Design Document: WRV package vignette—Process for the groundwater-flow model of the Wood River Valley

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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

The WRV package vignette follows:

Process the Groundwater Flow Model

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Contents

1 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 *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 reader of this document is familiar with the R-programming language and have read the help pages for functions and data sets in the **wrv** package.

2 Software

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. Open an R session and install required and suggested packages with the following commands:

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

Load **wrv** in the current R session and open the help documentation for functions and data sets in this package.

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

MODFLOW-USG is a computer program for simulating three-dimensional, steady-state and transient groundwater 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. Specify the file path of the MODFLOW-USG executable.

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

3 Datums

Spatial data sets are in units of meters (m), in conformance with the North American Datum of 1983 (NAD 83), and placed in a Idaho Transverse Mercator projection (IDTM). Elevation, in this document, refers to distance above the North American Vertical Datum of 1988 (NAVD 88). Depth is defined as the vertical distance below land surface.

4 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). 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 units: a coarse-grained sand and gravel unit (alluvium), a fine-grained silt and clay unit (clay), and a basalt unit (basalt) (Bartolino and Adkins, 2012).

5 Pre-Processing

5.1 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. A 100 m (328 feet [ft]) resolution for the rectilinear grid 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 (*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 (65.6 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.

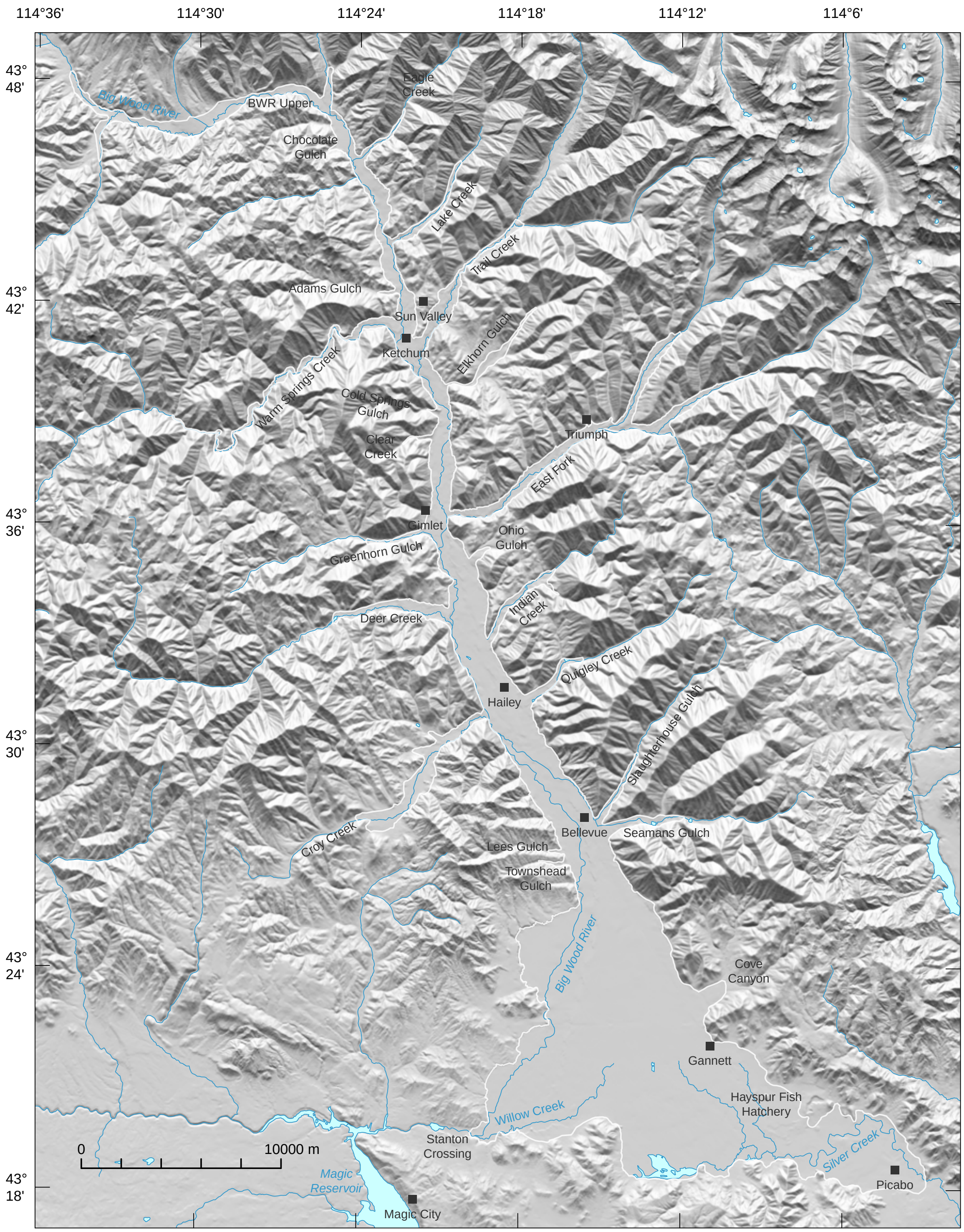

Figure 1: Land surface topography and extent of the aquifer system.

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

Thickness of the Quaternary sediment is easily calculated and shown in figure 2. Cells which are too thin can lead to numerical instability in the model; therefore, cells less than 1 m (3 ft) thick are made inactive.

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

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

```r
r <- rasterize(basalt.extent, rs, 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  # basalt cells
r <- as.factor(r)
rat <- levels(r)[[1]]  # raster attribute table
rat$att <- "Basalt"
levels(r) <- rat
names(r) <- "basalt.extent"
rs <- stack(rs, r)
```

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 and describe consistent unit thicknesses among wells of about 15 m (50 ft) for alluvium and 37 m (120 ft) for basalt. Summing these unit thicknesses gives the estimated depth 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[["land.surface"]] - depth.to.basalt.bottom
r[r > rs[["alluvium.bottom"]] | is.na(rs[["basalt.extent"]])] <- NA
basalt.bottom <- r
r <- rs[["alluvium.bottom"]]
is.basalt.cell <- !is.na(basalt.bottom)
r[is.basalt.cell] <- basalt.bottom[is.basalt.cell]
names(r) <- "bedrock"
rs <- stack(rs, r)
```

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

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

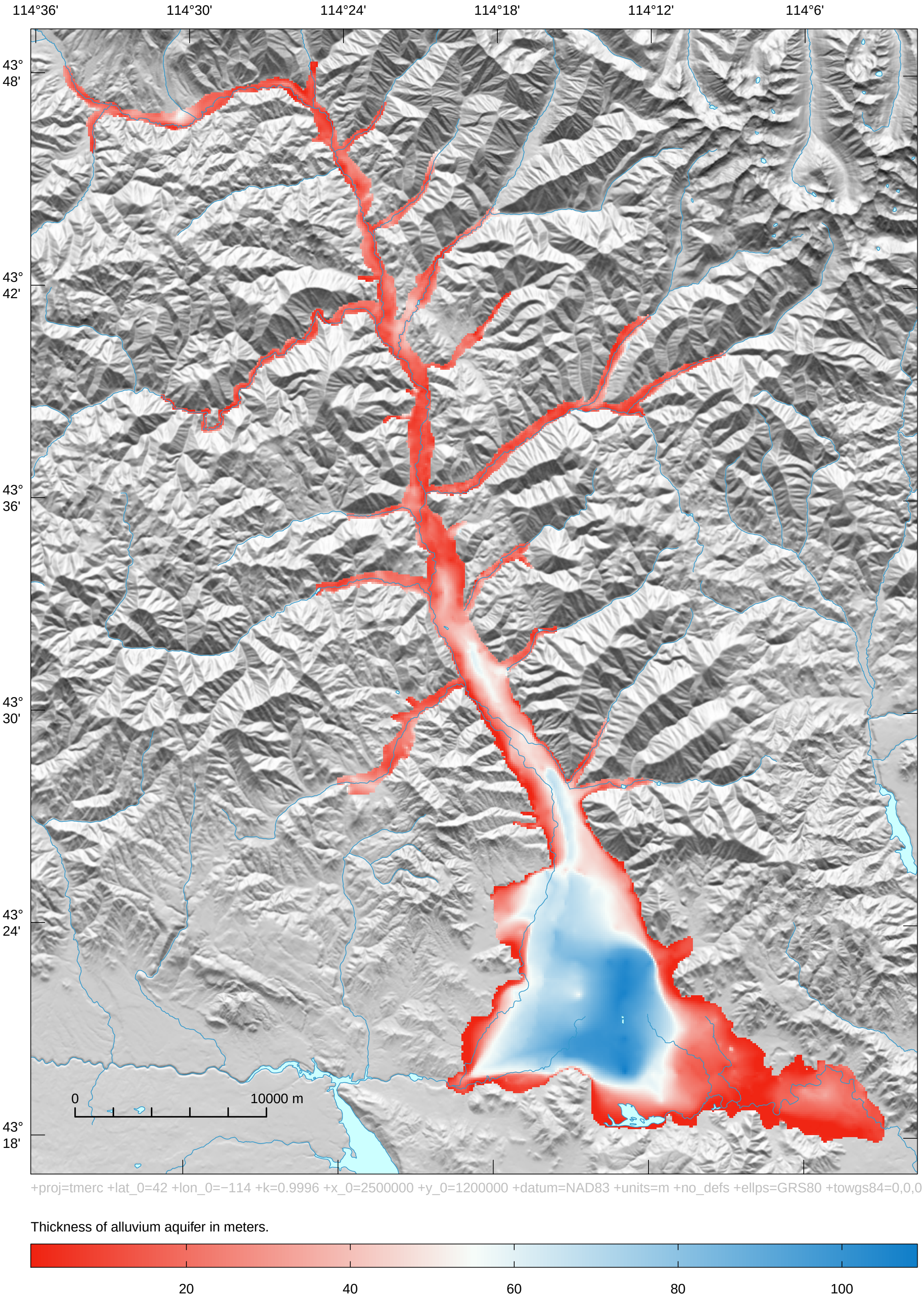

Figure 2: Thickness of Quaternary sediment in the aquifer system.

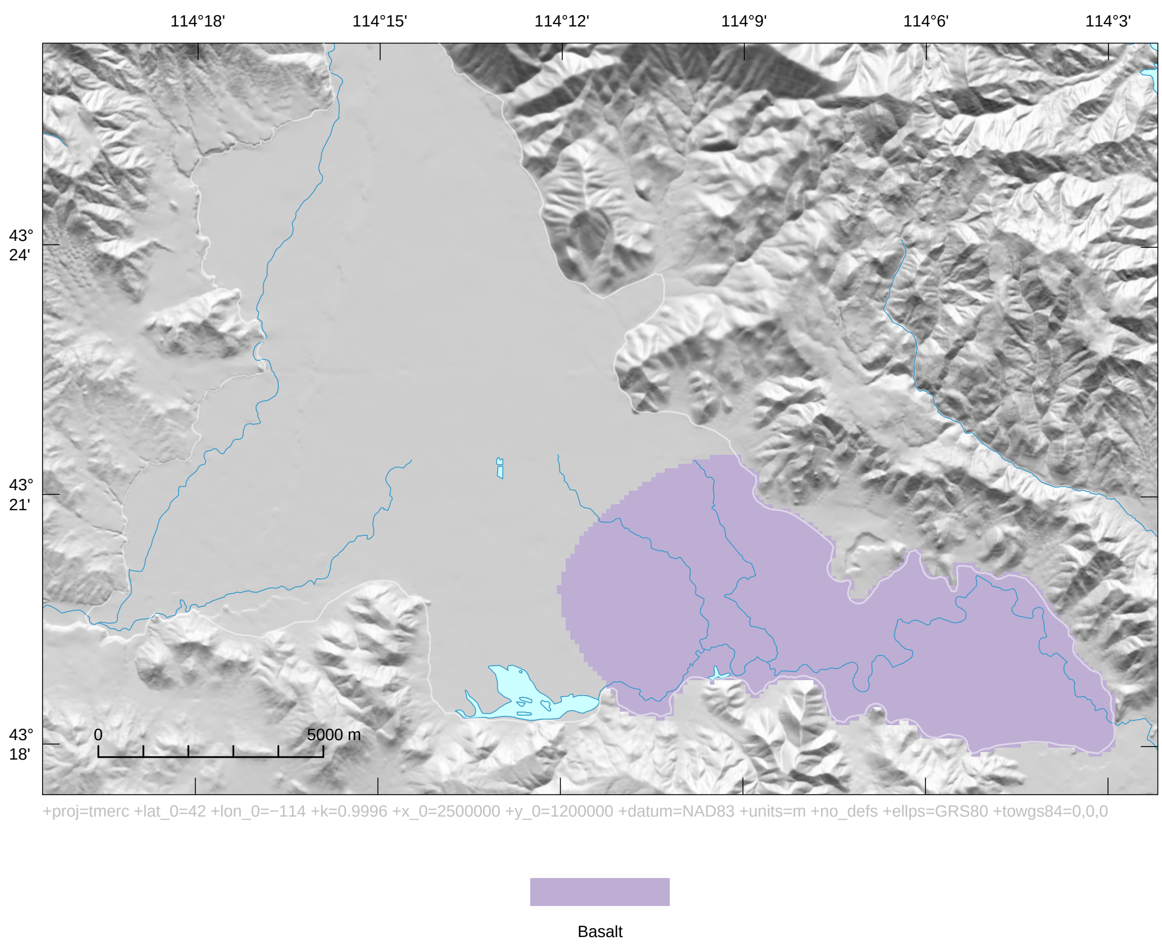

Figure 3: Extent of basalt in the aquifer system.

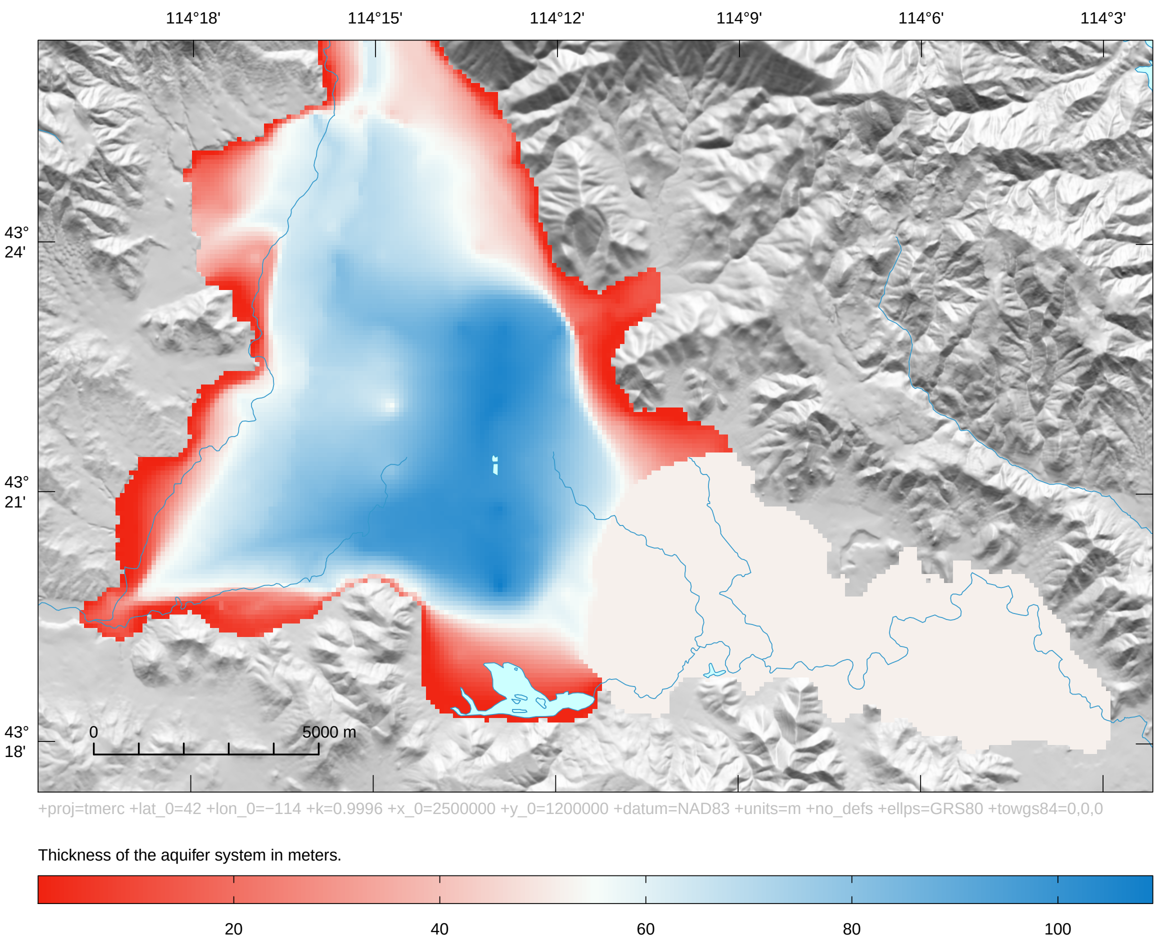

Figure 4: Thickness of the aquifer system.

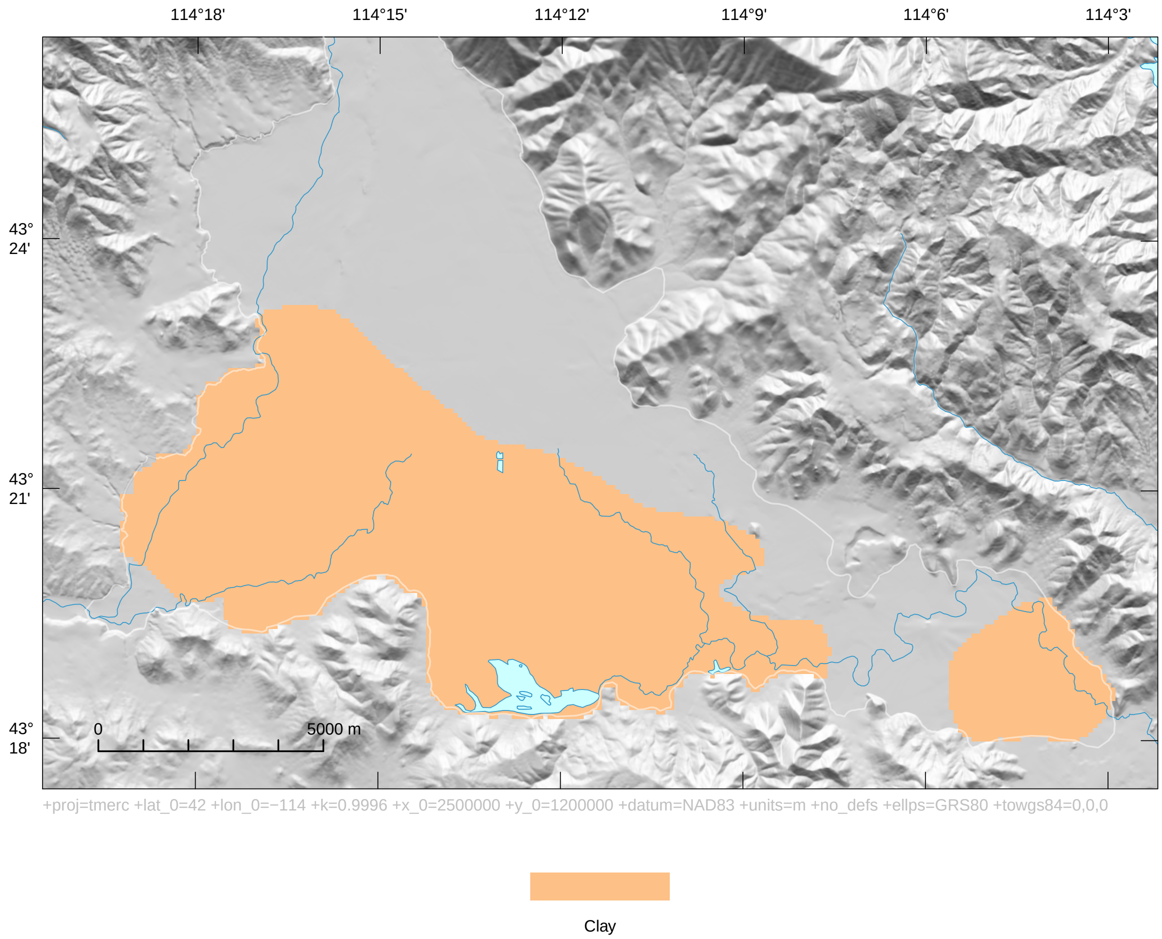

Figure 5: Extent of aquitard in the aquifer system.

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

```
r <- rasterize(aquitard.extent, rs, getCover = TRUE, silent = TRUE)
r[r < min.coverage] <- NA
r[!is.na(r)] <- 1L  # clay cells
r <- as.factor(r)
rat <- levels(r)[[1]]
rat$att <- "Clay"
levels(r) <- rat
names(r) <- "aquitard.extent"
rs <- stack(rs, 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 (100 ft).

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

```
names(r) <- "aquitard.top"
rs <- stack(rs, r)
```

Vertical connectivity among cells is ensured by setting a minimum vertical overlap between adjacent cells. Cells having less than 2 m (7 ft) of overlap are made inactive (fig. 6).

```
min.overlap <- 2  # min. vertical overlap between adjacent cells, in meters
r <- FindConnectedCells(rs[["bedrock"]], rs[["land.surface"]], min.overlap)
r <- as.factor(r)
rat <- levels(r)[[1]]
rat$att <- c("Inactive", "Active")
levels(r) <- rat
names(r) <- "is.connected"
rs <- stack(rs, 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). Source cells are identified using horizontal polygons (*source.locations*) with a single polygon allocated to each of the 22 source areas. Active cells intersecting a polygon line segment are defined as source cells. Non-source cells located within the body of the polygon are made inactive (fig. 7).

```
l <- gIntersection(as(source.locations, "SpatialLinesDataFrame"), aquifer.extent, TRUE)
source.lines <- SpatialLinesDataFrame(l, data = source.locations@data, match.ID = FALSE)
r <- rs[["alluvium.bottom"]]
is.in.aquifer <- !is.na(r)
is.in.poly <- !is.na(rasterize(source.locations, rs, silent = TRUE))
is.on.line <- !is.na(rasterize(source.lines, rs))
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 <- as.factor(r)
rat <- levels(r)[[1]]
rat$att <- c("Inactive", "Active", "Source")
levels(r) <- rat
names(r) <- "is.below.src"
rs <- stack(rs, 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 conceptual cross section through the 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.

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

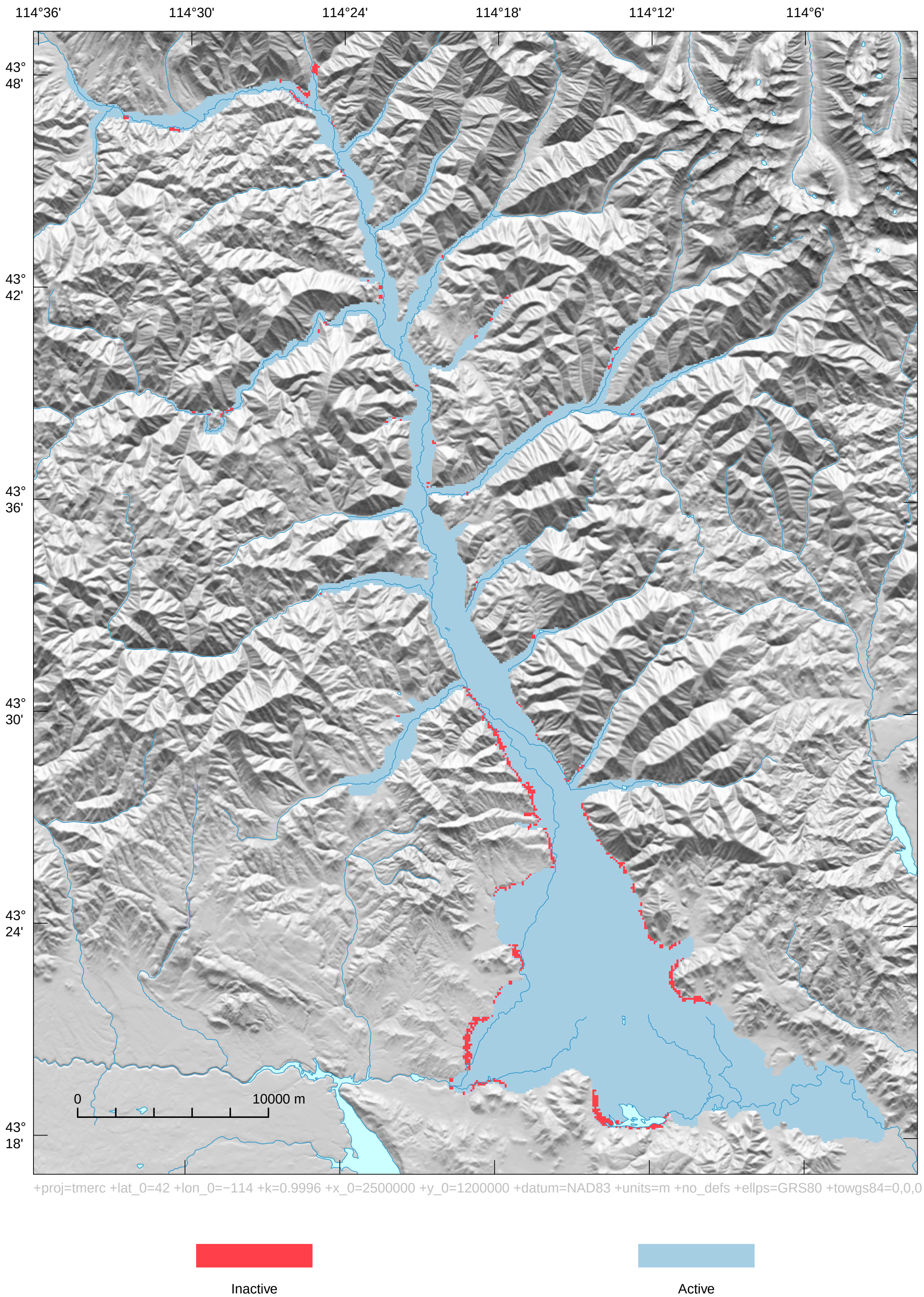

Figure 6: Vertical connectivity among cells.

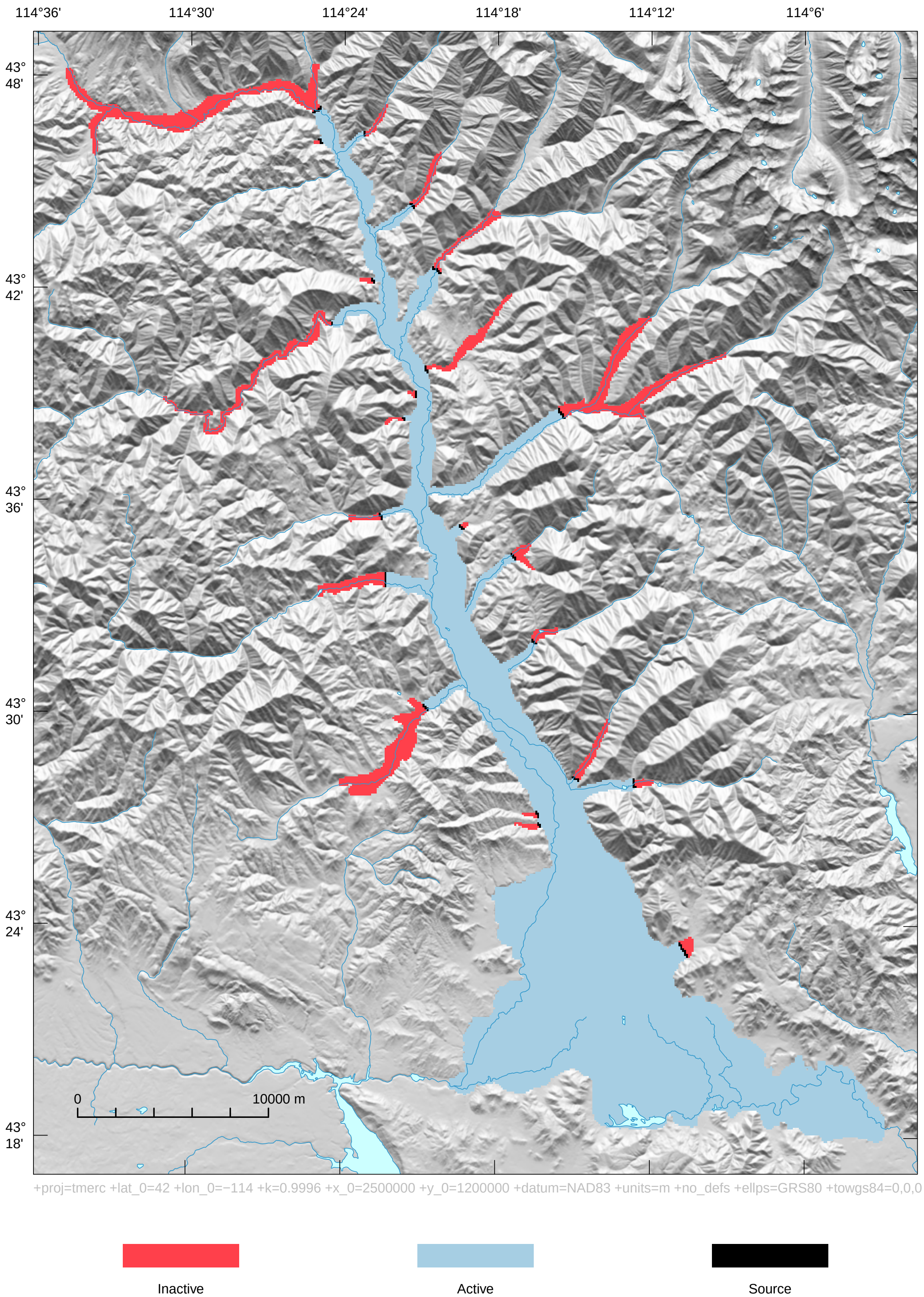

Figure 7: Location of source cells in the aquifer system.

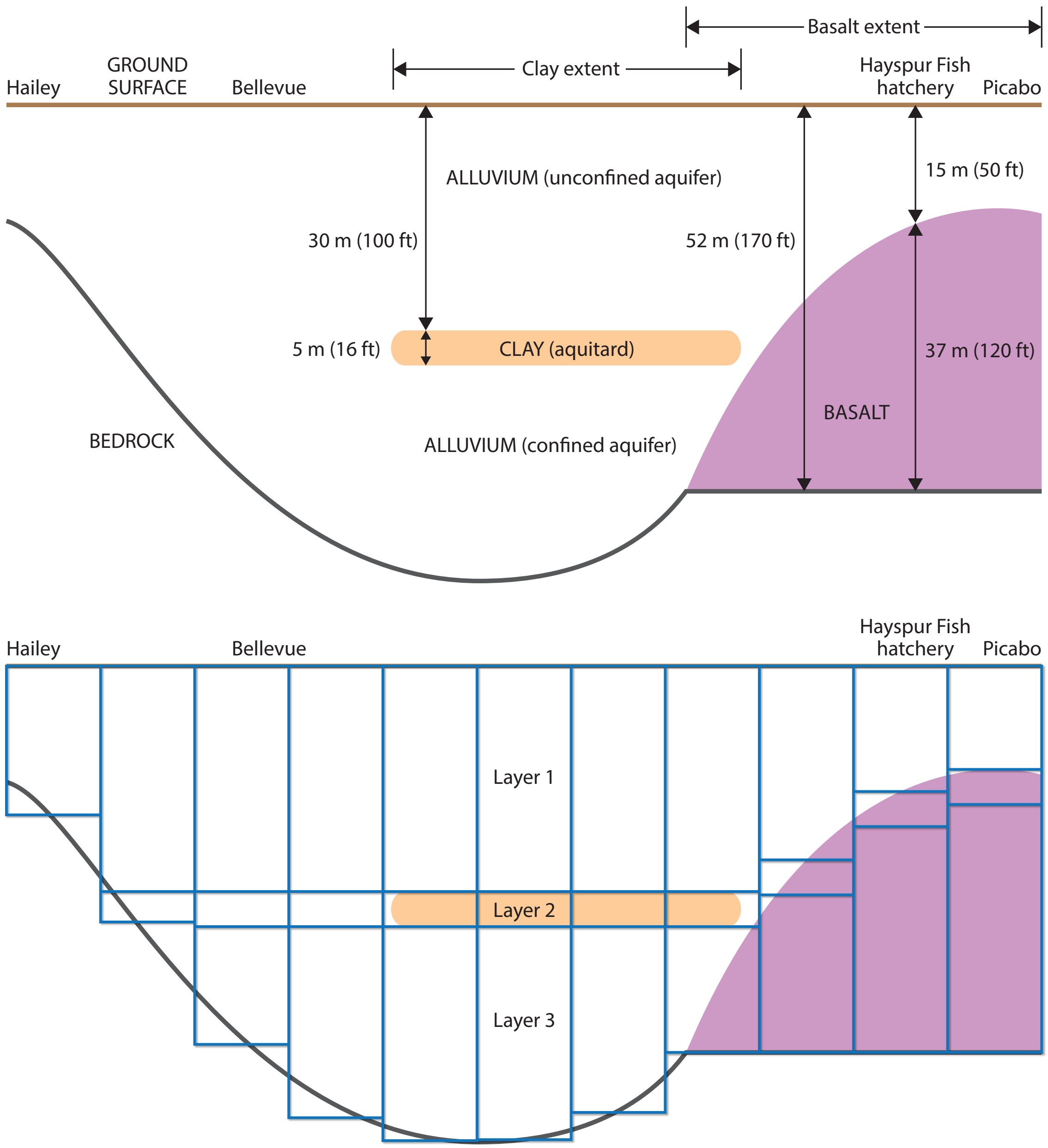

Figure 8: Schematic cross-section representation of the three-layer model grid.

```
names(r) <- "lay1.bottom"
rs.model <- r  # initialize second raster stack for model input
```

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.

```
r <- rs.model[["lay1.bottom"]] - aquitard.thickness
is.below <- rs[["bedrock"]] > r
r[is.below] <- rs[["bedrock"]][is.below]
r[(rs.model[["lay1.bottom"]] - r) < min.thickness] <- NA  # enforce min. 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[["bedrock"]]
r[is.na(rs.model[["lay2.bottom"]])] <- NA
r[(rs.model[["lay2.bottom"]] - r) < min.thickness] <- NA  # enforce min. thickness
r <- ExcludeSmallCellChunks(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 <- rs.model[["lay1.bottom"]]
is.adjusted <- r > rs[["bedrock"]] & is.na(rs.model[["lay2.bottom"]])
r[is.adjusted] <- rs[["bedrock"]][is.adjusted]
r <- ExcludeSmallCellChunks(r)
rs.model[["lay1.bottom"]] <- r
```

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

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

5.2 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. Figure 9 shows the delineation of hydrogeologic zones in model layer 1.

```
r <- rs.model[["lay1.bottom"]]
r[!is.na(r)] <- 1L  # alluvium cells
r <- as.factor(r)
rat <- levels(r)[[1]]
rat$att <- "Alluvium"
levels(r) <- rat
names(r) <- "lay1.zones"
rs.model <- stack(rs.model, r)
```

Figure 10 shows the delineation of hydrogeologic zones in model layer 2.

```
r <- rs.model[["lay2.bottom"]]
r[!is.na(r)] <- 1L  # alluvium cells
r[!is.na(r) & !is.na(rs[["aquitard.extent"]])] <- 3L  # clay cells
r[rs.model[["lay2.bottom"]] < rs[["alluvium.bottom"]]] <- 2L  # basalt cells
r <- as.factor(r)
rat <- levels(r)[[1]]
rat$att <- c("Alluvium", "Basalt", "Clay")
levels(r) <- rat
names(r) <- "lay2.zones"
rs.model <- stack(rs.model, r)
```

Figure 11 shows the delineation of hydrogeologic zones in model layer 3.

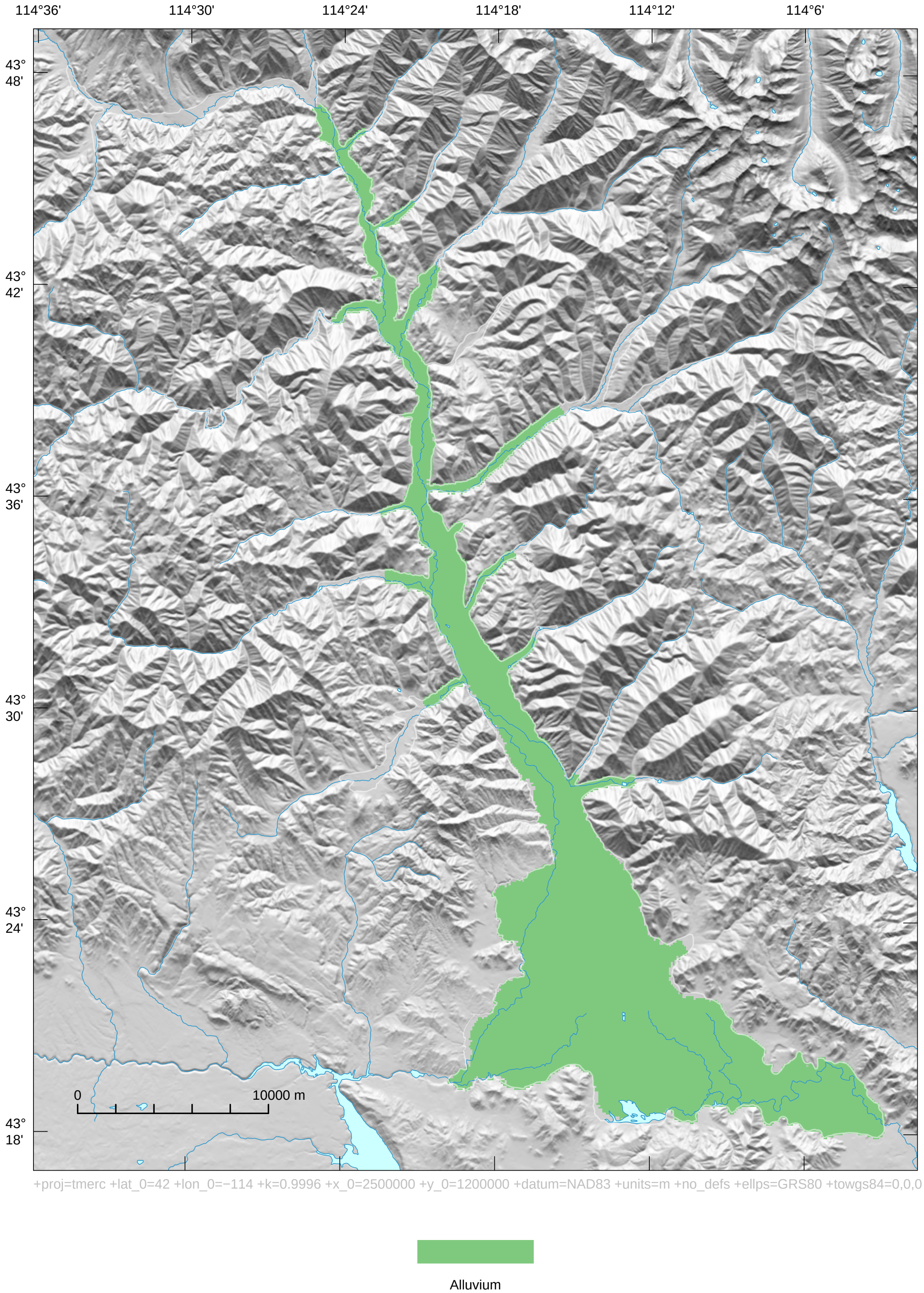

Figure 9: Hydrogeologic zones in model layer 1.

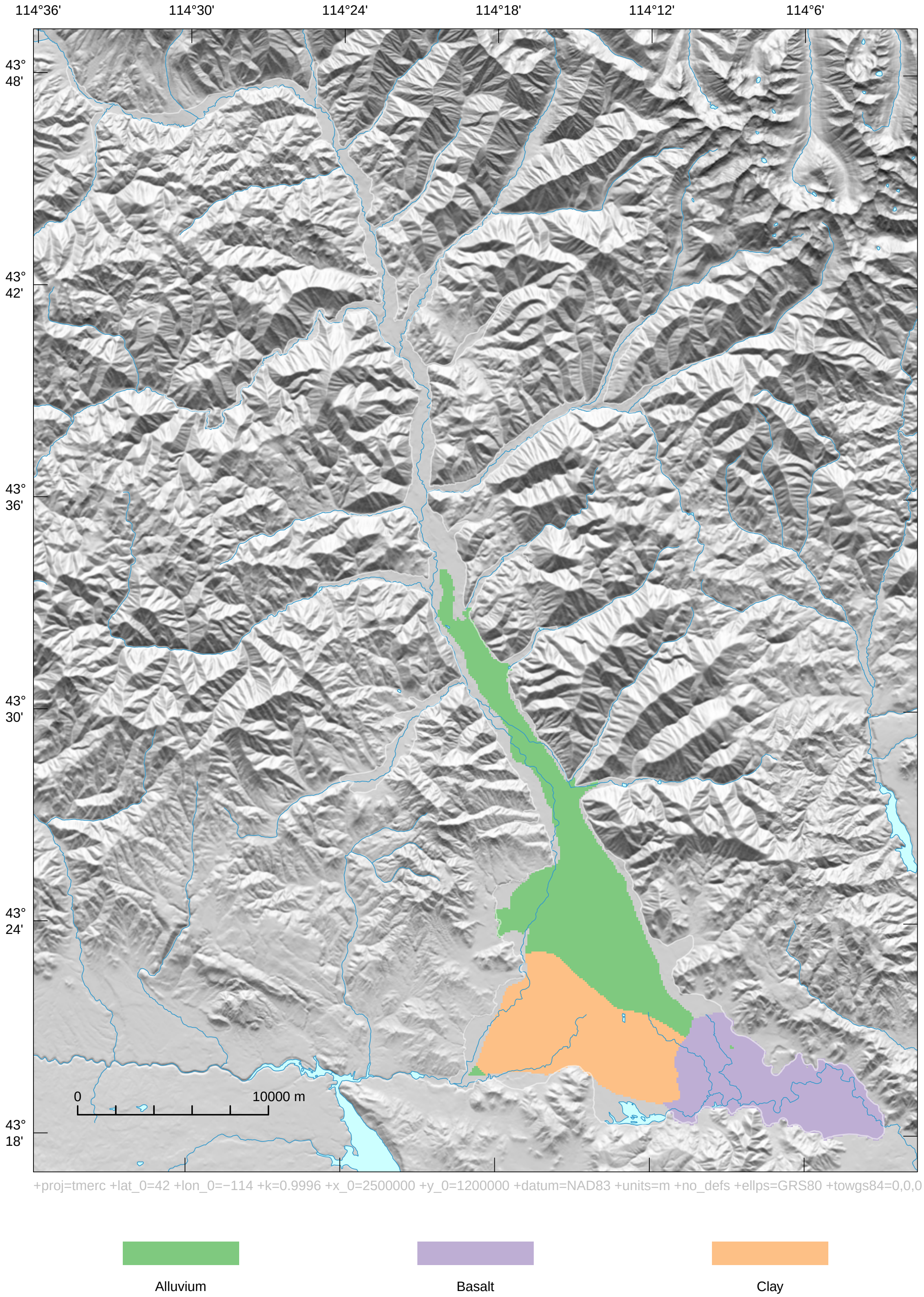

Figure 10: Hydrogeologic zones in model layer 2.

```
r <- rs.model[["lay3.bottom"]]
r[!is.na(r)] <- 1L  # alluvium cells
r[rs.model[["lay3.bottom"]] < rs[["alluvium.bottom"]]] <- 2L  # basalt cells
r <- as.factor(r)
rat <- levels(r)[[1]]
rat$att <- c("Alluvium", "Basalt")
levels(r) <- rat
names(r) <- "lay3.zones"
rs.model <- stack(rs.model, r)
```

5.3 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)	(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
src.cells <- which(!is.na(r.src[]))
adj.cells <- adjacent(r.src, src.cells, directions = 4)
```

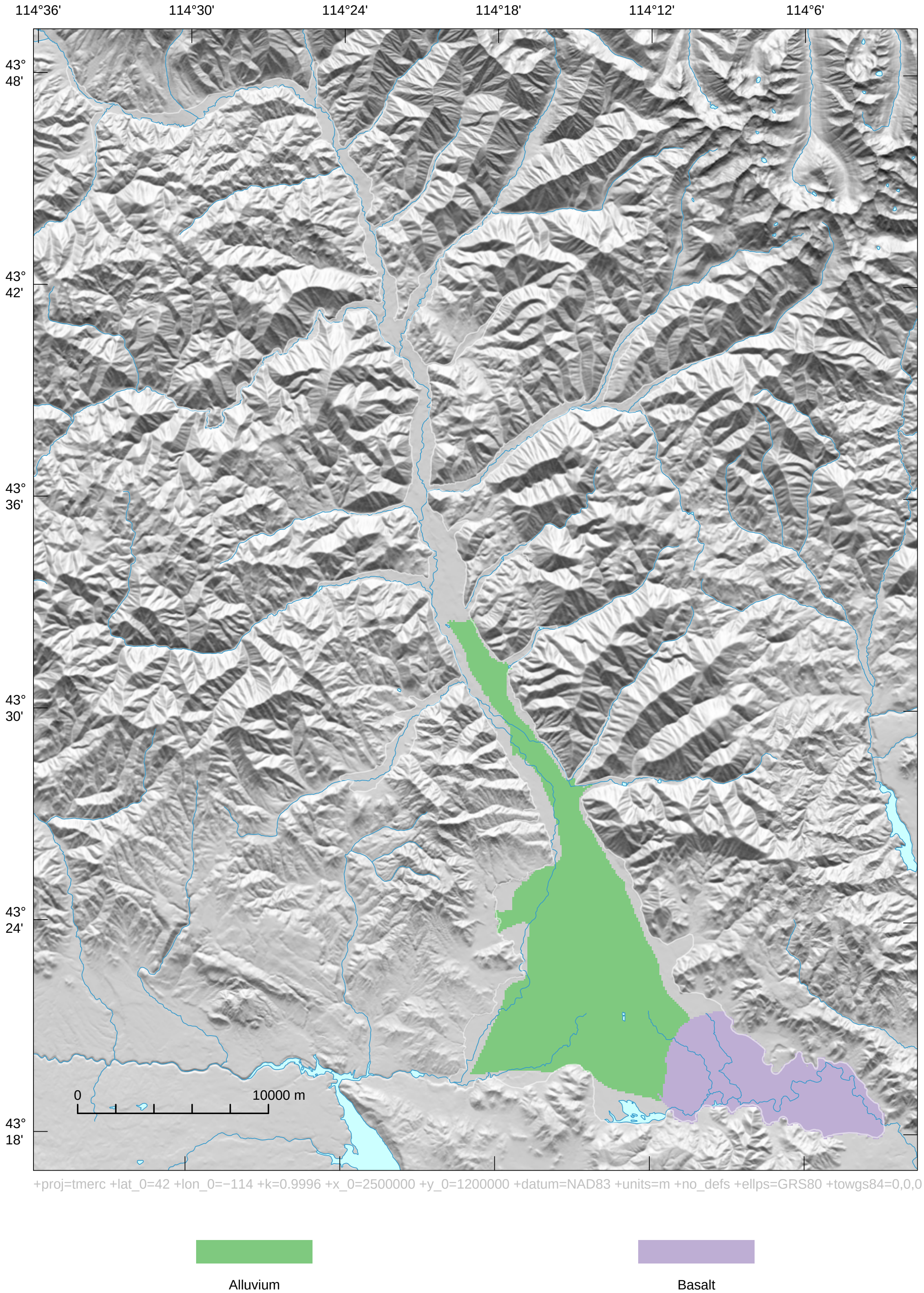

Figure 11: Hydrogeologic zones in model layer 3.

```
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)
```

5.4 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.

```
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 <- as.factor(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)	(ft)
Silver Creek	1,432	4,698
Stanton Crossing	1,470	4,823

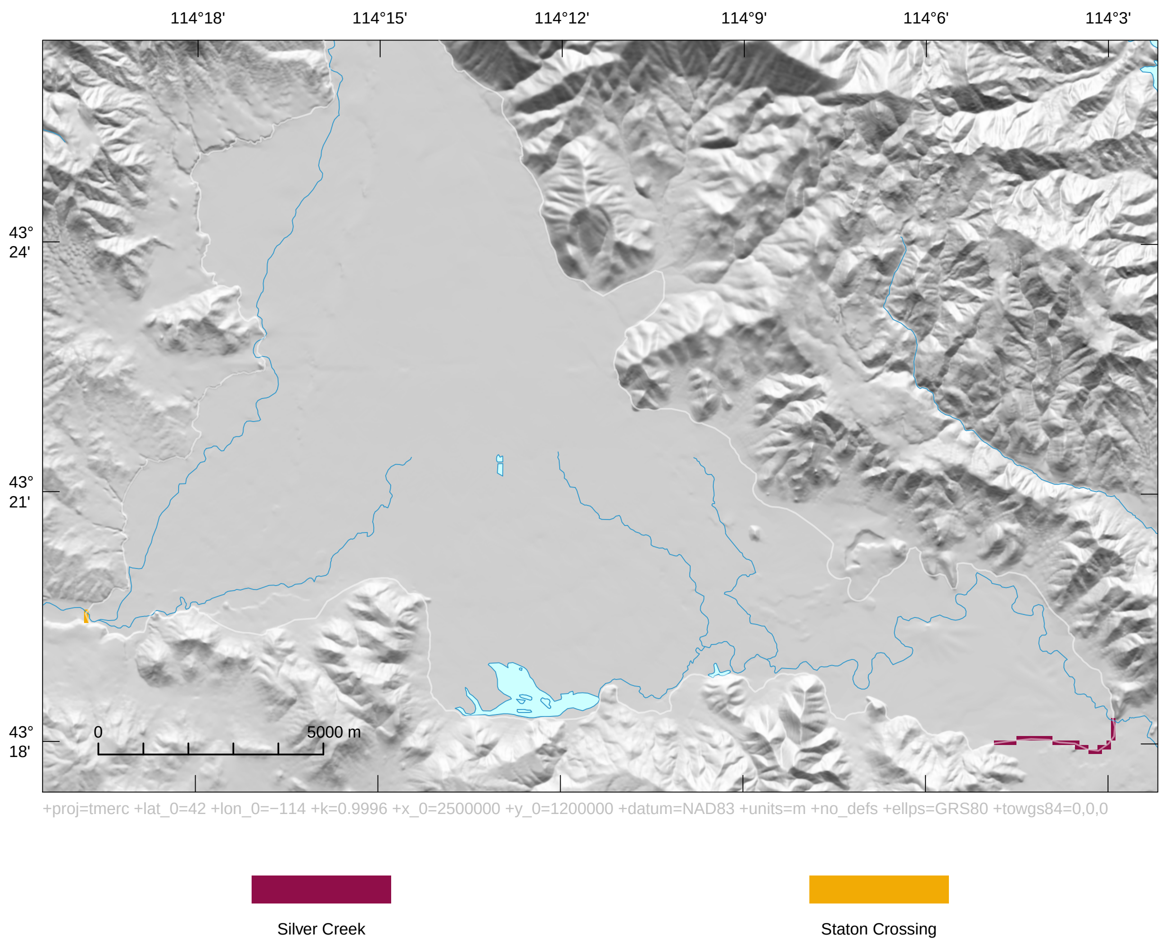

Figure 12: Location of sink cells in model layer 1.

5.5 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)	(ft)	Riverbed (m)	(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 (*bwr.sc*) 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 <- as.factor(r)
rat <- levels(r)[[1]]
rat$att <- c("Drain", "River")
levels(r) <- rat
names(r) <- "riv.bc"
```

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

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

```
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)
```

5.6 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.

```
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 x spacing (m)	100
Uniform y spacing (m)	100
World coordinates of model origin x (m)	2,466,200
World coordinates of model origin y (m)	1,344,139

Active and inactive cells are located in the model grid.

```
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)
```

5.7 Initial Head Distribution

The initial head distribution is specified as a fraction of the saturated thickness in model layer 1.

```
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)
```

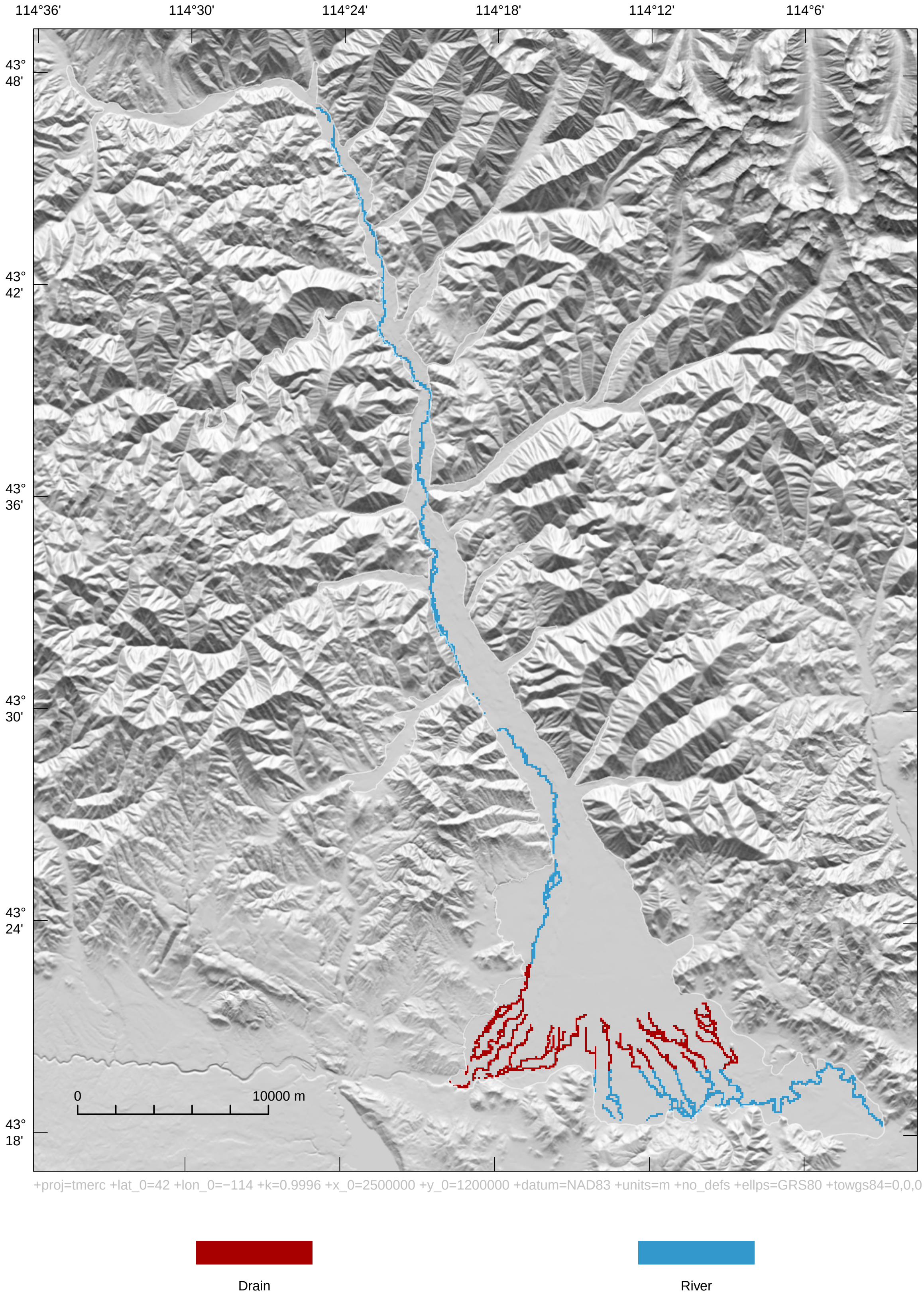

Figure 13: Stream-reach types in the Big Wood River and Silver Creek.

```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)
```

5.8 Export Raster Layers

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

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

6 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. Parameter values should be viewed as preliminary and subject to change during model calibration.

```r
id <- "wrv_ss_mfusg"  # identifier for the model run
p.run <- file.path(p, "Run")
CreateModflowInputFiles(rs.model, id, p.run, perlen = 5479, hk = c(30.48, 86.4, 8.64e-7),
                        vani = 1000, cond.riv = 850)
```

Table 5: Input parameters for model run.

Parameter	Value
Length of stress period (d)	5,479
Horizontal hydraulic conductivity of Alluvium (m/d)	30.48
Horizontal hydraulic conductivity of Basalt (m/d)	86.40
Horizontal hydraulic conductivity of Clay (m/d)	8.64e-07
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 <- c(paste("cd", shQuote(p.run)), paste(shQuote(p.exe), shQuote(paste0(id, ".nam"))))
f <- file.path(p.run, "Run.bat")
cat(cmd, file = f, sep = "\n")
Sys.chmod(f, mode = "755")
output <- system(shQuote(f), 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): 2014/02/24  8:00:53
##
##  Solving:  Stress period:     1    Time step:     1    Groundwater Flow Eqn.
##  Run end date and time (yyyy/mm/dd hh:mm:ss): 2014/02/24  8:03:09
##  Elapsed run time:  2 Minutes, 16.287 Seconds
##
##   Normal termination of simulation
```

The volumetric budget written to the MODFLOW listing file is given in table 6.

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

	Volume (m^3)	(acre-ft)	Rate (m^3/d)	(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	1,773,022,892	1,437,405	323,603	95,821
Specified flows in	325,233,440	263,670	59,360	17,577
Total in	2,098,256,332	1,701,074	382,963	113,398
Storage out	0	0	0	0
Constant head out	0	0	0	0
Drains out	974,032,618	789,657	177,776	52,641
River leakage out	1,124,231,730	911,424	205,189	60,758
Specified flows out	0	0	0	0
Total out	2,098,264,348	1,701,081	382,965	113,398
In minus out	-8,016	-6	-1	-0
Percent discrepancy	-0	-0	-0	-0

7 Post-Processing

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

```
f <- file.path(p.run, paste0(id, ".hds"))
r <- rs.model[[1]]
rs.heads <- ReadModflowBinaryFile(f, r)
```

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

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

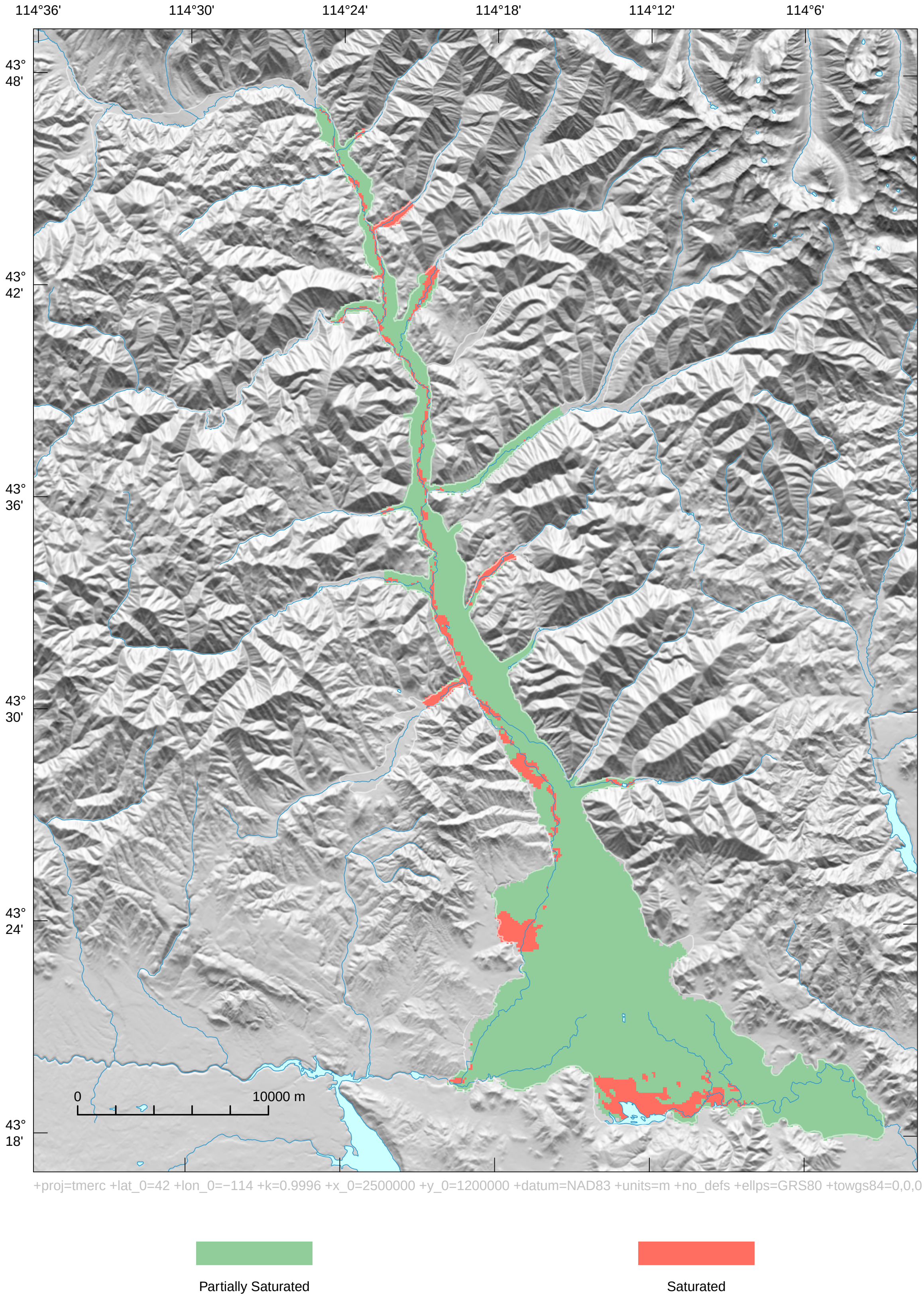

Figure 14: Saturated and partially-saturated cells in model layer 1.

Determine the simulated elevation of the water table (fig. 15). Heads greater than the land surface elevation are specified at land surface.

```
is.above.land.surface <- rs.heads[["ts1.sp1.lay1"]] > rs.model[["lay1.top"]]
is.in.lay2 <- rs.heads[["ts1.sp1.lay2"]] > rs.model[["lay2.bottom"]] &
              rs.heads[["ts1.sp1.lay2"]] < rs.model[["lay1.bottom"]]
is.in.lay3 <- rs.heads[["ts1.sp1.lay3"]] < rs.model[["lay2.bottom"]]
r <- rs.heads[["ts1.sp1.lay1"]]
r[is.above.land.surface] <- rs.model[["lay1.top"]][is.above.land.surface]
r[is.in.lay2] <- rs.heads[["ts1.sp1.lay2"]][is.in.lay2]
r[is.in.lay3] <- rs.heads[["ts1.sp1.lay3"]][is.in.lay3]
names(r) <- "water.table"
rs.heads <- stack(rs.heads, r)
```

Write simulated heads to georeferenced image files.

```
ExportRasterStack(p.run, rs.heads)
```

8 Reproducibility

To reprocess the groundwater flow model: view R code extracted from this vignette and manually transfer the code into an R session via a copy and paste operation.

```
browseURL(system.file("doc", "wrv-process.R", package = "wrv"))
```

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

- R version 3.0.2 (2013-09-25), `x86_64-w64-mingw32`
- Base packages: base, datasets, grDevices, graphics, methods, stats, utils
- Other packages: igraph 0.7.0, png 0.1-7, raster 2.2-12, rgdal 0.8-16, rgeos 0.3-3, sp 1.0-14, wrv 0.1-3, xtable 1.7-1
- Loaded via a namespace (and not attached): evaluate 0.5.1, formatR 0.10, grid 3.0.2, highr 0.3, knitr 1.5, lattice 0.20-24, stringr 0.6.2, tools 3.0.2

Total processing time for this vignette was 30 minutes.

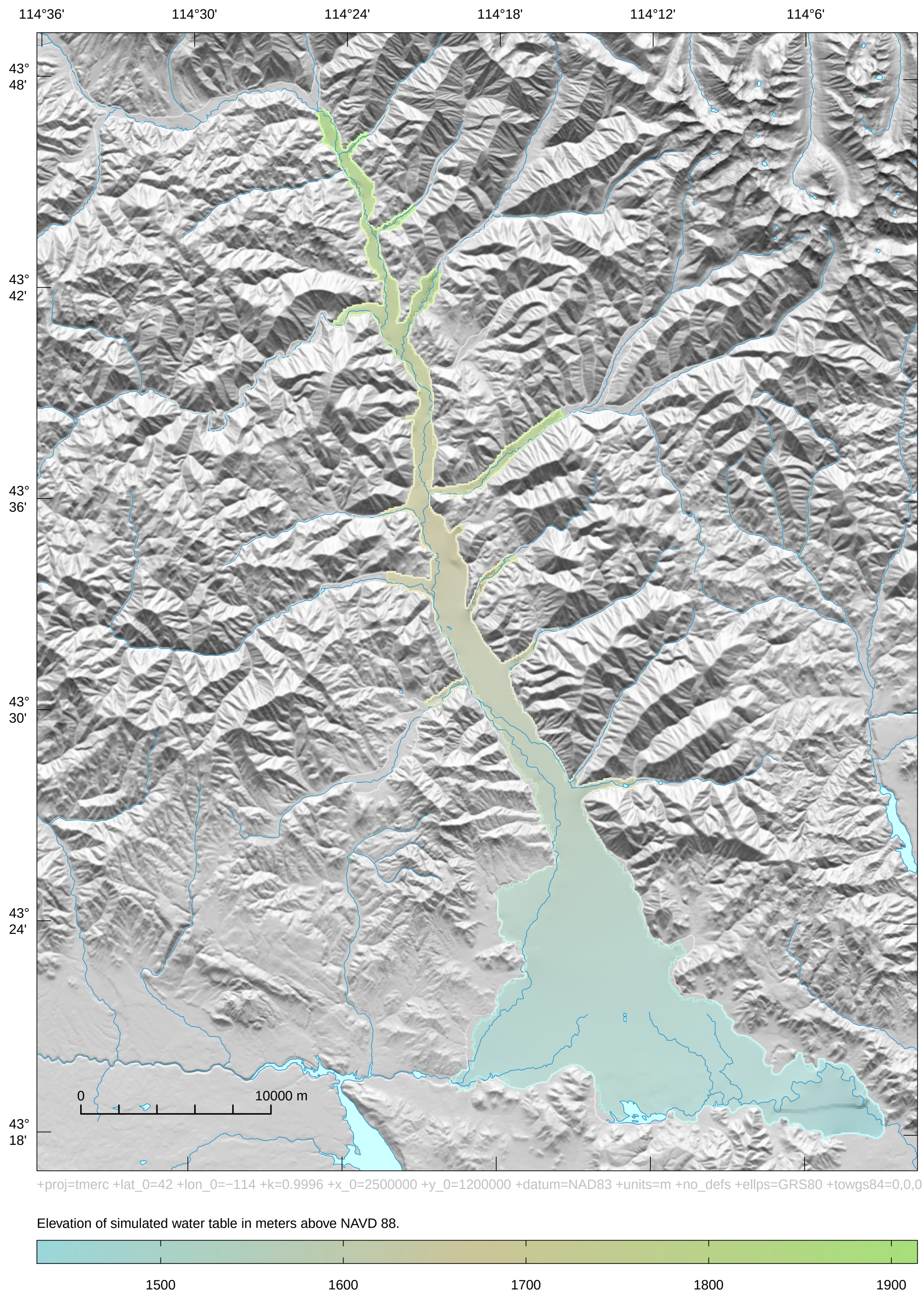

Figure 15: Simulated elevation of the water table.

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