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SPATIAL DISTRIBUTION OF WATER SUPPLY IN THE COTERMINOUS UNITED STATES[1]

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ABSTRACT: Available water supply across the contiguous 48 states was estimated as precipitation minus evapotranspiration using data for the period 1953-1994. Precipitation estimates were taken from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM). Evapotranspiration was estimated using two models, the Advection-Aridity model and the Zhang model. The evapotranspiration models were calibrated using precipitation and runoff data for 655 hydrologically undisturbed basins, and then tested using estimates of natural runoff for the 18 water resource regions (WRR) of the 48 contiguous states. The final water supply coverage reflects a mixture of outputs from the two evapotranspiration models. Political, administrative, and land cover boundaries were mapped over the coverage of mean annual water supply. Across the entire study area, we find that 53% of the water supply originates on forested land, which covers only 29% of the surface area, and that 24% originates on federal lands, including 18% on national forests and grasslands alone. Forests and federal lands are even more important in the West (the 11 western contiguous states), where 65% of the water supply originates on forested land and 66% on federal lands, with national forests and grasslands contributing 51%.

(KEY TERMS: water supply; evapotranspiration; runoff; forests.)

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INTRODUCTION

Water is a critical resource. As human populations increase, careful management of our water supplies becomes ever more important, both to satisfy human needs and to protect the environments of other species. Management relies on good policy, and for good policy to emerge, policy makers need an accurate broad-scale characterization of the resource. This paper aims to provide a key element of that characterization – spatially explicit estimates of the United States (U.S.) water supply as it originates on the watershed.

Our freshwater supply begins as precipitation falling on land and freshwaters. From there the water naturally has three principal destinations: the atmosphere via evapotranspiration, groundwater aquifers via infiltration, or the sea via rivers and streams. Water that evaporates or is transpired

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has largely escaped our grasp until it falls again elsewhere as precipitation. What remains is – until it reaches the sea – available for use by humans and other species, and in a broad sense is our freshwater supply.

As much of our water supply originates in forests, water runoff and its quality have long been a focus of forest management. The first national forest preserves were specifically set aside by Congress in the Organic Act of 1897 for the protection of water and timber supplies. Although national forests cover only 8% of the land area in the contiguous 48 states, they are of particular interest because they are generally located at basin headwaters. Various estimates of the proportion of the nation's water supply originating on national forests, and on forests in general, have been suggested over the years. For example, a 1970 review of public lands estimated that in the 11 contiguous western states 61% of the natural runoff originated on federal lands, with 54% coming from the national forests (Public Land Law Review Commission, 1970), and more recently a Forest Service report estimated that 14% of the water supply of the 48 states and 33% of the water supply of the West originated on national forests (Sedell *et al.*, 2000). Using newer data and models, we aimed to provide an improved set of estimates.

The approach taken here was to estimate water supply at its source as precipitation minus evapotranspiration for each cell of a grid covering the contiguous 48 states (Alaska and Hawaii were excluded because of lack of data). Overlaying political and land ownership boundaries or land cover delineations then allows estimation of the amount of water originating within distinct land units.

We took our precipitation estimates from a well-established model. Estimating evapotranspiration was more challenging, and we examined two quite different models. Finding that neither model estimated evapotranspiration with sufficient accuracy in all locations, and focusing clearly on our very practical objective of estimating mean annual contribution to water supply, we calibrated each model to improve the accuracy of the estimates, and then used one or the other model in specific basins where further testing indicated that it yielded the more accurate estimate. Next we explain the methods in some detail.

METHODS

Our basic approach was to estimate water supply (Q) as precipitation (P) minus actual evapotranspiration (ET_a) on a mean annual basis at each 5×5-km grid cell across the conterminous U.S.

$$Q = P - ET_a \tag{1}$$

Having these spatially distributed estimates of water supply at its source, boundaries were then overlaid. Aggregating estimates of Q across cells within a boundary indicates the amount of water supply originating within the designated area.

The logic of estimating mean annual Q as $P - ET_a$ relies on assumptions involving basin storage. More specifically, Q is

$$Q = P - ET_a - \Delta S_s - \Delta S_g \tag{2}$$

where ΔS represents changes in storage and subscripts s and g refer to surface and subsurface domains. Assuming a stable climate and an undisturbed basin, the long-term average annual net change in overall basin moisture storage is negligible and assumed to be 0, so Q devolves to Equation (1).

Precipitation is the most commonly measured hydrologic quantity, but because precipitation is spatially variable, especially in mountainous regions, models are needed for filling in between the locations of precipitation gages. For this purpose we selected the monthly precipitation estimates produced at a 5-km level of resolution by the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly *et al.*, 1994). PRISM combines climatologic and topographic data to interpolate between precipitation observations.

For ET_a we set out to adapt the Advection-Aridity (AA) model (Brutsaert and Stricker, 1979) for nationwide use. A subsidiary aim was to develop a model for estimating ET_a at the monthly time scale that could be applied over the contiguous U.S., which could then be used in other analyses that are not at issue here. The AA model is based on the complementary relationship of actual and potential evapotranspiration, described below, and relies largely on readily available weather data.

Unfortunately, the AA model was not able accurately to estimate ET_a for some areas of the U.S., largely because of insufficient data. In locations where the AA model performed poorly we used another model, one proposed by Zhang *et al.* (2001). The Zhang model employs a very different theoretical approach from that of the complementary relationship and estimates ET_a on a mean annual basis only. The loss of seasonality with the Zhang model was not a shortcoming in the current context, as our objective here is to estimate mean annual water supply. Both models are described briefly below, as are methods for model calibration and testing.

The AA Model for Estimating ET_a

In hydrology it has been customary to model ET_a as a function of potential evapotranspiration (ET_p) and soil moisture, where ET_p is the evapotranspiration that would theoretically occur were water not limiting. In this approach, ET_p is considered an independent climatic variable, constraining the amount of ET_a but remaining unaffected by the amount of ET_a and thus largely constant over ranges of actual moisture availability at a given location. However, as proposed by Bouchet (1963), ET_p is not unaffected by ET_a. Rather, when lack of soil moisture keeps ET_a below the level that available energy would support (i.e., ET_p), the surplus energy heats and dries the surrounding air, raising ET_p above what it would be if more moisture were available and ET_a were greater. When moisture is not limiting, ET_a equals ET_p at a rate referred to as wet environment evapotranspiration (ET_w). However, as Bouchet proposed, at regional scales and away from sharp environmental discontinuities, if moisture is limiting and the available energy is constant, energy not used for ET_a causes ET_p to rise above ET_w by the amount that ET_a falls below it

$$ET_a + ET_p = 2ET_w \tag{3}$$

Figure 1 illustrates the complementary relationship.

Complementary relationship models rely largely on atmospheric observations. The models avoid the need for data on soil moisture, stomatal resistance properties of the vegetation, or other surface aridity measures because vertical gradients of temperature and humidity in the atmospheric boundary layer reflect the presence of moisture availability at the surface.

Models based on the complementary relationship hypothesis have been successfully used to make predictions of regional ET_a at different temporal scales, thereby providing indirect evidence of its validity (Brutsaert and Stricker, 1979; Morton, 1983; Hobbins *et al.*, 2001a; Szilagyi, 2001). Furthermore, the complementary relationship has recently been demonstrated observationally with data from a set of sites across the freeze-free zone of the U.S. using annual pan evaporation measures to estimate ET_p, denoted here as ET_p^*, and a water balance approach to estimate ET_a, denoted here as ET_a^* (Hobbins *et al.*, 2004b). The water balance approach simply computes annual ET_a^* as precipitation (P) minus basin water supply estimated as streamflow (Q*) from the watersheds surrounding the pans

$$ET_a^* = P - Q^* \tag{4}$$

Plots of annual ET_p^* and ET_a^* matched closely the lines for ET_p and ET_a in Figure 1 (Hobbins *et al.*, 2004b; Ramirez *et al.*, 2005).

Several complementary relationship models are now available, the most widely known of which are the Complementary Relationship Areal Evapotranspiration (CRAE) model (Morton, 1983) and the AA model (Brutsaert and Stricker, 1979). Hobbins *et al.* (2001b) compared these two models for ability to estimate ET_a across the U.S. and selected the AA model as the most promising approach for such an application. In this model, ET_w is calculated based on derivations of the concept of equilibrium evapotranspiration under conditions of minimal advection, first proposed by Priestley and Taylor (1972), and ET_p is calculated by combining information from the energy budget and water vapor transfer in the Penman equation (Penman, 1948) [see Hobbins *et al.* (2001a) for details on the modified AA model that we employed].

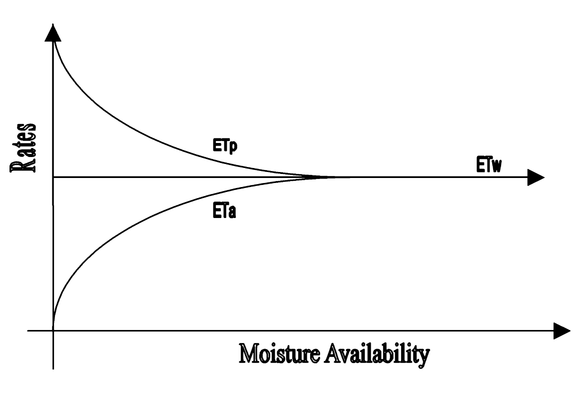

FIGURE 1. Schematic Representation of the Complementary Relationship.

Data for the AA Model. The AA model of ET_a requires data on temperature, humidity, solar radiation, wind speed, albedo, elevation, and latitude. Most of the available climatological data on these variables are point values collected at weather stations. Lacking more sophisticated models, like that available for precipitation, for generating spatially distributed estimates of ET_a (i.e., estimates for each grid cell), we used spatial interpolation techniques on the input variables and then applied the AA model at each cell (we could not interpolate from station estimates of ET_a because the input data station networks were not coincident). Kriging was the *a priori* preference for spatial interpolation of the climatological inputs whose station networks would support the inherent semivariogram estimation procedure (Oliver and Webster, 1990). Otherwise, an inverse-distance-weighted scheme was used.

The point data were gathered from various sources so as to create monthly time series for the period 1953-1994. The time period was constrained at either end by the availability of solar radiation data. The data used for the AA model are as follows:

1. Temperature was estimated as the mean of the average monthly maximum and average monthly minimum temperatures drawn from 9,271 stations in the "NCDC Summary of the Day" (EarthInfo, 1998a; NCDC, 2004b) database.
2. Humidity data, in the form of dew-point temperatures, were drawn from 324 stations in the "Solar and Meteorological Surface Observation Network (SAMSON)" (NCDC, 1993) and "NCDC Surface Airways" (EarthInfo, 1998b; NCDC, 2004a) databases.
3. Solar radiation was derived from the sum of diffuse radiation and direct radiation corrected for the effects of local slope and aspect (Hobbins *et al.*, 2004a). Solar radiation data were drawn from 258 stations in the SOLMET (NCDC, 2001), SAMSON (NCDC, 1993), and "NCDC Airways Solar Radiation" (EarthInfo, 1998b; NCDC, 2004a) databases.
4. Wind speed data were drawn from 568 stations in the SAMSON (NCDC, 1993) and "NCDC Surface Airways" (EarthInfo, 1998b; NCDC, 2004a) databases.
5. Average monthly albedo surfaces were based on Advanced Very High Resolution Radiometer (AVHRR) data from Gutman (1988). The AVHRR-derived albedo estimates have an original spatial resolution of about 15 km.
6. Elevation data were extracted from a 30-arc-second DEM.

Unfortunately, the density of stations is lower in the interior West, especially for humidity, solar radiation, and wind speed, which, given the West's extreme topographic heterogeneity, is precisely the region where application of a complementary relationship model would require the densest set of data points. The impact of this difficulty is seen below.

Model Testing and Calibration. The AA model was tested by comparing mean annual ET_a from the model (ET_a^{AA}) to water balance-derived estimates of actual evapotranspiration (ET_a^*) computed as in Equation (4) for 655 minimally impacted basins included in the Hydro-Climatic Data Network (HCDN) (Slack and Landwehr, 1992; Hydrosphere Data Products, 1996) (Figure 2). Streamflow data were extracted for U.S. Geological Survey (USGS) gages at the outlets of the 655 basins. Precipitation in the basins was estimated using the PRISM model as described above. Relating ET_a^{AA} to ET_a^* revealed considerable variance in the estimates of ET_a^{AA} (R^2 = 0.76, n = 655), and that ET_a^{AA} tended to underestimate ET_a^*, especially in wetter regions. Because of this problem, and in light of our objective of accurately estimating Q as $P - ET_a$, it was decided to use ET_a^* at the test-basins to calibrate the model.

Calibration of the AA model followed a detailed process where coefficients of the wind function of the model (Hobbins *et al.*, 2001a) were altered at each of a subset of the 655 test-basins so as to minimize the differences between monthly ET_a^{AA} and ET_a^*. Then the resulting models for the test-basins, or in some cases combinations of those models, were applied to surrounding watersheds to fill in the rest of the study area, producing calibrated estimates of ET_a^{AA} (see Hobbins *et al.*, 2001a for details). Resulting estimates of water supply (Q^{AA}) are then equal to $P - ET_a^{AA}$.

A plot (not reproduced here) of ET_a^{AA} from the regionally calibrated AA model against ET_a^* for the test-basins shows that the points are clustered about the 1:1 line, with relatively little scatter (R^2 = 0.88, n = 655), suggesting that the ET_a^*-based calibration of the AA model predicts ET_a fairly well, with no bias over the range of observed ET_a^*.

As another measure of the performance of the calibrated model, a water balance closure error was computed for each test-basin as follows:

$$\varepsilon = \frac{\sum_{i=1}^{42}\sum_{j=1}^{12}\left(ET^*_{a_{(i,j)}} - ET^{AA}_{a_{(i,j)}}\right)}{\sum_{i=1}^{42}\sum_{j=1}^{12} P_{(i,j)}} \times 100 \tag{5}$$

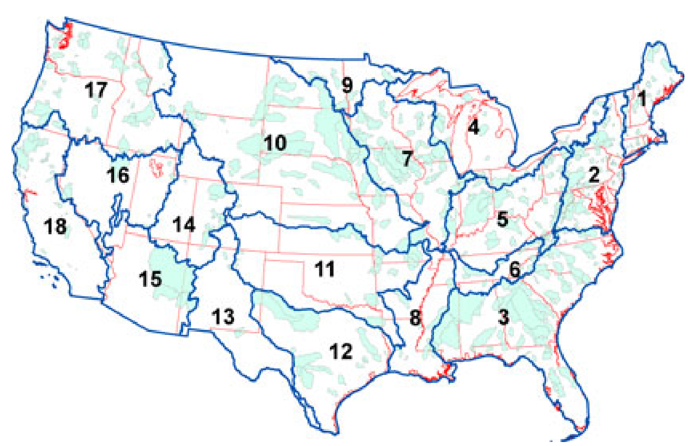

FIGURE 2. Locations of the 655 Test-Basins and Water Resource Regions in the Conterminous U.S. (see Table 1 for the key to the WRRs).

ε expresses the cumulative error as a percentage of cumulative precipitation (i and j refer to year and month, respectively). Across the 655 test-basins the mean ε is 0.15% (median = 0.12%, standard deviation = 4.9%, minimum = −47%, maximum = 31%), indicating a slight overall under-estimation of ET_a^*. Eighty-five percent of the ε are within the range from −5% to +5% of mean annual P. Possible explanations of nonzero ε are: (1) violations of the assumptions inherent in Equation (3) used to develop ET_a^* estimates, perhaps through unaccounted ground-water pumping, surface-water diversions, or net ground-water flow out of the basin; (2) violations of the assumption of stationarity in climatological forcing; and (3) errors induced by spatial interpolation of the climatic variables.

Model Performance at the WRR Level. Comparing modeled ET_a^{AA} with ET_a^* from the test-basins does not constitute an independent test because the test-basins were used for calibrating the model. Data for water resource regions (WRR) (Figure 2) allow a more independent test (although not a wholly independent test, as the test-basins cover 21% of the contiguous 48 states).

The WRRs were defined by the U.S. Water Resources Council (1978) for the purpose of large-scale assessment and planning. To assist such planning, the USGS estimated annual outflow from the WRRs using streamflow gage records for the period 1951-1983 (Graczyk *et al.*, 1986). From the USGS estimates, we subtracted inflows to WRRs 8 and 15 from upstream basins, and inflows to WRRs 9 and 17 from Canada, so as to isolate the amount of flow originating within the U.S. portions of the respective WRRs. We averaged the annual estimates of outflows for the WRRs (R) and then estimated mean annual virgin flow (Q^{USGS}) originating in the WRRs as

$$Q^{\mathrm{USGS}} = R - GD + RE + CU - IM \tag{6}$$

where GD is ground water depletion, RE is reservoir evaporation, CU is consumptive use from diversions, and IM represents net imports to the basin. GD, RE, and CU were taken from Foxworthy and Moody (1986) and IM was taken from Petsch (1985) and Mooty and Jeffcoat (1986) (because Petsch and Mooty and Jeffcoat estimated transfers for 1973-1982, the mean annual transfers were necessarily assumed to apply to the entire period of interest, 1953-1983). The resulting estimates of mean annual Q^{USGS} are listed in Table 1.

Estimates of mean annual water supply originating in the WRRs over the period 1953-1983 were computed from the distributed monthly estimates of Q^{AA} by summing across months and across the grid cells within a WRR (Table 1).

Figure 3 presents the comparison of the two sets of estimates of mean annual Q (listed in the first two columns of numbers in Table 1). The overall

TABLE 1. Mean Annual Water Supply (Q) Originating in WRRs for the Period 1953-1983, Estimated From USGS Gage Data and as $P - ET_a$ Using the Two Calibrated Models.

		Q (Bm^3)			**% Difference From USGS**	
WRR		**USGS**	**AA Model**	**Zhang Model**	**AA Model**	**Zhang Model**
1	New England	106	92	91	−13	−14
2	Mid-Atlantic	132	120	115	−9	−13
3	South-Atlantic-Gulf	298	273	281	−8	−6
4	Great Lakes	107	96	84	−10	−22
5	Ohio	192	182	179	−5	−6
6	Tennessee	60	62	61	5	3
7	Upper Mississippi	106	104	105	−2	−1
8	Lower Mississippi	101	120	130	18	28
9	Souris-Red-Rainy	9	11	10	30	16
10	Missouri	90	120	93	33	3
11	Arkansas-White-Red	87	99	80	13	−8
12	Texas-Gulf	51	42	47	−17	−7
13	Rio Grande	6	21	6	259	2
14	Upper Colorado	18	47	20	164	15
15	Lower Colorado	4	44	5	923	21
16	Great Basin	11	31	14	172	25
17	Pacific Northwest	323	320	297	−1	−8
18	California	112	103	102	−8	−9
48 states		1,811	1,885	1,721	4	−5

Note: Bm^3, billion cubic meters.

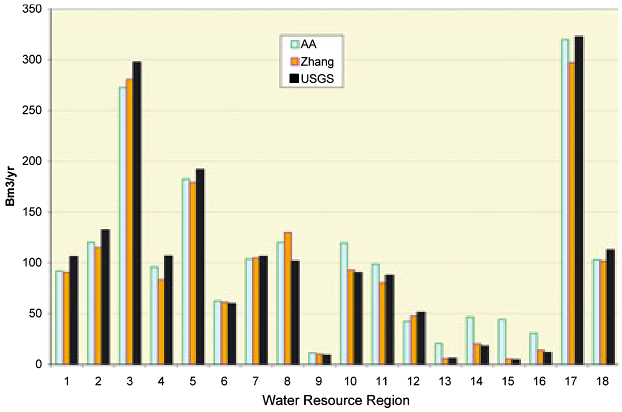

FIGURE 3. Mean Annual Water Supply for the 18 WRRs of the Conterminous U.S. for the Period 1953-1983 Estimated From USGS Data (Q^{USGS}) and as $P - ET_a$ Using the Two Evapotranspiration Models (Q^{AA} and Q^{ZH}).

relationship between the two sets is very good ($R^2 = 0.97$, $n = 18$). However, there are large differences for the four dry, southwestern basins (WRRs 13-16), where the AA model appears to underestimate ET_a. This comparison is not definitive because the USGS estimates are themselves subject to substantial error. However, the relative lack of weather station data in the Southwest for the AA model, and the scarcity of test-basins for model calibration in rangeland and desert areas (Figure 2), suggest that, in these areas, improvements in estimates of model-based Q are needed.

The Zhang Model of Mean Annual ET_a

The problem with the AA model in the Southwest led us to consider the newly available Zhang model (Zhang *et al.*, 2001) for improving the estimates. The Zhang model employs a different theoretical approach from that of the AA model, and has a more modest goal than our implementation of the AA model in that it estimates only mean annual ET_a. The model uses mean annual estimates of P and ET_w along with a parameter reflecting the dominant vegetation type.

The Zhang model of mean annual ET_a is

$$ET_a^{ZH} = P\frac{1 + w\eta}{1 + w\eta + \frac{1}{\eta}} \quad (7)$$

where w represents a relative measure of water available to plants and $\eta = ET_w/P$. Following Zhang *et al.* (2001), we set w to 2.0 for forest cover and 0.5 otherwise. We computed ET_w using the Priestley-Taylor equation, as in our implementation of the AA model. Mean annual P was again estimated using PRISM. Vegetation cover was taken from the national land cover database (U.S. Geological Survey, 1992), with forest cover composed of cover classes 41 (deciduous forest), 42 (evergreen forest), and 43 (mixed forest). Estimates were produced for each grid cell, both for the full study period (1953-1994) (Table 2) and for matching the USGS data for the WRRs (1953-1983).

TABLE 2. Comparison of Mean Annual Evapotranspiration (ET_a) From the Mixed Model With Mean Annual Precipitation (P) and Resulting Water Supply (Q) for the WRRs, for the Period 1953-1994.

		Volume (Bm^3)				
WRR		***P***	***ET_a***	***Q***	***ET_a/Q***	***ET_a/P***
1	New England	170	76	94	0.81	0.45
2	Mid-Atlantic	289	164	125	1.32	0.57
3	South-Atlantic-Gulf	886	612	275	2.23	0.69
4	Great Lakes	251	152	100	1.53	0.60
5	Ohio	466	280	187	1.50	0.60
6	Tennessee	145	82	63	1.30	0.56
7	Upper Mississippi	411	302	109	2.78	0.74
8	Lower Mississippi	361	236	125	1.88	0.65
9	Souris-Red-Rainy	80	70	10	7.15	0.88
10	Missouri	690	591	99	5.99	0.86
11	Arkansas-White-Red	498	409	89	4.61	0.82
12	Texas-Gulf	364	314	50	6.30	0.86
13	Rio Grande	124	118	7	17.72	0.95
14	Upper Colorado	111	90	21	4.34	0.81
15	Lower Colorado	117	111	6	19.38	0.95
16	Great Basin	111	97	14	7.08	0.88
17	Pacific Northwest	588	285	303	0.94	0.48
18	California	239	144	95	1.51	0.60
48 states		5,913	4,144	1,769	2.34	0.70

Model Testing and Calibration. The Zhang model was tested in a similar fashion to the AA model, by comparing ET_a^{ZH} with basin-derived estimates computed as in Equation (4) (ET_a^*) for the 655 test-basins. Comparison of ET_a from the two sources revealed considerable variance in the estimates (R^2 = 0.44, n = 655).

Because of this variation, model estimates of ET_a^{ZH} were adjusted, based on mean annual ET_a^* from the test-basins for 1953-1994. The calibration involved separating the test-basins into 14 groups based on inspection of the relationship of ET_a^{ZH} to ET_a^*, with each group representing a set of USGS 4-digit basins. Then within each group, test-basin data were used to compute coefficients for adjusting ET_a^{ZH} to more closely predict ET_a^* within the group. These adjustments for each group were applied throughout the set of four-digit basins represented by the group. Details on the calibration are available in the discussion paper "The source of water supply in the United States" (available at http://www.fs.fed.us/rm/value/discpapers.html).

When tested against the calibrating data (ET_a^*) for the 655 test-basins, the calibrated Zhang performed reasonably well. Plotting ET_a^{ZH} against ET_a^* shows that the points are clustered along the 1:1 line with no bias, but the scatter (R^2 = 0.73, n = 655) is greater than with the AA model. In terms of closure error (computed as in Equation (5) with ET_a^{ZH} replacing ET_a^{AA}), across the 655 test-basins mean ε is 0.22% (median = −0.08%, standard deviation = 8.1%, minimum = −50%, maximum = 36%). Only 63% of the ε are within the range from −5% to +5% of mean annual P, which again shows less precision than the AA model.

Model Performance at the WRR Level. As with the AA model, data at the WRR level allowed a relatively independent test of the calibrated Zhang model. Estimates of mean annual water supply originating in the WRRs were computed by summing $Q^{ZH} = P - ET_a^{ZH}$ across the grid cells within a WRR. Table 1 presents the results of this procedure, and Figure 3 shows the comparison of mean annual Q^{AA} and Q^{USGS}. The overall relationship between the two sets is very good (R^2 = 0.98, n = 18). Importantly, for the four problematic southwestern basins (WRRs 13-16), Q^{ZH} are much closer to Q^{USGS} than are Q^{AA}. The calibrated Zhang model also substantially outperforms the calibrated AA model in WRRs 9-12.

ET_a Model Selection

As seen in Table 1 and Figure 3, for most WRRs the estimate from at least one evapotranspiration model is close to the USGS estimate. Because the AA model produces generally smaller closure errors than the Zhang model, the AA model is to be preferred, all else equal. Among WRRs 1-8, 17, and 18 the AA model either produces the estimate that is closer to the USGS estimate or if not then produces an estimate that is very close to the Zhang model estimate. However, for WRRs 9-16 the Zhang model produces an estimate that is substantially closer to the USGS estimate than is the AA model estimate. Interestingly, these eight WRRs are among the driest, all with mean annual precipitation estimates of less than 700 mm, and have substantial nonforest (largely rangeland) cover. As mentioned earlier, data for the AA model and test-basins for its calibration are relatively sparse on rangelands. The models differ considerably in their estimates for rangelands but not for other cover types. Apparently the Zhang model, which attempts only to estimate mean annual ET_a, is less sensitive to data density and less dependent on calibration, and thus better able to estimate mean annual ET_a when data for estimation and calibration are sparse.

In sum, we used the Zhang model for WRRs 9-16 and the AA model elsewhere. This combination of the two models is called the Mixed model. We hasten to add, however, that our work, although adequate for our purposes, does not provide a definitive comparison of the models.

Administrative Boundaries and Cover Type

As a source of water supply, federal ownership was distinguished from nonfederal (state and private) ownership, and five categories of federal ownership (Forest Service, Park Service, Bureau of Land Management, Bureau of Indian Affairs, and other) were tracked. The federal boundaries were taken from the Federal Lands of the U.S. database (U.S. Geological Survey, 2004). Because of the many small units, this coverage was modeled at a 100-m resolution.

The national land cover database (U.S. Geological Survey, 1992) was used to distinguish among land cover types. Five cover classes were formed from the original 21 land cover classes as follows: forest (cover classes 41, 42, and 43), rangeland (classes 51 and 71), water/wetland (classes 11, 12, 91, and 92), agriculture (classes 61, 81, 82, 83, and 84), and other/developed classes (classes 21, 22, 23, 31, 32, 33, and 85).

Official boundaries of some states extend into major water bodies, such as the Great Lakes (e.g., Wisconsin) or major bays and estuaries (e.g., Washington). In these cases we clipped state boundaries at the water's edge.

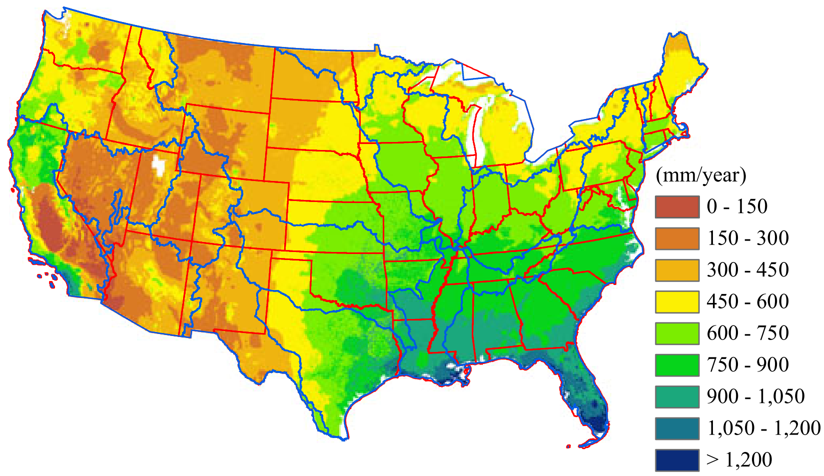

FIGURE 4. Mean Annual ET_a From the Mixed Model for the Period 1953-1994.

RESULTS

Distributed mean annual ET_a over the period 1953-1994, at the 5-km cell level, from the Mixed model is shown in Figure 4. In the energy-limited eastern states, these estimates show ET_a decreasing with energy supply as one moves northward, whereas in the moisture-limited western states ET_a generally decreases with P as one moves westward until the West Coast region is reached, and also increasing with elevation as does P.

Figure 5 shows the distribution of mean annual water supply, Q, computed as in Equation (1) using the ET_a estimates from the Mixed model. A general comparison of Figures 4 and 5 shows that, as expected, ET_a usually exceeds Q. In the East (WRRs 1-8), the overall ratio of ET_a to Q is 1.8, and along the West Coast (WRRs 17 and 18) the overall ratio is 1.1, whereas in the drier West (WRRs 9-16) the overall ratio is 6.1. Contrary to the general finding, Q exceeds ET_a in some areas, most notably in portions of WRRs 1 and 17, but also in parts of WRRs 2, 5, and 18.

Over the entire conterminous U.S., mean annual ET_a and Q are estimated to be 538 and 230 mm/year, respectively. Across the WRRs, mean annual ET_a ranges from 271 mm/year in WRR 16 to 910 mm/year in WRRs 3 and 8, whereas Q ranges from 16 mm/year in WRR 15 to 595 mm/year in WRR 6 (Figure 6). Figure 6 arranges the WRRs in order of increasing mean annual P, and shows several interesting findings. First, for the six WRRs with the lowest P, ET_a nearly matches P so that Q is minimal. Second, as expected, WRRs with more P also tend to have more ET_a and Q (R^2 of P with ET_a is 0.79, n = 18). Third, in two relatively moist and cool WRRs (1 and 17) Q exceeds ET_a. Fourth, although P

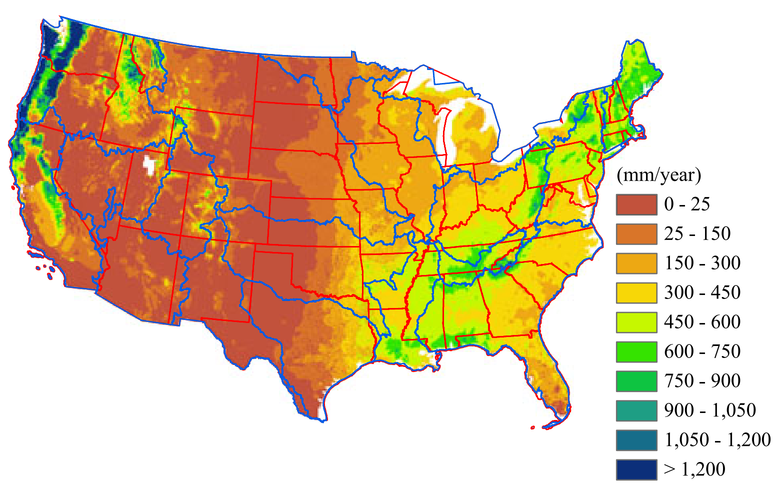

FIGURE 5. Mean Annual Water Supply (Q) Using ET_a From the Mixed Model, for the Period 1953-1994.

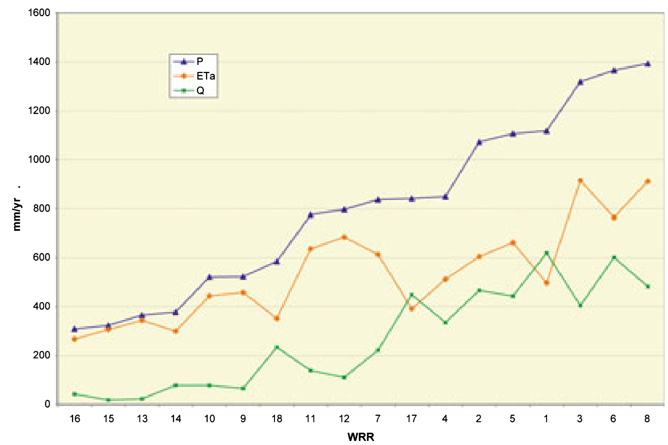

FIGURE 6. Mean Annual Depth (mm) by WRR, With ET_a From the Mixed Model, for the Period 1953-1994.

rises substantially as one moves from the dry intermountain West to the East and South, rising to over 1,300 mm/year in the three southeastern WRRs, ET_a also rises, especially in the southeastern WRRs, so that Q barely reaches 600 mm/year even in the most moist WRRs.

Twenty-four percent of the nation's (48 contiguous states only) water supply (429 billion m^3 per year) originates on federal land (Table 3). Eighteen percent of the nation's water supply originates on lands of the national forest system alone, although those lands occupy only about 11% of the surface area. Forest Service and Park Service lands yield on average 384 mm/year, while the other federal lands yield an average of only 58 mm/year and state and private lands yield an average of 238 mm/year.

Because federal lands are concentrated in the western portion of the country, the contributions of federal lands to water supply are greatest in the West. West of the Mississippi River, 42% of the water supply originates on federal land, with 32% on Forest Service land alone, compared with 9% and 7%, respectively, east of the Mississippi. Or, dividing the country into five sections, we see that in the western section, comprised of the 11 western states, 66% of the water supply originates on federal lands, with 51% on Forest Service lands (although Forest Service lands occupy only about 21% of the surface area) (Table 4). These estimates for the West are surprisingly close to those of the Federal Land Law Review Commission in 1970, which estimated that 61% came from federal lands, with 54% from the national forests (U.S. Public Land Law Review Commission, 1970).

TABLE 3. Water Supply of the Conterminous U.S. by Land Ownership Type, for the Period 1953-1994.

	Volume		
	Bm^3/Year	Percent	mm/Year
NFS	326	18	386
BLM	26	1	37
NPS	36	2	364
BIA	16	1	62
Other federal	24	1	141
State and private	1,339	76	238
Total	1,768	100	229

Note: NFS, National Forest System of the U.S. Forest Service; BLM, U.S. Bureau of Land Management; NPS, National Park Service; BIA, Bureau of Indian Affairs, U.S. Department of Interior.

Detailed tables of results for WRRs and states are presented in the Appendix. The role of federal lands differs dramatically across the WRRs. WRRs 1, 2, 3, 5, 7, 8, and 12 all receive less than 10% of their water supply from federal lands, whereas WRRs 14-16 receive at least 80% from federal lands (Table A1). The role of federal lands also differs greatly among the states, with 24 states receiving less than 10%, and seven states receiving more than 75% (Arizona, Colorado, Idaho, Montana, Nevada, Utah, and Wyoming), of their water supply from federal lands (Table A2).

Shifting to cover type, we find that 53% of the nation's water supply originates on forestland, 26% on agricultural land, and 8% on rangeland (Table 5). Forest contributes 65, 56, and 68% of the water supply in the West, South, and East sections of the U.S., respectively (Table 6). Agricultural land is most important in the Plains and Midwest, contributing 49 and 58% of the water supply, respectively.

The role of forests varies substantially across the WRRs, with WRRs 9 and 10 receiving less than 20% of their water supply from forests (Table A3), whereas WRRs 1, 6, and 17 receive at least 70%. Across the states, the role of forests varies as well, with five states receiving less than 10% of their water

TABLE 4. Water Supply of the Conterminous U.S. by Land Ownership Type and U.S. Region, for the Period 1953-1994 (Bm^3/year).

	West	Plains	Midwest	South	East	Total
NFS	245.2	3.4	18.6	51.9	6.6	325.7
BLM	26.0	0.0	0.0	0.0	0.0	26.0
NPS	31.7	0.2	0.5	3.5	0.4	36.3
BIA	11.7	1.7	2.1	0.3	0.2	16.0
Other federal	5.2	2.2	2.2	13.3	1.6	24.4
State and private	163.6	109.4	278.3	548.6	239.3	1339.2
Total	483.4	116.9	301.7	617.6	248.1	1767.7

Notes: West: AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, WY.
Plains: KS, ND, NE, OK, SD, TX.
Midwest: IA, IL, IN, MI, MN, MO, OH, WI.
South: AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, VA, WV.
East: CT, DC, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT.
See Table 2 for agency names.

TABLE 5. Water Supply of the Conterminous U.S. by Land Cover Class, for the Period 1953-1994.

	Volume		
	Bm^3/Year	Percent	mm/Year
Forest	931	53	417
Rangeland	146	8	55
Agriculture	461	26	225
Water/wetland	137	8	307
Other	93	5	284
Total	1,768	100	229

TABLE 6. Water Supply of the Conterminous U.S. by Land Cover Type and U.S. Region, for the Period 1953-1994 (Bm^3/year).

	West	Plains	Midwest	South	East	Total
Forest	313.0	19.9	83.0	346.2	169.2	931.2
Rangeland	111.6	25.8	3.8	4.4	0.3	145.9
Agriculture	23.6	57.3	173.8	163.6	42.9	461.2
Water/wetland	7.2	8.9	29.6	73.4	17.5	136.5
Other	28.0	5.1	11.5	30.1	18.2	92.9
Total	483.4	116.9	301.7	617.6	248.1	1,767.7

Note: For regional definitions, see Table 4.

supply from forests (Table A4) (Iowa, Kansas, North Dakota, Nebraska, South Dakota) and six states receiving more than 70% (Maine, New Hampshire, Oregon, Vermont, Washington, and West Virginia).

These results reflect our basic understanding of how ET_a responds to available moisture and energy. In dry environments, it is the availability of water that constrains ET_a. As water availability increases both ET_a and ET_p converge toward ET_w in very wet environments. Here it is the availability of energy that determines ET_a, and in such energy-limited environments, increasing P will not change ET_a but will increase Q (assuming storage changes remain negligible). Increasing energy in an energy-limited environment will drive ET_a upwards and consequently drive Q downwards. Overall, the WRRs span much of the continuum between the extremes of water and energy limitations. The most extreme situations are found in portions of WRRs or during certain seasons. For example, during winter in the Olympic Rainforest of WRR 17, the availability of energy limits ET_a regardless of the abundance of P; and the driest parts of the Basin and Range region of WRR 16 are water-limited in July, when so little P falls that it typically evaporates before it can wet the soil long enough for another P event to generate Q.

There is growing evidence that temperature, precipitation, and other variables affecting water supply in the U.S. are changing in response to natural and anthropogenic forcings (Seager *et al.*, 2007; Barnett *et al.*, 2008; Krakauer and Fung, 2008). These changes suggest that our estimates of mean annual water supply may already be slightly out of date, and that, if these hydro-meteorological trends persist, the estimates of water supply should, at some point in the future, be revisited in light of new data.

SUMMARY

We have estimated water supply as precipitation minus evapotranspiration at each 5-km by 5-km cell across the conterminous U.S. We used two evapotranspiration models (the AA and Zhang models) and compared our results with independent estimates for the WRRs. Based on this comparison, we selected ET_a results from the AA model for 10 of the WRRs and from the Zhang model in the other eight WRRs. Overlaying land ownership and land cover type boundaries on the water supply coverage allowed estimation of the quantity of water originating in different land areas of interest.

This procedure has resulted in what are likely the most accurate estimates available so far of overall U.S. water supply. The estimates show that forests are the source of 53% of the U.S. water supply, and of fully two-thirds of the water supply in the West and South. Further, national forests and grasslands are the source of 18% of the water supply nationwide and 51% of the water supply in the West, with all other federal lands contributing another 6% and 15%, respectively.

Because forests are also generally the source of the highest quality runoff (Brown & Binkley, 1994), it is not an exaggeration to say that forests play an extremely important role in the provision of water in the U.S. It may also be said that we are indebted to those of our forbears who set aside so much forest and other land in the public domain, thereby helping to maintain the quality of much of our water runoff, especially in the West. As private lands continue to be developed, public and other protected lands will grow in importance as sources of high quality runoff.

APPENDIX

The following four tables of mean annual water supply (Q) estimates are based on the Mixed model for the period 1953-1994.

TABLE A1. Water Supply (Mm^3/year) of the Conterminous U.S. by Land Ownership.

WRR	NFS	BLM	NPS	BIA	Other Federal	State & Private	Total
1	3,889	0	80	79	443	89,148	93,640
2	4,703	0	738	0	993	118,101	124,534
3	15,901	0	454	137	6,369	251,861	274,721
4	8,717	0	134	960	699	89,010	99,520
5	14,914	0	556	68	2,048	168,966	186,551
6	12,351	0	1,882	170	1,939	46,657	62,999
7	2,360	0	150	592	771	104,932	108,804
8	5,499	0	55	1	2,468	117,344	125,367
9	1,288	0	109	757	73	7,533	9,760
10	17,791	1,931	4,537	3,104	721	70,550	98,635
11	8,999	77	260	867	2,007	76,574	88,783
12	2,296	2	138	3	876	46,605	49,920
13	3,982	263	32	283	75	2,009	6,643
14	14,652	2,225	185	311	51	3,383	20,806
15	3,037	476	119	949	37	1,120	5,738
16	8,121	2,772	84	33	118	2,605	13,734
17	154,591	12,954	20,748	6,724	3,024	105,113	303,154
18	42,601	5,313	6,066	978	1,712	38,536	95,207
Total	325,691	26,013	36,326	16,018	24,423	1,340,045	1,768,516

Note: Mm^3, million cubic meters.

TABLE A2. Water Supply (Mm^3/year) of the Conterminous U.S. by State and Land Ownership.

State	NFS	BLM	NPS	BIA	Other Federal	State & Private	Total
AL	2,852	0	45	0	902	66,615	70,414
AR	6,170	0	128	0	1,263	51,323	58,884
AZ	2,517	213	93	949	35	902	4,709
CA	43,317	5,096	5,878	978	1,568	36,210	93,047
CO	15,384	1,509	478	107	75	5,006	22,559
CT	0	0	0	0	10	7,683	7,693
DC	0	0	6	0	3	72	81
DE	0	0	0	0	39	1,950	1,989
FL	2,149	0	303	103	1,982	39,930	44,467
GA	5,329	0	53	0	1,676	52,870	59,928
IA	0	0	1	4	153	31,141	31,299
ID	41,372	3,498	131	1,755	297	14,011	61,064
IL	1,451	0	0	0	272	38,347	40,070
IN	1,005	0	9	0	378	30,345	31,736
KS	0	0	7	92	218	16,147	16,464
KY	4,183	0	204	0	874	44,123	49,384
LA	1,713	0	38	1	1,379	52,485	55,616
MA	2	0	22	0	142	11,922	12,088
MD	0	0	80	0	146	9,393	9,619
ME	199	0	65	79	184	50,343	50,870
MI	6,569	0	76	289	392	39,560	46,886
MN	2,505	0	173	1,145	164	23,839	27,826
MO	3,490	0	130	0	458	46,642	50,720
MS	5,303	0	7	35	828	59,060	65,232
MT	29,805	1,084	4,057	2,855	234	10,584	48,620
NC	8,825	0	1,031	170	1,180	43,123	54,329
ND	84	1	3	78	51	3,871	4,088
NE	47	0	8	155	51	11,239	11,500

TABLE A2. (Continued)

State	NFS	BLM	NPS	BIA	Other Federal	State & Private	Total
NH	2,715	0	0	0	35	11,932	14,682
NJ	0	0	93	0	240	9,343	9,676
NM	2,468	286	11	365	70	2,287	5,486
NV	2,159	2,698	71	46	243	581	5,798
NY	30	0	15	164	420	64,441	65,070
OH	1,432	0	50	0	132	35,130	36,744
OK	714	0	7	864	866	21,318	23,769
OR	43,016	9,212	474	1,049	302	43,727	97,779
PA	1,783	0	84	0	245	59,249	61,362
RI	0	0	0	0	10	1,828	1,838
SC	2,034	0	34	0	621	25,634	28,323
SD	146	2	12	502	26	4,328	5,015
TN	2,949	0	1,036	0	1,864	55,960	61,809
TX	2,373	0	157	3	1,000	52,496	56,029
UT	6,903	801	34	133	27	2,040	9,936
VA	5,398	0	517	0	567	31,673	38,156
VT	1,915	0	0	0	97	11,150	13,162
WA	46,950	42	15,963	2,891	2,227	45,080	113,151
WI	2,177	0	85	668	220	33,257	36,407
WV	4,990	0	132	0	136	25,824	31,081
WY	11,270	1,578	4,542	539	127	3,168	21,224
Total	325,693	26,019	36,342	16,019	24,428	1,339,180	1,767,681

TABLE A3. Water Supply (Mm^3/year) of the Conterminous U.S. by WRR and Land Cover Class.

WRR	Forest	Rangeland	Agriculture	Water/Wetland	Other	Total
1	71,088	321	5,305	9,203	7,723	93,640
2	78,900	0	29,101	6,838	9,695	124,534
3	155,600	3,933	57,782	39,195	18,212	274,721
4	43,947	1,154	34,924	15,599	3,896	99,520
5	106,025	159	69,727	3,864	6,776	186,551
6	44,728	0	14,028	1,925	2,318	62,999
7	25,060	1,709	69,139	8,509	4,388	108,804
8	42,284	262	53,407	25,669	3,744	125,367
9	1,008	434	4,284	3,897	137	9,760
10	17,558	27,934	46,043	3,175	3,925	98,635
11	33,552	10,895	35,757	5,843	2,737	88,783
12	12,179	8,220	20,161	5,723	3,637	49,920
13	3,033	3,438	19	16	137	6,643
14	9,020	10,366	242	241	936	20,806
15	2,313	3,361	11	6	47	5,738
16	4,399	8,455	363	215	301	13,734
17	226,858	37,101	13,471	5,380	20,345	303,154
18	56,446	28,389	5,935	717	3,719	95,207
Total	933,998	146,131	459,699	136,016	92,673	1,768,516

TABLE A4. Water Supply (Mm^3/year) of the Conterminous U.S. by State and Land Cover Class.

State	Forest	Rangeland	Agriculture	Water/Wetland	Other	Total
AL	47,321	0	14,545	5,538	3,010	70,414
AR	27,245	69	24,148	6,119	1,303	58,884
AZ	1,927	2,734	5	5	37	4,709
CA	53,574	28,587	6,664	784	3,438	93,047
CO	9,453	11,301	508	224	1,073	22,559
CT	4,466	0	766	771	1,691	7,693
DC	18	0	0	0	63	81
DE	529	0	976	377	106	1,989
FL	15,094	3,947	7,124	12,822	5,481	44,467

TABLE A4. (Continued)

State	Forest	Rangeland	Agriculture	Water/Wetland	Other	Total
GA	35,955	116	13,252	6,133	4,472	59,928
IA	2,393	1,772	25,327	863	945	31,299
ID	38,182	15,756	3,506	863	2,758	61,064
IL	5,691	326	29,864	2,005	2,184	40,070
IN	6,442	135	22,887	999	1,273	31,736
KS	378	5,283	9,834	579	390	16,464
KY	29,720	0	16,728	1,613	1,323	49,384
LA	18,217	278	17,182	17,506	2,434	55,616
MA	7,375	16	643	1,508	2,546	12,088
MD	4,087	0	3,732	971	829	9,619
ME	40,569	291	2,411	5,318	2,281	50,870
MI	19,776	1,004	14,723	9,701	1,681	46,886
MN	6,346	203	12,477	7,995	805	27,826
MO	14,842	209	31,852	2,274	1,542	50,720
MS	32,512	10	21,885	8,506	2,320	65,232
MT	27,805	15,167	2,509	546	2,593	48,620
NC	34,087	0	11,540	6,122	2,580	54,329
ND	9	951	2,899	200	30	4,088
NE	16	3,769	7,178	366	171	11,500
NH	12,072	0	768	1,107	735	14,682
NJ	4,214	0	1,852	1,383	2,226	9,676
NM	2,537	2,826	74	11	38	5,486
NV	998	4,582	34	35	149	5,798
NY	43,133	0	14,240	3,944	3,754	65,070
OH	12,748	8	20,691	1,082	2,214	36,744
OK	6,388	5,887	9,429	1,361	704	23,769
OR	78,293	7,899	6,679	977	3,931	97,779
PA	41,310	0	15,707	1,107	3,237	61,362
RI	1,198	0	53	242	345	1,838
SC	15,671	0	6,336	4,275	2,041	28,323
SD	51	923	3,736	266	40	5,015
TN	38,059	0	18,392	2,663	2,695	61,809
TX	13,023	8,945	24,202	6,101	3,758	56,029
UT	4,261	5,061	178	111	325	9,936
VA	25,743	0	8,817	1,876	1,719	38,156
VT	10,203	13	1,799	773	374	13,162
WA	87,885	7,695	3,032	2,898	11,641	113,151
WI	14,760	155	15,944	4,659	889	36,407
WV	26,548	0	3,639	195	700	31,081
WY	8,077	10,009	391	730	2,017	21,224
Total	931,202	145,925	461,156	136,504	92,893	1,767,681

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