows.

8.4 EFFECT OF REMOVING BEAVER DAM ON AVAILABLE FLOOD STORAGE

The LiDAR/PhoDAR terrain surface used in the surface water model does not depict underwater bathymetry behind the beaver dam. The LiDAR/PhoDAR surface shows a flat area behind the beaver dam, due to the laser signal reflecting off of the water surface. The area behind the beaver dam is permanently filled with water, and therefore not available as storage volume to contain water during flood events. It has been theorized that removing the beaver dam could increase available storage volume and possibly result in lower water levels in Beltz Marsh during storm events.

In order to estimate the effect that removing the beaver dam would have on modeled water levels, we adjusted the terrain surface to reflect the estimated land surface inundated by the beaver dam. Based on field observations and review of the LiDAR/PhoDAR surface, we lowered the inundated area by an average of 2 feet. This adjustment resulted in 2.1 acre-feet of additional storage volume below the elevation of 8'. A new stage-storage relationship was developed from the modified surface, and the surface-water model predictive scenarios were re-run to determine if the additional storage would affect modeled water levels.

With the beaver dam removed, the additional storage lowered modeled water levels by a maximum of 0.1 feet. When plotted together, the water levels are not visibly different (Figure 8-2). Removing the beaver dam would not have a noticeable effect on water levels during storm conditions.

8.5 SIMULATION OF A HIGHER 8-FT TIDE GATE CLOSURE SETTING

The modern tide gate configuration is based on a Muted Tidal Regulator (MTR) design, which allows for adjusting the upstream water level at which the gate would close. Alternative Configuration #2 uses a closure setting of 7.0' (the tide gates close when the interior water levels reach 7.0'). Using a higher closure setting would allow for more frequent inundation of upper marsh areas. A higher closure setting would also allow more of the available storage volume behind Beltz Dike to be occupied by tide water, potentially leading to higher water levels during storm events when the tide gates are closed. Appendix H refers to modeling both 7.5 and 8-foot closure settings; however, results from first modeling the 8-foot setting indicated that additional modeling effort and expense to complete the intermediate 7.5-foot closure setting was not necessary.

8.5.1 Surface-Water Model Simulation of 8-ft Cutoff Modern Tide Gate

ESA re-ran the surface water model Modern Tide Gate scenario with the tide gate set to close when interior water levels reached 8.0' (1 foot higher than the original Modern Tide Gate scenario). A comparison of predicted water levels using 7-foot an 8-foot closure settings is shown in Figure 8-3.

This higher water level shut setting typically resulted in peak water levels within Beltz Marsh rising about 1 foot higher during each high tide during typical winter conditions and moderate storms. However, during the height of the storm scenario, the peak water levels were only 0.1' to 0.2' higher than in the initial Modern Tide Gate scenario that used a 7-foot closure setting. The resulting water level time series was provided to PGG to use as boundary conditions in the groundwater model.

8.5.2 Groundwater Model Simulation of 8-ft Cutoff Modern Tide Gate

PGG employed surface-water model predictions of tidal inundation in Beltz Marsh developed for the modern tide gate using an 8-foot cutoff elevation (described above) to evaluate whether raising the cutoff elevation by one foot would change predicted shallow groundwater elevations beneath TDM. Time-series marsh water levels for the 8-foot cutoff imported into the predictive model simulations (discussed in Section 7.3.1) showed no significant difference from model results for a 7-foot cutoff elevation at the modern tide gate. The TDM Shallow-Aquifer monitoring well closest to Beltz Marsh (PGG-1i) showed a maximum water-level increase of 0.01 feet (towards the end of the 10-day flooding event) between the 8-foot and the 7-foot predictions. More detailed documentation of model predictions for selected wells using the 7- and 8-foot cutoff elevations is provided in Appendix I.

8.6 SUPPLEMENTAL GROUNDWATER MODEL SENSITIVITY ANALYSIS

In a prior version of this report (Partial Draft #2), PGG recommended that additional model analysis be performed to evaluate the sensitivity of model predictions to hydraulic connectivity between Beltz Marsh and the Shallow Aquifer beneath TDM. Prior sensitivity analysis during steady-state calibration suggested that the model was not sensitive to K_s of the "skin sediments" beneath the marsh; however, lack of model sensitivity under steady-state calibration conditions does not necessarily imply lack of sensitivity under transient conditions (periodic tidal inundation or event-based tidal flooding). In order to evaluate the sensitivity of model predictions to an assumed enhanced connection between the marsh and the Shallow Aquifer beneath TDM, PGG developed an "enhanced marsh connectivity" (EMC) version of the Tillamook model realization (v12) by making the following changes:

- PGG increased the transmissivity of the Shallow Aquifer by 3x. This was accomplished by increasing K_h beneath the marsh from 27 to 81 ft/day; however, the intended effect of this modification was to increase the *effective thickness* of the aquifer by 3x. Transmissivity is equivalent to K_h times thickness – so increasing K_h by a given multiplier has the same effect as increasing thickness by the same multiplier. The original (calibrated) K_h of the Shallow Aquifer was already considered to be reasonable and representative of published values for sandy materials; however, field characterization of aquifer thickness beneath the marsh would be prohibitively expensive and was not included in the project scope. Saturated thickness estimates of 2.5 to 3 feet were developed by projecting the elevation of the top of the clay aquitard from observations in TDM boring logs to a log at Whalen Island (Section 5.2). Because the aquifer thickness beneath the marsh was not documented by field investigation, the 3x increase in transmissivity was used to evaluate model sensitivity to a 3x increase in aquifer thickness.

- Increased the value of K_s beneath the marsh by 30x from 0.4 to 12 ft/day. The original K_s value was based on NRCS soils mapping which showed fluvaquents-Histosols with a limiting K_v of 0.4 to 4 ft/d (Section 6.2.4). However, calibrated K_s values for model drain cells associated with beach sand had K_s values of 12 ft/d (Table 6-3). This 30x multiplier is likely to over-predict K_s for materials beneath Beltz Marsh and is therefore a highly-conservative assumption.

These changes were first applied to the steady-state and transient calibration runs of the Tillamook model realization and showed no significant impact to calibration success. The EMC transient Tillamook model was then run under predictive conditions to estimate how changing from the current tide gate to either the breach or the modern tide-gate conditions affects Shallow Aquifer groundwater responses beneath TDM. The largest predictive difference occurred at Well PGG-1i – the closest Shallow-Aquifer monitoring well to Beltz Marsh. For the breach configuration, the EMC model predicted a 0.01-foot WLE rise during the 28-day "average condition" period followed by a WLE reduction as large as 0.08 feet during the 10-day "storm" period. For the modern tide-gate configuration, the EMC model predict no difference during the 28-day "average condition" period followed by a WLE reduction as large as 0.1 feet during the 10-day "storm" period. More detailed documentation of calibration and predictive results is provided in Appendix I.

9.0 REFERENCES

Bauer, H.H. and J.J. Vaccaro. 1987. *Documentation of a Deep Percolation Model for Estimating Ground-Water Recharge.* U.S. Geological Survey Open-File Report 86-536.

Blainey & Criddle.

ESI (Environmental Simulations Inc.), 2018. *Groundwater Vistas Version 7*. www.groundwatermod-els.com.

FAO, 1986. Irrigation Water Management: Irrigation Water Needs.

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. 604 pp.

Halford, K., and Kuniansky, E., 2002. *Documentation of Spreadsheets for the Analysis of Aquifer-Test and Slug-Test Data*. U.S. Geological Survey Open-File Report 02-197.

Harbaugh, A.W., 2005, *MODFLOW-2005, the U.S. Geological Survey Modular Ground-water Model -- the Ground-Water Flow Process*. U.S. Geological Survey Techniques and Methods 6-A16.

Lane, K., Washburn, D., Krynine, D., 1946. *Capillarity tests by capillarimeter and by soil filled tubes. I*n: Highway Research Board Proceedings.

Morris, D.A. and A.I. Johnson, 1967. *Summary of hydrologic and physical properties of rock and soil materials as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey*, U.S. Geological Survey Water-Supply Paper 1839-D, 42p.

NRCS (Natural Resource Conservation Service), 2018. *Custom Soil Resource Report for Tillamook County, Oregon - Tierra Del Mar Area*. Dated February 17, 2018.

Philip Williams & Associates, 1995. *Design Guidelines for Tidal Channels in Coastal Wetlands.* The U.S. Army Corps of Engineers Waterways Experiment Station.

Rosas, J., Lopez, O., Missimer, T.M., Coulibaly, K.M., Dehwah, A.H., Sesler, K., Lujan, L.R. and Mantilla, D., 2014. *Determination of hydraulic conductivity from grain-size distribution for different depositional environments.* Groundwater, 52(3), pp.399-413.

Waterways Consulting, Inc., 2017. *Sitka Sedge Natural Area, Summary of Work Completed to Date. Final.* April 7, 2017.