~~DRAFT~~ FINAL INFILTRATION EFFECTS ASSESSMENT:
THURSTON HIGHLANDS
YELM, WASHINGTON

~~May~~ October 2008

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COMMON ABBREVIATIONS & ACRONYMS

APIH	Antecedent precipitation index for head
Cfs	Cubic feet per second
DEIS	Draft Environmental Impact Statement
Delta	Change
DGER	Washington Division of Geology and Earth Resources
Groundwater head	Groundwater elevation
HGHA	High Groundwater Hazard Area
Mgd	Million gallons per day
PGG	Pacific Groundwater Group
Qva	Advance outwash stratigraphic or hydrologic unit
Qvm	Moraine stratigraphic or hydrologic unit
Qvr	Recessional outwash stratigraphic or hydrologic unit
Qvt	Till stratigraphic or hydrologic unit
The Highlands	Thurston Highlands site as shown in Figure 1
USGS	United States Geological Survey
WWHM	Western Washington Hydrologic Model
WY	Water year

Signature

This report, and Pacific Groundwater Group's work contributing to this report, were reviewed by the undersigned and approved for release

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1.0 INTRODUCTION

This report summarizes work performed by Pacific Groundwater Group (PGG) for Thurston Highlands, LLC. The City of Yelm ~~is~~ prepared~~ing~~ an ~~Draft~~ Environmental Impact Statement (~~D~~EIS) for a 1,240-acre master planned community that would be built over the next 10 to 30 years in the area known as Thurston Highlands on the west side of Yelm (**Figure 1**).

In support of the ~~D~~EIS, PGG assessed existing conditions and effects of possible property development scenarios on groundwater flows to Thompson Creek. A first phase of PGG's field work was conducted during the summer of 2007. A second phase of field work was ~~recently~~ completed in March 2008 to better characterize wet season conditions. Field work in 2008 ~~and~~ included seven borings, five new piezometers, additional aquifer testing, and groundwater monitoring through August 27, 2008.

~~. This report is based on results of Phase 1 field work and the final will incorporate results of Phases 1 and 2.~~

Existing conditions and possible changes to groundwater recharge were evaluated using a numerical computer model. The model was designed to estimate changes in groundwater flow to Thompson Creek that would occur with site development.

~~This draft technical report is issued in support of the May 2008 DEIS. The final version of this technical report will be issued concurrent with the Final Environmental Impact Statement (FEIS). The final version of this report will present results of a second phase of PGG's field work conducted in March 2008 (seven borings, five new piezometers, and additional aquifer testing); on-going water level monitoring; and additional groundwater flow modeling including the new site data.~~

In addition to the May 2008 draft EIS technical report, o~~O~~ther work conducted by PGG for the City is reported in the *Draft Preliminary Hydrogeologic Analysis of Reclaimed Water Infiltration Feasibility* (2006), included in the *Draft Yelm Wastewater Technical Report* prepared by Parametrix (2007), and letter report: *Phase 2 Infiltration Evaluation* (2007).

1.1 Approach & Scope

Changes to groundwater and related hydrologic features caused by site development would be most pronounced at shallow depths closest to the location of the change. Therefore, work focused on shallow depths and Thurston Highlands site and adjacent Yelm Urban Growth Area (UGA). A ~~and included~~ numerical groundwater model was used~~ing~~ to predict effects of site development on Thompson Creek.

Because stormwater would be treated using best management practices and reclaimed water will be treated to Class A standards, infiltrating water was assumed to comply with quality standards and therefore quality impacts were not considered in the groundwater flow model.

Existing Conditions Assessment

To document existing conditions, site investigation was performed to assess whether shallow water-bearing strata exist on the Thurston Highlands site and, if so, their relation to Thompson Creek. Some of the wetlands have been shown to have some dependence on groundwater (Coot Company 2008B). With proximity to wetland features, Thompson Creek was considered likely to have some dependence on groundwater as well, at least in headwater areas. Shallow groundwater was defined to be within about 100 feet of ground surface and down to the elevation range of Thompson Creek (320 to 360 feet)[1].

Deeper aquifers have been under investigation at the Highlands in recent years to test their suitability for a water supply (e.g., Robinson & Noble 1995, and Golder Associates 2007). A shal-

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[1] For this project, the vertical datum is NGVD 29 and the horizontal datum is Washington State Plane Coordinate System, NAD 83\91.

lower aquifer above the Thompson Creek elevation range of 320 to 360 feet was not identified in documentation from those investigations.

The following work was performed to evaluate existing shallow groundwater at the Highlands:

- Installed and tested 17~~2~~ piezometers targeting the shallowest water-bearing strata to log lithology and monitor groundwater levels.
- Installed seven “stilling” wells adjacent to selected wetlands to measure surface water elevations and two temporary staff gages for same.
- Installed one temporary staff gage at Thompson Creek.
- Monitored groundwater and surface water levels ~~over the course of the field program during the field programs and~~ until August 27, 2008. Groundwater monitoring continues.
- Tested aquifer characteristics.
- Interpreted data to assess hydrogeologic properties.

Aquifer pump testing was originally scoped but was not conducted because the shallowest water-bearing strata are thin and would not produce sufficient water for a useful test. Slug- and bail-down tests were conducted in the piezometers instead; however, they were also compromised by the limited saturation.

Modeling

Results of field work were used to develop a conceptual hydrogeologic model for the site and to adapt an existing numerical groundwater model for Northern Thurston County built by the United States Geological Survey (Drost et al. 1999). The objectives of modeling in this study were to predict effects of possible development on groundwater recharge, groundwater flow, and Thompson Creek base flow.

The following work was performed during the modeling task:

- Modified the Drost (1999) Modflow model to be consistent with the hydrogeologic conceptual model developed for the Thurston Highlands site.
- Calibrated the model using field-measured water levels and estimated wet-season flows of groundwater to Thompson Creek.
- Ran the model with steady-state existing conditions to establish a base line ~~to which to~~for comparison to possible development scenarios.~~ compare development effects.~~
- Ran transient predictive simulations for a range of possible development scenarios. Recharge was based on median and maximum precipitation years.
- Provided other team members with predicted changes to groundwater flux to Thompson Creek resulting from the range of possible development scenarios.
- Estimated other impacts resulting from the range in development scenarios.
- Evaluated possible alternatives for mitigating development effects on groundwater.

Summary of Updates

This report updates and replaces the May *2008 Draft Infiltration Effects Assessment report* (PGG, 2008) that relied on field data collected through January 2008. Since issuing the Draft EIS, additional field work was conducted including drilling seven more borings, constructing five new piezometers, performing additional aquifer testing, and monitoring groundwater elevations through August 2008.

With the additional information (including current wet season conditions), PGG modified the conceptual hydrogeologic model and performed additional computer modeling including re-calibration of the baseline existing conditions scenario and re-running predictive simulations presented in the May 2008 draft.

Changes in modeling results may be attributed to the new data and modified interpretations. PGG (2008) indicated an area of the Thurston Highlands site where field investigations found neither shallow groundwater nor relatively impermeable till. Where this occurs, depth to groundwater is relatively deep and infiltrating water would tend to move downwards and away from Thompson Creek. Based on interpretations of new site data, the location of this "window" moved to the west and its size was increased.

Updated results include:

- Predicted groundwater flows to Thompson Creek were modified for 8 of the 14 development scenarios. These modified flows were provided to Brown & Caldwell for their simulations of Thompson Creek impacts (Brown & Caldwell, October, 2008).
- The current model simulations indicate that infiltration of stormwater distributed across the study area would result in somewhat lower groundwater flows into Thompson Creek than reported previously for 8 of the 14 modeled development scenarios. However, on average, and with rounding of model results, about 30% of the increased stormwater infiltration would still flow to Thompson Creek as reported in the Draft Infiltration Effects Assessment (PGG 2008).
- Infiltration of 1.5 million gallons per day (mgd) of reclaimed water in the area of the Future Sports Complex would result in less groundwater discharge to Thompson Creek than reported previously. About 15% of additional stormwater infiltration + reclaimed water would flow to Thompson Creek. (The Draft Infiltration Effects Assessment indicated about 30%.) While this is a smaller percentage than with stormwater alone, it represents about 0.15 mgd more flow to Thompson Creek than stormwater-only simulations.
- Changes in aquifer heads adjacent to the creek are generally lower than in previous simulations.

1.2 Authorization

The work was initially performed as part of the June 15, 2007 contract between PGG and Shea, Carr, and Jewell, Inc. for Project No. 605-02. Continued monitoring and modeling tasks were performed according to the December 12, 2007 contract between PGG and Thurston Highlands, LLC.

The work was performed, and this report was prepared, in accordance with generally accepted hydrogeologic practices used at this time and place, for the exclusive use of Thurston Highlands, LLC, and the City of Yelm for application to the Thurston Highlands property. This is in lieu of other warranties, express or implied.

2.0 SUMMARY OF FINDINGS

This section is a summary of the major findings resulting from the study. Refer to the remainder of this report for details.

Existing Hydrogeologic Conditions

- The Highlands site is underlain by a laterally and vertically variable sequence of Vashon- and pre-Vashon-age glacial soil deposits. Qvr (recessional outwash gravel) is prevalent to the east of the site on the Yelm prairie. Qvm (moraine silt and gravel) occurs over the majority of the Highlands site and is considered part of the Qvr hydrologic unit. Qvt (till) has been mapped by others to be present in northeastern areas of the site. Soils that derive from till exist at the site; however, there is evidence that till does not always occur where previously mapped and appears to be less prevalent than indicated on published maps. Qva (advance outwash sand and gravel) underlies the Qvt where the till is present otherwise it is in contact with the Qvr/Qvm. Sequences of older glacial and interglacial deposits underlie the Vashon materials.
- An average of about 40 inches of precipitation falls on the Highlands each year. Nearly half of the precipitation in an average year evaporates or is transpired by existing forest vegetation. Nearly all of the remainder infiltrates to become groundwater recharge. An ~~preliminary~~ estimate of total recharge by Brown & Caldwell (May, 2008) is about 1.8

feet per year on average. The recharge initially flows vertically downward through the variably saturated ~~moraine~~Qvm deposits, with lateral movement only occurring in saturated zones, which become more common with depth.

- Potential free-drainage infiltration rates at land surface were estimated by others (KPFF, 2008) to range between near 0 to more than 20 inches per hour and to vary across the site according to soil type.
- Depth to water in the shallowest water-bearing unit below the Thurston Highlands site varied from about 50 feet to more than 120 ~~feet in the summer of 2007~~feet.
- Water level elevations in the uppermost water-bearing unit varied between approximately 22~~7~~0 and 470 feet elevation. The groundwater follows flow paths of varying length until it discharges to Thompson Creek, the Nisqually River, tree roots, or pumping wells.
- Water level data between August 2007 and ~~February ~~August 2008 suggest that by about mid-December (ranged from mid-November to early January), groundwater started to rise in response to the onset of the wet season. Water levels in wetlands responded a month or so earlier, in October and November.
- In some areas of the site, fully saturated soils were not encountered while drilling until below the elevation of Thompson Creek. Nor was a substantial till unit encountered in some areas. It is inferred that vertical flow in these areas continues to a lower aquifer stratigraphically below the till, and not tributary to Thompson Creek.~~. Further monitoring will assess whether these conditions prevail.~~
- The hydrogeologic model has an area within Thurston Highlands without till (“window”). Till has a strong influence on shallow groundwater flow ~~in the Qvr, ~~and changes in groundwater levels from recharge ar~~ will b~~e sensitive to the presence (or absence) of till.
- The flowing segments of Thompson Creek vary seasonally and between years. The creek does not flow all the way to the Nisqually River each year. Some reaches flow throughout a typical year, some flow only rarely. The creek generally receives groundwater flow in its headwaters and looses water to the ground in ~~its ~~lower reaches.~~; however, the details of groundwater/surface water inter-actions are the subject of ongoing work.~~
- High groundwater hazard areas (HGHAs) have been delineated by Thurston County with several in the vicinity of the Thurston Highlands site. These are areas sensitive to rising groundwater. Some are mapped along Thompson Creek and in its headwater area.

Modeling

Refer to Section 7 (Summary of Potential Impacts) for additional summary of modeling results.

- ~~Modeling is consistent with field data indicating that Thompson Creek generally receives groundwater from shallow saturated strata during the wet season (i.e., gains from the Qvr and Qvt strata with a small proportion from the Qva). Some creek segments lose water to exposed strata.~~
- Proposed development would include capturing excess stormwater collected from impervious surfaces (e.g., pavement, roofs) and would reduce forest cover from existing conditions. The r~~R~~esulting reduced water loss~~es~~ from evaporation and vegetative transpiration (evapotranspiration) would ~~be expected~~tend to ~~generally ~~increase the amount of stormwater infiltrating at the site. Modeling results are consistent with this expectation and indicate that the more widespread the development, the more the increase in groundwater recharge.
- Thompson Creek generally receives groundwater from shallow saturated strata during the wet season (i.e., gains from the Qvr and Qvt strata with a small proportion from the Qva). Some creek segments lose water to exposed strata. Results suggest that the creek would be affected by changes in recharge caused by site development. Headwater segments closest to development areas

would generally be the most influenced by changes in recharge.

- Presence or absence of relatively impermeable till is an important parameter when assessing effects on groundwater from increased infiltration. A strong vertical groundwater gradient and large areas without strata that would tend to prevent vertical flow would cause recharge water to move downward to the most transmissive aquifers. Groundwater travels generally to the north in those aquifers, and does not contribute to flow in Thompson Creek.
- Because stormwater would be treated using best management practices and reclaimed water will be treated to Class A standards, effects of infiltration on groundwater quality will be small and are not assessed in this investigation.
- Existing site recharge is about 2 mgd (2,232 acre-feet per year, Brown & Caldwell, May, 2008).
- Effects of increased *stormwater* include:
  - Increases in stormwater recharge are estimated to range from 0.2 mgd with the Phase 1 development concept to 0.8 mgd with full build-out of the conceptual Preferred Alternative.
  - Based on the current conceptual development plans for stormwater infiltration, about 30% of the increased recharge from stormwater is expected to report to Thompson Creek.
  - Stormwater recharge that does not report to Thompson Creek would flow away from the creek or downward to the most transmissive strata where groundwater travels generally to the north.
  - The increased infiltration would have the effect of increasing groundwater elevations adjacent to Thompson Creek by an average of about 0.1 foot with Phase 1 development, and about 0.3 foot with full site development. Some downstream segments of Thompson Creek would not be affected (see Brown & Caldwell, October, 2008 for assessment of flooding potential on Thompson Creek).
- Consideration is also being given to infiltrating 1.5 mgd of reclaimed water in the future Regional Sports Complex on the Thurston Highlands site (see additional information on this subject in DEIS Section 3.3.5.
- Effects of increase in recharge from *reclaimed water* include:
  - Total increase in recharge from infiltration of 1.5 mgd *reclaimed water* + developed-condition *stormwater* would be 1.7 to 2.3 mgd for the various alternatives and years analyzed. With full build-out of the conceptual plan, reclaimed water infiltration would add about twice the additional recharge than would occur with stormwater alone (1.5 mgd reclaimed water versus 0.7 mgd stormwater).
  - If reclaimed water is infiltrated, about 15% of the increased recharge from stormwater + reclaimed water would report to Thompson Creek. The fraction of extra recharge reporting to the creek is lower for scenarios that include reclaimed water because the reclaimed water infiltration site is located in an area not underlain by till. Although the percentages of flows reporting to the creek are lower, it equates to an increase in water volume over stormwater recharge alone by a factor of about 1.5 for the full development scenario and about 3 for the Phase 1 scenario.
  - Reclaimed water recharge that does not report to Thompson Creek would flow away from the creek or downward to the most transmissive strata. Groundwater in those strata travels generally to the north and does not contribute to flow in Thompson Creek.
  - The increased infiltration would have the effect of increasing groundwater elevations adjacent to Thompson Creek by an average of about 0.3 foot with Phase 1 development, and about 0.5 foot with full site development. Some downstream segments of Thompson Creek would not be affected. (see Brown & Caldwell, Oc-

tober, 2008 for assessment of flooding potential on Thompson Creek).

  - The predictive simulations assumed that reclaimed water infiltration would occur in a 400-foot by 400-foot area of the Regional Sports Complex where relatively impermeable glacial till is absent. If the reclaimed water infiltration were to occur in an area where till is present, it is likely that effects on Thompson Creek would be greater.

- Estimates of increased groundwater discharge to Thompson Creek (about 30% of the recharge increase with stormwater only, and about 15% of reclaimed water + stormwater) are based on the creek flowing all the way to the Nisqually River all year. To the extent that the creek does not flow at certain times and places (and may not even flow every year), less of the additional recharge will report to the creek.
- Without infiltrating reclaimed water, modeling suggests that effects from full build-out elsewhere in the City of Yelm UGA (and unrelated to development that may occur at Thurston Highlands) may further increase groundwater flow to Thompson Creek by about 75~~40~~% relative to the increase that would occur with full build-out on the Thurston Highlands and Tahoma Terra sites alone. With full development in the Yelm UGA, groundwater elevations adjacent to Thompson Creek would be expected to rise an additional 0.1 feet (0 to 0.6~~3~~ feet).
- To mitigate the effects of development at the Thurston Highlands on Thompson Creek, the most promising option from the perspective of groundwater flow appears to be infiltrating excess stormwater in areas that would cause the least impact to the creek. The engineering and economic feasibility of capturing stormwater runoff and conveying it to favorable areas for infiltration was evaluated by KPFF (2008). Other options evaluated appear to offer some mitigation benefits used alone or in combination with other options

~~To mitigate the effects of development at the Thurston Highlands on Thompson Creek, the most promising option from the perspective of groundwater flow appears to be infiltrating excess stormwater in areas that would cause the least impact to the creek. The engineering and economic feasibility of capturing stormwater runoff and conveying it to favorable areas for infiltration would need to be evaluated by others. Other options evaluated appear to offer some mitigation benefits used alone or in combination with other options, but full implementation may have some feasibility issues. When engineering and economic feasibility is also considered, the overall feasibility of all options may change.~~

3.0 SUMMARY OF EXISTING CONDITIONS

Potential effects of Thurston Highlands site development on groundwater were evaluated by comparing existing conditions to a range of conceptual developed conditions. This section presents a summary of existing conditions. ~~The data collected in a second phase of field work conducted in March 2008 are being analyzed and will expand the current understanding of site hydrogeologic conditions~~

The 1,240-acre Thurston Highlands site is heavily-vegetated commercial forest land. The trees are generally Douglas fir, and range in age from about 5 to 25 years. The land was logged and replanted approximately 20 years ago when Weyerhaeuser was operating the land as a tree farm. A system of unpaved logging roads and a Centralia Utilities power line service road enable vehicle access to many parts of the Thurston Highlands property.

The site terrain is generally hummocky with closed depressions (including kettles) created by geologically-recent continental glaciations. The depressions in the north part of the site observed during field activities were dry. The Coot Company (2008B) suggests that this is typically the case even during wet parts of the season. Some depressions in the south contained wetlands.

This study focuses on current and possible future conditions related to the site groundwater system and how it may affect Thompson Creek. There is a relationship between shallow groundwater and Thompson Creek. The surface water conditions presented in this report are discussed in very general terms. The Thurston Highlands ~~Draft~~ Surface Water Technical ~~Memorandum~~ Report (Brown & Caldwell, October, 2008) describes surface water conditions in Thompson Creek in detail.

Surface Water

The Thurston Highlands site is part of the Yelm surface water sub-basin of the lower Nisqually River watershed (Water Resource Inventory Area [WRIA], number 11). A surface water divide occurs just west of the site where water drains toward the Deschutes River instead of Thompson Creek and the Nisqually River. Dominant surface water features of the Yelm area include Yelm Creek, Yelm Ditch, the Centralia Power Canal, and Thompson Creek.

Thompson Creek drains the western edge of the Yelm prairie adjacent to the Thurston Highlands site before discharging to the Nisqually River about ½ mile downstream of the Yelm Ditch (which includes Yelm Creek discharge). The Highlands site is completely within the Thompson Creek drainage basin. There are few records of Thompson Creek flow, but it was measured between about 0.5 cubic feet per second (cfs) and 0 cfs in 1949-1951 near the discharge to the Nisqually River (Murdorff et. al 1953). Recent wet-season stage readings between February 6 and 18, 2008 indicate a daily average creek flow between 4.0 and 6.6 cfs (February 10, 2008) just down stream of the Tahoma Terra bridge at the end of Longmire Street (**Figure 1**). The observations suggest perennial flow in headwaters and ephemeral flow in lower reaches below the Tahoma Terra development. Bank-full flow was observed at two locations adjacent to, and downstream of, the Highlands in Spring 2007. On February 7, 2008 Thompson Creek was observed to flow beneath Highway 510 and presumably all the way to the Nisqually River. Flow beneath Highway 510 was also noted to occur in the third week of March 2008. Creek flow to the Nisqually River occurs only during the wet season and may, or may not, occur during any given year. In 2007, the City initiated a Thompson Creek monitoring program to begin collecting baseline stream flow and water quality data.

A total of 35 wetland systems were identified on the Thurston Highlands property by the Coot Company (2008B). They are generally small, isolated systems within the bottoms of depressions that have no outlet. Some of the site wetlands are likely connected to the shallow aquifer system whereas others are perched above the shallow aquifer on low permeability soil. Wetlands connected to the shallow aquifer are those on the southeast part of the site in the Thompson Creek headwaters area (A and F Complex wetlands; see Coot Company 2008B).

There is a paucity of developed drainages at the site. Lack of developed surface water drainage systems suggests that significant precipitation is either intercepted by vegetation and/or is adsorbed into the subsurface. The Coot Company (2008B) indicates that where flowing surface water occurs on the site, it is a temporary seasonal condition confined within a wetland swale, not a scoured stream channel. These flowing surface waters occur along three outlet drainages on the property that have direct connections to Thompson Creek.

Two of these ephemeral surface water drainages comprise headwater areas for Thompson Creek. One of them (Wetlands A5, A7, A8) originates in a southeast part of the Highlands. The second drainage (Wetland F) originates south of the site, crosses a southeastern area of the site and merges with the first drainage east of the Highlands. Off-site portions around the combined drainage route have been extensively ditched and have significantly diminished perennial flows according to the Coot Company (2008B). The third drainage (Wetland H) occurs in the far northeast corner of the Highlands. Its headwaters are ditched, and runoff drains to an off-site wetland swale. An ephemeral stream connects this swale to Thompson Creek.

Groundwater

Inferring from other work (e.g., Robinson & Noble 2001), it appears that shallow groundwater on the Yelm prairie flows generally north toward the Nisqually River. Deeper groundwater beneath the prairie tends to flow more northwesterly (Golder Associates 2007). According to Golder Associates (2003), recharge to the shallow groundwater system is primarily through infiltration of precipitation. Recharge also occurs from surface water seepage, septic systems, reclaimed water infiltration (e.g., Cochrane Park), and irrigation return flow. Annual groundwater recharge from precipitation was estimated by Golder Associates (2003) to range between 1.9 and 2.1 feet per year.

Subsurface recharge at the Thurston Highlands site under existing conditions has been estimated for the purposes of this study by Brown and Caldwell (May, 2008). A finding of their work is that, on average, 1.8 feet per year of water infiltrates on the Thurston Highlands site under existing conditions, and essentially no surface water runoff leaves the site, instead infiltrating into the subsurface.

Groundwater sub-basins may roughly follow surface water watershed boundaries; however, significant variances can occur. The location of the groundwater divide between the Deschutes and the Nisqually Rivers was not identified in this study. Existing groundwater elevation data suggest that the groundwater divide between the Deschutes and the Nisqually Rivers is west of the Thurston Highlands site.

4.0 SUMMARY OF FIELD WORK

~~This section presents results of the first phase investigation conducted in the summer of 2007. Results of the second phase of field work conducted in March 2008 will be presented in a later report.~~

Twelve piezometers were installed in the summer of 2007 and five more in March 2008. Work also included installing seven temporary stilling wells, and four temporary staff gages. Aquifer characteristics were estimated using field and laboratory techniques.

4.1 PIEZOMETERS & STILLING WELLS

~~Twelve~~ Nineteen drilling locations were selected for logging soils and to install piezometers in the shallowest water-bearing strata for water level monitoring (**Figure 1**). Shallow groundwater was not encountered at two of these locations while drilling in March 2008 and two of these locations were not completed as piezometers. The~~is~~ investigation focused on conditions within and above the shallowest water-bearing (saturated) unit (the shallow aquifer). At the outset of the field investigation, the depth and characteristics of the shallowest groundwater were uncertain. Based on logs for onsite test wells (Robinson & Noble 1995), a substantial shallow water-bearing layer was not noted above a deep pre-Vashon-aged aquifer system (depths up to about 200 feet). It was not known if a shallow aquifer existed and, if so, if the shallowest water-bearing layer would be a fully-saturated, laterally continuous aquifer system or a series of seasonally-variable, variably-saturated, perched water-bearing zones with ~~dominant~~ strong downward gradients.

The drilling program began with air rotary drilling June 25 through June 29, 2007 (P1, P2, P3, P6, P7, and P11). Drilling started with what was planned to be a temporary 6-inch test well for aquifer testing (its label used for planning: TW1). However, the water-bearing strata did not produce sufficient water for an aquifer pump test, so this location was completed as a piezometer (and labeled P11).

Drilling continued July 9 through July 13, 2007 (P5 and P8) using a sonic drill rig. The goal of the sonic drilling was to obtain continuous soil cores for detailed lithologic logging. However, site conditions made sonic drilling slow with frequent equipment failures so an air rotary drill rig was used to install four more piezometers

(P4, P9, P10, and P12) August 6 through August 9, 2007.

A second phase of drilling occurred between March 12 and 17, 2008 to investigate wet-season conditions. Five on-site and two off-site locations were drilled and five piezometers were constructed. Shallow groundwater was not encountered at two on-site locations and no piezometers were constructed there.

~~Eleven~~ Fourteen of the ~~12~~ 17 piezometers were constructed within the Thurston Highlands~~ and~~ to depths up to about 127 feet below ground surface (BGS). Three piezometers were installed just~~near to and~~ east of Thompson Creek. In some cases, borings were advanced until refusal and/or to the approximate elevation of adjacent Thompson Creek headwaters (approximately 360 feet elevation), and/or until strata became fine-grained indicating a bottom to a shallower permeable unit.

Appendix A contains lithologic logs and piezometer construction details for the piezometers installed in this study, as well as logs for site test wells and for piezometers in the Tahoma Terra development. **Table 1** summarizes as-built information for stations installed during this investigation, as well as some selected stations installed by others.

4.2 WATER LEVEL MONITORING

Water level monitoring in piezometers and stilling wells commenced during the drilling investigation and continues. Manual water levels are measured using an electronic water level probe. The water level measuring point was marked and surveyed to a common datum with a 0.01-foot vertical accuracy allowing measured water depths to be converted to elevation. Water level data are presented in **Appendix B**.

To obtain additional water elevations at the Thurston Highlands site, stilling wells and temporary staff gages were placed during the drilling program. The stilling wells were placed by hand adjacent to mapped wetlands. Staff gages were used to directly measure surface water elevations at three wetlands and in Thompson Creek. Water elevation data were used to help assess seasonal changes in water levels and shallow groundwater flow. Inferred flow in the shallowest water-bearing unit is shown in **Figure 2**.

Between August 2007 and August 2008,~~ and November 2007,~~ water levels were periodically hand-measured. On November 15, 2007, pressure transducers with data loggers were installed in six piezometers: P2, P4, P6, P8, P10, and P12. In March 2008, the transducer in P8 was moved to P20. A barometric pressure unit was also installed in P12 to enable conversion of gage pressure measured by the transducers to absolute pressures that could be correlated with hand-measured water levels. It was noted that the test wells (NTW, WTW, and STW) and the Thompson Creek Monitor Well (TC MW) were also instrumented by the City of Yelm. Some of these data were made available for this work.

Water level data collected during this project and available data from others (see Section 4.3 below) was aggregated into a water level database for evaluating spatial and temporal variations, inferring hydraulic gradient, and calibrating of the groundwater model. Water level data through ~~March 12~~August 27, 2008 were used for analyses in this study.

4.3 WORK BY OTHERS

Other organizations participated in this work under separate contracts. KPFF Consulting Engineers, provided surveying services. Survey data is presented in **Table 1**. Brown & Caldwell estimated groundwater recharge under existing conditions and for a range of possible development scenarios. Insight Geologic generated infiltration rate estimates based upon mapped soil types, test pit logs, and the logs from the piezometers in this investigation. Golder Associates provided historical water level data for wells in the area that they have monitored for some time including the North Test Well (NTW), West Test Well (WTW), South Test Well (STW), and the Thompson Creek Piezometer.

5.0 HYDROGEOLOGY

Results of the field investigation performed for this study allow expanding the hydrogeologic model developed previously by others in the Yelm area.

Prior work included hydrogeologic studies, and mapping and interpretation of soil types and geologic exposures within Thurston Highlands and vicinity. The discussion below is organized as follows:

- Soil Units
- Geohydrologic Units
- Groundwater Occurrence and Flow

5.1 SOIL UNITS

Table 2 presents a summary of soil types exposed in the study area according to the Soil Survey of Thurston County (USDA 1990). In general, the soils formed in glacial deposits, and are deep. In some areas, flooding has occurred and/or a high water table occurs, especially during wetter months. **Figure 2** shows Thurston County-delineated HGHAs in the vicinity of the Thurston Highlands.

Based on this information, the most suitable soils for infiltration that are exposed within the Thurston Highlands site are: Everett, Tenino, and Indianola, due to permeability and depth to groundwater. In some areas, Yelm Series soils may also be suitable. Based on descriptions in USDA (1990), the most suitable soil series mapped in Thurston Highlands are highlighted in bold font in **Table 2.**

These suitable soil types comprise approximately 50% of the study area. The other less-suitable 50% is dominantly the Alderwood series soils in central areas of the site. On the Yelm prairie to the east of the site, the Nisqually and Spanaway-Nisqually Complex are also considered favorable for infiltration.

William Parnell (SCA Group 2006) prepared a soils report for Thurston Highlands summarizing findings from 94 test pits excavated to depths of up to 20 feet in November 2005. Findings generally corroborate mapping and description in the *Soil Survey of Thurston County* (USDA 1990), with some variations. Noted variations are presented in **Table 2**.

Insight Geologic, Inc. evaluated information from SCA Group (2006), USDA (1990), and lithologic logs from this study to estimate expected ranges of infiltration rates across the Highlands. KPFF (2008) incorporates Insight Geologic's work and uses these estimated infiltration rates for stormwater management planning.

5.2 GEOHYDROLOGIC UNITS

According to Washington Division of Geology and Earth Resources (DGER 2001), surface geology in the study area is glacial and was deposited about 15,000 years ago during the Vashon Stade of the Frasier Glaciation. The exposed geology at the Thurston Highlands site is generally ~~moraine~~Qvm material directly created by advancing glaciers. Ice blocks were buried in the moraine that subsequently melted-out, creating kettled topography.

Drost et al. (1998) is a common reference for hydrogeologic conditions in northern Thurston County, and is extrapolated to Yelm for the purpose of this study. Drost et al. (1998) have divided the most recent glacial deposits into three geohydrologic units summarized in **Table 3:** Qvr (recent alluvium, Vashon recessional outwash and end moraine—Qvm), Qvt (Vashon glacial till), and Qva (Vashon advance outwash). **Table 4** summarizes the geologic units as interpreted at the Highlands. More detailed descriptions of the three primary Vashon geohydrologic units are discussed below.

Recessional Outwash and Moraine (Qvr/Qvm)

Alluvium was deposited as the glaciers retreated to the north (recessional outwash). This outwash comprises the youngest Vashon glacial material. It commonly occurs at ground surface (e.g., Yelm Prairie), and overlies Qvt. The Yelm prairie has been described as a “kame terrace” indicating deposition between a glacier and an adjacent valley wall (the uplands area).

Where saturated and sufficiently thick, the Qvr deposits in Thurston County comprise the shallowest aquifer used by small private wells and some larger wells. Recessional outwash sands and gravels are described as permeable and allowing rapid infiltration. Surficial Qvr deposits in the Yelm area typically create Nisqually, Spanaway-Nisqually complex, Everett, and Yelm series soils, which are sandy and gravelly. Both Everett and Yelm series soils occur on the Thurston Highlands site. Qvr is mapped by the Washington Division of Geology and Earth Resources (DGER 2001) as outcropping in a small area on the central east edge of the Highlands and south of the Tahoma Terra development in the headwaters of Thompson Creek. Field observations and soil mapping suggest that Qvr deposits are more prevalent in the Tahoma Terra area than mapped by DGER (2001).

Analyses of hydrogeologic properties of the Qvr were not generated for this investigation. However, infiltration capacity estimates are provided in the *Soil Survey of Thurston County* (USDA 1990) for soils that developed on the Qvr, as well as in the *Thurston Highlands Grading, Drainage, and Utilities Technical Engineering Report* (KPFF 2008).

According to work summarized in the *Geologic Map of East Olympia* (Walsh et al. 2005), ~~moraine~~Qvm deposits in this area occur between where the Olympia Lobe and the Yelm Lobe converged west of Yelm and north of the town of Rainier. Vashon end moraine and interlobe moraine areas exhibit closed depressions (kettles, some of which create wetlands, ponds or lakes) and hummocky topography composed mainly of

> “*rudely stratified outwash sand and gravel containing local lenses or pods of till; locally this outwash material is overlain by fine sand and silt several feet thick.*”, Noble and Wallace (1966).

Noble and Wallace (1966) indicate that some end moraine deposits are sufficiently permeable to yield large supplies of groundwater, although data were limited in the relatively undeveloped Thurston Highlands area.

~~Moraine~~Qvm deposits, included in the Qvr geohydrologic unit of Drost et al. (1998), can create gravelly Tenino series soils that occur within Thurston Highlands. Drilling of test wells by others in the Thurston Highlands indicated ~~moraine~~Qvm deposits up to approximately 40 feet thick (Robinson & Noble 1995, Golder Associates 2005).

Analyses of soil texture for the Thurston Highlands project suggest that, where saturated, hydraulic conductivity of the Qvm deposits is on the order of 200 to 500 feet per day. That compares to a range of 14 to 2,100 feet per day (median: 150 feet per day) estimated by Drost et al. (1998) for Qvr.

Till (Qvt)

Drost et al. (1998) indicate that Qvt is present and continuous in the Yelm area. It is exposed at the surface in west Yelm, and in small northeastern areas of the Thurston Highlands site. Where not exposed, Qvt commonly underlies Qvr deposits. Thickness may vary from less than 25 feet to more than 100 feet (south of Yelm). Data collected during the current field investigation suggest that the areas at the margins of the Vashon glaciation like the Thurston Highlands do not have substantial Qvt strata. Moraine and outwash deposits would be expected to form between glacial lobes, and till may not be laterally continuous in this area near the margins of the most recent ice. Till may occur as pods or lenses in some areas of the moraine deposits.

Till in the area is generally described by drillers as dense, indurated clayey “hardpan” sometimes noted as bluish in color. It is usually relatively impermeable and limits, but does not eliminate, downward groundwater flow (i.e., it is aquitard material). Nonetheless, it can be highly variable exhibiting a range in permeability and thickness. Exposed Qvt in the Yelm area creates Alderwood series soils such as those that occur on the Thurston Highlands site.

Drost et al. (1998) report vertical hydraulic conductivity of the Qvt to be 0.01 to 0.002 feet per day, whereas Golder Associates (2005) models a value of 3 feet per day. The hydraulic conductivity of the Qvt at the Thurston Highlands site was not evaluated for this project.

Advance Outwash (Qva)

Qva in the area consists of relatively permeable sands and gravels, creating an important water supply aquifer for both private and municipal wells. Although exposures of Qva are not mapped in Yelm by DGER (2001), Drost et al. (1998) interprets that Qva is continuous and varies in thickness between less than 25 feet to more than 50 feet northwest of Yelm. The Qvt often creates a confining layer above this aquifer but where the Qvt is absent, the Qvr and Qva are connected, and the shallowest aquifer is unusually thick.

DGER (2001) does not map Qva outcrops within the Highlands or near-vicinity. Geologic interpretation in this study does not indicate exposures within the Thurston Highlands site except in a very small area in the Thompson Creek headwaters area.

Analyses of hydrogeologic properties of the Qva were not generated for this investigation. However, Drost et al. (1998) estimate hydraulic conductivity to range between 6.8 and 130,000 feet per day (median 180 feet per day).

Pre-Vashon Deposits

A series of glacial and non-glacial deposits underlie the Vashon glacial sequence. The Kitsap Formation (Qf) is a regional aquitard stratigraphically beneath the Qva. Some deeper units ~~that would be~~ below the Kitsap can create important aquifers that are used in Thurston County and the Yelm area for water supply (e.g., the Pre-Vashon Qc and TQu aquifers). These units are sufficiently deep (a few hundred feet) to have little effect on surface infiltration facilities, and therefore were not investigated in this field investigation.

Golder Associates (2005) focused on a pre-Vashon aquifer in Thurston Highlands. Golder Associates (2006) presents results from aquifer testing of the deeper aquifer unit.[2] Golder Associates (2007) summarizes results of recent groundwater modeling that also focused on deeper aquifer units.

5.3 GROUNDWATER OCCURRENCE AND FLOW

An annual average of about 40 inches of precipitation falls on the ~~soils and largely morrainal deposits of the~~ Thurston Highlands site. On average, with existing conditions at the Thurston Highlands site, about half of the precipitation evaporates or is transpired by existing forest vegetation according to work by Brown & Caldwell (May, 2008). Nearly all of the remainder infiltrates to become groundwater recharge. A small amount of runoff and interflow occur on a local scale, but at the scale of the site, nearly all runoff infiltrates in a short period of time. With existing conditions, total recharge equals about 1.8 feet per year. The recharge initially flows vertically downward through the variably-saturated moraine deposits, with lateral movement only occurring in saturated zones, which become more common with depth. Laterally-moving water follows flow paths of varying

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[2] Golder Associates, on the behalf of the City of Yelm, assisted with updating a three-dimensional, multi-layered numerical groundwater flow model, originally developed by the City of Olympia, for evaluation of hydrologic effects from future groundwater pumping at a well field in the Thurston Highlands.

length until discharge to Thompson Creek, the Nisqually River, tree roots, pumping wells, or springs and seeps. The discharge location of groundwater on the different flow paths is used to define two groundwater flow “regimes” or areas:

- *Regime A* is an area where shallow groundwater flows generally toward Thompson Creek and its headwater wetlands in water-bearing strata within shallow moraine or outwash deposits. (**Figure 2**). Downward flow also occurs to lower strata although vertical downward flow is limited in places by underlying till. Groundwater in Regime A occurs at about 20 feet depth (above 320 feet elevation) in sandy material in the vicinity of the entrance to Tahoma Terra (MW1 through 3 and the Thompson Creek Piezometer). Depth to groundwater in Regime A is significantly deeper in higher topographic areas in the west and south parts of the site, up to about 100 feet (about 440 feet elevation) along the west property line.

  It is Regime A that supplies perennial base flow to Thompson Creek headwaters, maintaining flows in the headwater through dry seasons. East of Thompson Creek on the Yelm prairie, shallow groundwater flow is generally northward and downward. The wetland elevation at stage gage S12 has not been contoured with the Regime A data (**Figure 2**). This interpretation is consistent with that wetland being underlain by till and not representative of the larger Qvr/Qvm aquifer heads.

- *Regime B* is an area where the shallow Qvr/Qvm~~Qvm~~ deposits are not saturated with groundwater because the Qvt aquitard doesn’t exist or is so permeable that groundwater tends to infiltrate through it. The shallowest aquifer in this regime occurs in deeper pre-Vashon strata that have been investigated as a possible water supply. Regime B is recharged by precipitation recharge within Regime B. The pre-Vashon aquifer is also recharged by downward flow from Regime A. Shallow saturated conditions were not encountered within Regime B over large portions of the site suggesting a thick, variably-saturated vadose zone **(Figure 2).** Groundwater in Regime B occurs at elevations between 210 and 260 feet at the site with a lateral gradient toward the north-northwest. Groundwater in Regime B connects with the McAllister gravels north of the Thurston Highlands site and does not enter Thompson Creek.

Hydrologic effects of land use change (recharge) and infiltration of reclaimed water will vary depending on where the changes in recharge occur. Changes within Regime A will most directly affect Thompson Creek. Changes in Regime B would have little or no effect.

To estimate historic water levels, 52 years of precipitation data from the Olympia Airport, corrected for conditions in Yelm, were analyzed using an antecedent precipitation index for head (APIH). The analysis correlated the long precipitation record with the shorter groundwater elevation record to estimate groundwater elevations at existing wells for periods when no field-measured elevations are available. Estimated historical groundwater elevations for existing wells were used for calibrating the groundwater model. See **Appendix C** for more detail on methods and results.

6.0 GROUNDWATER MODELING

The objectives of groundwater modeling were to:

a. Develop a quantitative model to simulate and understand hydrogeologic conditions at the Thurston Highlands site in three dimensions.
b. Estimate effects of possible future development on Thompson Creek flow.
c. Evaluate possible mitigation options.

Computer modeling focused on *changes* that would occur with development as opposed to absolute values. ~~Absolute values of recharge were not input to the model; changes in recharge were. Similarly, Thompson Creek flows are reported in terms of changes expected with development and not actual flows.~~ While the model calculated heads under existing and developed conditions, the primary result from groundwater modeling was the changes in groundwater~~aquifer~~ discharge ("aquifer flux") to Thompson Creek that would occur with development. These changes were used for input to the surface water model employed in Brown and Caldwell (October, 2008).

6.1 SUMMARY OF MODEL APPROACH & ASSUMPTIONS

The project model incorporated the regional hydrogeologic concepts defined by Drost et al. (1998). A previously-constructed Modflow model for Thurston County (Drost et al. 1999) and a later modification for the City of Lacey McAllister Springs area (CDM, 2002a, CDM, 2002b and Golder, 2006) were used as a starting base for model construction. Collectively, these are referred to as the "Olympia Model" in this report.

The model development approach and assumptions are summarized below. Some of these topics are further described in subsections that follow.

- The basic structure of the eight-layer Olympia Model is accepted, plus the following subsequent revisions by Golder Associates (2007) for the Yelm area: 1) Qvr (layer 2) was activated, and 2) a high transmissivity zone in the Qva aquifer was defined in the Yelm Prairie. See additional layering description in the following subsection.
- Hydraulic properties were initially those of the Olympia model, and were refined during calibration (see following subsection).
- Geologic structure within Thurston Highlands is consistent with the conceptual model explained in Section 5 of this report.
- Wet season recharge for the median water year (WY 1981) and wettest water year (WY 1997) is appropriate for impact calculations.
- Wet season recharge causes Thompson Creek to flow all the way to the Nisqually River under existing conditions.
- The effects of groundwater pumping were not included.
- In the model area, future development will occur within the City of Yelm UGA.
- Full build-out of the UGA in accordance with current zoning is a reasonable approximation of land use in the fully-developed UGA outside of Thurston Highlands and Tahoma Terra.
- Effects on groundwater recharge from future development within the UGA (outside of Thurston Highlands and Tahoma Terra) can be approximated by evaluating existing land use from aerial photography and by approximating future land use in accordance with current zoning.
- Shallow geology is variable, with areas where Qvr/Qvm is missing (Qvt exposed), and areas where Qvt is missing (Qvr and Qva in contact). Modflow requires that all layers be continuous. Therefore, where layers pinch out and are missing, the layer was assigned a thickness of one foot, and this area was assigned the properties of the underlying layer.
- The model assumes that infiltrating stormwater instantaneously recharges the shallowest water-bearing unit. Field data (WY 2008) indicate that lag times from precipitation to the recharge pulse reaching the water table varies from near zero where the water table is shallow to ~40 to 60 days in areas of Thurston Highlands where the water table is deep.
- In general, Thompson Creek is defined in (exposed to) layer 1 (Qvr). Areas in the model where the creek crossed surficial till (i.e., Qvr missing at surface), the creek cell was assigned to layer 2 (Qvt). Approxi-

mately 40% of the Thompson Creek river cells are exposed to layer 2. Three Thompson Creek river cells in the uplands area also crossed the area defined as missing till and were therefore assigned to layer 3 (Qva). New field observations suggest that the map presented in DGER (2001) overestimates the extent of till. Some minor adjustments were made in the model to account for this.

Groundwater flow to Thompson Creek changes in response to changes in recharge that would occur with development. KPFF (2008) and Brown & Caldwell (October, 2008) used hydrologic models to calculate water balances for Thurston Highlands, and provided results to PGG for simulating recharge in the groundwater model. The approach and assumptions used for estimating recharge included:

- Results and assumptions of KPFF (2008) WWHM for Thurston Highlands (including 86% forest cover in the existing condition).
- Olympia Airport precipitation from WY 1955 through WY 1999 with a correction factor of 0.8 for conditions in Yelm (i.e., Yelm precipitation is 80% of the precipitation at the Olympia Airport).
- Soil types: Soil series as mapped in USDA (1990).
- Soil infiltration capacities as indicated in USDA (1990).
- In the existing condition, all runoff generated is infiltrated. With development, runoff would be captured and infiltrated through many engineered infiltration basins distributed across the development area. It is assumed that each parcel (or sub-basin within Thurston Highlands) would infiltrate its own stormwater. The way the model simulates this is to apply change in recharge evenly across each model cell.

6.2 MODEL DOMAIN AND BOUNDARIES

A groundwater flow model was constructed using Modflow-Surfact (Hydrogeologic, Inc., 1996) with the Stream Flow Routing and River Packages (Prudic 1989), and input/output management with Groundwater Vistas (Environmental Simulations, Inc. 2000-2007).

The model domain covers approximately 20 miles from east to west and 13 miles north to south. (**Figure 5**). The western boundary is defined by the Deschutes River and the eastern boundary by the Nisqually River. The southern boundary is mainly defined by bedrock, and is simulated as a no-flow boundary. The northern boundary and southeastern boundary are defined by constant head cells.

The model domain consists of four primary geographic areas:

- The Thurston Highlands property,
- The Tahoma Terra development,
- The City of Yelm UGA outside of Thurston Highlands and Tahoma Terra ("other UGA"),
- The area outside of the Yelm UGA ("far field").

The model grid varies from 900 by 900 feet in the "far field" to 400 by 400 feet within Thurston Highlands.

Constant heads are assigned along the northern and southeastern boundaries of the model. The head values assigned to the cells were taken from the Olympia model and imported to the project model. The constant head boundaries are located more than five miles away from the Thurston Highlands site and are assumed to have little influence on the model results.

6.3 LAYERING

The project groundwater flow model uses the same eight layers to simulate the hydrostratigraphy as originally used by Drost et al. (1999). The top and bottom elevations of the eight layers were modified in the following way. The top layer elevation was defined using the ground surface digital elevation model (DEM). The top and bottom elevations of the upper three layers (Qvr, Qvt and Qva) were modified within the Thurston Highlands area using field data collected for the project. The data were interpreted with the aid of a three-dimensional geologic model developed in software by Rockworks, Inc. (Rockworks 2006).

The geologic model layers and Modflow layers are the same eight layers:

Layer 1:	Qvr/Qvm (or Qvt where till outcrops)
Layer 2:	Qvt (or Qva where the till is missing)
Layer 3:	Qva
Layer 4:	Qf
Layer 5:	Qc
Layer 6, 7 and 8:	TQu-1, 2 & 3

Below layer 8 is bedrock presumed to be impermeable. Layers 1, 2, and 3 are the primary layers of interest in this study. The model generated from existing information by Rockworks is shown in **Figures 3 and 4.** These layers also reflect Modflow model structure, although accommodations for discontinuous layers are required within Modflow and not Rockworks.

A constant "leakance" value was assigned to each layer in the model. Leakance is used to simulate the resistance to groundwater flow between layers, and is proportional to the vertical hydraulic conductivity assigned to the two layers and the thickness of the two layers. One option for computing leakance is to use the saturated thickness of the layers based on the starting heads of the simulation. This option results in different solutions depending on the initial heads. Furthermore, if the layer is calculated to be dry, then the model defaults to using the actual thickness of the layer. Another option is to write vertical hydraulic conductivity to the leakance input in the Modflow Surface input packages. This option uses the actual thickness of the layer for all calculations of leakance rather than the saturated thickness, and results in a constant leakance value. This option was chosen to provide consistency in model solutions. A sensitivity of using this option showed simulated heads to be higher and is therefore a conservative option.

6.4 HYDRAULIC PARAMETERS

The horizontal and vertical hydraulic conductivity values used in the Olympia model were initially assigned to each layer in the model and then later modified during the steady-state calibration process (see below). Golder Associates (2007) applied the Olympia model to the Yelm area and included a high hydraulic conductivity zone in the Qva (layer 3) aquifer beneath the City of Yelm. Horizontal hydraulic conductivity (Kh) ~~was~~ Golder assigned a value of 3,000 ft/day and a vertical hydraulic conductivity (Kv) of 300 ft/day. In this study, a Kh of 2,000 ft/day and a Kv of 300 ft/day were used. This adjustment was made during model calibration. See **Table 5** for a summary of hydraulic parameters used in this study and in the original Olympia Model.

A confined storage coefficient (S) of 0.005 and an unconfined storage coefficient (Sy) of 0.15 were assumed for all layers. These values are similar to what was used in the City of Lacey version of the Olympia model. A transient calibration was not performed, so S and Sy were not modified during the calibration process.

6.5 MODELED SURFACE WATERS

Except for Thompson Creek, all rivers, creeks, and lakes within the study area are simulated with the River Boundary Package for Modflow. River boundary locations were taken directly from the Olympia model and refined within the project grid. River bed thicknesses were assumed to be one-foot and widths and lengths were based on the cell dimensions in which the boundary conditions were assigned. Springs were simulated with the Drain Package of Modflow. Drain locations, elevations, and conductances were taken from the Olympia model. Drain locations in the project model were sometimes refined to accommodate a modified model grid.

Thompson Creek and the Ridgeline Trough are simulated with the USGS Stream Flow Routing and River Packages (Prudic 1988). Segmentation of Thompson Creek for modeling is shown in **Figure 6**. Both the Stream Flow-Routing and River packages simulate the flow of water between an aquifer and a stream based on the difference between the groundwater head and the stream stage. Water flows from the aquifer to the stream (a gaining stream reach) or from the stream to the aquifer (a losing stream reach), depending on whether stream stage or groundwater head is higher. In both packages, the rate of exchange is affected by the conductance of the streambed sediments. The conductance parameter is a measure of the ease with which water can flow through the streambed sediments, which is a function of streambed permeability, thickness, and stream bed area (width multiplied by length).

Both the River and Stream Flow Routing packages allow the user to partition streams into segments, so that groundwater interactions can be evaluated along parts of streams. The Stream Flow Routing package allows surface water to be routed from one segment to another as it exchanges with the groundwater in the downstream direction with depth of water within each stream cell calculated based on the Manning Formula. A roughness coefficient of 0.035 was assigned to all stream cells for use in the Manning Formula. Gains and losses to the aquifer can be evaluated for individual stream cells, segments, or cumulatively for multiple segments. Sections of the stream can also go dry if seepage to the aquifer is greater than the amount of flow in the stream.

Properties assigned to stream cells include: stream bed elevation, stream sediment thickness, stream sediment permeability, stream width, stream length, and slope. Stream bed elevations were assigned using survey data provided by KPFF (2008) for lower segments and LiDAR data for the remaining segments. Stream widths were assigned to each cell using surveyed average widths for lower reaches. Upper reaches were assumed to have a width of 15 feet. Stream lengths for each cell were measured from GIS polyline coverages of Thompson Creek (**Figure 1)**. Stream slopes were estimated based on elevation changes between cells and lengths. Stream bed permeability values were adjusted during the calibration process.

6.6 SOLVER

Consistent with the Olympia model, the Thurston Highlands model uses the Modflow-Surfact solver PCG4 to overcome numerical instability and convergence problems associated with the de-saturation and re-saturation of model cells. Modflow-Surfact uses a pseudo-soil retention function to allow re-saturation (Hydrogeologic, Inc. 1996).

6.7 GROUNDWATER RECHARGE

Effects on Thompson Creek from development of the Thurston Highlands Master Planned Community would be related to ~~the resulting~~ change in recharge~~ to the aquifer system~~. To evaluate the change in recharge, both existing condition and developed condition recharge were estimated and a difference (“~~“~~delta”) calculated for model input.

Recharge values from the Olympia model were assigned to most of the model domain (far field) for both existing and developed conditions (i.e., in the far field, change in recharge from the Thurston Highlands development equals zero). Site-specific analyses were made for three near-field areas within the Yelm UGA: Thurston Highlands, Tahoma Terra, and the rest of the UGA (“other UGA”). Recharge values for these areas were provided by Brown & Caldwell (May, 2008). See below for more discussion.

Existing Conditions Recharge

Recharge for steady-state simulation of existing conditions was estimated for areas of the UGA (Thurston Highlands, Tahoma Terra, and other UGA) and areas outside of the UGA. Recharge calculated from the precipitation record varied in space and time according to the WWHM and HSPF models used by KPFF (2008) and Brown & Caldwell (May, 2008) for use in this project.

The wet season mean recharge[3] from the median (WY 1981) and wettest year (WY 1997) was used to simulate steady-state existing conditions using Modflow. This approach intentionally resulted in the existing conditions model simulating wet season groundwater levels and stream flow.

Developed Condition Recharge

To simulate developed conditions, changes in recharge over the model area were calculated by subtracting existing-condition recharge from built-condition recharge. The differences were calculated for monthly time steps and added to the steady-state existing condition recharge. Methods of quantifying developed condition recharge for the different geographic areas are summarized below.

Thurston Highlands

KPFF (2008) is planning for stormwater design at the proposed Thurston Highlands development. They modeled stormwater using WWHM, which estimates stormwater runoff volumes considering site-specific information for the current and developed conditions including drainage sub-basins, precipitation, land use, vegetative cover, and soil types.

Brown & Caldwell used the input from KPFF's WWHM application within an HSPF model application to prepare groundwater recharge estimates for existing and developed conditions. Although the hydrologic parameters of the models are the same, HSPF allows output of groundwater recharge (HSPF parameter AGWI—Active Groundwater Inflow). AGWI was aggregated for every month in the precipitation record for 10 sub-basins, A through J.

In addition to recharge from stormwater, three developed-condition scenarios include infiltration of 1.5 mgd of reclaimed water in an infiltration system constructed in the area of ~~-~~the future Regional Sports Complex within Thurston Highlands (**Figure 5**). For modeling purposes, the infiltration system was assumed to be a surface basin with dimensions of 400 feet by 400 feet. (one model cell) and reclaimed water would be infiltrated steadily, 24 hours per day and 365 days per year. If reclaimed water infiltration at the site occurs, a~~A~~ctual infiltration system location, construction details, dimensions, and operational schedule would be evaluated in a later phase of work.

Tahoma Terra

Stormwater data from Tahoma Terra Divisions 1 & 2, and the commercial area were available and handled using HSPF methods described for Thurston Highlands. Recharge in the remaining area of Tahoma Terra was estimated using the methods described for "other UGA" below.

Other UGA

Changes in recharge with full build-out within the City of Yelm UGA outside of Thurston Highlands and two Tahoma Terra basins was estimated using recent aerial photos of Yelm (existing conditions) and the current zoning map for the Yelm UGA (to estimate developed conditions). Depending on development and geologic conditions, recharge was estimated and a recharge hydrograph was synthesized.

More specifically, changes in recharge for areas of the UGA outside of Thurston Highlands and Tahoma Terra were estimated by:

1. Evaluating existing conditions from aerial photography.

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[3] The wet season was defined as November through April.

2. Estimating per cent impervious area for UGA parcels in the existing and the fully-developed conditions that would theoretically be captured and infiltrated at the parcel.
3. Brown & Caldwell (May, 2008) developed estimates of recharge hydrographs for seven land use/ geologic conditions (till or outwash) for the entire precipitation record as shown in ~~Table 5~~Table 6. Although till and outwash have very different recharge characteristics, this study assumed that all runoff from till surfaces would be captured and infiltrated on the parcel where the precipitation fell. The net result of this assumption is that outwash and till have practically the same estimated recharge rates.
4. Existing and fully-developed-condition UGA recharge rates were simulated by combining the seven type hydrographs into 12 synthesized delta-recharge hydrograph combinations. It was assumed that developed conditions could be represented as different proportions of impervious and lawn-like conditions. ~~Table 6~~Table 7 summarizes the 12 combinations for which delta-recharge hydrographs were synthesized.
5. Each model cell of the "other UGA" area was classified as one of the 12 possible combinations. Where a cell had variable attributes, recharge was area-weighted averaged. ~~Table 7~~Table 8 presents recharge rates for forests and meadows and for the range of imperviousness estimated for developed conditions. ~~Table 8~~Table 9 presents recharge rates assumed for the various zoning designations representative of fully-built conditions.

If a model cell had a calculated negative delta-recharge (i.e., built condition recharge less than existing conditions), it was set to 0 (i.e., existing conditions recharge would approximate built conditions).

Far Field

Recharge values in the Olympia model were used in areas outside of the City of Yelm UGA. It was assumed that future development would concentrate in UGAs, and that the UGA that would most affect Thompson Creek is the Yelm UGA. The delta-recharge for the far field was therefore assumed to be 0 (i.e., existing conditions recharge approximate built conditions).

6.8 MODEL CALIBRATION

~~Methodology~~

Existing conditions were simulated with a steady-state model. The model was calibrated to achieve a best match between observed or estimated groundwater elevations and simulated groundwater elevations, and to achieve a reasonable groundwater flux to/from Thompson Creek. The existing conditions calibration is based on wet-season recharge and groundwater elevations.

The initial calibration used for the model presented in the May 2008 Draft Infiltration Effects Technical Report (PGG 2008) did not have ~~G~~groundwater elevation and stream flow data over a full year~~ were not available at the time of this writing for estimating wet season conditions~~. Improvements in calibration were possible in the Final technical report using data from new piezometers, a one-year groundwater elevation record in some cases (August 2007 through August 2008), and eight months of Thompson Creek flow data (collected by Envirovision downstream of the Tahoma Terra Bridge). Average ~~W~~wet season heads were ~~therefore~~ estimated by performing an antecedent precipitation index for head (APIH, see Appendix C for more detail on methodology) correlation of existing site ~~data through January 29, 2008~~data. Results of the APIH correlation were used to predict groundwater elevations for WY 1981 precipitation (median precipitation year in the 1955 to

1999 record). ~~These~~ APIH values are assumed to represent average wet season conditions.

~~.Also, ab. These data~~

Thompson Creek may, or may not, flow all the way to the Nisqually River during an average wet season. However, to assure that all changes in groundwater elevations are reflected in changes to creek flow, the existing conditions model simulates creek flow all the way to the Nisqually River. To the extent that groundwater levels remain below the creek bed (where and when the creek does not flow), the model will tend to over-predict changes in groundwater flux to the creek (i.e., a conservative estimate).

Observed groundwater heads (elevations) used as model calibration targets are based on APIH calculated heads for on-site wells ~~wells P2, P3, P6, P11, and TCMW~~ (**Figure 1**, **Table 10**). Groundwater elevation data collected to-date for these wells have a strong correlation with the precipitation index (R^2> 0.85). The APIH calculated heads used for targets are the maximum APIH heads calculated for ~~the~~ WY 1981 ~~season~~ precipitation (mean precipitation year). In general, APIH calculated heads are within about ~~2~~ a few feet of the current maximum *observed* heads ~~(**Table 9**)~~.

In some cases, ~~S~~secondary head targets for calibration were selected ~~in~~ for wells completed in deeper strata, ~~or or~~ off-site wells, ~~or where insufficient head data were available,~~ or wells where the APIH calculation was considered unreasonable. ~~: P4, NTW, STW, WTW, City TW1, Tahoma Terra wells MW1 and MW2, and the off-site Draght well.~~ Head targets for the secondary wells were assigned the ~~average~~ maximum head observed to-date in these wells.

The model was calibrated by making adjustments to the aquifer horizontal and vertical hydraulic conductivity and the permeability of the creek sediments. The match between head targets and observed and simulated groundwater heads is shown in **Figures 7** and **8**, and ~~**Table 9**~~**Table 10**.

The final calibrated model parameters are summarized in ~~**Table**~~ **Table 5**~~**10**~~. Model parameters used in the Olympia model are also shown in ~~**Table**~~ **Table 5**~~**10**~~ for context.

6.9 PREDICTIVE SIMULATIONS

The purpose of the predictive simulations is to assess potential impacts from the proposed Thurston Highlands development. Impacts are evaluated in terms of estimated *changes* (i.e., "deltas") in groundwater flux into, or out of, Thompson Creek under a variety of possible development scenarios. The comparison of existing and developed conditions is based on median (WY 1981) and wettest (WY 1997) years of precipitation. The predictive simulations were run with monthly stress periods with four time steps per stress period. Transient calibration was not conducted, and confined storage coefficient (S) of 0.005 and an unconfined storage coefficient (Sy) of 0.15 were assumed.

The seven development scenarios considered in this study are summarized in **Table 11** and range from the Phase 1 development concept at Thurston Highlands, to full build-out of the conceptual Preferred Alternative at Thurston Highlands and full build-out of Tahoma Terra. Three scenarios consider infiltration of both developed-condition stormwater and 1.5 mgd of Class A reclaimed water from the City's wastewater treatment process.

Two additional scenarios were run to estimate the effects of full build-out in accordance with, current zoning~~,~~ elsewhere in the Yelm UGA. The two UGA full build-out ~~effects~~ simulations allow estimation of effects to Thompson Creek ~~effects~~ from development elsewhere in the UGA independent of development at Thurston Highlands and Tahoma Terra. The seven scenarios thus address both project-specific~~,~~ and full development impacts.

Figure 9 shows a schematic water balance for the site with the various flow paths anticipated with site development. The predictive modeling simulations accounted for these various flows.

Methodology

Seasonal transient Modflow simulations were used for the predictive runs. Monthly changes to recharge based on possible future land use changes within Thurston Highlands, Tahoma Terra, and elsewhere in the UGA, were estimated as described above in Section 6. Changes to recharge ("Delta Recharge") were calculated for each stress period according to the following equation:

Delta Recharge =

Developed Condition Recharge

minus

Existing Condition Recharge

The delta-recharge values were then added to the steady-state recharge in the calibrated existing-conditions model for the different predictive scenarios.

Changes in groundwater flux ("Delta Groundwater Flux") to Thompson Creek for each time step were calculated according to the following equation:

Delta Groundwater Flux =

Existing Conditions Groundwater Flux (steady state value)

minus

Developed Condition Aquifer Flux

~~If delta groundwater flux is negative, it implies "gaining" conditions (creek receiving groundwater base flow).~~ The existing conditions model was used to provide the starting heads for each developed-condition simulation, which were run for three consecutive simulation years (total of 36 monthly stress periods with four time steps per stress period).

Results

Table 12a shows modeling results in terms of changes in recharge and creek flow, and also shows the proportion of the change in creek flow attributable to the change in recharge (i.e., change in recharge "reporting" to Thompson Creek). Table 12b shows modeling results in terms of the most the Thompson Creek segments most affected by the various development scenarios.

Stormwater recharge to the groundwater system would increase with site development. This is primarily because evapotranspiration losses would be reduced resulting in a larger fraction of the precipitation being available for runoff and infiltration. The more widespread the development, the more the increase in groundwater ~~system~~ recharge.

The model has an area within Thurston Highlands where field investigations suggest that there is no till (i.e., a window). In northern Thurston Highlands as well as to the north and south of the site, the model does have till. The model confirms that till has a strong influence on groundwater flow in shallow strata. Recharge in areas not underlain by till moves to lower strata, with less affect on Thompson Creek than recharge that occurs to the Qvr where the till is present.

~~The additional 1.5 mgd of *reclaimed water* adds 1.5 mgd to the onsite recharge~~Recall that existing conditions *stormwater* recharge was estimated by Brown & Caldwell to average about 1.8 ft/year. This equates to about 2 mgd over the 1,240 acre Thurston Highlands site. Adding an additional 1.5 mgd of *reclaimed water* would nearly double existing condition recharge. ~~although~~ T~~t~~o the extent that this water is derived from nearby wells the water would effectively be recycled. However, groundwater pumping was not considered in the simulations.

~~Modflow model output in the form of changes in groundwater flux to/from the creek was provided to Brown & Caldwell for routing downstream and flood assessment (Brown & Caldwell, 2008).~~

~~Simulated Thompson Creek tends to gain water from shallow saturated strata during the wet season (i.e., it gains); however, some creek segments contribute water to the shallow aquifer (i.e. losing segments; e.g., Segment 11, **Figure 6).** Results suggest that the creek would be affected by changes in recharge whether from stormwater or reclaimed water.~~

~~**Table 12a** summarizes changes in recharge and creek flow, and also shows the proportion of the change in creek flow attributable to the change in recharge (i.e., change in recharge reporting to Thompson Creek).~~Also, recall that the model assumes the creek is flowing all the way to the Nisqually River. Thompson Creek actually flows perennially in only some areas, and only seasonally in other areas. In some years, Thompson Creek may never flow all the way to the Nisqually River, with only some reaches flowing. In WY 2008, Thompson Creek has flowed all the way to the Nisqually River twice: once in early February, and again in the third week of March, and both times for just a few days. When Thompson Creek does not flow all the way to the Nisqually River, the model will over-predict changes to creek flow. Therefore, infiltration on the Thurston Highlands site will generally have lower impacts than the model results suggest.

Modeling scenarios with infiltration of 1.5 mgd *reclaimed water* assumed the infiltration to occur in a 400-foot by 400-foot area where there is no till. The model is appropriate for evaluation of regional effects from infiltration of reclaimed water, but not groundwater mounding below the infiltration site itself.

Additional model-predicted effects from site infiltration are summarized below:

~~Full site development (Scenario 3a) and WY 1997 weather conditions, would result in an estimated additional 0.84 mgd of *stormwater* being infiltrated into the shallow aquifer system, with 0.28 mgd (33%) entering Thompson Creek. With 1.5 mgd infiltration of *reclaimed water* (Scenario 3b), an estimated additional 1.5 mgd water would enter the shallow groundwater system with about 0.74 mgd (32%) entering Thompson Creek.~~

~~For all scenarios and WY 1981 and WY 1997, results indicate that the percent of additional recharge that would express as increased stream flow would vary from 27 to 37 percent, and would averages about 31 percent. This value has been rounded to 30 percent for project summaries.~~thate instance,

~~Recall that the model assumes the creek is flowing all the way to the Nisqually River. Thompson Creek actually flows perennially in only some areas, and only seasonally in other areas. In some years, Thompson Creek may never flow all the way to the Nisqually River, with only some reaches flowing. In WY 2008, Thompson Creek has flowed all the way to the Nisqually River twice: once in early February, and again in the third week of March, and both times for just a few days. When Thompson Creek does not flow all the way to the Nisqually River, the model will over-predict changes to creek flow. Therefore, infiltration on the Thurston Highlands site will generally be less than about 30% of the change in recharge.~~

~~**Table 12b** lists the creek segments that would be most affected[4] by the change in recharge. Headwater segments closest to development areas would generally be the most influenced by changes in recharge (Segments 4, 5, 6, and 10, **Figure 6**).~~

~~Results and observations regarding groundwater modeling~~

Effects on Recharge

From Stormwater Infiltration

- Increased development would result in increased stormwater recharge compared to existing conditions. In an average precipitation year (WY 1981), t~~T~~he Phase 1 development concept would increase recharge by

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[4] "Most affected" creek segments are those receiving 85% of the change in the creek's groundwater flux.

about 10% (~~10%,~~0.2 mgd annualized[5]) and the conceptual full build-out of the Preferred Alternative ~~development concept~~ would increase stormwater recharge ~~recharge by~~ by about ~~40%.~~35% (0.7 mgd annualized).

From Reclaimed Water Infiltration

- Recharge resulting from infiltration of 1.5 mgd reclaimed water + developed-condition stormwater would range from 85% greater than current condition recharge (an additional 1.7 mgd, Scenario 2b) to about 115% greater than current condition recharge (additional 2.3 mgd Scenario 3b WY 1997).

- ~~The estimated increases in stormwater recharge vary from 0.20 mgd (Scenario 2a WY 1981) to 0.84 mgd (Scenario 3a WY 1997).~~
- ~~Total increase in recharge resulting from infiltration of 1.5 mgd reclaimed water plus developed-condition stormwater would vary from 1.7 mgd (Scenario 2b) to 2.3 mgd (Scenario 3a WY 1997).~~Increase in stormwater recharge would be relatively small compared to a constant 1.5 mgd reclaimed water recharge. Using averages of WY 1981 and WY 1997 results and the fully-built scenario, the additional reclaimed water would be about twice the recharge occurring with stormwater-only (1.5 mgd versus 0.7 mgd). With Phase 1 development including reclaimed water infiltration, site recharge would increase by more than seven times the stormwater-only scenario.

- ~~The increase in stormwater recharge would be relatively small compared to 1.5 mgd reclaimed water recharge.~~*Reclaimed water* recharge not reporting to Thompson Creek would flow away from the creek or downward to the most transmissive strata (Qva, Qc, and TQu aquifers) where groundwater travels generally to the north and does not contribute to flow in Thompson Creek.

Effects on Creek Flow[6]

- Thompson Creek tends to gain water from shallow saturated strata during the wet season (i.e., it gains); however, some creek segments contribute water to the shallow aquifer (i.e. losing segments such as Segment 12, **Figure 6).** Results suggest that the creek would be affected by changes in recharge caused by site development. **Table 12b** lists the creek segments that would be most affected[7] by the change in recharge. Headwater segments closest to development areas would generally be the most influenced by changes in recharge (Segments 4, 5, 6, and 10, **Figure 6**).

From Stormwater Infiltration

- With full build-out of the Preferred Alternative concept (Scenarios 3 and 4), the most affected segments from stormwater recharge alone would be the Tahoma Terra Segment 10 and headwaters Segments 5 and 6. With partial-build scenarios (Scenarios 2), the most affected segments would be 10 and 6 **(Table 12b, Figure 6).**
- For all stormwater-only infiltration scenarios, the fraction of additional recharge that would express as increased stream flow would vary from 27 to 37%, and would average about 30%. This is the value used for project summaries.
- *Stormwater* recharge not reporting to Thompson Creek would flow away from the creek or downward to the most transmissive strata (Qva, Qc, and TQu aquifers) where groundwater travels generally to the north and does not contribute to flow in Thompson Creek.

From Reclaimed Water Infiltration

- With full build-out and with 1.5 mgd reclaimed water infiltration in the future Re-

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[5] Actual stormwater recharge would occur mostly during winter months so monthly or daily peaks would be higher during wet periods.

[6] i.e., aquifer flux to the creek; existing condition flux less developed condition flux.

[7] "Most affected" creek segments are those receiving 85% of the change in the creek's groundwater flux.

gional Sports Complex area (**Figure 5**); the most affected segments of Thompson Creek would be headwaters Segments 5 and 6 and Tahoma Terra Segment 10.

- For scenarios that include an additional 1.5 mgd reclaimed water infiltration, the fraction of additional recharge that would express as increased stream flow would vary from 12% to about 18%, and would average about 15%. This is the value used for project summaries for stormwater + reclaimed water. While a smaller percentage of increased recharge is estimated to report to Thompson Creek than stormwater-only scenarios (15% versus 30%), the water volume is higher.

  This 15% reporting to Thompson Creek represents a water volume increase by a factor of 1.5 times the stormwater-only volume for the *full-build scenario* (an increased 0.3 mgd reporting to Thompson Creek with stormwater + reclaimed water versus an increase of 0.2 mgd with stormwater alone). For the *Phase 1 scenario*, the 15% reporting to Thompson Creek represents a water volume increase of 3 times the stormwater-only volume (an increased 0.2 mgd reporting to Thompson Creek with stormwater + reclaimed water versus an increase of 0.06 mgd with stormwater alone). The difference in these two factors (1.5 for full development versus 3 for Phase 1 development) occurs because of the assumed position of reclaimed water infiltration and, relative to full-development, the stormwater volume generated with Phase 1 development is small.
- Full build-out of the Thurston Highlands Preferred Alternative concept with infiltration of 1.5 mgd reclaimed water would nearly double the effect on creek flow compared to what would occur with stormwater infiltration alone (WY 1997: 0.4 mgd for reclaimed + stormwater versus 0.2 mgd for stormwater alone).

Effects on Groundwater Elevations Adjacent to Thompson Creek[8]

- With increased recharge, development of the Thurston Highlands Master Planned Community would increase groundwater levels adjacent to Thompson Creek. Phase 1 development could cause groundwater adjacent to Thompson Creek to rise about 0.1 feet (0 to 0.5 feet depending upon location along the creek) and full development about 0.3 feet (0 to 0.8 feet). With the addition of 1.5 mgd reclaimed water to site recharge, groundwater levels adjacent to Thompson Creek could rise 0.3 feet (0 to 1 feet) with Phase 1 development, and about 0.5 feet (0 to 1 feet) with full build-out (see Brown & Caldwell, 2008 for assessment of flooding potential on Thompson Creek).

Effects from Development Elsewhere in the UGA

- Without infiltrating reclaimed water, modeling suggests that effects from full build-out elsewhere in the City of Yelm UGA (and unrelated to development that may occur at Thurston Highlands) may further increase groundwater flow to Thompson Creek by almost 75%[9] relative to the increase that would occur with full build-out on the Thurston Highlands and Tahoma Terra sites alone (increase of 0.14 mgd for UGA outside of Thurston Highlands and Tahoma Terra versus an increase of 0.19 mgd for Thurston Highlands and Tahoma Terra alone). With full development in the Yelm UGA, groundwater elevations adjacent to Thompson Creek would be expected to rise 0.1 feet (0 to 0.6 feet) in addition to effects from site development.

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[8] i.e., aquifer flux to the creek; existing condition less developed condition.

[9] Considering only one significant figure for increased flows to Thompson Creek, this would be calculated to be only 50% (0.1 mgd for the Yelm UGA alone versus 0.2 mgd for Thurston Highlands and Tahoma Terra alone).

7.0 SUMMARY OF POTENTIAL IMPACTS

~~Groundwater modeling focused on changes in groundwater flux along Thompson Creek predicted to be caused by development. This section uses the model output to address other potential impacts to the groundwater system that could result from Thurston Highlands site development~~. This section discusses modeling results for each of the major development scenarios.

Full Build-Out Conceptual Land Use Alternatives

Direct Impacts (Scenarios 3a and 3b)

- Infiltration would increase.

  Increased infiltration of stormwater would increase groundwater recharge by almost 40% over existing conditions (0.73 mgd increase stormwater infiltration plus 2.0 mgd with existing conditions).

  Reclaimed water infiltration would increase recharge further by about 50% (2.7 mgd stormwater recharge with development plus an additional 1.5 mgd reclaimed water).

- Groundwater flow to Thompson Creek would increase.

  Stormwater Infiltration:

  Almost 30% of increased stormwater infiltration would flow to Thompson Creek (0.19 mgd increased flow to Thompson Creek from the additional 0.73 mgd stormwater infiltration).

  The increased infiltration would have the effect of increasing groundwater elevations adjacent to Thompson Creek by up to 0.8 foot (Segment 5) with an average rise of 0.3 foot. Some downstream segments of Thompson Creek would not be affected.

  Reclaimed Water Infiltration:

  With reclaimed water infiltration, groundwater recharge would be increased further by about 50% (2.7 mgd stormwater infiltrating plus additional 1.5 mgd reclaimed water). Approximately 15% of the increased stormwater + reclaimed water infiltration would flow to Thompson Creek. (of 2.2 mgd additional stormwater + reclaimed water infiltration, 0.3 mgd would report to Thompson Creek).

  The increased infiltration would have the effect of increasing groundwater elevations adjacent to Thompson Creek by up to about 1 foot (Segment 6) with average rise of about 0.5 foot. Some downstream segments of Thompson Creek would not be affected.

- Recharge to deeper strata would increase.

  Recharge to strata not flowing towards Thompson Creek would increase by up to 0.6 mgd with stormwater alone. This would increase by a factor of up to about 2.5 with reclaimed water infiltration (to about 2 mgd) in an area with no till.

- Groundwater "mounding" beneath reclaimed water infiltration facility: not assessed.

  The extent of groundwater mounding below the infiltration site should be evaluated in more detail in later work phases. Adverse mound heights are least likely where vertical permeability is large, no low-permeability strata (e.g., till) obstruct downward flow, and groundwater is deep.

- Extents of some County-delineated HGHAs in the vicinity may be increased.

  A relationship between Thurston County-mapped HGHA inundation extents and groundwater head was developed for the closest HGHA, which is just downstream of Tahoma Terra in Thompson Creek Segment 10 (**Table 13**). The model-predicted average groundwater head increase in the example HGHA ranges from 0.13 feet for stormwater only, to 0.19 feet for stormwater + 1.5 mgd of reclaimed water infiltration. Using these model results and the relationship in **Table 13**, the rising heads would equate to about 8% and 11% increase in the extent of this HGHA. The relationship between groundwater rise and the area of groundwater flooding is unique for each flood area. These are expected to vary significantly, and should be considered in more detail in future work.

- Effects on wetlands: not assessed.

  Effects on wetlands were not specifically evaluated in the modeling effort. Development has the potential to affect wetland systems. Water levels in monitored wetlands rapidly increased one to five feet with the onset of WY 2008 rainfall. These data have been provided to the project wetland scientists for impact evaluations presented in Coot Company (2008B). In general, groundwater-sensitive wetlands in the A and F complexes may experience effects from increased groundwater levels, but these effects may be considered to be beneficial to the Thompson Creek headwaters area.

- ~~Modeling suggests that the shallow groundwater system would transmit about 30% of the increased recharge (with or without reclaimed water infiltration) to Thompson Creek. Headwater creek segments would receive most of the increased base flow.~~
- ~~Infiltration of 1.5 mgd reclaimed water within the future Regional Sports Complex area would approximately triple the total change in recharge (0.73 mgd stormwater in WY 1981, and 2.2 mgd stormwater + reclaimed water in WY 1981). Similarly, with reclaimed water infiltration, the model predicts an approximate tripling of the change in stream flow resulting from this increased recharge. Note that this is based on annual water volumes calculated by the model. Most of the additional creek flow would be added in upstream headwaters creek segments, and mostly during the wet season.~~
- ~~The full build-out of Tahoma Terra contributes an estimated 0.07 mgd and 0.08 mgd to recharge for the median and wet years, respectively. This results in an increase in the groundwater flux due to Tahoma Terra full build-out of 0.043 mgd and 0.056 mgd for the median and wet years, respectively.~~
- ~~Effects from the increased creek flow were assessed by Brown & Caldwell (2008).~~
- ~~Model results suggest that the change in flux downward from the till toward lower aquifer units would increase by up to 0.0036 mgd (approximately one per cent of average rain fall) with the increase in recharging stormwater. This increased flux would nearly double with infiltration of 1.5 mgd reclaimed water.~~
- ~~According to the Modflow model, infiltration of 1.5 mgd reclaimed water into a 400-foot by 400-foot area Based on would create a groundwater mound at least 10 feet high at the point of infiltration. This mounding is an estimate based upon conceptual development assumptions and hydrogeologic conditions understood at the time of this writing.~~
- ~~For stormwater alone, the model predicts that maximum groundwater head increases adjacent to Thompson Creek would range from 0 (Segment 13) to about 1-foot (Segment 5) and would average about 0.3 feet. The largest head~~

~~change would occur in the headwaters area.~~

- ~~For stormwater + 1.5 mgd reclaimed water infiltration, the model predicts that maximum groundwater head increases adjacent to Thompson Creek would range from 0 (Segment 13) to about 3 feet (Segment 5) and average about 0.8 feet. The largest head change would occur in the headwaters area.~~
- ~~A relationship between Thurston County-mapped HGHA inundation extents and groundwater head was developed for the closest HGHA, which is just downstream of Tahoma Terra in Thompson Creek Segment 10 (**Table 13**). The model-predicted groundwater head increase in the example HGHA ranges from 0.080 feet for stormwater only, to 0.13 feet for stormwater plus 1.5 mgd of reclaimed water infiltration. Using these model results and the relationship in **Table 13**, the rising heads would equate to about 5% and 8% increase in the extent of the HGHA. The relationship between groundwater rise and the area of groundwater flooding is unique for each flood area. These are expected to vary significantly, and should be considered in more detail in future work.~~
- ~~Effects on wetlands were not specifically evaluated in the modeling effort. Development has the potential to affect wetland systems. Water levels in monitored wetlands rapidly increased one to five feet with the onset of WY 2008 rainfall. These data have been provided to the project wetland scientists for impact evaluations presented in Coot Company (2008B). In general, groundwater-sensitive wetlands in the A and F complexes may experience effects from increased groundwater levels, but these effects are considered to be beneficial to the Thompson Creek headwaters area.~~

Indirect Impacts (Scenarios 3a and 3b)

According to the project Modflow model, indirect impacts to groundwater from Thurston Highlands site development would be limited. Particle tracking in the model shows the increased recharge moving downward through the Qvr and till (where present), and then moving northward mostly in the Qva. There is still a vertical gradient through the Qva that would drive the recharge into deeper aquifers, also with northward gradients. The model suggests that some of the increased recharge would flow downward into deeper aquifers, and would eventually move off-site under the influence of the regional groundwater system. Groundwater head increases in these deeper and more remote areas would be small and generally beneficial for stream and river base flows.

Phase 1 Development Concept

Direct Impacts (Scenarios 2a, 2b, and 2c)

- Infiltration would increase.

  Increased groundwater recharge from infiltration would be about 10% above existing conditions (0.20 mgd increase stormwater infiltration with Scenario 2a, 0.27 mgd with Scenario 2c versus 2.0 mgd with existing conditions).

  Reclaimed water infiltration would increase recharge further by almost 70% (2.2 mgd stormwater recharge with development plus an additional 1.5 mgd reclaimed water).

- Groundwater flow to Thompson Creek would increase.

  Stormwater Infiltration:

  Up to 30 to 40% of increased stormwater infiltration would flow to Thompson Creek (<0.06 mgd increased flow to Thompson Creek from the additional 0.2 mgd stormwater infiltration with Scenario 2a; <0.1 mgd increased flow to Thompson Creek from the additional 0.3 mgd stormwater infiltration with Scenario 2c).

The increased infiltration would have the effect of increasing groundwater elevations adjacent to Thompson Creek by up to 0.5 feet (Segment 5) with an average rise of 0.1 feet. Some downstream segments of Thompson Creek would not be affected.

Reclaimed Water Infiltration:

With reclaimed water infiltration, groundwater recharge would be increased further by about 70% (2.2 mgd stormwater infiltrating versus 1.5 mgd reclaimed water). Approximately 12% of the increased stormwater + reclaimed water infiltration would flow to Thompson Creek. (of 1.7 mgd additional stormwater + reclaimed water infiltration, 0.2 mgd would report to Thompson Creek).

The increased infiltration would have the effect of increasing groundwater elevations adjacent to Thompson Creek by up to about 1 foot (Segment 6) with average rise of about 0.3 feet. Some downstream segments of Thompson Creek would not be affected.

- Recharge to deeper strata would increase.

  Recharge to strata not flowing towards Thompson Creek would increase by up to 0.2 mgd with stormwater alone. With reclaimed water infiltration, this would increase by a factor of up to almost 8 (to about 1.7 mgd) in an area with no till.

- Groundwater “mounding” beneath reclaimed water infiltration facility: not assessed.

  The extent of groundwater mounding below the infiltration site should be evaluated in more detail in later work phases. Adverse .mound heights are least likely where vertical permeability is large, no low-permeability strata (e.g., till) obstruct downward flow, and groundwater is deep.

- Extents of some County-delineated HGHAs in the vicinity may be increased.

  A relationship between Thurston County-mapped HGHA inundation extents and groundwater head was developed for the closest HGHA, which is just downstream of Tahoma Terra in Thompson Creek Segment 10 (**Table 13**). The model-predicted average groundwater head increase in the example HGHA ranges from 0.06 feet for stormwater only, to 0.08 feet for stormwater + 1.5 mgd of reclaimed water infiltration. Using these model results and the relationship in **Table 13**, the rising heads would equate to about 4% and 5% increase in the extent of this HGHA. The relationship between groundwater rise and the area of groundwater flooding is unique for each flood area. These are expected to vary significantly, and should be considered in more detail in future work.

- Effects on wetlands: not assessed.

  Effects on wetlands were not specifically evaluated in the modeling effort. Development has the potential to affect wetland systems. Water levels in monitored wetlands rapidly increased one to five feet with the onset of WY 2008 rainfall. These data have been provided to the project wetland scientists for impact evaluations presented in Coot Company (2008B). In general, groundwater-sensitive wetlands in the A and F complexes may experience effects from increased groundwater levels, but these effects may be considered to be beneficial to the Thompson Creek headwaters area.

Indirect Impacts (Scenarios 2a, 2b, and 2c)

According to the project Modflow model, indirect impacts to groundwater from Thurston Highlands site development would be limited.

Particle tracking in the model shows the increased recharge moving downward through the Qvr and till (where present), and then moving northward mostly in the Qva. There is still a vertical gradient through the Qva that would drive the recharge into deeper aquifers, also with northward gradients. The model suggests that some of the increased recharge would flow downward into deeper aquifers, and would eventually move off-site under the influence of the regional groundwater system. Groundwater head increases in these deeper and more remote areas would be small and generally beneficial for stream and river base flows.

- ~~Modeling suggests that the shallow groundwater system would transmit up to about 30% of the increased recharge resulting from Phase 1 build-out (with or without reclaimed water infiltration) to Thompson Creek. Headwater segments would receive most of the increased base flow.~~
- ~~Compared with stormwater-only infiltration, infiltration of 1.5 mgd of reclaimed water in the future Regional Sports Complex area would increase the total change in recharge by up to a factor of about 6 (0.27 mgd stormwater in WY 1981, and 1.7 mgd stormwater + reclaimed water in WY 1981). Similarly, the model predicts the change in groundwater discharge to Thompson Creek to increase by a factor of about 5 with reclaimed water infiltration. Note that this is based on *annual* water volumes calculated by the model. Most of the additional creek flow would be added in headwater creek segments and during the wet season.~~
- ~~Effects from the increased creek flow were assessed by Brown & Caldwell (2008).~~
- ~~Model results suggest that the downward groundwater flow from the till toward lower aquifers would increase by up to 0.00085 mgd with the increase in recharging stormwater. This increase flux would approximately quintuple (factor of 5) with infiltration of 1.5 mgd reclaimed water.~~
- ~~According to the model, infiltration of 1.5 mgd reclaimed water into a hypothetical 400-foot by 400-foot area would create a groundwater mound at least 10 feet high at the point of infiltration. This mounding is an estimate based upon conceptual development assumptions and hydrogeologic conditions understood at the time of this writing.~~
- ~~For stormwater alone, the model predicts that maximum groundwater head increases adjacent to Thompson Creek range from 0 (Segments 12 and 13) to about 0.5 feet (Segment 5), and would average about 0.1 feet. The largest effects would occur in the headwaters area.~~
- ~~For stormwater + reclaimed water, the model predicts that maximum groundwater head increases adjacent to Thompson Creek would range from 0 (Segment 13) to about 2 feet (Segment 5), and would average about 0.6 foot. The largest effects would occur in the headwaters area.~~
- ~~A relationship between Thurston County-mapped HGHA inundation extents and groundwater head was developed for the closest HGHA, which is just downstream of Tahoma Terra in Thompson Creek Segment 10 (**Table 13**). The model-predicted groundwater head increase in the example HGHA ranges from 0.060 feet for stormwater only, to 0.070 feet for stormwater plus 1.5 mgd of reclaimed water infiltration. Using these model results and the relationship in **Table 13**, the rising heads would equate to about 4% increase in the size of the HGHA. The relationship between groundwater rise and the area of groundwater flooding is unique for each flood area. These are expected to vary significantly, and should be considered in more detail in future work.~~
- ~~Effects on wetlands were not specifically evaluated for the Phase 1 development concept.~~

No Action Alternative

Existing conditions at the Thurston Highlands site would continue with the No Action Alternative. The existing condition was used in the modeling effort to compare infiltration effects from development on groundwater. The model would therefore predict no impact for the No Action Alternative. However, effects on Thompson Creek would still be expected for future development elsewhere in the Yelm UGA (see discussion of full-build-out within the Thompson Creek Basin below).

Full Build Out Within the Thompson Creek Basin

The discussion above pertains to impacts from developing Thurston Highlands (Preferred Alternative concept) and Tahoma Terra. However, development elsewhere within the Thompson Creek Basin, and within the City of Yelm UGA, also has the potential to impact Thompson Creek. Two modeled predictive simulations (Scenarios 4a and 4b) were run to assess effects on Thompson Creek from full build-out within the UGA, outside of the Thurston Highlands and Tahoma Terra sites, in accordance with current zoning.

Without considering effects from infiltrating 1.5 mgd reclaimed water, model simulations suggest that full build-out in the Yelm UGA in accordance with existing zoning may add up to ~~about~~ almost ~~40~~75% more shallow groundwater input to Thompson Creek than with full build-out of Thurston Highlands alone[10]~~.~~.With full development of Tahoma Terra, Thurston Highlands, and the remainder of the UGA, g~~G~~roundwater elevations adjacent to Thompson Creek would also be expected to rise further between 0 feet (Segment 13) and about ~~0.3 feet~~ 1 foot (Segment ~~6~~5) and average about ~~0. 1 feet~~ 0.5 foot with most effect in headwaters areas.

8.0 MITIGATION OPTIONS

Modeling suggests that shallow groundwater flux into Thompson Creek is likely to increase with Thurston Highlands site development. While increased stream flow is often beneficial to aquatic wildlife, flooding may be exacerbated. Mitigation of impacts to Thompson Creek that would be associated with increased stormwater and reclaimed water infiltration is therefore considered. The following two lists summarize mitigation options for stormwater and reclaimed water infiltration, respectively.

KPFF Consulting Engineers (2008) discusses measures to mitigate impacts of increased stormwater quantity and quality. The mitigation options described below focus on minimizing impacts to Thompson Creek from increased recharge.

Stormwater Mitigation Options

1. Infiltrate excess stormwater in areas that would minimize impacts..
2. Reduce the volume of stormwater to be infiltrated.
3. Reduce wet season stormwater infiltration.
4. Improve the conveyance capacity of Thompson Creek.
5. Increase Thompson Creek basin storage.

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[10] According to the model, with full build-out in the Yelm UGA and no reclaimed water infiltration on the Thurston Highlands site, ~~O~~on ~~n an annualized~~ average annual~~basis~~ flow in~~, with full build-out elsewhere in the UGA,~~ Thompson Creek ~~flow~~ is expected to increase by about ~~40~~75% over the increase caused by development within Thurston Highlands and Tahoma Terra ~~alone~~. Under this UGA full build-out scenario, ~~and also under an annualized average basis,~~ shallow groundwater flow to Thompson Creek would increase by about 0.4 mgd over existing conditions. According to the model, at full UGA build-out and no reclaimed water infiltration, approximately 43% of the increased flow ~~in~~ to Thompson Creek would be attributable to full build-out *outside* of Thurston Highlands and Tahoma Terra.~~-~~ Full build-out of Thurston Highlands would contribute a similar amount to the increased flux to Thompson Creek. Tahoma Terra would contribute about 14%.

Reclaimed Water Mitigation Option

6. Infiltrate reclaimed water in areas that would minimize impacts.

7. Reduce, eliminate from consideration, or schedule reclaimed water infiltration on the Thurston Highlands site.

8.1 ASSUMPTIONS

- Seven modeling scenarios (2a, 2b, 2c, 3a, 3b, and effects from UGA build-out elsewhere in the Thompson Creek basin 4a, 4b; see **Table 11**) were considered to evaluate mitigation options. Three of these scenarios (2b, 3b, and 4b) include infiltration of 1.5 mgd of reclaimed water.

- Infiltration of excess water would occur according to applicable State and local regulations.

- Excess stormwater may be conveyed between site sub-basins (gravity flow preferred).

8.2 STORMWATER MITIGATION OPTION ASSESSMENT

Option 1: Infiltrate Excess Storm-water in Areas that Would Minimize Impacts.

Potential to mitigate effects on Thompson Creek: high.

Option 1 would focus recharge in areas with minimal impact to Thompson Creek. These low impact areas would be where till is absent or relatively permeable, and/or as far away from Thompson Creek as possible. This option would require that stormwater be captured and conveyed to low impact areas (see KPFF, 2008).

The project Modflow model was used to simulate effects on Thompson Creek if excess stormwater was re-routed to the west part of the Thurston Highlands site (sub-basin F). Without this mitigation, about 30% of the increase in recharge was predicted to discharge to Thompson Creek. According to the model, this mitigation option has the potential to reduce the impact on stream flow in Thompson Creek to near zero.

Mitigation Option 1 would also provide the benefit of supplying recharge to deeper aquifers. Drawbacks would include the need to convey excess stormwater to an infiltration facility, likely requiring pumping. Conveyance requirements would be minimized with development concentrated near the area(s) of infiltration.

Option 2: Reduce the Volume of Stormwater to be Infiltrated.

Potential to mitigate effects on Thompson Creek: limited.

Excess stormwater that is infiltrated may be reduced by enhancing evapotranspiration within the development. This may be accomplished by maintaining as much of the existing forest as possible, and/or by enhancing transpiration by select plantings.

Current hydrologic modeling assumes that 86 per cent of the current forest will be removed with the conceptual Preferred Alternative. The combination of reducing evapotranspiration and infiltration of all stormwater would have the effect of increasing groundwater recharge by about 13% for Phase 1 development, and by about 43% for full build-out of the Preferred Alternative. With about 30% of the excess stormwater recharge reporting to Thompson Creek, this mitigation option would reduce expected surface water flows relative to the unmitigated case.

Option 3: Reduce Wet Season Stormwater Infiltration.

Potential to mitigate effects on Thompson Creek: limited.

Option 3 would involve collection and storage of all or part of the excess stormwater during the wet season. The water could then be beneficially used (e.g., irrigation), or could be evaporated or infiltrated during the dry season. Storage would have to be provided sufficient to retain excess stormwater. The volume of excess stormwater reporting to Thompson Creek would vary from about 60 acre-feet (Scenario 2a, WY 1981) to about 440 acre-feet (Scenario 4a, WY 1997). Capture and beneficial use of surface water might require a water right from the State. This scenario could result in Thompson Creek flowing during part of the dry season where normally it would be dry.

Option 4: Improve the Conveyance Capacity of Thompson Creek.

> Potential to mitigate effects on Thompson Creek: moderate to high.

Channel improvements could offset effects on Thompson Creek attributable to development within the basin (Thurston Highlands, Tahoma Terra, and elsewhere within the City of Yelm UGA). Future feasibility assessment will evaluate the practicability of this option. A drainage/flood control district could be a mechanism for implementing conveyance capacity improvements and long-term channel maintenance (see KPFF 2008, and Brown & Caldwell, May 2008).

Option 5: Increase Thompson Creek Basin Storage.

> Potential to mitigate effects on Thompson Creek: moderate to high.

Increased basin storage for retaining excess Thompson Creek inflow without increased flooding could offset effects on the creek attributable to development within the basin (Thurston Highlands, Tahoma Terra, and elsewhere within the City of Yelm UGA). ~~Future feasibility assessment will evaluate the practicability of this option~~See the Brown & Caldwell Thurston Highlands final EIS surface water technical report, October, 2008).

8.3 RECLAIMED WATER MITIGATION OPTION ASSESSMENT

Option 6: Infiltrate Reclaimed Water in Areas that Would Minimize Impacts.

Option 6 would focus infiltration of reclaimed water not used for beneficial purposes (e.g., irrigation) in areas with minimal impact to Thompson Creek. These low impact areas would be where till is absent or relatively permeable, and/or as far away from Thompson Creek as possible. This option would require conveyance to low impact areas. Reclaimed water would require piping regardless of where it is ultimately infiltrated. Mitigation Option 6 would provide the benefit of supplying recharge to deeper aquifers.

Option 7: Reduce, Eliminate From Consideration, or Schedule Reclaimed Water Infiltration on the Thurston Highlands Site.

Declining to infiltrate reclaimed water, or reducing infiltration of reclaimed water in areas affecting Thompson Creek, would retain more conveyance capacity and storage in the creek system that can be used to handle stormwater.

Historically, Thompson Creek has been dry most of the year. It may be possible to infiltrate 1.5 mgd reclaimed water during the dry season with no or minimal adverse impact to the creek. Effectively implemented, dry-season infiltration may result in year around, flood-free creek flow and may possibly be considered beneficial.

8.4 MITIGATION OPTION SUMMARY

Based on a hydrologic perspective and groundwater modeling performed by PGG, the most promising option to mitigate impacts of excess stormwater infiltration is ~~currently considered to be~~ re-routing excess stormwater to areas that would cause the least impact (Option 1).~~ However~~. The feasibility of this option was evaluated by KPFF (August 29, 2008). ~~would be evaluated by others.~~ Other options offer some mitigation possibilities used alone or in combination offering potential benefits, but may not be considered feasible upon further evaluation. When engineering feasibility is also considered, the overall feasibility of any of the mitigation options may change.

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FIGURES

Figure 1. Site Map Insert

Figure 2. Groundwater Flow Insert

Figure 3. Conceptual Hydrogeologic Model Cross-Section A-A' Insert

Figure 4. Conceptual Hydrogeologic Model Cross-Section Approximately Along Thompson Creek Insert

Figure 5. Model Area Insert

Figure 6~~.~~ Thompson Creek Segmentation.

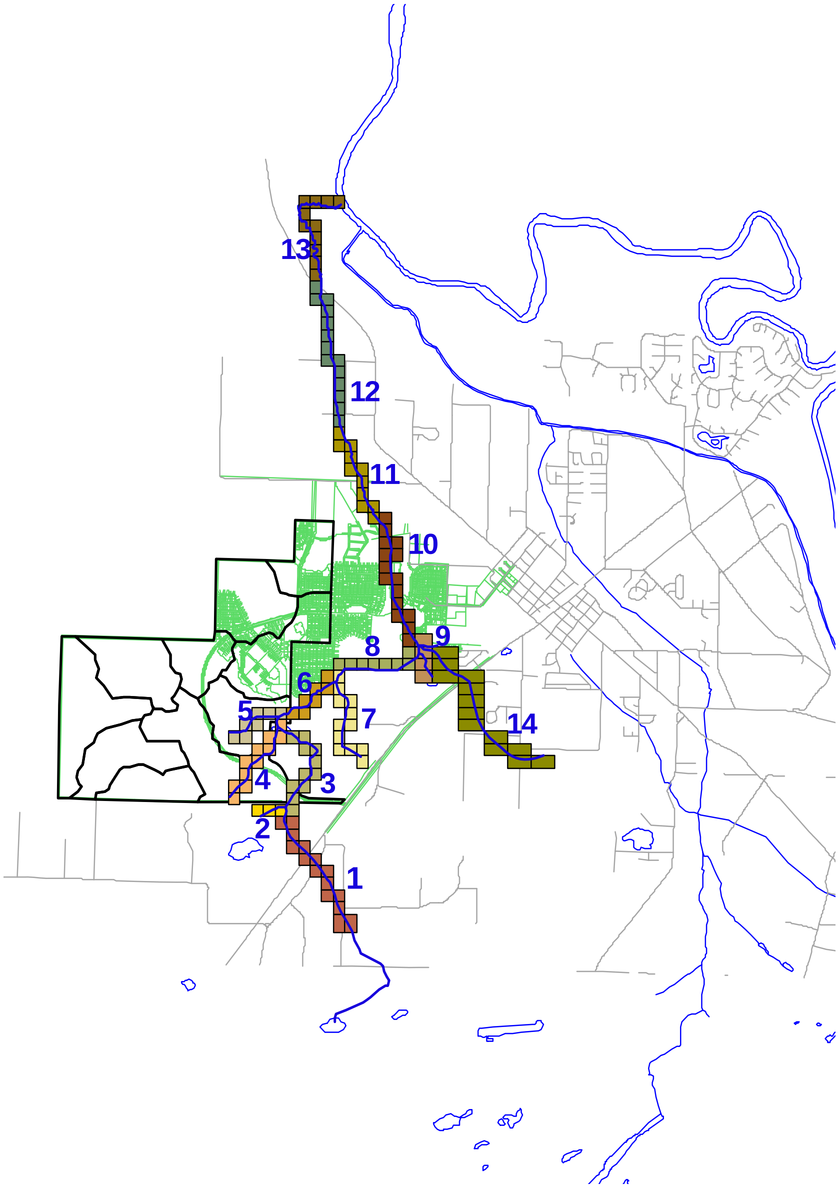
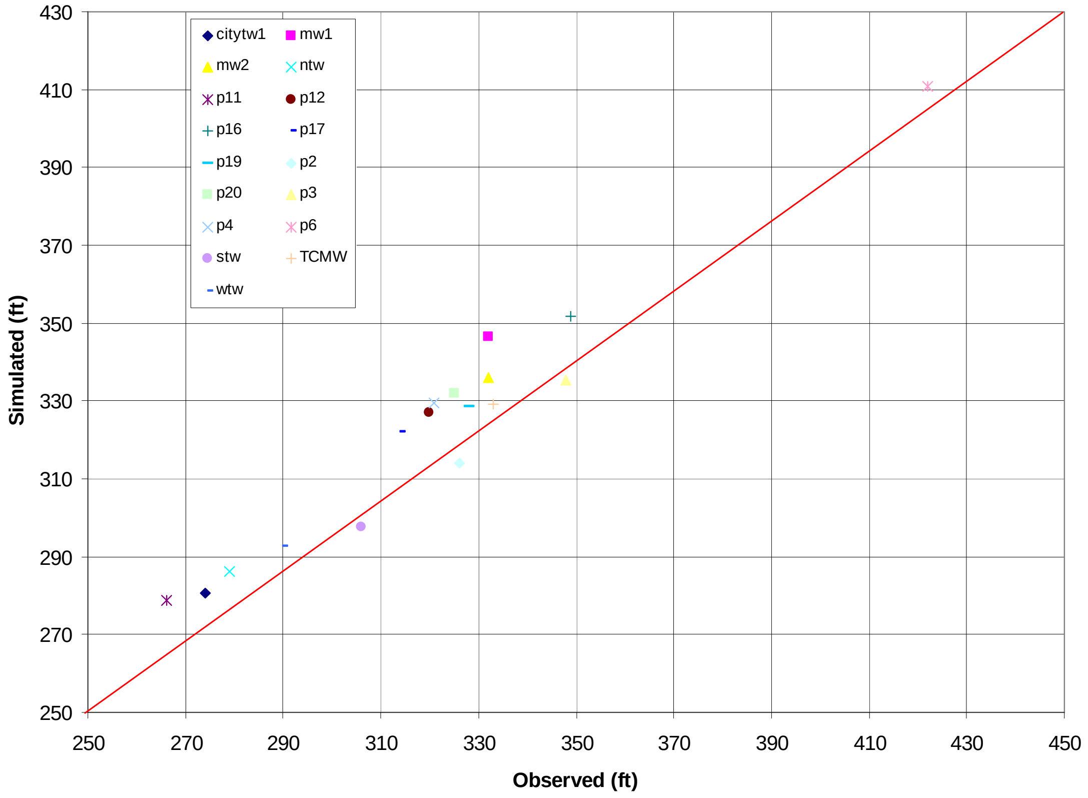


Figure 7a~~.~~ Simulated Heads vs. Observed Heads for the Calibrated Model (site wells~~APIH target wells~~).



430
410
390
370
350
330
310
290
270
250
Simulated (ft)
250
270
290
310
330
350
370
390
410
430
450
Observed (ft)
citytw1
mw1
mw2
ntw
p11
p12
p16
p17
p19
p2
p20
p3
p4
p6
stw
TCMW
wtw

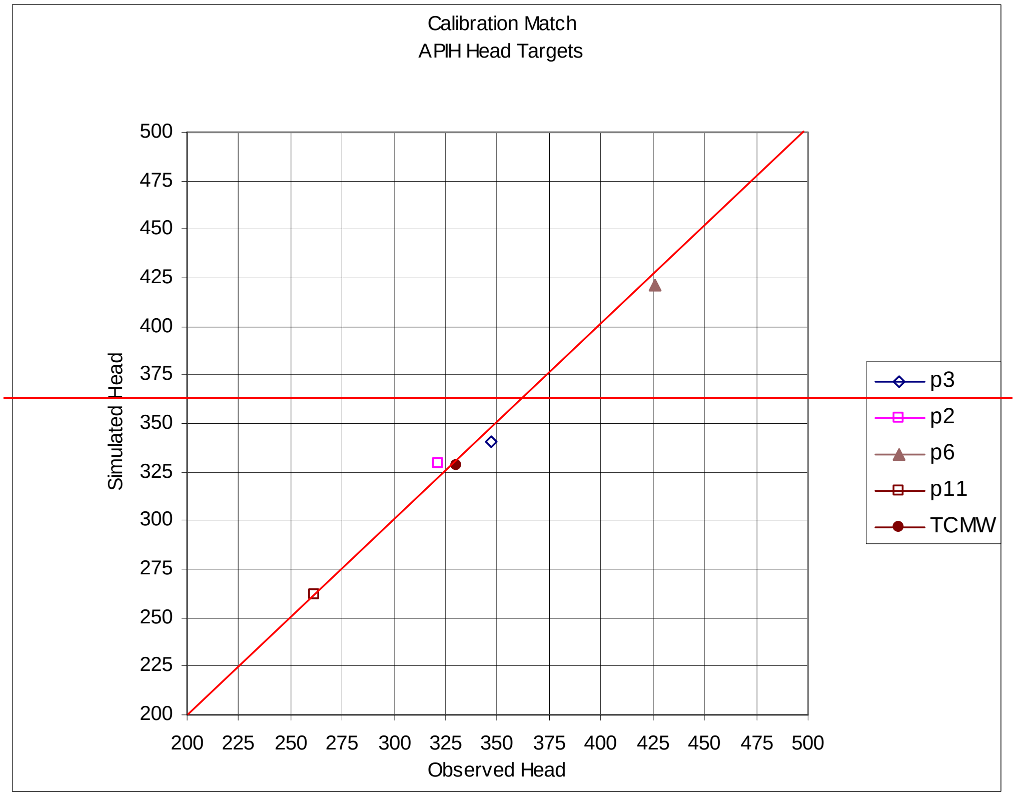

Calibration Match
APIH Head Targets
Simulated Head
500
475
450
425
400
375
350
325
300
275
250
225
200
200
225
250
275
300
325
350
375
400
425
450
475
500
Observed Head
p3
p2
p6
p11
TCMW

Figure 7b Simulated Heads vs. Observed Heads for the Calibrated Model (site wells by unit).

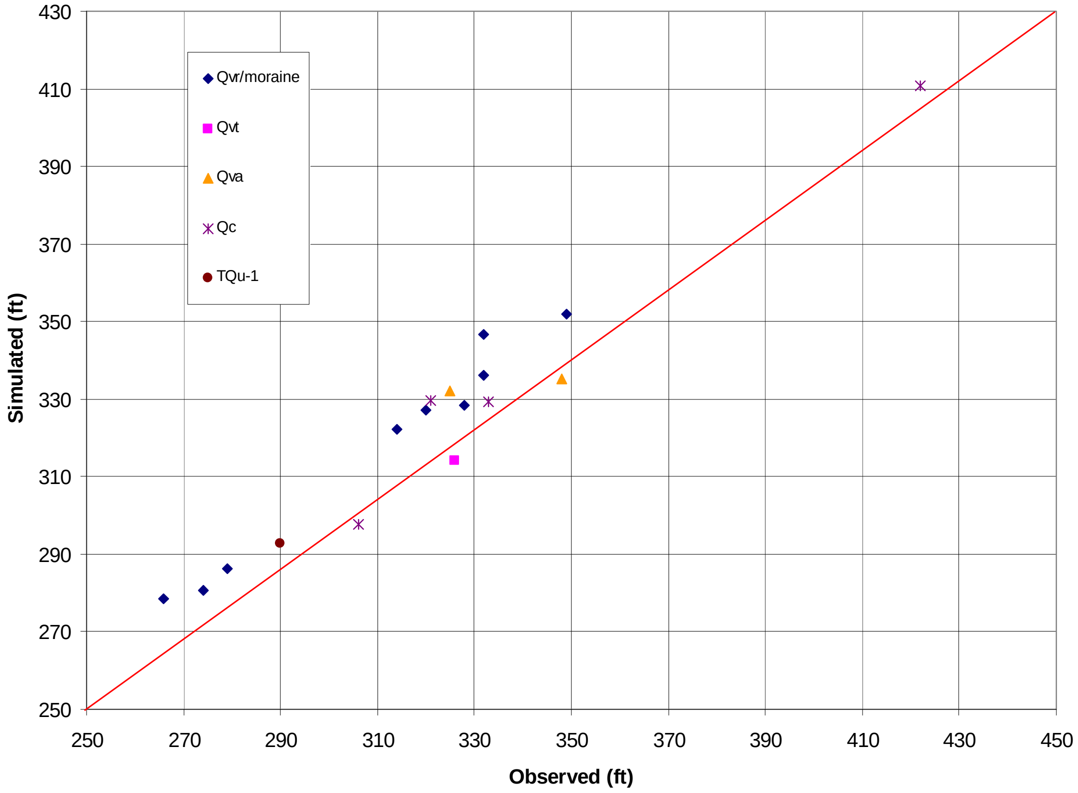
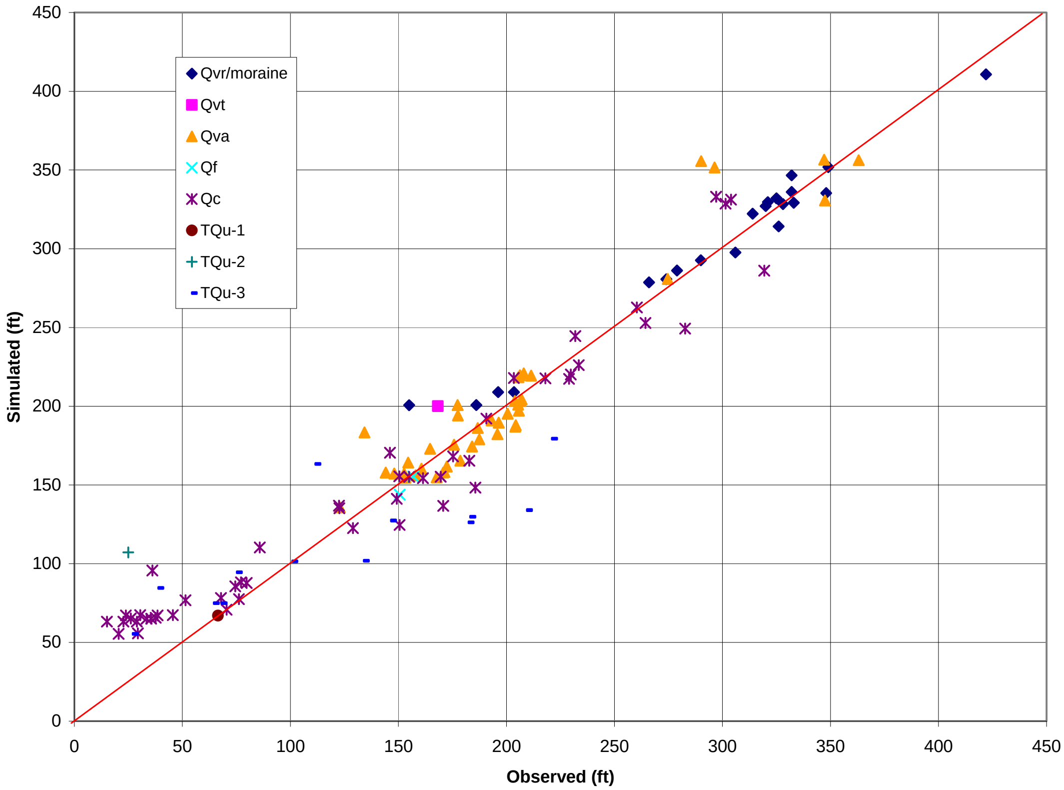


Figure 8 Simulated Heads vs. Observed Heads for the Calibrated Model (all wells in model by unit).



~~**Figure 8. Simulated Heads vs. Observed Heads for the Calibrated Model (all wells).**~~

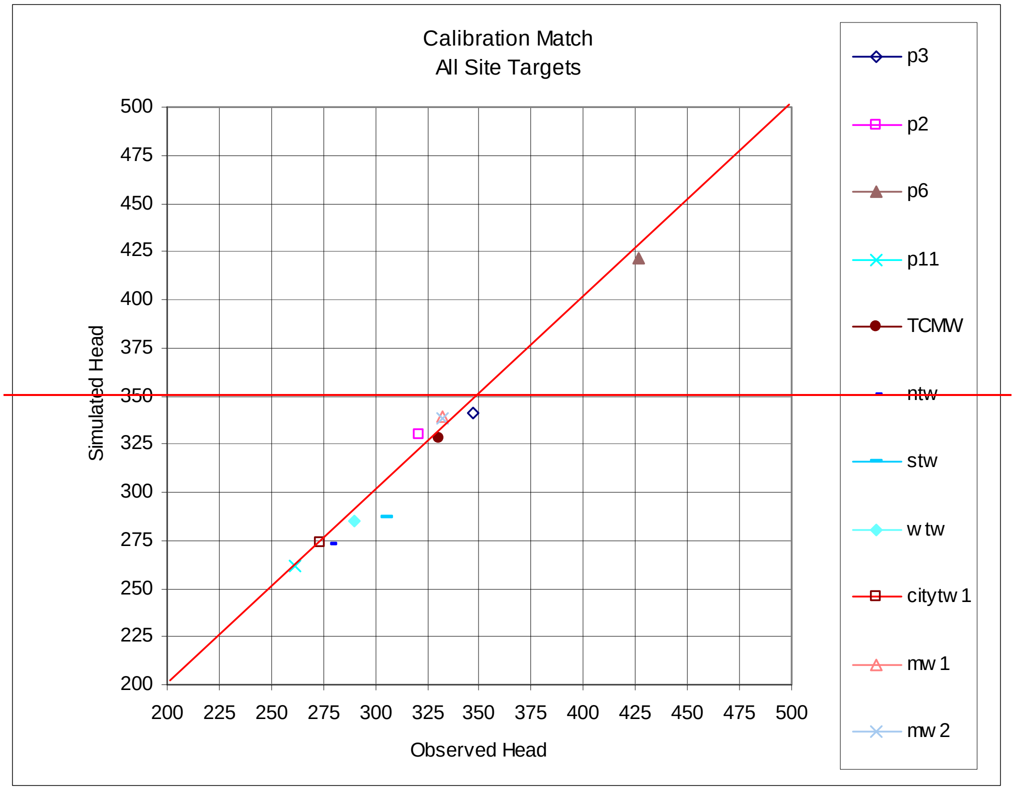


Figure 9. Thurston Highlands Water Balance Insert.

TABLES

Table 1. Summary of Well Completion Data

		Measurements & Dimensions								Survey (feet relative to datums)[3]				Calculated Elevations (feet relative to datums)[2]				
Type	Location	Date	Depth to Water (feet BMP)	Depth to Water (feet BGS)	Stickup (feet AGS)	Bottom of Casing (feet BGS)	Bottom of Hole (feet BGS)	Screen Interval (feet BGS)		Northing	Easting	Measuring Point	Ground Surface	Water Surface	Mid-point of Screen	Top of Screen	Bottom of Screen	Bottom of Hole
Piezometer	p1[1]	3/12/2008	dry	dry	2.5	74	120	53.5	73.5	594550.12	1103438.38	381.74	379.24	dry	315.74	325.74	305.74	259.24
	p2	3/12/2008	50.46	48.66	1.8	59.5	59.5	49	59	593173.21	1104343.34	375.85	374.05	325.39	320.05	325.05	315.05	314.55
	p3	3/12/2008	57.71	55.01	2.7	61.2	61.2	50.6	60.6	592457.39	1103020.35	405.12	402.42	347.41	346.82	351.82	341.82	341.22
	p4	3/12/2008	95.67	92.97	2.7	98.7	100	78.2	98.2	590461.58	1102569.38	415.74	413.04	320.07	324.84	334.84	314.84	313.04
	p5[1]	3/12/2008	dry	dry	2.2	75	118	64.5	74.5	591685.93	1100720.43	442.99	440.79	dry	371.29	376.29	366.29	322.79
	p6	3/12/2008	99.22	96.72	2.5	112.2	113	101.7	111.7	591433.67	1097640.52	528.46	525.96	429.24	419.26	424.26	414.26	412.96
	p7[1]	3/12/2008	dry	dry	2.7	100.7	140	90.2	100.2	589268.97	1100061.65	456.46	453.76	dry	358.56	363.56	353.56	313.76
	p8[2]	3/12/2008	50.13	47.13	3	48.7	99	38.2	48.2	588549.16	1097784.59	496.27	493.27	446.14	450.07	455.07	445.07	394.27
	p9[1]	3/12/2008	dry	dry	3	48.7	99	38.2	48.2	590630.50	1099200.14	474.54	471.54	dry	428.34	433.34	423.34	372.54
	p10	3/12/2008	124.81	122.31	2.5	127.6	130	102.1	127.1	588014.09	1101747.26	483.71	481.21	358.90	366.61	379.11	354.11	351.21
	p11	3/12/2008	117.53	114.83	2.7	121.1	121.1	110.6	120.6	594481.44	1103542.64	382.07	379.37	264.54	263.77	268.77	258.77	258.27
	p12	3/13/2008	17.16	17.51	-0.35	35.3	35.3	24.8	34.8	594957.44	1109339.89	337.42	337.77	320.26	307.97	312.97	302.97	302.47
	p16	3/17/2008	13	10.5	2.5	27.5	65	17	27	588454.86	1104196.44	362.35	359.80	349.35	337.80	342.80	332.80	294.80
	p17	3/17/2008	35.87	33.47	2.4	75.7	76	65.5	75.5	591059.63	1104639.48	349.56	347.16	313.69	276.66	281.66	271.66	271.16
	p18	3/17/2008	50.85	48.45	2.4	55.8	56	45.3	55.3	594477.37	1105030.51	381.07	378.67	330.22	328.37	333.37	323.37	322.67
	p19	3/17/2008	6.68	4.18	2.5	13	80	4.5	12.5	593456.93	1109656.37	334.52	331.97	327.84	323.47	327.47	319.47	251.97
	p20	3/17/2008	5.85	3.65	2.2	30	45	19.5	29.5	595021.58	1108800.27	332.52	330.32	326.67	305.82	310.82	300.82	285.32
Stilling Well	s1	3/12/2008	3.44	-0.62	4.1	6	6	3	6	589385.05	1097222.85	444.58	440.52	441.14	436.02	437.52	434.52	434.52
	s2	3/12/2008	2.93	-0.36	3.3	4	4	1	4	588303.89	1097528.32	477.10	473.81	474.17	471.31	472.81	469.81	469.81
	s6	3/12/2008	4.57	-0.59	5.2	2	2	0	2	588722.96	1102061.68	363.60	358.44	359.03	357.44	358.44	356.44	356.44
	s7	3/12/2008	5.11	1.34	3.8	3.8	3.8	1.4	3.8	587454.45	1103173.44	364.30	360.53	359.19	357.93	359.13	356.73	356.73
	s8	3/12/2008	4.69	1.01	3.7	4	4	1	4	588290.13	1104903.78	352.57	348.89	347.88	346.39	347.89	344.89	344.89
	s11	3/12/2008	3.36	-0.08	3.4	3	3	1	3	593825.57	1108823.92	331.74	328.3	328.38	326.30	327.30	325.30	325.30
	s12	11/30/2007	4.1	0.04	4.1	6	6	3	6	595217.99	1106217.10	349.84	345.78	345.74	341.28	342.78	339.78	339.78
Staff Gage[4]	s2 gage	8/9/2007	2.31	N/A	3	N/A	N/A	N/A	N/A	-	-	474.90	-	472.59	N/A	N/A	N/A	N/A
	s6 gage	8/9/2007	2.38	N/A	3	N/A	N/A	N/A	N/A	-	-	358.81	-	356.44	N/A	N/A	N/A	N/A
	s7 gage	8/9/2007	2.44	N/A	3	N/A	N/A	N/A	N/A	-	-	360.62	-	358.18	N/A	N/A	N/A	N/A
	tc gage	8/9/2007	2.69	N/A	3	N/A	N/A	N/A	N/A	593434.78	1108775.68	329.87	326.87	327.18	N/A	N/A	N/A	N/A
Other	City TC piezo	3/11/2008	7.08	3.08	4	17	17	12	17	593280.88	1108599.37	336.59	332.59	329.51	322.09	324.59	319.59	315.59
	City ntw	3/12/2008	167.6	165.80	1.8	251	251	195	225	591606.43	1100747.11	443.56	441.76	275.96	220.56	248.56	192.56	216.76
	City stw	3/12/2008	154.54	151.34	3.2	260	260	195	255	588320.47	1100170.69	457.75	454.55	303.21	230.25	262.75	197.75	199.55
	City wtw	3/12/2008	170.85	169.65	1.2	285	285	230	285	589658.31	1097182.44	455.79	454.59	284.94	198.29	225.79	170.79	169.59
	TH mw1	3/11/2008	16.32	16.62	-0.3	20.6	28	18	28	592770.99	1107381.10	348.14	348.44	331.82	328.84	330.14	327.54	320.44
	TH mw2	3/11/2008	18.83	19.13	-0.3	28	28	18	28	592865.49	1107741.43	350.76	351.06	331.93	327.76	332.76	322.76	323.06
	TH mw3	1/15/2008	28.64	28.94	-0.3	29.8	29.5	19.5	29.5	593363.47	1107331.62	361.41	361.71	332.77	336.76	341.91	331.61	332.21

Notes

1 Screened at depth considered most likely to be saturated. Upper aquifer considered absent.
2 Normally dry but water measured after construction and in March 2008.
3 Survey of Northing/Easting and Measuring Point by KPFF, August 2007 & March 2008. Horizontal datum: Washington State Plane Coordinate System, NAD 83\91; Vertical datum: *NGVD29.*
4 Gage measurements from top of 3-foot high gage down to water surface. 0 feet = mudline.

BMP	below measureing point
BGS	below ground surface
AGS	above ground surface
N/A	Not applicable

		Measurements & Dimensions								Survey (feet relative to datums)[2]				Calculated Elevations (feet relative to datums)[2]				
Type	Location	Date	Depth to Water (feet BMP)	Depth to Water (feet BGS)	Stickup (feet AGS)	Bottom of Casing (feet BGS)	Bottom of Hole (feet BGS)	Screen Interval (feet BGS)		Northing	Easting	Measuring Point	Ground Surface	Water Surface	Mid-point of Screen	Top of Screen	Bottom of Screen	Bottom of Hole
Piezometer	p1[1]	7/13/2007	75.08	72.58	2.5	74	120	53.5	73.5	594550.12	1103438.38	381.74	379.24	306.66	315.74	325.74	305.74	259.24
	p2	7/13/2007	51.7	49.9	1.8	59.5	59.5	49	59	593173.21	1104343.34	375.85	374.05	324.15	320.05	325.05	315.05	314.55
	p3	7/13/2007	57.49	54.79	2.7	61.2	61.2	50.6	60.6	592457.39	1103020.35	405.12	402.42	347.63	346.82	351.82	341.82	341.22
	p4	8/7/2007	94.36	91.66	2.7	98.7	100	78.2	98.2	590461.58	1102569.38	415.74	413.04	321.38	324.84	334.84	314.84	313.04
	p5[1]	7/13/2007	75.27	73.07	2.2	75	118	64.5	74.5	591685.93	1100720.43	442.99	440.79	367.72	371.29	376.29	366.29	322.79
	p6	7/13/2007	100.6	98.1	2.5	112.2	113	101.7	111.7	591433.67	1097640.52	528.46	525.96	427.86	419.26	424.26	414.26	412.96
	p7[1]	7/13/2007			2.7	100.7	140	90.2	100.2	589268.97	1100061.65	456.46	453.76		358.56	363.56	353.56	313.76
	p8[1]	7/13/2007	50.28	47.28	3	48.7	99	38.2	48.2	588549.16	1097784.59	496.27	493.27	445.99	450.07	455.07	445.07	394.27
	p9[1]	8/9/2007			3	48.7	99	38.2	48.2	590630.50	1099200.14	474.54	471.54		428.34	433.34	423.34	372.54
	p10	8/8/2007	122.43	119.93	2.5	127.6	130	102.1	127.1	588014.09	1101747.26	483.71	481.21	361.28	366.61	379.11	354.11	351.21
	p11	7/13/2007	115.38	112.68	2.7	121.1	121.1	110.6	120.6	594481.44	1103542.64	382.07	379.37	266.69	263.77	268.77	258.77	258.27
	p12	8/7/2007	22.33	22.68	-0.35	35.3	35.3	24.8	34.8	594957.44	1109339.89	337.42	337.77	315.09	307.97	312.97	302.97	302.47
Stilling Well	s1	7/13/2007	6.46	2.4	4.1	6	6	3	6	589385.05	1097222.85	444.58	440.52	438.12	436.02	437.52	434.52	434.52
	s2	7/13/2007	4.39	1.1	3.3	4	4	1	4	588303.89	1097528.32	477.10	473.81	472.71	471.31	472.81	469.81	469.81
	s6	7/13/2007	6.46	1.3	5.2	2	2	0	2	588722.96	1102061.68	363.60	358.44	357.14	357.44	358.44	356.44	356.44
	s7	7/13/2007	5.87	2.1	3.8	3.8	3.8	1.4	3.8	587454.45	1103173.44	364.30	360.53	358.43	357.93	359.13	356.73	356.73
	~~s8~~	~~7/13/2007~~	~~5.68~~	~~2~~	~~3.7~~	~~4~~	~~4~~	~~1~~	~~4~~	~~588290.13~~	~~1104903.78~~	~~352.57~~	~~348.89~~	~~346.89~~	~~346.39~~	~~347.89~~	~~344.89~~	~~344.89~~
	s11	7/13/2007	4.34	0.9	3.4	3	3	1	3	593825.57	1108823.92	331.74	328.3	327.40	326.30	327.30	325.30	325.30
	s12	7/13/2007	6.56	2.5	4.1	6	6	3	6	595217.99	1106217.10	349.84	345.78	343.28	341.28	342.78	339.78	339.78
Staff Gage[3]	s2 gage	8/9/2007	2.31	N/A	3	N/A	N/A	N/A	N/A	-	-	474.90	-	472.59	N/A	N/A	N/A	N/A
	s6 gage	8/9/2007	2.38	N/A	3	N/A	N/A	N/A	N/A	-	-	358.81	-	356.44	N/A	N/A	N/A	N/A
	s7 gage	8/9/2007	2.44	N/A	3	N/A	N/A	N/A	N/A	-	-	360.62	-	358.18	N/A	N/A	N/A	N/A
	tc gage	8/9/2007	2.69	N/A	3	N/A	N/A	N/A	N/A	593434.78	1108775.68	329.87	326.87	327.18	N/A	N/A	N/A	N/A
Other	City TC piezo	7/31/2007	10.17	6.17	4	17	17	12	17	593280.88	1108599.37	336.59	332.59	322.09	319.59	324.59	319.59	315.59
	City ntw	7/9/2007	164.94	163.14	1.8	251	251	195	225	591606.43	1100747.11	443.56	441.76	220.56	192.56	248.56	192.56	216.76
	City stw	7/13/2007	151.84	148.64	3.2	260	260	195	255	588320.47	1100170.69	457.75	454.55	230.25	197.75	262.75	197.75	199.55
	City wtw	7/13/2007	166.61	165.41	1.2	285	285	230	285	589658.31	1097182.44	455.79	454.59	198.29	170.79	225.79	170.79	169.59
	TH mw1	8/6/2007	20.01	20.31	-0.3	20.6	28	18	28	592770.99	1107381.10	348.14	348.44	325.14	320.14	330.14	327.54	320.44
	TH mw2	8/6/2007	22.84	23.14	-0.3	28	28	18	28	592865.49	1107741.43	350.76	351.06	327.76	322.76	332.76	322.76	323.06
	TH mw3	8/6/2007	0	0.30	-0.3	29.8	29.5	19.5	29.5	593363.47	1107331.62	361.41	361.71		331.91	341.91	331.61	332.21

Notes

1	dry on 8/9/07
2	Survey of Northing/Easting and Measuring Point by KPFF, August 2007
3	Gage measurements from top of 3-foot high gage down to water surface. 0 feet = mudline.
BMP	below measureing point
BGS	below ground surface
AGS	above ground surface
N/A	Not applicable

Table 2~~.~~ Summary of Soil Types Exposed in the Highlands (USDA, 1990; SCA, 2006)

Exposure	Series	Drainage-General	Permeability	Flooding Frequency & Water Table	Other
Major	Alderwood- gravelly sandy loam	moderately well drained	moderately rapid above hardpan	no flooding but seasonal high water table	15-50% slopes in Thurston Highlands; normally found on glacial till plains. Typical soil profile consists of gravelly sandy loam and weakly cemented hardpan.
	Everett- very gravelly sandy loam	**somewhat excessively drained**	**rapid**	**no flooding and deep water table**	**3-30% slopes in Thurston Highlands; normally found on terraces and outwash plains with sandy glacial outwash. According to a site soils investigation, this series frequently exhibited weakly-moderately indurated substratum with some cementations present (SCA, 2006).**
	Tenino- gravelly loam	**well drained**	**moderate above cemented horizon (not always present), very rapid below.**	**no flooding and deep water table**	**15-30% slopes in Thurston Highlands; normally found on terminal moraines in glacial till over glacial outwash. A weakly-cemented, strongly compacted horizon may occur. Depth to hardpan ranges from 25 to 40 inches. According to a site soils investigation, the hardpan was not observed in site soils (SCA, 2006).**
	Yelm- fine sandy loam	moderately well drained	moderately rapid	no flooding but seasonal high water table	3-15% slopes in Thurston Highlands; normally found on terraces in glacial outwash. According to a site soils investigation, this series sometimes exhibited indurated and cemented substratum soils more typical of Alderwood series (SCA, 2006).
Minor	**Indianola- loamy sand**	**somewhat excessively drained**	**rapid**	**no flooding and deep water table**	**15-30% slopes in Thurston Highlands; normally found on terraces, eskers, and kames with sandy glacial drift.**
	Mukilteo- muck	very poorly drained	moderate	no flooding but seasonal high water table	0-2% slopes in Thurston Highlands; generally found in upland depressions formed in organic material derived from sedges and generally found in the vicinity of wetlands.
	McKenna- gravelly silt loam	poorly drained	moderate above hardpan	no flooding but seasonal high water table	5% slopes in Thurston Highlands. generally found in depressions and drainage ways; formed in glacial drift
	Tisch- silt loam	well drained	moderately slow	rare flooding and seasonal high water table	0-3% slopes in Thurston Highlands; generally found in upland depressions and drainage ways.

Bold indicates soils most suitable for infiltration.

Table 3~~.~~ Geohydrologic Units in Northern Thurston County (Drost et al. 1998)

Age		Geologic Unit		Geohydrologic Unit	Typical Thickness (ft)	Lithologic Characteristics	Hydrologic Characteristics
Quaternary	Holocene	Alluvium		Qvr	10-50	Alluvial and deltaic sand and gravel along major water courses. Moderately to well-sorted glacial sand and gravel, including kettled end moraine.	An aquifer where saturated. Groundwater is mostly unconfined. Perched conditions occur locally.
	Pleistocene	Vashon Drift	Recessional outwash and end moraine				
			Till	Qvt	20-60	Unsorted sand, gravel, and boulders in a matrix of silt and clay.	Confining bed, but can yield usable amounts of water. Some thin lenses of clean sand and gravel.
			Advance outwash	Qva	15-35	Poorly to moderately well-sorted, well-rounded gravel in a matrix of sand with some sand lenses.	Groundwater mostly confined. Used extensively for public supplies.
Quaternary and Tertiary	Pleistocene, Miocene, Eocene	Older glacial and non-glacial deposits and ultimately sedimentary and igneous bedrock.					

Table 4~~.~~ Summary of Geologic Strata Encountered in this Study

Stratum	Lithology	Distribution	
Qvr	Sand & gravel	Prairie	Qvr is prevalent on Yelm prairie. Mapped in a small part of the study area on the east boundary. Piezometer P12 was installed on the west edge of the prairie in this material. Qvr has minor occurrence in the Highlands.
Qvm	Silt sand & gravel	Highlands	Qvm is mapped as prevalent in the Highlands. Qvm is treated as part of the Qvr geohydrologic unit in Drost (1998). Lithology varies laterally and with depth, characteristic of moraine deposits. Qvm may include reworked till material (as indicated by the Alderwood soils).
Qvt		Prairie & Highlands	Qvt is mapped (DGER, 2001) as prevalent between Highlands Qvm and prairie Qvr exposures. Mapped exposures at the Highlands are small (northeast and southeast corners of the site). Stratigraphically below the Qvr. Till encountered during field work at the Highlands suggests it is discontinuous and variable, and is a less dense than would be expected for a till deposited directly beneath former ice sheets and has similar lithology as some strata in the Qvm.
Qva	Sand & gravel	Prairie & Highlands	Qva is not mapped (DGER, 2001) as exposed at the Highlands but logged at depth during the drilling. Stratigraphically below Qvr, Qvm and Qvt.
Qc Pre Vashon	Variable	Prairie & Highlands	Stratigraphically below Qva. Upper strata silts and clays (Kitsap Formation). Not evaluated in this study.

Note: Shaded cells indicate aquitard characteristics.

Table 5 Calibrated Values for Hydraulic Conductivity (Kh/Kv, feet/day)

		Layer							
	Thompson Creek[1]	1 (Qvr)	2 (Qvt)	3 (Qva)	3 (Qva-High Hydraulic Conductivity Zone)	4 (Qf)	5 (Qc)	6 (TQu-1)	7 & 8 (Tqu-7 & 8)
Calibration Value	0.5 or 1	485/121	5/0.005	300/75	2000/200	1/0.006	47/4.7	1/0.007	75/0.03
Olympia Model	N/A	100/25	1/0.005	70/70	N/A	1/0.0025	47/4.7	1/0.0025	75/0.03

[1] Thompson Creek values are for parameter Kriv (stream bed permeability). A value of 0.5 was used in headwaters areas and where the creek discharges to the Nisqually (segment 13). A value of 1 was used elsewhere in prairie areas. Kriv is a model parameter included in the stream bed conductance term and was used as a calibration parameter and is not directly comparable to aquifer Kv.

[2] N/A means not applicable (the Olympia Model did not account for the High Transmissivity Zone in the Qva beneath the Yelm Prairie)

~~Table 5~~Table 6~~.~~ Land Cover/ Geology Types Represented in the UGA

Type	Land Cover	Geology
A	undeveloped forest	till
B	undeveloped pasture	till
C	undeveloped forest	outwash
D	undeveloped pasture	outwash
E	lawn	till
F	lawn	outwash
G	100% impervious	not relevant

~~Table 6~~Table 7~~.~~ Twelve Combinations of Land Cover/ Geology Types Represented in the UGA

Combination	Type	% Impervi-ous	Land Cover	Geology
1	A	0	undeveloped forest	till
2	B	0	undeveloped pasture	till
3	C	0	undeveloped forest	outwash
4	D	0	undeveloped pasture	outwash
5	Proportions of E & G	90	developed impervious & lawn-like cover	till
6	Proportions of E & G	75	developed impervious & lawn-like cover	till
7	Proportions of E & G	25	developed impervious & lawn-like cover	till
8	Proportions of E & G	5	developed impervious & lawn-like cover	till
9	Proportions of F & G	90	developed impervious & lawn-like cover	outwash
10	Proportions of F & G	75	developed impervious & lawn-like cover	outwash
11	Proportions of F & G	25	developed impervious & lawn-like cover	outwash
12	Proportions of F & G	5	developed impervious & lawn-like cover	outwash

~~Table 7~~Table 8~~.~~ Recharge Rate Estimates for Land Cover/ Geology Conditions in the UGA (ft/day)

			Developed Conditions Recharge			
Geology	Forest	Pasture	90% impervious	75% impervious	25% impervious	5% impervious
Till	0.00496	0.00527	0.00759	0.00730	0.00634	0.00595
Outwash	0.00492	0.00526	0.00759	0.00732	0.00640	0.00603

~~Table 8~~Table 9~~.~~ Calculated Recharge Estimates for UGA Zoning

	Land Use					
	Undeveloped		Developed		Derived Land-use Weighted Recharge (ft/d)	
Zoning	% Forest	% Pasture	% Lawn-like	% Impervious	Till	Outwash
Arterial commercial			10%	90%	0.00759	0.00759
Central business district			10%	90%	0.00759	0.00759
Commercial zone			25%	75%	0.00730	0.00732
Heavy Commercial zone			25%	75%	0.00730	0.00732
High density residential			75%	25%	0.00634	0.00640
Industrial district			25%	75%	0.00730	0.00732
Institutional district			25%	75%	0.00730	0.00732
Large lot commercial			25%	75%	0.00730	0.00732
Light industrial			25%	75%	0.00730	0.00732
Low density residential			95%	5%	0.00595	0.00603
Moderate density residential			75%	25%	0.00634	0.00640
Parks	50%	50%			0.00511	0.00509
Rural residential			95%	5%	0.00595	0.00603
Service commercial			25%	75%	0.00730	0.00732
Master planned community			75%	25%	0.00634	0.00640

~~Table 9~~Table 10~~.~~ Observed and Simulated Heads for the Calibrated Model

				Simulated Heads (feet)		Observed Groundwater Elevations (feet)	
Well	**Layer**	**Target Head Elevations (feet)**		**Elevation**	**Residual**	**Minimum**	**Maximum**
citytw1	6 (Tqu-1)	274	max observed	280.6	-6.6	251	274
mw1	1 (Qvr)	332	max observed	346.6	-14.6	327	332
mw2	1 (Qvr)	332	max observed	336.1	-4.1	327	332
ntw	5 (Qc)	279	max observed	286.1	-7.1	261	279
p11	5 (Qc)	266	APIH max 1981	278.6	-12.6	263	267
p12	1 (Qvr)	320	APIH max 1981	327.1	-7.1	313	321
p16	1 (Qvr)	349	max observed	351.8	-2.8	342	349
p17	3 (Qva)	314	max observed	322.2	-8.2	309	314
p19	1 (Qvr)	328	max observed	328.4	-0.40	321	328
p2	1 (Qvr)	326	max observed	314.2	11.8	318	326
p20	1 (Qvr)	325	APIH max 1981	332.0	-7.0	317	327
p3	1 (Qvr)	348	APIH max 1981	335.3	12.7	346	348
p4	3 (Qva)	321	max observed	329.6	-8.6	318	321
p6	1 (Qvr)	422	APIH max 1981	410.7	11.3	425	429
stw	5 (Qc)	306	max observed	297.6	8.4	295	306
TCMW	1 (Qvr)	333	APIH max 1981	329.2	3.8	326	330
wtw	5 (Qc)	290	max observed	292.7	-2.7	264	290

Note: Anticedent Precipitation Index for Heads (APIH) were generally used as head target elevations when sufficent field data existed and is intended to be representative of average wet season conditions. If the calculated APIH values were suspect (small record, eratic record, or uncertainties with the data), maximum observed groundwater elevations were used for head targets.

		Target Heads (feet)		Simulated Heads (feet)		Observed Groundwater Elevations (feet)		
Well	**Layer**	**Elevation**	**Type**	**Elevation**	**Residual**	**Maximum**	**Minimum**	**28-Jan-08**
p3	1 (Qvr)	346.73	APIH max 1981	340.89	5.84	348	346	347
p2	1 (Qvr)	321.02	APIH max 1981	329.55	-8.53	324	318	321
p6	1 (Qvr)	426.40	APIH max 1981	421.09	5.31	428	425	427
p11	5 (Qc)	261.79	APIH max 1981	261.82	-0.03	267	264	264
~~TCMW~~	~~1 (Qvr)~~	~~330.12~~	~~APIH max 1981~~	~~328.11~~	~~2.01~~	~~334~~	~~330~~	~~330~~
ntw	5 (Qc)	278.78	max observed	273.04	5.74	279	261	276
stw	5 (Qc)	305.82	max observed	287.04	18.78	306	295	303
wtw	5 (Qc)	289.64	max observed	284.87	4.77	290	264	285
citytw1	6 (Tqu-1)	273.64	max observed	274.08	-0.44	274	130	271
mw1	2 (Qvt)	332.13	max observed	339.22	-7.09	332	327	332
mw2	2 (Qvt)	332.25	max observed	338.67	-6.42	332	327	332

~~Table 10. Calibrated Values for Hydraulic Conductivity (Kh/Kv, feet/day)~~

		Layer							
	Thompson Creek[1]	**1 (Qvr)**	**2 (Qvt)**	**3 (Qva)**	**3 (Qva-High T Zone)**	**4 (Qf)**	**5 (Qc)**	**6 (TQu-1)**	**7 & 8 (Tqu-7 & 8)**
Calibration Value	0.5 or 1	485/121	5/0.005	300/75	3000/300	1/0.004	47/4.7	1/0.007	75/0.03
~~Olympia Model~~	~~N/A~~	~~100/25~~	~~1/0.005~~	~~70/70~~	~~N/A~~	~~1/0.0025~~	~~47/4.7~~	~~1/0.0025~~	~~75/0.03~~

[1] Thompson Creek values are for parameter Kriv (stream bed permeability). A value of 0.5 was used in headwaters areas and where the creek discharges to the Nisqually (segment 13). A value of 1 was used elsewhere in prairie areas. Kriv is a model parameter included in the stream bed conductance term and was used as a calibration parameter and is not directly comparable to aquifer Kv.

Table 11. Summary of Modeling Scenarios

		Thurston Highlands				Tahoma Terra		Other UGA		Far Field
Scenario		Existing	Ph. 1	Full	1.5 MGD	Existing	Full	Existing	Full	Existing
1	baseline	x				x		x		x
2	a		x			x		x		x
	b		x		x	x		x		x
	c		x				x	x		x
3	a			x			x	x		x
	b			x	x		x	x		x
4	a			x			x		x	x
	b			x	x		x		x	x

Table 12a~~.~~ Summary of Modeling Results (Change in Recharge & Creek Flow).

Scenario[8]			WY[5]	Annualized[4] Delta[9] Recharge (mgd[6])	Annualized[4] Delta[9] Creek Flow (mgd[6])	Source[1]	Percent of Delta[9] Recharge Occuring in Thompson Creek[7]
2	a	TH: ph 1	1981	0.20	< 0.057	DEIS[2]	<28%
			1997	0.24	<0.064	DEIS[2]	<27%
	b	TH : ph1+1.5 mgd	1981	1.7	0.21	FEIS[3]	12%
			1997	1.7	0.21	FEIS[3]	12%
	c	TH: ph1; TT: full	1981	0.27	<0.10	DEIS[2]	<38%
			1997	0.32	<0.12	DEIS[2]	<38%
3	a	TH: full; TT: full	1981	0.73	0.19	FEIS[3]	26%
			1997	0.84	0.22	FEIS[3]	27%
	b	TH: full; TT: full+ 1.5 mgd	1981	2.2	0.34	FEIS[3]	15%
			1997	2.3	0.37	FEIS[3]	16%
4	a	TH, TT, UGA: full	1981	1.2	<0.33	DEIS[2]	<28%
			1997	1.4	<0.39	DEIS[2]	<28%
	b	TH, TT, UGA: full+1.5 mgd	1981	2.7	0.45	FEIS[3]	17%
			1997	2.9	0.51	FEIS[3]	18%

NOTES:

1 If delta creek flow for WY 1997 for the original DEIS simulation differed by more than 10% from the WY 1997 simulation done in September 2008 for the FEIS, then both the WY 1981 and 1997 simulations were redone and FEIS values are reported. If the difference in the WY 1997 simulations was 10% or less, the DEIS results for both water years were considered sufficiently accurate.

2 Results in this row from PGG (May 2008) DEIS. ModFlow run 102. "<" means "less than or equal to". September 2008 simulations for the FEIS indicate that values reported in the DEIS are sufficiently accurate in these cases and that DEIS aquifer flux estimates are high ("conservative").

3 Results in this row are from September 2008 Modflow model run 11 v.2 for the FEIS.

4 "Annualized" means average over entire modeled area and whole water year (WY) & includes injection of 1.5 mgd reclaimed water for "b" cases.

5 1981= median precipitation water year, 1997=wettest precipitation water year.

6 Results above were converted from cubic feet in a given year to mgd to facilitate comparisons

7 Thompson Creek usually does not flow all the way to the Nisqually River. In WY 2008 to date, the creek was observed to flow beneath Highway 510 during two few-day periods: early February and mid March. Delta recharge to Thompson Creek (last column) assumes year-round flow to the Nisqually River and to the extent that the creek does not actually flow all the way to the Nisqually, actual increased discharge to the creek will be less. The delta recharge to Thompson Creek is intended to represent a conservative maximum.

8	ph 1	Phase 1 of Thurston Highlands development concept
	TH:	Thurston Highlands
	TT	Tahoma Terra
	UGA	City of Yelm Urban Growth Area
	mgd	million gallons per day
9	Delta	Reported values are not "absolute" values. Delta (or change) is calculated by subtracting the develpement case from the steady-state case. Annualized average recharge with existing conditions is approximately 2 mgd.

Scenario			WY	Annualized Delta Recharge (mgd)	Annualized Delta Creek Flow (mgd)	Delta Recharge to Thompson Creek (per cent of delta recharge)
2	a	TH: ph 1	1981	0.20	0.057	28%
			1997	0.24	0.064	27%
	b	TH : ph1+1.5 mgd	1981	1.7	0.50	29%
			1997	1.7	0.51	29%
	c	Th: ph1; TT: full	1981	0.27	0.10	37%
			1997	0.32	0.12	37%
3	a	TH: full; TT: full	1981	0.73	0.24	32%
			1997	0.84	0.28	33%
	b	TH: full; TT: full+ 1.5 mgd	1981	2.2	0.70	31%
			1997	2.3	0.74	32%
4	a	TH, TT, UGA: full	1981	1.2	0.33	28%
			1997	1.4	0.39	28%
	b	TH, TT, UGA: full+1.5 mgd	1981	2.7	0.80	30%
			1997	2.9	0.86	30%

Notes:

1 Average over entire modeled area and whole water year (WY) & includes injection of 1.5 mgd reclaimed water for "b" cases.

2 1981: representative median precipitation year, 1997 representative wettest precipitation year.

3 Results above were converted from cubic feet in a given year to mgd to facilitate comparisons

4 Thompson Creek usually does not flow all the way to the Nisqually River. In WY 2008 to date, the creek was observed to flow beneath Highway 510 during two few-day periods: early February and mid March. Delta recharge to Thompson Creek (last column) assumes year-round flow to the Nisqually River and to the extent that the creek does not actually flow all the way to the Nisqually, actual increased discharge to the creek will be less. The delta recharge to Thompson Creek is intended to represent a conservative maximum.

5

ph 1	Phase 1 of Thurston Highlands development concept
TH:	Thurston Highlands
TT	Tahoma Terra
UGA	City of Yelm Urban Growth Area
mgd	flow of million gallons per day

Table 12b Summary of Modeling Results (Most Affected Creek Segments)

Scenario[6]			WY[5]	Most Affected Segments[1]
2	a	TH: ph 1[2,4]	1981	6
				4
				10
				3
				8
				14
				7
			1997	6
				4
				3
				10
				8
				7
	b	TH : ph1+1.5 mgd[3]	1981	6
				10
				5
				4
				7
				3
				8
				11
				14
			1997	6
				5
				10
				4
				7
				3
				8
				11
	c	Th: ph1; TT: full[2,4]	1981	10
				6
				4
				3
				8
			1997	10
				6
				4
				3
				8
3	a	TH: full; TT: full[3]	1981	10
				5
				6
				4
				3
				2
			1997	10
				5
				6
				4
				3
				2
				1
	b	TH: full; TT: full+ 1.5 mgd[3]	1981	10
				5
				6
				4
				3
				7
				1
				11
			1997	10
				5
				6
				4
				3
				7
				1
				11

Scenario[6]			WY[5]	Most Affected Segments[1]
4	a	TH, TT, UGA: full[2,4]	1981	6
				10
				5
				3
				4
				11
				7
				1
			1997	6
				10
				5
				3
				4
				11
				7
				1
	b	TH, TT, UGA: full+1.5 mgd[3]	1981	10
				5
				6
				4
				3
				11
				7
				8
			1997	10
				6
				5
				4
				11
				3
				7
				8

Notes:
1 The segments receiving 85% of total annual increase in groundwater flux. Ranked highest to lowest.
All listed segments are gaining (receiving groundwater flux from aquifer).
2 Results from PGG (May 2008) DEIS. ModFlow run 102.
September simulations for the FEIS indicate that values reported in the DEIS are sufficiently accurate
and the DEIS simulations suggest aquifer flux estimates are high ("conservative").
3 Results incorporating September 2008 Modflow model run 11 v.2 for the FEIS.
4 If delta creek flow for WY 1997 for the original DEIS simulation differed by more than 10% from the WY 1997 simulation
done in September 2008 for the FEIS, then both the WY 1981 and 1997 simulations were redone and FEIS values are reported.
If the difference in the WY 1997 simulations was 10% or less, the DEIS results for both water years were considered sufficiently accurate.
5 1981: representative median precipitation water year, 1997 representative wettest precipitation water year.
6 ph 1 Phase 1 of Thurston Highlands development concept
TH: Thurston Highlands
TT Tahoma Terra
UGA City of Yelm Urban Growth Area
mgd flow of million gallons per day

~~Table 12b. Summary of Modeling Results (Most Affected Creek Segments)~~

Scenario			WY	Most Affected Segments[1]
2	a	TH: ph 1	1981	6
				4
				10
				3
				8
				14
				7
			1997	6
				4
				3
				10
				8
				7
	b	TH : ph1+1.5 mgd	1981	6
				5
				4
				3
				7
				1
			1997	6
				5
				4
				3
				7
				1
	c	Th: ph1; TT: full	1981	10
				6
				4
				3
				8
			1997	10
				6
				4
				3
				8
3	a	TH: full; TT: full	1981	6
				10
				5
				4
				3
				1
			1997	6
				10
				5
				4
				3
				1
	b	TH: full; TT: full+ 1.5 mgd	1981	6
				5
				4
				3
				10
				1
			1997	5
				6
				4
				10
				3
				1
4	a	TH, TT, UGA: full	1981	6
				10
				5
				3
				4
				11
				7
				1
			1997	6
				10
				5
				3
				4
				11
				7
				1
	b	TH, TT, UGA: full+1.5 mgd	1981	6
				5
				4
				3
				10
				7
				1
			1997	6
				5
				4
				3
				10
				7
				1

Notes: 1 The segments receiving 85% of total annual increase in groundwater flux.
Ranked highest to lowest.
All listed segments are gaining (receiving groundwater flux from aquifer).

Table 13~~.~~ Estimate of Effects of Raising Groundwater Levels on Extents of High Groundwater Hazard Areas (HGHA, Creek Segment 10)

Modeled Increased Groundwater Elevation (feet)	Estimated Increase in HGHA (%)
0	0
0.5	30
1	50
1.5	70

Modeled Increased Groundwater Elevation (feet)	Estimated Increase in HGWHA (%)
0	0
0.5	30
1	50
1.5	70

INSERT APPENDICES