PACIFIC groundwater GROUP

JY1006

June 18, 2013

Ducks Unlimited
17800 SE Mill Plain Blvd., Suite 120
Vancouver, WA 98683

Attn: Graham Peters
Re: Supplemental Model Runs for Leque Island Restoration Project

Dear Graham:

This letter report presents the results of supplemental model simulations performed with Pacific Groundwater Group's 3D MODFLOW model developed to assess whether proposed restoration of Leque Island is likely to cause groundwater flow reversals beneath the northeast edge of Camano Island. PGG performed these supplemental simulations per your request in response to comments provided by EPA hydrogeologist Mohamed Hantush during the May 29 2013 stakeholders meeting. Specifically, Mr. Hantush suggested that the following supplemental simulations would be helpful in assessing the model's capacity to predict flow reversals to the following conditions:

1) Leque Island groundwater heads exceeding the estimated post-restoration head of 6.9 feet NAVD88;
2) Drought conditions; and,
3) Clogging of local drainage ditches.

As documented in our recent report (*Hydrogeologic Evaluation of Proposed Leque Island Restoration, December 2012*), PGG developed four versions ("realizations") of the 3D MODFLOW model. Model stratigraphy was represented in two ways:

- Extending the glacial stratigraphy observed beneath Camano Island to the Leque Lowland ("GS", or "glacial stratigraphy" configurations). Model runs for this configuration are numbered as Version 15.
- Representing layering and anisotropy beneath the Leque Lowland by assigning anisotropies to various sedimentary textures ("LA" or "lumped anisotropy" configurations). Model runs for this configuration are numbered as Version 16.

For each configuration, PGG evaluated the model sensitivity to hydraulic conductivity of surface-water features. Version "C" (15C, 16C) simulations use "best-fit" hydraulic conductivities for drains and rivers as estimated during calibration. Version "D" (15D, 16D) simulations reduce the best-fit river and drain conductances by an order of magnitude. All four model simulations were run under current conditions and restoration conditions (where heads in the top model layer beneath Leque Island were fixed at 6.9 feet NAVD88). The restoration simulations showed no significant reversal of groundwater flow beneath the Camano Island upland escarpment.

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Water Resource & Environmental Consulting

In order to address Mr. Hantush's suggestions, PGG performed the following additional simulations:

1. PGG investigated the impacts on greater-than-anticipated heads beneath Leque Island by gradually increasing the value of the constant head cells inserted in layer 1 for the restored condition. Heads were increased by 1-foot intervals starting at 7-feet NAVD88 until a significant flow reversal was observed beneath the eastern edge of Camano Island (adjacent to Leque Island). Simulations of this condition are referred to as "Hmax" simulations".

2. PGG investigated the impacts of drought by gradually increasing modeled pumping withdrawals by multipliers of 1.5 while representing the restored condition on Leque Island (constant head = 6.9 feet NAVD88). All modeled pumping occurs beneath Camano Island in Aquifer D. Simulated recharge to Camano Island was not changed because the thick surficial till and glaciomarine sediments blanketing Camano Island are expected to moderate drought-scale variations in precipitation recharge. Recharge was not changed beneath Leque Island because post-restoration recharge is derived from marine inundation (represented by the constant-head condition). Recharge to the lowland between Leque and Camano islands was decreased by 50 percent. Simulations of drought conditions after Leque Island restoration are referred to as "RQx" simulations.

3. PGG investigated the impacts of clogging of local ditches by reducing the modeled hydraulic conductivity of the "ditch-bed" by an order of magnitude beyond the "D" series runs. Hydraulic conductivity values for local drains were decreased to 0.001 to 0.005 ft/d – two orders of magnitude below the values developed during model calibration. These values equate to 4E-07 to 2E-06 cm/sec, and are considered very low. These model simulations were designated "F"-series runs (15F, 16F), and were run for all model representations (current condition, restored condition ("R"), increased Leque Island head ("Hmax"), and drought pumping ("RQx").

Table 1 summarizes the prior model simulations and the simulations run for preparation of this letter-report. All series (15C, 15D, 15F, 16C, 16D and 16F) have been run under current, "R", "Hmax" and "RQx" conditions. The occurrence of flow reversal beneath the eastern edge of Camano Island was evaluated using particle tracking with the USGS program MODPATH. Lines of multiple particles were placed along the eastern edge of the island and distributed vertically throughout model layers 1 through 7 (one particle in the middle of each layer). These 7 layers represent a thickness of almost 70 feet beneath the lowland, and are the same layers used to represent Aquifer D beneath the Camano upland.

The following sections present the results of the supplemental simulations discussed above. Once each model simulation identified the condition (head or pumping rate) at which flow reversals were predicted to occur, PGG documented these reversals with screen-shots of predicted particle traces, as shown on **Figures 1** through **6**.

Greater-Than-Anticipated Heads Beneath Leque Island

In assessing the potential for reversal of groundwater flow to Camano Island due to higher restoration heads beneath Leque Island, PGG differentiated between the formation of isolated, localized “flow recirculation cells” along the edge of the upland escarpment and significant flow reversals that carry groundwater from the lowland into substantial portions of the upland groundwater flow system. Previous model simulations of the restored condition predicted two small two flow recirculation cells on the north and south corners of the eastern edge of the upland escarpment[1]. Neither of these two small cells was considered to pose significant risk to public health or the availability of water supply from Aquifer D. For this analysis, PGG focused on Leque Island head values that would cause significant flow reversals rather than edge effects. As shown on **Table 1**, the model predicts that Leque Island head values required to form significant (regional) reversals of flow ranged from 10 to 14 feet NAVD88 (3.1 to 7.1 feet above current estimates of restored head).

Note that the layer-1 velocity vectors for the lumped-anisotropy (series 16) model simulations show groundwater in Aquifer D discharging to the lowland despite the fact that the particle traces show reversed groundwater transport from the lowland to the upland. For these simulations, predicted particle pathlines occur deeper in the groundwater system - predominantly into Aquifer C. Higher Leque Island heads would be needed to cause predicted flow reversal from the lowland into Aquifer D. USGS hydrogeologic characterization does not show any wells completed in Aquifer C, and PGG has lower confidence in predictions of hydrogeologic impact to Aquifer C because it did not play a significant role in model calibration.

Drought Conditions

As discussed above, simulation of drought conditions included reduction of lowland recharge and increasing Camano Island groundwater pumping until a flow reversal was predicted. Because the groundwater model is run in steady-state mode, it does not simulate the gradual adjustment of the groundwater system to drought conditions. Instead, it simulates instantaneous and full adjustment to drought conditions as if drought had been ongoing in perpetuity. This drought representation is highly conservative in that full equilibration to drought conditions is unlikely to occur within a time period typical of drought conditions (e.g. 5 years). In order to incorporate consideration of the duration of a drought event, PGG limited the duration of particle tracking to 10 years of transport and increased groundwater withdrawals until particle penetrated several hundred feet beneath the Camano Island upland[2]. The logic behind this formulation was that several hundred feet of penetration along the upland edge during a drought event would be reversed and flushed out between drought events. The 10-year migration period was considered conservatively long for a drought occurrence.

Table 1 shows that the model predicts that pumping withdrawals would need to be increased by factors of 5x to 7x to cause sufficient flow reversal for lowland water to penetrate several hundred feet beneath the upland. These multipliers are significantly higher than those realistically expected during a drought event.

Clogging of Local Ditches

Reducing the modeled hydraulic conductivity (K) of local drains by two orders of magnitude (relative to the calibrated values) had little effect on model predictions of head under current

[1] See Figures C-14 and C-15 of PGG’s 2012 report. The southeast cell was interpreted as formed due to USGS localized over-prediction of recharge, presumably an artifact of their computer algorithm.
[2] The model employed a porosity value of 0.25 for all aquifers.

conditions, but significantly reduced predictions of ditch flow to unrealistically low values. **Table 2** summarizes modeled head residuals and ditch flows under current conditions and shows associated estimates of ditch flow to be around 0.0003 cfs (0.1 gpm). Despite the fact that this K value predicts unrealistic values of ditch flow, running the “Hmax” and “RQx” simulations under this condition did not cause a significant departure from the “C” and “D” series model simulations as summarized on **Table 1**.

Summary of Findings

The supplemental model simulations performed by PGG suggest that:

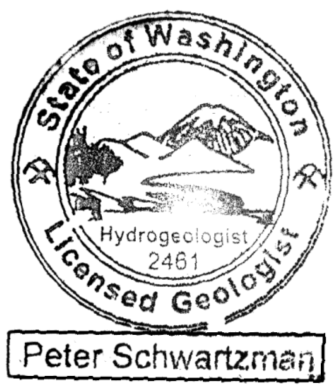
1. Post-restoration heads beneath Leque Island would have to be 3.1 to 7.1 feet higher than predicted to cause significant reversal of groundwater flow from the lowland to the Camano Island upland.
2. Realistic depictions of drought conditions would not cause a flow reversal from the lowland to the Camano Island upland. Drought pumping would need to increase by factors of 5x to 7x to cause such a flow reversal.
3. Clogging of ditches, to the degree suggested by Mr. Hantush, does not significantly change the two findings above.

These supplemental simulations increase the robustness of prior model findings, that reversal of flow beneath Camano Island due to Leque Island restoration is unlikely.

We hope that this letter-report is helpful in understanding the model sensitivity towards predicting flow reversals as a result of the conditions mentioned by Mr. Hantush. Please feel free to contact us should you have any related questions.

Sincerely,
Pacific Groundwater Group

Peter Schwartzman
Principal Hydrogeologist



Attachments:
Tables 1 & 2
Figures 1-6

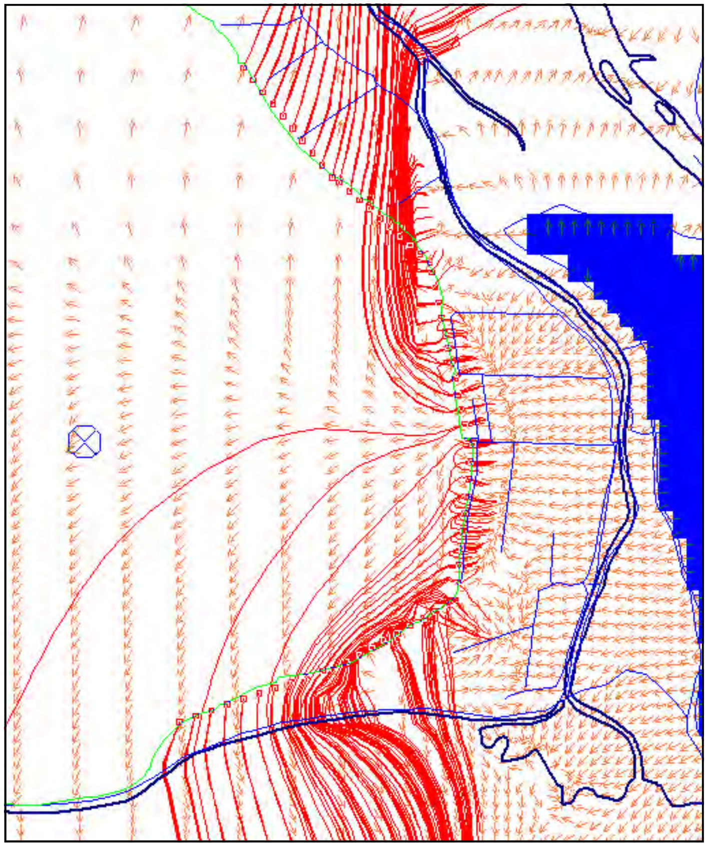
Table 1 - Summary of Model Simulations

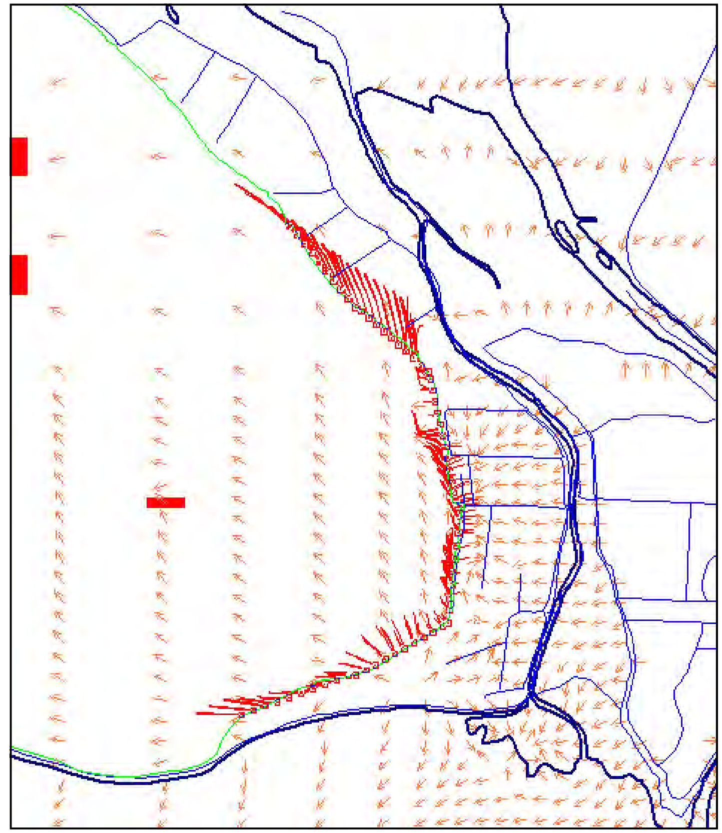
Run ID	Condition	Model Structure	Leque Island Head Required for Significant Flow Reversal (ft NAVD88)	Drain Conductance Multiplier (Relative to Calibration)	River Conductance Multiplier (Relative to Calibration)	Leque Lowland Recharge Multiplier	Pumping Multiplier Required for 10-yr Particles to Penetrate Beneath Upland
15c	current	Glacially Statified	n/a	1	1	1	n/a
15c-R	restored	Glacially Statified	n/a	1	1	1	n/a
15c-Hmax	maxed LI head	Glacially Statified	14	1	1	1	n/a
15c-RQx	restored w drought pumping	Glacially Statified	n/a	1	1	0.5	5.1
15d	current	Glacially Statified	n/a	0.1	0.1	1	n/a
15d-R	restored	Glacially Statified	n/a	0.1	0.1	1	n/a
15d-Hmax	maxed LI head	Glacially Statified	11	0.1	0.1	1	n/a
15d-RQx	restored w drought pumping	Glacially Statified	n/a	0.1	0.1	0.5	5.1
15f	current	Glacially Statified	n/a	0.01	0.1	1	n/a
15f-R	restored	Glacially Statified	n/a	0.01	0.1	1	n/a
15f-Hmax	maxed LI head	Glacially Statified	11	0.01	0.1	1	n/a
15f-RQx	restored w drought pumping	Glacially Statified	n/a	0.01	0.1	0.5	5.1
16c	current	Lumped Anisotropy	n/a	1	1	1	n/a
16c-R	restored	Lumped Anisotropy	n/a	1	1	1	n/a
16c-Hmax	maxed LI head	Lumped Anisotropy	12	1	1	1	n/a
16c-RQx	restored w drought pumping	Lumped Anisotropy	n/a	1	1	0.5	7.6
16d	current	Lumped Anisotropy	n/a	0.1	0.1	1	n/a
16d-R	restored	Lumped Anisotropy	n/a	0.1	0.1	1	n/a
16d-Hmax	maxed LI head	Lumped Anisotropy	11	0.1	0.1	1	n/a
16d-RQx	restored w drought pumping	Lumped Anisotropy	n/a	0.1	0.1	0.5	7.6
16f	current	Lumped Anisotropy	n/a	0.01	0.1	1	n/a
16f-R	restored	Lumped Anisotropy	n/a	0.01	0.1	1	n/a
16f-Hmax	maxed LI head	Lumped Anisotropy	10	0.01	0.1	1	n/a

Table 2
Model Calibration Results

Target Name	Observed Head (ft)	Residual GS 15c	Residual GS 15d	Residual GS 15f	Residual LA 16c	Residual LA 16d	Residual LA 16f
Well 6.8a	6.8	0.35	0.32	0.31	0.65	0.64	0.64
Well 6.7	6.7	0.15	0.13	0.12	0.43	0.42	0.42
Well 6.5a	6.5	0.04	0.01	0.00	0.37	0.36	0.36
Well 6.6a	6.6	-0.02	-0.03	-0.04	0.23	0.23	0.22
Well 7	7.0	0.49	0.47	0.46	0.82	0.81	0.81
Well 5.6	5.6	-0.93	-0.96	-0.96	-0.72	-0.73	-0.74
Well 6.3	6.3	-0.24	-0.27	-0.28	-0.07	-0.08	-0.09
Well 6.6b	6.6	0.04	0.01	0.00	0.17	0.16	0.15
Well 6.3	6.3	-0.27	-0.30	-0.31	-0.14	-0.16	-0.16
Well 6.4	6.4	-0.34	-0.35	-0.36	-0.45	-0.45	-0.45
Well 6.8b	6.8	-0.51	-0.53	-0.54	-0.65	-0.66	-0.66
Well 6.6c	6.6	-0.06	-0.07	-0.08	0.05	0.05	0.05
Well 7.9	7.9	-0.18	-0.19	-0.20	-0.15	-0.16	-0.16
Well 6.5b	6.5	-0.47	-0.49	-0.49	-0.35	-0.36	-0.36
Well 11.9	11.9	2.41	2.39	2.39	2.49	2.49	2.49
Well 5.2	5.2	-1.42	-1.45	-1.46	-1.28	-1.30	-1.30
Well 7.3	7.3	-2.21	-2.23	-2.23	-2.01	-2.01	-2.02
Well 5.5	5.5	-0.78	-0.80	-0.81	-0.26	-0.27	-0.27
Well 10.8	10.8	0.53	0.52	0.51	0.76	0.76	0.76
Well 5.7	5.7	-0.82	-0.85	-0.86	-0.40	-0.41	-0.42
Oksendahl	7.3	0.40	0.36	0.35	0.74	0.71	0.70
N1S	6.0	0.28	0.17	0.15	0.53	0.46	0.46
N2D	5.9	-0.36	-0.45	-0.46	0.21	0.16	0.15
N2S	5.7	-0.13	-0.27	-0.29	0.09	-0.01	-0.02
N3S	5.2	-0.64	-0.75	-0.77	-0.48	-0.56	-0.57
S1D	7.0	0.90	0.80	0.79	1.16	1.11	1.11
S1S	6.8	0.84	0.70	0.68	0.98	0.91	0.90
S2S	6.6	0.35	0.28	0.26	0.52	0.47	0.46
S3S	6.9	0.47	0.40	0.39	0.58	0.53	0.52
Leque	5.4	0.02	-0.05	-0.05	0.18	0.14	0.14
Residual Mean	- - -	-0.07	-0.12	-0.13	0.13	0.11	0.10
Absoluate Residual Mean	- - -	0.55	0.55	0.55	0.60	0.59	0.58
Residual Std. Deviation	- - -	0.79	0.79	0.78	0.80	0.79	0.79
Sum of Squares	- - -	18.95	18.90	18.94	19.60	19.22	19.16
RMS Error	- - -	0.79	0.79	0.79	0.81	0.80	0.80
Min. Residual	- - -	-2.21	-2.23	-2.23	-2.01	-2.01	-2.02
Max. Residual	- - -	2.41	2.39	2.39	2.49	2.49	2.49
Number of Observations	- - -	30.00	30.00	30.00	30.00	30.00	30.00
Range in Observations	- - -	6.77	6.77	6.77	6.77	6.77	6.77
Scaled Residual Std. Deviation	- - -	12%	12%	12%	12%	12%	12%
Scaled Absolute Residual Mean	- - -	8%	8%	8%	9%	9%	9%
Scaled RMS Error	- - -	12%	12%	12%	12%	12%	12%
Scaled Residual Mean	- - -	-1%	-2%	-2%	2%	2%	2%
Drain Flux on Monitoring Site (cfs)		0.019	0.002	0.0003	0.013	0.002	0.0002

NOTES:
All values in feet unless otherwise specified.





Particle Starting Locations

Particle Traces

Layer 1 Velocity Vectors

Wells

Surface-Water Features

Upland Escarpment

Constant Head Cells

Note: See Table 1 for head and pumping values used in depicted simulations.

Figure 1
Particle Traces from Model Simulation 15c

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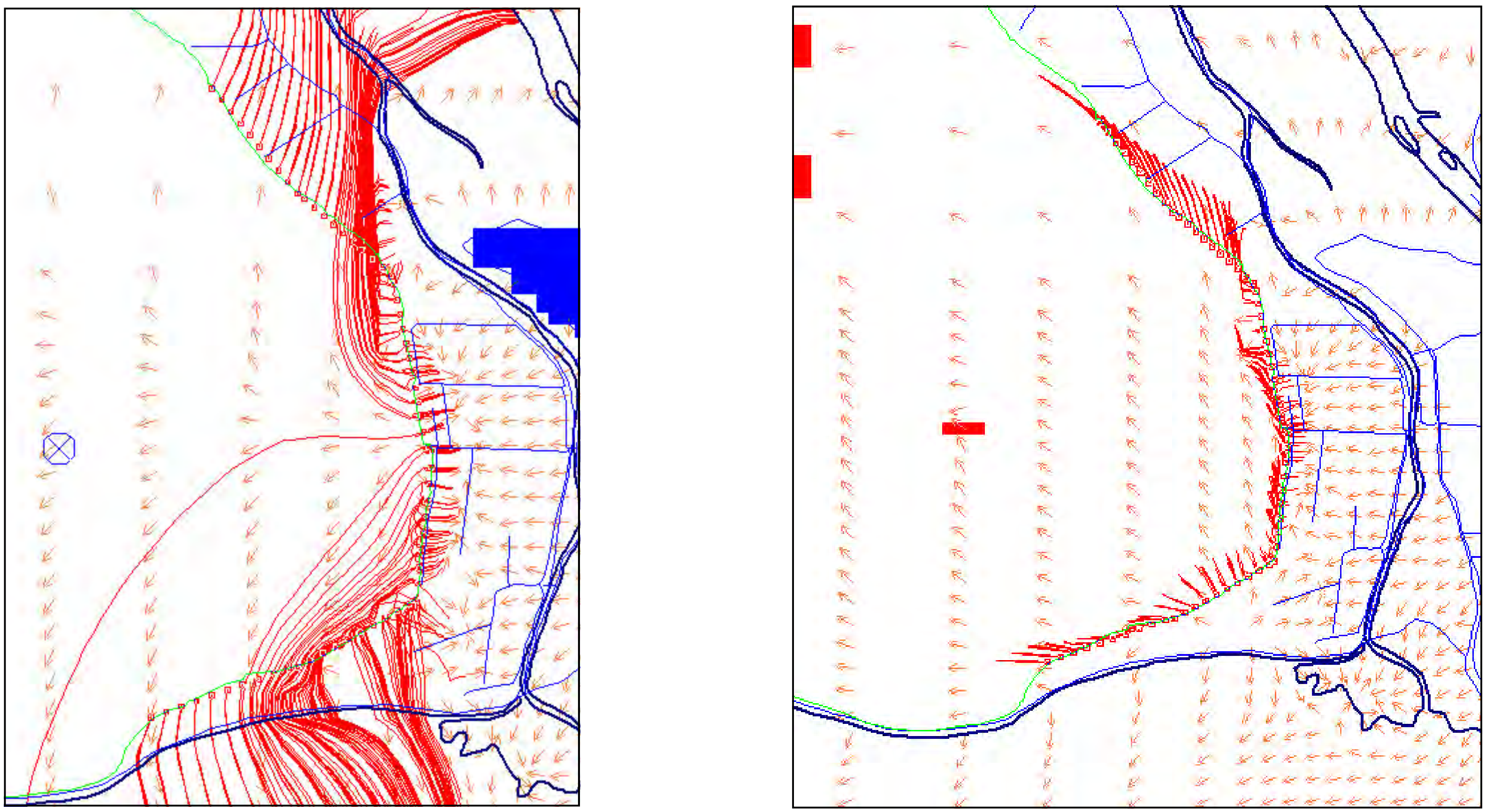
Leque Island Restoration

PgG

Hmax **RQx**



Particle Starting Locations

Particle Traces

Layer 1 Velocity Vectors

Wells

Surface-Water Features

Upland Escarpment

Constant Head Cells

Note: See Table 1 for head and pumping values used in depicted simulations.

Figure 2
Particle Traces from Model Simulation 15d

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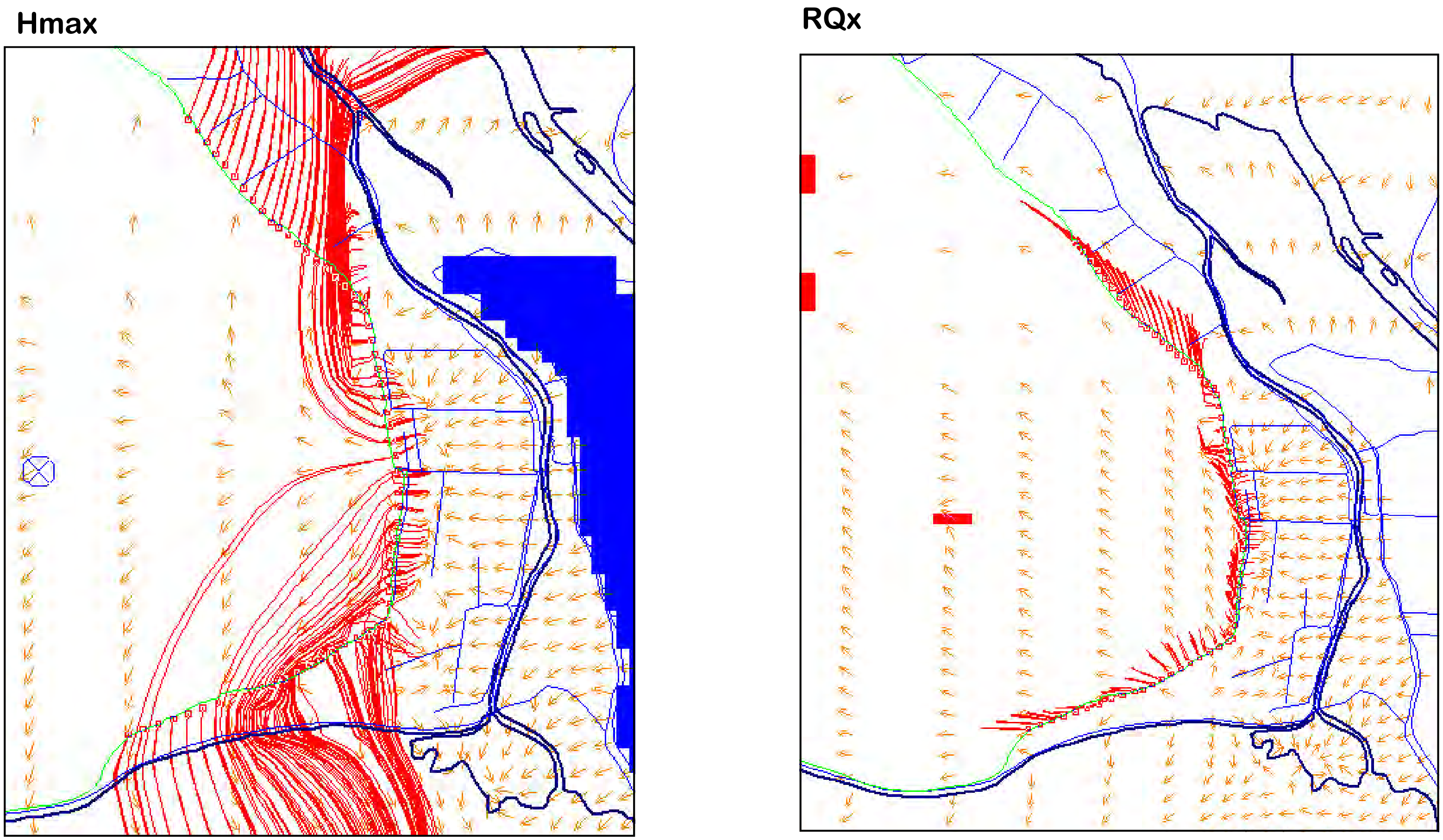

Particle Starting Locations

Particle Traces

Layer 1 Velocity Vectors

Wells

Surface-Water Features

Upland Escarpment

Constant Head Cells

Note: See Table 1 for head and pumping values used in depicted simulations.

Figure 3
Particle Traces from Model Simulation 15f

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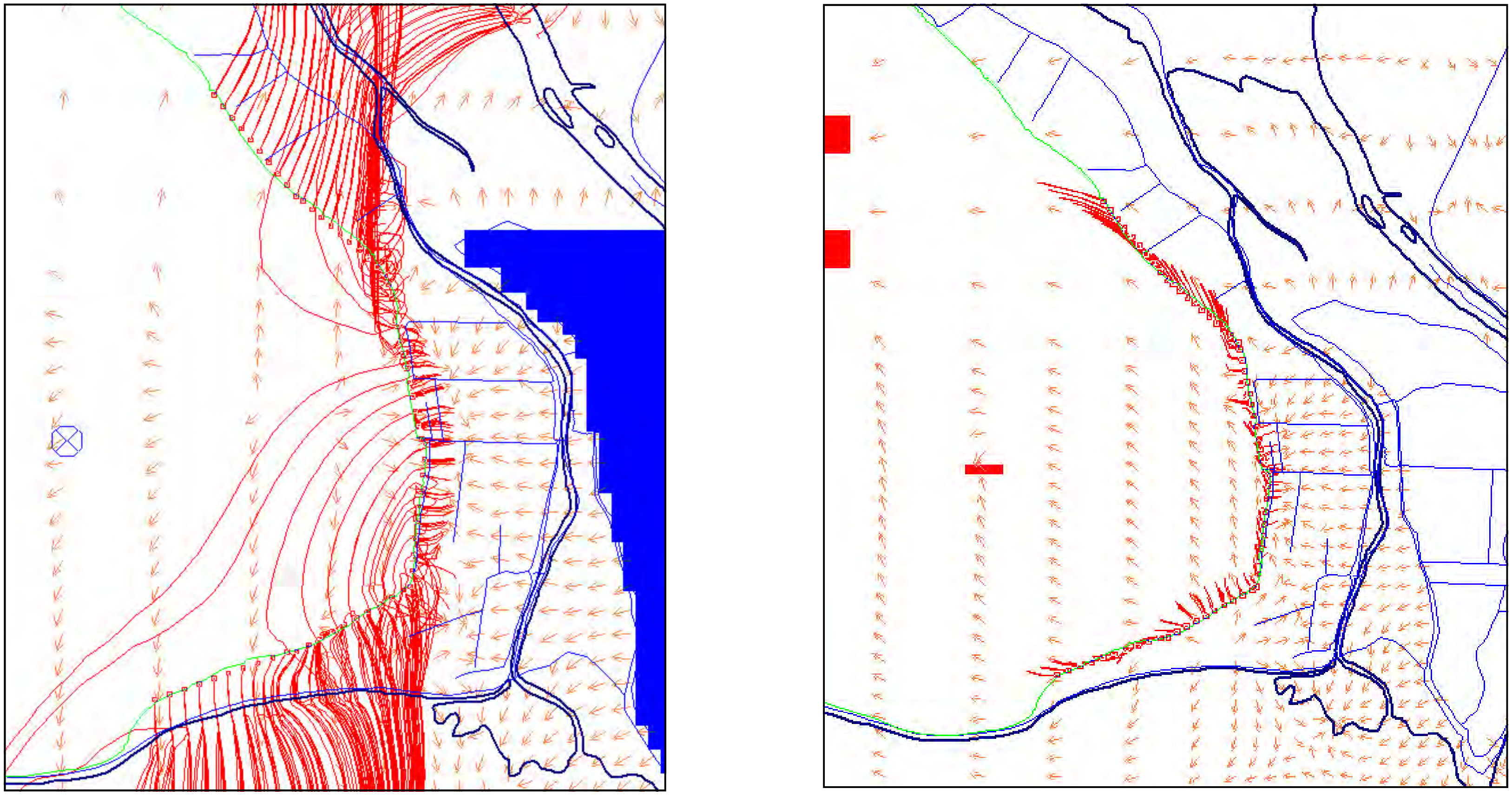
Leque Island Restoration

PGG

Hmax

RQx



- Particle Starting Locations
- Particle Traces
- Layer 1 Velocity Vectors
- Wells
- Surface-Water Features
- Upland Escarpment
- Constant Head Cells

Note: See Table 1 for head and pumping values used in depicted simulations.

Figure 4
Particle Traces from Model Simulation 16c

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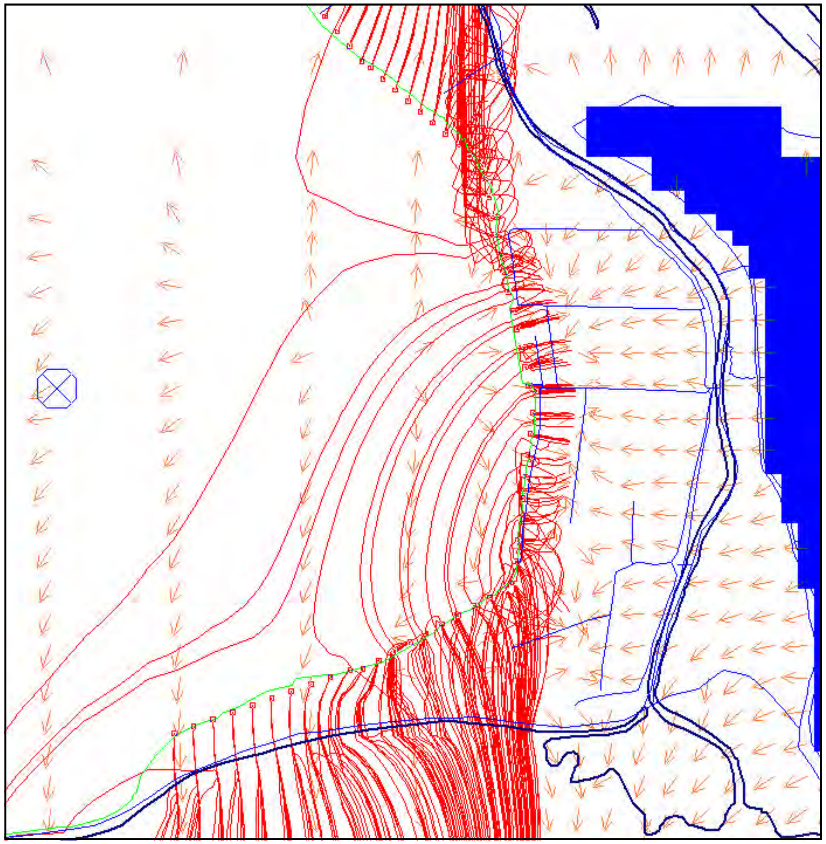
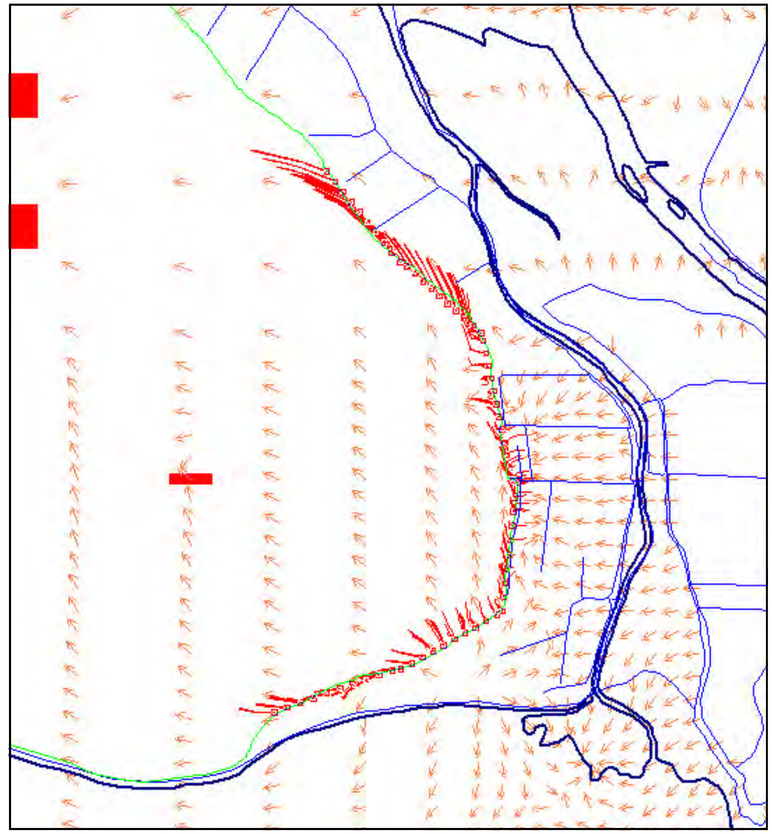
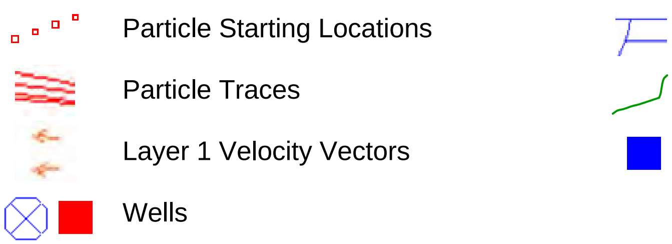
PgG

Hmax



RQx





Note: See Table 1 for head and pumping values used in depicted simulations.

Figure 5
Particle Traces from Model Simulation 16d

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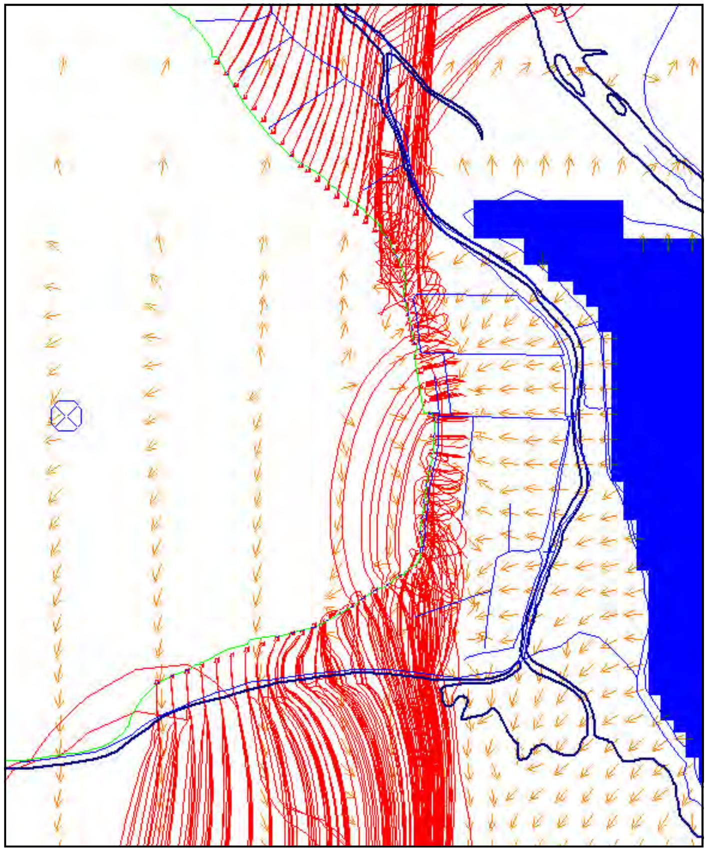
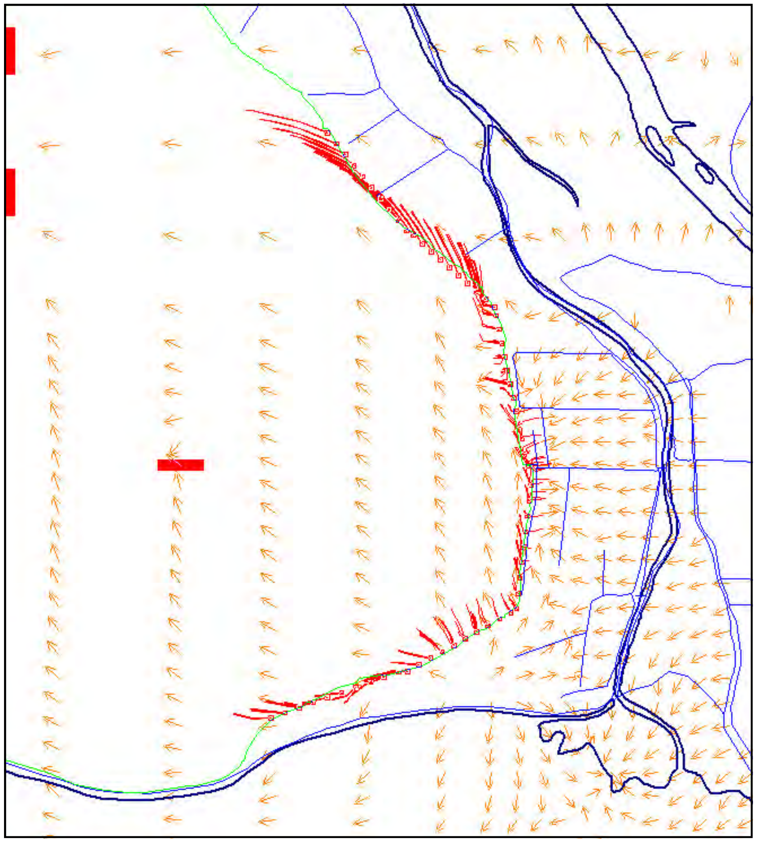
PgG

Hmax



RQx



Particle Starting Locations

Particle Traces

Layer 1 Velocity Vectors

Wells

Surface-Water Features

Upland Escarpment

Constant Head Cells

Note: See Table 1 for head and pumping values used in depicted simulations.

Figure 6
Particle Traces from Model Simulation 16f

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