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

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Contents

Figures

Tables

Conversion Factors and Datums

Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.28084	foot (ft)
meter (m)	1.09361	yard (yd)
kilometer (km)	0.621371	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.7639	square foot (ft^2)
square kilometer (km^2)	247.104	acre
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 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 steps taken to process the model; its contents should be viewed as provisional until model and report completion in 2015 (Fisher *et al.*, 2015). The reader of this vignette should be familiar with the R-programming language and have read the help pages for functions and data sets in the **wrv** package.

A 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 dynamically and inserted into the final document. 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. Note that embedded code can be extracted from this vignette, which allows for truly reproducible research; see 'Reproducibility' section for details.

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 $\geq$ 3.1) is not already installed on your computer, download and install the latest binary distribution from the Comprehensive R Archive Network (CRAN). Extend the capabilities of R by installing an assorted group of user-contributed packages available online; start an R session and type the following commands in your R Console window:

```
repos <- c("http://cran.us.r-project.org", "<SPECIFIED WHEN REPORT IS PUBLISHED>")
update.packages(ask = FALSE, repos = repos[1])
install.packages("wrv", repos = repos, dependencies = TRUE, type = "both")
```

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 $\geq$ 1.2) is not already installed on your computer, download and decompress the latest file archive. Contained within this file archive is an executable file for Windows; users of a Unix-like operating system will need to compile MODFLOW-USG on their own. The full path name to the executable file is specified using the following R command (change path as needed):

```
file.exe <- "C:/WRDAPP/mfusg.1_2/bin/mfusg_x64.exe"  # path specified with forward slashes
```

To gain access to the contents of the **wrv** package in R, type 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 (1) a single unconfined aquifer that underlies the entire valley, (2) an underlying confined aquifer that is present only in the southern part of the valley, and (3) 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: (1) a coarse-grained sand and gravel unit (alluvium unit), (2) a fine-grained silt and clay unit (clay unit), and (3) a basalt unit (Bartolino and Adkins, 2012, pg. 3).

Space-Time Model Grid

Model Grid Conceptualization

The creation of the model grid is the first step in developing the groundwater flow model, because all model inputs including hydraulic properties and boundary conditions are assigned to the model cells. The three-dimensional model grid is rectilinear (square cells) horizontally, distorted vertically, and not rotated from the east-west and north-south axes. 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 observed data and the ability to get continuous grid coverage in the narrow and steep tributary canyons of the WRV.

A solid-boundary representation of the land surface (fig. 1) and an estimated thickness for the Quaternary sediment (fig. 2) as defined by Bartolino and Adkins (2012, fig. 7), are used to generate the basic structure of the model grid.

```
rs.data <- stack()  # initialize a raster stack, a collection of raster layers
rs.data <- stack(rs.data, land.surface)  # add raster layer to raster stack
rs.data <- stack(rs.data, alluvium.thickness)
```

The elevation of the pre-Quaternary bedrock surface and top of Quaternary basalt is calculated by subtracting the thickness of the Quaternary sediment from land surface elevations.

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

The estimated aerial extent of the basalt unit in the WRV aquifer system, as defined by Bartolino and Adkins (2012, Plate 1), is shown in figure 3.

```
r <- rasterize(basalt.extent, rs.data, getCover = TRUE, silent = TRUE)
r[r > 0] <- 1
r[r < 1] <- NA
r <- ratify(r)  # add a raster attribute table
levels(r) <- cbind(levels(r)[[1]], att = "basalt")
names(r) <- "basalt.extent"
rs.data <- stack(rs.data, r)
```

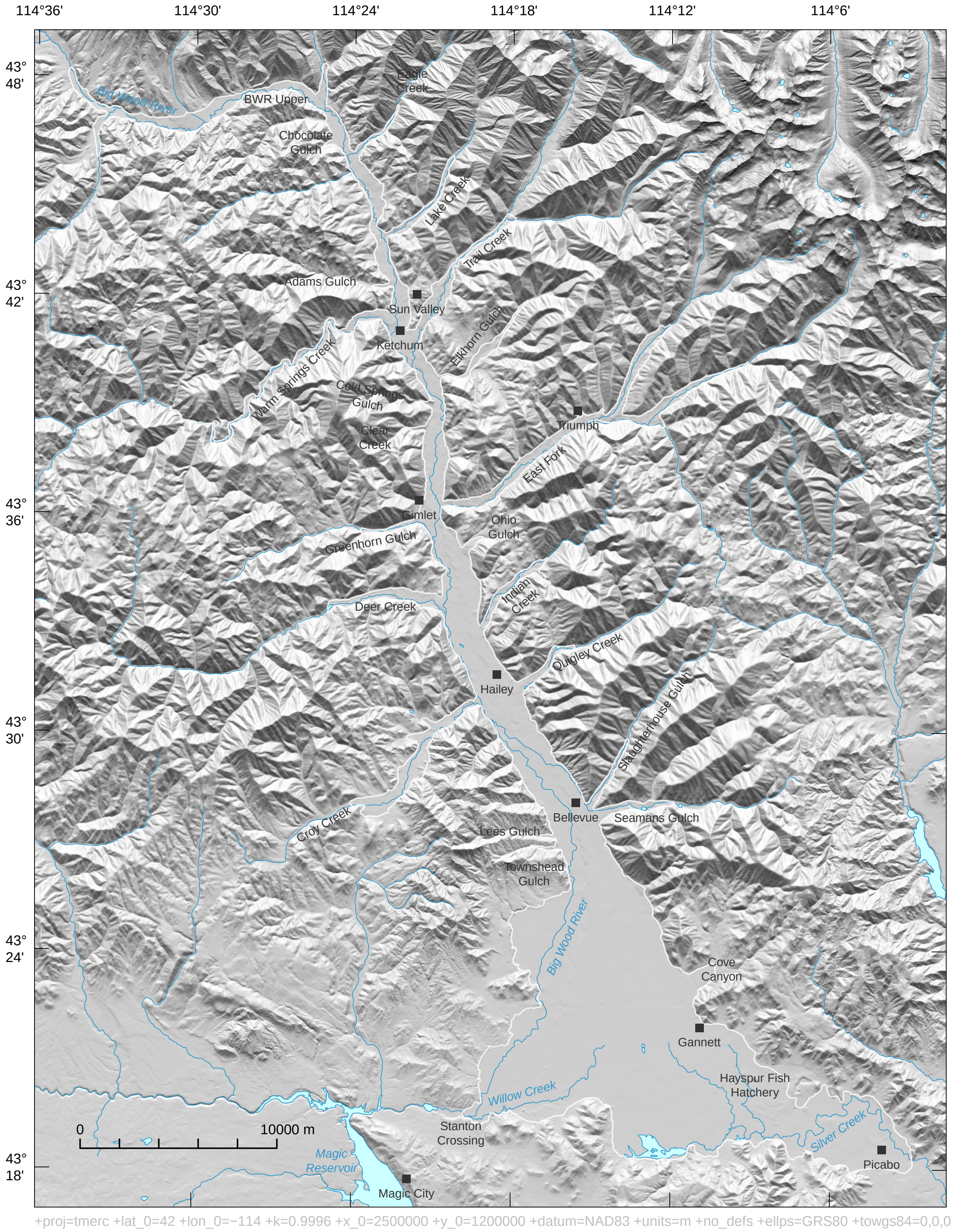

Figure 1: Land surface topography and extent of the aquifer system.

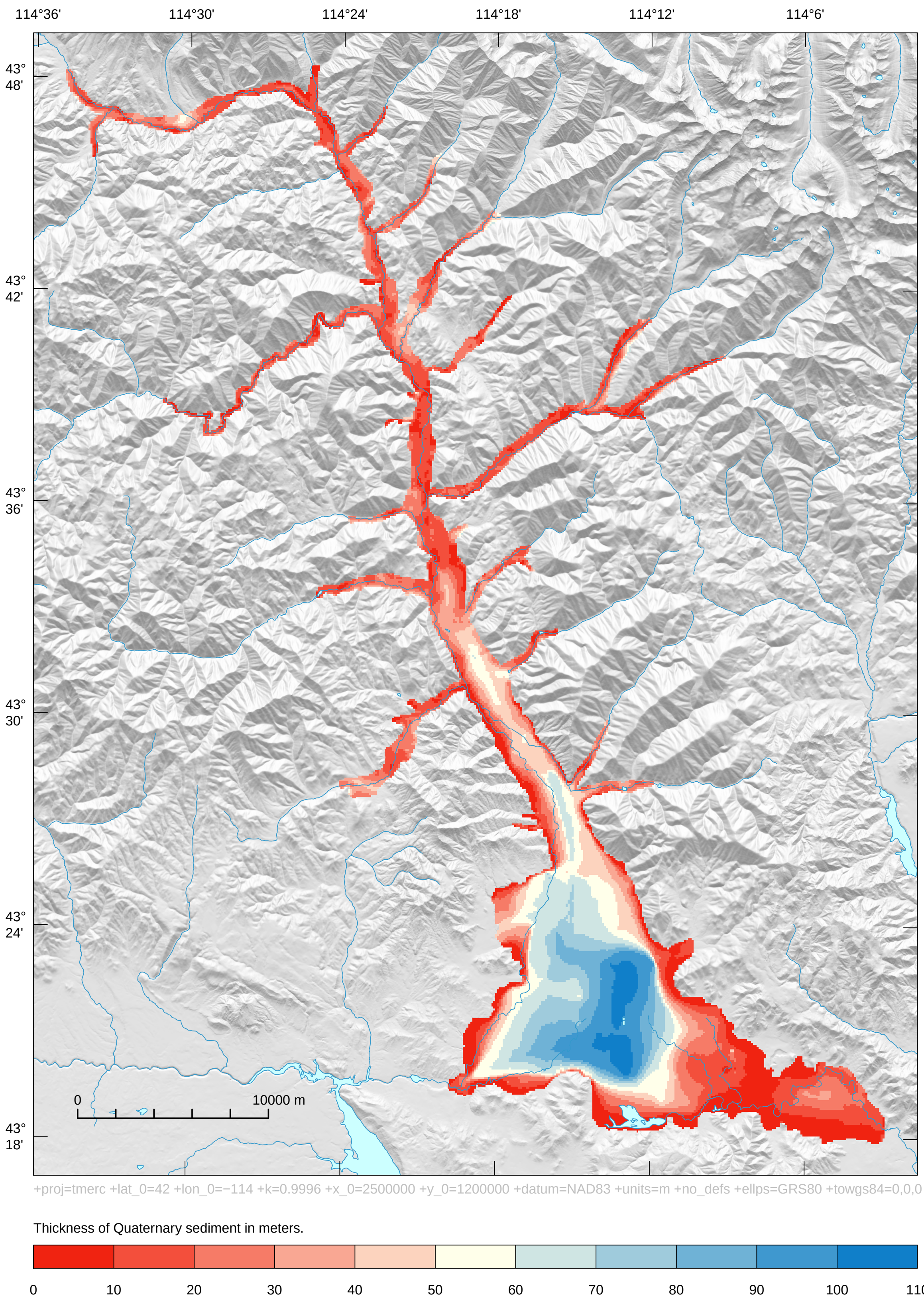

Figure 2: Thickness of Quaternary sediment in the aquifer system.

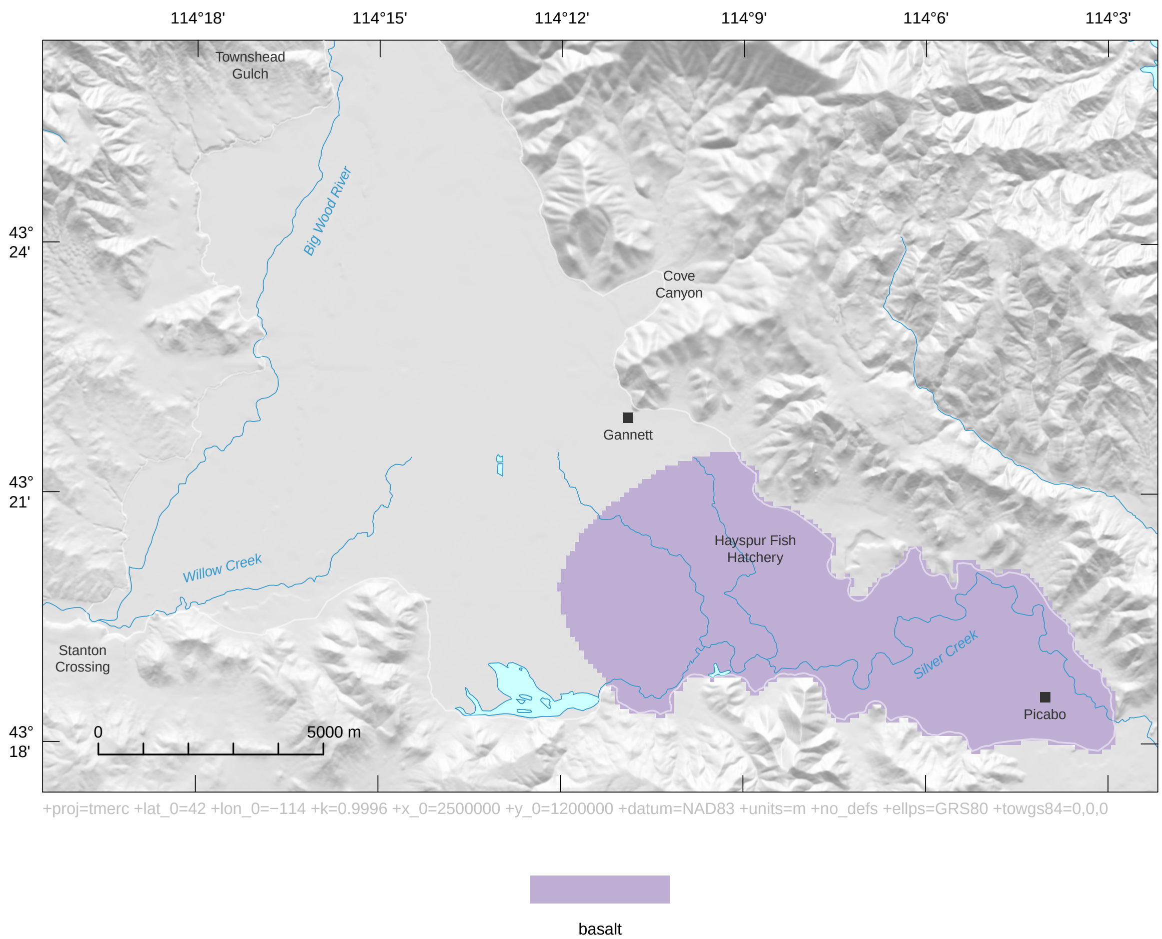

Figure 3: Extent of basalt unit in the aquifer system.

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 because of insufficient data to describe these materials. The bedrock surface elevation for the aquifer system is then calculated by integrating units:

```
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 <- rs.data[["land.surface"]] - rs.data[["bedrock"]]
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 clay unit in the WRV aquifer system, as defined by Moreland (1977), is shown in figure 5.

```
r <- rasterize(gUnaryUnion(aquitard.extent), rs.data, getCover = TRUE, silent = TRUE)
r[r > 0] <- 1
r[r < 1] <- NA
r <- ratify(r)
levels(r) <- cbind(levels(r)[[1]], att = "clay")
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) below land surface.

```
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 adjusted by incrementally dropping the cells bottom elevation until the minimum vertical overlap is attained (fig. 6).

```
min.overlap <- 2  # minimum vertical overlap between adjacent cells, in meters
r <- BumpDisconnectedCells(subset(rs.data, c("land.surface", "bedrock")), min.overlap)
rs.data[["bedrock"]] <- rs.data[["bedrock"]] + r
names(r) <- "cell.adjustment"
rs.data <- stack(rs.data, r)
```

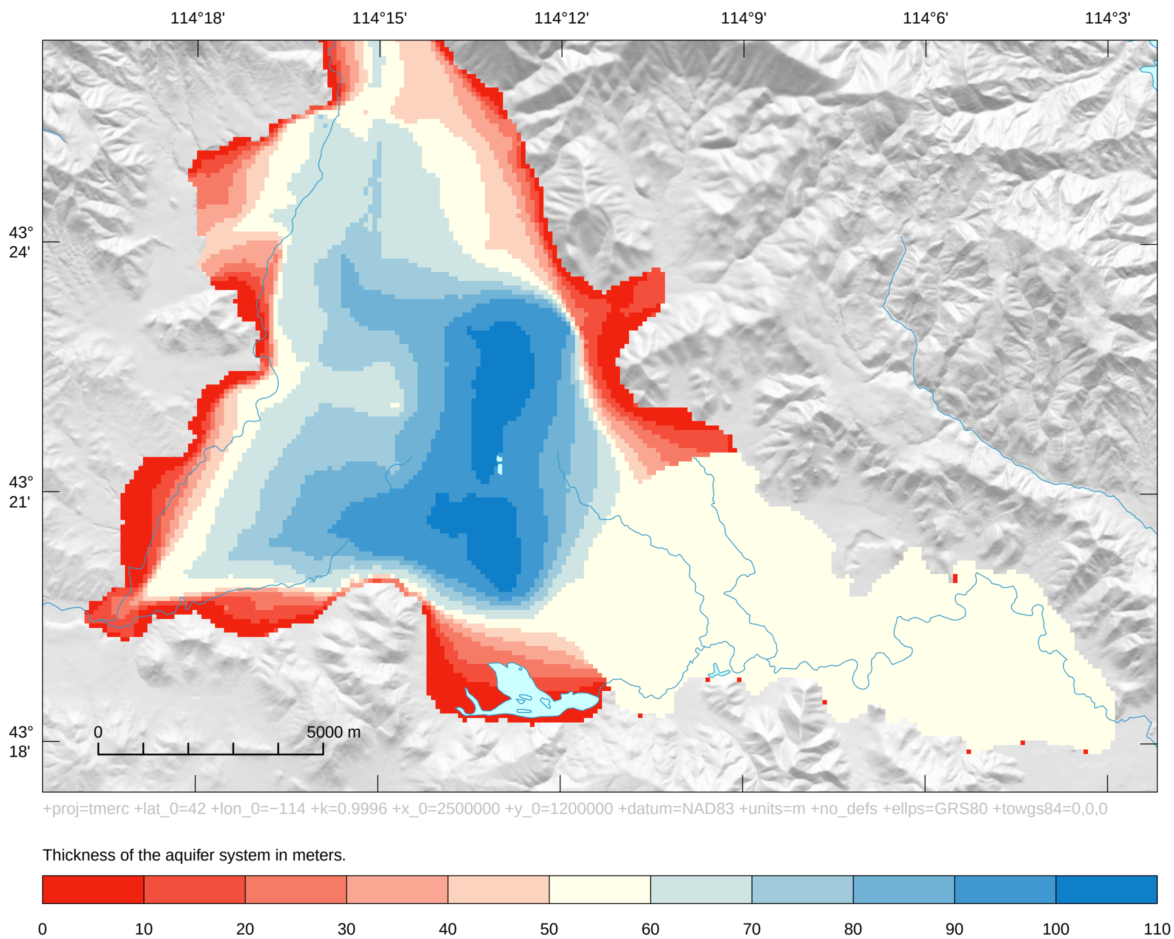

Figure 4: Thickness of the aquifer system in the southern part of the WRV.

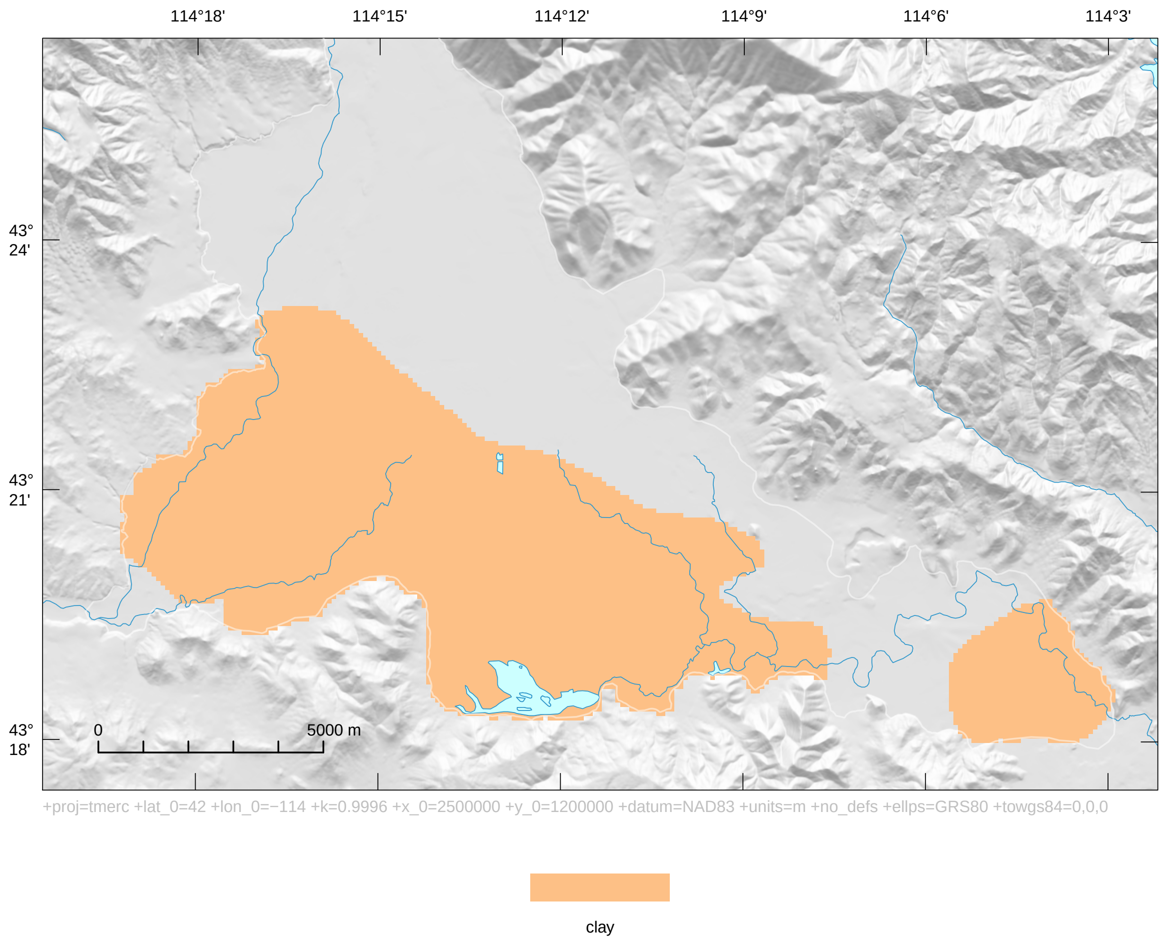

Figure 5: Extent of clay unit in the aquifer system.

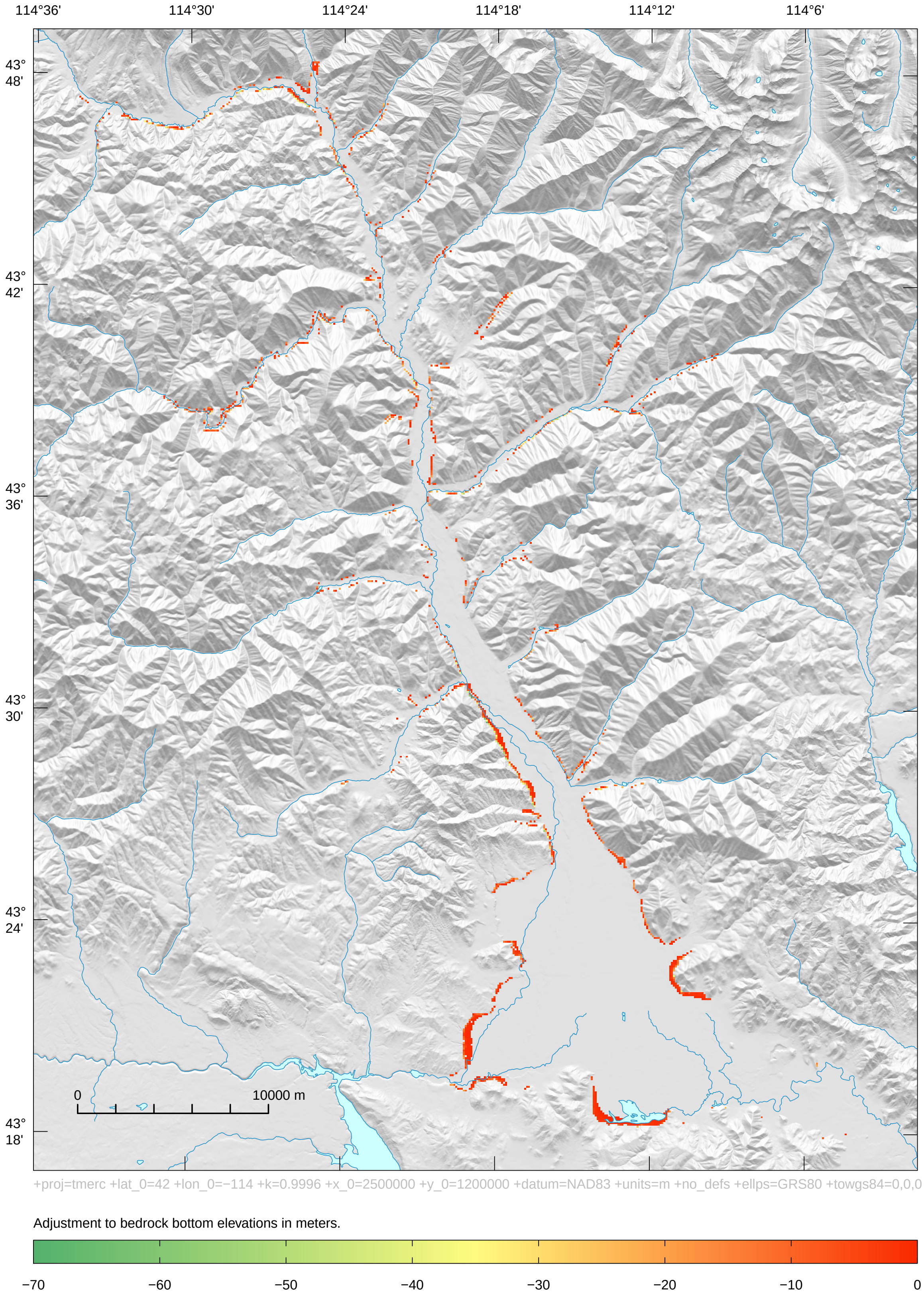

Figure 6: Vertical adjustment to bedrock bottom elevations to account for vertically disconnected cells.

The total number of vertically adjusted cells is 1,817, or 6 percent of active cells, with a mean and standard deviation of −7.6 m and 9.6 m, respectively.

Groundwater enters the model domain through *specified flow 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' in fig. 1). A sparsity of field observations in the major tributary canyons indicates large uncertainty in the historic flow contribution from each of the tributary canyons. Therefore, specified flow cells are placed in the upper part of the tributary canyons to help contain errors that may propagate into the model from these boundaries. Simulated hydraulic heads in the tributary canyons should be considered less reliable than in the WRV. Also taken into consideration when designating the location of specified flow cells was (1) maintaining continuous grid coverage in the narrow and steep tributary canyons and (2) leveraging existing observation wells. An intended consequence of these boundaries is a reduction in the extent of the modeled aquifer system.

Specified flow cells are identified using horizontal polygons with a single polygon allocated to each of the 22 boundaries (fig. 7). Active cells intersecting a polygon line segment are defined as specified flow cells, and cells located within the body of a polygon made inactive.

```
l <- gIntersection(as(tributaries, "SpatialLinesDataFrame"), aquifer.extent, TRUE)
trib.lines <- SpatialLinesDataFrame(l, data = tributaries@data, match.ID = FALSE)
r <- rs.data[["alluvium.bottom"]]
is.in.aquifer <- !is.na(r)
is.in.poly <- !is.na(rasterize(tributaries, rs.data, silent = TRUE))
is.on.line <- !is.na(rasterize(trib.lines, rs.data))
r[is.in.aquifer &  is.in.poly] <- 0  # inactive cells
r[is.in.aquifer & !is.in.poly] <- 1  # active cells
r[is.in.aquifer &  is.on.line] <- 2  # specified flow cells
cells <- which(r[] == 2)
adj.cells <- adjacent(r, cells, directions = 4)
is.valid <- adj.cells[, 2] %in% which(r[] == 1)
rm.cells <- cells[!(cells %in% unique(adj.cells[is.valid, 1]))]
r[rm.cells] <- 0
r <- ratify(r)
att <- c("inactive cells", "active cells", "specified flow cells")
levels(r) <- cbind(levels(r)[[1]], att = att)
names(r) <- "ibound"
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 (fig. 5). A schematic cross-section representation of the hydrogeologic units and the three-layer model grid is shown figure 8. Embedded clay within the basalt unit is assumed to have a negligible effect on groundwater flow and is not represented by the model. Note that model cells in layers 2 and 3 become inactive north of Hailey (fig. 1). Model 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.

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.

```
rs.model <- stack()  # initialize a raster stack for model input
r <- rs.data[["land.surface"]] - depth.to.aquitard.top
is.below <- rs.data[["alluvium.bottom"]] > r
r[is.below] <- rs.data[["alluvium.bottom"]][is.below]
min.thickness <- 1  # in meters
r[(rs.data[["land.surface"]] - r) < min.thickness] <- NA  # enforce min. layer thickness
r[rs.data[["ibound"]] == 0] <- NA
```

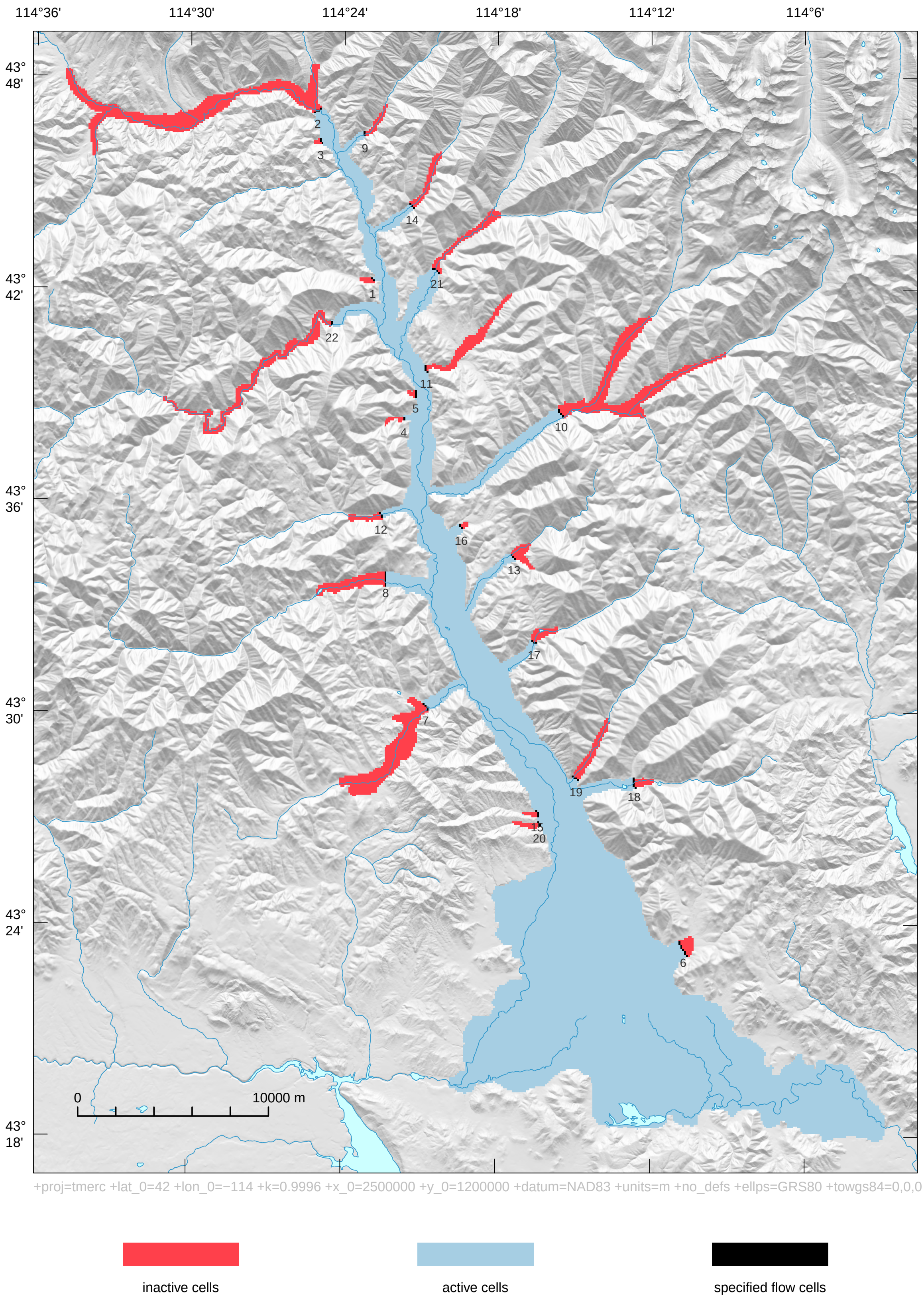

Figure 7: Location of specified flow cells in the aquifer system.

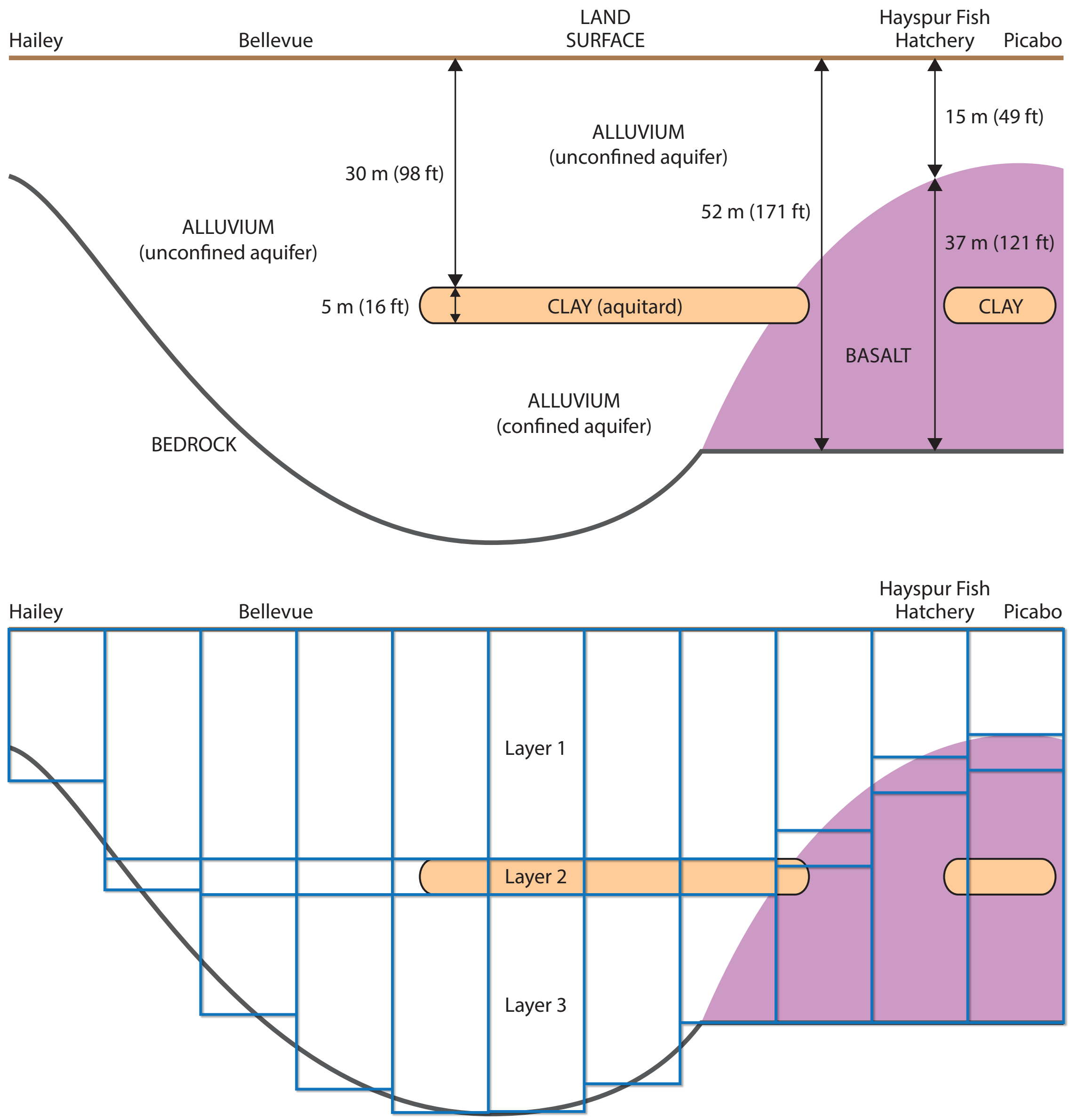

Figure 8: Schematic cross-section representation of hydrogeologic units and three-layer model grid.

```
r <- ExcludeSmallCellChunks(r)  # ensure horizontal connectivity among cells
names(r) <- "lay1.bot"
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.

```
r <- rs.model[["lay1.bot"]] - aquitard.thickness
is.below <- rs.data[["bedrock"]] > r
r[is.below] <- rs.data[["bedrock"]][is.below]
r[(rs.model[["lay1.bot"]] - r) < min.thickness] <- NA  # enforce minimum thickness
r <- ExcludeSmallCellChunks(r)
names(r) <- "lay2.bot"
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.bot"]])] <- NA
r[(rs.model[["lay2.bot"]] - r) < min.thickness] <- NA  # enforce minimum thickness
r <- ExcludeSmallCellChunks(r)
names(r) <- "lay3.bot"
rs.model <- stack(rs.model, r)
```

Bottom elevations of model layer 1 are adjusted to bedrock in cells where the layer 1 bottom elevation is above bedrock and the vertically adjacent layer 2 cell is classified as inactive.

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

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

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

Spatial Discretization

Removing outer rows and columns that are composed entirely of inactive model cells results in the horizontal model grid. A summary of the structured model grid attributes is shown in table 1.

```
model.extent <- trim(rs.model[["lay1.bot"]])
FUN <- function(i) {
  return(crop(rs.model[[i]], model.extent))
}
rs.model <- stack(lapply(names(rs.model), FUN), quick = TRUE)
```

Table 1: Summary description of the structured model grid attributes.

Attribute	Value
Number of rows	542
Number of columns	299
Number of layers	3
Number of active model cells	54,922
Uniform spacing in the easting direction, in meters	100
Uniform spacing in the northing direction, in meters	100
Easting coordinate of model origin, in meters	2,466,200
Northing coordinate of model origin, in meters	1,344,139

Temporal Discretization

The interval of discretization for time is the *time step*. A uniform time step is specified for the groundwater flow model. Time steps are grouped into *stress periods*, where time dependent input data can be changed every stress period (Harbaugh *et al.*, 2000, pg. 8). Individual stress periods in a simulation can either be steady-state or transient. The transient groundwater flow model of the WRV aquifer system is assumed to start from a period when the aquifer system was in steady-state equilibrium. The first stress period is specified as steady state and all subsequent stress periods as transient; that is, the initial value of transient analysis is the first stress period solution. Steady-state flow was simulated to represent conditions in December 1994 with average recharge from April 2004 through March 2005, a period that included a relatively large number of water-level measurements and conditions similar to December 1994. The transient stress periods simulate groundwater flow between 1995 and 2010, a 16 year duration. Each month in the 16-year simulation corresponds to a single stress period, there are a total of 192 stress periods in the simulation. The length of each stress period is dependent on the number of days in the corresponding month and date of year.

```
ss.interval <- as.Date(c("2004-04-01", "2005-04-01"), tz = "MST")  # steady state
tr.interval <- as.Date(c("1995-01-01", "2011-01-01"), tz = "MST")  # transient
ss.stress.periods <- seq(ss.interval[1] , ss.interval[2], "1 month")
tr.stress.periods <- seq(tr.interval[1] , tr.interval[2], "1 month")
```

Hydraulic Properties

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.

Horizontal hydraulic conductivity values for the hydrogeologic zones are based on previous estimates by Bartolino and Adkins (2012, table 2, pg. 25-26). Hydraulic property values (table 2) should be viewed as preliminary and subject to change during model calibration. The hydraulic properties are specified for all cells using the MODFLOW Layer-Property Flow Package (Harbaugh *et al.*, 2000; Harbaugh, 2005).

Table 2: Hydraulic properties for each hydrogeologic zone in the model.

Name	Horizontal hydraulic conductivity (m/d)	Vertical anisotropy (unitless)	Specific storage (1/m)	Specific yield (m^3/m^3)
Zone 1	2.1e+01	50	7.5e-05	0.3
Zone 2	1.5e+01	50	3.6e-05	0.2
Zone 3	8.6e-07	50	1.1e-02	0.1
Zone 4	1.3e+01	50	7.5e-05	0.3

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

```r
r <- rs.model[["lay1.bot"]]
r[!is.na(r)] <- 1
r <- ratify(r)
levels(r) <- merge(levels(r)[[1]], zone.properties, by.x = "ID", sort = FALSE)
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.bot"]]
r[!is.na(r)] <- 1
r[!is.na(r) & !is.na(crop(rs.data[["aquitard.extent"]], model.extent))] <- 3
r[rs.model[["lay2.bot"]] < crop(rs.data[["alluvium.bottom"]], model.extent)] <- 2
r <- ratify(r)
levels(r) <- merge(levels(r)[[1]], zone.properties, by.x = "ID", sort = FALSE)
names(r) <- "lay2.zones"
rs.model <- stack(rs.model, r)
```

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

```r
r <- rs.model[["lay3.bot"]]
r[!is.na(r)] <- 1
r[!is.na(r) & rs.model[["lay2.zones"]] == 3] <- 4
r[rs.model[["lay3.bot"]] < crop(rs.data[["alluvium.bottom"]], model.extent)] <- 2
r <- ratify(r)
levels(r) <- merge(levels(r)[[1]], zone.properties, by.x = "ID", sort = FALSE)
names(r) <- "lay3.zones"
rs.model <- stack(rs.model, r)
```

The horizontal hydraulic conductivity is specified for each cell in the model.

```r
r <- deratify(rs.model[["lay1.zones"]], "hk")
names(r) <- "lay1.hk"
rs.model <- addLayer(rs.model, r)
r <- deratify(rs.model[["lay2.zones"]], "hk")
names(r) <- "lay2.hk"
rs.model <- addLayer(rs.model, r)
r <- deratify(rs.model[["lay3.zones"]], "hk")
names(r) <- "lay3.hk"
rs.model <- addLayer(rs.model, r)
```

Hydrologic Boundaries

Groundwater Fluxes from the Tributary Canyons and Upper Big Wood River Valley

Groundwater entering the aquifer system through the major tributary canyons and upper Big Wood River Valley is simulated using the MODFLOW Well Package (Harbaugh *et al.*, 2000), a specified flow boundary condition. Figure 7 shows the location of these boundaries in the model. The average volumetric flow for each boundary is calculated using Darcy's law and shown in table 3. A scaling index is used to represent the temporal variation in volumetric flows (fig. 12).

```r
mult <- GetSeasonalMultiplier(hailey.discharge, 2, 273.932, tr.stress.periods)
mult <- data.frame(Date = head(tr.stress.periods, -1),
                   multiplier = rep(mult$multiplier, each = 3))
```

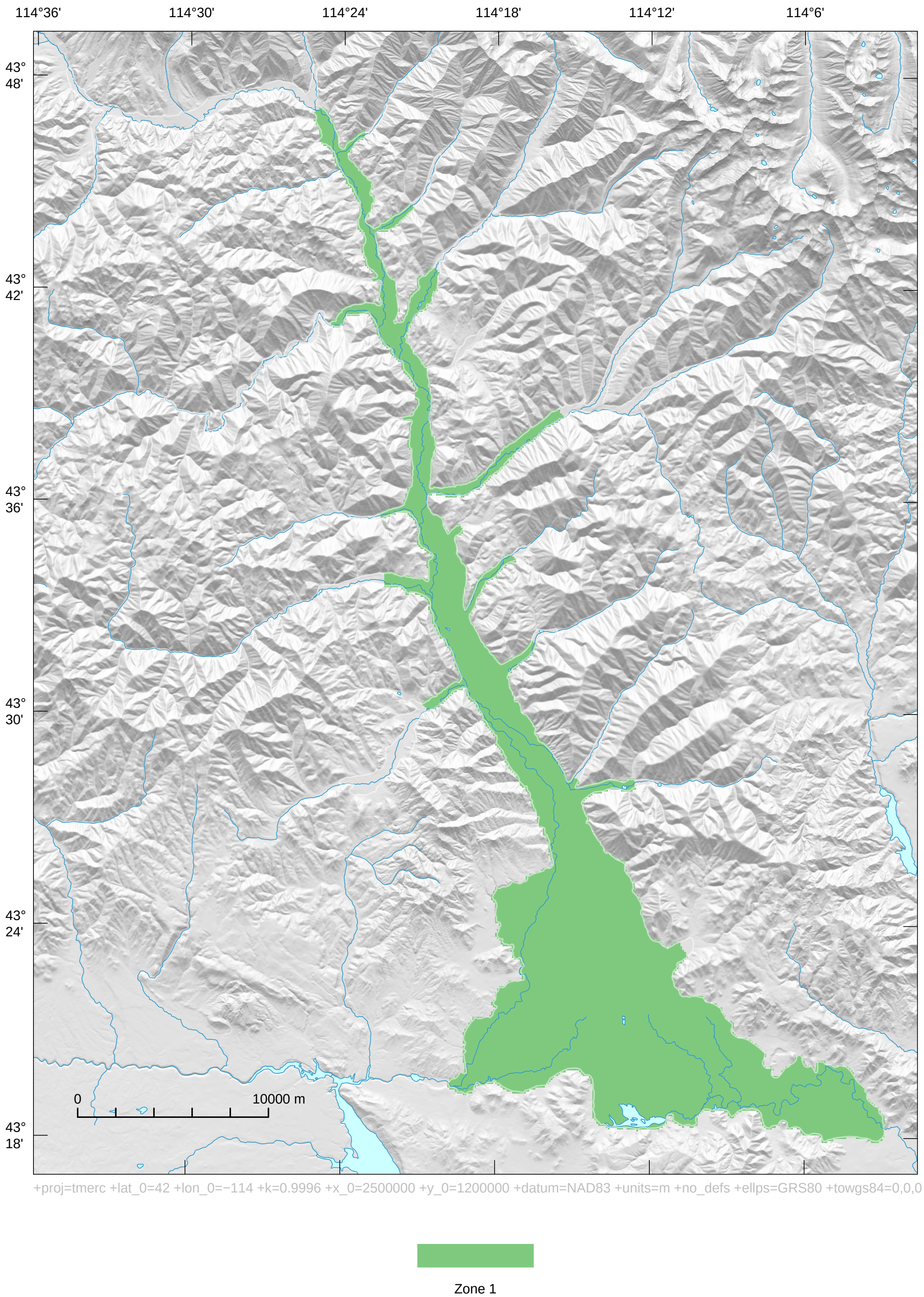

Figure 9: Hydrogeologic zones in model layer 1.

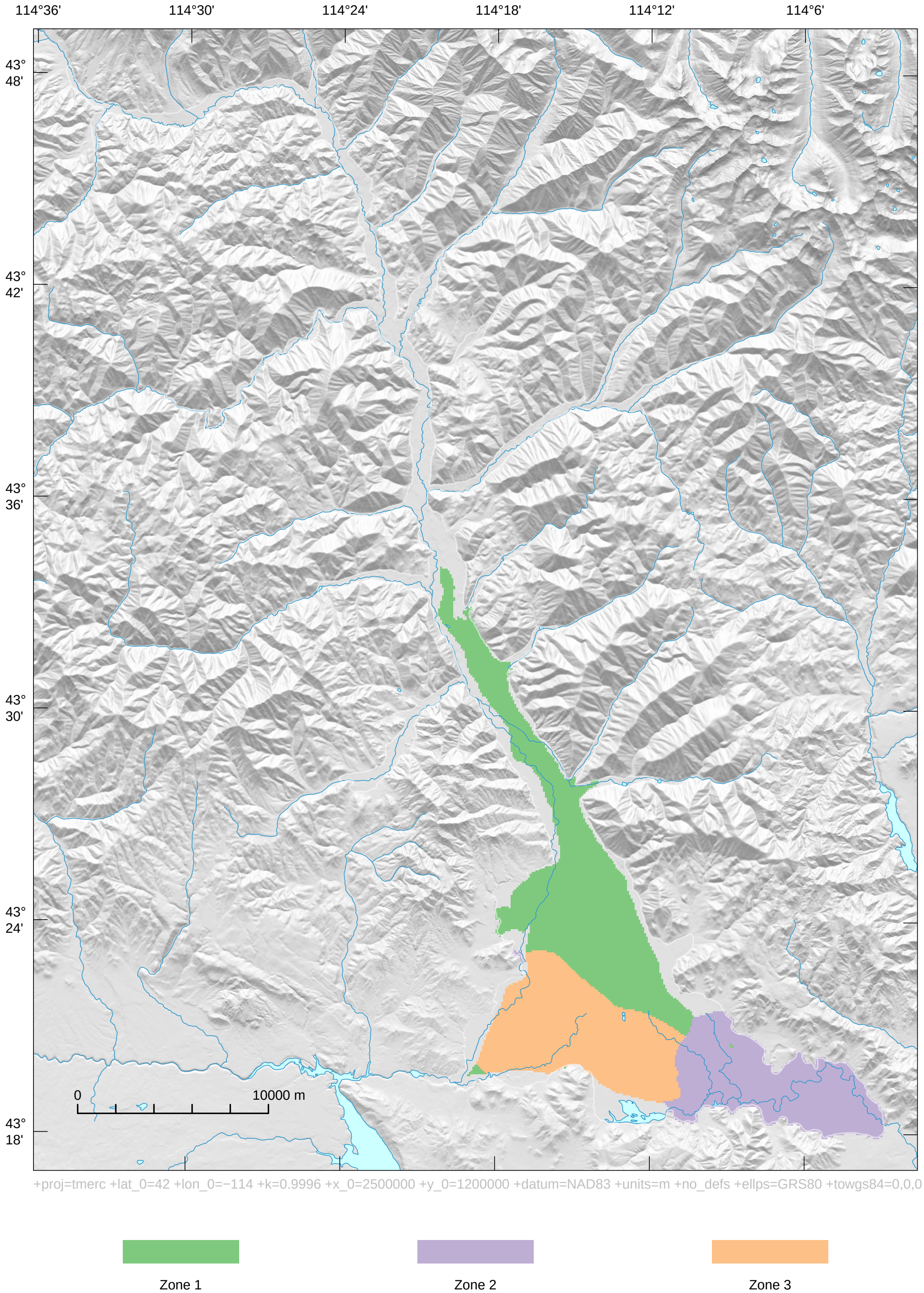

Figure 10: Hydrogeologic zones in model layer 2.

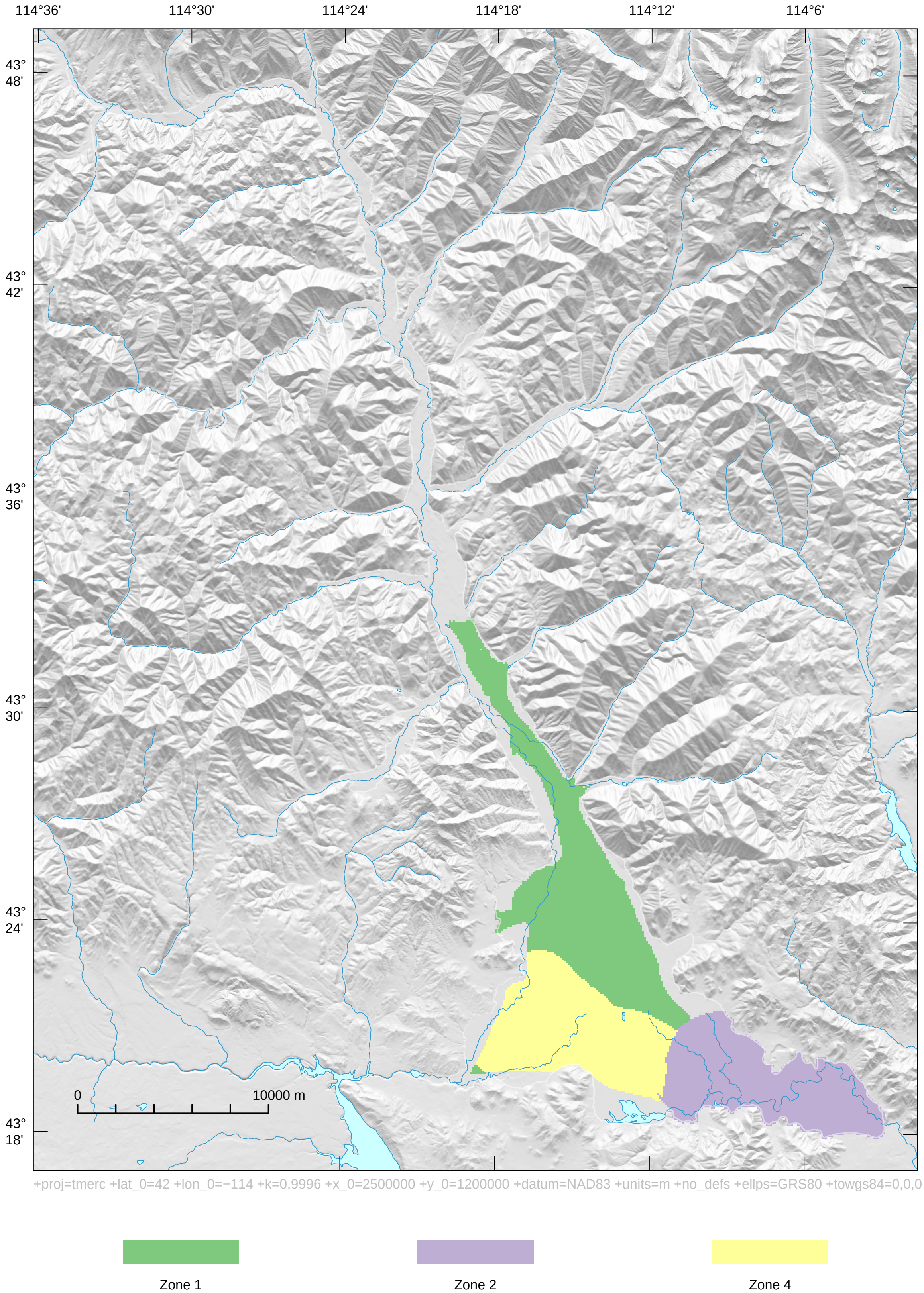

Figure 11: Hydrogeologic zones in model layer 3.

```
flow <- t(vapply(tributaries$Flow, function(i) mult$multiplier * i,
                 rep(0, nrow(mult))))
colnames(flow) <- format(mult$Date, format = "%Y%m")
rownames(flow) <- tributaries$Name
```

Steady-state volumetric flows are calculated for each boundary by averaging flows over time.

```
ss <- apply(flow[, format(head(ss.stress.periods, -1), "%Y%m")], 1, mean)
flow <- cbind(flow, ss)
```

The volumetric flow for each boundary is uniformly distributed among its specified flow cells.

```
r <- rasterize(trib.lines, rs.model)
r[crop(rs.data[["ibound"]], model.extent) != 2] <- NA
rat <- levels(r)[[1]]
rat <- merge(rat, freq(r), by.x = "ID", by.y = "value", all.x = TRUE, sort = FALSE)
rat <- merge(rat, cbind(flow, ID = match(row.names(flow), rat$Name)),
             by = "ID", sort = FALSE)
rat[, colnames(flow)] <- rat[, colnames(flow)] / rat$count
levels(r) <- rat
names(r) <- "tributaries"
rs.model <- stack(rs.model, r)
```

Table 3: Average volumetric flows in the major tributary canyons and upper Big Wood River valley.

Name	Map No.	Flow rate (m^3/d)	Flow rate (acre-ft/yr)
Adams Gulch	1	2,874	851
BWR Upper	2	490	145
Chocolate Gulch	3	176	52
Clear Creek	4	463	137
Cold Springs Gulch	5	675	200
Cove Canyon	6	490	145
Croy Creek	7	2,377	704
Deer Creek	8	4,937	1,462
Eagle Creek	9	3,428	1,015
East Fork	10	1,591	471
Elkhorn Gulch	11	172	51
Greenhorn Gulch	12	2,303	682
Indian Creek	13	8,128	2,407
Lake Creek	14	8,125	2,406
Lees Gulch	15	453	134
Ohio Gulch	16	865	256
Quigley Creek	17	1,891	560
Seamans Gulch	18	6,582	1,949
Slaughterhouse Gulch	19	1,709	506
Townshead Gulch	20	196	58
Trail Creek	21	9,787	2,898
Warm Springs Creek	22	1,645	487

Modeled groundwater fluxes are placed into single data table.

```
cells <- which(!is.na(r[]))
cells <- cells[order(r[cells])]
trib <- cbind(cell = cells, lay = 1, rowColFromCell(r, cells), deratify(r)[cells])
```

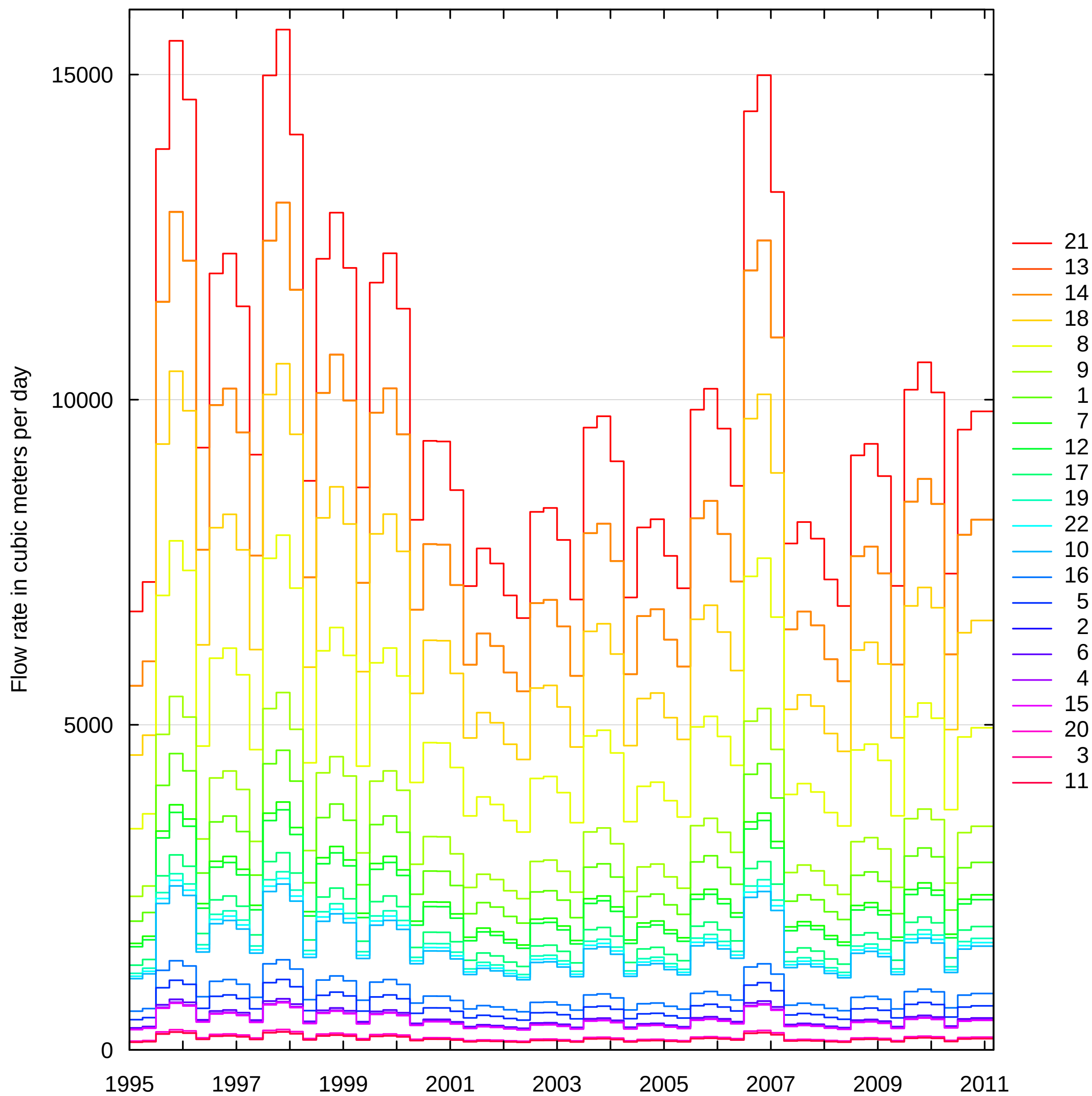

Figure 12: Seasonal flow rate in the tributary canyons and upper Big Wood River valley.

```
trib <- as.data.frame(trib)
trib$Name <- as.factor(rat$Name[trib$Name])
```

Groundwater Flow Beneath Stanton Crossing and Silver Creek Outlet Boundaries

Groundwater leaving the aquifer system beneath Silver Creek and Stanton Crossing outlet boundaries (fig. 1) is simulated using the MODFLOW Drain Package (Harbaugh *et al.*, 2000), a head-dependent flux boundary condition. If the hydraulic head in a drain cell falls below a certain threshold, the flux drops to zero; therefore, these model cells will only allow groundwater to leave the aquifer system. The drain conductance and elevation threshold at Silver Creek and Stanton Crossing outlet boundaries are shown in table 4.

Table 4: Drain conductance and elevation threshold for drain cells along the outlet boundaries.

Name	Drain conductance (m^2/d)	Elevation threshold (m above NAVD 88)
Stanton Crossing	210	1,461
Silver Creek	152	1,450

The location of drain cells in model layer 1 are shown in figure 13. Note that the Silver Creek drain cells also reside in model layers 2 and 3; mirroring the configuration of drain cells in layer 1.

```
l <- gIntersection(drains, as(aquifer.extent, "SpatialLinesDataFrame"), TRUE)
drain.lines <- SpatialLinesDataFrame(l, data = drains@data, match.ID = FALSE)
r <- rasterize(drain.lines, rs.model)
r[!is.na(r) & is.na(rs.model[["lay1.bot"]])] <- NA
r <- ratify(r)
levels(r) <- cbind(levels(r)[[1]], drains@data)
names(r) <- "drains"
rs.model <- stack(rs.model, r)
```

Stream-Aquifer Flow Exchange

Stream-aquifer flow exchange 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 MODFLOW 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, major stream reaches were identified and shown in figure 14. A stream reach is defined as a section of a stream that has (1) uniform water depth that may change over time, (2) uniform riverbed thickness, and (3) uniform riverbed conductance (table 5). Surface-water entities that are not accounted for by the major stream reaches (fig. 14) are represented in the model as aerial recharge; see 'Aerial Recharge and Well Pumping' section for details.

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

```
r <- rasterize(bwr.sc, rs.model, field = "ReachNo")
r[is.na(rs.model[["lay1.bot"]]) | !is.na(rs.model[["drains"]])] <- NA
r <- ratify(r)
levels(r) <- merge(levels(r)[[1]], bwr.sc@data, by.x = "ID", by.y = "ReachNo")
names(r) <- "riv.reach"
rs.model <- stack(rs.model, r)
```

The stream-stage elevation is initialized at land surface.

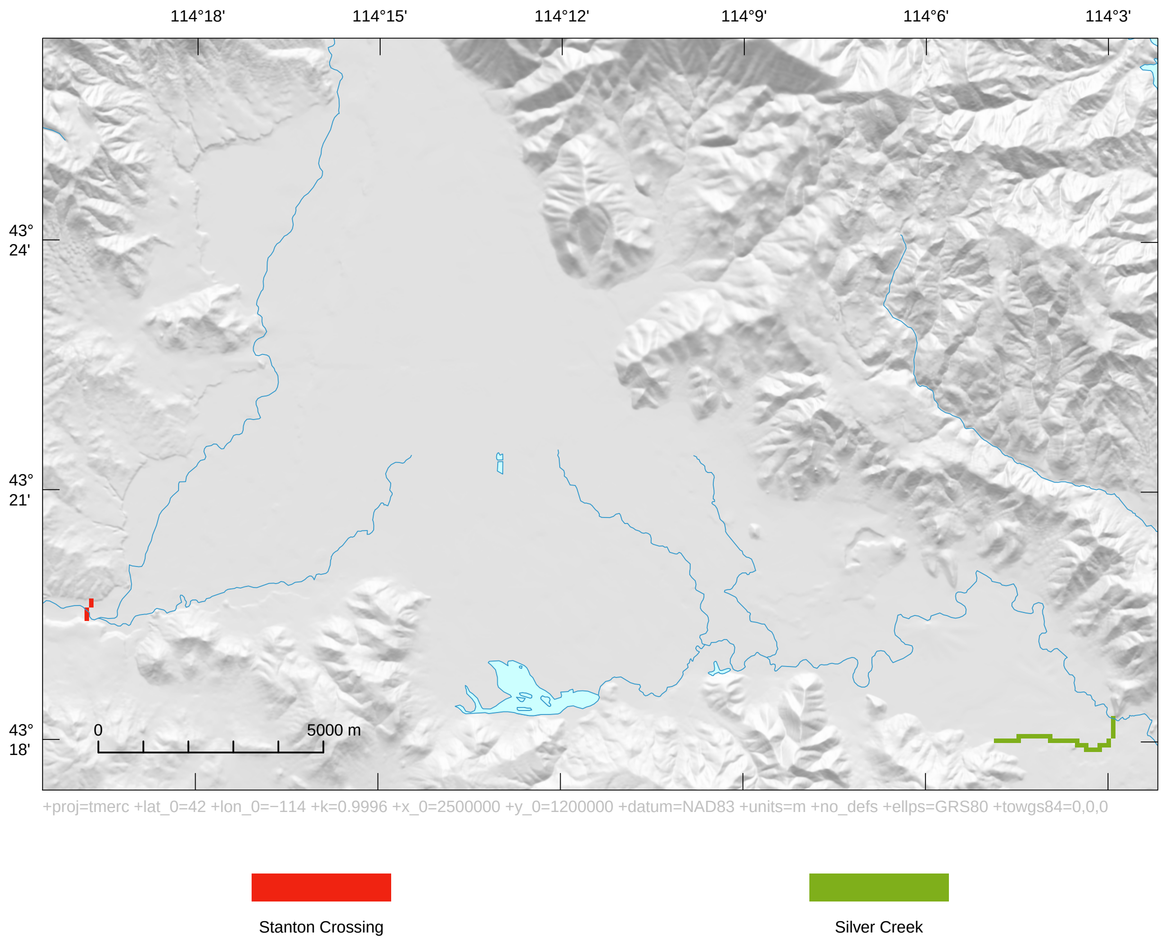

Figure 13: Location of drain cells along outlet boundaries in model layer 1.

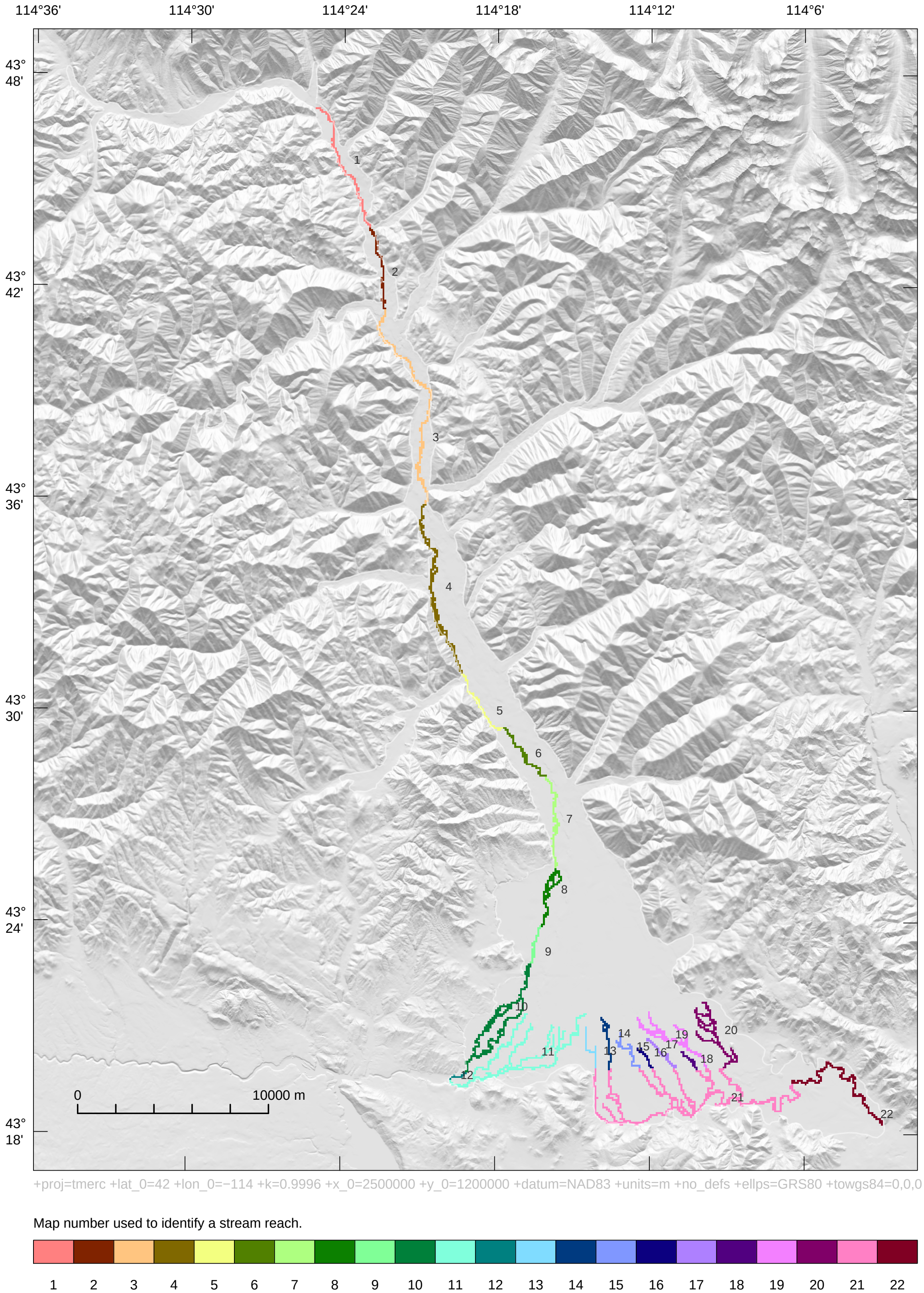

Figure 14: Stream reaches in the Big Wood River and Silver Creek.

Table 5: Description of stream reaches in the Big Wood River and Silver Creek.

Name	Map No.	Ave. water depth (m)	Riverbed thickness (m)	Riverbed conductance (m^2/d)
Big Wood, Nr Ketchum to Hulen Rd	1	0.6	0.3	850
Big Wood, Hulen Rd to Ketchum	2	0.6	0.3	850
Big Wood, Ketchum to Gimlet	3	0.6	0.3	850
Big Wood, Gimlet to Hailey	4	0.6	0.3	850
Big Wood, Hailey to N Broadford	5	0.6	0.3	850
Big Wood, N Broadford to S Broadford	6	0.6	0.3	850
Big Wood, S Broadford to Glendale	7	0.6	0.3	850
Big Wood, Glendale to Sluder	8	0.6	0.3	850
Big Wood, Sluder to Wood River Ranch	9	0.6	0.3	850
Big Wood, Wood River Ranch to Stanton Crossing	10	0.6	0.3	850
Willow Creek	11	0.3	0.9	850
Big Wood, Stanton Crossing to Nr Bellevue	12	0.6	0.3	850
Buhler Drain abv Hwy 20	13	0.3	0.9	850
Patton Creek abv Hwy 20	14	0.3	0.9	850
Cain Creek abv Hwy 20	15	0.3	0.9	850
Chaney Creek abv Hwy 20	16	0.3	0.9	850
Mud Creek abv Hwy 20	17	0.3	0.9	850
Wilson Creek abv Hwy 20	18	0.3	0.9	850
Grove Creek abv Hwy 20	19	0.3	0.9	850
Loving Creek abv Hwy 20	20	0.3	0.9	850
spring creeks blw Hwy 20	21	0.6	0.9	850
Silver Creek, Sportsman Access to Nr Picabo	22	0.6	0.9	850

```
r <- mask(rs.model[["lay1.top"]], rs.model[["riv.reach"]])
names(r) <- "riv.stage"
rs.model <- stack(rs.model, r)
```

Stream-stage elevations are lowered if they violate the laws of physics; that is, water always flows downhill.

```
r <- BumpRiverStage(rs.model[["riv.stage"]], drain.lines)
rs.model[["riv.stage"]] <- rs.model[["riv.stage"]] + r
```

Subtracting the average water depth and riverbed thickness from stream-stage gives the elevation of the riverbed bottom.

```
r.riv.depth <- deratify(rs.model[["riv.reach"]], "Depth")
r.riv.thick <- deratify(rs.model[["riv.reach"]], "BedThk")
r <- rs.model[["riv.stage"]] - r.riv.depth - r.riv.thick
names(r) <- "riv.bottom"
rs.model <- stack(rs.model, r)
```

Flow between adjacent river cells is ensured by decreasing river bottom elevations in those cells prohibiting vertical connectivity.

```
r <- BumpDisconnectedCells(subset(rs.model, c("riv.stage", "riv.bottom")),
                           min.overlap = 0.2)
rs.model[["riv.bottom"]] <- rs.model[["riv.bottom"]] + r
```

The stream thickness, calculated by subtracting riverbed-bottom elevations from stream-stage elevations, ranges from 0.91 m to 6.5 m, with a mean and standard deviation of 1.3 m and 0.39 m, respectively.

Bypass and diversion channels are known to divert flows from the main river channel and result in dry river bed conditions for some of the stream reaches. Dry-bed conditions are represented in the model by specifying the stream stage at the riverbed bottom elevation.

```
r <- rs.model[["riv.reach"]]
cells <- sort(which(!is.na(rs.model[["riv.reach"]][])))
d1 <- data.frame(lay = 1L, rowColFromCell(rs.model[["riv.reach"]], cells),
                 bottom = rs.model[["riv.bottom"]][cells],
                 stage = rs.model[["riv.stage"]][cells],
                 id = rs.model[["riv.reach"]][cells])
d1 <- cbind(d1, factorValues(r, d1$id, att = c("cond", "Reach")))
lay1.bot <- rs.model[["lay1.bot"]][cells]
lay2.bot <- rs.model[["lay2.bot"]][cells]
lay3.bot <- rs.model[["lay3.bot"]][cells]
d2 <- d1[!is.na(lay2.bot) & d1[, "bottom"] < lay1.bot, , drop = FALSE]
d3 <- d1[!is.na(lay3.bot) & d1[, "bottom"] < lay2.bot, , drop = FALSE]
d2$lay <- 2L
d3$lay <- 3L
river <- rbind(d1, d2, d3)
```

Something

```
river <- merge(river, drybed, by.x = "Reach", by.y = "row.names", all.x = TRUE)
river <- river[order(river$id, river$lay), ]
rownames(river) <- NULL
```

Something

```
is.drybed <- as.matrix(river[, colnames(drybed)])
is.drybed[is.na(is.drybed)] <- FALSE
stage     <- matrix(river$stage,  nrow = nrow(river), ncol = ncol(drybed))
stage.dry <- matrix(river$bottom, nrow = nrow(river), ncol = ncol(drybed))
stage[is.drybed] <- stage.dry[is.drybed]
river[, colnames(drybed)] <- stage
```

Something

```
ss <- apply(river[, format(head(ss.stress.periods, -1), "%Y%m")], 1, mean)
river <- cbind(river, ss)
```

Aerial Recharge and Well Pumping

Something... in figure 15.

```
l <- ProcessRecharge(tr.stress.periods, rs.model[["lay1.bot"]], efficiency,
                     canal.seep, TRUE, ss.stress.periods)
cells <- which(!is.na(l[["aerial.rech"]][[1]][]))
rc <- rowColFromCell(l[["aerial.rech"]], cells)
rech <- cbind(lay=1, row=rc[, 1], col=rc[, 2], l[["aerial.rech"]][cells])
```

Something...

```
well <- GetWellConfig(l[["pod.rech"]], rs.model)
```

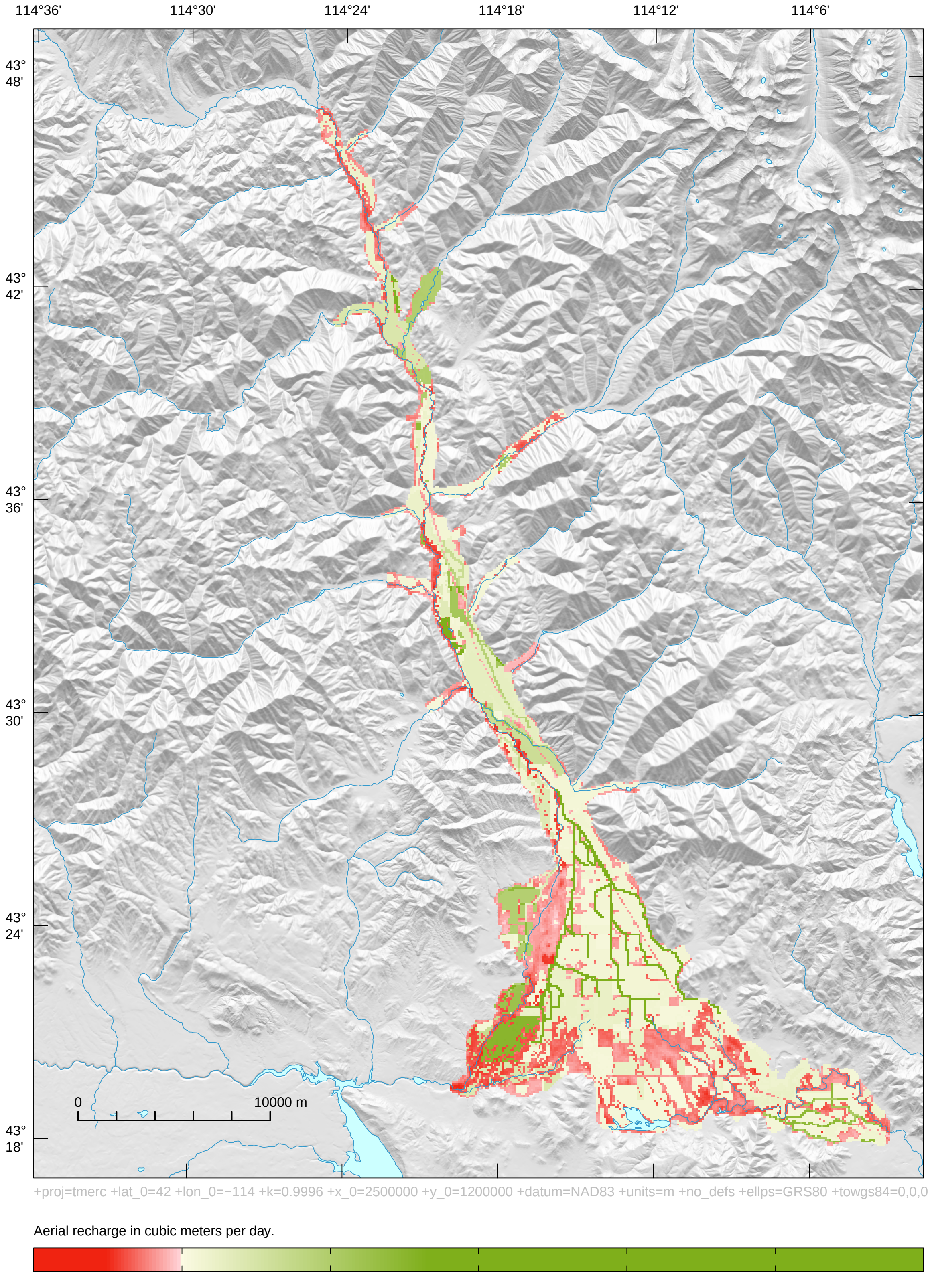

Figure 15: Steady-state aerial recharge in the aquifer system.

Starting Hydraulic Head Distribution

The starting head distribution for the steady-state stress period is specified at 1 meter below land surface.

```
starting.head.depth <- 1  # in meters
r <- rs.model[["lay1.top"]] - starting.head.depth
names(r) <- "lay1.strt"
rs.model <- stack(rs.model, r)
r <- rs.model[["lay1.strt"]]
r[is.na(rs.model[["lay2.bot"]])] <- NA
names(r) <- "lay2.strt"
rs.model <- stack(rs.model, r)
r <- rs.model[["lay1.strt"]]
r[is.na(rs.model[["lay3.bot"]])] <- NA
names(r) <- "lay3.strt"
rs.model <- stack(rs.model, r)
```

Model Run

Groundwater flow in the WRV aquifer system is simulated using the MODFLOW-USG numerical model. This model was chosen for its ability to solve complex unconfined groundwater flow simulations.

```
id <- "wrv_mfusg"  # model run identifier
dir.run <- file.path(dir.out, "Run")
CreateModflowInputFiles(rs.model, rech, well, trib, river, id, dir.run,
                        is.convertible = TRUE, ss.perlen =  diff(ss.interval),
                        tr.stress.periods = tr.stress.periods,
                        time.step = 1L, verbose = FALSE)
```

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

```
cmd <- c(paste("cd", shQuote(dir.run)),
         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)
```

The total elapsed time for the simulation was 5 hours, 23 minutes, 57 seconds. The volumetric budget at the end of the simulation is shown in table 6.

Simulated Hydraulic Heads

Simulated hydraulic heads are read for each model layer and placed in a raster stack (figs. 16 and 17).

```
heads <- ReadModflowBinaryFile(file.path(dir.run, paste0(id, ".hds")))
rs.run <- stack()  # initialize a raster stack for simulated heads
r <- raster(rs.model)
r[] <- heads[[1]]$d
r[is.na(rs.model[["lay1.bot"]])] <- NA
names(r) <- "lay1.head"
rs.run <- stack(rs.run, r)
r[] <- heads[[2]]$d
```

Table 6: Volumetric budget for entire model at end of time step 1 stress period 193.

	Volume (m^3)	Volume (acre-ft)
Storage in	995,959,854	807,433
Constant head in	0	0
Wells in	2,402,320,566	1,947,582
Drains in	0	0
River leakage in	772,033,642	625,894
Total in	4,170,314,061	3,380,909
Storage out	1,001,234,385	811,709
Constant head out	0	0
Wells out	1,552,449,200	1,258,584
Drains out	212,301,611	172,115
River leakage out	1,404,328,805	1,138,501
Total out	4,170,314,002	3,380,909
In minus out	60	0
Percent discrepancy	0	0

```
r[is.na(rs.model[["lay2.bot"]])] <- NA
names(r) <- "lay2.head"
rs.run <- stack(rs.run, r)
r[] <- heads[[3]]$d
r[is.na(rs.model[["lay3.bot"]])] <- NA
names(r) <- "lay3.head"
rs.run <- stack(rs.run, r)
```

A hydraulic head value that exceeds land-surface elevation indicates cell saturation (fig. 18).

```
r <- rs.run[["lay1.head"]] > rs.model[["lay1.top"]]
r <- ratify(r)
levels(r) <- cbind(levels(r)[[1]], att = c("partially saturated", "saturated"))
names(r) <- "lay1.saturated"
rs.run <- stack(rs.run, r)
```

Reproducibility

The groundwater flow model can be reprocessed in a single step. Use the following command to evaluate R code extracted from this vignette; note that software installations are not included in this evaluation, see 'Software' section for installation instructions.

```
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 3.1.2 (2014-10-31), `x86_64-w64-mingw32`
- Base packages: base, datasets, grDevices, graphics, methods, stats, utils

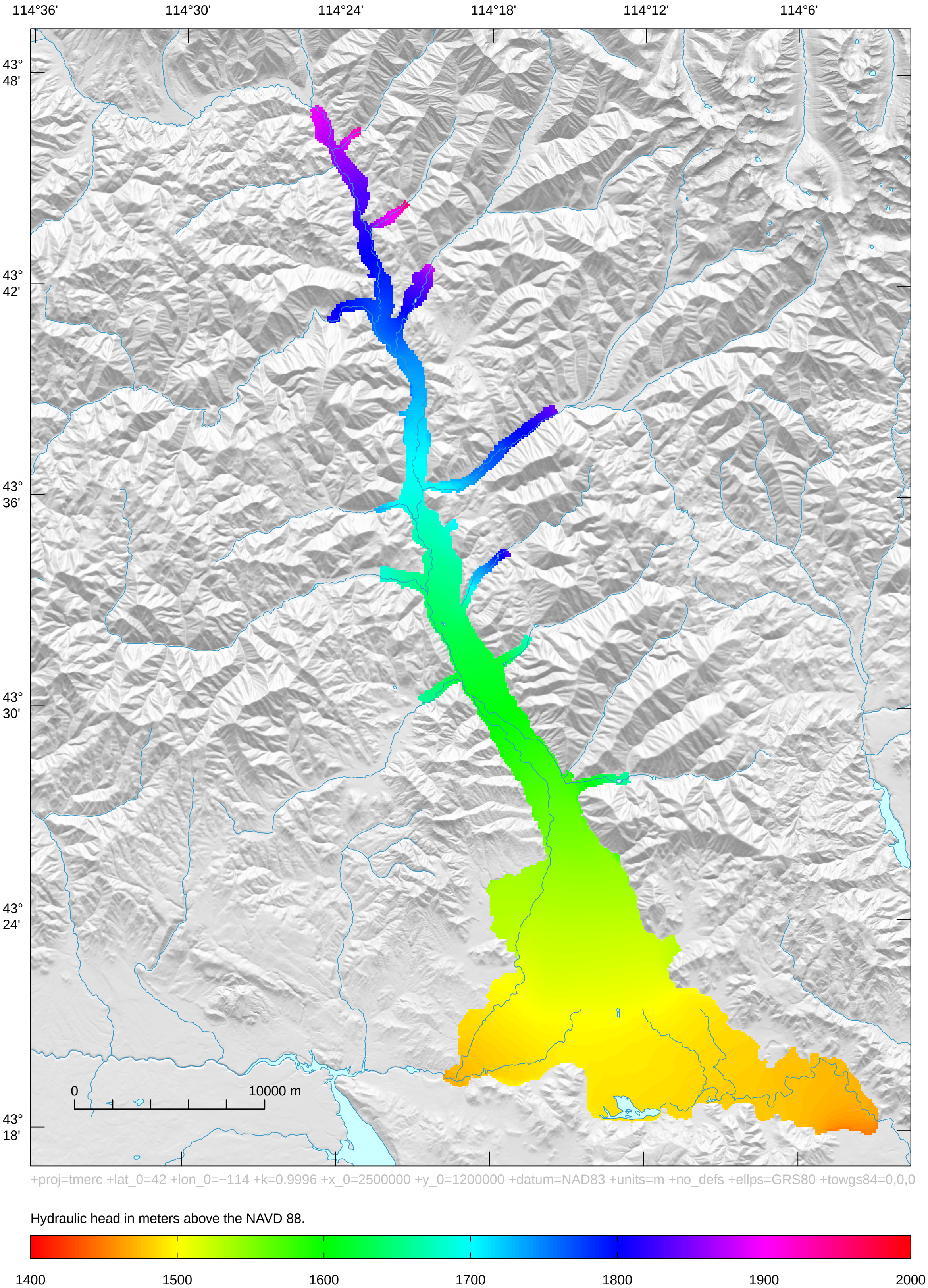

Figure 16: Hydraulic head in model layer 1 at the end of the simulation.

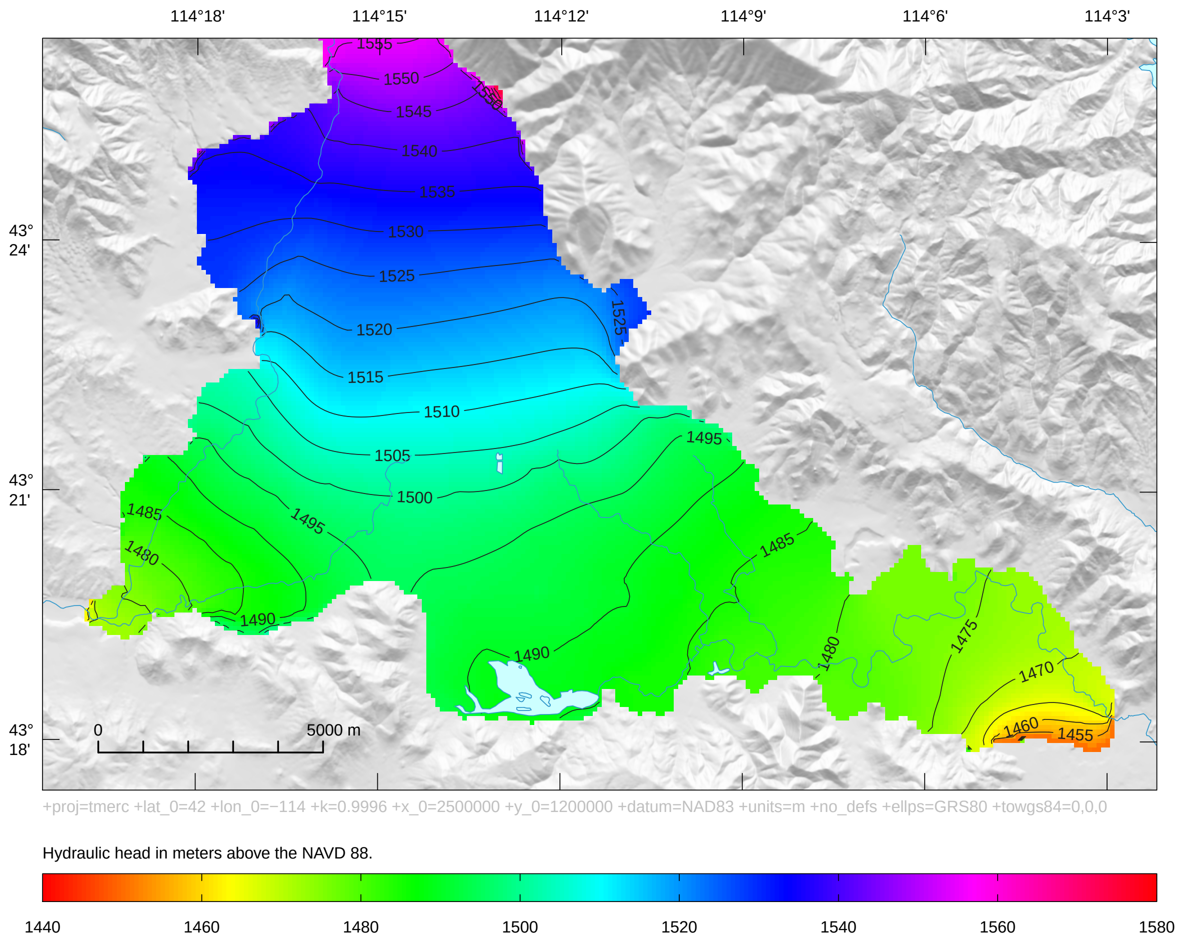

Figure 17: Hydraulic head in the southern part of model layer 1 at the end of the simulation.

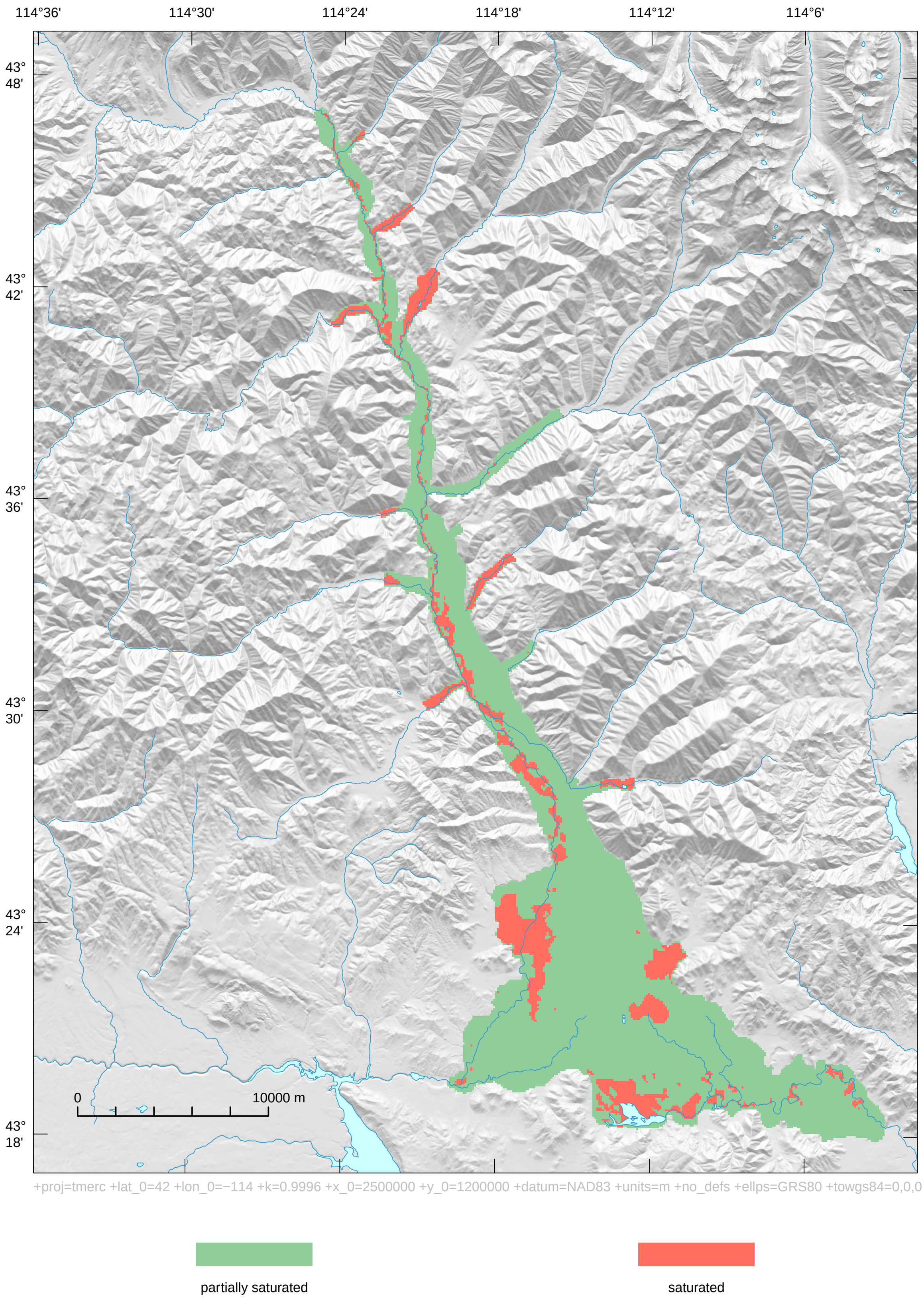

Figure 18: Saturated and partially-saturated cells in model layer 1 at the end of the simulation.

- Other packages: RCurl 1.95-4.3, bitops 1.0-6, igraph 0.7.1, raster 2.3-12, rgdal 0.9-1, rgeos 0.3-8, sp 1.0-16, wrv 0.2-1, xtable 1.7-4
- Loaded via a namespace (and not attached): evaluate 0.5.5, formatR 1.0, grid 3.1.2, highr 0.4, knitr 1.8, lattice 0.20-29, stringr 0.6.2, tools 3.1.2

Total processing time for this vignette was 5.6 hours, built on November 30, 2014.

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