Development of Representative Indicators of Hydrological Alteration

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EGU General Assembly
Vienna, Austria
13 – 18 April 2008

Introduction

It is common practice to summarize how well a reservoir is operating by reporting only one or two summary statistics such as its mean annual yield or reliability. More recently there is a realization that the environment is a legitimate user of the river and that "ecological flows" or instream flows should be maintained as a part of reservoir operations. But what indicators should we use to summarize instream flow properties analogous to the use of mean annual yield and reliability for human water uses?

In order to study the effect of different reservoir operation policies on a river and design optimal operation policy, we need indicators to evaluate the health of the river and evaluate the degree of the hydrological alteration caused by a particular operation policy. Currently over 170 indicators have been recommended to describe various aspects of the flow regimes. One example is the Indicators of Hydrological Alteration (IHA), which is a set of 33 commonly used indicators for characterizing the impact of regulation on the flow regimes (http://www.nature.org/). Many of these indicators are strongly correlated, creating a redundancy of information and difficulty in managing flows. Consequently, there is an increasing need to identify a smaller set of independent, representative indicators. This study aims to tackle this problem.

Objective

1) Develop a small set of representative IHA indicators that best characterize hydrological alteration caused by regulation of streamflow in a river
2) Find, if any, the relationship between the IHA indicators and other generalized indicators such as the ecodeficit/ecosurplus and evaluate their effectiveness as an overall index of hydrological alteration caused by regulation in a river

Data

The raw data used in this study are the percentage of changes in the median values of 32 IHA indicators between unregulated (pre-dam) and regulated (post-dam) flow regimes of two sets of data, a simulated set and a real set.

The "Number of zero-flow" days was excluded from the analysis, because when the river was unregulated, there were no zero-flow days for most of the rivers, thus the percentage of change could not be computed (the denominator was zero) for this parameter.

The **simulated data set** consists of streamflow data generated with 96 different operation policies of an imaginary reservoir in a computer program called WEAP (Water Evaluation And Planning System). The **real data set** consists of historical streamflow records at 189 USGS gages, each of which was located downstream of a dam (Figure 1).

The real data set is further separated:

- by storage ratio (s)
  1. All s (n = 189)
  2. s < 0.1 (n = 139)
  3. s < 0.01 (n = 102)
  4. s > 0.01 (n = 87)
- by hydrologic region
  5. East Region (n = 75)
  6. West Region (n = 59)

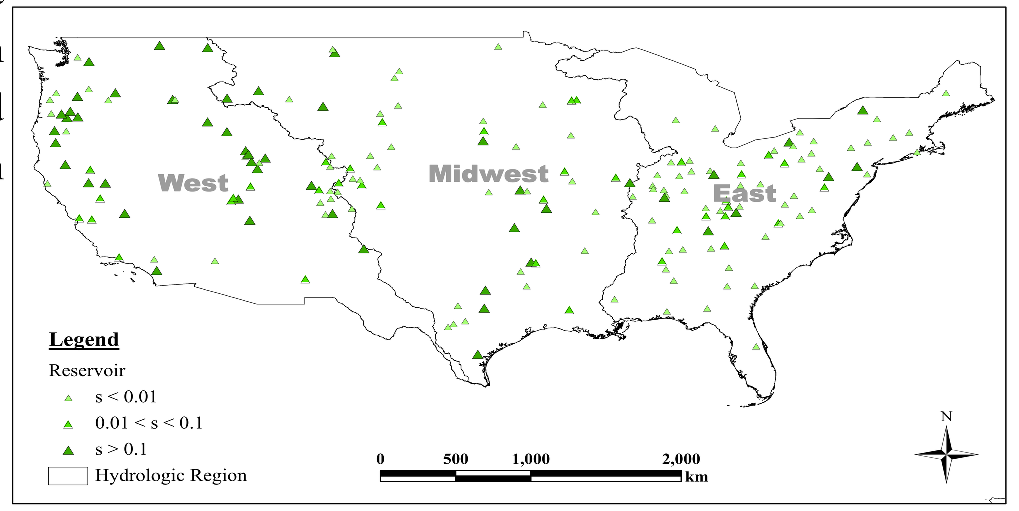

Figure 1. Location of the Dams Used in the Study

Methodology

- Principal Component Analysis (PCA)
  ⇒ Reduce the dimensionality of a data set that consists of a large number of interrelated variables (the 32 IHA indictors)
  ⇒ Each PC is a linear combination of the original variables. Most of the variation of the original data set can be explained by the first few PCs
  ⇒ The representative IHA indicators are selected from the original set based on the loading of the PCs retained

- Ecodeficit and Ecosurplus (Vogel, et. al. 2007)
  ⇒ Ecodeficit is the area below the unregulated flow duration curve (FDC) and above the regulated FDC (Figure 2). On the other hand, ecosurplus is the area above the unregulated FDC and below the regulated FDC. They are further divided into two types, annual and seasonal (winter, spring and summer)

- The Dundee Hydrological Regime Alteration Method (DHRAM) (Black et al, 2005)
  ⇒ Measure the total degree of hydrologic alteration caused by a certain reservoir operation in a scoring system

- Multivariate Regression Analyses
  ⇒ Regress each of the overall indices (annual and seasonal ecodeficit and ecosurplus; and DHRAM) versus the 32 IHA parameters to determine if any of the indices is correlated to the IHA parameters and if it can be an effective overall index to represent all IHA parameters
  ⇒ Value of Kendall's Tau were calculated between an index and each PC to determine if there is any correlation between them

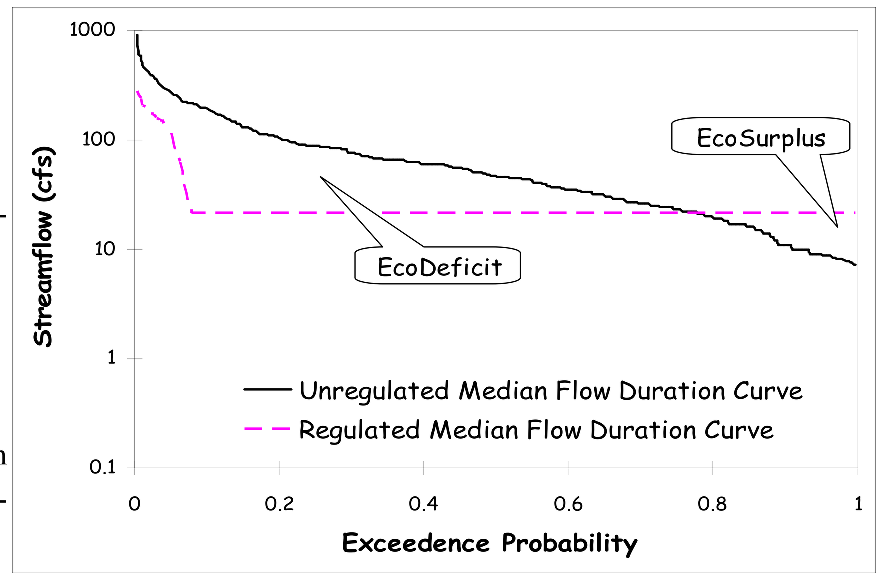

Figure 2. Definition of Ecodeficit and Ecosurplus

Conclusion

- Both ecodeficit/ecosurplus and DHRAM appear to nicely capture the overall degree of hydrological alteration. Ecodeficit/ecosurplus appears to be a better overall index than DHRAM (more so in the real data set)
- Kendall's Tau values show that there is a correlation between ecodeficit/ecosurplus and the first 3 PCs
- Annual ecodeficit is the best overall metric among the overall indices in the **simulated data set**. Winter ecosurplus and summer ecosurplus are the single best overall metrics among the indices in the **real data set**
- Separation of reservoirs into different hydrologic regions or storage ratios did not provide significant explanatory power

Future work

There are several inconclusive aspects to our findings. Additional work includes:

- Bootstrapping results to determine impact of sampling on general findings
- Research on methods of selecting representative subset of IHA indicators rather than PC loadings

Reference

- Black, A.R., Rowan, J.S., Duck, R.W., Bragg, O.M. and Clelland, B.E. (2005). DHRAM: A Method for Classifying River Flow Regime Alterations for the EC Water Framework Directive. Aquatic Conservation, 15, 427-446.
- Vogel, R.M., J. Sieber, S.A. Archfield, M.P. Smith, C.D. Apse, and A. Huber-Lee (2007). Relations among Storage, Yield and Instream Flow. Water Resources Research, 43, doi:10.1029/2006WR005226.

Results

1) Cumulative percentage explained by the PCs

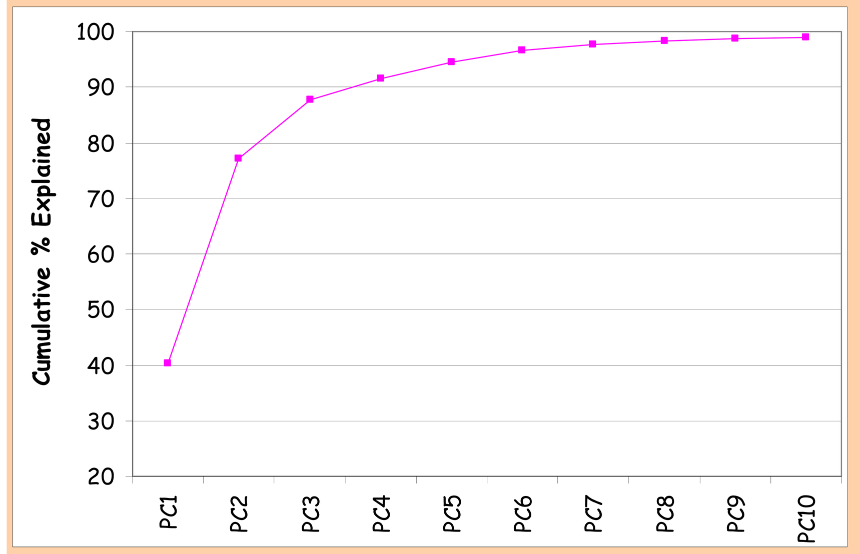

Figure 3a. % of Variation Explained by the First 10 PCs (Simulated Data Set)

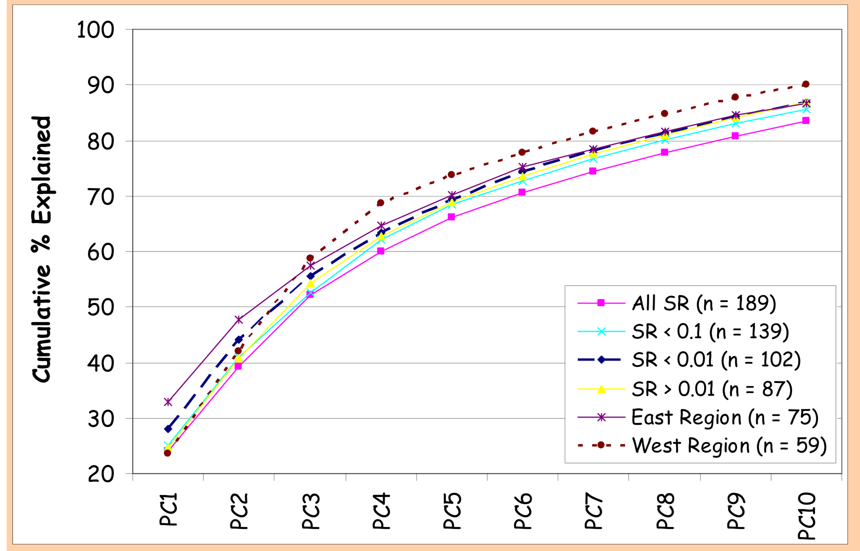

Figure 3b. % of Variation Explained by the First 10 PCs (Real Data Set)

2) IHA subset selection

⇒ IHA indicators (that have the highest loading of the first few PCs that retained 80% of the variation) were selected

⇒ The cells highlighted in the following table contain the highest loading of the PC

Loadings of the First Few PCs of the Two Data Sets

IHA Indictor	*Simulated Data Set*			*Real Data Set*					
	PC1	PC2	PC3	PC1	PC2	PC3	PC4	PC5	PC6
October	-0.337	0.858	-0.267	-0.499	-0.168	0.082	0.411	-0.029	-0.290
November	-0.832	0.295	-0.296	-0.247	-0.044	0.470	**0.625**	-0.190	-0.235
December	-0.907	0.089	-0.183	-0.217	-0.004	0.658	0.595	-0.091	0.049
January	-0.868	0.320	-0.272	-0.164	-0.030	0.754	0.476	-0.007	0.143
February	-0.879	0.290	-0.218	-0.184	0.079	**0.771**	0.331	-0.099	0.265
March	-0.914	-0.104	-0.122	-0.317	0.308	0.476	-0.213	-0.173	**0.434**
April	-0.924	-0.208	0.231	-0.269	0.479	0.122	-0.259	-0.401	0.239
May	**-0.967**	-0.093	0.137	-0.198	0.442	0.051	-0.196	-0.526	-0.050
June	-0.791	0.460	-0.352	-0.475	0.376	-0.032	-0.221	**-0.572**	-0.185
July	-0.361	0.847	-0.287	-0.732	0.056	-0.131	-0.181	-0.304	-0.249
August	-0.246	0.940	-0.127	-0.884	-0.075	-0.185	-0.090	0.085	-0.068
September	-0.281	0.918	-0.157	-0.715	-0.158	-0.168	0.146	0.244	-0.099
1-day minimum	-0.112	0.944	0.088	-0.785	-0.007	-0.269	0.099	0.326	0.327
3-day minimum	-0.119	0.946	0.081	-0.863	-0.019	-0.252	0.078	0.267	0.256
7-day minimum	-0.128	0.949	0.067	-0.940	-0.033	-0.206	0.014	0.124	0.101
30-day minimum	-0.151	**0.956**	0.019	**-0.949**	-0.043	-0.154	0.061	-0.006	-0.032
90-day minimum	-0.388	0.894	-0.151	-0.739	-0.017	0.096	-0.025	-0.133	-0.226
1-day maximum	-0.870	-0.210	0.394	0.135	0.851	0.000	0.091	0.327	-0.098
3-day maximum	-0.868	-0.193	0.412	0.125	0.896	-0.015	0.089	0.313	-0.111
7-day maximum	-0.877	-0.199	0.391	0.046	**0.919**	-0.020	0.091	0.295	-0.135
30-day maximum	-0.897	-0.182	0.357	-0.095	0.916	0.020	0.086	0.149	-0.101
90-day maximum	-0.918	-0.166	0.320	-0.102	0.869	0.050	0.028	-0.015	0.031
Base flow	0.274	0.863	-0.164	-0.932	-0.076	-0.229	0.024	0.136	0.128
Date of minimum	0.264	0.510	0.612	-0.011	0.011	0.282	-0.201	0.007	0.396
Date of maximum	0.634	0.479	-0.107	0.019	-0.112	-0.085	0.116	0.093	-0.390
Low pulse count	-0.270	-0.801	-0.251	0.101	-0.254	0.542	-0.364	0.360	-0.094
Low pulse duration	0.402	0.450	-0.195	0.202	0.029	-0.246	0.003	0.093	0.219
High pulse count	-0.853	-0.438	0.001	-0.110	-0.133	0.706	-0.387	0.341	-0.012
High pulse duration	-0.284	0.582	0.548	0.023	0.098	-0.248	0.076	-0.412	0.126
Rise rate	0.278	0.448	**0.728**	-0.274	0.068	0.435	-0.481	0.102	-0.066
Fall rate	0.272	0.454	0.721	-0.493	0.026	0.493	-0.527	0.090	-0.182
Number of reversals	-0.562	-0.699	-0.350	-0.170	-0.202	0.536	-0.226	0.045	-0.331

Subset Selection by PCA

Simulated Data Set:	*Real Data Set:*
April	November
May	February
3-day minimum	March
7-day minimum	June
30-day minimum	7-day minimum
90-day maximum	30-day minimum
Rise rate	7-day maximum
Fall rate	30-day maximum

3) Ecodeficit and ecosurplus are good overall indices

Adjusted Coefficient of Determination (R^2-adj) of the Multivariate Regression Analysis between an Index and the 32 IHA Parameters

Simulated Data Set	Annual Ecodeficit	Annual Ecosurplus	Winter Ecodeficit	Winter Ecosurplus	Spring Ecodeficit	Spring Ecosurplus	Summer Ecodeficit	Summer Ecosurplus	Annual Ecochange	Total Seasonal Ecochange	DHRAM Score
	0.998	0.989	0.990	0.898	0.995	0.783	0.998	0.993	**0.998**	0.997	0.988

Real Data Set	Annual Ecodeficit	Annual Ecosurplus	Winter Ecodeficit	Winter Ecosurplus	Spring Ecodeficit	Spring Ecosurplus	Summer Ecodeficit	Summer Ecosurplus	Annual Ecochange	Total Seasonal Ecochange	DHRAM Score
All s	0.603	0.663	0.453	**0.919**	0.699	0.559	0.296	**0.929**	0.251	0.807	0.540
s < 0.1	0.578	0.738	0.375	**0.940**	0.652	0.756	0.445	**0.857**	0.286	0.770	0.331
s < 0.01	0.654	0.825	0.522	**0.883**	0.552	0.821	0.385	**0.912**	0.548	0.797	0.521
s > 0.01	0.626	0.554	0.460	**0.938**	0.716	0.487	0.304	**0.928**	0.181	0.818	0.633
East Region	0.690	0.772	0.626	**0.865**	0.734	0.656	0.304	**0.882**	0.743	0.866	0.766
West Region	0.748	0.646	0.580	**0.980**	0.851	0.663	0.466	**0.978**	0.393	0.897	0.631

N.B. Annual Ecochange = Annual Ecodeficit + Annual Ecosurplus   Total Seasonal Ecochange = Sum of all Seasonal Ecodeficit and Ecosurplus

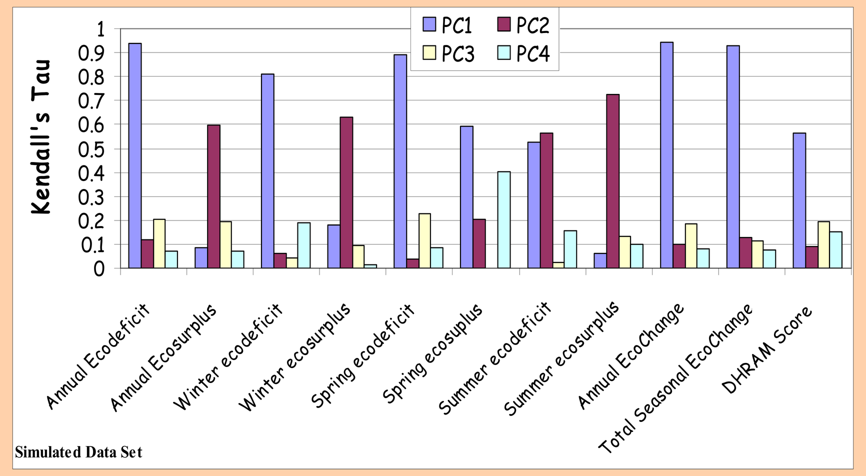

Figure 4a. Kendall's Tau between an index and the First 4 PCs of the Simulated Data Set

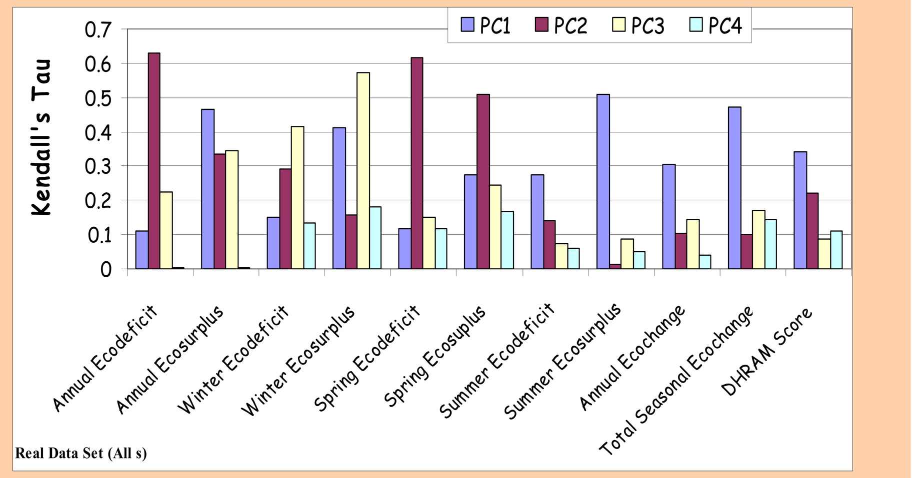

Figure 4b. Kendall's Tau between an index and the First 4 PCs of the Real Data Set

Acknowledgements • Colin Apse and Mark Smith (The Nature Conservancy) • Stacey Archfield (U.S. Geological Survey) • Antarpreet Jutla and Jim Limbrunner (Tufts University) • Jack Sieber and Brian Joyce (Stockholm Environment Institute)