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An improved model of shade-affected stream temperature in Soil & Water Assessment Tool

Efrain Noa-Yarasca et al.

Correspondence to: Efrain Noa-Yarasca (enoay7@yahoo.com)

S1 Including Water Rights into SWAT Model

Oregon establishes that water belongs to the public. Irrigation, business, and other water-use activities must obtain a license from the Water Resources Department of Oregon for taking and using water from any source. This law is applied to all types of water sources (rivers, lakes, groundwater). Thus, since the approval of this law, in the DMW like in other areas of Oregon, water-use rights have been given to users, which were considered here for flow modelling (OWRD, 2018).

S1.1 Stakeholder Water Rights

Statewide water-right spatial data in ArcGIS format was obtained from the Oregon Water Resources Department website (OWRD, n.d.). This information involves metadata of Point-of-Diversion (POD), Places of Use (POU) with water rights. The POU data involves information such as the purpose of water use, land area, the certificate number, priority, the SNP id, among others. The POD data involves information such as the catchment point location, the purpose of water use, the certificate number, source (stream, lake, well), SNP id, allowed period to take water, duty (maximum volume of water allowed to take from the source), maximum rate of water allowed to take from the source, among other data.

After processing water-rights metadata for irrigation purposes (codes: irrigation and supplemental irrigation) for DMW, 785 POUs and 937 PODs were found. The difference between the number of PODs and POUs was because in some cases, one POU was irrigated by two or three PODs, and in very few cases one POD irrigated more than one POU (Fig. S1). PODs and POUs were matched by using the SNAP-ID. Thus, for DMW, 785 pairs of POD-POU were obtained (Fig. S2).

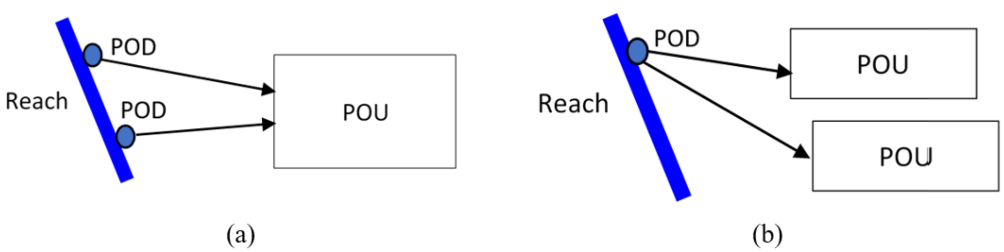


Figure S1. (a) one POU irrigated by two PODs. (b) one POD irrigating two POUs

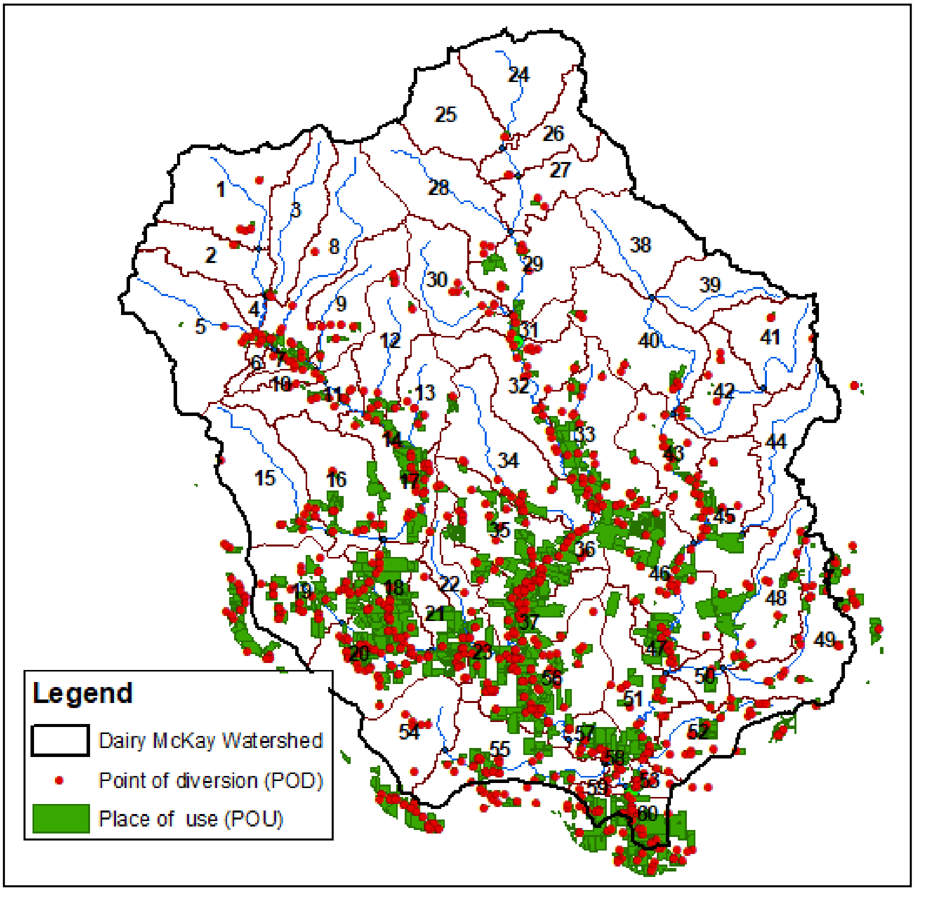


Figure S2. Distribution of Points of diversion (PODs) and Places of use (POUs) with water rights within the Dairy McKay watershed.

S1.1.1 Period of Operation according to Water Rights

According to water rights, 75.2% of PODs are allowed to uptake water from their source over the year, by 21.7% of PODs are allowed to uptake water over eight months (from March to October), and only 3.1% of PODs are allowed to uptake water for less than eight months. For modelling purposes, this research considered only two periods for uptake of water (twelve and eight months).

S1.1.1 Assignation of Maximum Water Volume to HRUs.

Edges of POUs do not necessarily matched with edges of SWAT Hydrologic Response Unit (HRU), so that, to transfer the information of the maximum water volumes assigned to the POUs to the HRUs, a weighting relationship of proportion of areas was employed. Thus, the maximum volume of water of an HRU was equal to the sum of the maximum volume of water of each POU multiplied by its percentage of the area lying over the HRU (Eq. S1, Fig. S3).

$$V_{HRU_j} = \sum_{i=1}^{n} \frac{w_{ij} . V_{POU_{ij}}}{100} \qquad \text{(S1)}$$

Where V_{HRU_j} is the maximum volume of uptaking water for HRU_j, $V_{POU_{ij}}$ is the maximum volume of uptaking water of the POU_i, w_{ij} is the rate of the POU_i lying over the HRU_j, n is the number of POUs that have common areas with the HRU_j. Therefore, the sum $(\sum_{i=1}^{n} w_{ij})$ does not necessarily is equal to 1, but the sum $\sum_{i=1}^{n} w_i$ must be equal to 1.

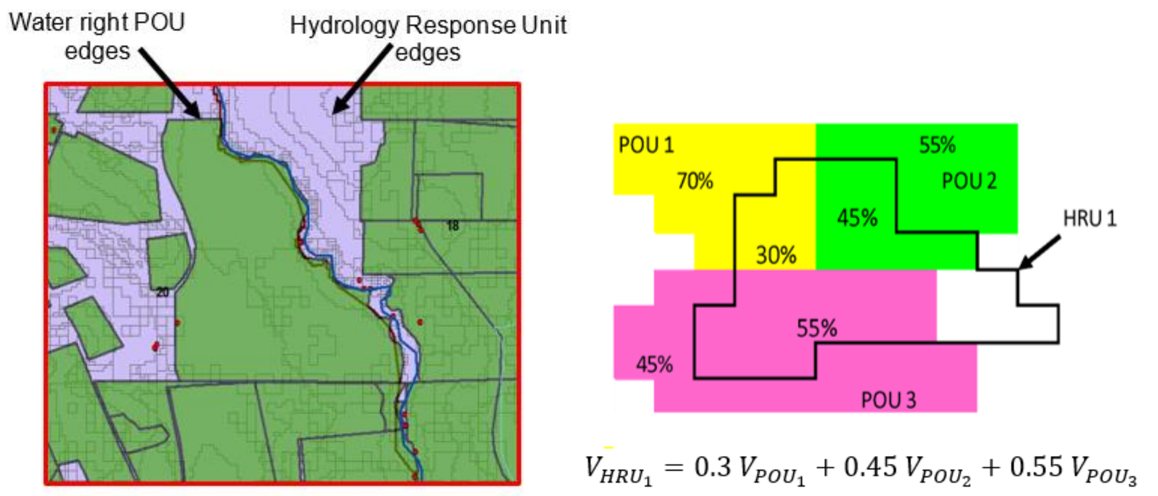


Figure S3. Assignation of maximum water volume to Hydrological Response Units (SWAT units)

S1.2 Including Instream Water Rights (Instream Minimum Flow) into SWAT model

Instream flows in Oregon are protected by the 30th Anniversary of Oregon's Instream Water Right Act. The purpose of this amount of water is to support aquatic life and minimize pollution. According to this law, if a river carries a flow less than or equal to the instream flow water right, no one can withdraw water from the river unless they have a water right prior to the water right established for that stream.

For DMW, six water rights of instream flows were found. These water rights establish control of minimum flows in four sites (McKay Creek measured at or near River mile 15.5 (IWR-1), Denny Creek and its tributaries above its mouth measured at or near the mouth (IWR-2), Plenty-water Creek and its tributaries above its mouth measured at or near the mouth (IWR-3), and East Fork Dairy Creek and its tributaries above river mile 13 measured at or near river mile 13 (IWR-4)) and along two rivers (The West Fork of Dairy Creek and its tributaries at the Highway 47 crossing at banks, and maintained to the mouth (IWR-5), and Dairy Creek from headwaters to the mouth at river mile 0 (IWR-6)). Most of these water rights do not consider a constant flow during the year as shown in Fig. S4. These water rights were also considered here in the SWAT flow modeling as the minimum instream flow for irrigation diversion.

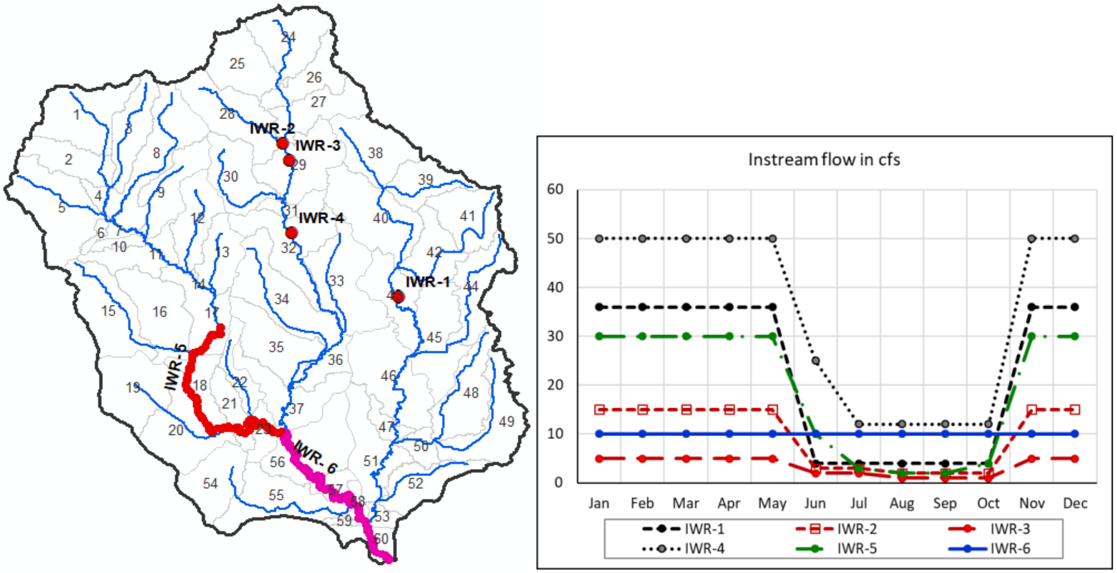


Figure S4. DMW streams with water rights establishing the minimum in-stream flow

S2 Shade Factor Calculation

The shade factor was computed as the rate of solar radiation blocked by the topography and riparian vegetation divided by the potential solar radiation that would reach the stream surface. The blocked solar radiation was determined by the shaded area in the stream generated by the topography and vegetation of the stream banks.

The blocked solar radiation was determined for time intervals of 0.01 hours and was accumulated during the day (from sunrise to sunset) to determine a more accurate SF for the whole day and for all days in the year. This calculation process was developed in the Python environment and then input into the SWAT hydrological model (https://github.com/noayarae/SF_model.git). Side banks have been distinguished throughout the calculation process to identify the contribution of each bank in the SF increase and then in the stream temperature decrease. Table S1 shows the steps followed to calculate the SF. These steps were repeated for 365 days and for each stream within the DMW. Below are the equations used in the calculation of the shade factor.

Table S1. Steps to calculate the shade factor for each day (pseudocode)

```
Calculate latitude, stream azimuth, and stream length
Calculate the topographic angle from DEM
Get stream width from the SWAT model
Get height tree for each stream bank from the Landfire database
Start loop through the 24 hr. (Δt = 0.01 hr.)
   Calculate solar angle and solar azimuth for each time step (Eq. S2, Eq. S5)
   Calculate the solar radiation for each time step (Eq. S6)
   If solar angle > 0 & Potential solar radiation > 0
      Calculate the length of the shadow parallel to the solar azimuth (Eq. S9)
      Calculate the length of the shadow normal to the stream (Eq. S10)
      Calculate the shadow over the stream
      If top_angle > solar angle: (The shade is caused by topography)
         The shade corresponds to the topography
      If top_angle < sola angle: (The shade is caused by riparian vegetation)
         The shade corresponds to the riparian vegetation
         Identify the riparian bank causing the shadow
            If sin (solar_angle – strm_azimuth) > 0 → Right bank
            If sin (solar_angle – strm_azimuth) < 0 → Left bank
   Calculate the accumulated solar radiation no reaching the stream during the day
   Calculate the potential solar radiation that might reach the stream during the day
Calculate the daily shade factor (SF_i = SR_daily / SR_potential) (Eq. S11)
```

S2.1 Solar Angle and Solar Azimuth

The solar angle is measured between the observer's horizon and the sun. It is a function of the stream latitude, declination of the sun, and the time of the day (Eq. S2-S4).

$$\alpha = \sin^{-1}(\sin\phi . \sin\delta + \cos\phi . \cos\delta . \cos\tau) \quad \text{(S2)}$$

$$\delta = 23.45 \left(\frac{2\,\pi}{360}\right) cos\left(\frac{2\,\pi\,(172-JD)}{365}\right) \tag{S3}$$

$$\tau = \big(180 - long - t_m - (360\ hr/24)\big)\ (2\pi/360) \tag{S4}$$

Where: α is the solar altitude (solar angle), ϕ is the stream latitude, δ is the declination of the sun, τ is the local hour angle of the sun, JD is the Julian day (1-365), $long$ is the stream longitude, t_m is the local time zone meridian (degrees), and hr is the hour of the day. These equations are explained in depth by Boyd (Boyd 2003).

The solar azimuth is the angle formed by north and the horizontal projection of the sun (on the observer's horizon) measured clockwise (Eq. S5).

$$Sun_{az} = \cos^{-1}\left(\frac{\sin\delta - \sin\alpha\,.\ \sin\phi}{\cos\alpha\,.\ \cos\phi}\right) \tag{S5}$$

Stream azimuths were measured from the north to the stream center line in the flow direction. These values were obtained in the GIS environment for each stream of each sub-basin.

S2.2 Sub Daily Solar Radiation

Solar radiation for sub-daily time scales was obtained using the Kaplanis approach (Kaplanis, 2006; Khatib & Elmenreich, 2015). This approach proposes solar radiation at any time as a cosine function limited by the sunrise and sunset and conditioned to the day (Eq. S6).

$$h_{ij} = a.n_j + b.n_j\ cos\ (\frac{2\,\pi\,t_{ss}}{24}) \tag{S6}$$

Where h_{ij} is the solar radiation at any time within the day, t_i is the time in hours, n_j is the Julian day, and a and b are coefficients determined for any site and any day. These coefficients are determined by solving the Eq. (S6) for the following boundary conditions: the integration of the above equation over h, from sunrise (t_{sr}) to sunset (t_{ss}) is equal to the measured daily solar radiation, and the solar radiation when h equals t_{ss} is zero (For t_i = t_{ss}, h_{ij} = 0) (Kaplanis, 2006) (Eq. S7-S8).

$$H_j = \int_{t_{sr}}^{t_{ss}} h_{ij}\ dt \tag{S7}$$

$$a.n_j + b.n_j.\cos(2\,\pi\ t_{ss}/24) = 0 \tag{S8}$$

S2.3 Shadow over the Stream

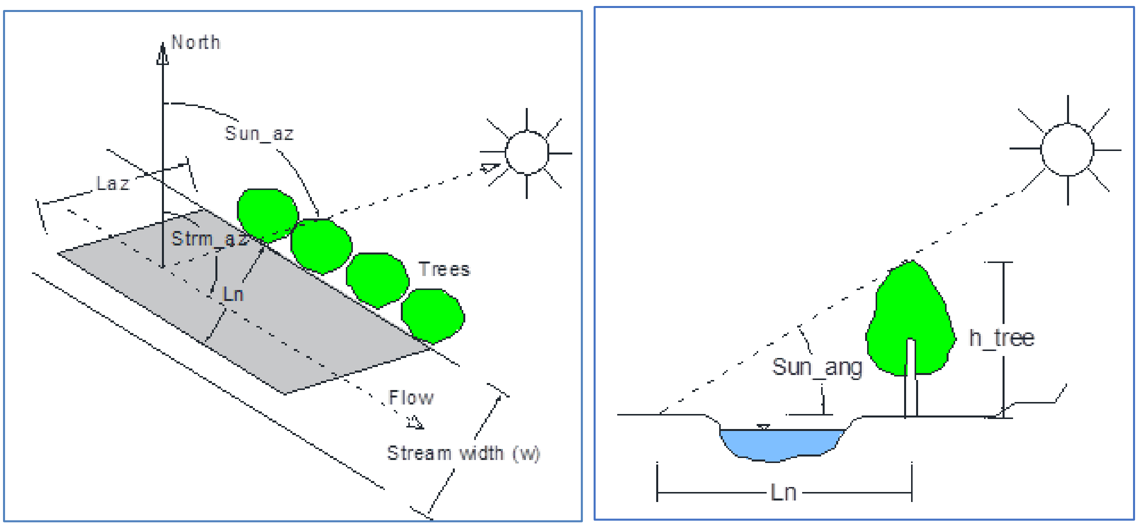
The length of the shadow (Laz) (either by riparian or the topography) parallel to the solar azimuth and length of the shadow normal to the streamflow are obtained by geometry (Fig. S5) (Eq. S9-S10).

$$Laz = \frac{h\_tree}{tan\ (\alpha)} \tag{S9}$$

$$L_n = L_{az}\ .sin\ (sun_{az} - strm_{az}) \tag{S10}$$

Where h_tree is the tree height in riparian vegetation, α is the solar angle, sun_{az} is the solar azimuth, and $strm_{az}$ is the stream azimuth.

The normal shadow was then multiplied by the stream length. Thus, three shading scenarios on the stream can be observed: no shadow over the stream, partial shadow over the stream, and full shadow over the stream. In this calculation, the shade factor corresponding to the topography, left bank and right bank (defined in the direction of flow) has been identified and then calculated separately to determine the contribution of each barrier in the stream SF.



.(a) (b)

Figure S5. Diagram showing the variables to calculate the length of the shadow parallel to the azimuth (Laz) and perpendicular to the streamline (Ln). (a) perspective and (b) side view.

Finally, the shade factor for each day and each sub-basin was obtained by dividing the accumulated amount of blocked solar radiation by the potential solar radiation representing the solar heat flux (both diffuse and direct beam) that would reach the stream surface without barriers (S11).

$$SF_{ijk} = \frac{\sum_{k=t_{sr}}^{t_{ss}} Shade_{ijk} . h_{ijk}}{L_j . W_j \, H_{ijk}} \qquad \text{(S11)}$$

Where i indicates the number of sub-basin (from 1 to 60 for DMW), j is the day in the year (from 1 to 365), k is the time in the day, $Shade_{ijk}$ is the shade of the barrier on stream, h_{ijk} is the solar radiation at the time k, L_j is the stream length, W_j is the surface water width determined by the SWAT model, H_{ijk} is the registered daily solar radiation.

S3 Calibrated Parameters

S3.1 Calibrated parameters for flow

After considering several parameters in the flow calibration process, seventeen were selected which are shown in Table S2.

Table S2. Flow Calibration Parameters.

ID	Parameter	Name	Value	
			SB #31	SB #59
001	ALPHA_BF.gw	Baseflow recession constant	0.92	0.65
002	CH_N2.rte	Manning's "n" value for the main channel	0.029	0.072
003	CN2.mgt	SCS runoff curve number factor	x 0.85	x 0.75
004	DDRAIN.mgt	Depth to subsurface drain (mm)	993.5	993.5
005	EPCO.hru	Plant uptake compensation factor	0.34	0.33
006	ESCO.hru	Soil evaporation compensation coefficient	0.34	0.50
007	GDRAIN.mgt	Drain tile lag time (hrs)	34.5	34.5
008	GW_DELAY.gw	Groundwater delay (days)	303.48	11.69
009	GW_REVAP.gw	Groundwater "revap" coefficient	0.19	0.17
010	GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	4978	2025
011	HRU_SLP.hru	Average slope steepness (m/m)	x 0.88	x 1.0
012	LAT_TTIME.hru	Lateral flow travel time (days)	10.6	10.3
013	OV_N.hru	Manning's "n" value for overland flow	0.025	0.052
014	RCHRG_DP.gw	Deep aquifer percolation fraction	0.19	0.06
015	REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	418.3	305.5
016	SOL_K.sol	Saturated hydraulic conductivity (mm/hr)	56.0	52.2
017	TDRAIN.mgt	Time to drain soil to field capacity (hrs)	18.0	18.0

S3.2 Calibrated parameters for stream temperature

Table S3. Stream Temperature Calibration Parameters for the Modified Ficklin et al. Model

Calibration site	λ	T_{air}-lag (days)	C_1	C_2
SB #31	0.88	5	0.67	1.16
SB #59	1.06	6	0.74	1.17

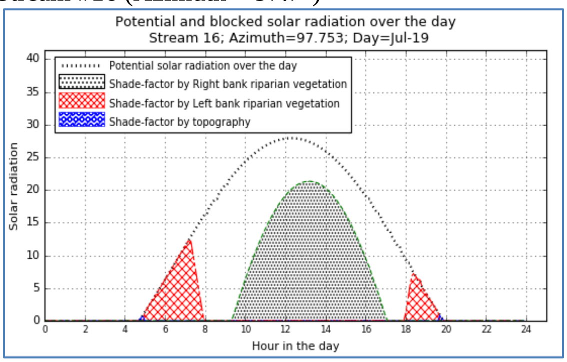
S4 Shade Factor Temporal Variation

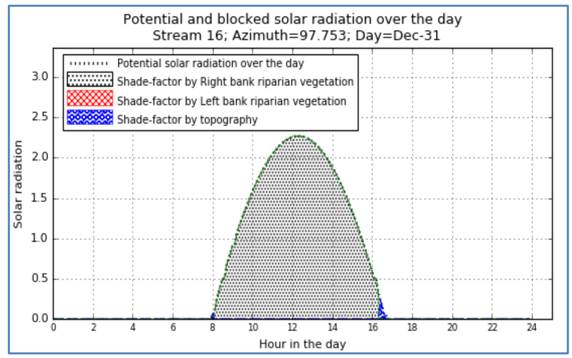
S4.1 Shade Factor Variation over the Day

Fig. S6 shows the potential solar radiation and the amount of blocked solar radiation by the topography and riparian vegetation for three streams (stream #16, #29, and #39) with different stream azimuths (97.7°, 179.5°, and 269.0°, respectively) and for a typical summer (July 19) and winter (Dec 31) day.

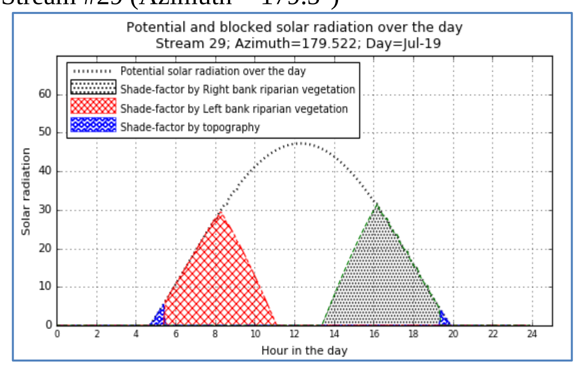
Summer day **Winter day**

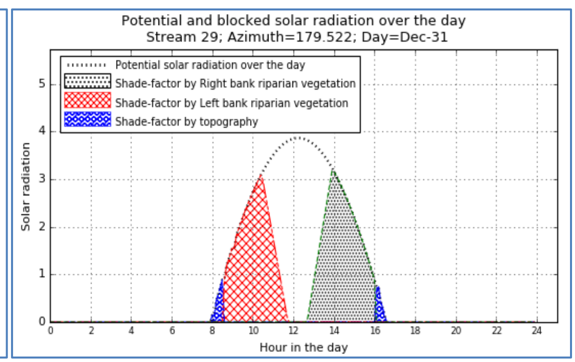
Stream #16 (Azimuth = 97.7°)



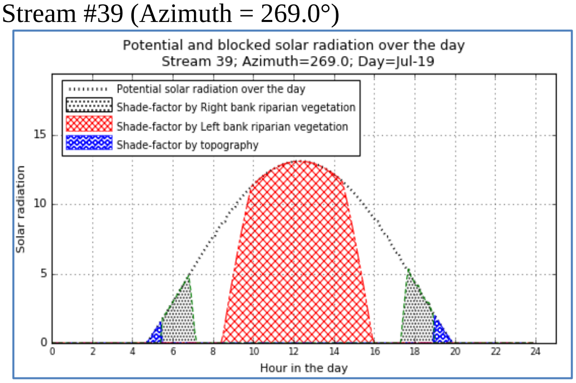


Stream #29 (Azimuth = 179.5°)





Stream #39 (Azimuth = 269.0°)



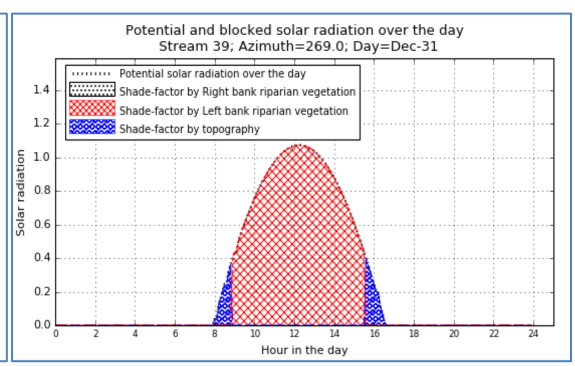


Figure S6. Potential solar radiation and blocked solar radiation identifying the blocking barrier for three streams with different azimuths and for a typical summer and winter day (Jul-19, Dec-31).

S4.2 Shade Factor Variation over the Year

Fig. S7 shows the variation of the shade factor for three streams with varied stream azimuths during the year. For example, in stream #16 (Azimuth = 97.7°) and stream #39 (Azimuth = 269.0°), the northern bank contribution is much lower compared to the southern bank contribution over the year, while for stream #29 both banks contribute in similar amounts to the shade factor.

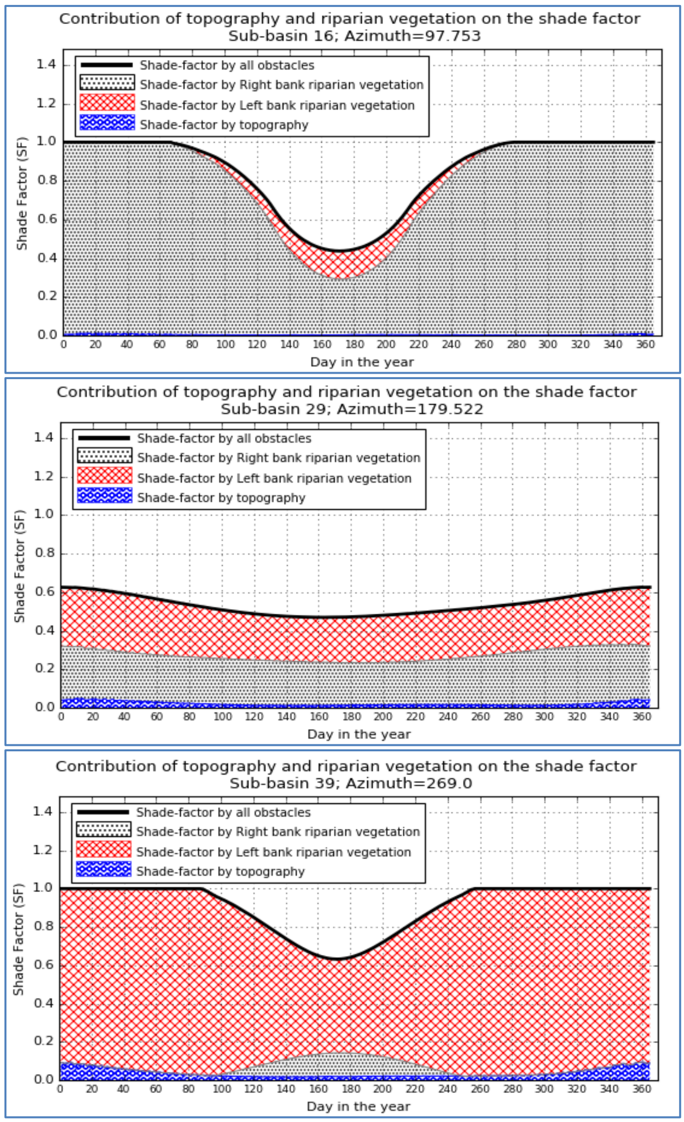


Figure S7. Shade factor variation over the year for three DMW streams with different azimuths.

S5 Effects of Riparian Vegetation on the Shade-Factor and Stream Temperature

Fig. S8 shows the contribution of each bank blocking the solar radiation in scenarios 1 (current riparian vegetation), scenario 2 (full riparian vegetation), and scenario 3 (efficient riparian vegetation) for stream #16 (Azimuth = 97.75°), #29 (Azimuth = 179.5°), and #39 (Azimuth = 269.0°), which have noticeable differences in azimuth, for a summer day (Jul. 19). In streams oriented from W-E and E-W as stream #16 and #39 respectively, the contribution of the northern side riparian vegetation is much less than the southern side. This minor contribution is only shown in the early morning and late afternoon. Scenario 3 practically resembles scenario 2, despite the fact that scenario 3, for streams-oriented E-W and W-E, does not consider the implementation of the northern side vegetation.

Fig. S9 shows the contribution of each bank on the shade factor for stream #16 (Azimuth = 97.75°), stream #29 (Azimuth = 179.5°), and stream #39 (Azimuth = 269.0°) during the year. Here one can also see that in streams oriented from W-E and E-W (stream #16 and #36), the contribution of the northern side riparian vegetation is much less than the southern side. This minor contribution is only shown in summer. Scenario 3 practically resembles scenario 2, despite the fact that scenario 3, for streams oriented from E-W and W-E, does not consider the implementation of the northern side vegetation.

Fig. S10 shows the percentage of contribution of the topography and riparian vegetation in increasing the shade factor as a function of the stream azimuth. The stream azimuth and banks are considered in reference to the flow direction. To illustrate, in sub-basin #55 (azimuth = 94.1°), the right-bank contribution is 94.7% while the left-bank and topography contribution is only 5.2% and 0.1%, respectively.

Fig. S11 shows the percentage of contribution of the riparian vegetation on the stream temperature reduction as a function of the stream azimuth. The stream azimuth and banks are considered in reference to the flow direction. For instance, in sub-basin #55 (azimuth < 180°), the right-bank contribution is 89.8% while the left-bank contribution is only 10.2%.

Fig. S12 shows the relationship between the reduction of the number of days in the year (a) and in summer (b) with 7dAM stream temperatures exceeding 18 °C, and the shade factor increase for Scenarios 2 and 3. The Fig. shows a positive relationship between these two variables, indicating that as the shade factor increases, the reduction of number of days with 7dAM exceeding 18 °C also increases.

Fig. S13 shows two hydrographs. The first corresponding to the reduction of the average temperature (Fig. S13a) and the second to the reduction of the number of days that exceed 18 °C (Fig. S13b) for scenarios of full and efficient restoration. In both cases, it can be visually observed that both restoration scenarios reach similar reductions.

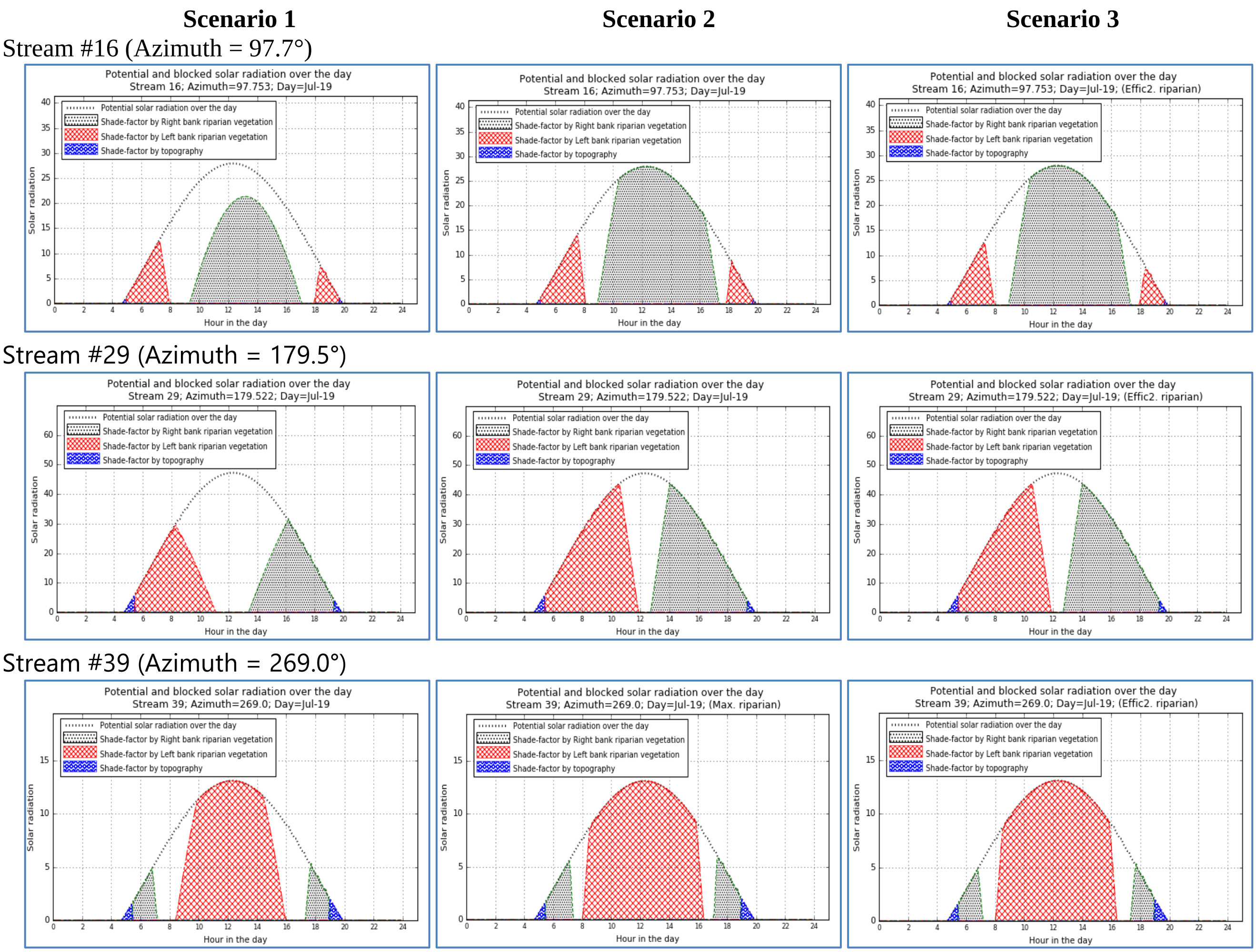
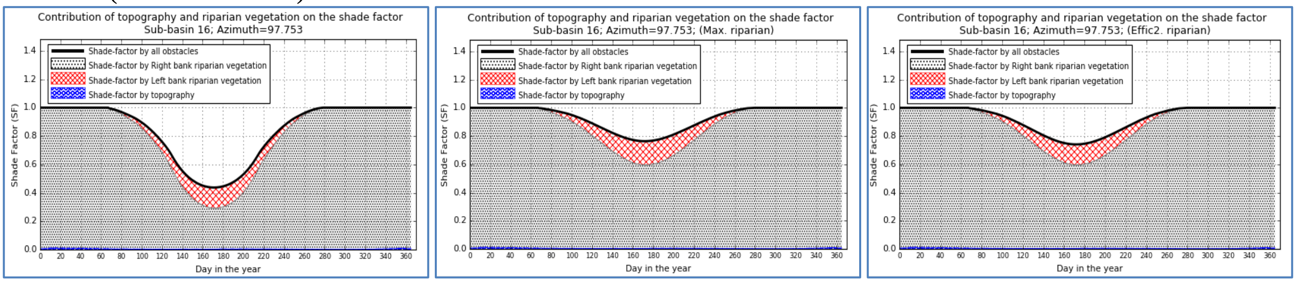


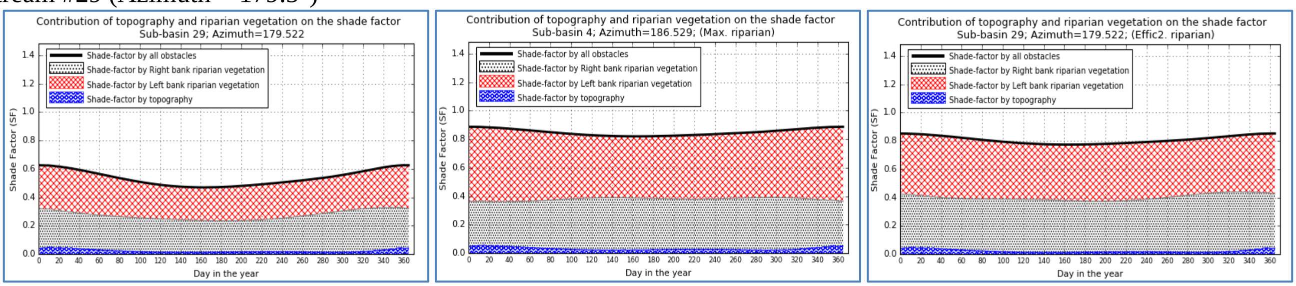
Figure S8. Potential solar radiation and blocked solar radiation identifying the blocking barrier for three streams with different azimuths, for a typical summer day (Jul-19), and for scenarios 1, 2, and 3.

Scenario 1 **Scenario 2** **Scenario 3**

Stream #16 (Azimuth = 97.7°)



Stream #29 (Azimuth = 179.5°)



Stream #39 (Azimuth = 269.0°)

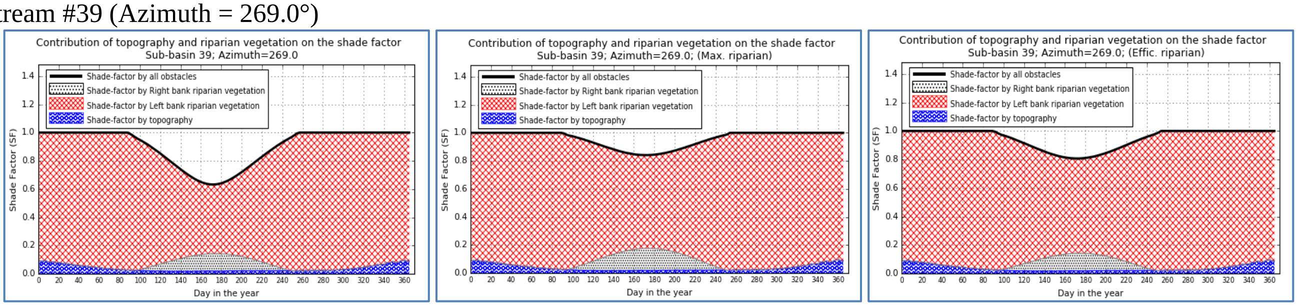


Figure S9. Shade factor variation over the year for three DMW streams with different azimuths and for scenarios 1, 2, and 3.

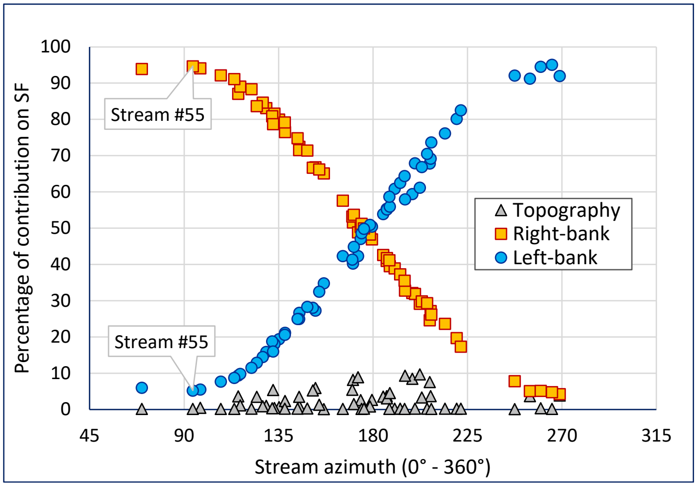


Figure S10. Contribution of each bank on SF versus stream orientation (azimuth). The right and left bank were defined in the flow direction.

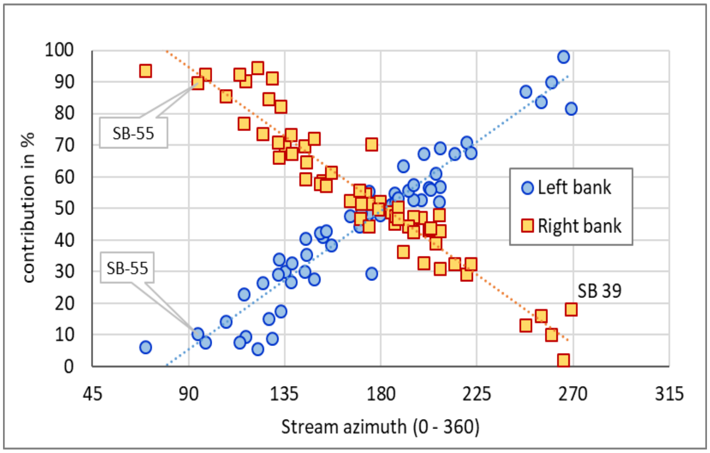
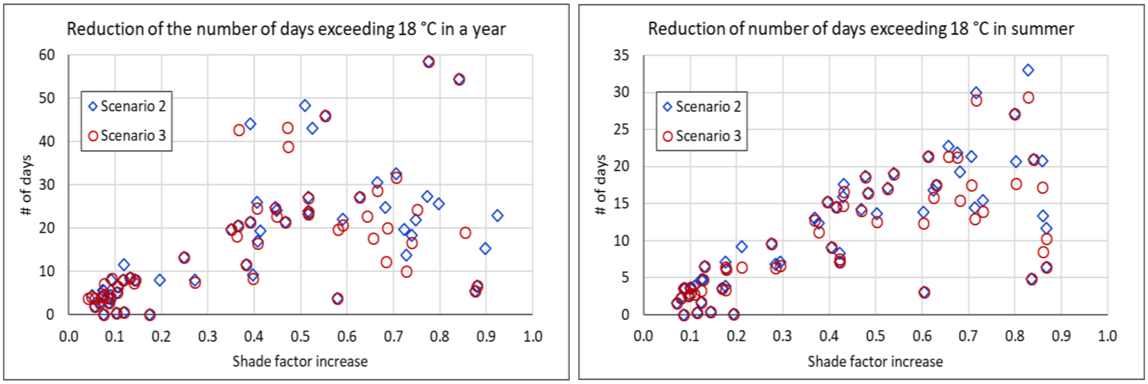
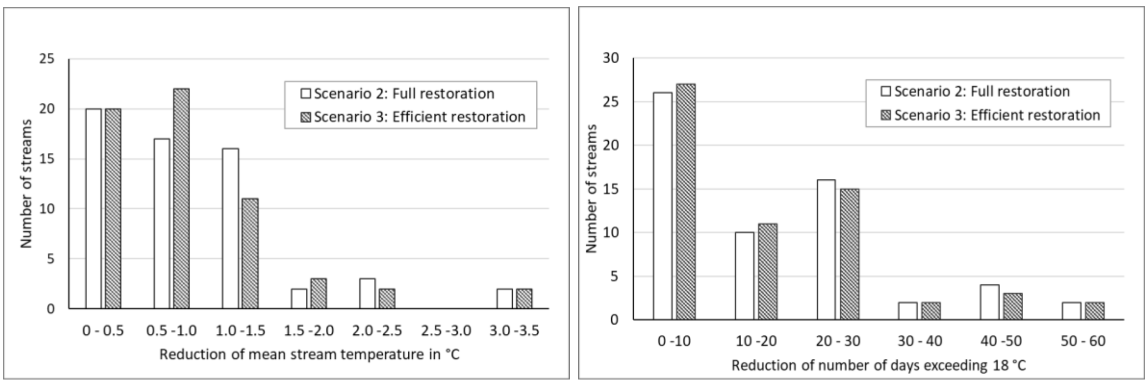


Figure S11. Percentage of contribution of each bank riparian vegetation on the stream temperature reduction versus the stream orientation (azimuth). The right and left bank were defined in the flow direction



.(a) (b)

Figure S12. Relationship between the reduction of the number of days in the year (a) and in summer (b) with 7dAM stream temperatures exceeding 18 °C, and the shade factor increase for Scenarios 2 and 3.



.(a) (b)

Figure S13. (a) Histogram of stream temperature reductions in the 60 DMW streams for full and efficient riparian restoration. (b) Histogram of reduction of the number of days that exceed 18 °C in the 60 DMW streams for cases of full and efficient riparian restoration.

S6 Steps to calibrate the stream temperature model embedded into the SWAT model.

The following tables (S4 and S5) show the steps we followed to calibrate the modified Ficklin et al. stream temperature model. The code, input data, and other resources employed here are available in the Zenodo repository at https://doi.org/10.5281/zenodo.6301709 (Noa-Yarasca, 2022).

Table S4. Steps to run the "run_stream_temp_calib_V3.py" file that includes the python code to run iteratively the SWAT model

Step	Description
1	Define value ranges of the four coefficients and saved as "parm_ranges.csv"
2	Execute the "run_stream_temp_calib_V3.py" code
3	Read the file "parm_ranges.csv"
4	Generate n sample sets of the 4 variables and save them in "set_parms.csv"
5	this samples are stored in rows
6	Start loop through the n sample sets
7	for set_i in range(len(n))
	The set_i is saved as "iter_params.csv" containing only 4 coefficient values
	Call the file "run_swat.py" that runs the SWAT executable file
11	Compute the NSE and MAE values for all the simulated stream temperature
12	Select manually the optimal values of the four coefficients

Table S5. Steps when running the "run_swat.py" file that includes the code to run the SWAT executable file (swat_rel64.exe)

Step	Description
1	Read the "iter_params.csv"
2	Read the "index_sf.csv" file containing the shade factor pre-computed in the ArcGIS environment
3	Execute all the SWAT modules.
4	The improved stream temperature sub model included the "sort_trib" and "wtmp_e" files in Fortran code
5	The SWAT files in Fortran, including the two added files, were compiled into the executable file "swat_rel64.exe"
6	The simulated stream temperature is stored in the "alltsim.csv" file
7	Back to the python code

S7 Cost of riparian reforestation/restoration for both scenarios: Full riparian and efficient restoration

Table S6. Reforestation cost of **left bank buffer** areas using vegetation density (identified and manually pre-processed in the GIS environment).

		Buffer area according to forest percentage (acre)										Subtotal area	Restoration cost of	Restoration cost of
Stream	Stream	No-forest	Area with partial forest (acre)						Area with full forest %			of buffer with	buffer with partial forest	buffer with partial forest
id	Azimuth	0 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	70 - 80	80 - 90	90 - 100	partial forest	for fully restored	for Efficient restored
		0.95	0.85	0.75	0.65	0.55	0.45	0.35	0.25	0.15	0.05	(10% - 70%)	scenario (USD)	scenario (USD)
1	152.6	0.40	0.00	0.27	3.98	1.46	7.17	17.65	5.18	0.00	0.00	13.4	62,784	62,784
2	170.5	0.96	0.00	0.55	3.72	1.52	2.07	6.75	1.10	0.00	0.00	7.9	36,959	36,959
3	198.8	2.26	0.00	0.15	1.51	1.06	8.00	27.61	13.58	0.00	0.00	17.1	80,235	80,235
4	186.5	7.18	0.00	0.45	2.09	1.79	2.24	1.35	2.09	0.00	0.00	11.0	51,549	51,549
5	115.8	7.60	0.36	0.72	3.98	3.38	9.41	12.54	4.95	0.60	0.00	21.1	99,244	99,244
6	129.2	3.00	0.00	0.00	0.38	0.50	0.38	1.25	0.38	0.00	0.00	4.0	18,673	18,673
7	116.7	12.31	0.14	1.35	2.70	1.35	0.54	0.27	0.00	0.00	0.00	15.7	73,529	73,529
8	202.3	18.70	0.00	1.01	3.91	4.49	19.13	26.09	7.10	0.14	0.00	41.3	193,798	193,798
9	207.1	16.92	0.00	0.00	0.30	0.15	0.90	4.94	15.27	1.05	0.00	18.5	86,772	86,772
10	135.2	3.31	0.00	0.26	1.19	0.26	0.00	0.00	0.00	0.00	0.00	4.3	20,007	20,007
11	127.5	19.38	0.13	1.20	2.67	1.47	0.40	0.13	0.13	0.00	0.00	22.2	104,248	104,248
12	184.8	6.27	0.00	0.14	0.57	0.85	2.85	11.53	17.37	1.28	0.00	12.2	57,359	57,359
13	186.6	12.09	0.00	0.60	1.66	3.32	5.74	3.93	2.87	0.00	0.00	18.8	88,271	88,271
14	133.0	15.62	0.13	0.52	1.16	0.26	0.00	0.00	0.00	0.00	0.00	16.2	76,232	76,232
15	138.1	15.55	0.13	0.25	2.42	3.95	6.63	12.49	14.91	0.76	0.00	26.2	122,846	122,846
16	97.8	16.21	0.00	0.00	0.39	0.13	0.00	0.00	0.00	0.00	0.00	15.7	73,799	73,799
17	200.0	27.96	0.14	1.43	4.42	3.00	1.00	0.86	0.00	0.00	0.00	33.0	155,053	155,053
18	156.6	45.92	0.00	0.41	0.82	1.09	2.18	1.36	0.00	0.14	0.00	46.5	218,398	218,398
19	132.0	11.52	0.00	0.00	0.83	1.19	1.54	1.66	0.00	0.00	0.00	13.4	62,978	62,978
20	107.5	32.21	0.00	0.24	0.61	0.24	0.12	0.00	0.00	0.00	0.00	31.4	147,276	147,276
21	69.9	23.43	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.4	105,065	105,065
22	165.7	37.22	0.14	0.00	0.55	0.42	0.97	0.28	0.00	0.00	0.00	36.6	171,843	171,843
23	113.9	19.94	0.00	0.58	0.58	0.58	0.58	0.29	0.14	0.00	0.00	20.4	95,927	95,927
24	172.9	0.57	0.00	0.14	0.85	1.42	9.49	14.31	6.09	0.00	0.00	11.3	52,836	52,836
25	195.3	0.53	0.00	0.00	0.93	0.40	0.80	1.33	0.53	0.00	0.00	2.2	10,102	10,102
26	151.3	1.86	0.13	0.13	1.07	1.07	1.73	3.33	0.67	0.00	0.00	5.2	24,441	24,441
27	188.0	5.53	0.00	0.00	2.18	1.02	1.60	5.38	1.45	0.00	0.00	9.8	46,161	46,161
28	124.6	0.36	0.12	0.36	1.82	1.95	4.87	21.53	16.06	0.00	0.00	12.7	59,662	59,662
29	179.5	6.96	0.00	0.15	0.87	2.61	4.21	13.20	1.74	0.00	0.00	15.2	71,554	71,554
30	132.4	0.69	0.41	0.00	3.15	4.39	8.77	23.44	13.02	0.41	0.00	17.6	82,707	82,707
31	174.2	3.58	0.00	0.00	0.29	1.00	1.43	3.87	1.15	0.00	0.00	6.1	28,845	28,845
32	154.4	35.62	0.00	0.40	4.64	5.69	8.74	11.52	4.37	0.00	0.00	48.3	226,539	226,539
33	178.6	31.95	0.00	0.00	0.74	0.74	2.06	7.22	5.45	0.00	0.00	34.7	162,888	162,888
34	144.9	34.41	0.26	2.76	2.36	3.55	6.43	9.19	7.49	0.00	0.00	44.6	209,295	209,295
35	219.9	24.34	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	23.2	109,036	109,036
36	221.9	34.24	0.45	0.75	2.69	3.14	2.84	1.05	0.00	0.00	0.00	38.6	181,209	181,209
37	190.4	24.89	0.44	2.06	2.50	2.21	1.33	0.59	0.00	0.00	0.00	29.2	137,130	137,130
38	144.8	0.00	0.00	0.00	0.00	0.74	3.58	16.44	11.99	0.37	0.00	7.8	36,496	36,496
39	269.0	0.91	0.26	2.86	3.38	3.38	5.86	15.09	10.54	0.00	0.13	15.2	71,413	0
40	170.1	2.52	0.00	0.00	0.28	0.98	3.63	22.78	18.73	0.00	0.00	12.7	59,716	59,716
41	207.4	0.00	0.00	0.15	0.29	2.19	11.22	15.16	10.35	0.00	0.00	11.9	55,672	55,672
42	254.7	1.72	0.27	0.66	1.59	2.65	3.71	13.79	13.92	0.00	0.00	11.3	53,279	0
43	170.9	40.14	0.00	0.58	3.48	3.62	4.64	8.55	3.19	0.00	0.00	47.9	224,863	224,863
44	203.2	10.04	0.00	0.30	1.05	4.34	6.74	33.55	11.98	0.00	0.00	27.6	129,614	129,614
45	259.9	14.95	0.00	0.00	0.28	0.00	0.97	0.28	0.28	0.00	0.00	14.9	70,045	0
46	193.0	24.60	0.15	0.58	3.49	5.39	7.57	7.86	0.73	0.00	0.00	35.3	165,807	165,807
47	187.8	9.63	0.00	0.42	0.99	0.85	1.13	0.42	0.28	0.00	0.00	11.2	52,761	52,761
48	205.7	49.50	0.00	0.15	0.45	0.45	1.20	4.93	3.59	0.00	0.00	49.9	234,451	234,451
49	214.3	54.75	0.00	0.71	1.27	1.55	0.56	0.85	0.71	0.00	0.00	54.8	257,160	257,160
50	265.3	10.27	0.00	0.14	0.41	1.78	1.10	4.11	1.78	0.00	0.00	13.0	61,208	0
51	195.1	24.06	0.29	1.46	3.21	5.98	6.85	2.04	1.02	0.15	0.00	33.4	156,688	156,688
52	247.5	36.68	0.00	0.29	4.64	3.62	1.01	0.14	0.00	0.00	0.00	40.6	190,517	0
53	207.8	8.80	0.00	0.15	1.82	1.82	1.97	0.61	0.00	0.00	0.00	11.8	55,220	55,220
54	174.5	14.07	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.5	63,269	63,269
55	94.1	32.93	0.00	0.65	9.98	7.26	4.67	3.76	0.39	0.00	0.00	45.7	214,409	214,409
56	144.1	35.67	0.41	1.10	3.57	3.98	3.43	3.43	0.69	0.00	0.00	42.3	198,670	198,670
57	122.1	11.82	0.00	0.41	1.65	2.20	4.95	4.67	0.82	0.00	0.00	17.7	83,041	83,041
58	138.0	9.50	0.00	0.59	2.38	1.78	0.45	0.45	0.00	0.00	0.00	12.4	58,001	58,001
59	175.7	1.25	0.00	0.38	0.38	0.00	0.00	0.00	0.00	0.00	0.00	1.7	8,049	8,049
60	148.7	10.83	0.00	1.62	3.11	4.47	3.25	1.08	0.00	0.00	0.00	17.8	83,670	83,670
	Sum	966.1										1,318.3	6,189,270	5,742,806

Table S7. Reforestation cost of **right bank buffer** areas using vegetation density (identified and manually pre-processed in the GIS environment).

Stream Id	Stream Azimuth	Buffer area according to forest percentage (acre)										Subtotal area of buffer with partial forest (10% - 70%)	Restoration cost of buffer with partial forest for fully restored scenario (USD)	Restoration cost of buffer with partial forest for Efficient restored scenario (USD)
		No-forest	Area with partial forest (acre)						Area with full forest %					
		0 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	70 - 80	80 - 90	90 - 100			
		0.95	0.85	0.75	0.65	0.55	0.45	0.35	0.25	0.15	0.05			
1	152.6	0.14	0.00	0.00	0.69	0.27	5.49	21.00	7.82	0.69	0.00	10.5	49,529	49,529
2	170.5	3.53	0.00	0.28	1.55	1.98	2.26	5.79	1.27	0.00	0.00	8.7	40,883	40,883
3	198.8	3.41	0.00	0.39	1.44	2.36	4.59	22.82	18.76	0.39	0.00	15.8	74,302	74,302
4	186.5	10.67	0.00	0.00	2.77	1.11	1.39	1.11	0.14	0.00	0.00	13.6	63,689	63,689
5	115.8	8.55	0.14	0.68	4.88	3.80	5.29	13.97	5.56	0.68	0.00	21.3	99,893	0
6	129.2	2.94	0.00	0.00	1.03	1.62	0.29	0.00	0.00	0.00	0.00	4.5	21,044	0
7	116.7	11.20	0.00	0.41	3.87	2.21	0.55	0.41	0.00	0.00	0.00	15.1	70,782	0
8	202.3	15.32	0.00	0.13	1.80	3.73	14.42	32.44	12.49	0.26	0.00	35.7	167,685	167,685
9	207.1	8.03	0.00	0.13	0.13	0.76	1.53	9.82	17.98	1.15	0.00	12.4	58,004	58,004
10	135.2	3.51	0.15	0.30	0.91	0.15	0.00	0.00	0.00	0.00	0.00	4.4	20,499	20,499
11	127.5	19.22	0.40	1.08	1.88	1.48	0.81	0.67	0.00	0.00	0.00	22.0	103,471	0
12	184.8	7.90	0.00	0.27	1.09	1.23	3.13	7.90	18.39	0.95	0.00	13.3	62,292	62,292
13	186.6	15.45	0.00	0.14	0.28	1.10	3.17	5.38	4.55	0.14	0.00	18.9	88,645	88,645
14	133.0	13.65	0.14	2.23	1.11	0.42	0.14	0.00	0.00	0.00	0.00	15.8	74,060	0
15	138.1	11.53	0.28	0.70	4.36	4.36	4.36	18.14	12.79	0.56	0.00	25.3	118,589	118,589
16	97.8	15.44	0.00	0.00	0.51	0.51	0.13	0.13	0.00	0.00	0.00	15.4	72,229	0
17	200.0	32.91	0.14	0.69	2.33	0.69	1.23	0.82	0.00	0.00	0.00	34.6	162,577	162,577
18	156.6	48.13	0.00	0.56	0.84	0.98	0.98	0.42	0.00	0.00	0.00	47.8	224,514	224,514
19	132.0	16.30	0.00	0.29	0.15	0.00	0.00	0.00	0.00	0.00	0.00	15.8	74,205	0
20	107.5	32.35	0.00	0.14	0.54	0.41	0.00	0.00	0.00	0.00	0.00	31.4	147,456	0
21	69.9	22.36	0.67	0.27	0.27	0.00	0.00	0.00	0.00	0.00	0.00	22.2	104,183	0
22	165.7	35.97	0.00	0.14	1.01	2.02	0.29	0.14	0.00	0.00	0.00	36.2	170,078	170,078
23	113.9	19.76	0.00	0.97	1.11	0.84	0.00	0.00	0.00	0.00	0.00	20.7	97,133	0
24	172.9	0.40	0.00	0.00	0.67	1.47	5.61	17.23	7.35	0.13	0.00	10.2	47,791	47,791
25	195.3	0.00	0.00	0.00	0.00	0.00	0.53	2.92	1.06	0.00	0.00	1.3	5,924	5,924
26	151.3	1.79	0.00	0.00	1.64	0.45	0.75	3.43	1.79	0.15	0.00	4.5	21,342	21,342
27	188.0	0.79	0.00	0.26	0.40	1.19	0.66	7.13	6.73	0.00	0.00	4.7	21,849	21,849
28	124.6	0.14	0.00	0.00	0.42	2.40	4.52	24.74	14.85	0.00	0.00	12.4	58,350	0
29	179.5	15.54	0.00	0.27	3.35	2.41	1.88	5.22	1.07	0.00	0.00	21.1	99,253	99,253
30	132.4	0.79	0.26	0.66	4.89	4.36	7.40	20.87	13.74	1.32	0.00	17.7	83,006	0
31	174.2	9.75	0.00	0.13	0.53	0.40	0.26	0.00	0.26	0.00	0.00	10.0	47,120	47,120
32	154.4	44.22	0.85	2.96	7.18	6.76	3.38	4.79	0.85	0.00	0.00	56.5	265,421	265,421
33	178.6	29.50	0.00	0.14	0.96	0.55	1.23	7.68	8.09	0.00	0.00	32.3	151,621	151,621
34	144.9	35.92	0.28	0.41	3.32	3.32	4.97	11.33	6.91	0.00	0.00	44.9	210,573	210,573
35	219.9	23.83	0.00	0.13	0.13	0.13	0.26	0.00	0.00	0.00	0.00	23.0	108,066	108,066
36	221.9	31.87	0.26	1.68	4.90	2.97	2.71	0.77	0.00	0.00	0.00	38.1	178,711	178,711
37	190.4	20.44	0.00	2.15	3.76	3.36	3.50	0.81	0.00	0.00	0.00	27.2	127,604	127,604
38	144.8	0.29	0.00	0.00	0.73	1.45	3.49	13.36	11.33	2.47	0.00	7.8	36,590	36,590
39	269.0	0.51	0.00	0.13	1.16	2.44	8.10	23.27	6.81	0.00	0.00	14.5	67,923	67,923
40	170.1	1.61	0.00	0.00	0.67	0.67	2.28	18.63	24.79	0.27	0.00	9.9	46,376	46,376
41	207.4	0.00	0.00	0.41	1.23	1.91	6.15	20.63	9.02	0.00	0.00	12.1	57,036	57,036
42	254.7	2.33	0.00	0.52	0.91	0.26	6.34	19.42	8.54	0.00	0.00	13.0	60,953	60,953
43	170.9	45.63	0.14	0.70	3.63	2.79	4.88	5.16	1.26	0.00	0.00	51.9	243,609	243,609
44	203.2	9.08	0.00	0.26	1.18	2.76	6.18	33.94	14.60	0.00	0.00	25.8	120,984	120,984
45	259.9	12.00	0.00	0.12	0.59	0.83	1.31	1.43	0.48	0.00	0.00	13.4	63,011	63,011
46	193.0	18.29	0.14	1.09	4.78	6.41	9.69	8.05	1.91	0.00	0.00	32.1	150,795	150,795
47	187.8	4.38	0.00	0.44	1.61	2.48	1.90	2.78	0.15	0.00	0.00	8.7	40,996	40,996
48	205.7	47.28	0.00	0.13	0.39	0.77	2.44	5.78	3.47	0.00	0.00	48.8	229,178	229,178
49	214.3	51.28	0.26	1.06	3.30	2.38	0.79	0.79	0.53	0.00	0.00	53.8	252,693	252,693
50	265.3	9.92	0.00	0.64	1.14	2.54	2.03	1.40	1.91	0.00	0.00	13.4	63,134	63,134
51	195.1	17.70	0.13	1.88	6.71	5.36	6.44	5.63	1.21	0.00	0.00	30.5	143,279	143,279
52	247.5	28.41	0.00	0.37	10.54	5.33	1.24	0.25	0.25	0.00	0.00	37.7	176,986	176,986
53	207.8	2.26	0.00	0.13	2.80	2.26	3.73	3.86	0.13	0.00	0.00	8.3	39,157	39,157
54	174.5	14.08	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	13.4	63,085	63,085
55	94.1	39.67	0.13	0.40	7.64	6.30	4.56	0.94	0.00	0.00	0.00	48.9	229,627	0
56	144.1	29.71	0.14	1.57	5.28	3.14	6.28	5.57	0.57	0.00	0.00	39.5	185,286	185,286
57	122.1	9.19	0.00	1.04	3.37	4.14	6.60	2.07	0.13	0.00	0.00	17.7	82,951	0
58	138.0	9.62	0.28	0.57	2.12	1.42	0.85	0.28	0.00	0.00	0.00	12.4	58,447	58,447
59	175.7	0.20	0.00	0.00	0.60	0.40	0.00	0.60	0.20	0.00	0.00	1.0	4,747	4,747
60	148.7	7.85	0.00	0.95	4.47	2.98	5.41	2.71	0.00	0.00	0.00	16.1	75,538	75,538
		934.5										1,296	6,084,755	4,766,365

Table S8. Total cost of riparian reforestation and Benefit/Cost ratio for the full restoration scenario.

Stream	Left bank		Rigth bank		Total	Cumulative	Reduction of	Benefit/Cost ratio in n_days/mill-USD
Id	Area to restore	Cost	Area to restore	Cost	cost	cost	number of days > 18 C	
SB	acre	USD	acres	USD	USD	USD	(Benefit -days)	B / C
1	10.5	49,529	13.4	62,784	112,313	112,313	2.69	24.0
2	8.7	40,883	7.9	36,959	77,842	190,156	0.08	0.4
3	15.8	74,302	17.1	80,235	154,537	154,537	4.38	28.4
4	13.6	63,689	11.0	51,549	115,238	459,931	3.77	8.2
5	21.3	99,893	21.1	99,244	199,137	199,137	11.54	57.9
6	4.5	21,044	4.0	18,673	39,717	698,785	8.00	11.4
7	15.1	70,782	15.7	73,529	144,311	1,204,579	19.77	16.4
8	35.7	167,685	41.3	193,798	361,483	361,483	8.08	22.3
9	12.4	58,004	18.5	86,772	144,776	144,776	6.46	44.6
10	4.4	20,499	4.3	20,007	40,506	1,389,861	18.38	13.2
11	22.0	103,471	22.2	104,248	207,719	1,597,580	24.85	15.6
12	13.3	62,292	12.2	57,359	119,651	119,651	8.08	67.5
13	18.9	88,645	18.8	88,271	176,916	176,916	13.23	74.8
14	15.8	74,060	16.2	76,232	150,293	1,867,524	27.38	14.7
15	25.3	118,589	26.2	122,846	241,436	241,436	8.46	35.0
16	15.4	72,229	15.7	73,799	146,028	387,463	4.46	11.5
17	34.6	162,577	33.0	155,053	317,629	2,362,070	30.54	12.9
18	47.8	224,514	46.5	218,398	442,912	3,192,445	32.54	10.2
19	15.8	74,205	13.4	62,978	137,183	137,183	15.31	111.6
20	31.4	147,456	31.4	147,276	294,732	431,915	23.00	53.3
21	22.2	104,183	22.4	105,065	209,248	3,833,608	25.62	6.7
22	36.2	170,078	36.6	171,843	341,921	341,921	54.46	159.3
23	20.7	97,133	20.4	95,927	193,060	4,368,589	21.85	5.0
24	10.2	47,791	11.3	52,836	100,627	100,627	2.77	27.5
25	1.3	5,924	2.2	10,102	16,026	116,653	0.01	0.1
26	4.5	21,342	5.2	24,441	45,783	162,437	0.62	3.8
27	4.7	21,849	9.8	46,161	68,009	230,446	0.38	1.7
28	12.4	58,350	12.7	59,662	118,012	118,012	5.54	46.9
29	21.1	99,253	15.2	71,554	170,807	519,265	8.00	15.4
30	17.7	83,006	17.6	82,707	165,713	165,713	5.62	33.9
31	10.0	47,120	6.1	28,845	75,965	760,942	9.15	12.0
32	56.5	265,421	48.3	226,539	491,960	1,252,902	24.77	19.8
33	32.3	151,621	34.7	162,888	314,509	314,509	20.54	65.3
34	44.9	210,573	44.6	209,295	419,868	419,868	19.77	47.1
35	23.0	108,066	23.2	109,036	217,102	636,970	5.54	8.7
36	38.1	178,711	38.6	181,209	359,920	1,927,331	27.23	14.1
37	27.2	127,604	29.2	137,130	264,734	2,829,035	23.31	8.2
38	7.8	36,590	7.8	36,496	73,087	73,087	1.85	25.3
39	14.5	67,923	15.2	71,413	139,336	139,336	4.46	32.0
40	9.9	46,376	12.7	59,716	106,092	318,515	3.85	12.1
41	12.1	57,036	11.9	55,672	112,708	112,708	4.15	36.9
42	13.0	60,953	11.3	53,279	114,232	226,940	8.08	35.6
43	51.9	243,609	47.9	224,863	468,472	1,013,927	27.15	26.8
44	25.8	120,984	27.6	129,614	250,597	250,597	5.08	20.3
45	13.4	63,011	14.9	70,045	133,056	383,654	13.85	36.1
46	32.1	150,795	35.3	165,807	316,602	1,714,182	21.46	12.5
47	8.7	40,996	11.2	52,761	93,757	1,807,940	11.54	6.4
48	48.8	229,178	49.9	234,451	463,629	463,629	46.08	99.4
49	53.8	252,693	54.8	257,160	509,854	509,854	58.46	114.7
50	13.4	63,134	13.0	61,208	124,342	1,097,825	44.08	40.1
51	30.5	143,279	33.4	156,688	299,967	3,205,732	21.38	6.7
52	37.7	176,986	40.6	190,517	367,504	367,504	43.15	117.4
53	8.3	39,157	11.8	55,220	94,377	3,667,613	26.00	7.1
54	13.4	63,085	13.5	63,269	126,353	126,353	6.69	53.0
55	48.9	229,627	45.7	214,409	444,036	570,389	48.38	84.8
56	39.5	185,286	42.3	198,670	383,955	7,581,579	24.00	3.2
57	17.7	82,951	17.7	83,041	165,992	7,747,571	19.38	2.5
58	12.4	58,447	12.4	58,001	116,447	8,434,407	22.15	2.6
59	1.0	4,747	1.7	8,049	12,796	12,114,817	24.08	2.0
60	16.1	75,538	17.8	83,670	159,208	12,274,025	17.00	1.4
Total	1,296	6,084,755	1,318	6,189,270	12,274,025			

Table S9. Total cost of riparian reforestation and Benefit/Cost ratio for the efficient restoration scenario.

Stream	Left bank		Rigth bank		Total	Cumulative	Reduction of	Benefit/Cost ratio in
Id	Area to restore	Cost	Area to restore	Cost	cost	cost	number of days > 18 C	n_days/mill-USD
SB	acre	USD	acres	USD	USD	USD	(Benefit -days)	B / C
1	10.5	49,529	13.4	62,784	112,313	112,313	2.69	24.0
2	8.7	40,883	7.9	36,959	77,842	190,156	0.08	0.4
3	15.8	74,302	17.1	80,235	154,537	154,537	4.38	28.4
4	13.6	63,689	11.0	51,549	115,238	459,931	3.77	8.2
5		0	21.1	99,244	99,244	99,244	8.38	84.5
6		0	4.0	18,673	18,673	577,848	7.31	12.6
7		0	15.7	73,529	73,529	1,012,861	17.62	17.4
8	35.7	167,685	41.3	193,798	361,483	361,483	8.08	22.3
9	12.4	58,004	18.5	86,772	144,776	144,776	6.46	44.6
10	4.4	20,499	4.3	20,007	40,506	1,198,143	16.62	13.9
11		0	22.2	104,248	104,248	1,302,390	19.77	15.2
12	13.3	62,292	12.2	57,359	119,651	119,651	8.08	67.5
13	18.9	88,645	18.8	88,271	176,916	176,916	13.23	74.8
14		0	16.2	76,232	76,232	1,498,274	22.77	15.2
15	25.3	118,589	26.2	122,846	241,436	241,436	8.46	35.0
16		0	15.7	73,799	73,799	315,235	3.92	12.4
17	34.6	162,577	33.0	155,053	317,629	1,992,819	28.69	14.4
18	47.8	224,514	46.5	218,398	442,912	2,750,966	31.69	11.5
19		0	13.4	62,978	62,978	62,978	10.00	158.8
20		0	31.4	147,276	147,276	210,254	19.08	90.7
21		0	22.4	105,065	105,065	3,066,285	24.31	7.9
22	36.2	170,078	36.6	171,843	341,921	341,921	54.46	159.3
23		0	20.4	95,927	95,927	3,504,133	20.00	5.7
24	10.2	47,791	11.3	52,836	100,627	100,627	2.77	27.5
25	1.3	5,924	2.2	10,102	16,026	116,653	0.01	0.1
26	4.5	21,342	5.2	24,441	45,783	162,437	0.62	3.8
27	4.7	21,849	9.8	46,161	68,009	230,446	0.38	1.7
28		0	12.7	59,662	59,662	59,662	3.85	64.5
29	21.1	99,253	15.2	71,554	170,807	460,915	7.46	16.2
30		0	17.6	82,707	82,707	82,707	4.08	49.3
31	10.0	47,120	6.1	28,845	75,965	619,586	8.31	13.4
32	56.5	265,421	48.3	226,539	491,960	1,111,546	24.62	22.1
33	32.3	151,621	34.7	162,888	314,509	314,509	20.54	65.3
34	44.9	210,573	44.6	209,295	419,868	419,868	19.77	47.1
35	23.0	108,066	23.2	109,036	217,102	636,970	5.54	8.7
36	38.1	178,711	38.6	181,209	359,920	1,785,975	27.23	15.2
37	27.2	127,604	29.2	137,130	264,734	2,687,678	23.23	8.6
38	7.8	36,590	7.8	36,496	73,087	73,087	1.85	25.3
39	14.5	67,923		0	67,923	67,923	3.77	55.5
40	9.9	46,376	12.7	59,716	106,092	247,101	3.77	15.3
41	12.1	57,036	11.9	55,672	112,708	112,708	4.15	36.9
42	13.0	60,953		0	60,953	173,661	7.23	41.6
43	51.9	243,609	47.9	224,863	468,472	889,234	27.08	30.4
44	25.8	120,984	27.6	129,614	250,597	250,597	5.08	20.3
45	13.4	63,011		0	63,011	313,608	12.23	39.0
46	32.1	150,795	35.3	165,807	316,602	1,519,444	21.46	14.1
47	8.7	40,996	11.2	52,761	93,757	1,613,201	11.54	7.2
48	48.8	229,178	49.9	234,451	463,629	463,629	46.08	99.4
49	53.8	252,693	54.8	257,160	509,854	509,854	58.46	114.7
50	13.4	63,134		0	63,134	1,036,617	42.85	41.3
51	30.5	143,279	33.4	156,688	299,967	2,949,786	21.38	7.2
52	37.7	176,986		0	176,986	176,986	38.92	219.9
53	8.3	39,157	11.8	55,220	94,377	3,221,150	24.69	7.7
54	13.4	63,085	13.5	63,269	126,353	126,353	6.69	53.0
55		0	45.7	214,409	214,409	340,762	43.31	127.1
56	39.5	185,286	42.3	198,670	383,955	6,575,767	23.85	3.6
57		0	17.7	83,041	83,041	6,658,808	18.15	2.7
58	12.4	58,447	12.4	58,001	116,447	7,116,017	20.77	2.9
59	1.0	4,747	1.7	8,049	12,796	10,349,964	22.69	2.2
60	16.1	75,538	17.8	83,670	159,208	10,509,172	16.46	1.6
Total	1,015	4,766,365	1,223	5,742,806	10,509,172			

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