# Implementation of SAFE approach

The calculation of seepage discharge from the riverbeds to groundwater is carried out at the element nodes. The groundwater head and the Stream head for each river node are known from the previous iteration or the initial conditions.

Diagram

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Figure Schematic illustration of the river section

The river stage is calculated as

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Where is the elevation of the bottom of the riverbed and is the riverbed thickness.

Based on the river stage the wetted perimeter is calculated from user defined rating tables.

Next saturated thickness of the aquifer is calculated as the sum of the elevation of the phreatic surface (with datum at the bottom of the user selected geologic layer) plus the thickness of the capillary fringe.

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Where is the elevation of the selected geologic layer and represents the thickness of the capillary fringe.

Then the normalized depth and normalized wetted perimeter can be calculated as

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Based on the normalized depth and wetted perimeter the coefficients and are estimated from the following table

**Table

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The flat isotropic conductance is a function of the parameters and and the coefficients and

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Approximate the equivalent river width using the assumption of the rectangular river cross section:

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Which is then used to calculate the

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Next Safe calculates a correction for the isotropic conductance . The correction depends on the anisotropy ration.

For isotropic aquifers the correction is given by

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Where .

For anisotropic aquifer first we calculated the following:

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Where and is the aquifer horizontal and vertical hydraulic conductivity.

Then the correction is calculated by considering the anisotropy as follows:

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The last step in the Safe method is to correct the value of or to account for the presence of the riverbed clogging layer.

For isotropic aquifers the correction is given by

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For the anisotropic aquifers the calculation is identical to eq (19) after replacing the with the outcome of eq. (18) .

The head difference in Safe method is used by subtracting the incipient desaturation from the stream head . The incipient desaturation is calculated as:

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Where is the entry pressure and it is a user input that depends on the riverbed material.

Finally, the seepage discharge is calculated

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## Calculation of Asymmetric Seepage Discharge

The first task is to calculate a representative groundwater head left and right of each stream segment. There are two approaches. One calculates the groundwater head by interpolating the groundwater head from the finite element solution and the other approach is based on the mass balance.

For the latter approach the left and right representative groundwater head is given by the following equations

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Where is the effective porosity, and are the area of influence of the stream nodes left and right of the stream and , is the net of water volume that flows in and out of the left and right element respectively.

# Applications

## Central Valley – Coarse grid

In this section we applied the Safe approach to a coarse grid version of the C2VSim Central Valley model. Currently the model is under development, and the calibration has not been completed. In addition, the original model uses the stream package 4.2 which does not calculate the wetted perimeter using rating tables. In this application we assigned wetted perimeter values for the rating tables using the formula . The river stage values were obtained from the rating tables of the 4.2 stream package input files, while the river width was estimated using an empirical formula (Figure 1). The above equation assumes that the river cross section is trapezoid with 60 degrees angle.

Chart

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Figure Stream width as function of total cumulative volume

The model was simulated for comparison using the stream package 4.2. In the following paragraphs we will explore the differences between the two approaches. It should be noted that the two approaches do not differ only in the way the seepage discharge is calculated but they also use different riverbed conductance values. Typically, the riverbed conductance is a calibrated parameter. However, the Safe approach assumes knowledge of the riverbed material and the riverbed conductance is directly associated with the actual material. However, due to the lack of knowledge of the riverbed material we run a sensitivity analysis. Initially, we assume that the main material of the riverbed is clay, therefore the conductance value was set and the entry pressure . In all simulations the riverbed thickness was set equal to . We can observe that the calibrated riverbed conductance of the original C2VSim model falls around the values of the clay material. It should also be noted also that the original model includes several river nodes with 0 conductance.

Chart, histogram

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Figure Histogram of riverbed conductance values of the original C2VSim model.

### Seepage Discharge

The primary variable of interest in this report is the seepage discharge. The cumulative seepage discharge (SPD) across the entire Central Valley it seems to exhibit higher variability using the stream package 4.2 compared to SAFE method (Figure 3), while the mean cumulative value for each package (Safe:0.1145, SP4.2 0.42 MAF) suggests that under Safe approach the majority of the stream nodes are gaining and for the SP4.2 the river nodes are loosing. However, if we exclude the river nodes 516-520 that correspond to the Sacramento river the agreement between the two is improved significantly (Figure 5). Figure 6 plots the cumulative seepage discharge for the river nodes 516-520 where we can see that there is a 5 orders of magnitude difference between the two models.

Chart

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Figure Cumulative seepage discharge across the Central Valley

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Figure Cumulative seepage discharge across the Central Valley excluding the river nodes 516-520 of the Sacramento river

Graphical user interface, application

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Figure Cumulative seepage discharge of the Sacramento river nodes 516-520.

The mean yearly SPD values in both methods exhibit similar trends (Figure 7 top). In both methods there is a declining trend from 1984 to 1995 which is reversed up to 1999, followed by a continuous decline until the end of the simulation. Overall, the mean value for the Safe method appears higher than the original IWFM 4.2 method. On the other hand, the yearly standard deviation of the IWFM approach is considerably higher (Figure 7 bottom). In some case e.g., 1986,1995,1996 the difference between minimum (-2 MAF) and maximum (1[MAF]) discharge is as high as 3 MAF. The variability of the safe method is more subtle and the differences between minimum and maximum values are less than 200 TAF. In addition, the difference between yearly minimum and maximum values take place over a longer period of time (Figure 8). In 1995 both models calculate the minimum SPD for the March which is -0.25 and 2 MAF for Safe and IWFM respectively. For IWFM the maximum SPD is observed the next month and it is equal to 0.84 MAF. For the Safe approach, the SPD is continuously increased until the November of 1995, while in IWFM the SPD after April oscillates with an amplitude that is dampen over time until November

Chart, line chart, histogram

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Figure 7 Top Mean yearly seepage discharge. Bottom Standard deviation of the yearly SPD. In both plots the river nodes 516-520 have been excluded

Chart, histogram

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Figure 8 Highlight of cumulative SPD for selected years

Next, we will compare the SPD for a few selected stream nodes. In Figure 9 we have removed the monthly variation by calculating the mean yearly SPD in a similar manner to Figure 7.The comparison shows that there is no consistent discrepancy pattern between the two methods. There exist stream nodes where the yearly mean SPD is similar in both methods (Figure 9 first row of panels ). However there are cases where IWFM 4.2 calculates higher positive of lower negative values compared to Safe and vice versa. In Figure 9 we use the normalized dynamic time warping (Dtw) distance to compare the time series of SPD calculated by the two approaches. The Dtw can be used as a measure of how close two time series are. Here we have calculated the Dtw for all river nodes and normalized the Dtw values between 0 and 1 where 0 corresponds to best match and 1 to worst match. Based on the normalized Dtw we can plot the measure in a map (Figure 10). The Dtw distance doesn’t not show only the correlation but it is also influenced by the absolute differences. For example, river node 70 (center panel) has a normalized Dtw distance equal to 0.35 while node 26 has lower value mainly because the yealy mean SPD ranges for 0 to 1.2 MAF while the range for node 70 is one order of magnitude higher. The majority of river nodes have a relatively low normalized distance. 80% of river nodes have a nDtw value less than 0.5 while 60% had nDtw less than 0.3. The highest discrepancies occur at the fist nodes of the Kern river, the second half of the Kings river and the Fresno Slough. Interestingly it appears that an abrupt discrepancy appears in the nodes where two or more rivers meet.

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Figure Seepage Discharge for a few river nodes. The blue line corresponds to the Mean yearly values of the IWFM 4.2 and the red to Safe method

Map

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Figure Map of the normalize dynamic time warping distance between IWFM 4.2 and Safe mean yearly values

### Groundwater Head

The groundwater head is also an important variable in groundwater simulations and has a direct influence on the calculation of the Seepage discharge. The groundwater head is both temporal and spatially variable. First, we analyze the temporal variation between IWFM 4.2 and Safe package. For each monthly time step we calculated the difference between IWFM groundwater head and SAFE groundwater head for each node and calculated the percentiles across all nodes. The calculation was carried out for each layer separately and it is shown in Figure 11. We can observe that in all layers there is a bias where SAFE method calculates higher groundwater heads compared to IWFM 4.2. The mean difference of the median value is -2.2, -1.5, -1.3, -0.97 ft which indicates that safe method tends to calculate 1-2 ft higher groundwater head. Similarly, we observe that the 25th percentile values vary around -17 - -15 ft (after 1985) while the 75th percentiles vary around 7-9 ft. When we consider the 5th and 95th percentile we observe that the IWFM has calculated differences where the head was estimated up to 60 ft higher while the groundwater nodes where the SAFE values are greater, the range is less than 40 ft. It appears that IWFM tends to calculate more extreme values in certain areas.Graphical user interface, chart

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Figure 11 Groundwater head difference between IWFM 4.2 and SAFE method. Each panel shows the percentiles of the head differences for each layer

Figure 11 shows the percentiles of the differences between IWFM and Safe across all nodes for each time step. Therefore, this figure is not indicative of the actual differences. On the other hand, Figure 12 shows the absolute differences of groundwater heads between the two methods. The median absolute discrepancy is very similar for all layers. The first ten years of the simulation, the discrepancy increases from zero to about 10 ft for 50% of the simulated heads and about 20 ft for 75% of the nodes. After 1985 the discrepancy oscillates around the mean value and increases slightly after 1995. While the discrepancies are of similar order for all layers, we observe that the extreme differences e.g of 5% of the groundwater nodes with highest discrepancies , area larger for the top layer and they reduced as the examine the heads in the deeper parts of the aquifer.

Chart

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Figure Absolute difference of groundwater heads between IWFM 4.2 and Safe

Chart

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Figure Groundwater head difference between IWFM and SAFE method for the last time step. Examples of hydrographs at the locations with highest discrepancy.

### Stream Stage

### Total Water budget

In this paragraph we will compare a few of the total water budget terms across the entire study area or split by subregions

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Figure Groundwater Budget for the entire Central Valley region

## Central Valley Fine grid

### Seepage Discharge

Chart

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Figure 17 Cumulative Seepage discharge across all groundwater nodes

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Figure 18 Comparison of mean yearly cumulative seepage discharge and yearly standard deviation

### Groundwater Head

Graphical user interface, chart

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Chart, histogram

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### Total Water Budget

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### Convergence

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