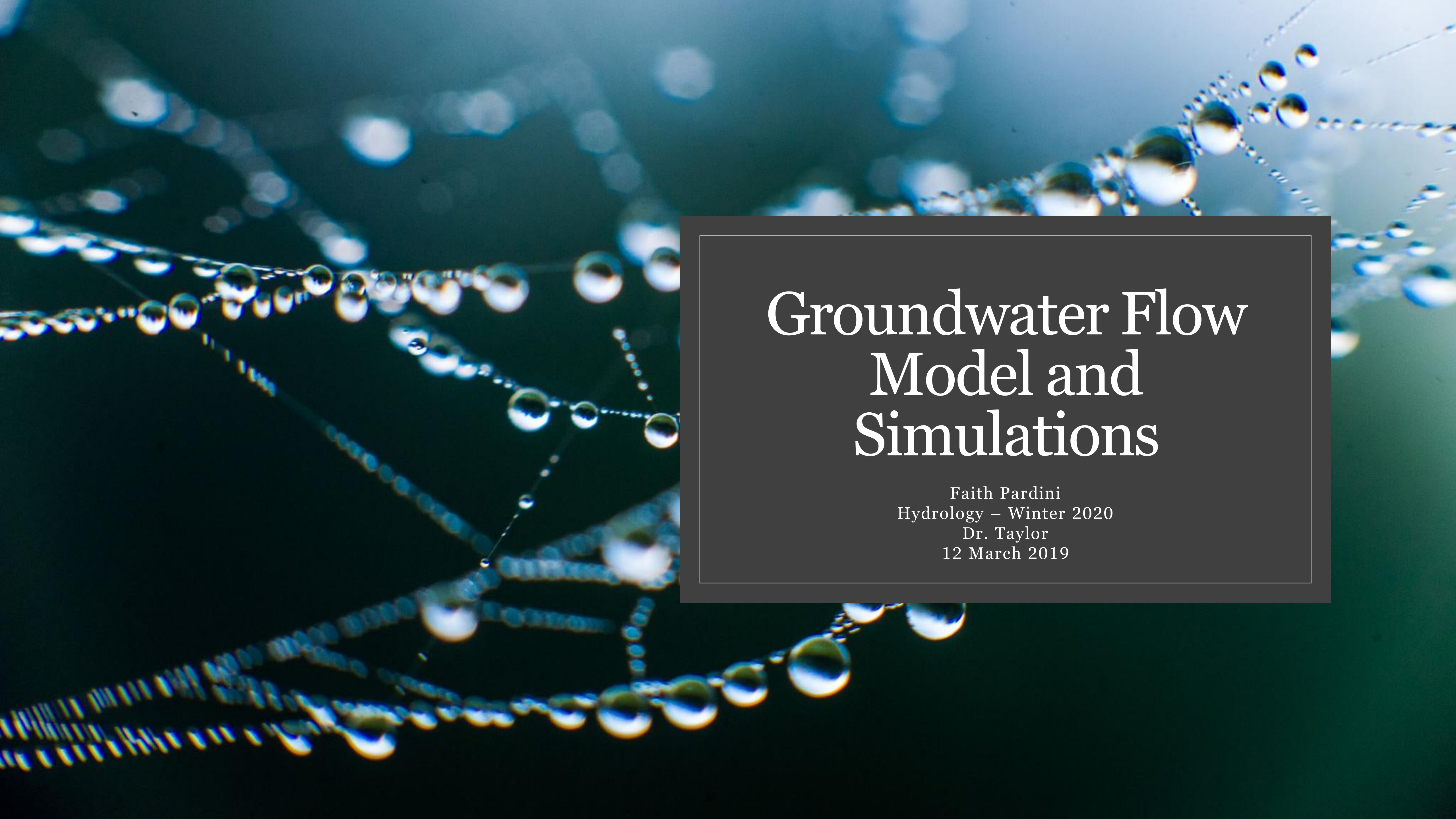

Groundwater Flow Model and Simulations

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Overview

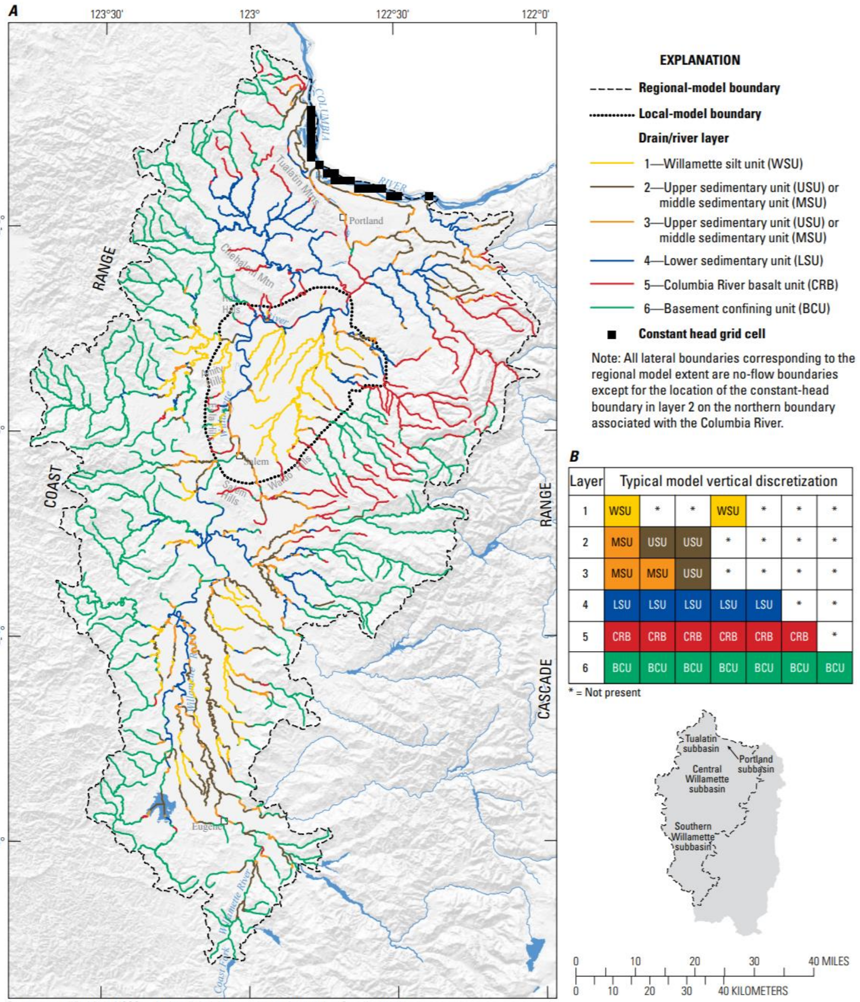
- Purpose and scope of the models
- Description of the models
  - Regional
  - Local
  - Parameters
- Simulations
  - Regional
  - Local
  - Takeaways
- What simulations reveal about the Willamette Basin Aquifer System

Purpose and Scope of Models

- Simulated pumping scenarios were designed to represent:
  - pre-development conditions,
  - full use of current groundwater rights, and
  - possible increases in groundwater pumping
- Simulations report the resultant changes in groundwater flow under specified conditions.

- Two areas were simulated:
  - A regional, steady state model was developed to test:
    - the conceptional understanding of regional groundwater flow and its interaction with streams, and
    - evaluate the steady-state response of the groundwater system under current and future conditions.
  - A local, transient model of the Central Willamette subbasin was developed to show:
    - changes in the amount and timing of water-level fluctuations in the basin-fill sediments and
    - changes in groundwater discharge to streams induced by seasonal variations

Description of the Models



Note: All lateral boundaries corresponding to the regional model extent are no-flow boundaries except for the location of the constant-head boundary in layer 2 on the northern boundary associated with the Columbia River.

Layer	Typical model vertical discretization						
1	WSU	*	*	WSU	*	*	*
2	MSU	USU	USU	*	*	*	*
3	MSU	MSU	USU	*	*	*	*
4	LSU	LSU	LSU	LSU	LSU	*	*
5	CRB	CRB	CRB	CRB	CRB	CRB	*
6	BCU	BCU	BCU	BCU	BCU	BCU	BCU

* = Not present

Base map modified from USGS and other digital data sources, various scales. Coordinate system: UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 4. (*A*) Locations of constant head, river, and drain cells, boundary conditions, and (*B*) typical vertical configurations of hydrogeologic units in model layers, Willamette Basin, Oregon. Stream reaches, simulated using river and drain cells, are color coded by layer and hydrogeologic unit. Gaps in the vertical configuration are simulated using thin pseudo-cells that easily transmit water in the vertical direction.

General Information on Model

- Numeric flow models were developed for both models to simulate the effect of changes in groundwater pumping on water levels, groundwater flow, and surface-water flow in the Willamette Basin.
- Numerical models used for development of the flow models:
  - MODFLOW-2000 (USGS modular, 3D, finite-difference groundwater flow model)
- Sensitivity processes defined by Hill and others, 2000
- Parameter estimation processes defined by Hill and others, 2000

These numerical models were used to determine water levels, calculate model sensitivity, calibrate the model, and obtain missing parameter values

PARAMETERS

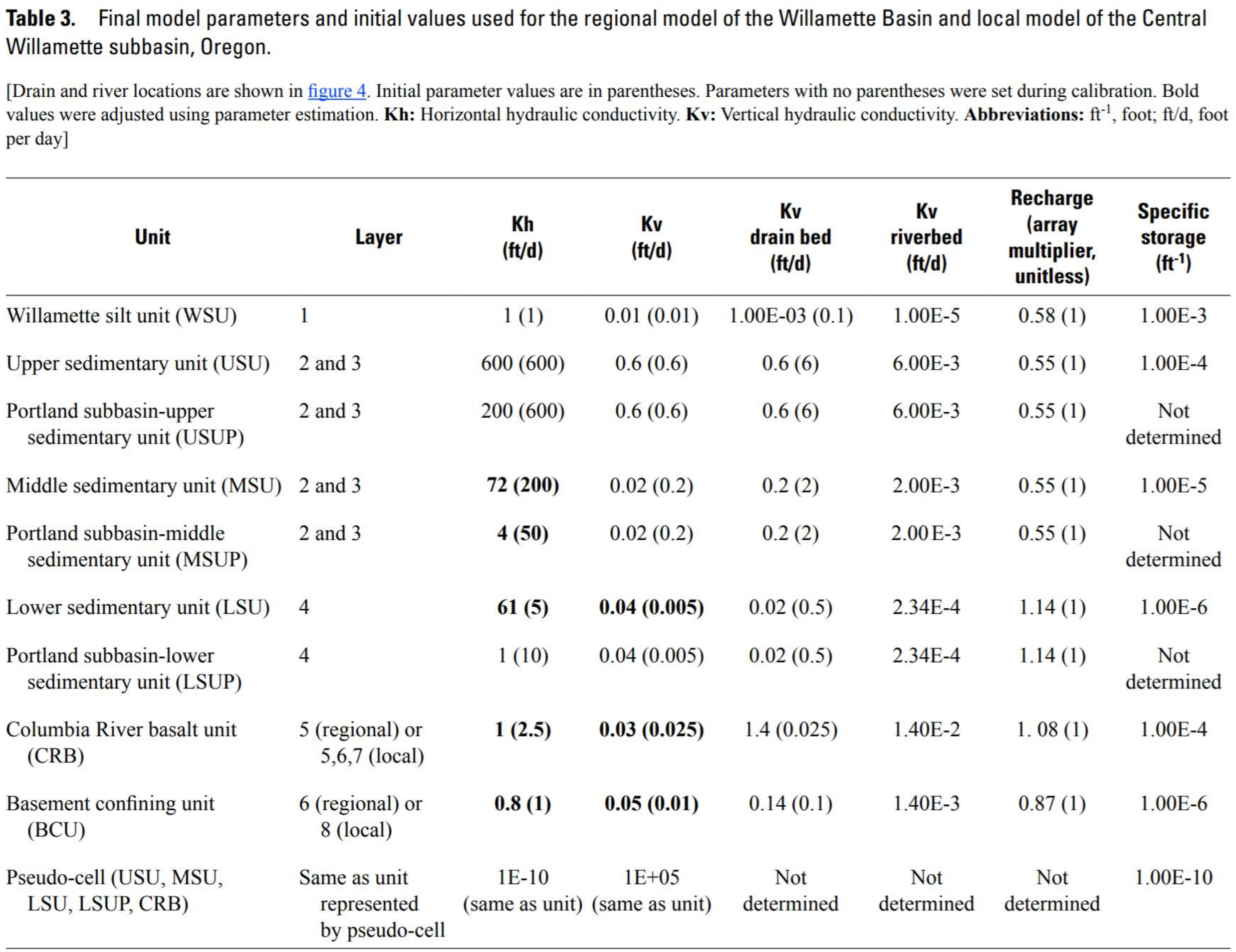


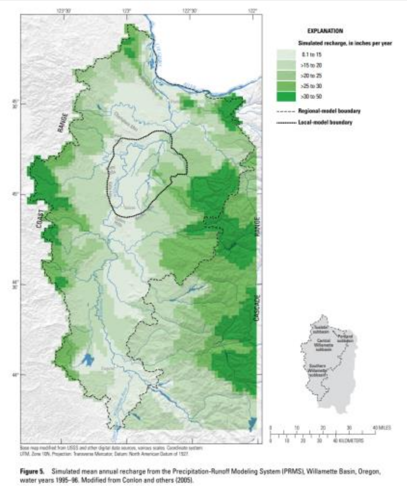
Table 3. Final model parameters and initial values used for the regional model of the Willamette Basin and local model of the Central Willamette subbasin, Oregon.

[Drain and river locations are shown in figure 4. Initial parameter values are in parentheses. Parameters with no parentheses were set during calibration. Bold values were adjusted using parameter estimation. **Kh:** Horizontal hydraulic conductivity. **Kv:** Vertical hydraulic conductivity. **Abbreviations:** ft^{-1}, foot; ft/d, foot per day]

Unit	Layer	Kh (ft/d)	Kv (ft/d)	Kv drain bed (ft/d)	Kv riverbed (ft/d)	Recharge (array multiplier, unitless)	Specific storage (ft^{-1})
Willamette silt unit (WSU)	1	1 (1)	0.01 (0.01)	1.00E-03 (0.1)	1.00E-5	0.58 (1)	1.00E-3
Upper sedimentary unit (USU)	2 and 3	600 (600)	0.6 (0.6)	0.6 (6)	6.00E-3	0.55 (1)	1.00E-4
Portland subbasin-upper sedimentary unit (USUP)	2 and 3	200 (600)	0.6 (0.6)	0.6 (6)	6.00E-3	0.55 (1)	Not determined
Middle sedimentary unit (MSU)	2 and 3	**72 (200)**	0.02 (0.2)	0.2 (2)	2.00E-3	0.55 (1)	1.00E-5
Portland subbasin-middle sedimentary unit (MSUP)	2 and 3	**4 (50)**	0.02 (0.2)	0.2 (2)	2.00 E-3	0.55 (1)	Not determined
Lower sedimentary unit (LSU)	4	**61 (5)**	**0.04 (0.005)**	0.02 (0.5)	2.34E-4	1.14 (1)	1.00E-6
Portland subbasin-lower sedimentary unit (LSUP)	4	1 (10)	0.04 (0.005)	0.02 (0.5)	2.34E-4	1.14 (1)	Not determined
Columbia River basalt unit (CRB)	5 (regional) or 5,6,7 (local)	**1 (2.5)**	**0.03 (0.025)**	1.4 (0.025)	1.40E-2	1. 08 (1)	1.00E-4
Basement confining unit (BCU)	6 (regional) or 8 (local)	**0.8 (1)**	**0.05 (0.01)**	0.14 (0.1)	1.40E-3	0.87 (1)	1.00E-6
Pseudo-cell (USU, MSU, LSU, LSUP, CRB)	Same as unit represented by pseudo-cell	1E-10 (same as unit)	1E+05 (same as unit)	Not determined	Not determined	Not determined	1.00E-10

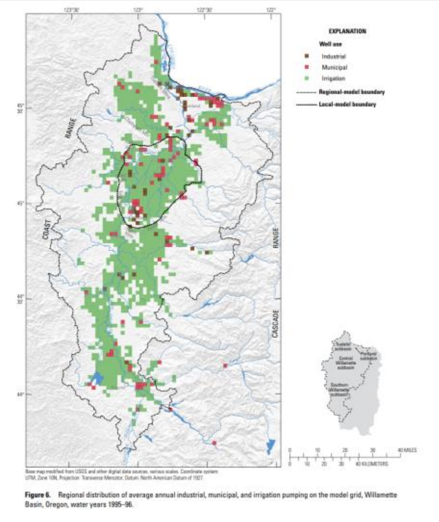
Regional Model

- Developed to simulate steady-state conditions in the Willamette Basin to test the conceptual model of groundwater flow and to understand the effects of pumping on surface water and groundwater
- Steady State: describes a system where there is no net change in hydraulic head.
- Average annual recharge and streamflow data from water years 1995-96 and water level data from that time were used to calibrate the model
- 7000x7000ft grid cells
  - 117 rows, 66 columns
- 6 layers for each of the hydrogeological units
  - WSU, USU, MSU, LSU, CRB, BCU
- 3 boundary types specified:
  - No-flux (geographic boundaries)
  - constant head (geographic boundaries)
  - specified flux (hydrologic process boundaries)
    - Recharge, leakage, pumping



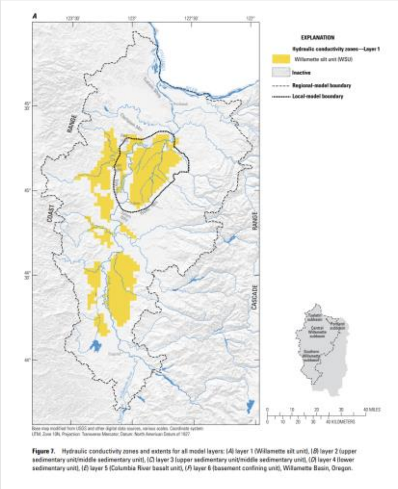
Base map modified from USGS and other digital data sources, various scales. Coordinate system UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 5. Simulated mean annual recharge from the Precipitation-Runoff Modeling System (PRMS), Willamette Basin, Oregon, water years 1995–96. Modified from Conlon and others (2005).



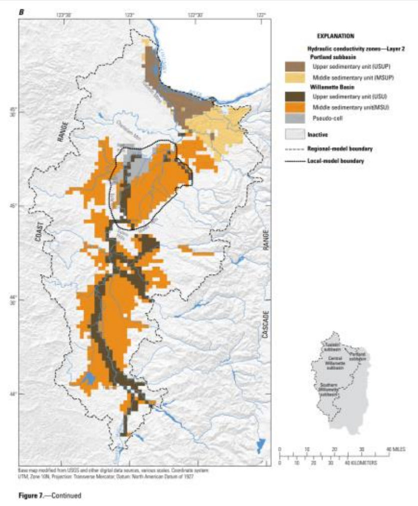
Base map modified from USGS and other digital data sources, various scales. Coordinate system UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 6. Regional distribution of average annual industrial, municipal, and irrigation pumping on the model grid, Willamette Basin, Oregon, water years 1995–96.



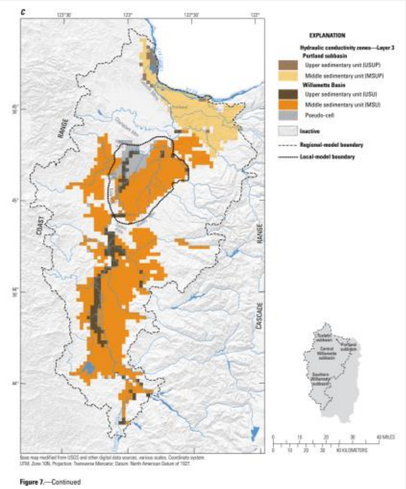
Base map modified from USGS and other digital data sources, various scales. Coordinate system UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 7. Hydraulic conductivity zones and extents for all model layers: (*A*) layer 1 (Willamette silt unit), (*B*) layer 2 (upper sedimentary unit/middle sedimentary unit), (*C*) layer 3 (upper sedimentary unit/middle sedimentary unit), (*D*) layer 4 (lower sedimentary unit), (*E*) layer 5 (Columbia River basalt unit), (*F*) layer 6 (basement confining unit), Willamette Basin, Oregon.



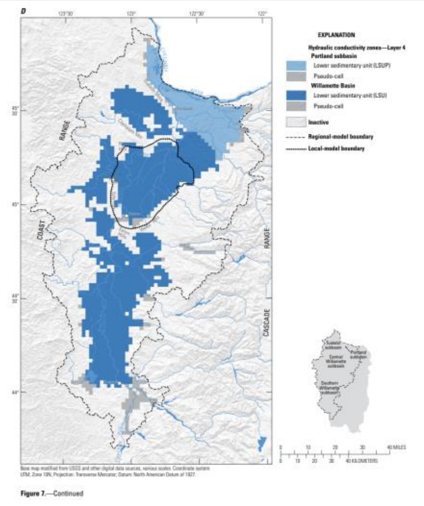
Base map modified from USGS and other digital data sources, various scales. Coordinate system UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 7.—Continued



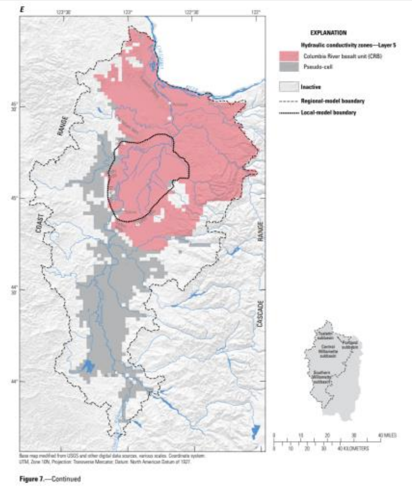
Base map modified from USGS and other digital data sources, various scales. Coordinate system UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 7.—Continued



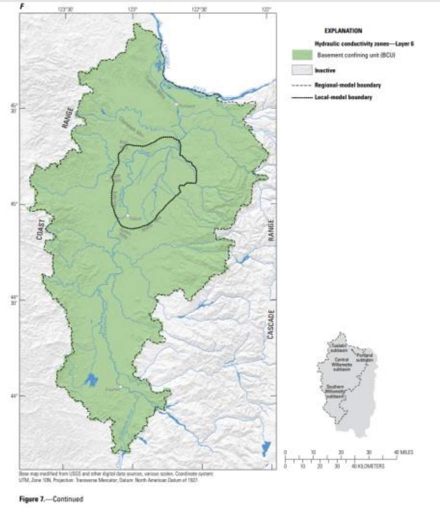
Base map modified from USGS and other digital data sources, various scales. Coordinate system UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 7.—Continued



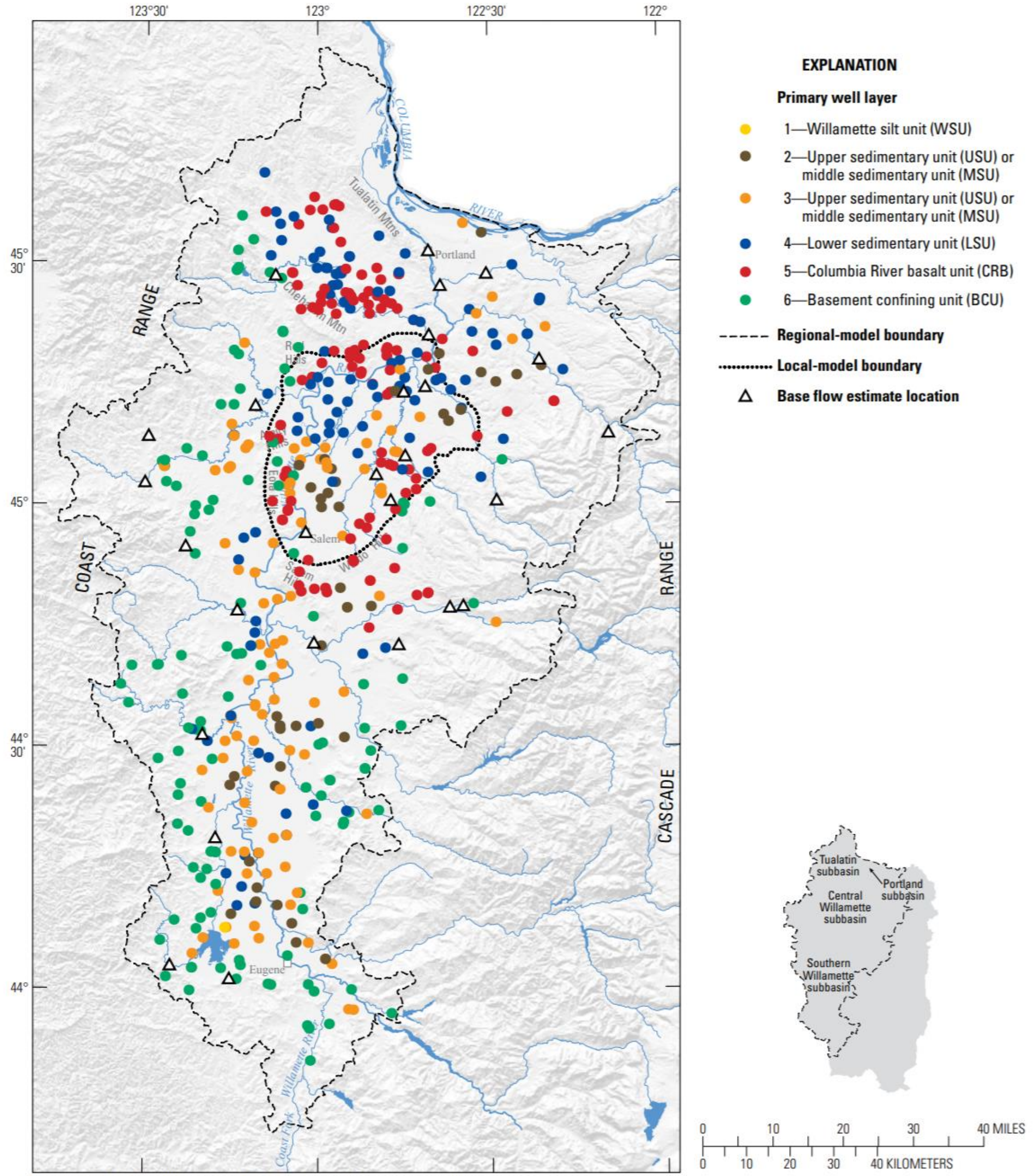
Base map modified from USGS and other digital data sources, various scales. Coordinate system UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 7.—Continued



Base map modified from USGS and other digital data sources, various scales. Coordinate system UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 7.—Continued



Base map modified from USGS and other digital data sources, various scales. Coordinate system: UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Regional Model

- Calibrated using water level measurements from 488 observation wells and 27 stream gaging stations
- To simulate the flow of water, CFC levels and MODMATH (a MODFLOW-2000 processor) were used to simulate the paths of 100 particles.

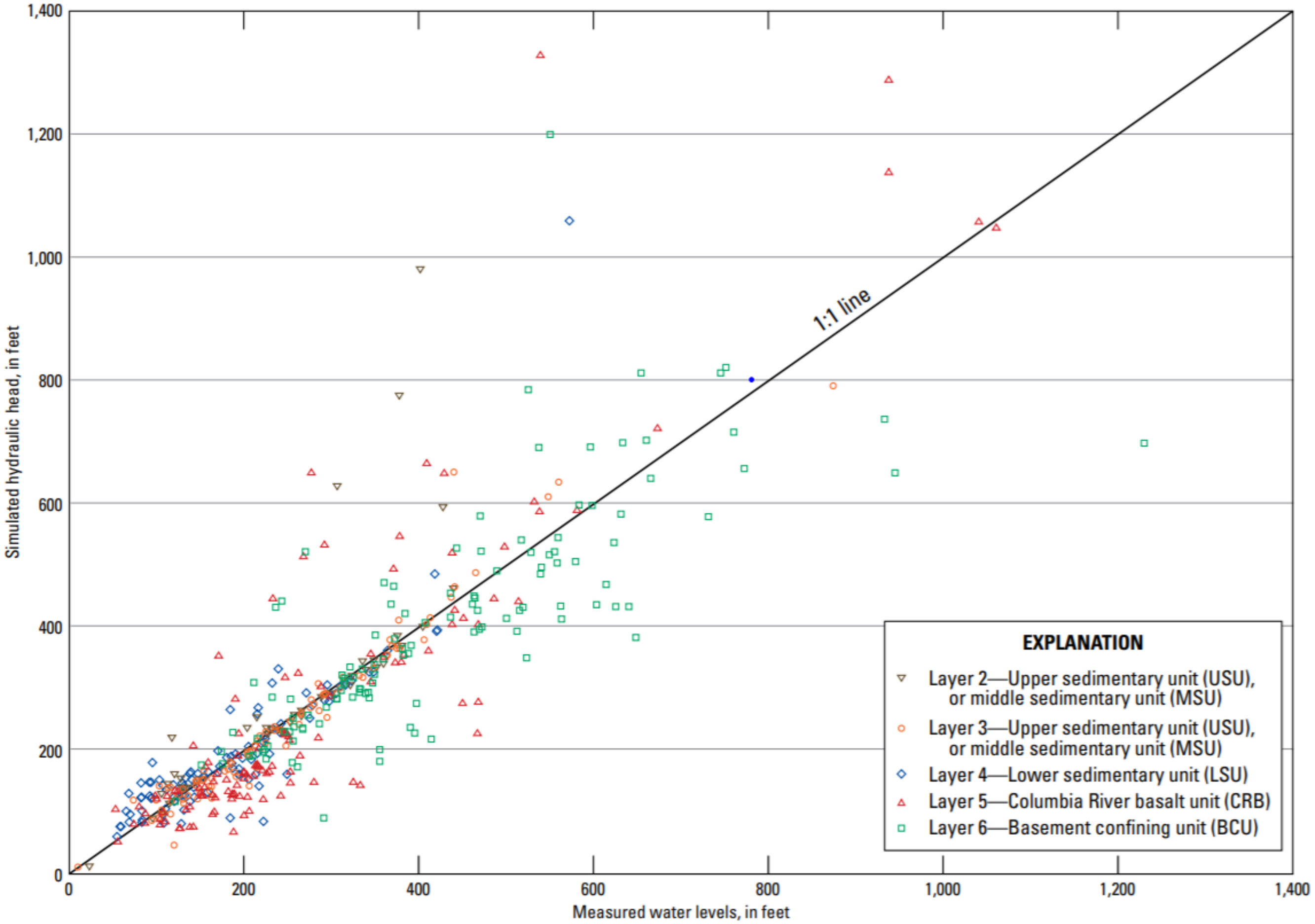


Figure 12. Comparison of simulated hydraulic head values with measured water levels for the regional steady-state model of the Willamette Basin, Oregon.

Regional Model Fit

Model fits well, though the model may not accurately simulate head variation over short distances because of the large cell size of the model

(Pumping effects are localized, not evident on regional model)

Local Model

- Chosen for the Central Willamette subbasin, where there is increasing demand for ware for agricultural and other uses.
- Summer streamflow is fully allocated in the subbasin, additional groundwater development is being considered to augment surface water conditions.
- 1000x1000ft grid cells
  - 177 rows, 164 columns
  - 8 layers
    - 1-4 the same as regional, 5-7 represent the CRB, 8 represents BCU
- Water years 1999-2000 were used to calibrate the model, divided into 24 stress periods to simulate monthly changes.
  - Specified flux is constant within each stress period.

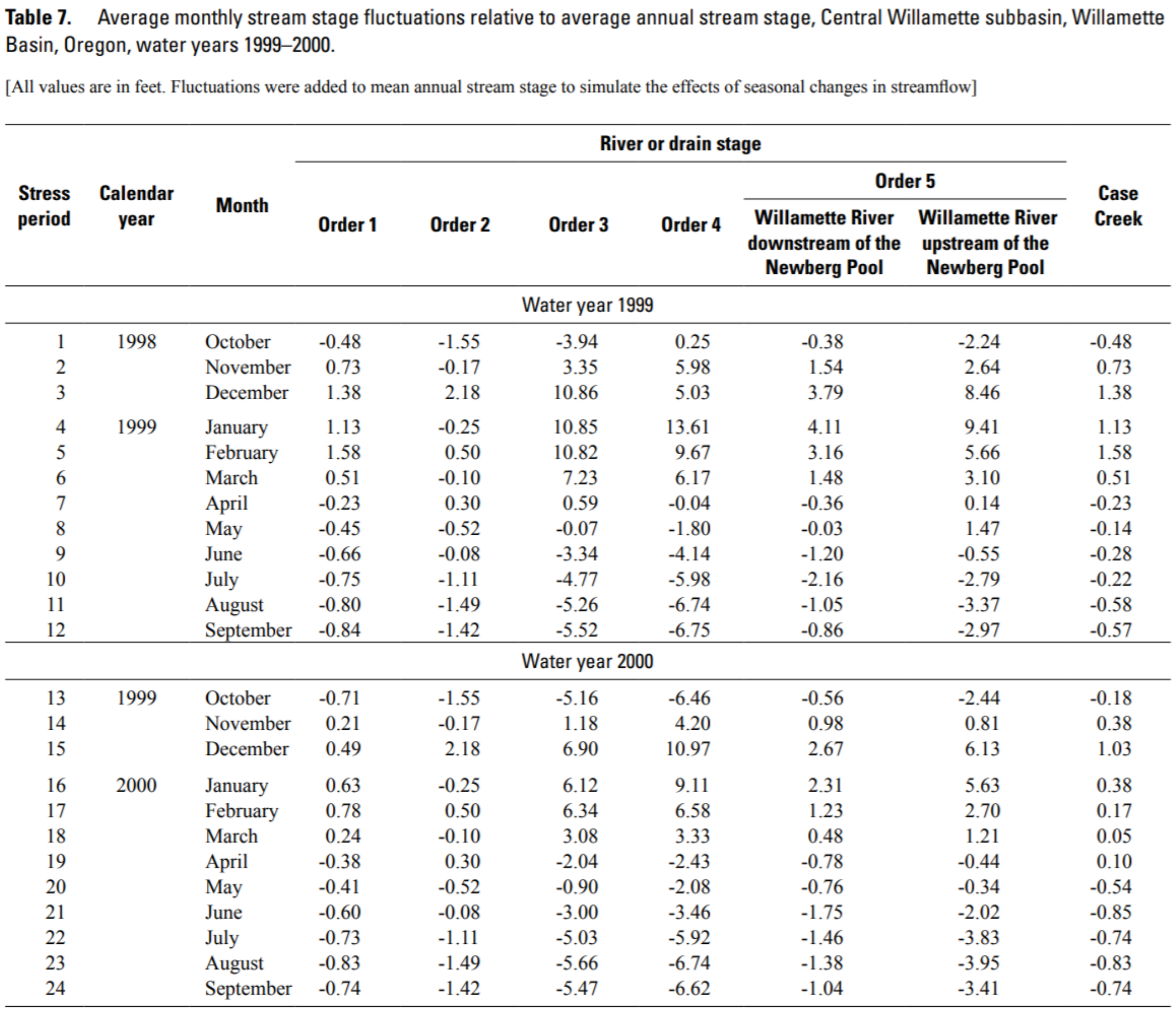


Table 7. Average monthly stream stage fluctuations relative to average annual stream stage, Central Willamette subbasin, Willamette Basin, Oregon, water years 1999–2000.

[All values are in feet. Fluctuations were added to mean annual stream stage to simulate the effects of seasonal changes in streamflow]

Stress period	Calendar year	Month	River or drain stage						Case Creek
			Order 1	Order 2	Order 3	Order 4	Order 5		
							Willamette River downstream of the Newberg Pool	Willamette River upstream of the Newberg Pool	
Water year 1999									
1	1998	October	-0.48	-1.55	-3.94	0.25	-0.38	-2.24	-0.48
2		November	0.73	-0.17	3.35	5.98	1.54	2.64	0.73
3		December	1.38	2.18	10.86	5.03	3.79	8.46	1.38
4	1999	January	1.13	-0.25	10.85	13.61	4.11	9.41	1.13
5		February	1.58	0.50	10.82	9.67	3.16	5.66	1.58
6		March	0.51	-0.10	7.23	6.17	1.48	3.10	0.51
7		April	-0.23	0.30	0.59	-0.04	-0.36	0.14	-0.23
8		May	-0.45	-0.52	-0.07	-1.80	-0.03	1.47	-0.14
9		June	-0.66	-0.08	-3.34	-4.14	-1.20	-0.55	-0.28
10		July	-0.75	-1.11	-4.77	-5.98	-2.16	-2.79	-0.22
11		August	-0.80	-1.49	-5.26	-6.74	-1.05	-3.37	-0.58
12		September	-0.84	-1.42	-5.52	-6.75	-0.86	-2.97	-0.57
Water year 2000									
13	1999	October	-0.71	-1.55	-5.16	-6.46	-0.56	-2.44	-0.18
14		November	0.21	-0.17	1.18	4.20	0.98	0.81	0.38
15		December	0.49	2.18	6.90	10.97	2.67	6.13	1.03
16	2000	January	0.63	-0.25	6.12	9.11	2.31	5.63	0.38
17		February	0.78	0.50	6.34	6.58	1.23	2.70	0.17
18		March	0.24	-0.10	3.08	3.33	0.48	1.21	0.05
19		April	-0.38	0.30	-2.04	-2.43	-0.78	-0.44	0.10
20		May	-0.41	-0.52	-0.90	-2.08	-0.76	-0.34	-0.54
21		June	-0.60	-0.08	-3.00	-3.46	-1.75	-2.02	-0.85
22		July	-0.73	-1.11	-5.03	-5.92	-1.46	-3.83	-0.74
23		August	-0.83	-1.49	-5.66	-6.74	-1.38	-3.95	-0.83
24		September	-0.74	-1.42	-5.47	-6.62	-1.04	-3.41	-0.74

Local Model

Average monthly stream flucuations

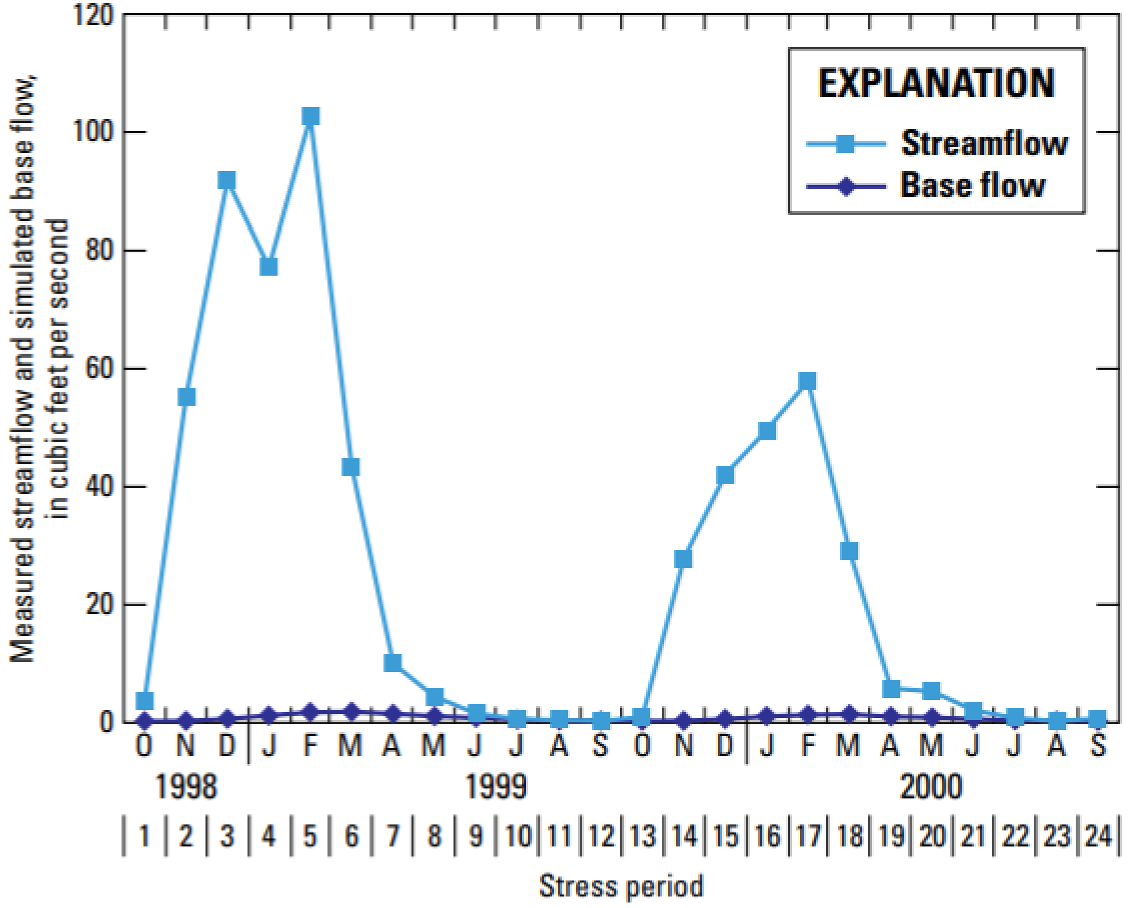


Figure 28. Monthly mean measured streamflow and simulated groundwater discharge (base flow) to Zollner Creek, Central Willamette subbasin, Oregon.

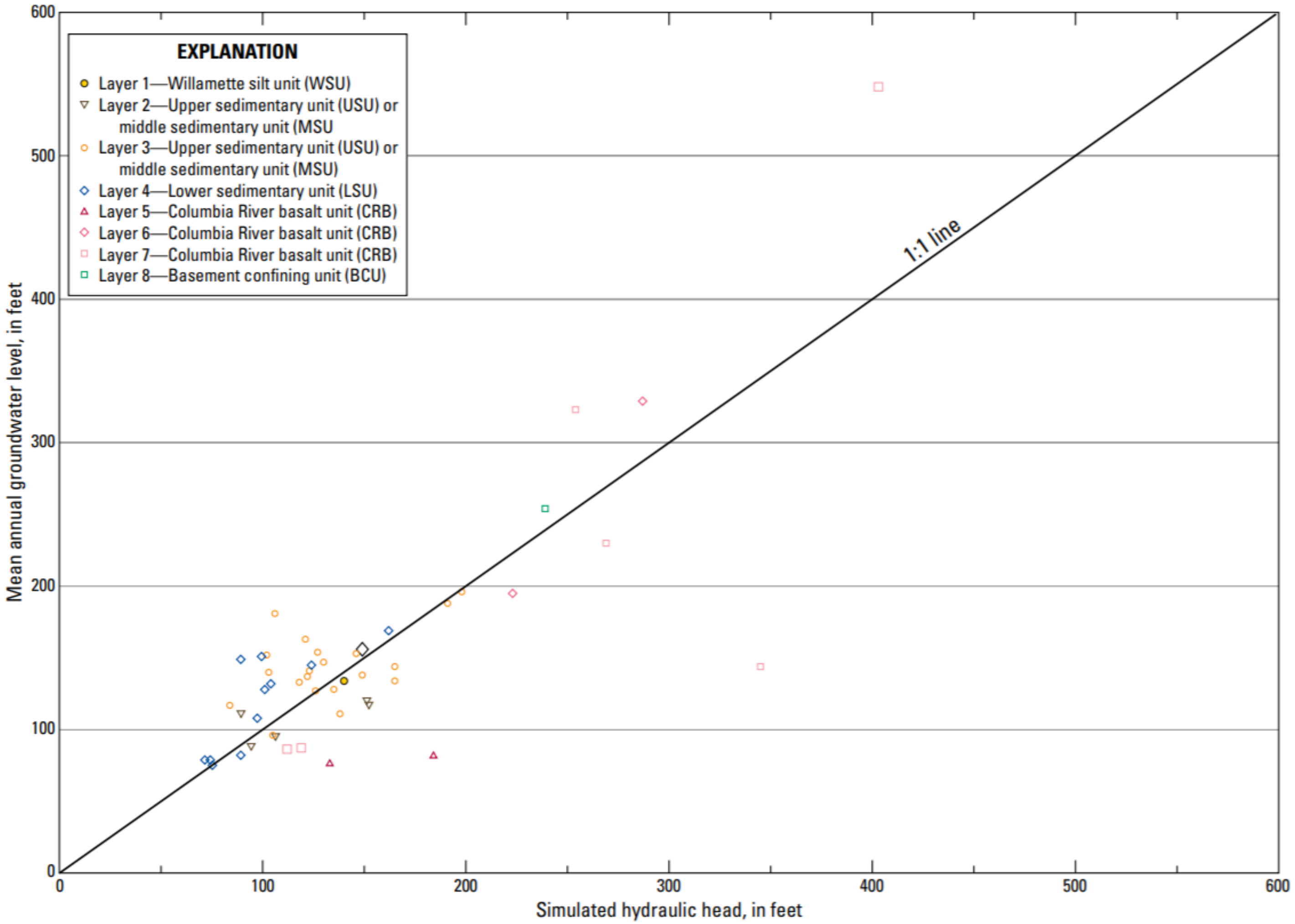


Figure 23. Simulated hydraulic head compared with mean annual groundwater levels for the local steady-state model, Central Willamette subbasin, Willamette Basin, Oregon.

Simulations

Regional Model

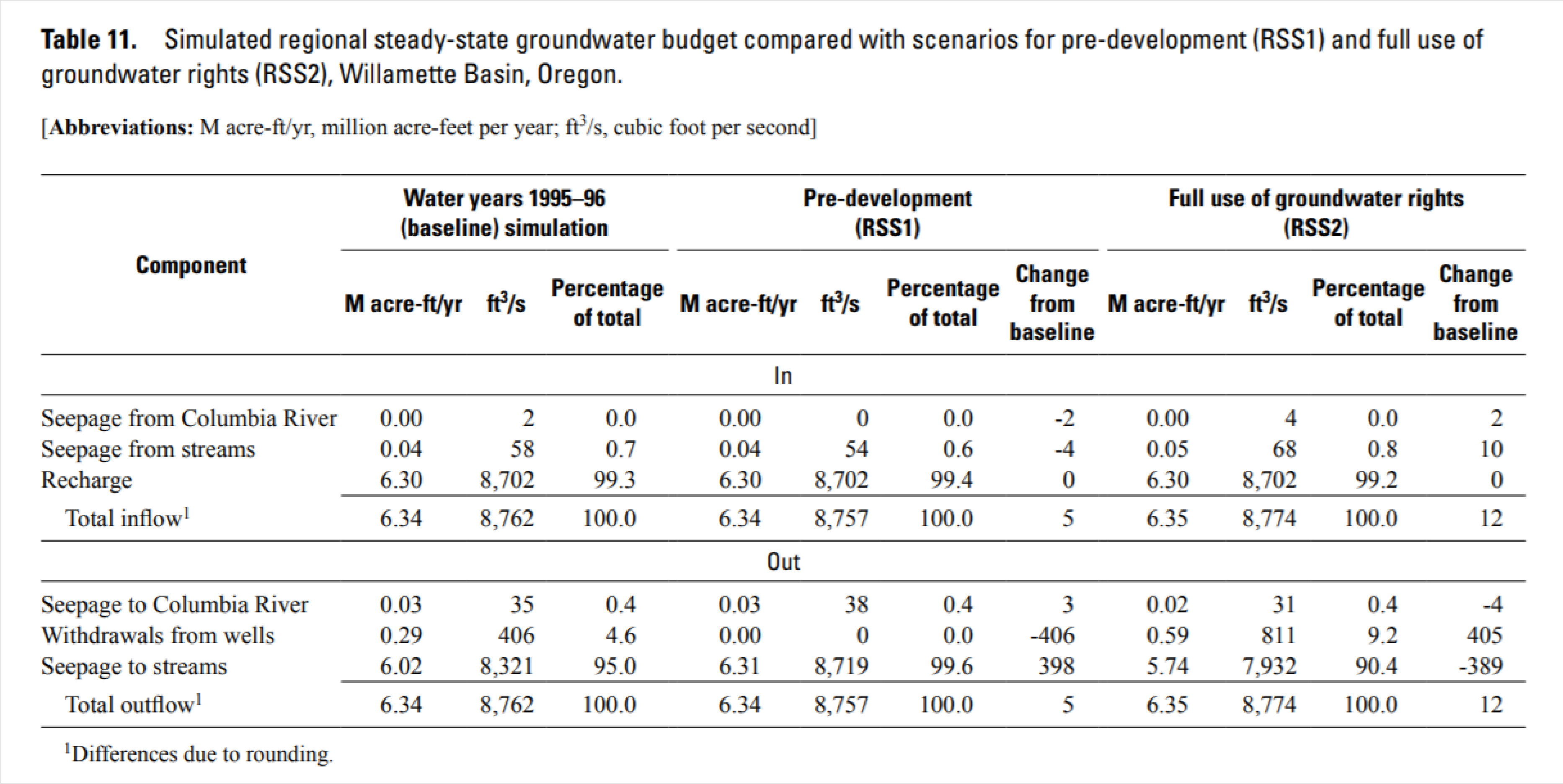


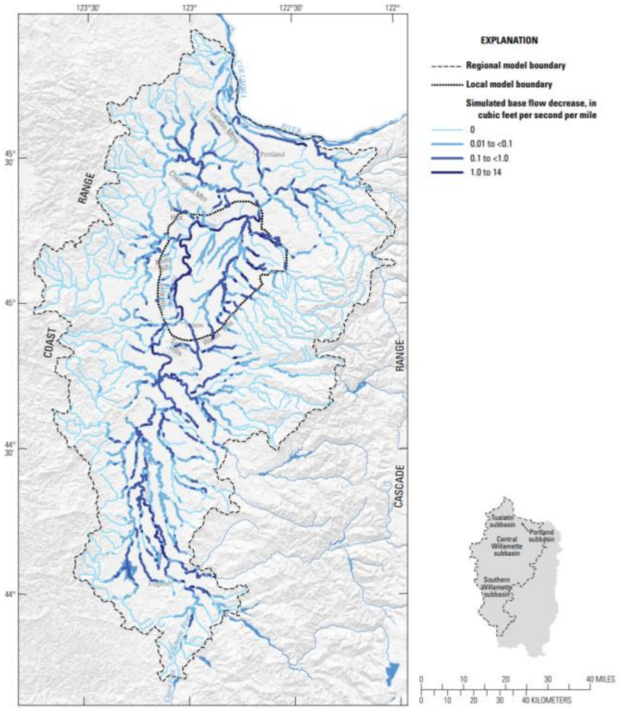
Table 11. Simulated regional steady-state groundwater budget compared with scenarios for pre-development (RSS1) and full use of groundwater rights (RSS2), Willamette Basin, Oregon.

[**Abbreviations:** M acre-ft/yr, million acre-feet per year; ft^3/s, cubic foot per second]

Component	Water years 1995–96 (baseline) simulation			Pre-development (RSS1)				Full use of groundwater rights (RSS2)			
	M acre-ft/yr	ft^3/s	Percentage of total	M acre-ft/yr	ft^3/s	Percentage of total	Change from baseline	M acre-ft/yr	ft^3/s	Percentage of total	Change from baseline
In											
Seepage from Columbia River	0.00	2	0.0	0.00	0	0.0	-2	0.00	4	0.0	2
Seepage from streams	0.04	58	0.7	0.04	54	0.6	-4	0.05	68	0.8	10
Recharge	6.30	8,702	99.3	6.30	8,702	99.4	0	6.30	8,702	99.2	0
Total inflow[1]	6.34	8,762	100.0	6.34	8,757	100.0	5	6.35	8,774	100.0	12
Out											
Seepage to Columbia River	0.03	35	0.4	0.03	38	0.4	3	0.02	31	0.4	-4
Withdrawals from wells	0.29	406	4.6	0.00	0	0.0	-406	0.59	811	9.2	405
Seepage to streams	6.02	8,321	95.0	6.31	8,719	99.6	398	5.74	7,932	90.4	-389
Total outflow[1]	6.34	8,762	100.0	6.34	8,757	100.0	5	6.35	8,774	100.0	12

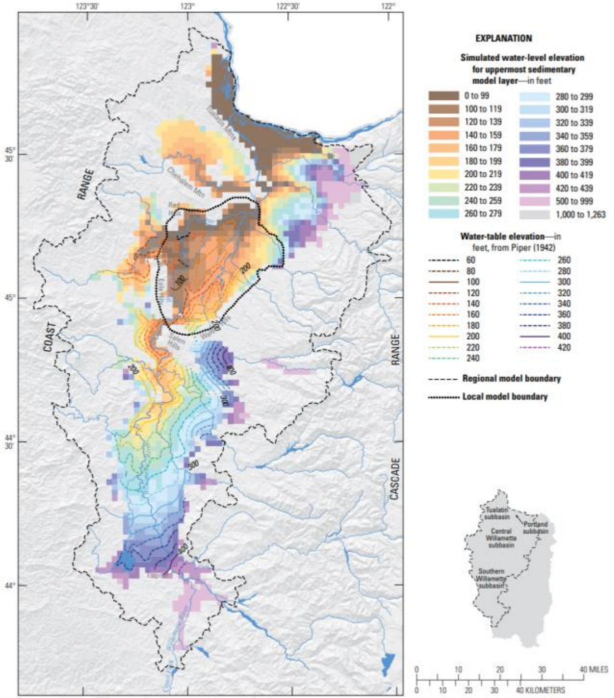
[1] Differences due to rounding.

Pre-development conditions



Base map modified from USGS and other digital data sources, various scales. Coordinate system: UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

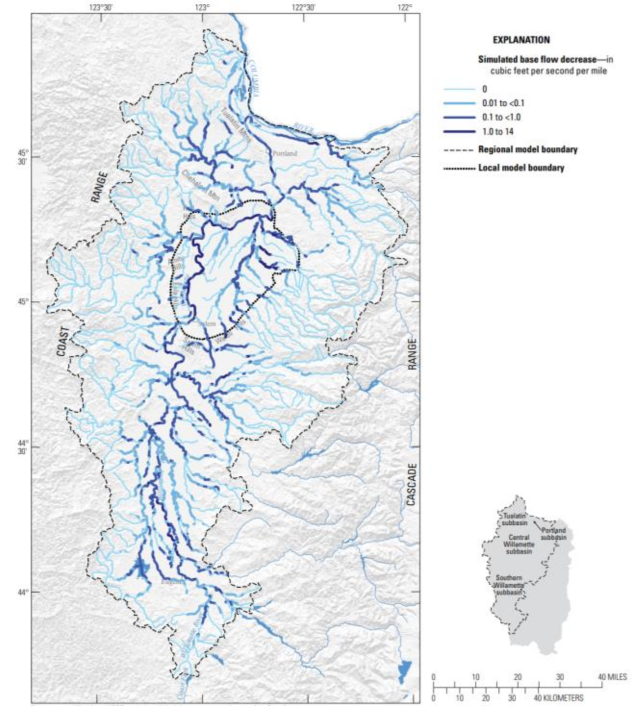
Figure 33. Simulated average annual decrease in base flow since pre-development conditions (scenario RSS1) using the regional groundwater-flow model of the Willamette Basin, Oregon.



Base map modified from USGS and other digital data sources, various scales. Coordinate system: UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 35. Simulated pre-development (scenario RSS1) water-level elevation for the uppermost sedimentary model layer (Willamette silt unit, upper sedimentary unit, middle sedimentary unit, or lower sedimentary unit) compared with 1935 pre-development water-table elevations of Piper (1942), Willamette Basin, Oregon.

Full-Use



Base map modified from USGS and other digital data sources, various scales. Coordinate system: UTM, Zone 10N, Projection: Transverse Mercator; Datum: North American Datum of 1927.

Figure 36. Simulated average annual decrease in base flow with the full use of groundwater rights model scenario RSS2, Willamette Basin, Oregon.

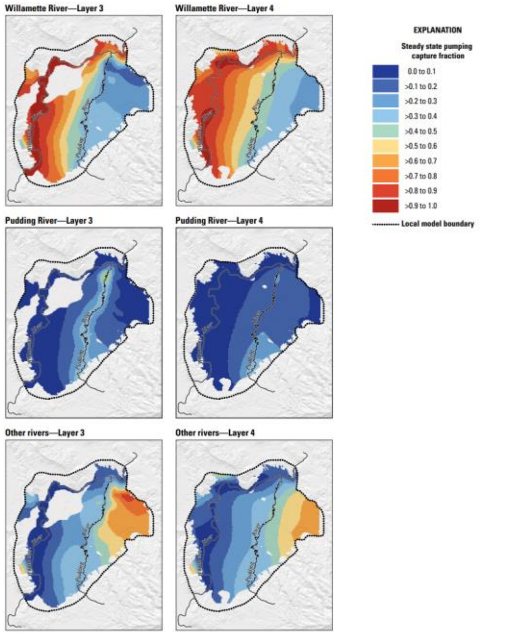


Figure 45. Computed steady-state capture fraction that would result from withdrawal of water from model layer 3 (upper sedimentary unit/middle sedimentary unit) or layer 4 (lower sedimentary unit) at a constant rate in the Willamette, Pudding, and other selected rivers in the Central Willamette subbasin, Willamette Basin, Oregon. The color at any location represents the fraction of the withdrawal rate at that location that can be accounted for as changes in outflow from and inflow to the sedimentary unit at model cells with boundary conditions representing the Willamette, Pudding, or other selected rivers.

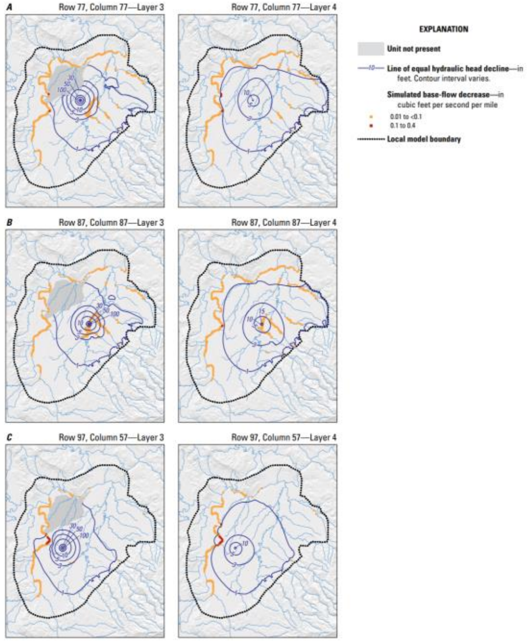


Figure 43. Simulated steady-state hydraulic-head decline in model layers 3 (upper sedimentary unit/middle sedimentary unit) and 4 (lower sedimentary unit) and base-flow decrease from pumping an additional annual 10 cubic feet per second from model layer, (*A*) near Woodburn, (*B*) near the Pudding River, and (*C*) between the Willamette and Pudding Rivers in the Central Willamette subbasin, Willamette Basin, Oregon.

LOCAL MODEL

Simulation Takeaways

- Regional:
  - The greatest effect from pumping was in the Central Willamette subbasin
  - Simulation results indicate that mean average annual hydraulic head and groundwater-supplied base flow have decreased since pre-development in most areas of the Central Willamette subbasin and localized areas of the Portland and Southern Willamette subbasins, and will continue to decrease if full use of permitted groundwater rights occurs.
  - Increased pumping in the Willamette Basin has resulted in increased stream capture from streams primarily in the lowland areas
  - Model simulation results indicate that substantial decreases in base flow have resulted from the relatively high conductivity of the sedimentary aquifers (USU and MSU), in which most wells are completed, and their proximity to sources of recharge from nearby streams
  - Both the pre-development and full-use simulations indicate that pumping stresses applied in units hydrologically connected to major streams (for example, a well completed in the USU with a nearby stream channel in the same unit) cause less drawdown in the surrounding area, but capture flow that normally would be present in nearby streams.
  - Pumping from the USU near the Willamette River generally produces less head reduction in the surrounding aquifer and more Willamette River capture than pumping from the MSU or LSU due to the high transmissivity of the USU.
  - The influence of pumping wells is controlled by the hydrologic properties and spatial distribution of the aquifer in which the pumping is located, as well as by the proximity of streams.

Simulation Takeaways

- Capture fraction calculations show that on a long-term, average annual basis, Willamette River capture will generally supply most of the groundwater for pumping in the Central Willamette subbasin, except for the northeast area of the subbasin near the Molalla River
- Pudding River capture is induced primarily by pumping wells in the USU or MSU and is small relative to Willamette River capture. In areas where the MSU is relatively thin, steep drawdowns occur in close proximity to pumping, inducing greater capture from the Pudding River and nearby streams.
- Pudding River capture is induced primarily by pumping wells in the USU or MSU and is small relative to Willamette River capture. In areas where the MSU is relatively thin, steep drawdowns occur in close proximity to pumping, inducing greater capture from the Pudding River and nearby streams.
- Results from transient simulations comparing predevelopment and full use of groundwater rights with baseline (average annual) conditions indicate that groundwater levels and streamflows have changed since pre-development and would continue to change under full use of groundwater rights conditions.
- Full-use conditions result in a doubling of baseline fluctuations in groundwater levels, and cause further declines in average annual groundwater levels. With groundwater pumping (baseline and full use of groundwater rights conditions), a summer-low/winter-high pattern occurs in Willamette River base flow from the Central Willamette subbasin, indicating influence by summer pumping

What Simulations Reveal…

- Initially during pumping, well discharge is supplied by aquifer storage, with the percentage supplied diminishing over the long term. The source of most summer pumping is water released from storage. Over time, the source of water to well pumping shifts from contributions from aquifer storage to contributions from stream capture—the average annual change in storage diminishes to zero as stream capture increases to fully supply pumping demands and a new equilibrium is reached
- Large hydraulic head declines lead to an increase of movement of low-quality water from the basement confining unit
- Allow us to evaluate the long-term effects of changes in groundwater pumping on water levels and streams
- Large declines in heads in the upper and middle sedimentary units could lead to increased pumping costs, increased number of dry wells during times of high demand, and increased seasonal changes in aquifer storage.

THANK YOU!