Design Document: Processing instructions for the groundwater-flow model of the Wood River Valley, Idaho

By J.C. Fisher, USGS

Design document description and purpose

The U.S. Geological Survey (USGS), in collaboration with the Idaho Department of Water Resources (IDWR) is constructing a MODFLOW numerical groundwater-flow model of the Wood River Valley aquifer system in order to simulate potential anthropogenic and climatic effects on groundwater and surface-water resources. This model will serve as a tool for water-rights administration and water-resource management and planning. The study will be conducted over a 3-year period from late 2012 until model and report completion in 2015.

One of the goals of the modeling study is to develop the model in an open and transparent manner. To this end, a Technical Advisory Committee was formed to provide for transparency in model development and to serve as a vehicle for stakeholder input. Technical representation was solicited by the IDWR and includes such interested parties as water-user groups and current USGS cooperating organizations in the Wood River Valley.

The design, construction, and calibration of a groundwater-flow model requires a number of decisions such as the number of layers, model cell size, or methodologies used to represent processes such as evapotranspiration or pumpage. While these decisions will be documented in a final USGS report, intermediate decision documents will be prepared in order to facilitate technical discussion and ease preparation of the report. These decision documents should be considered preliminary status reports and not final products.

Design decision

Processing Instructions for the Groundwater Flow Model of the Wood River Valley, Idaho

By Jason C. Fisher

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Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.28084	foot (ft)
kilometer (km)	0.621371	mile (mi)
meter (m)	1.09361	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.104	acre
square meter (m^2)	10.7639	square foot (ft^2)
square kilometer (km^2)	0.386102	square mile (mi^2)
	Volume	
cubic meter (m^3)	0.0008107	acre foot (acre-ft)
cubic meter (m^3)	35.3147	cubic foot (ft^3)
	Volume per unit time	
cubic meter per day (m^3/d)	0.296107	acre-foot per year (acre-ft/yr)

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Elevation, as used in this document, refers to distance above vertical datum.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Maps are based on the Idaho Transverse Mercator projection (IDTM).

Introduction

The **wrv** package (Fisher, 2014) is a pre- and post-processing program for the numerical groundwater flow model of the Wood River Valley (WRV) aquifer system, south-central Idaho. This document (also known as a *package vignette*) explains the steps taken to process the model; its contents should be viewed as provisional until model and report completion in 2015 (Bartolino *et al.*, 2015). It is assumed that the readers of this vignette are familiar with the R-programming language and have read the help pages for functions and data sets in the **wrv** package.

Software

Software items needed to run the processing instructions for the groundwater flow model include R and MODFLOW-USG. R is a language and environment for statistical computing and graphics (R Core Team, 2014). If R (version $\geq$ 3.0) is not already installed on your computer, download and install the latest binary distribution from CRAN. Extend the capabilities of R by installing user-created packages, such as **wrv**. Start an R session and type the following commands in your R Console window:

```
install.packages(c("rgdal", "raster", "igraph", "rgeos", "RCurl", "png", "xtable"))
install.packages("wrv", repos = "http://jfisher-usgs.github.com/R/")
```

MODFLOW-USG is a computer program for simulating three-dimensional, steady-state and transient ground-water flow using a control volume finite-difference formulation (Panday *et al.*, 2013). If MODFLOW-USG (version $\geq$ 1.1) is not already installed on your computer, download and decompress the latest file archive. The file archive contains an executable file for Windows. Users of a Unix-like operating system will need to compile MODFLOW-USG. Specify the full path name to the executable file using the following R command (change path if needed):

```
file.exe <- "C:/WRDAPP/mfusg.1_1/bin/mfusg_x64.exe"  # path specified with forward slashes
```

This package vignette integrates R code in a LaTeX document. The code is run when the vignette is built, and all data analysis output (figures, tables, etc.) is created on the fly and inserted into the final document. Note that embedded code can be extracted from the vignette, which allows for truly reproducible research; see the 'Reproducibility' section for details. Small chunks of stylized code are shown throughout the vignette and are intended to be used interactively. Commands that comprise these *code chunks* are essential for processing the groundwater flow model, and describe approaches to model development and analysis decisions.

To gain access to the contents of the **wrv** package in R, use the following command:

```
library(wrv)
```

To open help pages for functions and data sets in the **wrv** package, type:

```
help(package = "wrv")
```

Hydrogeologic Framework

The WRV aquifer system is composed of a single unconfined aquifer that underlies the entire valley, an underlying confined aquifer that is present only in the southern part of the valley, and a confining unit separating the two aquifers (Bartolino and Adkins, 2012, pg. 3). The land-surface topography and spatial extent of the aquifer system are shown in figure 1. The aquifer system primarily consists of Quaternary deposits that can be divided into three hydrogeologic units: a coarse-grained sand and gravel unit (alluvium unit), a fine-grained silt and clay unit (clay unit), and a basalt unit (Bartolino and Adkins, 2012, pg. 3).

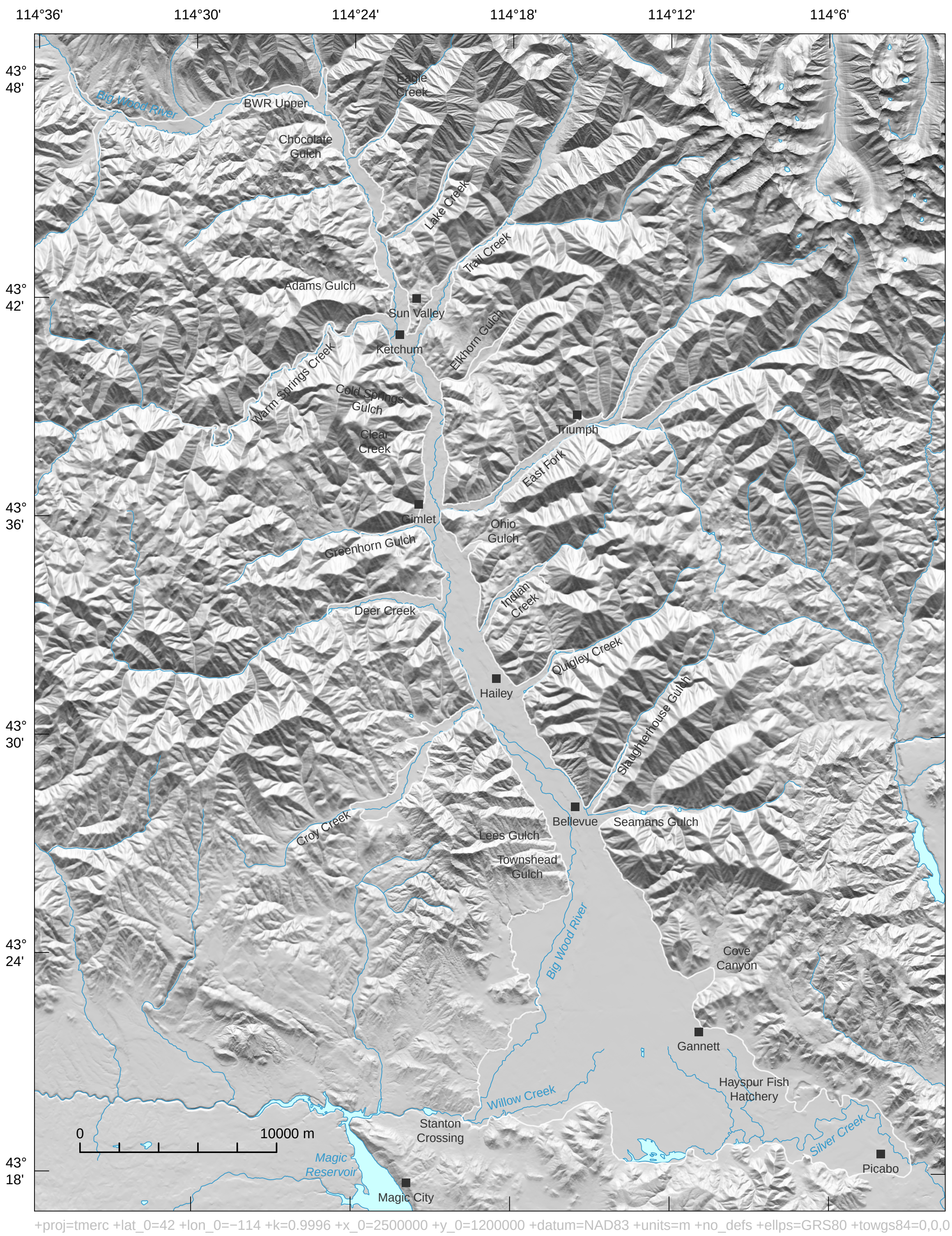

Figure 1: Land surface topography and extent of the aquifer system.

Pre-Processing

Conceptualization of Model Grid

The creation of the model grid is the first step in developing the groundwater flow model, because all model inputs including hydraulic properties, wells, and boundary conditions are assigned to the model cells. The three-dimensional model grid is rectilinear (square cells) horizontally, distorted vertically, and not rotated. The decision to use a structured grid, rather than exploit the unstructured grid capabilities of MODFLOW-USG, was based on a desire to avoid the added complexities of designing pre- and post-processing algorithms for an unstructured grid. A preliminary sensitivity analysis to changes in grid resolution indicated that a 100 m (330 feet [ft]) resolution provides the optimal tradeoff between the inherent spatial variability of the data and the ability to get continuous grid coverage in the narrow and steep tributary canyons.

Solid-boundary representations of the pre-Quaternary bedrock surface and top of Quaternary basalt (alluvium bottom) and land surface are used to generate the basic structure of the model grid. Note that these raster layer data sets share the same spatial extent and resolution. To lower the spatial resolution of the raster layers from 20 m (66 ft) to that of the model grid at 100 m requires cell aggregation. Aggregation groups rectangular areas to create larger cells; an aggregation factor specifies the number of cells to group in each direction.

```
fact <- 5L  # aggregation factor, the L suffix indicates that the number is an integer
rs.data <- stack()  # initialize a raster stack, a collection of raster layers
r <- aggregate(raster(alluvium.bottom), fact)
names(r) <- "alluvium.bottom"
rs.data <- stack(rs.data, r)  # add raster layer to raster stack
r <- aggregate(raster(land.surface), fact)
names(r) <- "land.surface"
rs.data <- stack(rs.data, r)
```

Thickness of the Quaternary sediment is calculated by subtracting alluvium-bottom elevations from land surface elevations (fig. 2). Cells which are too thin can lead to numerical instability in the model; therefore, cells less than 1 m (3.3 ft) thick are made inactive.

```
r <- rs.data[["land.surface"]] - rs.data[["alluvium.bottom"]]
min.thickness <- 1.0  # minimum cell thickness
is.too.thin <- r[] < min.thickness
rs.data[["alluvium.bottom"]][is.too.thin] <- NA
r[is.too.thin] <- NA
names(r) <- "alluvium.thickness"
rs.data <- stack(rs.data, r)
```

The estimated extent of basalt in the WRV aquifer system is shown in figure 3.

```
r <- rasterize(basalt.extent, rs.data, getCover = TRUE, silent = TRUE)
min.coverage <- 1L  # min. percentage of each cell that is covered by the polygon (1-100)
r[r < min.coverage] <- NA
r[!is.na(r)] <- 1L
r <- ratify(r)  # add a raster attribute table
rat <- levels(r)[[1]]
rat$att <- "Basalt"
levels(r) <- rat
names(r) <- "basalt.extent"
rs.data <- stack(rs.data, r)
```

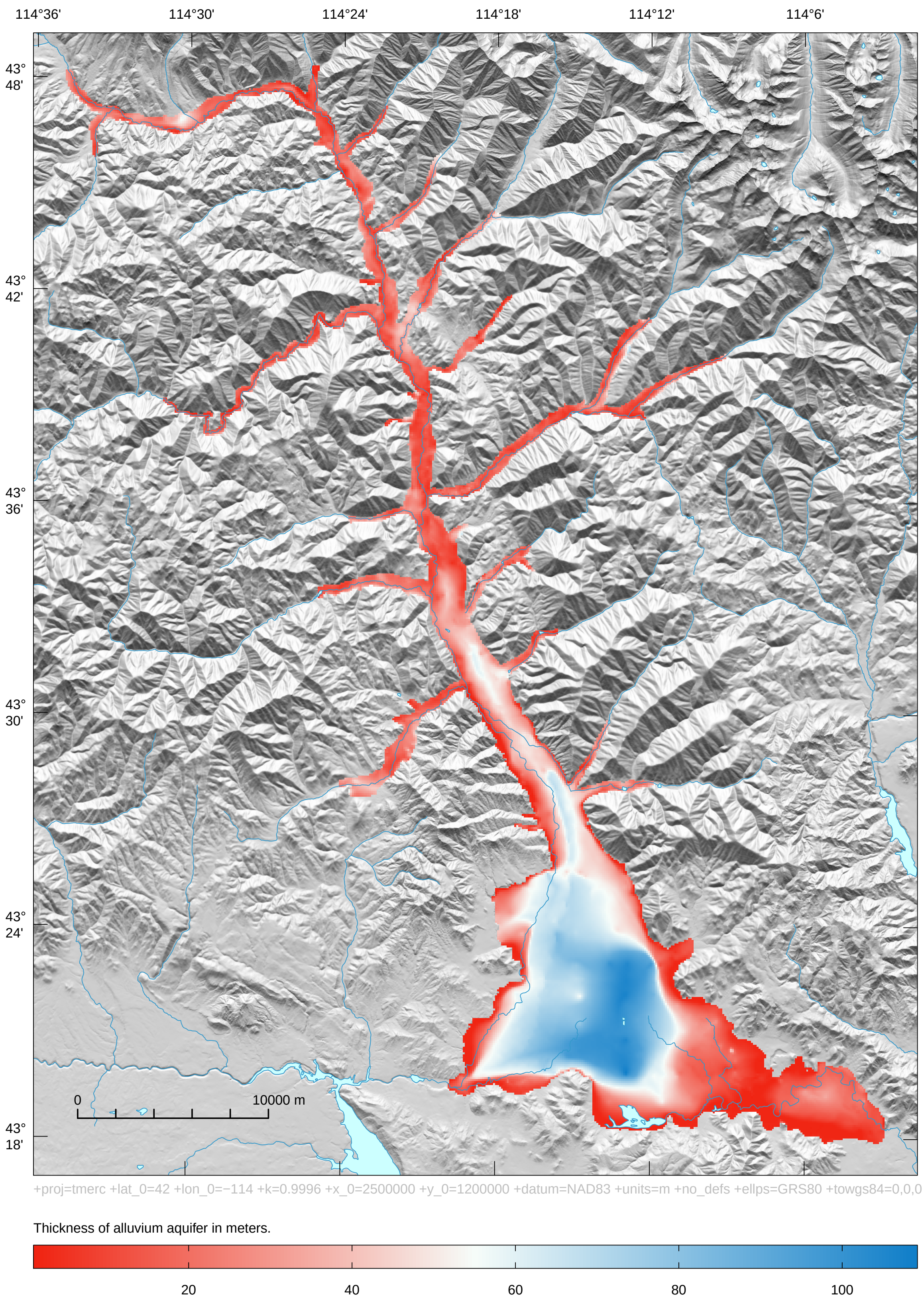

Figure 2: Thickness of Quaternary sediment in the aquifer system.

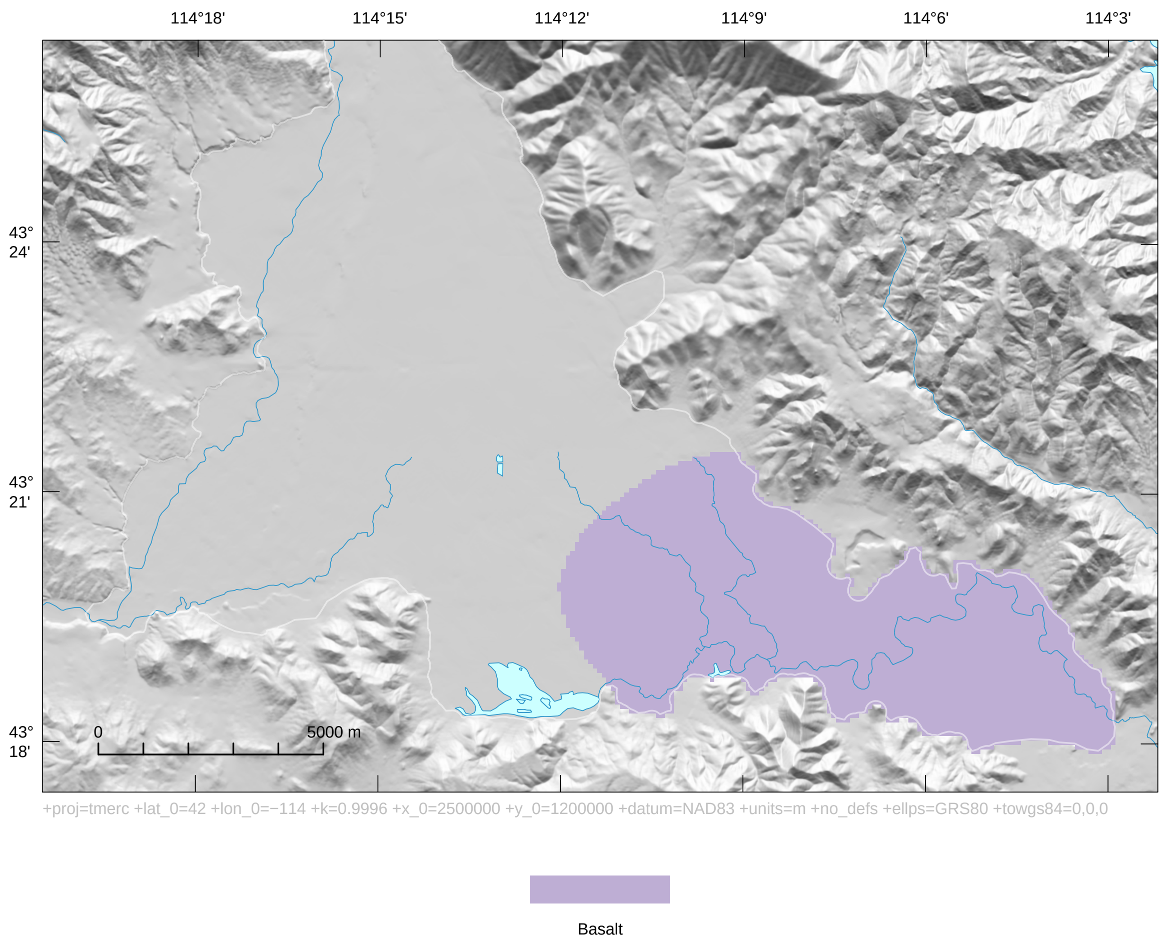

Figure 3: Extent of basalt in the aquifer system.

Basalt underlies the Quaternary sediment; however, very little data is available to describe the unit thickness of basalt. The few wells that penetrate the basalt unit are located at the Hayspur Fish Hatchery (fig. 1) and describe consistent unit thicknesses among wells of about 15 m (49 ft) for alluvium and 37 m (121 ft) for basalt. Summing these unit thicknesses gives the estimated depth, measured as the distance below land surface, to the bottom of the basalt unit at 52 m (170 ft). Note that this depth is assumed constant throughout the extent of the basalt unit. Transmissive materials that may be present beneath the basalt unit are neglected due to insufficient data to describe these materials. The bedrock surface elevation for the aquifer system is then calculated by integrating units.

```r
depth.to.basalt.bottom <- 52  # in meters
r <- rs.data[["land.surface"]] - depth.to.basalt.bottom
r[r > rs.data[["alluvium.bottom"]] | is.na(rs.data[["basalt.extent"]])] <- NA
basalt.bottom <- r
r <- rs.data[["alluvium.bottom"]]
is.basalt.cell <- !is.na(basalt.bottom)
r[is.basalt.cell] <- basalt.bottom[is.basalt.cell]
names(r) <- "bedrock"
rs.data <- stack(rs.data, r)
```

Subtracting bedrock surface elevations from land surface elevations gives the thickness of the WRV aquifer system (fig. 4).

```r
r <- rs.data[["land.surface"]] - rs.data[["bedrock"]]
r[is.na(rs.data[["alluvium.bottom"]])] <- NA
names(r) <- "aquifer.thickness"
rs.data <- stack(rs.data, r)
```

The aquitard separating the unconfined aquifer from the underlying confined aquifer is represented with the clay unit. The estimated extent of the aquitard in the WRV aquifer system is shown in figure 5.

```r
r <- rasterize(gUnaryUnion(aquitard.extent), rs.data, getCover = TRUE, silent = TRUE)
r[r[] < min.coverage] <- NA
r[!is.na(r)] <- 1L
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- "Clay"
levels(r) <- rat
names(r) <- "aquitard.extent"
rs.data <- stack(rs.data, r)
```

Well driller reports and geophysical surveys describe the clay unit as about 5 m (16 ft) thick, and generally lying at a depth of about 30 m (98 ft).

```r
aquitard.thickness <- 5  # in meters
depth.to.aquitard.top <- 30  # in meters
r <- rs.data[["land.surface"]] - depth.to.aquitard.top
r[r < rs.data[["alluvium.bottom"]] | is.na(rs.data[["aquitard.extent"]])] <- NA
names(r) <- "aquitard.top"
rs.data <- stack(rs.data, r)
```

Vertical connectivity among cells is ensured by setting a minimum vertical overlap between adjacent cells. Cells having less than 2 m (6.6 ft) of overlap are made inactive (fig. 6).

```r
min.overlap <- 2  # minimum vertical overlap between adjacent cells, in meters
r <- FindConnectedCells(rs.data[["bedrock"]], rs.data[["land.surface"]], min.overlap)
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- c("Inactive", "Active")
```

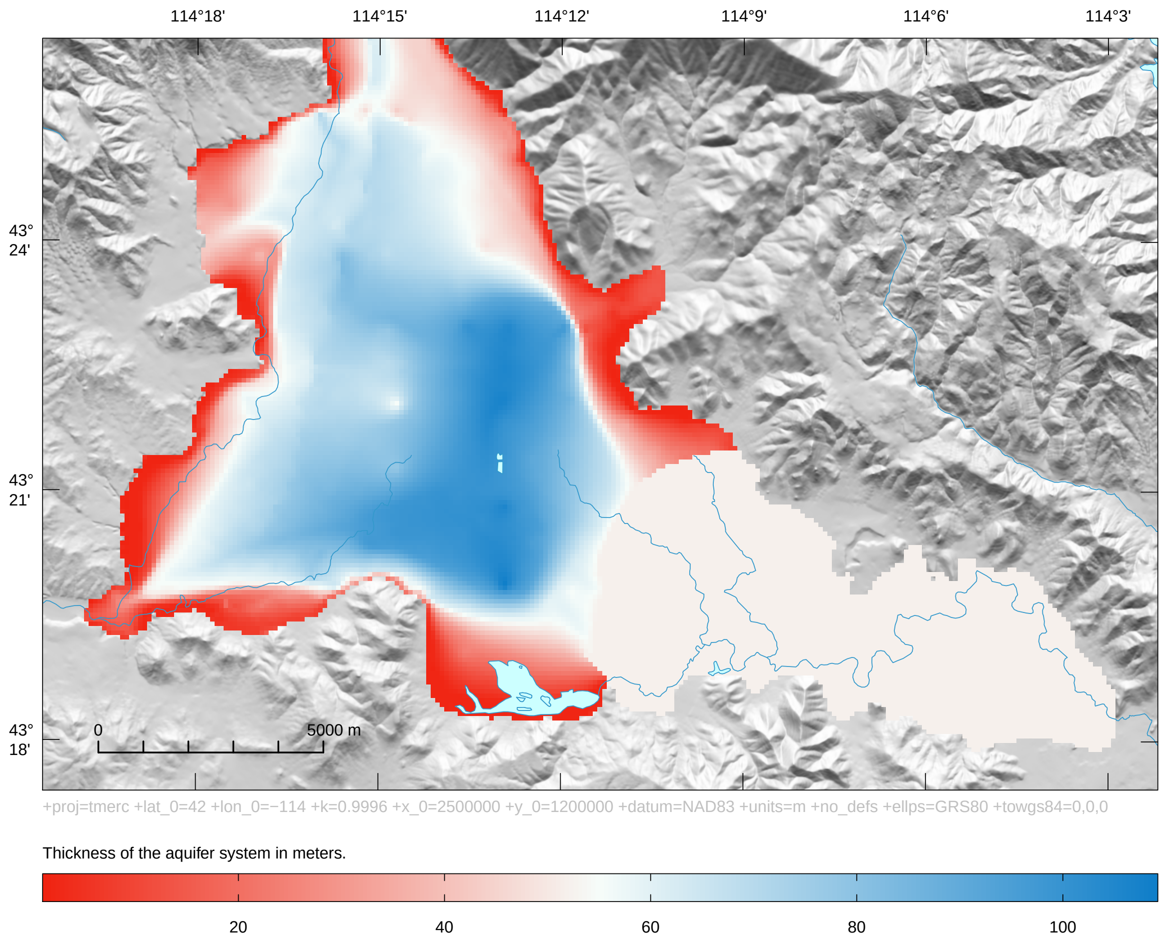

Figure 4: Thickness of the aquifer system.

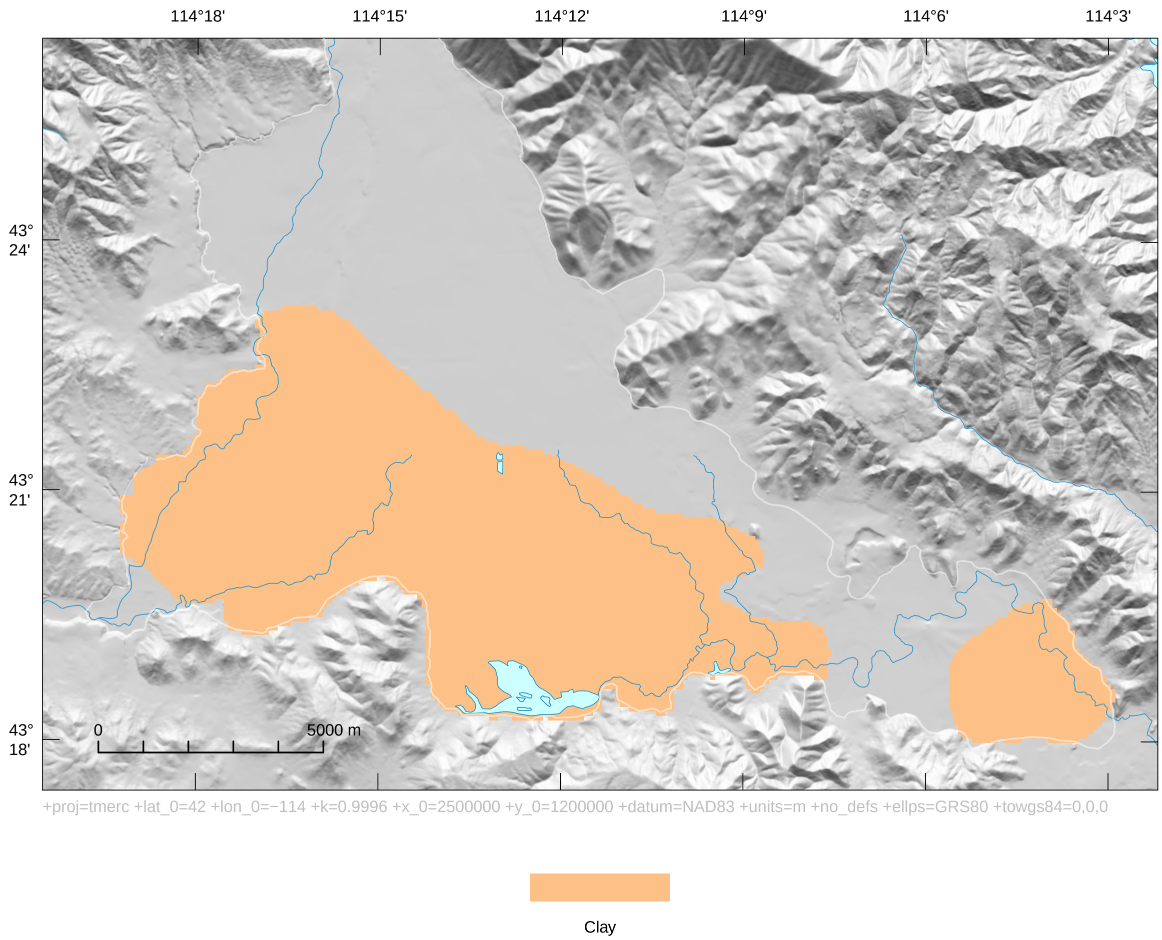

Figure 5: Extent of aquitard in the aquifer system.

```r
levels(r) <- rat
names(r) <- "is.connected"
rs.data <- stack(rs.data, r)
```

Groundwater enters the model domain through source cells located in the major tributary canyons and beneath the valley floor at the confluence of the Big Wood River and the North Fork Big Wood River (BWR Upper). A sparsity of field observations in the major tributary canyons indicates large uncertainty (or errors) in the historic flow contribution from each of the tributary canyons. Source cells are placed in the upper part of the tributary canyons to help contain the errors that propagate into the model from these boundaries. Therefore, computational results in the tributary canyons should be considered less reliable than in the WRV. Source cells are identified using horizontal polygons with a single polygon allocated to each of the 22 source areas. Active cells intersecting a polygon line segment are defined as source cells, and cells located within the body of a polygon are made inactive (fig. 7).

```r
l <- gIntersection(as(source.locations, "SpatialLinesDataFrame"), aquifer.extent, TRUE)
source.lines <- SpatialLinesDataFrame(l, data = source.locations@data, match.ID = FALSE)
r <- rs.data[["alluvium.bottom"]]
is.in.aquifer <- !is.na(r)
is.in.poly <- !is.na(rasterize(source.locations, rs.data, silent = TRUE))
is.on.line <- !is.na(rasterize(source.lines, rs.data))
r[is.in.aquifer &  is.in.poly] <- 0L  # inactive cells
r[is.in.aquifer & !is.in.poly] <- 1L  # active cells
r[is.in.aquifer &  is.on.line] <- 2L  # source cells
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- c("Inactive", "Active", "Source")
levels(r) <- rat
names(r) <- "is.below.src"
rs.data <- stack(rs.data, r)
```

Flow through the low-permeability aquitard that separates the alluvium aquifers may significantly influence groundwater pressure responses, necessitating a multi-layer model. Model layering was designed to allow accurate representation of the aquitard. Figure 8 shows a schematic cross-section representation of the hydrogeologic units and the three-layer model grid. Embedded clay within the basalt unit is assumed to have a negligible effect on groundwater flow. Model cells in model layers 2 and 3 become inactive north of Hailey (fig. 1).

The bottom elevation of model layer 1 is calculated by subtracting the depth to the top of the aquitard (30 m) from land surface. Cell values lying beneath the pre-Quaternary bedrock surface and top of Quaternary basalt are replaced with alluvium bottom elevations.

```r
rs.model <- stack()  # initialize a raster stack for model input
r <- rs.data[["land.surface"]] - depth.to.aquitard.top
r[is.na(rs.data[["alluvium.bottom"]])] <- NA
is.below <- rs.data[["alluvium.bottom"]] > r
r[is.below] <- rs.data[["alluvium.bottom"]][is.below]
r[(rs.data[["land.surface"]] - r) < min.thickness] <- NA  # enforce min. layer thickness
if ("is.connected" %in% names(rs.data))
  r[rs.data[["is.connected"]] == 0L] <- NA
r[rs.data[["is.below.src"]] == 0L] <- NA
r <- ExcludeSmallCellChunks(r)  # ensure horizontal connectivity among cells
names(r) <- "lay1.bottom"
rs.model <- stack(rs.model, r)
```

Subtracting the aquitard thickness (5 m) from the bottom of model layer 1 gives the bottom elevation of model layer 2. Cell values lying beneath the bedrock surface are replaced with bedrock elevations.

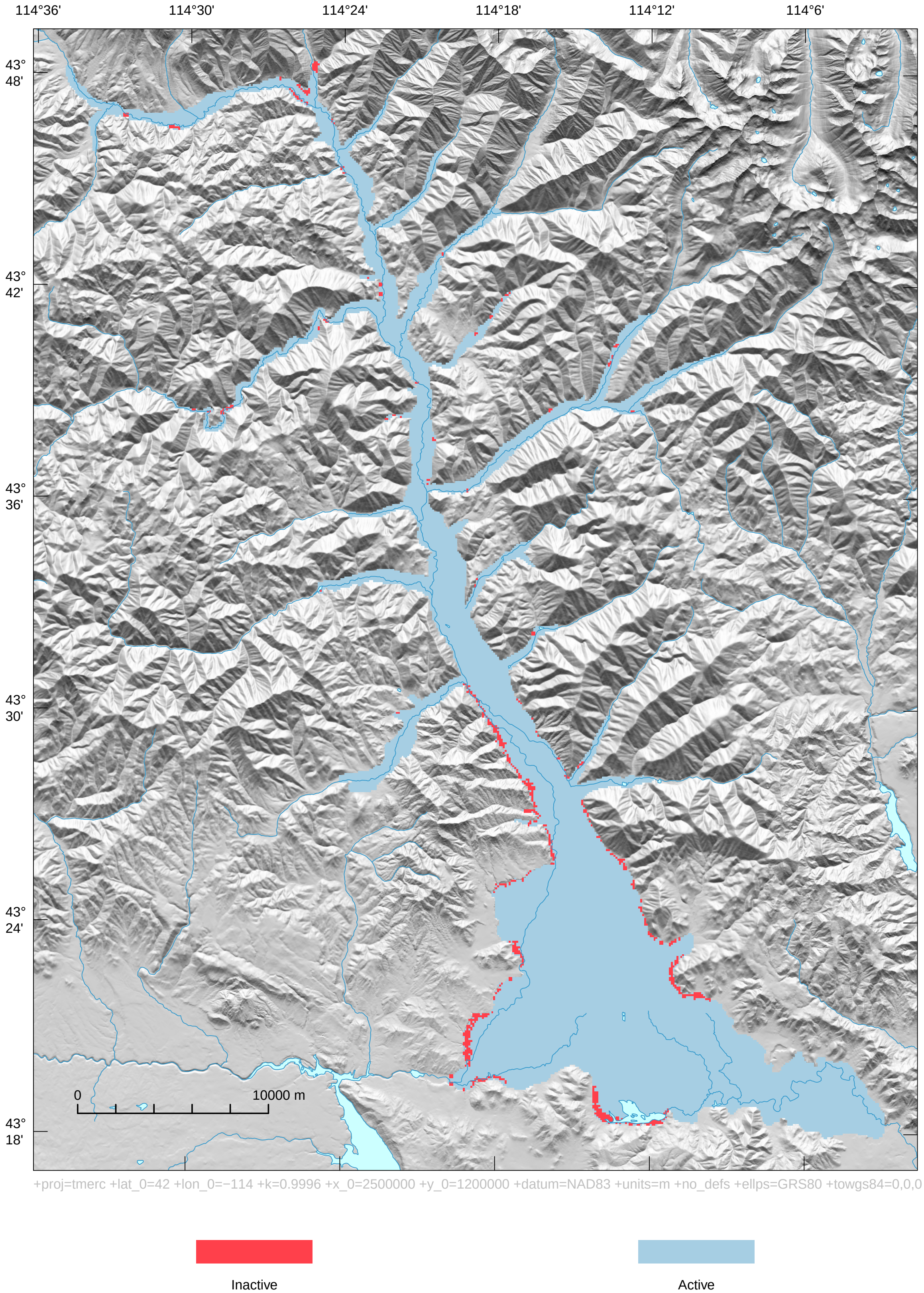

Figure 6: Vertical connectivity among cells.

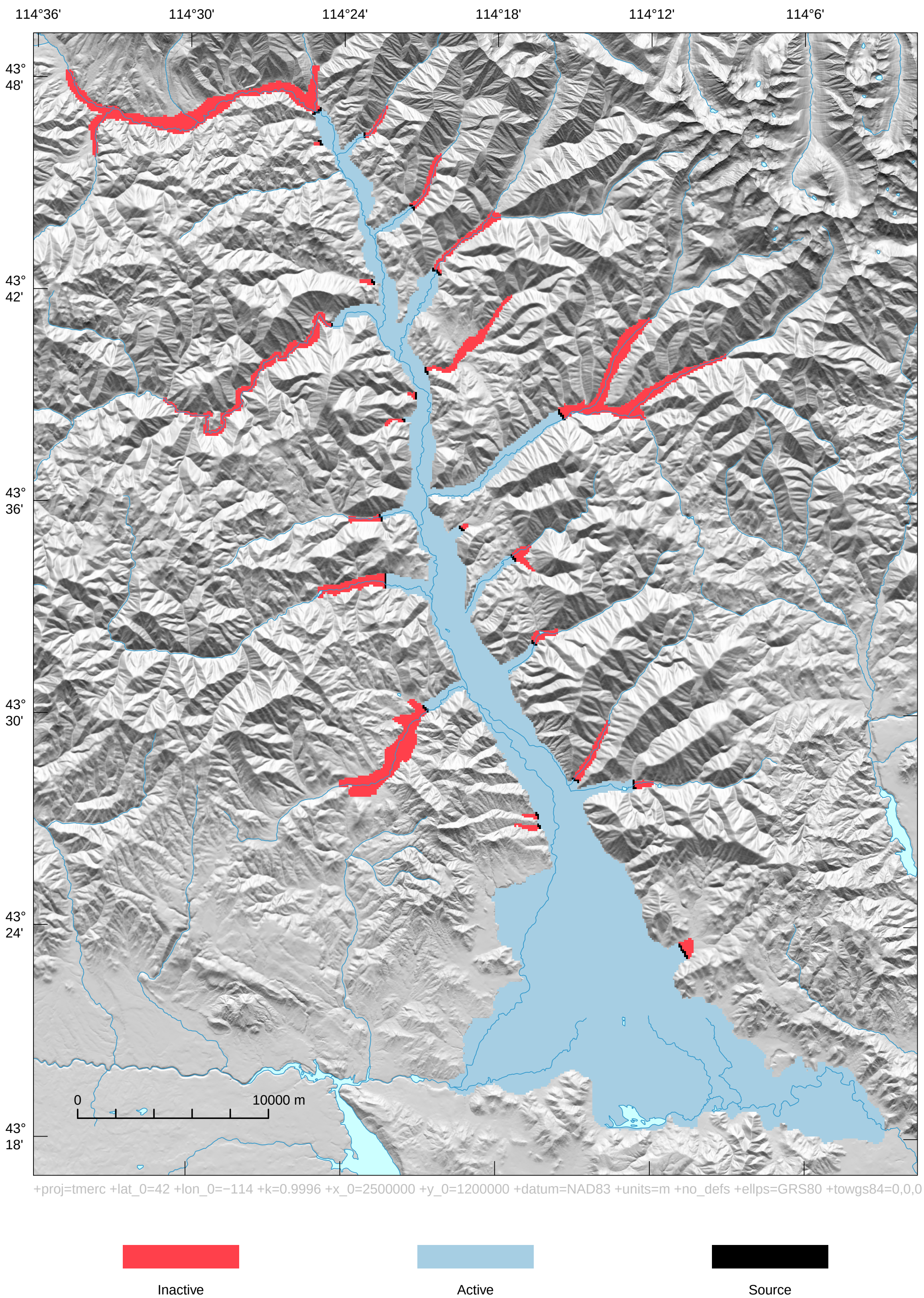

Figure 7: Location of source cells in the aquifer system.

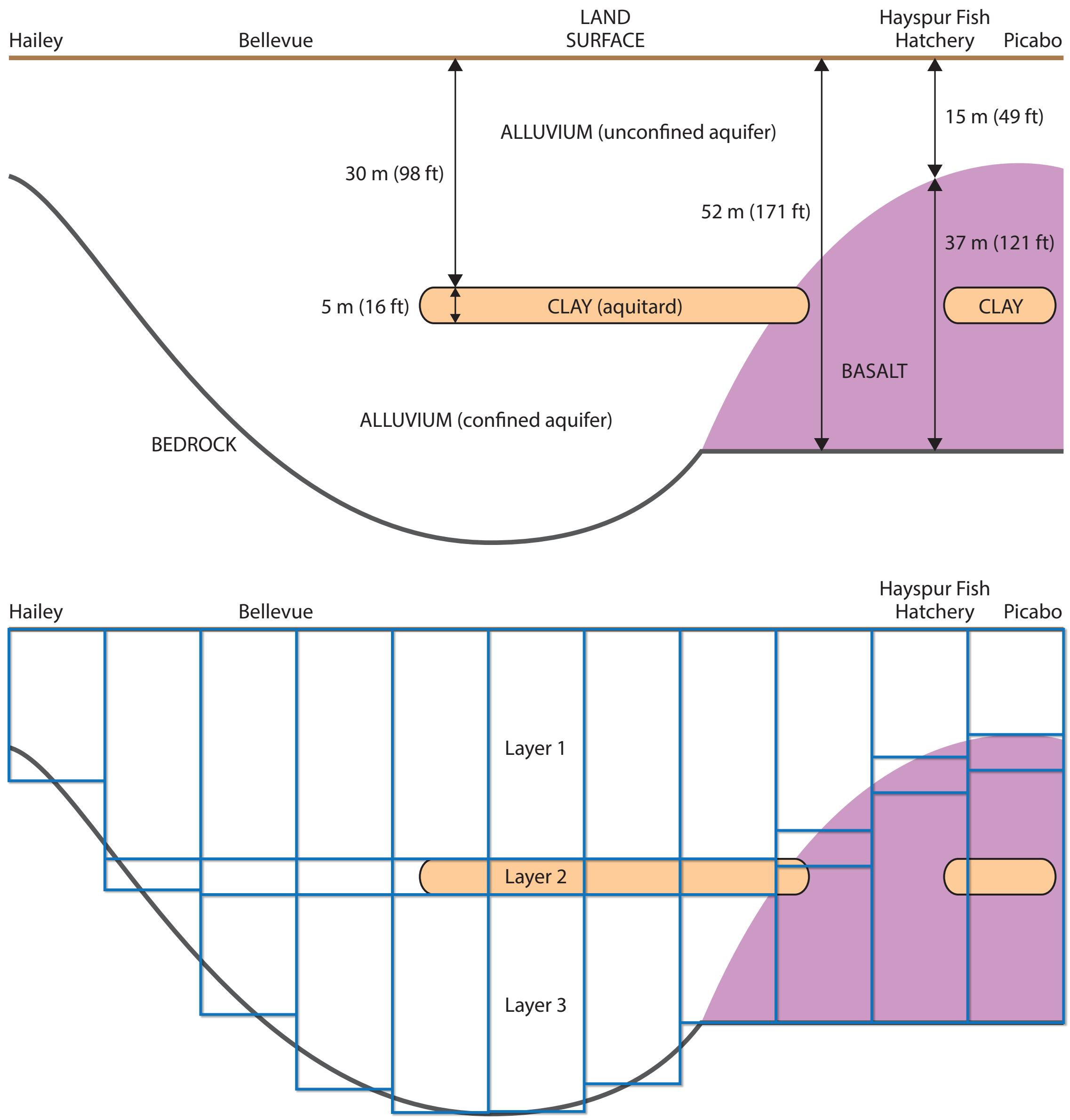

Figure 8: Schematic cross-section representation of hydrogeologic units and three-layer model grid.

```
r <- rs.model[["lay1.bottom"]] - aquitard.thickness
is.below <- rs.data[["bedrock"]] > r
r[is.below] <- rs.data[["bedrock"]][is.below]
r[(rs.model[["lay1.bottom"]] - r) < min.thickness] <- NA  # enforce minimum thickness
r <- ExcludeSmallCellChunks(r)
names(r) <- "lay2.bottom"
rs.model <- stack(rs.model, r)
```

The bottom elevation of model layer 3 is at bedrock.

```
r <- rs.data[["bedrock"]]
r[is.na(rs.model[["lay2.bottom"]])] <- NA
r[(rs.model[["lay2.bottom"]] - r) < min.thickness] <- NA  # enforce minimum thickness
r <- ExcludeSmallCellChunks(r)
```

```r
names(r) <- "lay3.bottom"
rs.model <- stack(rs.model, r)
```

Bottom elevations of model layer 1 are adjusted to bedrock where the cell value is above bedrock and its vertically adjacent cell is inactive in model layer 2.

```r
r <- rs.model[["lay1.bottom"]]
is.adjusted <- r > rs.data[["bedrock"]] & is.na(rs.model[["lay2.bottom"]])
r[is.adjusted] <- rs.data[["bedrock"]][is.adjusted]
r <- ExcludeSmallCellChunks(r)
rs.model[["lay1.bottom"]] <- r
```

The top elevation of model layer 1 is at land surface.

```r
r <- rs.data[["land.surface"]]
r[is.na(rs.model[["lay1.bottom"]])] <- NA
names(r) <- "lay1.top"
rs.model <- stack(rs.model, r)
```

Hydrogeologic Zones

Prior to model calibration, the distribution of hydraulic properties (such as hydraulic conductivity) is based on hydrogeologic zones, groups of model cells with uniform hydraulic properties that compose part or all of a hydrogeologic unit. The model consists of four hydrogeologic zones described as follows:

Zone 1: composed of the alluvium unit under unconfined conditions and located in all three model layers;

Zone 2: composed of the basalt and clay units and located in model layers 2 and 3;

Zone 3: composed of the clay unit and located in model layer 2; and

Zone 4: composed of the alluvium unit under confined conditions and located in model layer 3.

The delineation of hydrogeologic zones in model layer 1 is shown in figure 9.

```r
r <- rs.model[["lay1.bottom"]]
r[!is.na(r)] <- 1L  # alluvium unit (unconfined aquifer)
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- "Zone 1"
levels(r) <- rat
names(r) <- "lay1.zones"
rs.model <- stack(rs.model, r)
```

The delineation of hydrogeologic zones in model layer 2 is shown in figure 10.

```r
r <- rs.model[["lay2.bottom"]]
r[!is.na(r)] <- 1L  # alluvium unit (unconfined aquifer)
r[!is.na(r) & !is.na(rs.data[["aquitard.extent"]])] <- 3L  # clay unit (aquitard)
r[rs.model[["lay2.bottom"]] < rs.data[["alluvium.bottom"]]] <- 2L  # basalt & clay units
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- c("Zone 1", "Zone 2", "Zone 3")
levels(r) <- rat
names(r) <- "lay2.zones"
rs.model <- stack(rs.model, r)
```

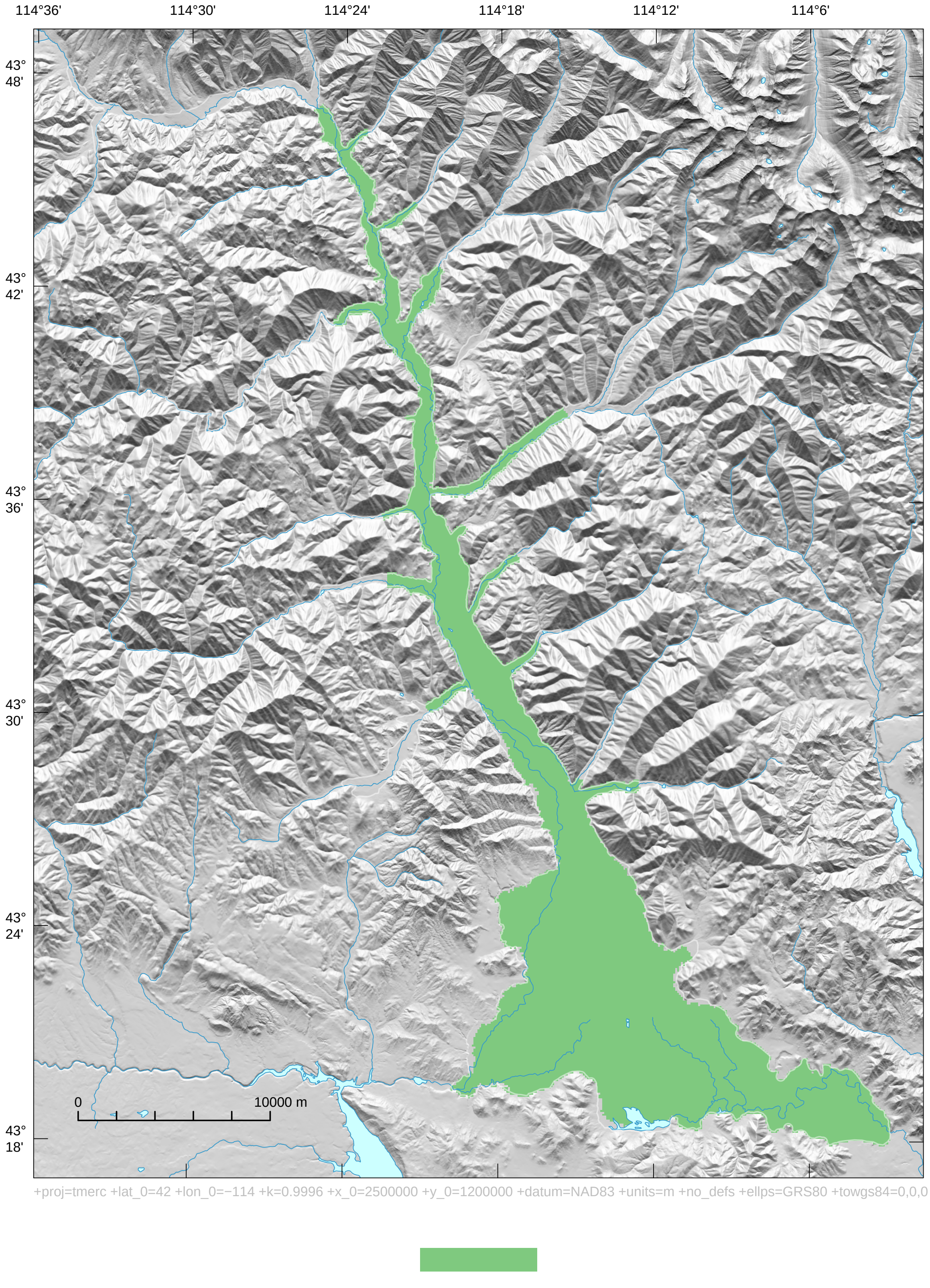

Figure 9: Hydrogeologic zones in model layer 1.

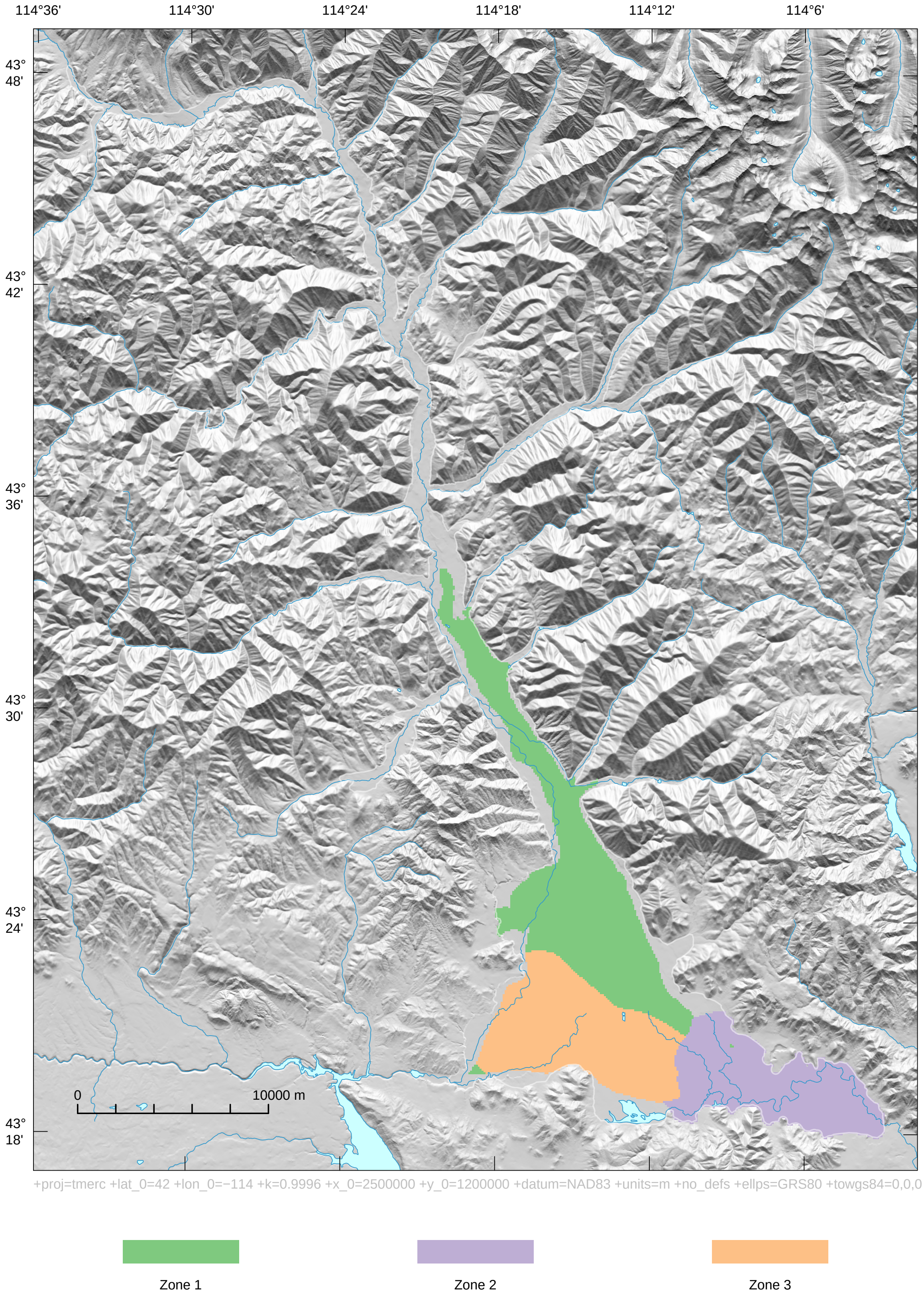

Figure 10: Hydrogeologic zones in model layer 2.

The delineation of hydrogeologic zones in model layer 3 is shown in figure 11.

```
r <- rs.model[["lay3.bottom"]]
r[!is.na(r)] <- 1L  # alluvium unit (unconfined aquifer)
r[!is.na(r) & rs.model[["lay2.zones"]] == 3L] <- 4L  # alluvium unit (confined aquifer)
r[rs.model[["lay3.bottom"]] < rs.data[["alluvium.bottom"]]] <- 2L  # basalt & clay units
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- c("Zone 1", "Zone 2", "Zone 4")
levels(r) <- rat
names(r) <- "lay3.zones"
rs.model <- stack(rs.model, r)
```

Groundwater Flow in the Tributary Canyons and Upper Big Wood River Valley

Groundwater entering the aquifer system (source) through the tributary canyons and upper Big Wood River Valley is simulated using the Flow and Head Boundary Package (Leake and Michael, 1997), a specified flow boundary condition. The estimated volumetric flux for a source area is based on steady-state conditions and given in table 1. For each source area, the volumetric flux is uniformly distributed among model cells where this boundary condition is applied (source cells).

Table 1: Volumetric flux in the tributary canyons and upper Big Wood River valley.

Name	Flow (m^3/d)	Flow (acre-ft/yr)
Adams Gulch	2,874	851
BWR Upper	491	145
Chocolate Gulch	176	52
Clear Creek	463	137
Cold Springs Gulch	675	200
Cove Canyon	490	145
Croy Creek	2,378	704
Deer Creek	4,937	1,462
Eagle Creek	3,428	1,015
East Fork	1,591	471
Elkhorn Gulch	172	51
Greenhorn Gulch	2,303	682
Indian Creek	8,129	2,407
Lake Creek	8,125	2,406
Lees Gulch	453	134
Ohio Gulch	865	256
Quigley Creek	1,891	560
Seamans Gulch	6,582	1,949
Slaughterhouse Gulch	1,709	506
Townshead Gulch	196	58
Trail Creek	9,787	2,898
Warm Springs Creek	1,645	487

```
r <- rs.model[[1]]
r[] <- NA
r.src <- rasterize(source.lines, r)
is.active <- !is.na(rs.model[["lay1.bottom"]][])
r.src[!is.active] <- NA
```

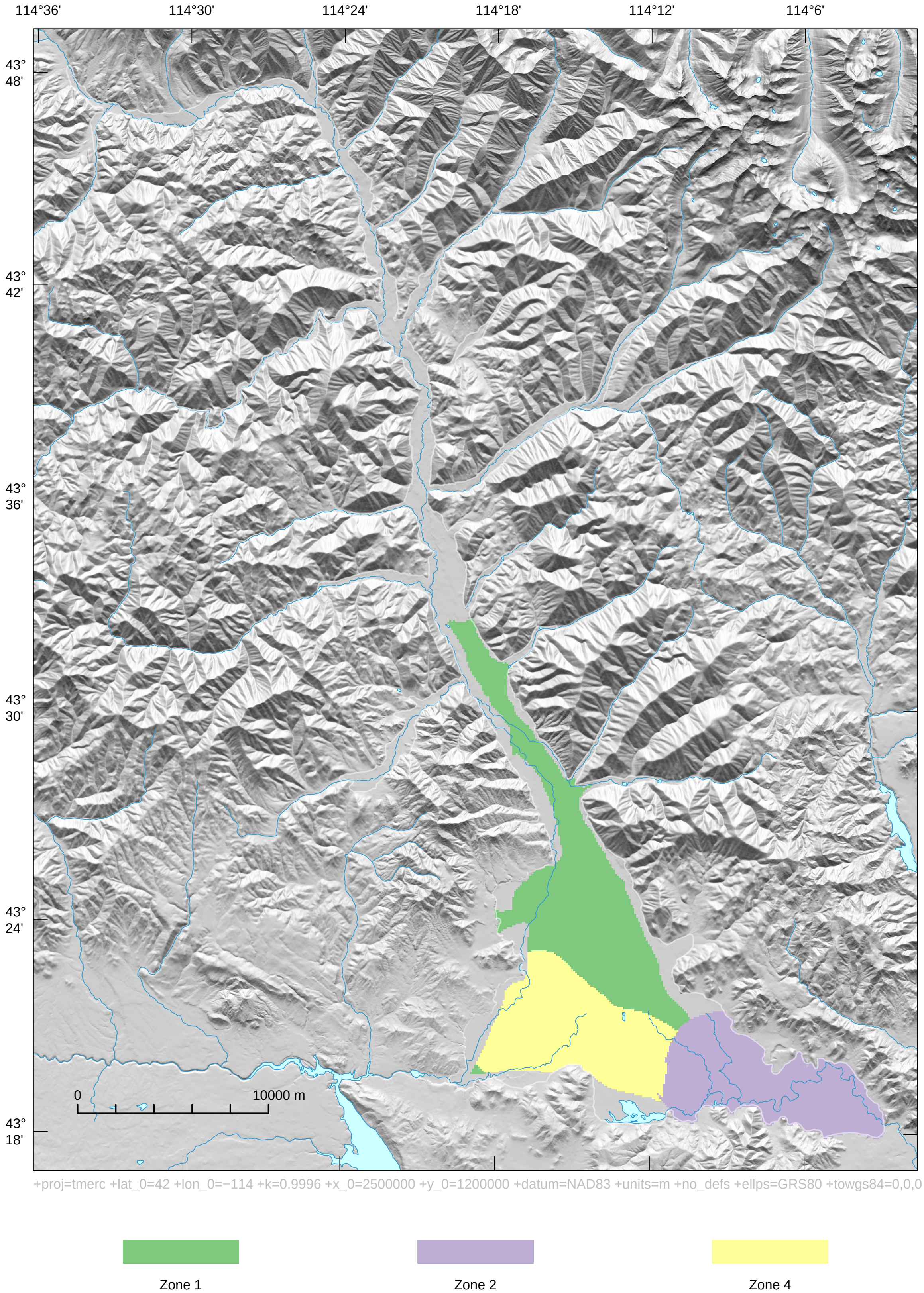

Figure 11: Hydrogeologic zones in model layer 3.

```r
src.cells <- which(!is.na(r.src[]))
adj.cells <- adjacent(r.src, src.cells, directions = 4)
is.valid.src <- adj.cells[, 2] %in% which(is.active) & !(adj.cells[, 2] %in% src.cells)
rm.src.cells <- src.cells[!(src.cells %in% unique(adj.cells[is.valid.src, 1]))]
rs.model[["lay1.bottom"]][rm.src.cells] <- NA
rs.model[["lay1.top"]][rm.src.cells] <- NA
r.src[rm.src.cells] <- NA
rat <- levels(r.src)[[1]]
for (i in seq_len(nrow(rat))) {
  trib.cells <- which(r.src[] == rat$ID[i])
  r[trib.cells] <- rat$Flow[i] / length(trib.cells)
}
names(r) <- "lay1.bdry.sources"
rs.model <- stack(rs.model, r)
```

Groundwater Flow Beneath Silver Creek and Stanton Crossing

Groundwater leaving the aquifer system (sink) beneath Silver Creek and Stanton Crossing (fig. 1) is simulated using the MODFLOW Drain Package (Harbaugh *et al.*, 2000), a head-dependent flux boundary condition. If the head in a model cell falls below a certain threshold, the flux drops to zero; therefore, these model cells will only allow groundwater to leave the aquifer system (sink cells). The specified head threshold at Silver Creek and Stanton Crossing are given in table 2. The location of sink cells in model layer 1 is shown in figure 12. Note that the Silver Creek sink cells also reside in model layers 2 and 3.

```r
l <- gIntersection(sink.locations, as(aquifer.extent, "SpatialLinesDataFrame"), TRUE)
sink.lines <- SpatialLinesDataFrame(l, data = sink.locations@data, match.ID = FALSE)
r <- rasterize(sink.lines, rs.model, field = "Head")
r[!is.na(r) & is.na(rs.model[["lay1.bottom"]])] <- NA
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- c("Silver Creek", "Staton Crossing")
levels(r) <- rat
names(r) <- "lay1.bdry.sinks"
rs.model <- stack(rs.model, r)
r <- rasterize(sink.lines, rs.model, field = "Head")
r[!is.na(r) & is.na(rs.model[["lay2.bottom"]])] <- NA
names(r) <- "lay2.bdry.sinks"
rs.model <- stack(rs.model, r)
r <- rasterize(sink.lines, rs.model, field = "Head")
r[!is.na(r) & is.na(rs.model[["lay3.bottom"]])] <- NA
names(r) <- "lay3.bdry.sinks"
rs.model <- stack(rs.model, r)
```

Table 2: Specified hydraulic head thresholds for sink cell boundary conditions.

Name	Head (m)	Head (ft)
Silver Creek	1,432	4,698
Stanton Crossing	1,470	4,823

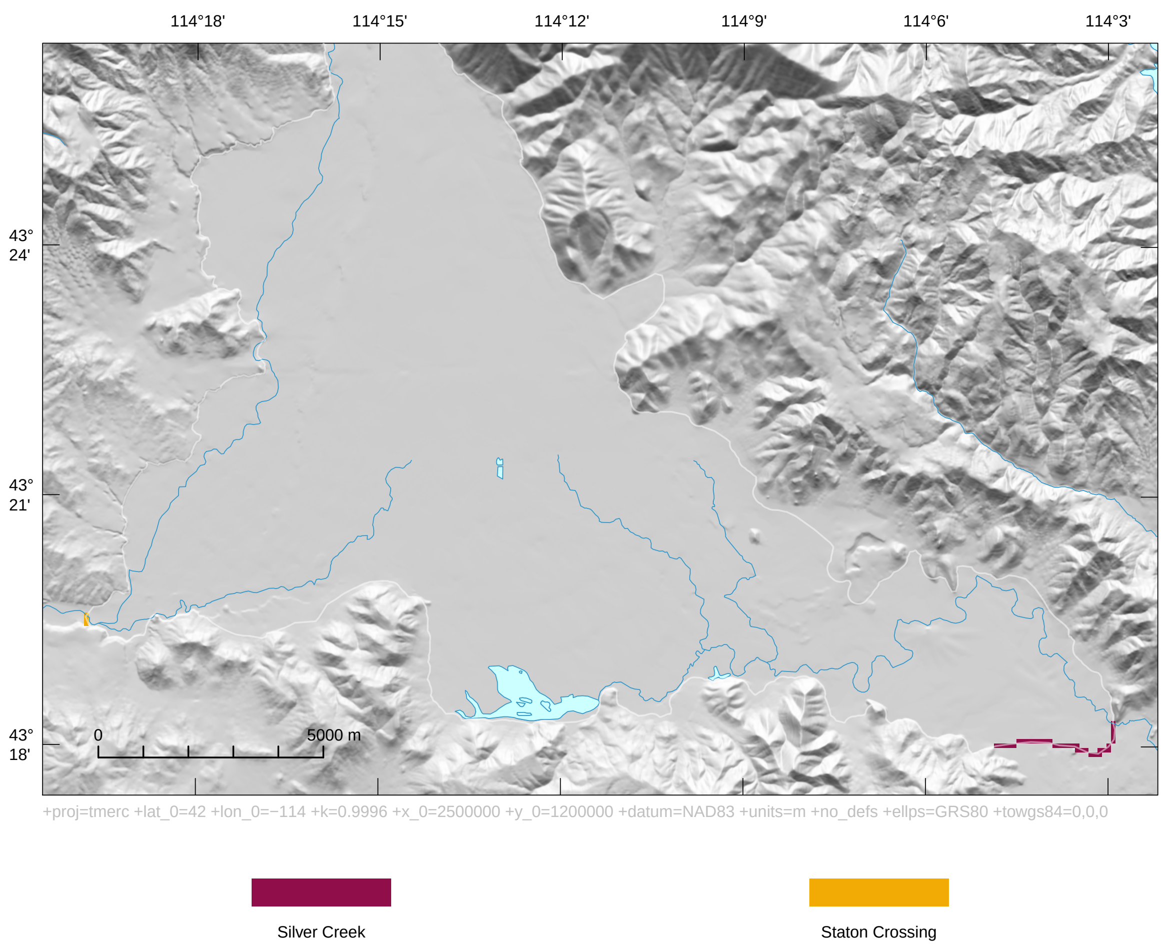

Figure 12: Location of sink cells in model layer 1.

Stream-Aquifer Flow Exchange in the Big Wood River and Silver Creek

Stream-aquifer flow exchange in the Big Wood River and Silver Creek is simulated using the MODFLOW River Package (Harbaugh *et al.*, 2000), a head-dependent flux boundary condition. Note that the River Package does not account for the amount of flow in streams. Use of a more sophisticated package that accounts for streamflow, such as the Streamflow-Routing Package (Niswonger and Prudic, 2005), is infeasible due to insufficient data to describe these flows. To simplify the structural complexity of the rivers, 21 major stream reaches were identified. A stream reach is defined as a section of a stream that has uniform (1) depth, (2) riverbed thickness, and (3) riverbed conductance (table 3).

Table 3: Description of stream reaches in the Big Wood River and Silver Creek.

Reach name	Type	Depth (m)	Depth (ft)	Bed (m)	Bed (ft)
Big Wood, Nr Ketchum to Hulen Rd	river	0.6	2	0.3	1
Big Wood, Hulen Rd to Ketchum	river	0.6	2	0.3	1
Big Wood, Ketchum to Gimlet	river	0.6	2	0.3	1
Big Wood, Gimlet to Hailey	river	0.6	2	0.3	1
Big Wood, Hailey to N Broadford	river	0.6	2	0.3	1
Big Wood, N Broadford to S Broadford	river	0.6	2	0.3	1
Big Wood, S Broadford to Glendale	river	0.6	2	0.3	1
Big Wood, Glendale to Sluder	river	0.6	2	0.3	1
Big Wood, Sluder to Wood River Ranch	river	0.6	2	0.3	1
Big Wood, Wood River Ranch to Stanton Crossing	drain	0.6	2	0.3	1
Willow Creek	drain	0.3	1	0.9	3
Buhler Drain abv Hwy 20	drain	0.3	1	0.9	3
Patton Creek abv Hwy 20	drain	0.3	1	0.9	3
Cain Creek abv Hwy 20	drain	0.3	1	0.9	3
Chaney Creek abv Hwy 20	drain	0.3	1	0.9	3
Mud Creek abv Hwy 20	drain	0.3	1	0.9	3
Wilson Creek abv Hwy 20	drain	0.3	1	0.9	3
Grove Creek abv Hwy 20	drain	0.3	1	0.9	3
Loving Creek abv Hwy 20	drain	0.3	1	0.9	3
Spring creeks blw Hwy 20	river	0.6	2	0.9	3
Silver Creek, Sportsman Access to Nr Picabo	river	0.6	2	0.9	3

River cells are identified using horizontal polylines with a single polyline allocated to each of the 21 stream reaches.

```
r <- rasterize(bwr.sc, rs.model[[1]], field = "ReachNo")
r[is.na(rs.model[["lay1.bottom"]]) | !is.na(rs.model[["lay1.bdry.sinks"]])] <- NA
names(r) <- "riv.reach"
rs.model <- stack(rs.model, r)
```

Stream stage is based on the stream reach type (table 3). For stream reaches of type "river", the stream depth is assumed at land surface; whereas for type "drain", the depth is specified at the riverbed bottom. Figure 13 shows the delineation of stream reach types.

```
r <- rasterize(bwr.sc, rs.model[[1]], field = "DrainRiver")
r[is.na(rs.model[["riv.reach"]])] <- NA
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- c("Drain", "River")
levels(r) <- rat
names(r) <- "riv.bc"
```

```r
rs.model <- stack(rs.model, r)
```

Calculate the stream stage and riverbed bottom elevation of river cells.

```r
r.depth <- rasterize(bwr.sc, rs.model[[1]], field = "Depth")
r.riverbed <- rasterize(bwr.sc, rs.model[[1]], field = "BedThk")
r <- rs.model[["lay1.top"]] - r.depth - r.riverbed
r[is.na(rs.model[["riv.reach"]])] <- NA
names(r) <- "riv.bottom"
rs.model <- stack(rs.model, r)
```

Model Grid

Removing outer rows and columns that are all inactive results in the horizontal model grid. A summary of the model grid attributes is given in table 4.

```r
rs.model <- crop(rs.model, trim(rs.model[["lay1.bottom"]]))
```

Table 4: Summary description of the model grid attributes.

Attribute	Value
Number of rows	542
Number of columns	299
Number of layers	3
Number of active model cells	53,841
Uniform spacing in the easting direction (m)	100
Uniform spacing in the northing direction (m)	100
Easting coordinate of model origin (m)	2,466,200
Northing coordinate of model origin (m)	1,344,139

Active and inactive cells are located in the model grid.

```r
r <- rs.model[["lay1.bottom"]]
r[] <- as.integer(!is.na(r[]))
names(r) <- "lay1.ibound"
rs.model <- stack(rs.model, r)
r <- rs.model[["lay2.bottom"]]
r[] <-  as.integer(!is.na(r[]))
names(r) <- "lay2.ibound"
rs.model <- stack(rs.model, r)
r <- rs.model[["lay3.bottom"]]
r[] <-  as.integer(!is.na(r[]))
names(r) <- "lay3.ibound"
rs.model <- stack(rs.model, r)
```

Initial Head Distribution

The initial head distribution is specified as a fraction of the saturated thickness in model layer 1. For example, a fraction of 0.9 indicates that 90 percent of model layer 1 is saturated, and layers 2 and 3 are completely saturated.

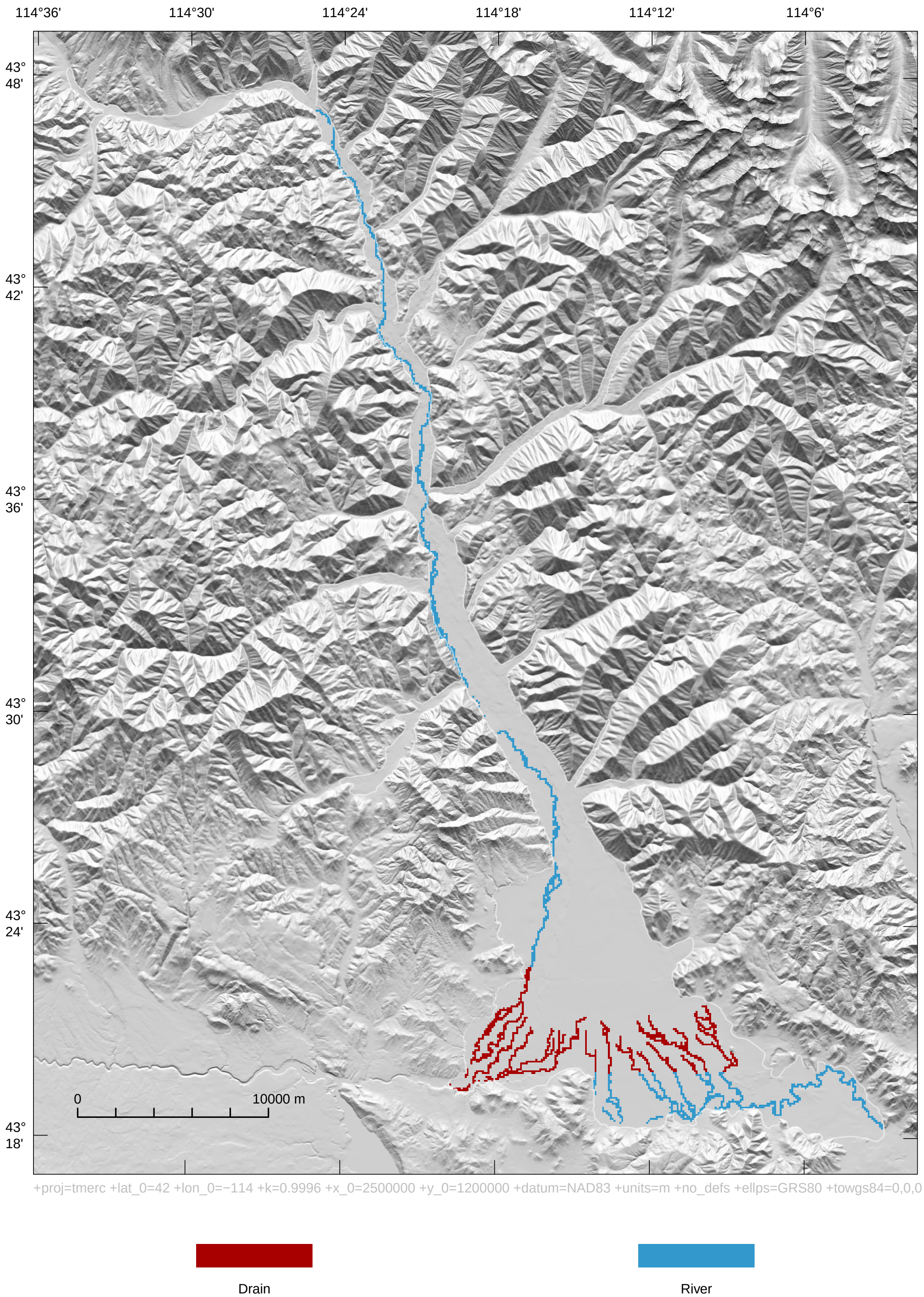

Figure 13: Stream-reach types in the Big Wood River and Silver Creek.

```r
initial.head.frac <- 0.90
r <- rs.model[["lay1.bottom"]] + rs.model[["lay1.thickness"]] * initial.head.frac
names(r) <- "lay1.strt"
rs.model <- stack(rs.model, r)
r <- rs.model[["lay1.strt"]]
r[is.na(rs.model[["lay2.bottom"]])] <- NA
names(r) <- "lay2.strt"
rs.model <- stack(rs.model, r)
r <- rs.model[["lay1.strt"]]
r[is.na(rs.model[["lay3.bottom"]])] <- NA
names(r) <- "lay3.strt"
rs.model <- stack(rs.model, r)
```

Export Raster Layers

Create georeferenced image files from layers in the raster stacks. Place these files in a subdirectory of the working directory.

```r
dir.out <- file.path(getwd(), paste0("wrv_", format(Sys.time(), "%Y%m%d%H%M%S")))
dir.create(path = dir.out)
ExportRasterStack(file.path(dir.out, "Data"), rs.data)
ExportRasterStack(file.path(dir.out, "Model"), rs.model)
```

Model Run

Steady-state flow in the WRV aquifer system is simulated using the MODFLOW-USG groundwater flow model. This numerical model was chosen for its ability to solve complex unconfined groundwater flow simulations. Input files for MODFLOW-USG are created from raster layers and parameters given in table 5. Horizontal hydraulic conductivity values for the hydrogeologic zones are based on previous estimates by Bartolino and Adkins (2012, table 2, pg. 25-26). Parameter values should be viewed as preliminary and subject to change during model calibration.

```r
id <- "wrv_ss_mfusg"  # model run identifier
dir.run <- file.path(dir.out, "Run")
args <- list(rs.model = rs.model, id = id, dir.run = dir.run, perlen = 5479,
             hk = c(21.0, 15.2, 8.6e-7, 12.8), vani = 1000, riv.cond = 850)
do.call(CreateModflowInputFiles, args)
```

Table 5: Input parameters for model run.

Parameter	Value
Length of stress period (d)	5,479
Horizontal hydraulic conductivity of Zone 1 (m/d)	21
Horizontal hydraulic conductivity of Zone 2 (m/d)	15.2
Horizontal hydraulic conductivity of Zone 3 (m/d)	8.6e-07
Horizontal hydraulic conductivity of Zone 4 (m/d)	12.8
Global vertical anisotropy	1,000
Global conductance of riverbed (m^2/d)	850

Create and execute a *batch file* containing commands that run MODFLOW-USG.

```r
cmd <- NULL
cmd[1] <- paste("cd", shQuote(dir.run))
cmd[2] <- paste(shQuote(file.exe), shQuote(paste0(id, ".nam")))
file.bat <- file.path(dir.run, "Run.bat")
cat(cmd, file = file.bat, sep = "\n")
Sys.chmod(file.bat, mode = "755")
output <- system(shQuote(file.bat), intern = TRUE)
```

Captured output from running the model is provided below.

```
#                                   MODFLOW-USG
#     U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUNDWATER FLOW MODEL
#                              Version 1.1.00 08/23/2013
#
#  Using NAME file: wrv_ss_mfusg.nam
#  Run start date and time (yyyy/mm/dd hh:mm:ss): 2014/03/25 12:04:56
#
#  Solving:  Stress period:     1    Time step:     1    Groundwater Flow Eqn.
#  Run end date and time (yyyy/mm/dd hh:mm:ss): 2014/03/25 12:07:01
#  Elapsed run time:  2 Minutes,  5.236 Seconds
#
#   Normal termination of simulation
```

The volumetric budget at the end of the 15 year simulation is given in table 6.

Table 6: Volumetric budget for entire model at end of time step 1 stress period 1.

	Vol. (m^3)	Vol. (acre-ft)	Rate (m^3/d)	Rate (acre-ft/yr)
Storage in	0	0	0	0
Constant head in	0	0	0	0
Drains in	0	0	0	0
River leakage in	1,023,633,780	829,869	186,829	55,321
Specified flows in	325,233,440	263,670	59,360	17,577
Total in	1,348,867,220	1,093,538	246,189	72,898
Storage out	0	0	0	0
Constant head out	0	0	0	0
Drains out	277,392,985	224,885	50,628	14,991
River leakage out	1,071,474,524	868,653	195,560	57,907
Specified flows out	0	0	0	0
Total out	1,348,867,509	1,093,538	246,189	72,898
In minus out	-290	-0	-0	-0
Percent discrepancy	-0	-0	-0	-0

Post-Processing

Read simulated hydraulic heads (heads) for each model layer into a raster stack.

```r
heads <- ReadModflowBinaryFile(file.path(dir.run, paste0(id, ".hds")))
rs.head <- stack()  # initialize a raster stack for simulated heads
r <- rs.model[[1]]
```

```
r[] <- heads[[1]]$d
r[!rs.model[["lay1.ibound"]]] <- NA
names(r) <- "lay1.head"
rs.head <- stack(rs.head, r)
r[] <- heads[[2]]$d
r[!rs.model[["lay2.ibound"]]] <- NA
names(r) <- "lay2.head"
rs.head <- stack(rs.head, r)
r[] <- heads[[3]]$d
r[!rs.model[["lay3.ibound"]]] <- NA
names(r) <- "lay3.head"
rs.head <- stack(rs.head, r)
```

Determine which model cells are saturated in model layer 1 (fig. 14).

```
r <- rs.head[["lay1.head"]] > rs.model[["lay1.top"]] & rs.head[["lay1.head"]] < 1e30
r <- ratify(r)
rat <- levels(r)[[1]]
rat$att <- c("Partially Saturated", "Saturated")
levels(r) <- rat
names(r) <- "lay1.saturated"
rs.head <- stack(rs.head, r)
```

Determine the simulated elevation of the water table (fig. 15). Heads above land surface are specified using the land surface elevation.

```
is.above.land.surface <- rs.head[["lay1.head"]] > rs.model[["lay1.top"]]
is.in.lay2 <- rs.head[["lay2.head"]] > rs.model[["lay2.bottom"]] &
              rs.head[["lay2.head"]] < rs.model[["lay1.bottom"]]
is.in.lay3 <- rs.head[["lay3.head"]] < rs.model[["lay2.bottom"]]
r <- rs.head[["lay1.head"]]
r[is.above.land.surface] <- rs.model[["lay1.top"]][is.above.land.surface]
r[is.in.lay2] <- rs.head[["lay2.head"]][is.in.lay2]
r[is.in.lay3] <- rs.head[["lay3.head"]][is.in.lay3]
names(r) <- "water.table"
rs.head <- stack(rs.head, r)
```

Write simulated heads to georeferenced image files.

```
ExportRasterStack(dir.run, rs.head)
```

Reproducibility

To reprocess the groundwater flow model, evaluate R code extracted from this vignette using the following command:

```
source(system.file("doc", "wrv-process.R", package = "wrv"), echo = TRUE)
list.files(dir.out, full.names = TRUE, recursive = TRUE)  # path names of output files
```

Version information about R and attached or loaded packages is as follows:

- R version 3.0.3 (2014-03-06), `x86_64-w64-mingw32`
- Base packages: base, datasets, grDevices, graphics, methods, stats, utils

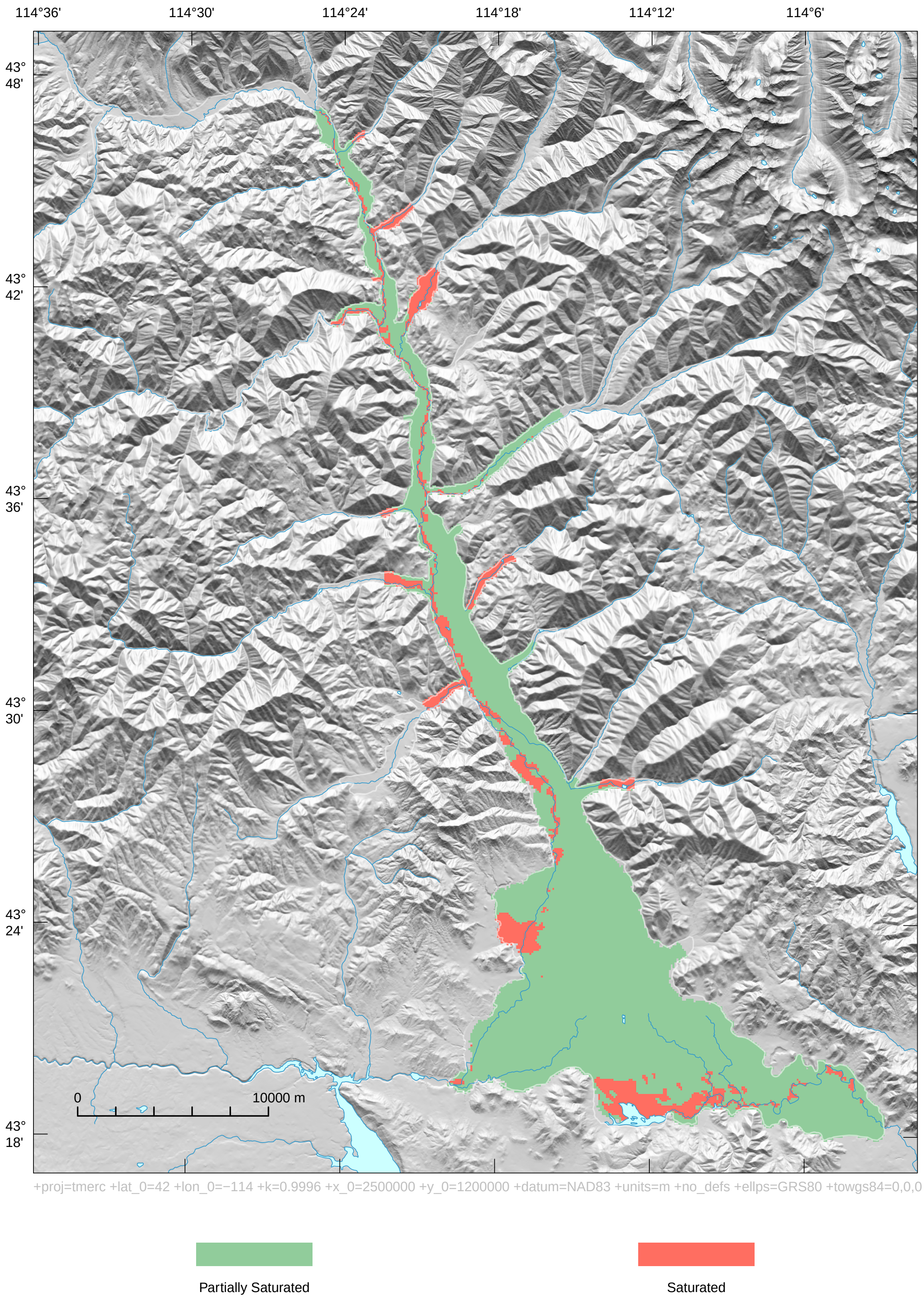

Figure 14: Saturated and partially-saturated cells in model layer 1.

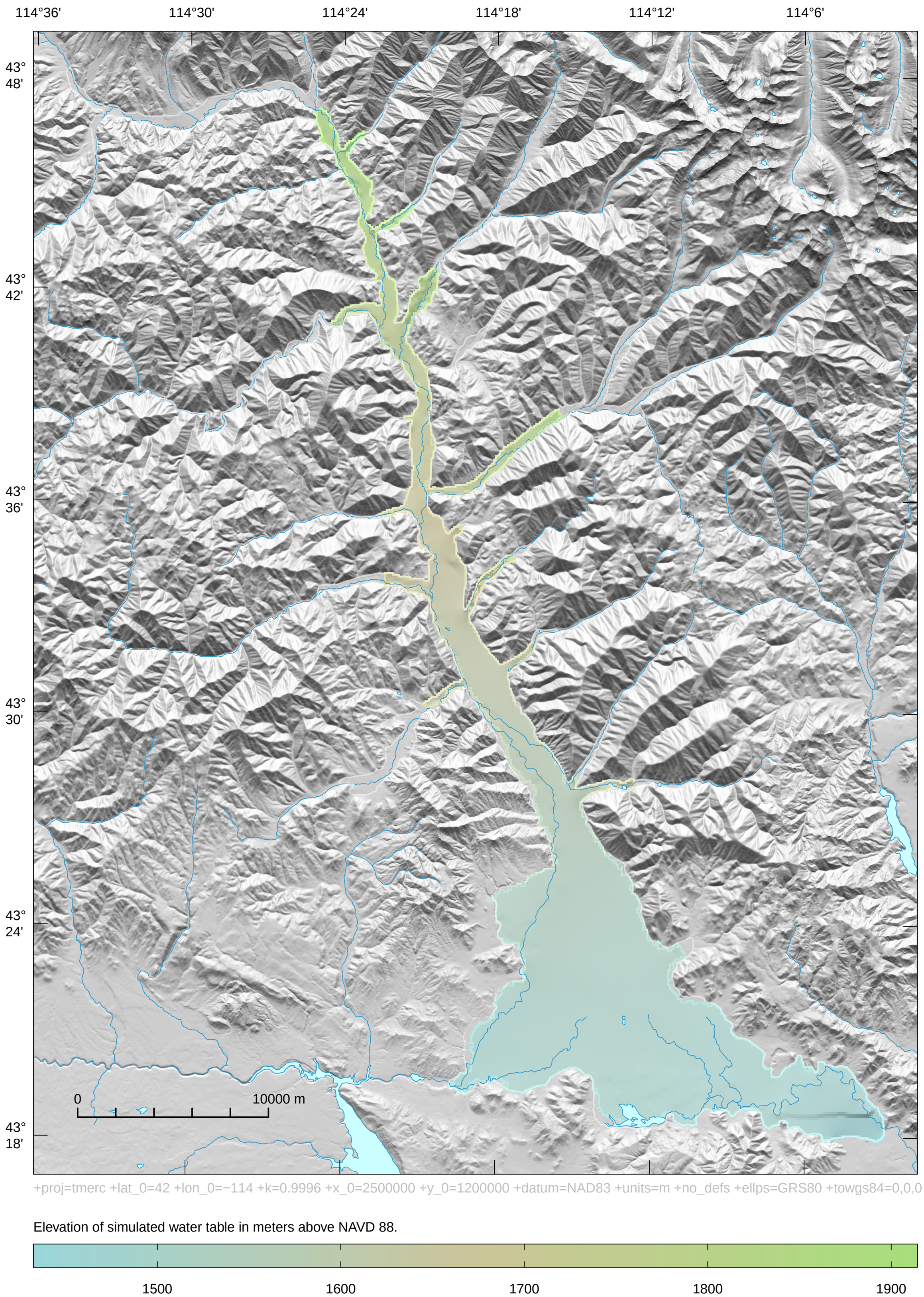

Figure 15: Simulated elevation of the water table.

- Other packages: RCurl 1.95-4.1, bitops 1.0-6, igraph 0.7.0, png 0.1-7, raster 2.2-31, rgdal 0.8-16, rgeos 0.3-3, sp 1.0-14, wrv 0.1-4, xtable 1.7-3
- Loaded via a namespace (and not attached): evaluate 0.5.1, formatR 0.10, grid 3.0.3, highr 0.3, knitr 1.5, lattice 0.20-27, stringr 0.6.2, tools 3.0.3

Total processing time for this vignette was 31 minutes, built on March 25, 2014.

References

Bartolino J, Adkins C (2012). "Hydrogeologic framework of the Wood River Valley aquifer system, south-central Idaho." *Scientific Investigations Report 2012-5053*, U.S. Geological Survey. URL http://pubs.usgs.gov/sir/2012/5053/.

Bartolino J, Fisher J, Wylie A, McVay M, Sukow J, Vincent S (2015). "Groundwater flow model of the Wood River Valley aquifer system, south-central Idaho." U.S. Geological Survey: Scientific Investigations Report.

Fisher J (2014). *Pre- and post-processing program for the groundwater-flow model of the Wood River Valley, Idaho*. U.S. Geological Survey. R package version 0.1, URL https://github.com/jfisher-usgs/wrv.

Harbaugh A, Banta E, Hill M, McDonald M (2000). "MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model-User guide to modularization concepts and the Ground-Water Flow Process." *Open-File Report 00-92*, U.S. Geological Survey. URL http://pubs.er.usgs.gov/publication/ofr200092.

Leake S, Michael R (1997). "Documentation of a computer program (FHB1) for assignment of transient specified-flow and specified-head boundaries in applications of the Modular Finite-Difference Ground-Water Flow Model (MODFLOW)." *Open-File Report 97-571*, U.S. Geological Survey. URL http://pubs.er.usgs.gov/publication/ofr97571.

Niswonger R, Prudic D (2005). "Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams-A modification to SFR1." In *Techniques and Methods*, chapter A13, p. 50. U.S. Geological Survey. URL http://pubs.usgs.gov/tm/2005/tm6A16/.

Panday S, Langevin C, Niswonger R, Ibaraki M, Hughes J (2013). "MODFLOW-USG version 1: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation." In *Techniques and Methods*, chapter A45, p. 66. U.S. Geological Survey. URL http://pubs.usgs.gov/tm/06/a45.

R Core Team (2014). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.