INDICATORS OF IMPACTS OF GLOBAL CLIMATE CHANGE ON U.S. WATER RESOURCES

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ABSTRACT: Environmental and socioeconomic indicators are selected to study the impacts of global warming on the water resources of the United States. One of the indicators, regional reservoir storage vulnerability, is a particularly useful index summarizing the effectiveness of regional water supply systems to meet demands. A comparison of indicator tabulation and evaluation methods finds that reporting an indicator as a fraction of its stress threshold is most effective. Indicator display methods are compared, and the star diagram proves most effective as a visual aggregation technique. Indicators and evaluation methods are applied to the present climate and to one possible climate change scenario assuming economic growth. It is apparent that the primary impacts of global warming occur in the western U.S. and include (1) fewer relative stresses on hydroelectric systems due to an increase in energy supply from other sources, and (2) more stresses on available water resources due to increases in total withdrawals and, in some cases, decreases in flows. The writers believe that with wise indicator display methods, mathematical aggregation of indicators into indices may be unnecessary.

INTRODUCTION

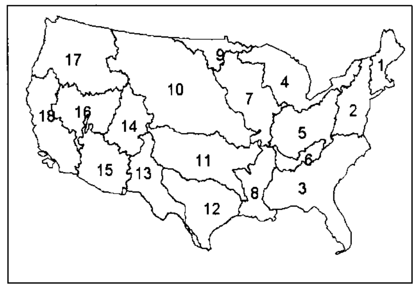
There is considerable interest in the use of indicators and indices to display relations among natural resource and economic information. An indicator can be defined as ''a performance measure that aggregates information into useable form'' (World Bank definition given in Rogers et al. 1997), whereas an index is an aggregated set of indicators. This study examines issues involved in the application of environmental and socioeconomic indicators to the continental United States (U.S.) to investigate the integrated impacts of potential global warming on water resources. Impacts are measured in terms of water resource stress; a water resource system is considered stressed if it is unable to deliver the necessary quantities of water for environmental, social, and economic purposes and objectives. The indicators are applied to the 18 U.S. Water Resources Council (1970) regions of the U.S., illustrated and named in Fig. 1. The first section of this paper presents background information on global warming from the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al. 1996). Next, a literature review is provided along with an introduction to a large set of indicators suitable for water resource investigations. This is followed by an examination of methods for combining and evaluating indicators including scaling, threshold, and percent change approaches. A comparison is presented of the results when each method is partially applied to evaluate regional water resources stresses in the U.S. under the present climate. Various methods of displaying indicators are then reviewed. Using the most effective combination and display methods from the above analysis, the indicators are then used to analyze the potential impacts of global warming on U.S. water resources under a climate change with economic growth scenario. The paper concludes with suggestions for future applications and display of indicators.

Summarizing results loses detail, yet decision makers often insist that indicators be aggregated into indices so that more information can be expressed more efficiently. Indicators can be aggregated using weighted or unweighted sums, products, or other mathematical relations. The use of indicators is emphasized in this paper because information is lost when indicators are aggregated into indices. We believe that with wise display methods of indicators, mathematical aggregation may be unnecessary.

GLOBAL WARMING

The IPCC (Houghton et al. 1996) reports that the temperature of the Earth's surface is increasing due to anthropogenic emissions of greenhouse gases that trap radiation emitted from the Earth. The temperature has increased by 0.3 to 0.6°C over the last century, with the greatest increases in the last few decades. Without reductions in the gas emissions, the average surface temperature could increase from 1 to 3.5°C by 2100.

The IPCC reports that because of changing temperatures and climate, hydrologic conditions will also change worldwide. Potential evapotranspiration is expected to increase. Some studies show precipitation increasing in higher and mid-latitude areas and decreasing in lower latitudes areas. There are also expected to be increases in the occurrence of extreme events. Streamflows will change in response to these hydrologic changes; some research shows high latitudes possibly experiencing increased streamflows and lower latitudes having lower streamflows. Water demands will also change due to



Region	Region Name
1	New England
2	Mid-Atlantic
3	South Atlantic Gulf
4	Great Lakes
5	Ohio
6	Tennessee
7	Upper Mississippi
8	Lower Mississippi
9	Souris-Red-Rainy
10	Missouri
11	Arkansas-White-Red
12	Texas-Gulf
13	Rio Grande
14	Upper Colorado
15	Lower Colorado
16	Great Basin
17	Pacific Northwest
18	California

FIG. 1. United States Water Resource Regions

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climate change. For example, because of increased temperatures, both irrigation and domestic use of water could increase.

The IPCC (Houghton et al. 1996) describes many of the studies that have been conducted on the possible impacts of climate change on hydrologic and water resources systems. Most of these studies have focused on one watershed or region. The research reported here is part of a larger study that examines the environmental and socioeconomic impacts of climate change on water resources for all regions of the United States using a variety of methods. This paper focuses on the use of indicators.

REVIEW OF INDICATORS AND INDICES IN ENVIRONMENTAL ANALYSIS

There is significant interest in the use of indicators to assess socioeconomic and environmental status and impacts at the national or regional level (Rogers 1999). For example, the United Nations (U.N.) (*Indicators* 1996) developed 130 indicators for national assessments of social, economic, environmental, and institutional aspects of sustainable development. In a study for the Asian Development Bank, Rogers et al. (1997) present reviews of past (starting from the 1960s) and recent environmental quality indicator applications. They also critique many of the methods employed in developing and applying indicators and aggregating them to form indices. They suggest the use of new indices (cost-of-remediation, environmental elasticity) and environmental diamonds; a concept they borrow from the World Bank's development diamonds. A variation of environmental diamonds to display indicators is discussed in later sections.

There is a history of indicators and indices being used in water resources assessment. The U.S. Water Resources Council compiled a comprehensive water supply and demand database in the Second National Water Assessment (U.S. Water Resources Council 1979). The assessment was designed to assist federal and local agencies in establishing and implementing water resource policies and programs by cataloging regional and subregional water availability and use. The nation's water supply, use, and critical water problems were presented for the then-current situation in 1975 and also projected 10 and 25 years in the future (the years 1985 and 2000). Problem regions are indicated using present and projected instream flow deficits, and the ratios of total streamflow to offstream consumptive use and other losses, instream use, and total use. Falkenmark (1989) uses the indicator of water barrier or the per capita amount of the water available in each nation to analyze water issues in Africa. Gleick (1990) introduces an unweighted index to evaluate the climate change vulnerability of water systems within the 18 water resource regions of the U.S. The index is composed of five indicators of regional vulnerability: storage ratio, demand ratio, hydropower use, ground-water overdraft, and streamflow variability. Relying on previous works and scientific judgment, Gleick established warning levels or thresholds for each of the indicators. The total number of indicator warnings is reported as the overall vulnerability of that region. Hoekstra (1995) presents a large set of indicators and indices for use at the global to the river basin level in integrated water policy analysis. An aggregation scheme is used to summarize all the indicators into the three indices of water system pressure, state, and satisfaction. The indices were developed as part of the TARGETS project of the Netherlands National Institute of Public Health and the Environment. Raskin et al. (1997) examine water resource stress internationally by combining hydrologic and socioeconomic indicators to form a composite water resource vulnerability index. Five easily measurable indicators were measured on two global scales: 159 nations and 10 international regions. These five indicators were subdivided into four classifications (no stress to high stress). The five indicators were then weighted and aggregated into a single water resource vulnerability index. In this way, each nation or region was assigned a label of no stress, low stress, stress, and high stress. The U.S. Environmental Protection Agency (U.S. EPA 1997) developed a large set of indicators to evaluate the environmental health of U.S. watersheds. Indicators were used to characterize the condition of watersheds and their vulnerability to future problems. Vogel et al. (1999a) use indicators of reservoir yield, reliability, resiliency, and vulnerability to assess the impacts of climate change on reservoirs in the U.S. by region.

INDICATORS FOR WATER RESOURCES ASSESSMENT

Regional Indicators of Environmental and Socioeconomic Water Resource Stress

Socioeconomic indicators measure fiscal or societal effects of water resource availability. Environmental indicators measure impacts of water resource availability and use on the environmental domain. In the initial phase of this research, 16 socioeconomic and environmental indicators were identified and defined as in Tables 1 and 2, respectively.

An indicator must be measurable, accessible, not redundant (which can create confusion when different indicators are compared or aggregated), and practical to be useful. Furthermore, all indicators should be defined uniformly in terms of increasing (or decreasing) water resource stress. For example, greater water resource stress is reported in terms of greater numerical

TABLE 1. Socioeconomic Indicators

Indicator name (1)	Description (2)	Indicator source (3)
Consumptive use	Measure of level of development in the region; internal consumptive water use in the region, plus its exports, divided by sum of internally generated surface and renewable ground waters (referred to as internal flow), plus water imports from both transfers and natural upstream systems	Gleick 1990
Storage vulnerability	Measure of region's ability to cope with extreme water events; regional reservoir storage capacity (internal and upstream) divided by reservoir yield, which is approximated by consumptive demand	This study
Import demand ratio	Measure of significance of interbasin water transfers; amount of water imported into a region divided by its total internal withdrawals	This study
Hydropower	Measure of dependence on hydropower electricity; ratio of electricity supplied by hydropower in the region to total basin electricity production	Gleick 1990
Spending power	Measure of a region's ability to overcome an environmental crisis by purchasing expensive infrastructure or technology; approximated by per capita income/regional consumer price index	This study
Poverty	Measure of percentage of a region's population without resources to spare; percent living below national poverty level	This study
Infant mortality	Measure of overall health of the region; percent of newborn deaths to total live births	*Indicators* 1996
Voter participation	Measures public feeling of responsibility and empowerment toward local and national issues; percent of eligible voters who did vote in 1992 elections in each region	This study

TABLE 2. Environmental Indicators

Indicator name (1)	Description (2)	Indicator source (3)
Withdrawal ratio	Measure of intensity of water use in the region; annual water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems	Raskin 1997
Surface water stress	Measure of surface water availability; annual surface water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems	This study
Ground-water stress	Measure of ground-water availability; annual ground-water withdrawals divided by sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems	This study
Dependence ratio	Measure of a region's independence from upstream flow and transfers; ratio of internal flow to the sum of internally generated surface and renewable ground waters, plus water imports from both transfers and natural upstream systems	Raskin 1997
Coefficient of variation	Measure of variability in region's hydrology; standard deviation of regional annual internal water flow divided by the mean annual internal water flow in each region	This study
Runoff ratio	Measure of streamflow per square mile in the region; percentage of the precipitation converted to internally generated surface and renewable ground waters	This study
Biota stress	Measure of ecological integrity; region's number of vulnerable vertebrates divided by region's total native vertebrate species	*Indicators* 1996
Water quality	Measure of flow weighted biological oxygen demand (BOD) concentration in each region	*Indicators* 1996

indicator value. Some of the 16 indicators in Tables 1 and 2 are not independent, practical, and/or measurable, hence they are excluded or replaced. The indicators biota stress, poverty, infant mortality, and voter participation are discarded as impractical because they cannot be estimated under future climate regimes. The indicators surface water and ground-water stresses are eliminated because they sum to the withdrawal ratio and are thus redundant with it.

Three indicators need to be altered so that an increase in the indicator value represents an increase in stress. The indicator spending power becomes the relative poverty indicator. This new indicator is calculated by taking the reciprocal of the original. The runoff indicator becomes it's reciprocal (precipitation/streamflow) so the indicator increase is in the proper direction. The dependence ratio is calculated as in Table 2 and then subtracted from one.

Like many others, we consider the use of a storage ratio (storage/mean annual streamflow) to measure the value that reservoirs provide regions by delivering adequate water supplies. In another study (Vogel et al. 1999a), however, it was found that reservoir system vulnerability better reflects water resources system stress than does the storage ratio. Vogel et al. (1999a) found that reservoir system vulnerability D, defined as the magnitude of a water supply failure as a fraction of annual yield, could be computed from the storage-yield ratio using

$$D = 0.452 \cdot \left(\frac{S}{Y}\right)^{1.27} \quad (1)$$

where S = reservoir storage capacity and Y = annual reservoir yield. Here D reflects the average magnitude of a water supply failure as a fraction of the annual yield.

This indicator is powerful because its calculation involves modeling each individual reservoir system within a region. This is also its drawback; in its application to this research, we were required to simulate the operation of hundreds of reservoirs in each region using the sequent peak algorithm. We then averaged the values of D for all reservoirs in a region to obtain a regional value. The complexity of calculating this indicator does lower its value as an indicator, but we feel its strength compensates for this.

The calculation of the water quality indicator is difficult because of limited data available from the U.S. Environmental Protection Agency (EPA) Storage and Retrieval System for Water and Biological Monitoring Data (STORET) database. The STORET data is too sparsely distributed to permit regional generalizations. We chose instead to use the regional BOD loading estimates from the 1975 U.S. Water Assessment (U.S. Water Resources Council 1979). There are two estimates for BOD loading: present and with Best Available Technology (BAT). Since 1975, BAT has become almost fully implemented; therefore the BAT estimates are used. The regional BOD loadings are divided by regional mean streamflow estimates to determine BOD concentrations. The accuracy of this calculation is obviously limited by the age of the input data; however, it seems to be the best available data.

Many of the indicators require a regional value of the internally generated surface and renewable ground waters (referred to as internal flow). These are derived using equations that relate mean and variance of annual streamflow at the mouth (thus measuring both surface and ground waters) of any watershed within each of the 18 regions to basin temperature, precipitation, and area. These equations were developed by Vogel et al. (1999b) using regional regression methods and data from 1,556 undeveloped watersheds located in the various regions. These basins were selected by the U.S. Geological Survey to represent basins suited for climate sensitivity studies (Slack et al. 1993). This database is known as the Hydro Climatologic Data Network (HCDN). These regional regression equations are applied in this study to the 220 USGS subregions and aggregated up to the 18 water resource regions used in this analysis to obtain estimates of the mean and coefficient of variation of annual runoff for each of the 18 regions.

Considering these exclusions and replacements, the revised set of indicators is

Socio-Economic	Environmental
Consumptive Use	Withdrawal Ratio
Storage Vulnerability	Water Quality
Relative Poverty	Coefficient of Variation
Hydropower	Runoff Ratio
Import Demand Ratio	Dependence Ratio

The data collected to estimate the above indicators are gathered in many formats from numerous sources, including the U.S. Water Resources Council (1970), Petsch (1986), U.S. Army Corps of Engineers (*Water control* 1996), U.S. Department of Commerce (1990), Daley et al. (1994), and Solley et al. (1993). Some of the data require conversion from original units or aggregation from the original scale (e.g., county, state, reservoir site) to an appropriate scale for each of the 18 USGS regions through the use of the ArcView Geographic Information System (*ArcView* 1997).

FUTURE CLIMATE AND SOCIO-ECONOMIC SCENARIO

The indicators are applied to present (considered to be 1990) climate and economic conditions and one possible scenario for 2100. The scenario application requires estimates of both future possible regional streamflows and environmental and socioeconomic conditions. The regional streamflow values under climate change are developed using the regional regression equations detailed above. Assuming that the changes in precipitation and temperature capture most of the hydrologic impacts of climate change, and since the temperature and precipitation ranges in a region are similar to the expected range under each climate change scenario, only temperature and precipitation alterations under climate change are needed. These are taken from the 2100 decadal-averaged output of the transient, coupled General Circulation Model (GCM) from the Goddard Institute for Space Studies (GISS) (see Russell et al. 1995) and spatially averaged over the 2,111 USGS cataloging units in the continental U.S. These GISS model data are selected from many GCMs as one example of a climate scenario. Given the known inaccuracies of GCMs, the temperature and precipitation values used in the hydrologic regressions were adjustments of the actual GCM values, using the common approach described in Kirshen and Fennessey (1995) and elsewhere. That is, the temperatures under climate change were calculated by adding to the historic temperatures the expected changes in temperatures of the GCM scenario compared with the GCM modeled present climate. Precipitation was estimated by multiplying the historical precipitation by the ratio of the GCM scenario precipitation to the GCM present climate precipitation. The GISS scenario is a relatively modest climate change scenario. By 2100, the average annual temperature in all 18 water resources regions increases by approximately 2°C. While precipitation increases in all regions except Region 13, streamflows in most basins decrease—with large decreases in Regions 4, 9, 13, 14, and 16 of 10–40%. A notable increase of 28% in streamflow occurs in Region 11.

The 2100 water demands of the scenario are based on the 2050 ‘‘business as usual’’ scenario of water use and economic activity for North America in Raskin et al. (1997). Lacking better information, it is assumed that the 2050 values are suitable for a water use scenario for 2100. Tables 3 and 4 illustrate the assumed scenario values for water use, thermoelectric energy, population, and Gross Domestic Product for North America for the year 2050. The future values of consumptive use and water withdrawals for each water use sector of each region are calculated by changing the present values of the variables by the proportional change in North America (final row of Table 3); final water use in each region is then the sum over all sectors. Since this calculation has both consumption and withdrawals increasing by the same rate, this method may be an oversimplification—water consumption rates may increase faster than water withdrawals because of increased water recycling and water reclamation.

The indicators also require estimates of other environmental and socioeconomic activities besides water use. Future BOD loads are calculated as directly proportional to population growth projections by assuming that population and BOD loads are directly correlated. The ratio of hydropower production to total electric production is estimated by assuming that changes in hydropower production are directly proportional to changes in streamflow. Total electric production is assumed to increase in each region by 81%, the 2050 increase in the Raskin et al. (1997) scenario. Regional economic projections are calculated by assuming these economic trends are constant across the U.S. This scenario is referred to hereafter as the GISS climate scenario.

TABLE 3. Water Demand Projections (Raskin et al. 1997)

Year (1)	Domestic (km^3) (2)	Manufacturing and refining (km^3) (3)	Thermoelectric power cooling (km^3) (4)	Agriculture (km^3) (5)
1990	69	34.8	205	200
2050	65	46.3	260	250
Increase	−6%	33%	27%	25%

TABLE 4. Power, Population, and Economic Projections (Raskin et al. 1997)

	Thermoelectric demand projections for North America (10^{12} KWh) (1)	Population projections for North America (2)	Gross domestic product projections for North America (billions U.S. $, 1990) (3)
1990	3.1	2.77E+08	$6,040
2050	5.6	3.22E+08	$21,063
Increase	81%	16%	250%

TABLE 5. Indicator Values under Current Climate

	Socioeconomic Indicators					Environmental indicators				
Region (1)	Consumptive use (2)	Storage vulnerability (3)	Relative poverty (4)	Hydropower ratio (5)	Import demand (6)	Withdrawal ratio (7)	Water quality (8)	Coefficient of variation (9)	Runoff ratio (10)	Dependence ratio (11)
1	0.01	0.13	0.10	0.08	0.04	0.06	0.53	0.24	1.69	0.00
2	0.03	0.22	0.11	0.04	0.10	0.24	1.17	0.30	2.38	0.02
3	0.02	0.21	0.13	0.04	0.00	0.15	0.41	0.38	3.24	0.00
4	0.02	0.10	0.11	0.14	0.00	0.32	0.84	0.27	2.76	0.00
5	0.01	0.13	0.13	0.01	0.00	0.18	2.13	0.34	1.98	0.25
6	0.01	0.10	0.13	0.24	0.00	0.21	1.84	0.27	2.44	0.00
7	0.03	0.04	0.12	0.01	0.00	0.27	4.77	0.46	3.88	0.05
8	0.02	1.07	0.15	0.02	0.00	0.05	2.16	0.41	0.80	0.73
9	0.02	1.13	0.13	0.12	0.00	0.04	1.62	0.72	8.78	0.00
10	0.24	0.67	0.13	0.07	0.01	0.75	11.53	0.64	10.53	0.01
11	0.12	0.45	0.13	0.06	0.01	0.24	1.40	0.72	5.74	0.00
12	0.17	0.44	0.13	0.00	0.00	0.38	0.88	0.78	8.00	0.00
13	1.20	1.94	0.14	0.07	0.02	2.09	1.67	0.82	34.36	0.04
14	0.27	2.34	0.12	0.05	0.00	0.66	19.95	0.60	7.43	0.00
15	1.44	0.97	0.14	0.11	0.00	1.89	7.81	0.51	14.65	0.50
16	0.65	1.42	0.12	0.02	0.01	1.35	1.25	1.06	18.36	0.01
17	0.05	0.54	0.12	0.87	0.00	0.16	0.66	0.34	2.37	0.00
18	0.34	2.30	0.10	0.23	0.10	0.58	3.96	1.01	3.52	0.06

REPORTING INDICATOR VALUES

We explore three methods for tabulating and reporting indicator values for the purpose of evaluating current regional water resource stresses. Table 5 displays data using the first method, which simply reports all indicator values. This simplest reporting method is useful for a clear and comprehensive presentation of the numerical indicator value; for example, the consumption ratio for Regions 13 and 15 are greater than 1.0 due to ground-water overdraft.

We also examine the use of indicator scaling to aid in interpretation. In this method, each regional indicator is normalized from zero to one based on the indicator range for the current climate scenario over all regions. This reporting method may be useful in fitting the indicators onto a graph, yet was ultimately discarded because it seemed to obscure the meaning and hence interpretation of each indicator value.

The third method is termed the threshold exceedence method. In this method, the indicator value is compared with a threshold value that adds context to each indicator. For each indicator, a stress warning threshold exists that distinguishes a nonstressed region from a stressed region. The warning thresholds are identified through previous works or determined through judgment, as shown in Table 6.

The warning thresholds are used to determine stress levels for each indicator in two ways. An indicator can either exceed or not exceed the threshold and be reported as a zero or one; or, the indicator can be reported as a fraction of the threshold. We believe the second method provides more information and interpretive power to the reviewer. Table 7 illustrates the indicator values as a fraction of the threshold, where 1.0 represents each indicator threshold. For brevity, and because most of the exceedances are in Regions 10–18, the values are reported only for those regions. Although we assume the thresholds are constant across the U.S., they could be unique to each region. These two methods are useful in identifying the indicators that cause the most stress, yet their effectiveness is limited by their sensitivity to the warning thresholds.

Table 7 shows that the indicators in the more arid western regions of 13–16 and 18 are significantly greater than their thresholds for the consumption, storage vulnerability, relative poverty, withdrawal, coefficient of variation, and runoff ratio indicators.

TABLE 6. Warning Thresholds for Regional Indicators

Category (1)	Indicator (2)	Warning thresholds (3)	Source or definition (4)
Socioeconomic stress	Consumptive use	>0.2	Gleick 1990
	Storage vulnerability	>1	—
	Relative poverty	>0.12	Average value in present climate
	Hydropower	>0.25	Gleick 1990
	Import demand	>0.1	—
Environmental stress	Withdrawal ratio	>0.2	Raskin 1997
	Water quality	>7 mg/L	*Better* 1996
	Coefficient of variation	>0.4	—
	Runoff ratio	>0.2	Median value in present climate
	Dependence ratio	>0.1	—

GRAPHICAL AGGREGATION OF INDICATORS

The density of information in Table 7 provides a good example of the problem of effectively displaying results. In this section, our goal is to determine an effective approach by which to communicate the information contained in the regional indicators. There are many graphical methods for illustrating the indicators; each has advantages and disadvantages, depending on one's objective. For ease of presentation, we apply the display methods only to the socioeconomic indicators calculated as ''percent of threshold,'' the method we found most useful in the previous section. Again, for brevity and because most of the negative impacts are in Regions 10–18, in some cases the values are displayed only for those regions. Our findings on the display methods are applicable to other indicators, no matter how they are calculated.

Fig. 2 illustrates each socioeconomic indicator relative to its threshold. In this example 1.0 represents the threshold, and values in excess of the threshold (>1.0) indicate increased regional stress. Exceedances greater than 2.0 are shown as 2.0.

This method is especially useful for comparing indicators across regions; the highly stressed semiarid regions 13–16 stand out dramatically. It is more difficult to make a comparison across indicators because the 3D graph can be viewed only in two dimensions here. For example, one cannot tell if the relative poverty in Region 1 is equivalent to that in Regions 15 or 17.

Fig. 3 illustrates the use of another graphical method in which each region is represented by a star diagram illustrating

TABLE 7. Indicators Reported as Ratio of Warning Threshold for Current Climate

	Socio-economic Indicators					*Environmental Indicators*				
Region	Consm. Use	Storage Vulner	Relative Poverty	Hydro Ratio	Import Demand	Withdraw	Water Quality	Cv	Runoff Ratio	Dependence Ratio
10	**1.21**	0.67	**1.04**	0.29	0.11	**3.75**	**1.65**	**1.60**	**1.43**	0.08
11	0.60	0.45	**1.05**	0.24	0.11	**1.18**	0.20	**1.79**	0.78	0.03
12	0.83	0.44	**1.03**	0.02	0.00	**1.88**	0.13	**1.94**	**1.08**	0.00
13	**6.02**	**1.94**	**1.16**	0.27	0.20	**10.43**	0.24	**2.06**	**4.65**	0.41
14	**1.36**	**2.34**	**1.00**	0.20	0.00	**3.31**	**2.85**	**1.51**	**1.01**	0.00
15	**7.19**	0.97	**1.13**	0.44	0.00	**9.47**	**1.12**	**1.27**	**1.99**	**4.96**
16	**3.24**	**1.42**	0.96	0.07	0.10	**6.77**	0.18	**2.65**	**2.49**	0.14
17	0.27	0.54	0.98	**3.47**	0.01	0.81	0.09	0.85	0.32	0.00
18	**1.70**	**2.30**	0.83	0.91	0.96	**2.90**	0.57	**2.54**	0.48	0.56

Note: Threshold exceedances are shaded.

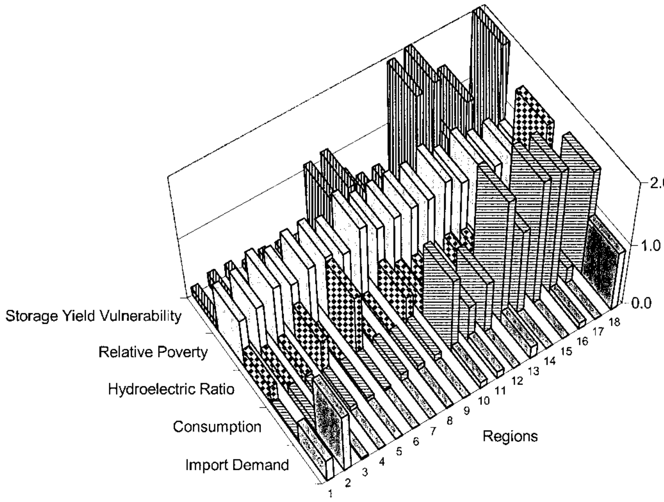

FIG. 2. Socioeconomic Indicators as Fraction of Warning Threshold under Current Climate

the set of five socioeconomic indicators. Here, the dark star outline represents the set of indicator thresholds and the gray shading represents the indicator data relative to that threshold. The method is based on the environmental diamonds introduced by Rogers et al. (1997). The stars in Fig. 3 are cut off at 200% of the threshold for display purposes (e.g., in Region 13 under Consumptive Use). The relative thickness of the gray shading at the truncation point on the star diagram allows comparison with other truncated points.

The multiattribute graphical method in Fig. 3 is particularly useful for denoting unique regions. For example, one can see immediately that regions 10–12 are much less stressed than regions 13–18 because indicators in regions 10–12 never exceed or are close to the threshold. This type of graph is also efficient for comparisons between indicators in a single region and to display the dominant stresses in a region. For example, clearly Region 12 is unstressed in all socioeconomic indicators except relative poverty and consumptive use. This method is more space intensive than the previous method.

Fig. 4 uses the stacked bar chart to indicate the sum of the components of the socioeconomic stress indicators. As in Fig. 3, the indicator value relative to its threshold is calculated, 1.0 representing the threshold. In this figure, relative percentages are stacked or added together, creating a regional cumulative percent. In other words, a cumulative percent of 5.0 represents a region where, or average, each of the five indicators is at its threshold. This method is useful for quick identification of cumulatively stressed regions, but confusing (because of the stacking of bars in the figure) when determining the value of an indicator relative to its threshold and comparing indicator values across regions.

Fig. 5 illustrates the indicators, using pie charts, on a regional map of the U.S. to identify both regions of high stress and the components of stress. Fig. 5 employs the same cumulative percent relative to a threshold as Fig. 4. The size of the pie chart is proportional to the sum of all the indicator values in a region, expressed in this example as a percent of their thresholds. The wedges of the pie represent the components of that cumulative percent. The relative sizes of the wedges for an indicator across all regions represent their relative values. For examples, Regions 13, 15, and 16 all exhibit high cumulative stresses and are dominated by the consumptive use indicator. Since the area of the poverty wedge of Region 3 is approximately equivalent to that of Region 12, they both have the same value.

Comparison of Graphical Methods

Depending on one's preference or needs, each graphical technique can be flexible and useful. The 3D bar chart is useful for discerning which region or regions have indicators with much greater or less stress than their threshold values. The 3D method is weak where the star method is strong: perceiving specific relationships to the threshold or particular intraregional comparisons. The star diagram method also facilitates comparison of the overall stresses across regions, as does the stacked bar graph. The mapping technique used with the pie charts also illustrates regional indicator variations (through the variation in pie sizes). The mapping technique has the added benefit of allowing one to consider spatial relationships among

FIG. 3. Socioeconomic Indicators under Current Climate, by Region

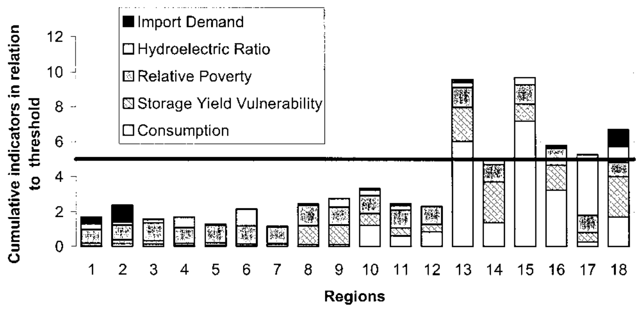

FIG. 4. Socioeconomic Indicators under Current Climate

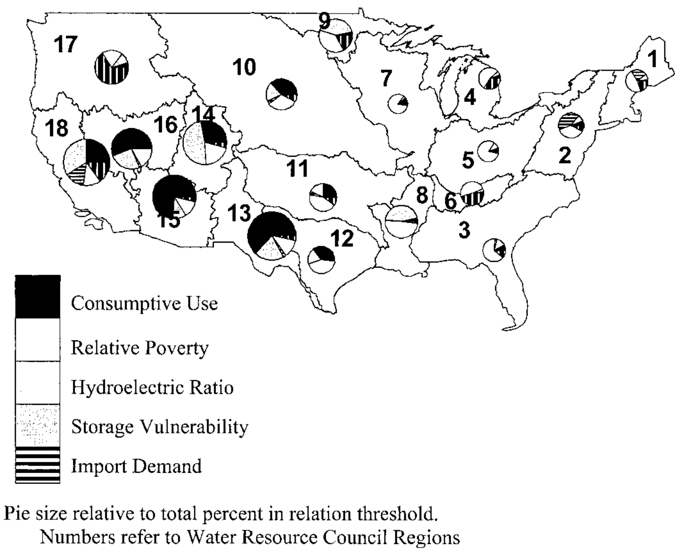

FIG. 5. Socioeconomic Indicators under Current Climate

indicators. With the mapping technique, however, it is impossible to determine the actual value of the indicator (no matter how it is measured), as the pies lack scales. Table 8 summarizes some of the methods' strengths and weaknesses using a plus sign (+) and negative sign (−) to indicate where a display technique is more or less effective, respectively. It is clear from the table that no single method is uniformly dominant.

USING INDICATORS TO COMPARE CLIMATE SCENARIOS

Until now, all results pertain to the analysis of one scenario. In analyzing the possible impacts of climate change, it is useful to compare indicators between climate scenarios. Below, we identify three methods of comparing indicators between climate scenarios.

The simplest method is to compare the indicator/index values side by side to enable comparison of similarities and differences. Tables 7 and 9 display the indicator values for the present climate and the GISS climate scenario presented in this paper. Unless one knows what to look for, it is difficult to draw conclusions by comparing Tables 7 and 9.

A more effective approach is to view the relationship between the indicators under the two climate scenarios. Fig. 6 illustrates the relationship between the consumptive use indicator in the current and GISS climate scenario. The numbers represent regions; those that fall along the diagonal are regions with no change. Markers above the diagonal represent regions in which the stress increases in the future climate; the distance between the marker and the line indicates the magnitude of change.

Another approach is to focus on the change from one scenario to another. Here, the percent change from the current climate is calculated for each indicator under the climate

TABLE 8. Evaluation of Multivariate Graphical Methods

Display methods (1)	Display of numerical value (2)	Cross-regional comparison (3)	Intraregional comparison (4)	Ease of computation (5)	Intraindex comparison (6)	Ease of interpretation (7)
Tables	+	−	−	+	+	−
3D bar chart	−	+	−	+	−	−
Star diagrams	−	+	+	−	+	+
Stacked bar charts	−	+	−	+	−	+
Pie charts on map	−	+	+	−	−	−

Note: + denotes strength of method. − denotes weakness of method.

TABLE 9. Indicators Reported as Ratio of Warning Threshold for GISS Climate Scenario

	Socio-economic Indicators					Environmental Indicators				
Region (1)	Consm. Use	Storage Vulnera	Relative Poverty	Hydro Ratio	Import Demand	Withdraw	Water Quality	Cv	Runoff Ratio	Dependence Ratio
10	**1.11**	0.90	0.30	0.11	0.09	**4.48**	**1.85**	**1.85**	**2.89**	0.08
11	0.44	0.52	0.30	0.14	0.09	**1.13**	0.18	**1.79**	**1.31**	0.02
12	0.84	0.46	0.30	0.01	0.00	**2.43**	0.16	**1.92**	**2.35**	0.00
13	**7.86**	**2.80**	0.33	0.00	0.17	**17.28**	0.39	**2.27**	**12.70**	0.57
14	**1.71**	**2.78**	0.29	0.01	0.00	**5.31**	**4.36**	**1.79**	**2.64**	0.00
15	**4.67**	0.98	0.32	0.01	0.00	**7.25**	**1.29**	**1.27**	**2.69**	**6.61**
16	**3.65**	**2.31**	0.28	0.00	0.08	**9.86**	0.25	**3.55**	**6.34**	0.17
17	0.27	0.59	0.28	**3.63**	0.01	**1.07**	0.12	0.92	0.71	0.00
18	**1.74**	**2.79**	0.24	0.40	0.81	**3.71**	0.72	**2.73**	**1.07**	0.60

Note: Threshold exceedances are shaded.

change scenario with the assumption that any change from the current situation merits identification and discussion. With this method, a positive percent change always signifies an increase in stress. Table 10 illustrates the percentage changes in the GISS climate scenario (Table 9) from the current climate (Table 7). It shows, for example, that the consumptive use is changing dramatically in some regions (e.g., 13–15) and little in other regions (e.g., 17 and 18). These percent changes can be displayed with all the graphical techniques previously discussed. As in the case of the graphical display methods, the choice of comparison methodology depends upon the analysis objectives.

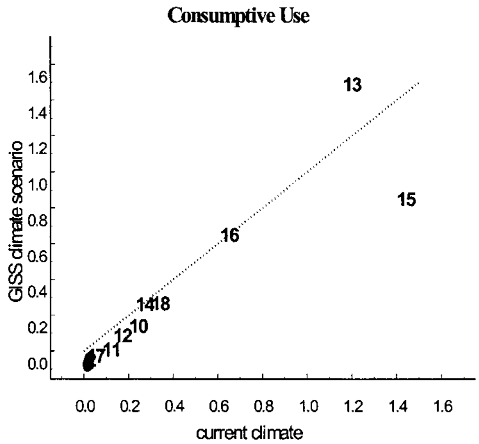

FIG. 6. Relationship between Consumptive Use under GISS Climate Scenario and Current Climate

A weighting system can be used to adjust for large percent changes in unstressed indicators. The warning thresholds in Table 6 are employed to determine a weighting scheme using this method. A percent change indicator is given a weight of 0.5 if it is below the warning threshold in both the current and the future climate scenarios. In all other situations, indicators are equally weighted. In other words, if an indicator is not stressed in the current climate (as determined by its warning threshold) and still not stressed under a climate change scenario, then it is assumed that this change has less impact than if stressed currently or in the future, and the percent change is weighted by 0.5. In another example, if an indicator exhibits stress under the current climate, it is assumed that *any* change in the indicator under future climate scenarios is more important than not being currently stressed, so this percentage change is weighted by 1.0. Similarly, if an indicator is not stressed in the current climate, any changes under a future climate scenario—which causes the indicator to become stressed—are weighted with 1.0.

TABLE 10. Percentage Changes from Current Climate to GISS Climate Scenario

	Socioeconomic Indicators					Environmental Indicators				
Region (1)	Consumptive use (2)	Storage vulnerability (3)	Relative poverty (4)	Hydropower ratio (5)	Import demand (6)	Withdrawal ratio (7)	Water quality (8)	Coefficient of variation (9)	Runoff (10)	Dependence ratio (11)
10	−8.84	35.68	−71.32	−61.96	−19.00	19.45	12.45	15.68	1.53	−3.24
11	−26.56	15.50	−71.32	−39.53	−18.05	−4.87	−9.43	0.00	−15.54	−22.05
12	2.04	4.40	−71.32	−76.42	0.00	28.96	25.87	−0.85	8.92	0.00
13	30.50	44.78	−71.32	−98.52	−16.40	65.69	63.74	10.24	36.83	38.53
14	25.61	18.58	−71.32	−93.34	0.00	60.55	52.86	18.98	31.75	0.00
15	−35.05	1.63	−71.32	−97.60	0.00	−23.45	15.99	0.07	−32.16	33.18
16	12.67	62.70	−71.32	−96.86	−17.83	45.53	39.40	33.93	27.76	19.59
17	1.77	8.86	−71.32	4.42	−18.49	32.53	25.58	8.08	10.63	8.03
18	2.09	21.16	−71.32	−56.27	−15.29	27.91	26.60	7.63	12.39	8.37

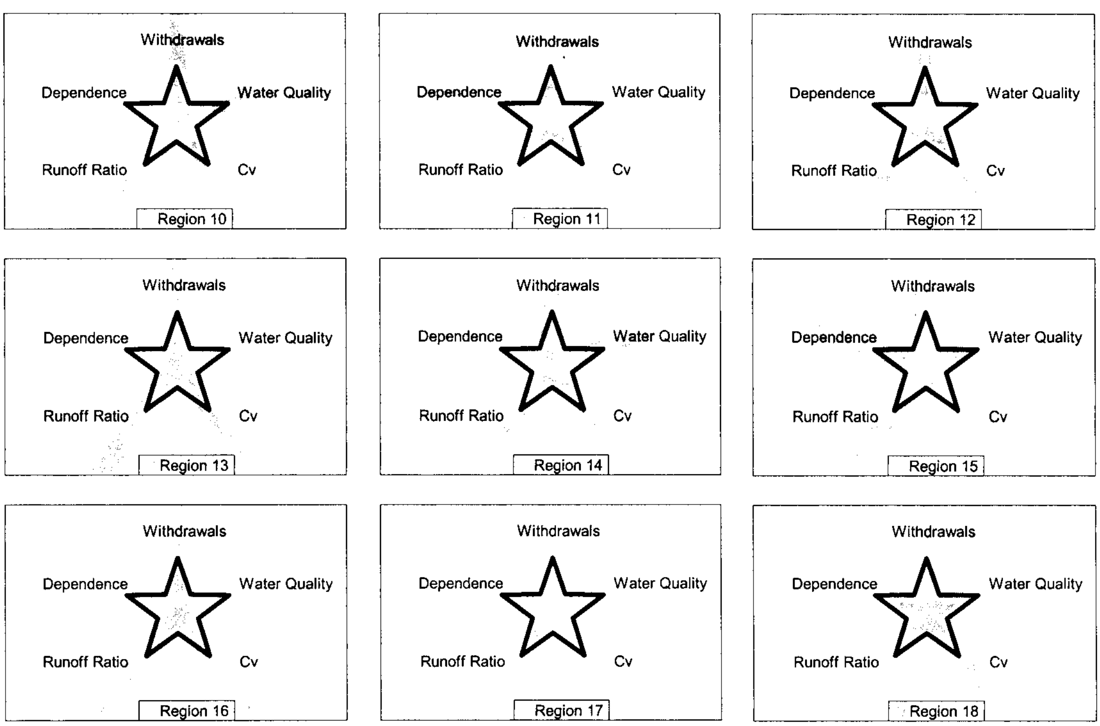

FIG. 7. Environmental Indicators under Current Climate, by Region

APPLICATION

The threshold method of calculating indicators is unique for its ability to add value and context to each indicator. The star method has most general appeal to display indicators. The percentage change method seems to be the most valuable for comparing scenarios. As an illustration of the application of these techniques, the potential impact of global warming upon U.S. water resources is studied using the GISS climate scenario.

Shown in Fig. 3 is the full set of threshold socioeconomic indicators applied to Regions 10–18 under the present climate. Fig. 7 shows the environmental indicators. The amount of area outside of the boundaries of the stars in Fig. 3 indicates that the western U.S. generally exhibits socioeconomic stress, particularly the far west. This is particularly true in terms of con-

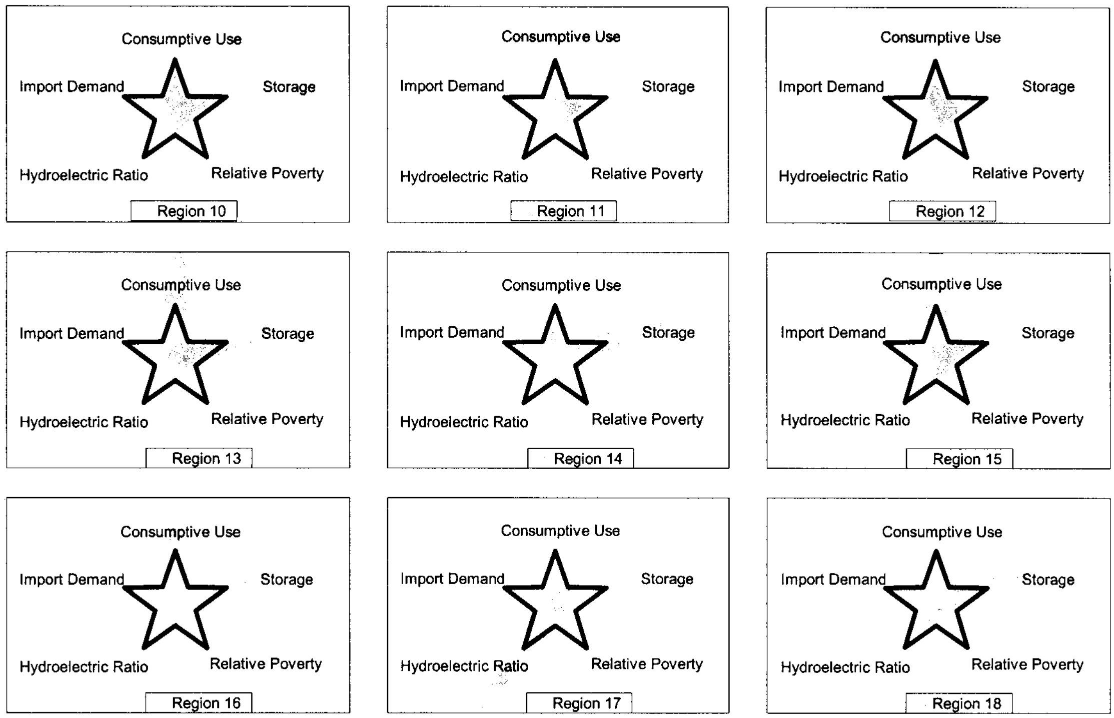

FIG. 8. Socioeconomic Indicators under GISS Climate Scenario, by Region

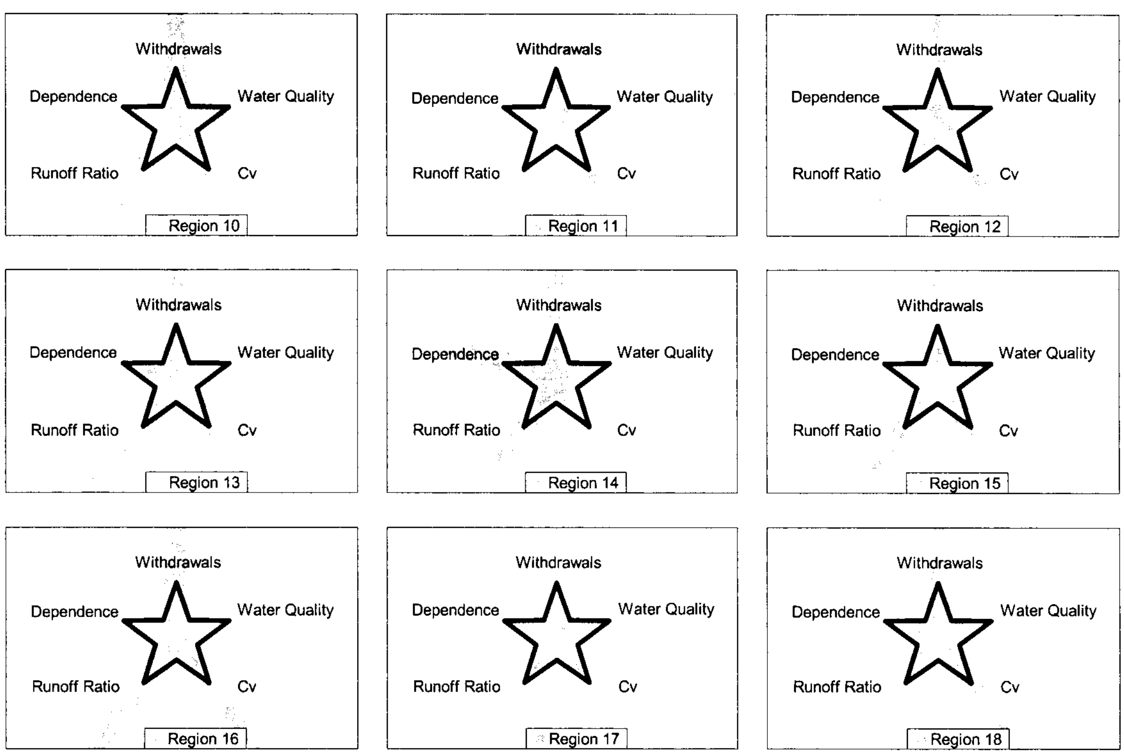

FIG. 9. Environmental Indicators under GISS Climate Scenario, by Region

sumptive use and storage vulnerability, or the average magnitude of a failure of a reservoir system to meet its demand. Fig. 7 also demonstrates that the western U.S. is environmentally stressed. Total (surface and ground water) withdrawals, compared with water availability, are particularly high in the west. Flow variability in the west is also particularly high, which contributes to high storage vulnerability. Fig. 8 illustrates the socioeconomic indicators applied to Regions 10–18 under the GISS climate scenario, compared with their thresholds. Fig. 9 displays the environmental indicators. Under this scenario, the west remains vulnerable to failures of its reservoir systems, has high consumption and withdrawals considering the available water, and has high flow variability.

A rapid method to compare the impacts of the present climate and the scenario is with the stars shown in Figs. 10 and 11. These show the weighted percent change in each threshold indicator for each displayed region. As described earlier, a weight of 0.5 is applied to the difference in indicator values if in both scenarios the indicator value is below its threshold. In other cases, the weight is 1.0. The outline of a star in Figs. 10 and 11 represents no change between the present climate and the scenario. A value within a star represents a weighted decrease in a threshold indicator; a value outside represents a weighted increase in a threshold indicator. A review of Fig. 10 makes it apparent that in the future GISS climate there is less stress on some hydroelectric systems throughout the West, compared with the present climate. This is not immediately obvious from comparing Figs. 3 and 8. The change results because generally the increase in total energy production dwarfs any changes in hydroelectric energy production. Also,

FIG. 10. Socioeconomic Indicators under GISS Climate Scenario, Compared with Current Climate

FIG. 11. Environmental Indicators under GISS Climate Scenario, Compared with Current Climate

note that because of the scale of the drawings here, it is difficult to discern the smaller changes. The seemingly dramatic decreases in relative poverty in all western regions result from the simplistic assumption of increased per capita income with no changes in the consumer price index. As shown in Fig. 11, the environmental stress on western water systems increases under the climate change scenario because of increases in the withdrawal ratios. The ratios increase under the scenario because of the increases in withdrawals and decreases in flow in some regions under the GISS scenario. Therefore, by using the percent change stars, it is readily apparent that the major overall impacts of global warming in the western U.S. for this scenario, compared to the present climate, are (1) less stresses on hydroelectric systems, and (2) more stresses on available water. While not shown, there are generally few changes in indicator values in the eastern U.S. between the present climate and this GISS scenario.

CONCLUSIONS

In this paper, a broad set of indicators is developed to measure socioeconomic and environmental impacts of climate change on U.S. water resources. A practical subset of these indicators is selected, using the criteria that an indicator must be measurable, accessible, nonredundant, and practical to be useful. Various indicator reporting methods are examined and compared. The threshold method distinguishes itself for its ability to add value and context to each indicator. We survey multivariate display techniques for communicating the indicator values for the five socioeconomic indicators throughout the 18 regions. Each method is shown to have its strengths and weaknesses, but the star method has the most general appeal. This result is consistent with the conclusions of Rogers et al. (1997). The indicators are also compared for the current climate and a future climate scenario using correlation scatterplots and the weighted percentage change method, which can be displayed and analyzed using any of the graphical display techniques. The percentage change method is shown to be most useful. We apply the recommended methods to examine the impacts of global warming on U.S. water resources using the GISS GCM 2100 scenario with economic development. It is apparent that the major overall impacts of global warming for this scenario, compared with the present climate, occur in the western U.S. and include (1) less stresses on hydroelectric systems because of the increase in electricity production from other sources, and (2) more stresses on available water due to increases in total withdrawals and, in some cases, decreases in flows.

We believe weighting and/or aggregating indicators to form indices adds more complexity than value. With the careful and clever presentation of indicators, the calculation of indices (or aggregation of indicators) is unnecessary.

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