Electronic supplementary material (ESM)

Groundwater Flow Modeling and Safe Yield Estimation of a Transboundary Hardrock-Alluvium Aquifer in North Oman Mountains

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The following supplementary explanations have been included for more clarification of some sections of the main article.

1. Geology and physiography

The study area consists of three physiographic subdivisions, which from the head of the area to the international border between Oman and the United Arab Emirates (UAE) consist of: i) mountainous zone, ii) piedmonts zone, and iii) alluvial fan zone.

These three physiographic subdivision are directly related to the Semail Nappes, Hawasina Nappes and the post nappe strata, respectively. The mountainous terrain is rugged and complex and rises to a maximum elevation of 1401 m asl. The mountains are supported by ophiolite bedrock which present generally steep rock surfaces nearly devoid of soils and vegetation. These rocks are generally massive but show some major structural deformations and lineaments indicating an intense structural disturbance experienced in the geological past. The piedmont zone consists of a narrow alluvial plain along the mountain front and a wide band of low mountains consisting of deformed ridges of Hawasina Nappes and post nappe rocks. The alluvial plain consists of a series of coalescing alluvial fans which grade from the ophiolite mountains towards the western edge of the Hawasina Nappes and post nappe rocks. The narrow piedmont plain grades westward into a zone of deformed hardrock where numerous north-south aligned strike ridges of hardrock block the westward drainage of surface water and groundwater. The narrow belt of piedmont alluvium at the mountain front is hydrologically important in that it provides the alluvial materials in which most of the groundwater recharge and storage takes place.

2. Groundwater conceptual model

2.1. The stratigraphy

A stratigraphic model representing the vertical and spatial extent of four principal hydro-geologic units (specifically, the Hawasina, ophiolite, Tertiary and alluvium) was generated using data collected from 119 drilled boreholes and 77 virtual boreholes. Virtual boreholes were used as supporting points to increase precision of the generated stratigraphy. By interpretation of geological maps and information provided by local consultants, geological cross sections were prepared (Figs. S1 and S2).

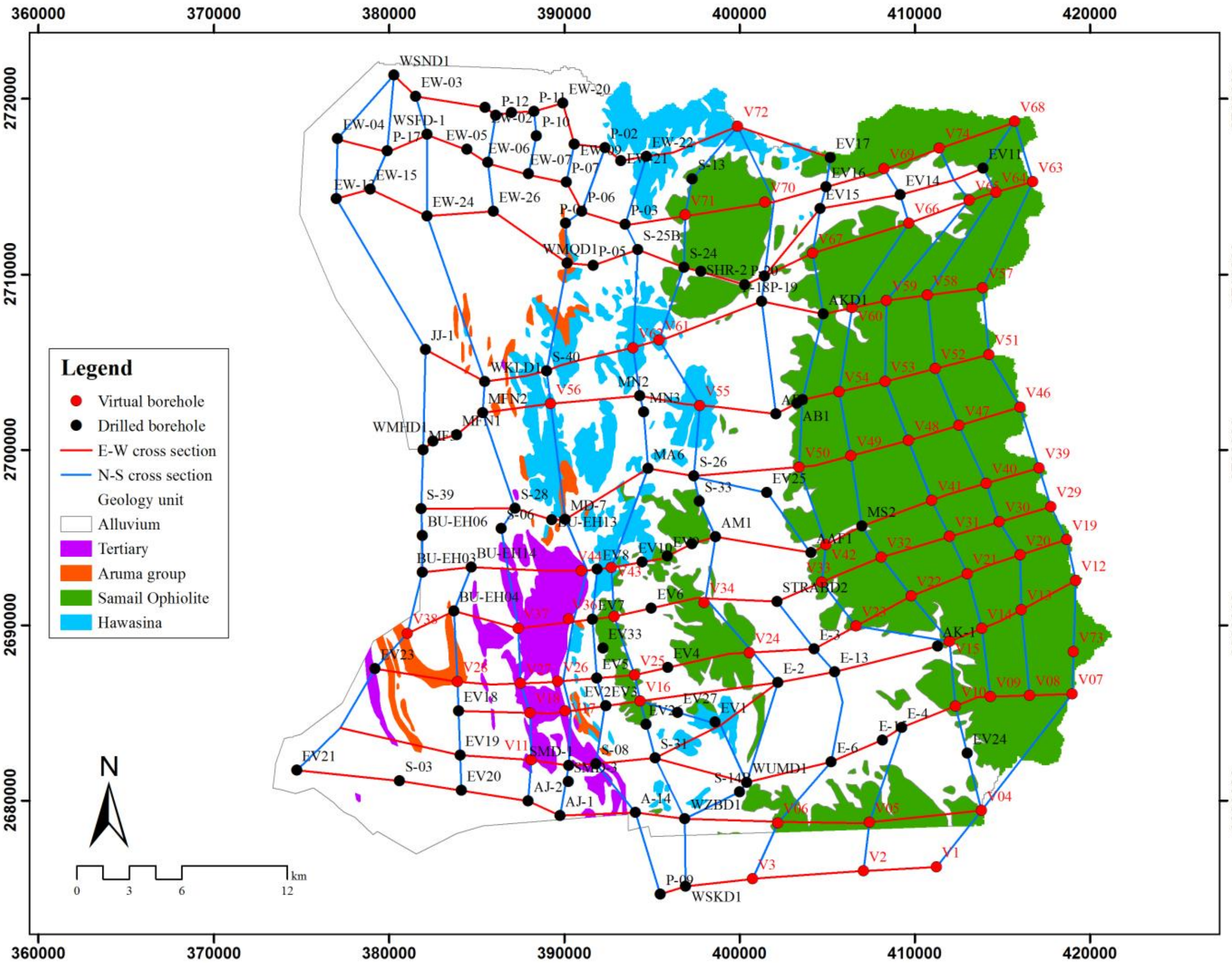


Fig. S1 Plan view of the drilled and virtual boreholes along with N-S and E-W cross sections

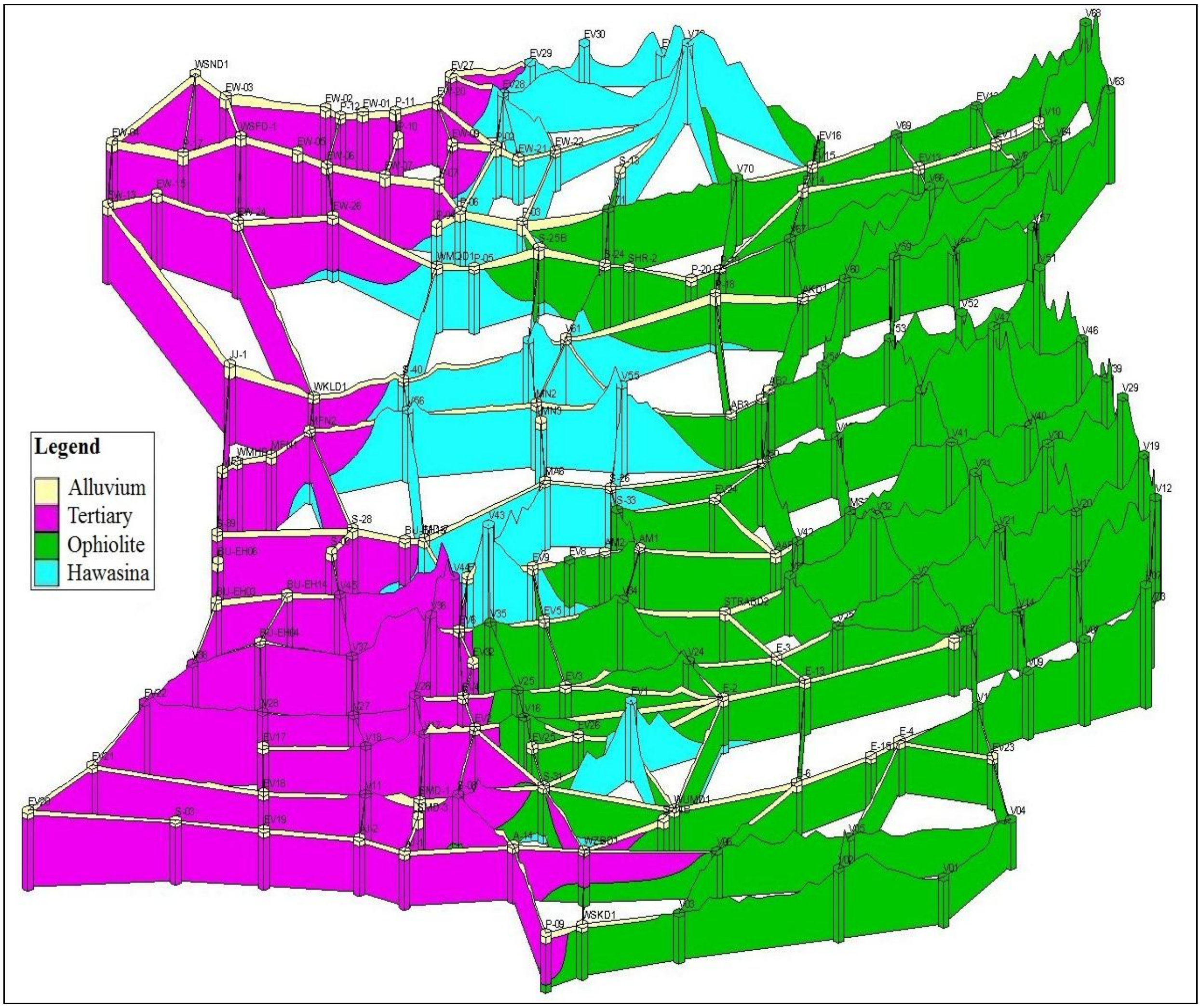


Fig. S2 3D view of all considered N-S and E-W cross sections

Regarding the prepared E-W and N-S cross-sections (Figs. S1 and S2), the stratigraphy was generated for the study area.

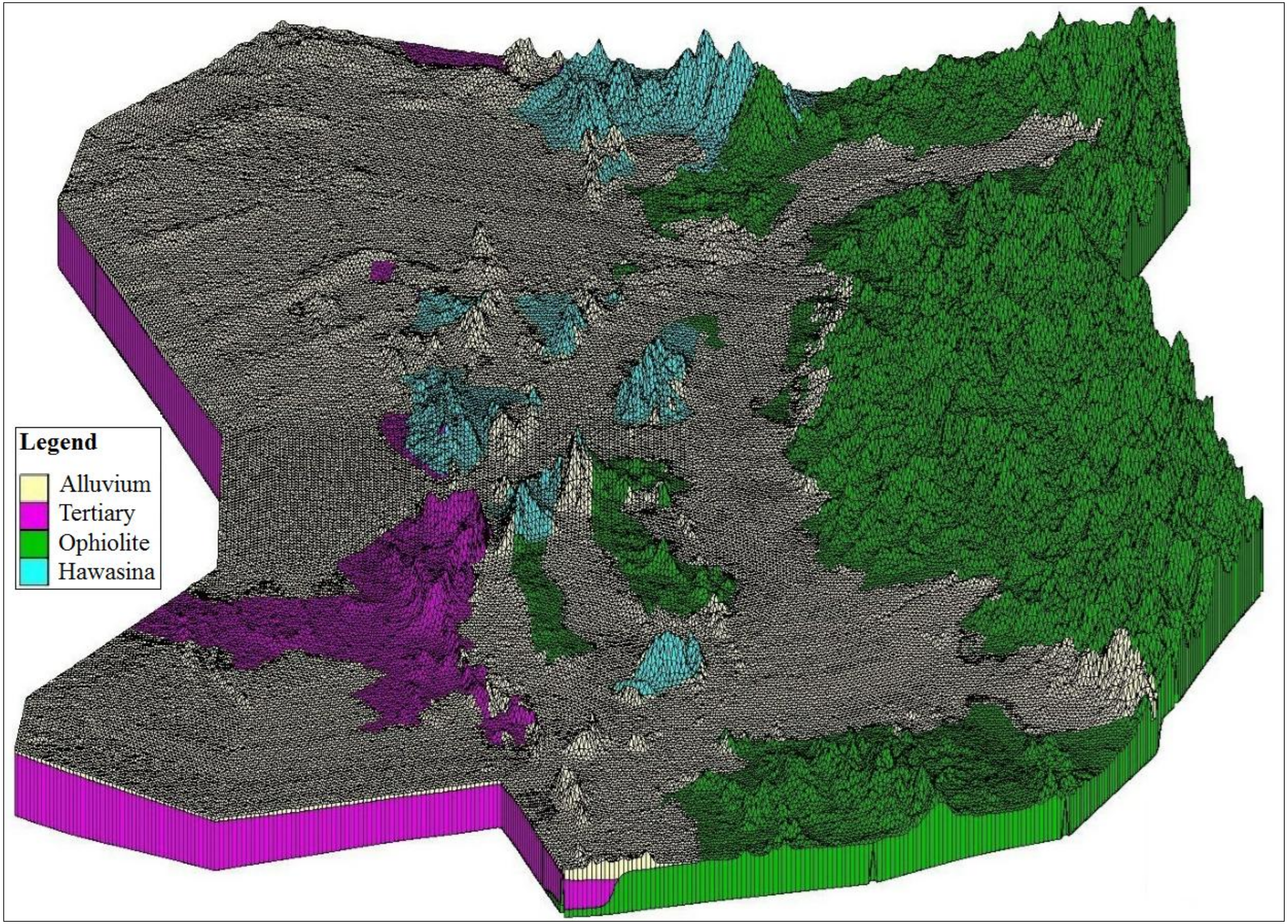


Fig. S3 3D view of the developed Al-Buraimi stratigraphy

The total thickness varies from 300 to 700 meters in the different parts of the study area. The thickness of alluvium varies in different places and ranges from 27 m to 77 m (Fig. S4). Maximum alluvium thickness is observed in the northeast of the study area.

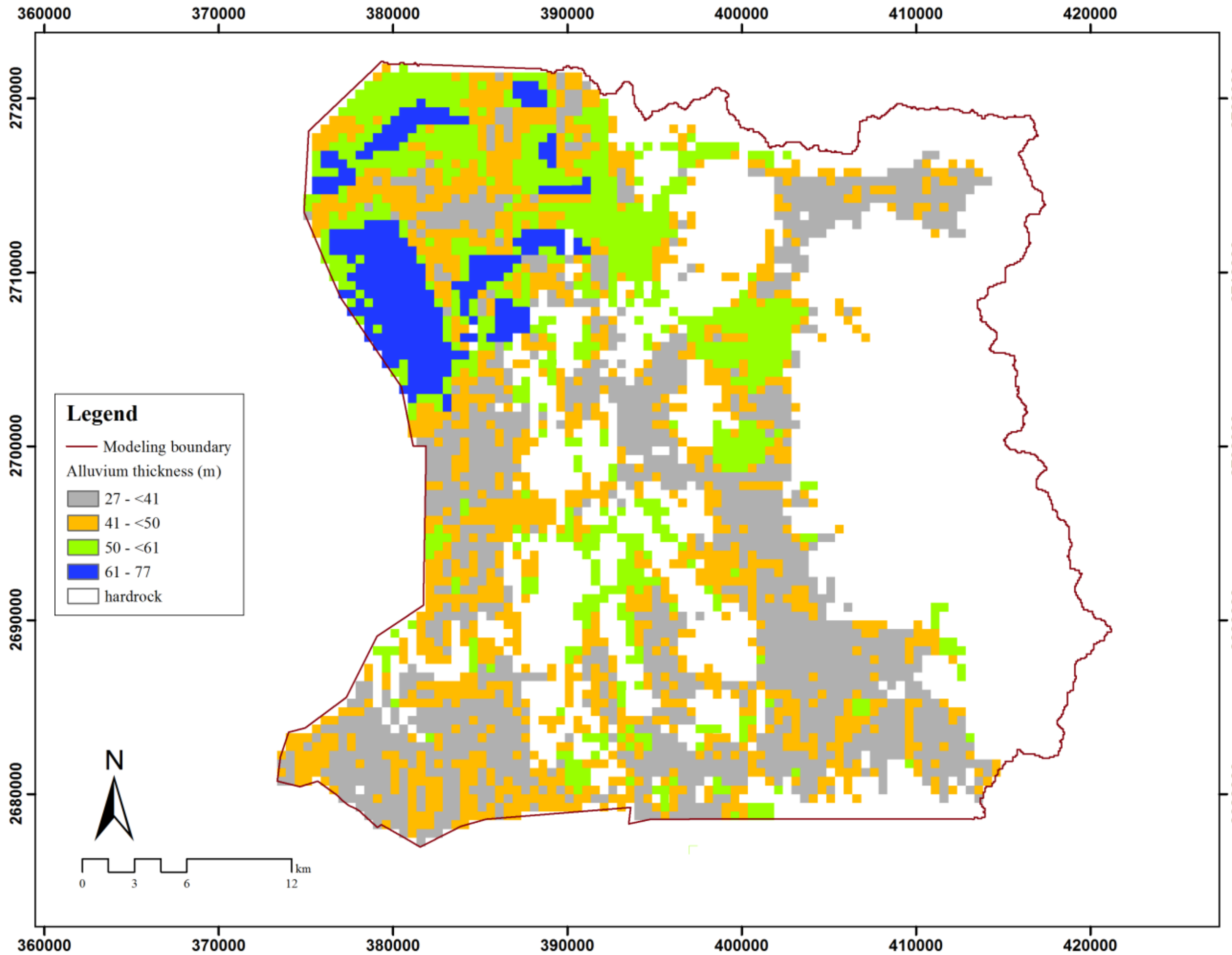
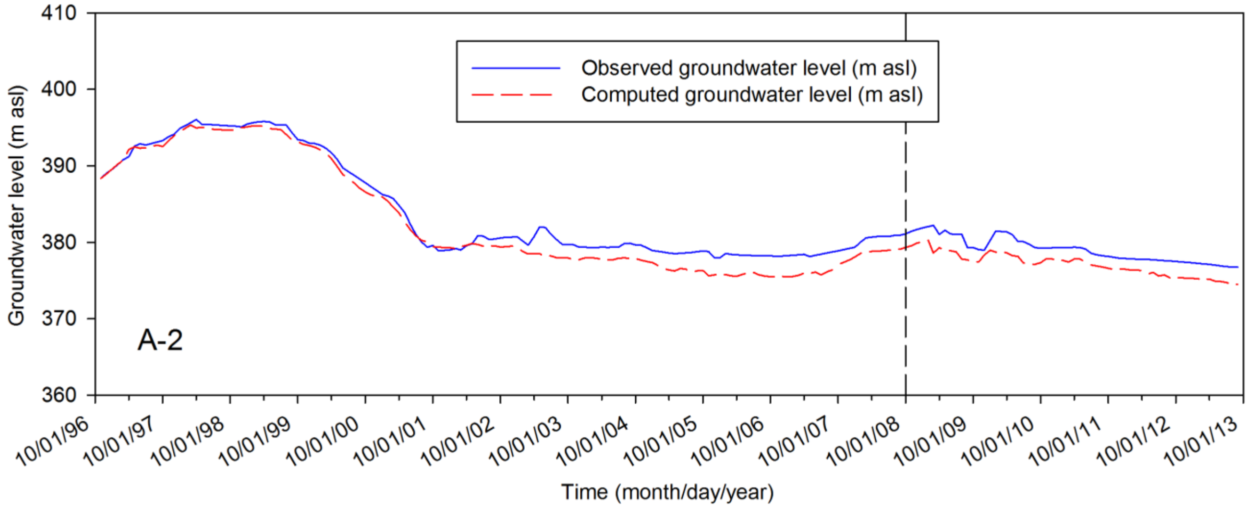


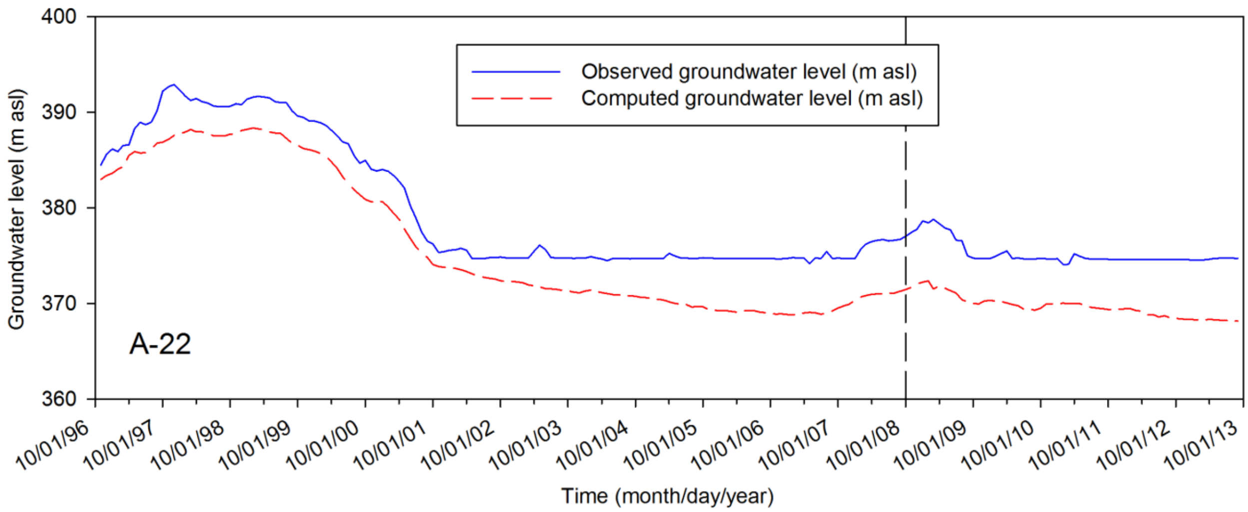
Fig. S4 Spatial pattern of alluvium thickness for the Al-Buraimi study area

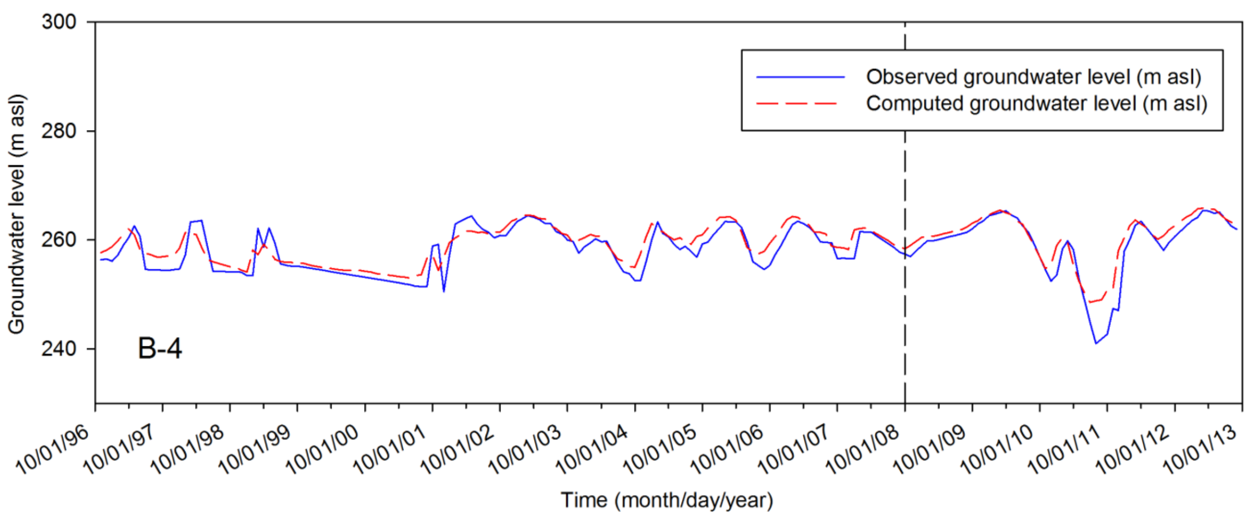
3. Results and discussion

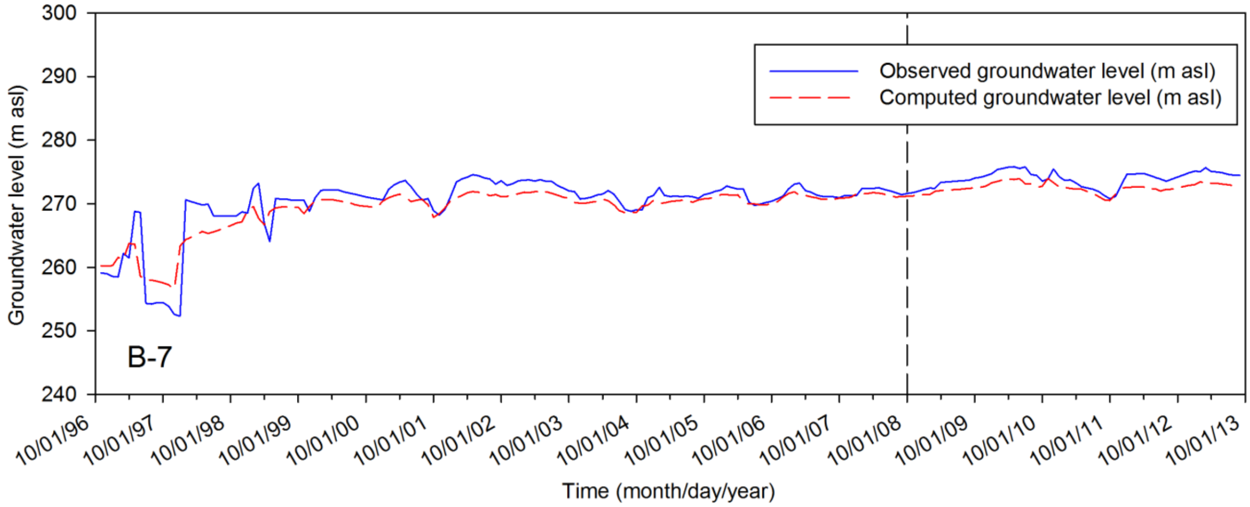
3.1. Model Calibration

Plots of observed and computed groundwater levels during calibration (Oct. 1996 to Sep. 2008) and validation (Oct. 2008 to Sep. 2013) periods for all observation wells are shown in Fig. S11.

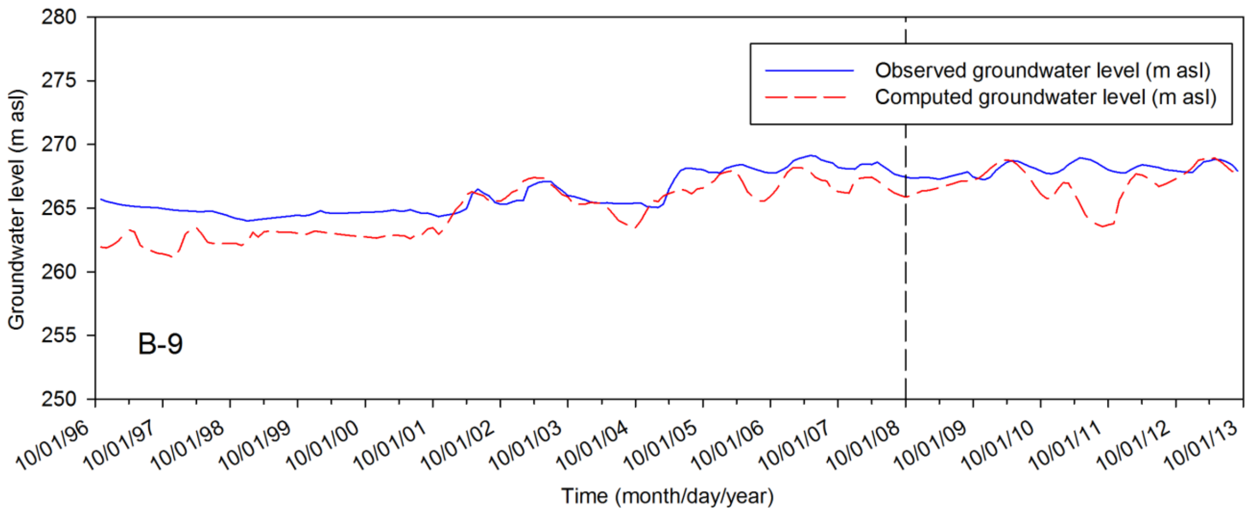

Observed groundwater level (m asl)
Computed groundwater level (m asl)
A-2
Groundwater level (m asl)
Time (month/day/year)
410
400
390
380
370
360
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13


Observed groundwater level (m asl)
Computed groundwater level (m asl)
A-22
Groundwater level (m asl)
Time (month/day/year)
400
390
380
370
360
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13

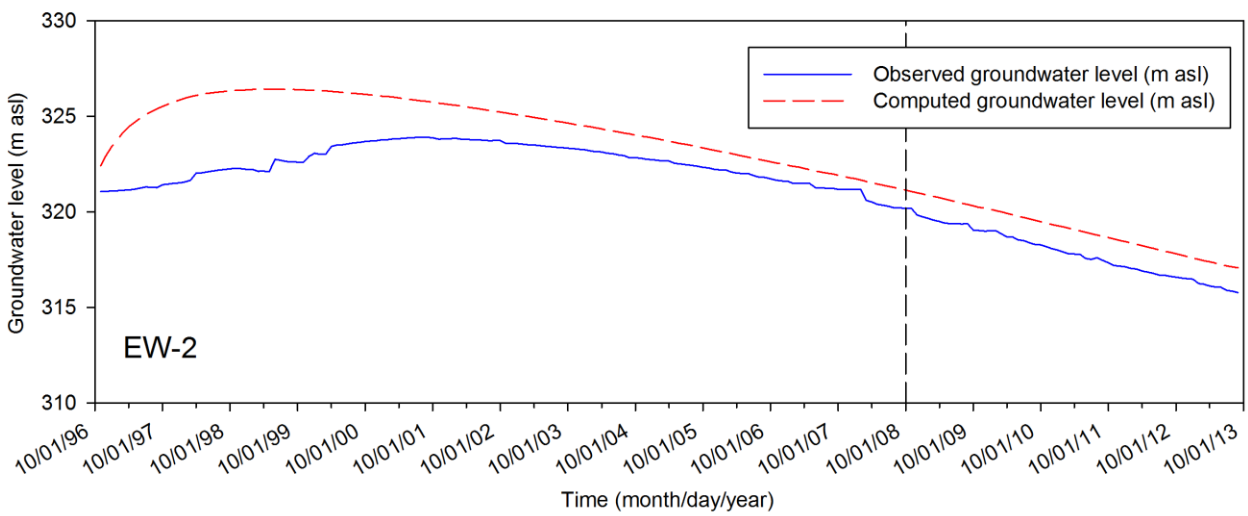

Observed groundwater level (m asl)
Computed groundwater level (m asl)
B-4
Groundwater level (m asl)
Time (month/day/year)
300
280
260
240
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13



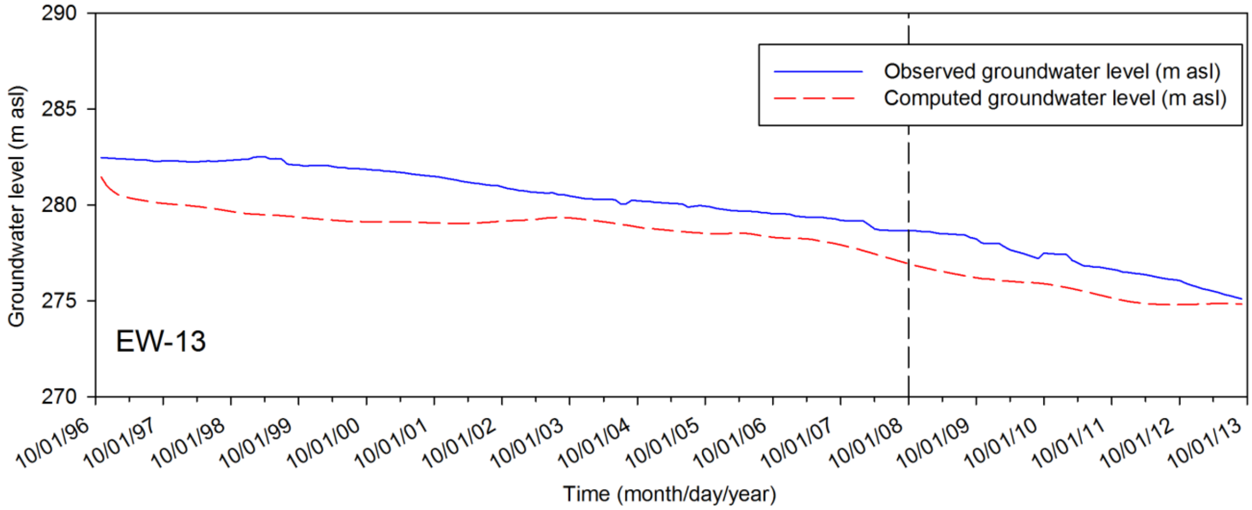
Groundwater level (m asl)
300
290
280
270
260
250
240
Observed groundwater level (m asl)
Computed groundwater level (m asl)
B-7
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)

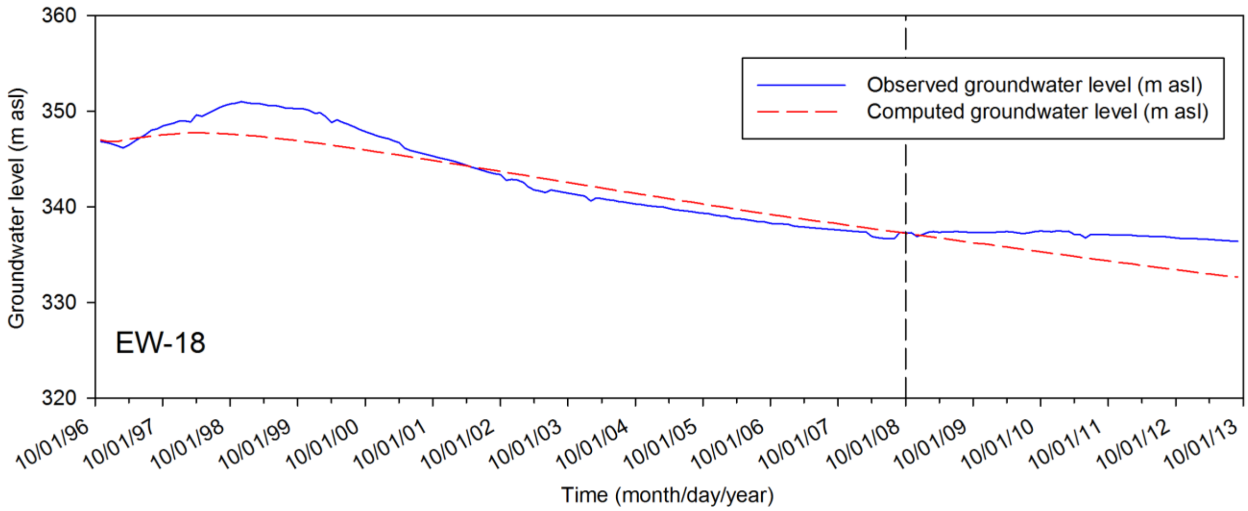


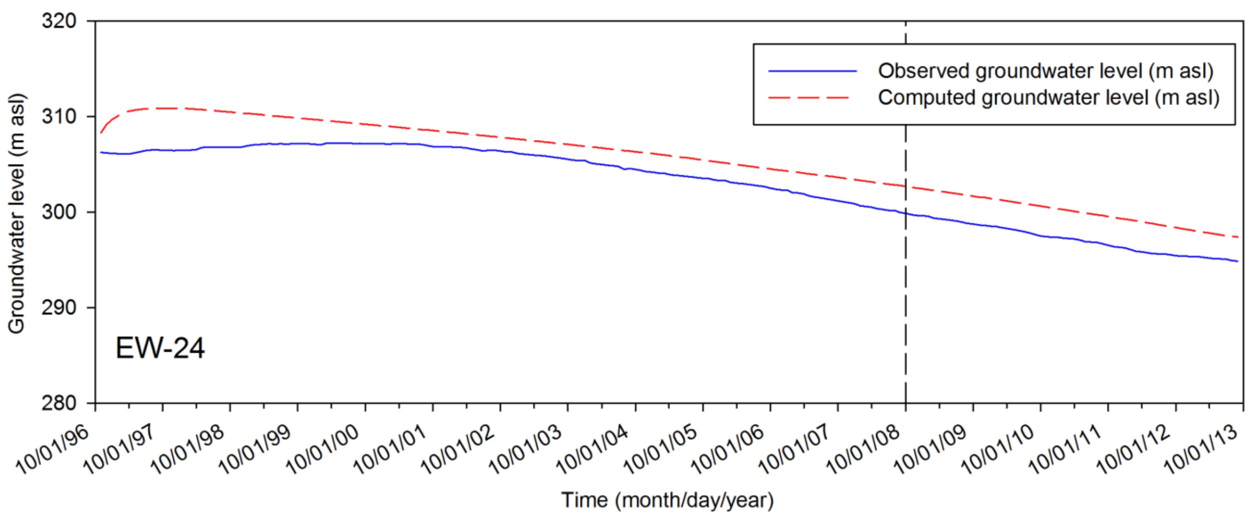
Groundwater level (m asl)
280
275
270
265
260
255
250
Observed groundwater level (m asl)
Computed groundwater level (m asl)
B-9
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)

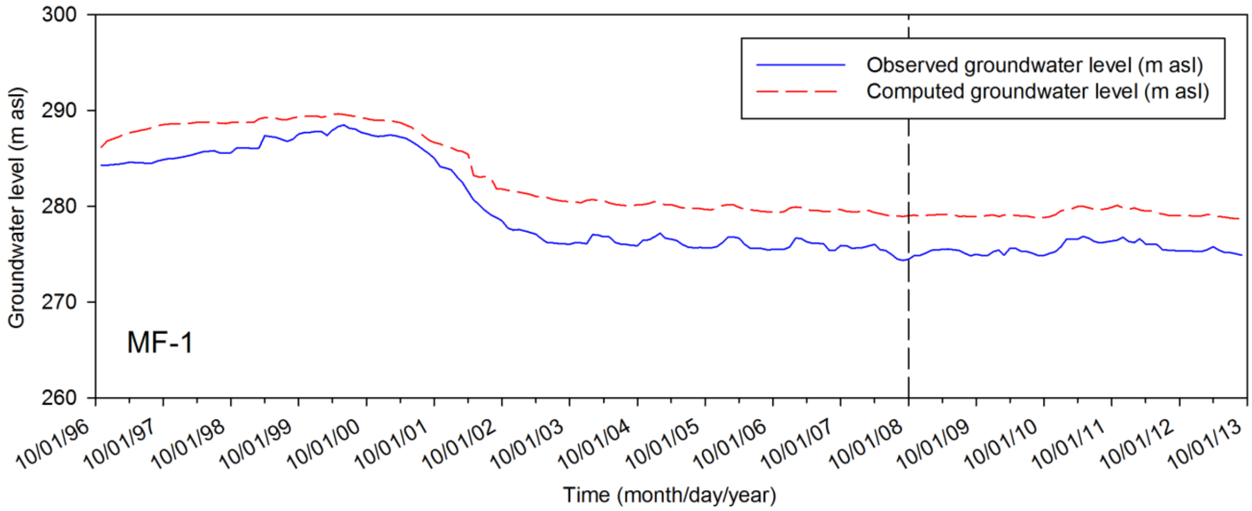


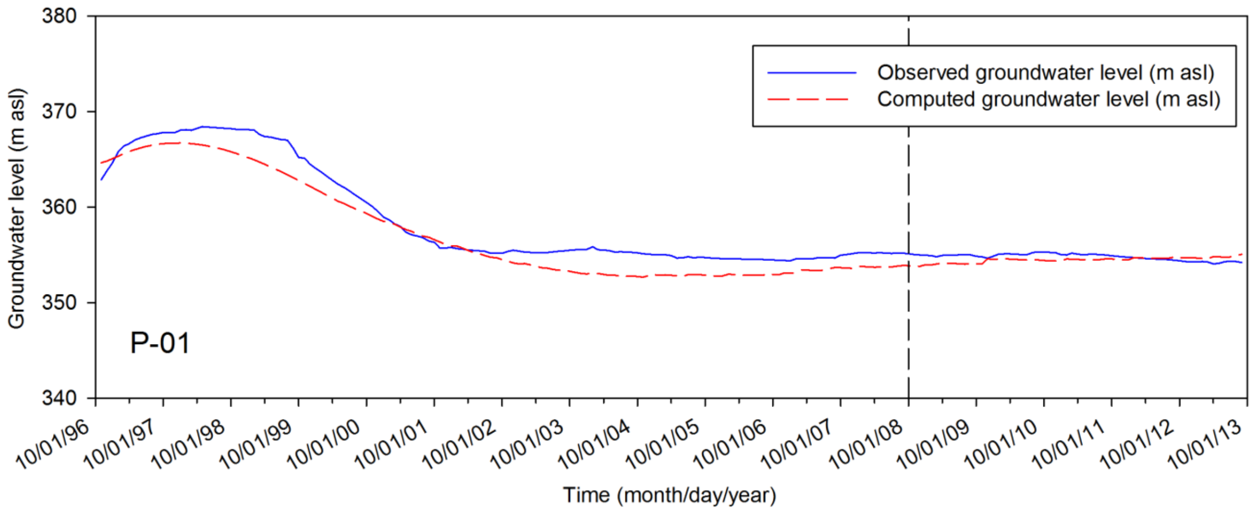
Groundwater level (m asl)
330
325
320
315
310
Observed groundwater level (m asl)
Computed groundwater level (m asl)
EW-2
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)

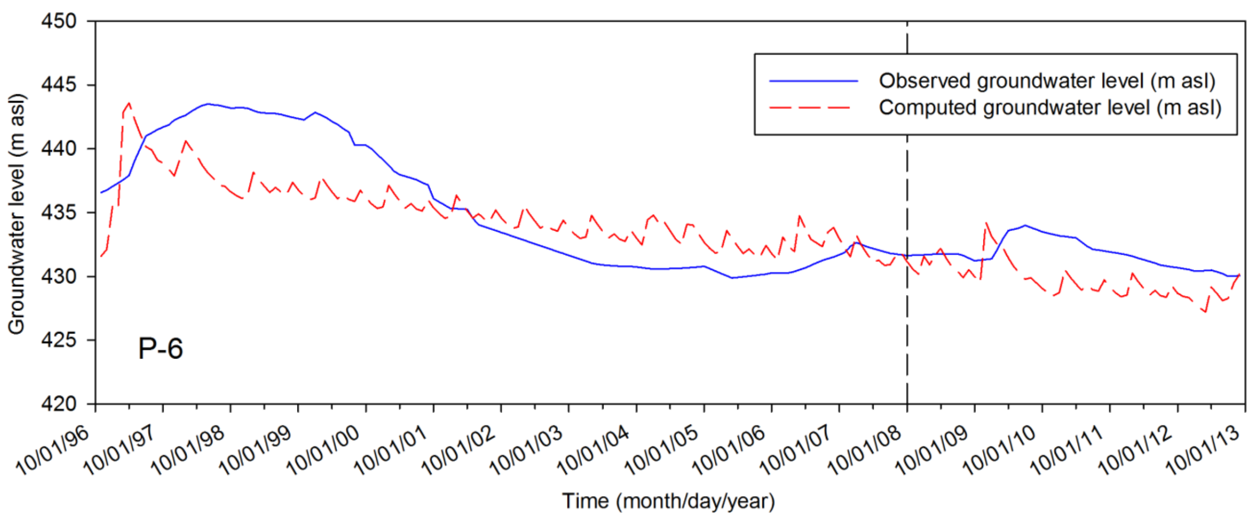

290
285
280
275
270
Groundwater level (m asl)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
EW-13
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)

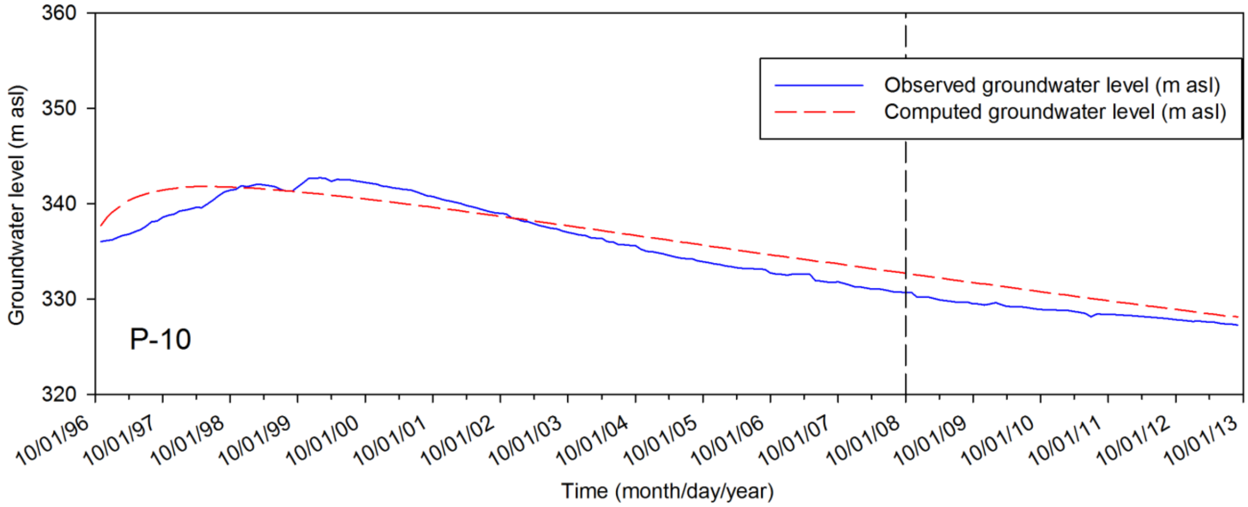

360
350
340
330
320
Groundwater level (m asl)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
EW-18
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)


320
310
300
290
280
Groundwater level (m asl)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
EW-24
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)


300
290
280
270
260
Groundwater level (m asl)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
MF-1
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)


380
370
360
350
340
Groundwater level (m asl)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
P-01
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)


450
445
440
435
430
425
420
Groundwater level (m asl)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
P-6
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
10/01/06
10/01/07
10/01/08
10/01/09
10/01/10
10/01/11
10/01/12
10/01/13
Time (month/day/year)


Groundwater level (m asl)
Time (month/day/year)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
P-10
320
330
340
350
360
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
10/01/05
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10/01/08
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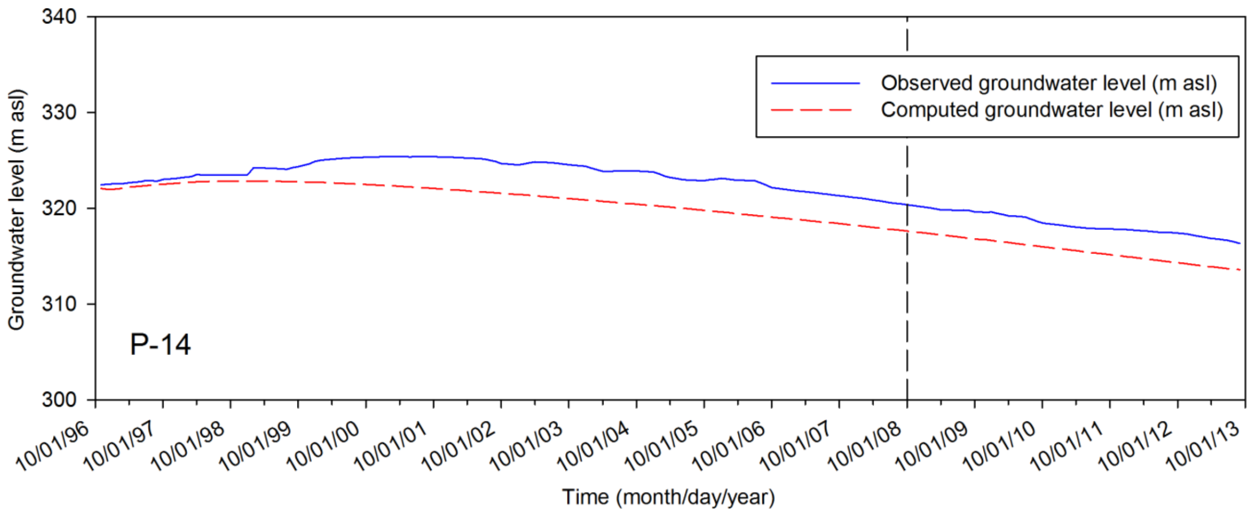
10/01/11
10/01/12
10/01/13


Groundwater level (m asl)
Time (month/day/year)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
P-14
300
310
320
330
340
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
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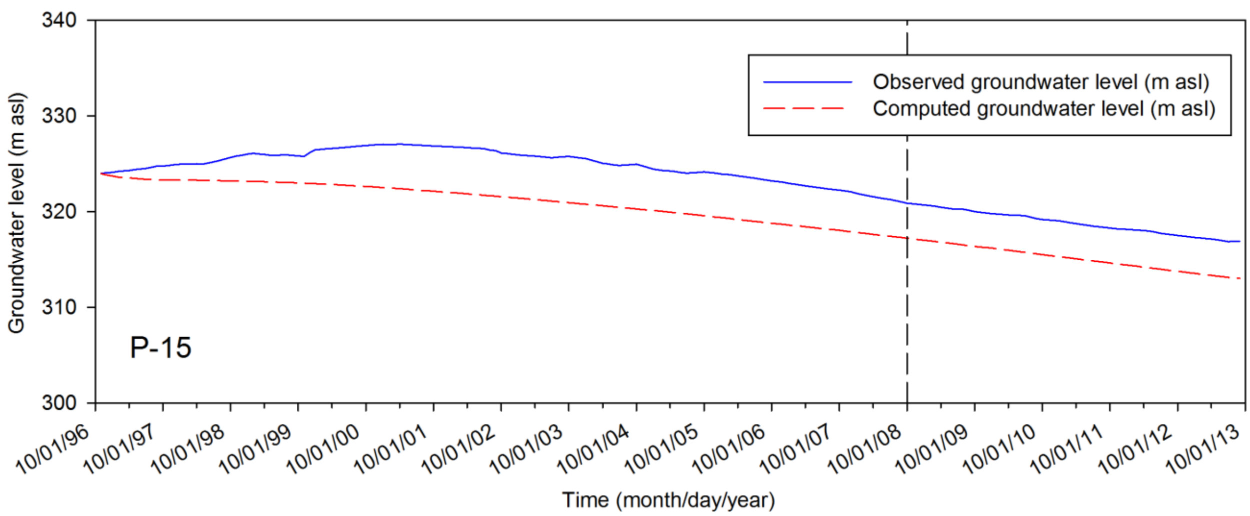
10/01/12
10/01/13


Groundwater level (m asl)
Time (month/day/year)
Observed groundwater level (m asl)
Computed groundwater level (m asl)
P-15
300
310
320
330
340
10/01/96
10/01/97
10/01/98
10/01/99
10/01/00
10/01/01
10/01/02
10/01/03
10/01/04
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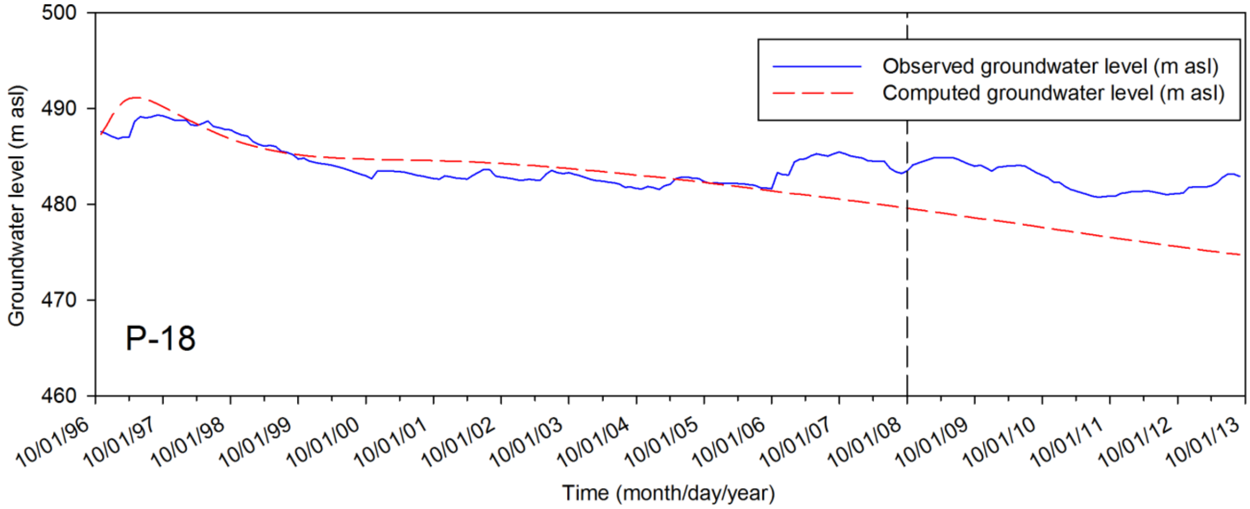
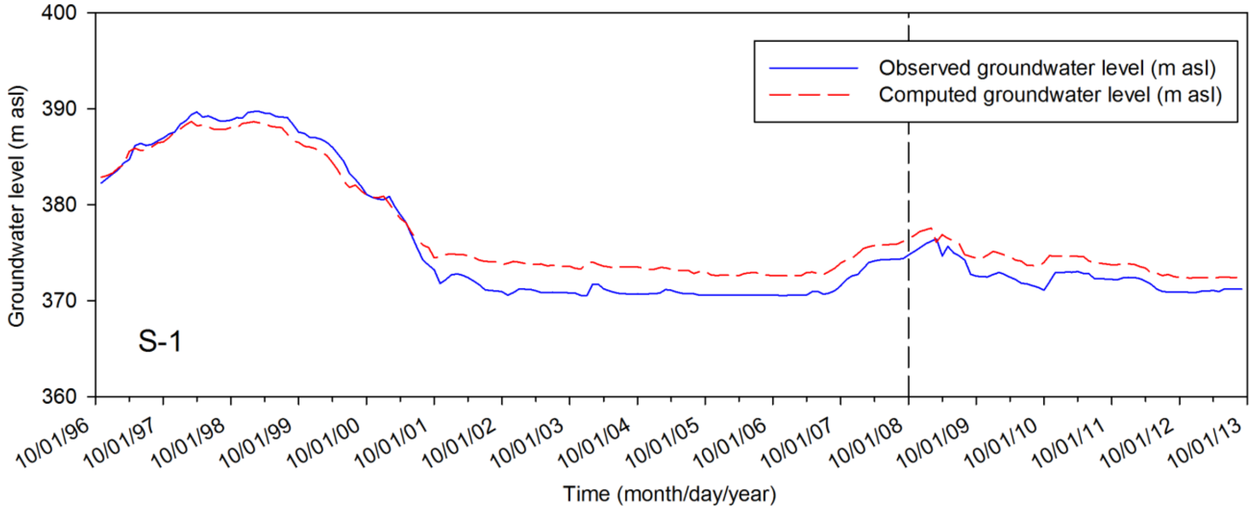
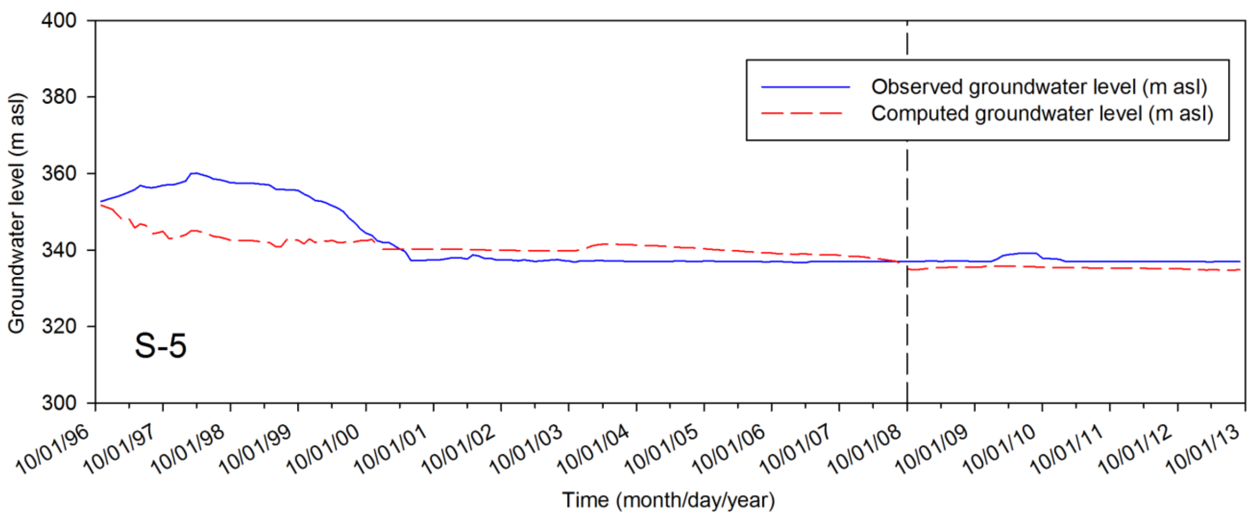
10/01/12
10/01/13



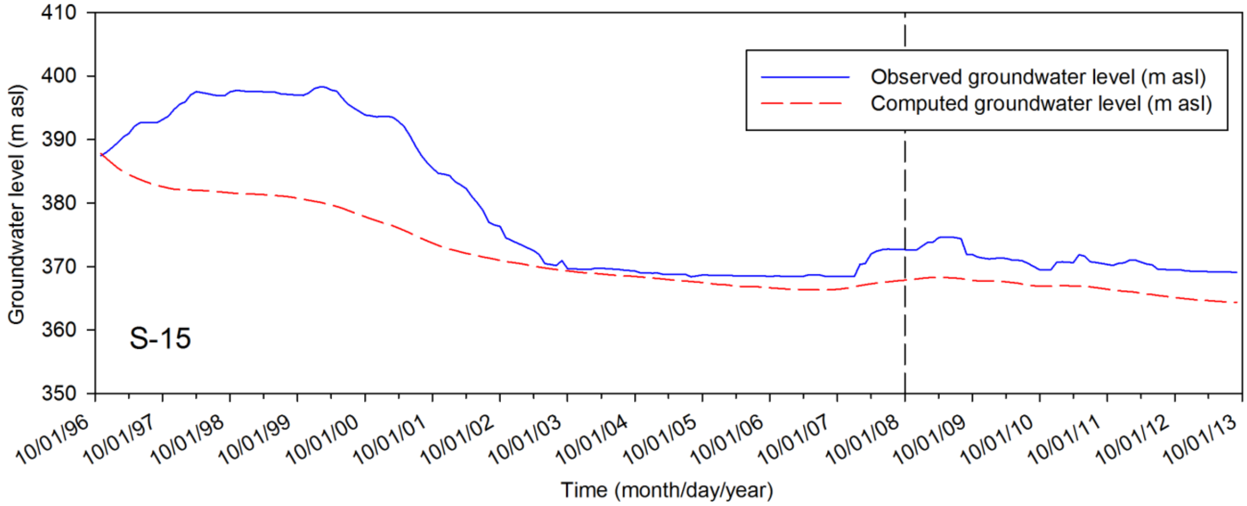
Observed groundwater level (m asl)
Computed groundwater level (m asl)
P-18
Groundwater level (m asl)
Time (month/day/year)



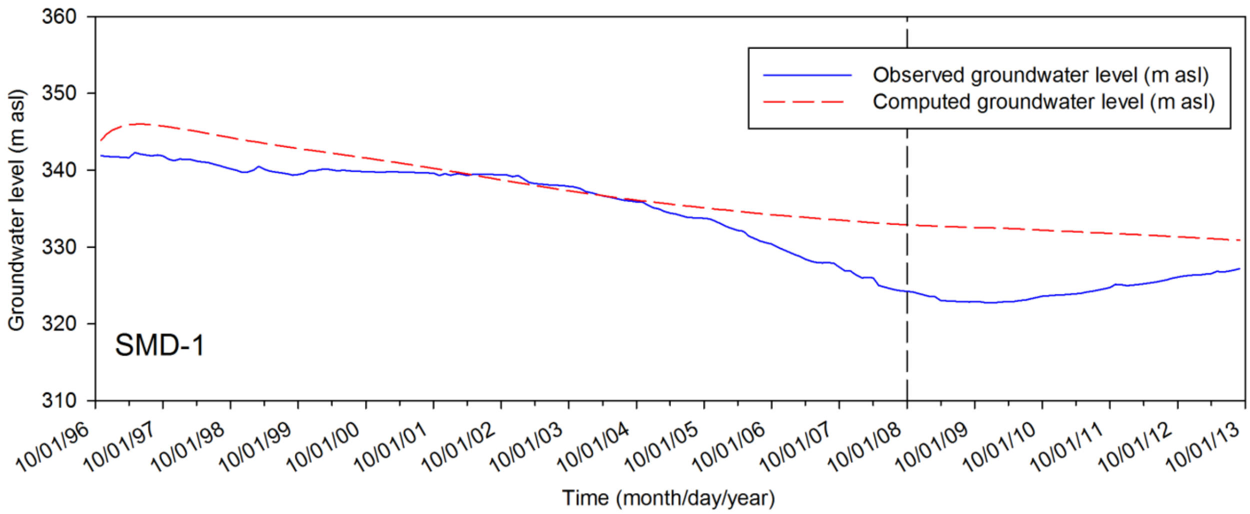
Observed groundwater level (m asl)
Computed groundwater level (m asl)
S-1
Groundwater level (m asl)
Time (month/day/year)



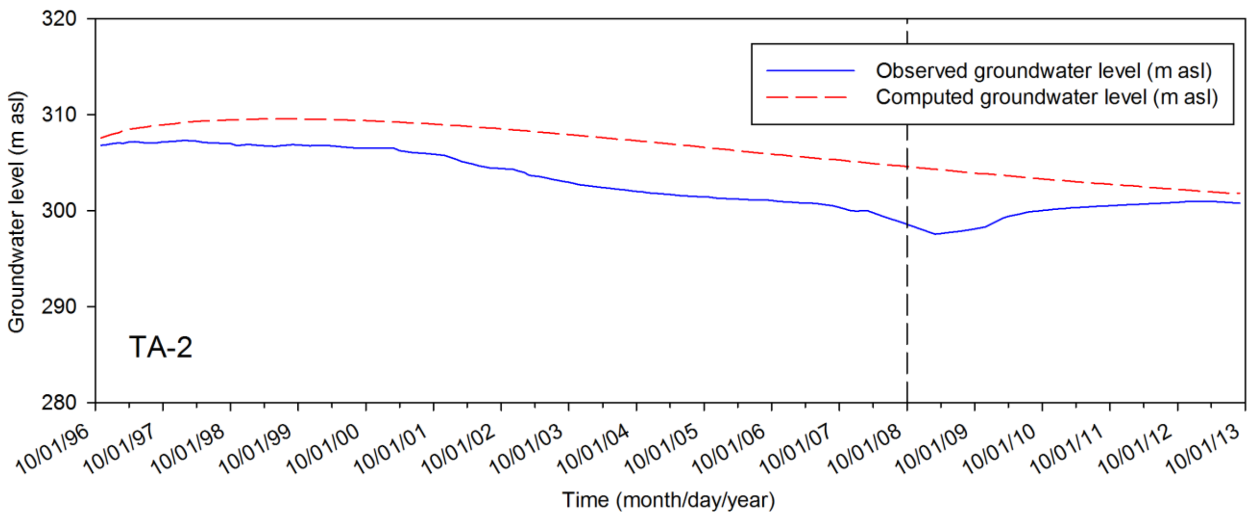
Observed groundwater level (m asl)
Computed groundwater level (m asl)
S-5
Groundwater level (m asl)
Time (month/day/year)



Groundwater level (m asl)
S-15
Observed groundwater level (m asl)
Computed groundwater level (m asl)
Time (month/day/year)



Groundwater level (m asl)
SMD-1
Observed groundwater level (m asl)
Computed groundwater level (m asl)
Time (month/day/year)



Groundwater level (m asl)
TA-2
Observed groundwater level (m asl)
Computed groundwater level (m asl)
Time (month/day/year)

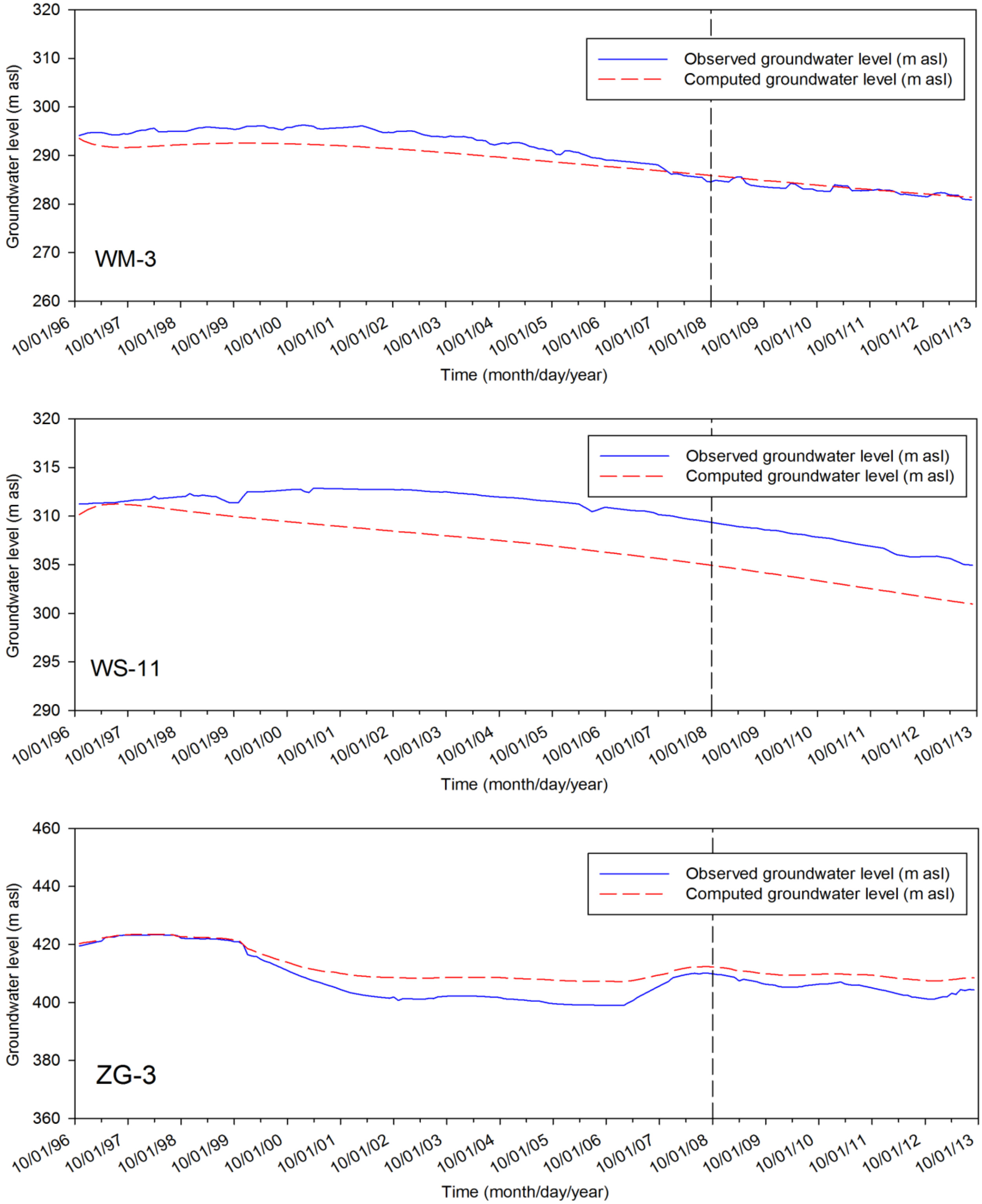


Fig. S5 Plots of observed and computed groundwater level during calibration (Oct. 1996 to Sep. 2008) and validation (Oct. 2008 to Sep. 2013) periods.