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Hydroclimatic regimes: a distributed water-balance framework for hydrologic assessment and classification

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Abstract

Runoff-based indicators of terrestrial water availability are appropriate for humid regions, but have tended to limit our basic hydrologic understanding of drylands – the dry-sub-humid, semi-arid, and arid regions which presently cover nearly half of the global land surface. In response, we introduce an indicator framework that gives equal weight to humid and dryland regions, accounting fully for both vertical (precipitation + evapotranspiration) and horizontal (groundwater + surface-water) components of the hydrologic cycle in any given location – as well as fluxes into and out of landscape storage. We apply the framework to a diverse hydroclimatic region (the conterminous USA), using a distributed water-balance model consisting of 53 400 networked landscape hydrologic units. Our model simulations indicate that about 21 % of the conterminous USA either generated no runoff or consumed runoff from upgradient sources on a mean-annual basis during the 20th century. Vertical fluxes exceeded horizontal fluxes across 76 % of the conterminous area. Long-term average total water availability (TWA) during the 20th century, defined here as the total influx to a landscape hydrologic unit from precipitation, groundwater, and surface water, varied spatially by about 400 000-fold, a range of variation ~ 100 times larger than that for mean-annual runoff across the same area. The framework includes, but is not limited to classical, runoff-based approaches to water-resource assessment. It also incorporates and re-interprets the green-blue water perspective now gaining international acceptance. Implications of the new framework for hydrologic assessment and classification are explored.

1 Introduction

Scarcity of freshwater for human and ecosystem needs is one of the critical global challenges of the 21st century. Water scarcity, in any given location or hydrologic unit (Appendix A, Supplement, and Fig. 1a), may partly result from human interactions with the ground- and surface-water systems of the hydrologic unit (Vörösmarty and

Sahagian, 2000; Weiskel et al., 2007; Hoekstra et al., 2012; Vörösmarty et al., 2013). Direct human-hydrologic interactions include water withdrawals, transfers, and return flows (Weiskel et al., 2007), while indirect human interactions include deforestation, urbanization, agricultural land use (Karimi et al., 2012; Lo and Famiglietti, 2013; Gerten, 2013), anthropogenic climate change (Milly et al., 2005; Hagemann et al., 2013), dam construction, river and wetland channelization, wetland filling, and other human processes (Vörösmarty et al., 2013). Patterns of water scarcity and availability may also reflect baseline hydroclimatic diversity that is largely independent of human effects. In fact, one of the principal ways in which the hydrologic community has responded to the contemporary water-scarcity challenge is by constructing climatically forced, spatially distributed, regional-to-global-scale water-balance models that simulate fundamental hydrologic processes such as runoff generation and streamflow under specified baseline conditions (e.g., Vörösmarty et al., 2000; Döll et al., 2003; Milly et al., 2005; Oki and Kanae, 2006; Röst et al., 2008; Hoff et al., 2010; Hagemann et al., 2013). Subsequently, these models have been used to simulate hydrologic responses to land-cover, water-use, and climate change, at a range of spatial and temporal scales.

It is important to note that the term "baseline" can no longer be equated, without qualification, with pristine, pre-development, or long-term average conditions, largely because of two recent insights on the part of the hydrologic community. First, it is now broadly understood that the Industrial Revolution launched a new period of earth history – the Anthropocene epoch. During this epoch, human effects on the climate, the hydrosphere, and the land-surface portion of the Earth system have become pervasive, though not necessarily equally distributed in space (Vogel, 2011; Vörösmarty et al., 2013; Savenije et al., 2014). The second insight is the renewed appreciation of the non-stationary component of hydrologic processes (Milly et al., 2008; Matalas, 2012; Rosner et al., 2014). In light of these developments, we use the term "baseline" in this paper to denote an explicitly specified period of observational record, or of model simulation, that can serve as a basis for comparison with other periods characterized by different climate, land-cover, or water-use conditions.

In order to facilitate comparative analysis and communication in the growing fields of comparative hydrology and global hydrology (Falkenmark and Chapman, 1989; Thompson et al., 2013), we suggest that a coherent new framework of quantitative water-availability indicators is needed. The purpose of this paper is to derive such a framework, using the landscape water-balance equation as the organizing principle. The framework is spatially and temporally distributed, compatible with existing water-balance models such as those cited above, and unbiased – in the sense of being equally applicable to humid and dryland (Appendix A) regions. Moreover, the framework is informed by both classical (runoff-based) and emerging perspectives on water availability, including the green-blue water paradigm now gaining acceptance in the water management community (Falkenmark and Rockström, 2004, 2006, 2010; cf. Special Issue, J. Hydrol., 384, 3–4, 2010). The green-blue paradigm contains critical insights, which we re-interpret for this paper. After deriving the new framework, we demonstrate it across a diverse hydroclimatic region (the conterminous USA). Finally, we discuss the implications of the framework for hydrologic assessment and classification.

2 Theoretical background

2.1 The landscape water balance

The water balance of a hydrologic unit (Fig. 1a) may be stated as follows:

$$P(\Delta t) + L_{\mathrm{in}}(\Delta t) + H_{\mathrm{in}}(\Delta t) = E_{\mathrm{T}}(\Delta t) + L_{\mathrm{out}}(\Delta t) + H_{\mathrm{out}}(\Delta t) + \mathrm{d}S_{\mathrm{T}}/\mathrm{d}t(\Delta t) \quad (1)$$

where P = precipitation, $L_{\mathrm{in,\,out}}$ = saturated landscape (ground-water + surface-water) inflows to, and outflows from a hydrologic unit, $H_{\mathrm{in,\,out}}$ = human inflows to, and withdrawals from a hydrologic unit (Weiskel et al., 2007), E_{T} = evapotranspiration, and $\mathrm{d}S_{\mathrm{T}}/\mathrm{d}t = [(P + L_{\mathrm{in}}) - (E_{\mathrm{T}} + L_{\mathrm{out}})]$ = the rate of change (positive, negative, or zero) of total water storage in the soil moisture, groundwater, surface water, ice, snow, and human water infrastructure of the hydrologic unit – with all terms averaged over a time period (or step) of interest, Δt, in units of L^3T^{-1} per unit area of the hydrologic unit, or LT^{-1}. Human flows (H_{in} and H_{out}) and the artificial component of total storage are initially set equal to zero for development of the baseline framework of the present paper.

2.2 Green and blue water

Water availability may be viewed from either an open-system, hydrologic-unit spatial perspective (Fig. 1a) or from a semi-closed, catchment perspective (Fig. 1b, and Appendix A). Working within the catchment spatial context of Fig. 1b, Falkenmark and Rockström (2004, 2006, 2010) refer to the outflow terms E_{T} and L_{out} as "green" and "blue" water flows, respectively, and explore the consequences of this distinction for land and water management. Precipitation, in their framework, is viewed as an undifferentiated inflow term, and is therefore symbolized by white arrows on Fig. 1b.

Working within the open-system, hydrologic-unit context of Eq. (1) and Fig. 1a, we re-interpret the green-blue water perspective as follows. We define both types of land–atmosphere water exchange with a hydrologic unit (P and E_{T}) as green water fluxes, and both types of horizontal flow through a hydrologic unit (L_{in} and L_{out}) as blue water fluxes (Fig. 1a). Consistent with Falkenmark and Rockström (2004), we also make a clear distinction between green and blue water *fluxes* and green and blue water *storage compartments*. We follow these authors in defining the unsaturated (or vadose) zone above the water table as the green (or soil moisture) storage compartment of a hydrologic unit, and all saturated groundwater and surface-water zones, including accumulated ice and snow, as blue storage compartments.

2.3 Hydroclimatic regimes, total water availability, and regime indicators

We define the hydroclimatic regime of a hydrologic unit as the particular combination of green and blue water-balance components that characterizes the baseline functioning of a particular hydrologic unit (of any size) averaged over a specific time step of interest (of any length). For the purposes of our initial theoretical analysis, human flows and artificial storage are excluded from consideration, as noted above, and green and blue storage changes are lumped into a total storage change term. Consistent with Milly et al. (2008), we also define hydroclimatic regimes in temporally explicit terms (i.e., for particular time periods or steps).

To facilitate understanding of hydroclimatic regimes and the relative magnitudes of all water balance components, it is useful to normalize each term in Eq. (1) to the total inflow available to a hydrologic unit during a time step (cf., Lent et al., 1997; Weiskel et al., 2007). We refer to this total inflow as the "total water availability" (TWA). TWA is defined, for a given time step, as the larger of two quantities: (1) inflow from local precipitation and upgradient landscape sources ($P + L_{\text{in}}$); or (2) inflow from these sources plus "inflow" from depletion of internal storage. That is, $\text{TWA} = \max\{(P + L_{\text{in}}), (P + L_{\text{in}} + [-\text{d}S_{\text{T}}/\text{d}t])\}$ for a time step. As stated previously, the $\text{d}S_{\text{T}}/\text{d}t$ term of Eq. (1) may be either positive, negative, or zero during a time step. Therefore, during periods when $\text{d}S_{\text{T}}/\text{d}t$ is either 0 (steady-state periods) or positive (accretion periods), $\text{TWA} = P + L_{\text{in}}$. When $\text{d}S_{\text{T}}/\text{d}t$ is negative (depletion periods), $\text{TWA} = P + L_{\text{in}} + [-\text{d}S_{\text{T}}/\text{d}t]$. Normalization of Eq. (1) to TWA yields the following dimensionless form of the landscape water balance equation, expressed in lower-case symbols, for conditions of storage accretion or zero change (Eq. 2a) and depletion (Eq. 2b), respectively:

$$p + l_{\text{in}} = \text{et} + l_{\text{out}} + \text{d}s_{\text{T}}/\text{d}t = 1; \quad \text{when } (\text{d}s_{\text{T}}/\text{d}t \geq 0) \tag{2a}$$

$$p + l_{\text{in}} + [-\text{d}s_{\text{T}}/\text{d}t] = \text{et} + l_{\text{out}} = 1; \quad \text{when } (\text{d}s_{\text{T}}/\text{d}t < 0) \tag{2b}$$

Each term in Eq. (2a) and (2b) represents a fraction of the total water balance, and the fractions on each side of the equations sum to 1. During periods of storage accretion ($\text{d}s_{\text{T}}/\text{d}t > 0$; Eq. 2a), the total storage change term may be treated as an outflow to storage. During periods of storage depletion ($\text{d}s_{\text{T}}/\text{d}t < 0$; Eq. 2b), the storage change term may be treated as an inflow from storage.

Hydroclimatic regimes may be represented graphically on plots of et vs. p (Fig. 1c, central square). This square regime space comprises the full diversity of potential hydroclimatic regimes found at the Earth's land surface; the corners of the plot correspond to end-member regimes where p and et take on their limiting values. For example, at the headwater source end member (Fig. 1c), $p = 1$, et = 0, $l_{\text{in}} = 0$ and $l_{\text{out}} = 1$. At the pure-green, headwater no-flow end member, $p = 1$, et = 1, $l_{\text{in}} = 0$ and $l_{\text{out}} = 0$. At the terminal sink end member, $p = 0$, et = 1, $l_{\text{in}} = 1$ and $l_{\text{out}} = 0$. Finally, at the pure-blue, terminal flow-through end member, $p = 0$, et = 0, $l_{\text{in}} = 1$ and $l_{\text{out}} = 1$. Example regimes a through d (Fig. 1c and e) approach the respective end members; their water budgets and associated indicators are presented in Table 1.

We use combinations of p and et to define a new set of hydroclimatic indicators (Table 2): the green-blue index (GBI = $[p + \text{et}]/2$), the hydrologic-unit evapotranspiration ratio (et$/p$), and the source/sink index (SSI = $p - \text{et}$). The green-blue index (GBI) indicates the relative magnitudes of green ($P + E_{\text{T}}$) vs. blue ($L_{\text{in}} + L_{\text{out}}$) water fluxes experienced by a hydrologic unit during a period of interest (see Table 2). A hydrologic unit dominated by precipitation inflows and evapotranspiration outflows (headwater no-flow end member, Fig. 1c) has a GBI near 1, while a hydrologic unit dominated by landscape flows (terminal flow-through end member) has a GBI near 0. The remaining two indicators, SSI and et$/p$, differentiate runoff-generating source regimes ($P > E_{\text{T}}$) from runoff-consuming sink regimes ($E_{\text{T}} > P$), where sources of water for E_{T} include local precipitation, landscape inflows, and (on a transient basis) storage depletion. A hydrologic unit near the headwater-source end member (Fig. 1c) has an SSI near +1 and an et$/p$ near 0; a hydrologic unit near the terminal sink end member has an SSI near -1 and an et$/p \gg 1$, approaching the local value of the aridity index (AI) (the long-term average ratio of potential evapotranspiration [PE$_{\text{T}}$] to P).

Note that et$/p$ is mathematically equivalent to the classical catchment evapotranspiration ratio (actual E_{T}/P; Fig. 1d) under runoff-generating conditions ($P > E_{\text{T}}$) linking our open-system, hydrologic-unit framework to the semi-closed, catchment framework of classical hydroclimatology (Budyko, 1974; Sankarasubramanian and Vogel, 2003).

This linkage is expressed graphically in Fig. 1c and d. The top, horizontal axis of our two-dimensional regime space ($p = 1$; Fig. 1c) duplicates the one-dimensional axis of Fig. 1d. However, the second, vertical dimension of our space ($p < 1$) allows runoff-consuming regimes ($E_T > P$; $\mathrm{et}/p > 1$) to be characterized as well.

3 Methods

3.1 Continental water-balance model and data sources

A hydrologic model allowing for runoff consumption in river corridors was developed by coupling a simple water-balance model to a river network. The water-balance model was applied to the 53 400 networked hydrologic units defined by the individual segments of the River-File 1 (RF1) river network (Nolan et al., 2002). Flow generated in the hydrologic units is routed downstream through the river network. Using the terms introduced in this paper, the L_{in} volume for a hydrologic unit equals the sum of L_{out} volumes from the immediately upgradient hydrologic units. Depending on climatic conditions, runoff consumption in a stream corridor or terminal sink hydrologic unit (i.e., evapotranspiration of landscape inflows [L_{in}]) is allowed to occur to satisfy the evapotranspiration demand of a hydrologic unit. Note that L_{in} is a lumped term, comprising both groundwater and surface water inflows to a hydrologic unit; see Fig. 1a, and Supplement.

The water-balance model uses a monthly accounting procedure based on concepts originally presented by Thornthwaite (1948) and described in detail by McCabe and Markstrom (2007). Climate inputs to the model are mean monthly temperature and monthly total precipitation from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) modeling system, for the 1896 to 2006 period (diLuzio et al., 2008). The water-balance model tracks major components of the hydrologic unit water budget including precipitation, potential evapotranspiration ($\mathrm{PE_T}$), actual evapotranspiration (E_T), snow accumulation, snow melt, soil moisture storage, and runoff delivered to the stream network.

As landscape flow is routed through the river network, some portion of the flow can be "lost" in a downstream hydrologic unit through evapotranspiration. The quantity of lost landscape flow is assumed to be a function, in part, of excess PE_T in the hydrologic unit, which is defined as the PE_T that is in excess of actual E_T computed by the water-balance model. The model assumes that excess PE_T within a river corridor places a demand on water entering the hydrologic unit from upstream flow and that the river corridor is 30 % of the total hydrologic unit area. Furthermore, it is assumed that the amount of upstream flow that can be diverted to satisfy excess PE_T is limited to 50 % of the total upstream flow. The percentages used in the calculations were determined by subjective calibration of the model to measured streamflow in arid-region rivers that are known to lose water due to ground- and surface-water evapotranspiration in the downstream direction. Runoff consumption in a hydrologic unit occurs when locally generated landscape flow, computed from the water-balance model, is less than the computed landscape flow loss. For hydrologic units that are specified as terminal sinks in the RF-1 network, the total evapotranspiration from the hydrologic unit is set equal to total water available to the unit on a long-term mean basis ($P + L_{in}$). In certain arid and semi-arid hydrologic units of the conterminous USA where no RF-1 stream reaches have been defined, we assume that long-term mean precipitation (obtained from the PRISM dataset) equals total E_T from each unit, that $L_{in} = L_{out} = 0$, and that $p = \mathrm{et} = 1$. See Eqs. (1), (2), and associated text for definitions of terms.

The performance of the linked water-balance and river-network model was evaluated by comparing estimated landscape flows to measured streamflows for river corridors with a complete data record for water-year 2004 (October 2003 to September 2004). The correlation between estimated and measured mean-annual flow for all conterminous USA streamgages was 0.99. Correlation coefficient values for selected river corridors with runoff consuming hydrologic units were 0.75 (Colorado River), 0.98 (Missouri River), 0.99 (Yellowstone River), and 0.70 (Humboldt River). The lower correlation coefficients for some of the river corridors likely reflect the simplifying assumptions concerning runoff consumption used in this study (described above), the use of a lumped, landscape-flow approach (cf., Supplement), and the potential effects of human water use (Weiskel et al., 2007), which were not explicitly considered in this analysis.

3.2 Transient watershed model

A published watershed model of the Ipswich River Basin, Massachusetts, USA (Zarriello and Ries, 2000), developed using the Hydrological Simulation Program-FORTRAN (HSPF) code, was used to illustrate temporal variation in hydroclimatic regimes. The published model was calibrated to observed daily streamflows at two long-term US Geological Survey streamgages in the basin (gages 01101500 and 01102000). For the purpose of our analysis, hourly model output values for the 1961–1995 period were aggregated to produce 420 consecutive monthly values of all water-balance components (Eq. 1) for a selected model hydrologic unit in the upper basin (Reach 6, Lubbers Brook). Resulting normalized regime indicators were then calculated and plotted, at the monthly, median-monthly, and mean-annual time scales for the period of interest.

4 Results

4.1 Spatial regime variation, conterminous USA

In order to illustrate continental-scale spatial variation of long-term, mean-annual hydroclimatic regimes (both within and between individual river basins), we chose basins from humid, semi-arid, and humid-to-arid regions of the conterminous USA for analysis. Maps of et/p, and plots of et vs. p are used to demonstrate spatial variation in mean conditions for the 20th century (Fig. 2a, b, d, and e; cf. Fig. 1e for locations).

The plotted regimes (Fig. 2d) of the humid Connecticut River Basin, New England (Fig. 2a), showed a roughly linear pattern across the regime space, from headwaters

($p = 1$) to mouth ($p = 0.0014$). Runoff-generating regimes were indicated for the entire region; et/p ranged from 0.28 to 0.64, as a function of elevation and latitude. Green flows exceeded blue flows (GBI > 0.5) in 55 % of the 349 hydrologic units. Such moderate-source regimes (et/p near 0.5) are common in humid, temperate regions where locally generated runoff is an important component of the landscape water balance.

The 150 hydrologic units of the semi-arid Loup River Basin, a subbasin of the Platte Basin in central Nebraska (Fig. 2a and d), had a median et/p ratio almost twice as large as the Connecticut Basin ratio (0.94 vs. 0.51). The ratios also varied over a narrower range (0.85 to 1.05). Consistent with the semi-arid climate, 73 % of the hydrologic units in the Loup Basin were dominated by green regimes and 6.7 % were simulated as runoff-consuming on a long-term average basis ($E_T > P$, with L_{in} meeting a portion of the evapotranspiration demand). The Loup River Basin illustrates the low-runoff, P-and-E_T-dominated hydroclimatic regimes common to the semi-arid steppes, savannas, and arid high deserts that comprise most of the world's dryland ecosystems on all continents, from the sub-tropics to the mid-latitudes (Reynolds et al., 2007).

The regimes of the 310 000 km^2 Great Basin of the intermountain USA (Figs. 1e and 2b, e) contrast markedly with the relatively uniform regimes of New England and the central High Plains. The Great Basin's headwater catchments ($p = 1$, top axis, Fig. 2e) and other high elevation hydrologic units near the eastern and western boundaries of the Basin were runoff-generating, yet 29 % of the basin's 908 hydrologic units, and 34 % of its total area was runoff-consuming. The Great Basin is endorheic, or closed, under current climate; all landscape flow paths ultimately terminate in lowland sinks where E_T is the only outflow term in the water balance (et = 1, right-vertical axis, Fig. 2e). Temporally averaged et/p varied 17-fold across the Basin during the 20th century, from 0.28 in the High Sierras (western boundary) to 4.6 in Slough Creek in the central part of the Basin (site c of Fig. 1c and 2e; Table 1). The Great Basin is the major North American example of a closed, humid-mountain-to-arid-lowland domain with extreme spatial variation in hydroclimatic regimes. Comparable endorheic systems include the closed basins of Western China, the Aral and Caspian Seas in Central Asia, Lake Chad in Central Africa, Lake Titicaca in Peru/Bolivia, and Lake Eyre in Australia (Zang et al., 2012; Micklin, 2010; Lemoalle et al., 2012).

Runoff-consuming regimes are also found along arid river corridors in open (exorheic) basins, such as the downstream portions of the Colorado, Nile, Yellow, and Indus River basins. In such settings, blue-water evaporation rates are high and transpiration by riparian vegetation can be quantitatively important for the landscape water balance (Nagler et al., 2009; Karimi et al., 2012). Such runoff-consuming landscapes (long-term $\mathrm{et}/p > 1$), comprise a subset of the world's drylands with distinct hydroclimatic, ecological, and geochemical characteristics (Tyler et al., 2006; Nagler et al., 2009).

4.2 Temporal regime variation, Upper Ipswich Basin, New England, USA

Regime plots may also be used to display temporal regime variation, including storage dynamics, for individual hydrologic units over a range of time scales. Using a previously published watershed model, we analyzed regime variations in a selected hydrologic unit (Fig. 2c) in the Upper Ipswich River Basin, New England (Fig. 1e) (see Methods Sect. 3.2). Regimes are plotted for the 420 consecutive months of the simulation period (1961–1995), and are aggregated to the median-monthly and mean-annual time scales (Fig. 2f). Simulated monthly et/p varied by about 7000-fold and GBI by 30-fold over the period. Most of this variation can be attributed to the strongly seasonal E_T cycle of the northeastern USA, since monthly precipitation is relatively constant year-round in the region (Vogel et al., 1999).

On a median-monthly basis over the study period, this hydrologic unit generated runoff from September to May, and consumed runoff from June to August. Blue fluxes (L_in, L_out) dominated the water balance from October through June, while green fluxes (P, E_T) dominated from July through September. Accretion of total storage occurred from September to February, and depletion of storage from March to August. Large seasonal and inter-annual hydroclimatic variation is indicated (Fig. 2f), in a region where spatial variation in hydroclimate is modest on a mean-annual basis (Vogel et al., 1999). The size, shape, and orientation of the regime point cloud and median-monthly polygon (Fig. 2f) illustrate the seasonal dynamics of the various water-balance components (P, E_T, L_in, L_out, $\mathrm{d}S_\mathrm{T}/\mathrm{d}t$) and capture the hydrologic functioning of this hydrologic unit over the 35-year period of interest.

5 Discussion

5.1 Implications for water-resource assessment

Classical hydroclimatic indicators such as local runoff, the aridity index, and the catchment evapotranspiration ratio (Table 2) have been used for decades in water-resource assessments at all spatial scales (Budyko, 1974; Gebert et al., 1987; Vogel et al., 1999; Sankarasubramanian and Vogel, 2003; Milly et al., 2005). The regime indicators of this paper complement these classical indicators and address some of their limitations as indicators of water availability. Below, we demonstrate how our new indicators (total water availability, the green-blue index, and the hydrologic-unit evapotranspiration ratio) address the limitations of two classical indicators – local runoff and the aridity index.

5.1.1 Local runoff, total water availability, and the green-blue index

Maps of local runoff, constructed by contouring long-term, temporally-averaged runoff ($P - E_\mathrm{T}$) values assigned to the centroids of gaged catchments (e.g., Gebert et al., 1987) effectively capture one aspect of hydroclimatic variation in runoff-generating regions; local runoff varied ~3300-fold across the conterminous USA on a long-term, mean-annual basis during the 20th century (Figs. 3a and S1a). However, equating water availability for humans and ecosystems with local runoff can hinder basic understanding of water availability (cf. Falkenmark and Rockström, 2004). A runoff-focused approach minimizes the role of precipitation as a source of water to landscapes, especially in semi-arid regions with moderate precipitation (~ 250–$500\,\mathrm{mm\,yr^{-1}}$), comparably high evapotranspiration, and very low (or zero) runoff (e.g., Table 1, site b). In addition, maps of local runoff (Fig. 3a) neglect the networked character of water availability, that is, the role of hydrologic position (see Appendix A) as well as local climate in governing the total amount of water available as inflow to a landscape hydrologic unit. These limitations are addressed by our newly introduced total water availability indicator (TWA; Eq. 2, Figs. 3b and S1a), and dimensionless green-blue index (GBI; Figs. 3d and S1c). The TWA indicator incorporates both vertical (green), and horizontal (blue) components of inflow to a hydrologic unit, in units of volumetric inflow to the hydrologic unit per unit area of the receiving hydrologic unit ($\mathrm{L^3\,L^{-2}\,T^{-1}}$, or $\mathrm{L\,T^{-1}}$). Because both precipitation and landscape inflows are incorporated into TWA, it is an exceptionally sensitive indicator, and can vary spatially over a large range. In the conterminous USA, for example, TWA varied spatially by nearly five orders of magnitude ($\sim 450\,000$-fold) on a mean-annual basis during the 20th century (Fig. 3b, S1a). At the low end of the TWA spectrum are found arid upland hydrologic units with low precipitation and no significant blue-water inflow ($\mathrm{TWA} < 10^2\,\mathrm{mm\,yr^{-1}}$); at the high end, hydrologic units at the mouths of large rivers ($\mathrm{TWA} > 10^6\,\mathrm{mm\,yr^{-1}}$, essentially all from blue-water inflow).

We introduce the green-blue index (GBI, Fig. 3d) as a dimensionless counterpart to TWA. It quantifies the relative magnitudes of total green ($P+E_\mathrm{T}$) vs. total blue ($L_\mathrm{in}+L_\mathrm{out}$) fluxes experienced by a hydrologic unit. GBI was also found to be highly sensitive, varying spatially across the conterminous area by $\sim 24\,000$-fold (Fig. S1c). Note that GBI is best viewed in tandem with precipitation (Figs. 3c and S1b). This allows upland semi-arid ($P \sim 250$–$500\,\mathrm{mm\,yr^{-1}}$) and desert ($P < 250\,\mathrm{mm\,yr^{-1}}$) landscapes with equally high GBI values to be distinguished from each other.

5.1.2 Aridity index and the hydrologic-unit E_T ratio (et/p)

The aridity index (AI), the long-term average ratio of potential evapotranspiration to precipitation at a location ($\mathrm{PE_T}/P$) is commonly used to show spatial variation in potential energy available for evapotranspiration (Sankarasubramanian and Vogel, 2003), estimate actual evapotranspiration (Budyko, 1974), and map the global distribution of drylands (UNEP, 1997). The main limitation of the aridity index (Figs. 3e and S1d) is that it fails to distinguish two basic dryland types: (a) uplands where E_T demand is met strictly by soil moisture derived from local precipitation; and (b) runoff-consuming lowlands where E_T demand is met by a combination of local precipitation, as well as groundwater and surface water derived from upgradient hydrologic units. The hydrologic-unit evapotranspiration ratio (et/p; Figs. 3f and S1e) complements AI by quantifying actual rather than potential E_T rates across the full range of $\mathrm{PE_T}$ values found in a region. Maps of et/p allow a more realistic representation of runoff-consuming, arid lowlands (both endorheic sinks and runoff-consuming river corridors) than maps of the aridity index alone.

For example, our et/p map (Fig. 3f) indicates an east-west pattern of weak-sink river corridors in the High Plains of the central USA. When compared to an aridity map of the region (Fig. 3e), the et/p map suggests that spatial variation in High Plains actual evapotranspiration in the 20th century was likely governed as much by the local geography of its river corridors – and the availability of blue water from Rocky Mountain source areas to the west – as it was by longitudinal variations in $\mathrm{PE_T}$ and precipitation alone. It is important to note that the areal extent and magnitude of runoff consumption in a river corridor (under either pre-development or developed conditions) depends on the spatial scale of averaging. The relatively coarse scale used our continental analysis ($\sim 138\,\mathrm{km}^2$ hydrologic units) may overestimate the spatial extent, and underestimate the local magnitude, of actual runoff consumption by evaporation and by transpiration through riparian vegetation in individual High Plains river corridors. Improved quantification of E_T using remote sensing techniques and other methods could help to address this limitation (Nagler et al., 2009; Karimi et al., 2012; Sanford and Selnick, 2013).

5.2 Implications for hydrologic classification

The development of a coherent hydrologic classification system is widely recognized as a critical need within hydrology (McDonnell and Woods, 2004; McDonnell et al., 2007; Sawicz et al., 2011; Toth, 2013; cf. Special Issue on Catchment Classification; Hydrol. Earth Syst. Sci., 15, 2011). However, there is presently no quantitative, generally accepted classification system that both encompasses the world's hydrologic diversity and allows quantitative specification of hydrologic thresholds and similarities, in a manner comparable to the dimensionless Reynolds and Froude numbers used to classify hydraulic systems (Wagener et al., 2007, 2008). Most researchers have focused their classification efforts on catchments (watersheds, basins) and their hydrologic function (cf. summary by Sawicz et al., 2011). Others have focused on the conceptualization and classification of hydrologic landscapes (Winter, 2001; Wolock et al., 2004), lakes (Martin et al., 2011), or wetlands (Brinson, 1993; Lent et al., 1997).

In this section, we propose a hydrologic classification that uses the water balance of a hydrologic unit, i.e., Eq. (1), as its organizing principle. This approach encompasses both catchments ($L_{\mathrm{in}} = 0$; $p = 1$) and all types of non-catchment systems ($L_{\mathrm{in}} > 0$; $p < 1$), such as wetlands, lakes, stream corridors, upland landscape units, and aggregations of hydrologic units (i.e., hydrologic landscapes).

5.2.1 A new classification of hydroclimatic regimes

We begin the classification by specifying the local climate (et/p) of a hydrologic unit during a period of interest. The et/p indicator is used to define four regime classes (Fig. 4a): *strong source* ($\mathrm{et}/p < 0.5$), where locally generated runoff ($P - E_{\mathrm{T}}$) exceeds local E_{T}; *weak source* ($0.5 < \mathrm{et}/p < 1$), where local E_{T} exceeds local runoff ($P - E_{\mathrm{T}}$); *weak sink* ($1 < \mathrm{et}/p < 2$) where P exceeds the local consumption of landscape inflows ($E_{\mathrm{T}} - P$); and *strong sink* ($\mathrm{et}/p > 2$) where ($E_{\mathrm{T}} - P$) exceeds P. The relative magnitude of green vs. blue fluxes associated with a hydrologic unit, indicated by GBI, is then used to divide each of these four classes into two subclasses: *green*, where land–atmosphere fluxes (P and E_T) dominate, and *blue*, where landscape fluxes (L_{in} and L_{out}) dominate the water balance (Fig. 4a).

The boundaries of these classes (source/sink, weak/strong, green/blue) are not arbitrary; each boundary marks a threshold in the value of a continuous, dimensionless, ratio variable (et/p or GBI). We suggest that these ratio variables represent hydrologic analogues to the Reynolds and Froude numbers of fluid mechanics, as called for by Wagener et al. (2007). For example, just as the Reynolds number (ratio of inertial forces to viscous forces in a fluid) can be used to indicate a critical threshold in a flow regime (transition from laminar to turbulent flow), the dimensionless hydrologic unit E_T ratio, et/p, can be used to indicate a critical threshold in a landscape hydroclimatic regime – the transition from runoff-generating (source) to runoff-consuming (sink) conditions. This transition is an important hydrologic feature of the humid-mountain-to-arid-basin landscapes found on all of the world's continents.

5.2.2 Hydroclimatic regime classification: the conterminous USA example

Our model simulations indicate that weak source and weak sink hydroclimatic regimes dominated the conterminous USA during the 20th century. We estimate that weak source and sink regimes covered about 73 and 14 % of the conterminous land area, respectively (Fig. 4b), at the scale of discretization considered (53 400 hydrologic units; mean area = 138 km^2). Strong source and strong sink regimes covered 6.6 and 0.6 % of the conterminous area, respectively, and 6.2 % of the area was considered to generate no runoff (i.e., $0.99 < et/p < 1.01$) on a long-term, mean-annual basis during this period. Green and blue regimes predominated across 76 and 24 % of the conterminous area, respectively (Fig. 4b). The results for arid regions of the conterminous USA should be considered approximate, because of the simplified model assumptions used in our simulation of runoff consumption (see Sect. 3).

6 Summary and conclusions

Classical, runoff-based indicators of terrestrial water availability have proved useful for characterizing water availability in the world's humid regions. However, they have often hindered our basic hydrologic understanding of dryland environments – the dry-sub-humid, semi-arid, and arid regions which presently cover nearly half of the global land surface. To address this problem, we introduce a distributed, networked, open-system approach to the landscape water balance. Indicators derived from the resulting framework can be used to characterize humid source areas that generate groundwater and surface-water runoff; high deserts, steppes, and savannas that neither receive nor generate significant runoff; arid lowlands that consume runoff derived from upgradient groundwater and surface water source areas; river corridors under all climates; and landscapes with mixed hydroclimatic regimes.

The new framework seeks to deepen understanding of the full range, or diversity, of terrestrial hydrologic behavior. The framework provides a general, quantitative basis for the traditional practice of water-resources assessment (Gebert et al., 1987), and the emerging disciplines of comparative hydrology (Falkenmark and Chapman, 1989; Thompson et al., 2013), and hydrologic classification (Wagener et al., 2007). The indicators presented are two-dimensional (Fig. 1c) rather than one-dimensional (Fig. 1d), incorporating both the local climate of a hydrologic unit (humid to arid) and its hydrologic position in the landscape (headwater to terminal), at any spatial or temporal scale of interest. Finally, the framework re-interprets the green-blue water perspective that is now gaining acceptance internationally, and integrates this perspective with classical understandings of terrestrial water availability.

Appendix A

Glossary of terms

Basin: see *catchment*.

Blue water: blue water flows consist of groundwater and surface water flows into and out of a hydrologic unit during a period of interest (see *landscape inflows* and *outflows* defined below, and Fig. 1a). Blue water storage consists of the saturated portion of *total landscape water storage* (see below) in a hydrologic unit. Blue water storage comprises surface water, groundwater, ice, snow, and water stored in human water infrastructure.

Catchment: the drainage area that contributes water to a particular point along a stream network (Wagener at al., 2007). From the perspective of the present paper, a catchment is a particular type of *hydrologic unit*, with boundaries defined such that *landscape inflows* (L_{in}) = 0 and precipitation is the only type of inflow (Fig. 1b). Although *watershed* is the preferred term for this type of hydrologic unit in the USA, the equivalent term *catchment* is generally preferred in Europe and many other parts of the world. *Basin* is generally the preferred equivalent for large catchments (e.g., the Nile River basin).

Drylands: drylands are defined by the United Nations Environment Programme (1997) as regions where the long-term ratio of potential evapotranspiration to precipitation (aridity index), is greater than 1.5; 41 % of the Earth's land surface, and 32 % of the conterminous USA meet this definition. Drylands are further classified as dry-subhumid (AI = 1.5 to 2); semi-arid (2 to 5); arid (5–20), and hyper-arid (> 20) (UNEP, 1997).

Green water: for the purposes of this paper, green water flows are defined as the vertical, or land–atmosphere flows into and out of a hydrologic unit during a period of interest (Fig. 1a). These flows are (1) precipitation (P), and (2) the sum of evaporation and transpiration (evapotranspiration, E_T). This definition differs from that of Falkenmark and Rockström (2004), who equated green water flow with E_T outflow only, and considered P to be an undifferentiated inflow. Both Falkenmark and Rockström (2004) and the present paper define green water storage as soil moisture stored in the unsaturated (or vadose) zone of a landscape.

Human flows (H_in and H_out): human withdrawals from a hydrologic unit for local use or export are defined as human outflows (H_out). Human return flows to a hydrologic unit after local withdrawal and use, or after import and use, are defined as human inflows (H_in). See Weiskel et al. (2007).

Hydroclimatic regime: the hydroclimatic regime is the particular combination of green and blue water-balance components (P, L_in, E_T, L_out, $\mathrm{d}S_\mathrm{T}/\mathrm{d}t$) that characterizes the baseline, pre-development hydrologic functioning of a hydrologic unit averaged over a specific time period (or step) of interest (For the purposes of the baseline analysis in this paper, *human flows* (H_in and H_out), and the artificial component of *total landscape storage* are set equal to zero.) The water-balance components which comprise the regime may be expressed either in units of L^3 per unit area of the hydrologic unit per unit time, LT^{-1} (Eq. 1), or in the lower-case, dimensionless terms of Eq. (2): p, l_in, et, l_out, $\mathrm{d}s_\mathrm{T}/\mathrm{d}t$. These terms indicate the relative magnitudes of the water-balance components, as fractions of the *total water availability*.

Hydrologic position: the upgradient/downgradient position of a hydrologic unit in a networked system of hydrologic units. Under runoff-generating conditions ($P > E_\mathrm{T}$), hydrologic position is indicated by the longterm-average value of normalized precipitation, p, and ranges from 1 (headwater location) to 0 at the terminal flow-through location (see end-member diagram, Fig. 1c). Under runoff-consuming conditions ($E_\mathrm{T} > P$), hydrologic position is indicated by the longterm-average value of the normalized landscape outflow term term, l_out (= 1 – et), and ranges from near 1 (flow-through location, typically found at the mountain front in a humid-to-arid, basin-and-range landscape), to 0 at a downgradient terminal sink location (Fig. 1c).

Hydrologic unit: (1) narrow definition: an area of land surface that contributes water to a defined stream reach or segment of coastline (cf. Seaber et al., 1987). (2) Broad definition: a bounded unit of the Earth's land surface, of any size or shape, which is free to receive inflow from either the atmosphere as precipitation (P) or from upgradient hydrologic units as landscape (groundwater + surface-water) inflow (L_in). See Fig. 1a and Supplement.

Landscape inflow (L_in): the sum of groundwater and surface-water inflow to a hydrologic unit, from one or more upgradient hydrologic units during a period of interest, in units of L^3 per unit area of the hydrologic unit per unit time, or $\mathrm{L\,T}^{-1}$. See Fig. 1a, Table 2, and Supplement.

Landscape outflow (L_out): the sum of groundwater and surface-water outflow from a hydrologic unit to one or more downgradient hydrologic units during a period of interest, in units of L^3 per unit area of the hydrologic unit per unit time, or $\mathrm{L\,T}^{-1}$. See Fig. 1a, Table 2, and Supplement.

Total landscape water storage (S_T): the volume of all water stored in a hydrologic unit – soil moisture, groundwater, surface water, ice, snow, and artificial storage in human water infrastructure – all averaged over a time period (or step) of interest, of any length, in units of L^3 per unit area, or L. (For the purposes of the baseline analysis presented here, the artificial component of S_T is set equal to zero.) Change in total landscape storage ($\mathrm{d}S_\mathrm{T}/\mathrm{d}t$), averaged over a time step of interest (in units of $L^3L^{-2}T^{-1}$, or LT^{-1}), may be either positive (storage accretion), negative (storage depletion), or zero (steady state). See Fig. 1a, Table 2, and Eqs. (1) and (2).

Total water availability (TWA): the total inflow to a hydrologic unit from up to three sources during a time step of interest. The first two sources are precipitation (P) and landscape inflow (L_{in}). During periods of depletion of total landscape storage ($\text{d}S_\text{T}/\text{d}t < 0$), when total outflow from a hydrologic unit ($E_\text{T} + L_{\text{out}}$) exceeds total inflow ($P + L_{\text{in}}$), we define "inflow" from total landscape water storage ($-\text{d}S_\text{T}/\text{d}t$; a positive quantity) to be a third, transient component of TWA. In mathematical terms, $\text{TWA} = \max\{(P + L_{\text{in}}), (P + L_{\text{in}} + [-\text{d}S_\text{T}/\text{d}t])\}$ for any time step.

Water availability: water that is present and able to be used by humans or other terrestrial and non-marine-aquatic populations.

Water scarcity: s condition in which the amount of water available for meeting human and ecosystem needs is insufficient.

Watershed: see *catchment*.

Supplementary material related to this article is available online at http://www.hydrol-earth-syst-sci-discuss.net/11/2933/2014/hessd-11-2933-2014-supplement.pdf.

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A distributed water-balance framework

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Table 1. Water balance components and hydroclimatic regime indicators, sites a, b, c, and d (Fig. 1e). Each regime approaches one of four end-members shown on Fig. 1c. See Table 2 for indicator definitions. Mean-annual (1896–2006) water-balance components obtained from distributed water-balance model of the conterminous USA (see Sect. 3). HUC-8, 8-digit hydrologic-unit code (see Supplement); HU ID, hydrologic-unit identifier, water-balance model; DA, drainage area. P, precipitation; E_{T}, evapotranspiration; L_{in}, landscape (surface water + groundwater) inflow; L_{out}, landscape outflow; $\mathrm{d}S_{\mathrm{T}}/\mathrm{d}t$, change in total landscape storage; all fluxes are per unit area of the local HU, in units of mm yr^{-1}; rounded to 3 significant figures. The terms et and p (normalized evapotranspiration and precipitation), et/p (hydrologic-unit E_{T} ratio), SSI (source-sink index), GBI (green-blue index) are dimensionless; see Table 2.

Hydrologic unit name, location, and HUC-8	HU ID	HU DA km^2	Up-gradient DA km^2	P mm yr^{-1}	L_{in} mm yr^{-1}	E_{T} mm yr^{-1}	L_{out} mm yr^{-1}	$\mathrm{d}S_{\mathrm{T}}/\mathrm{d}t$ mm yr^{-1}	et	p	et/p	SSI	GBI
(a) Upper Chehalis River Washington (17100104)	57 994	44	0	6050	0	498	5540	0	0.08	1.00	0.08	0.92	0.54
(b) Middle Loup River Nebraska (10210001)	24 038	1476	2853	532	19	519	32	0	0.94	0.97	0.95	0.02	0.98
(c) Slough Creek Nevada (16060005)	46 385	20	2327	218	793	1010	0	0	1.00	0.22	4.63	−0.78	0.61
(d) Upper Connecticut R. New Hampshire (01080101)	1077	212	3996	957	11 500	539	11 900	0	0.04	0.08	0.56	0.03	0.06

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Table 2. Indicators of terrestrial water availability. P, precipitation; E_T, evapotranspiration; $\mathrm{PE_T}$, potential evapotranspiration. Landscape inflows and outflows (L_in, L_out) include both surface and groundwater flows (Fig. 1a). All length per time units ($\mathrm{LT^{-1}}$) are equivalent to $\mathrm{L^{-3}L^{-2}T^{-1}}$, where $\mathrm{L^2}$ refers to the area of the local hydrologic unit (HU) that is receiving or donating water. LR is the mean local runoff during a specified, long-term period; other indicators may be defined for a specified period, or time step, of any length.

Indicator	Simple Definition	Expanded Definition	Measurement Units	Permissible Range	Reference
Local runoff, LR	$P - E_\mathrm{T}$	same	$\mathrm{LT^{-1}}$	≥ 0	Bras, 1989
Landscape inflow, L_in	L_in	same	$\mathrm{LT^{-1}}$	≥ 0	This paper
Landscape outflow, L_out	L_out	same	$\mathrm{LT^{-1}}$	≥ 0	This paper
Total storage change, $\mathrm{d}S_\mathrm{T}/\mathrm{d}t$	$\mathrm{d}S_\mathrm{T}/\mathrm{d}t$	$(P + L_\mathrm{in}) - (E_\mathrm{T} + L_\mathrm{out})$	$\mathrm{LT^{-1}}$	positive, negative, or zero	Bras, 1989
Aridity index, AI	$\mathrm{PE_T}/P$	same	dimensionless	≥ 0	Budyko, 1974
Catchment E_T Ratio, $E_\mathrm{T}R$	E_T/P	same	dimensionless	$0 \leq E_\mathrm{T}R \leq 1$	Budyko, 1974
Runoff Ratio, RR	$1 - (E_\mathrm{T}/P)$	same	dimensionless	$0 \leq \mathrm{RR} \leq 1$	Budyko, 1974
Total Water Availability, TWA	–	$\max\{(P + L_\mathrm{in}), (E_\mathrm{T} + L_\mathrm{out} + [-\mathrm{d}S_\mathrm{T}/\mathrm{d}t])\}$	$\mathrm{LT^{-1}}$	≥ 0	This paper
Normalized precipitation, p	p	P/TWA	dimensionless	$0 \leq p \leq 1$	This paper
Normalized evapotranspiration, et	et	$E_\mathrm{T}/\mathrm{TWA}$	dimensionless	$0 \leq \mathrm{et} \leq 1$	This paper
Normalized total storage change	$\mathrm{d}s_\mathrm{T}/\mathrm{d}t$	$(\mathrm{d}S_\mathrm{T}/\mathrm{d}t)/\mathrm{TWA}$	dimensionless	$-1 \leq \mathrm{d}s_\mathrm{T}/\mathrm{d}t \leq 1$	This paper
Source-Sink Index, SSI	$p - \mathrm{et}$	$(P - E_\mathrm{T})/\mathrm{TWA}$	dimensionless	$-1 \leq \mathrm{SSI} \leq 1$	This paper
Green-Blue Index, GBI	$(p + \mathrm{et})/2$	$(P + E_\mathrm{T})/(P + E_\mathrm{T} + L_\mathrm{in} + L_\mathrm{out})$	dimensionless	$0 \leq \mathrm{GBI} \leq 1$	This paper
Hydrologic unit E_T ratio, et/p	et/p	$E_\mathrm{T,\,HU}/P$	dimensionless	≥ 0	This paper

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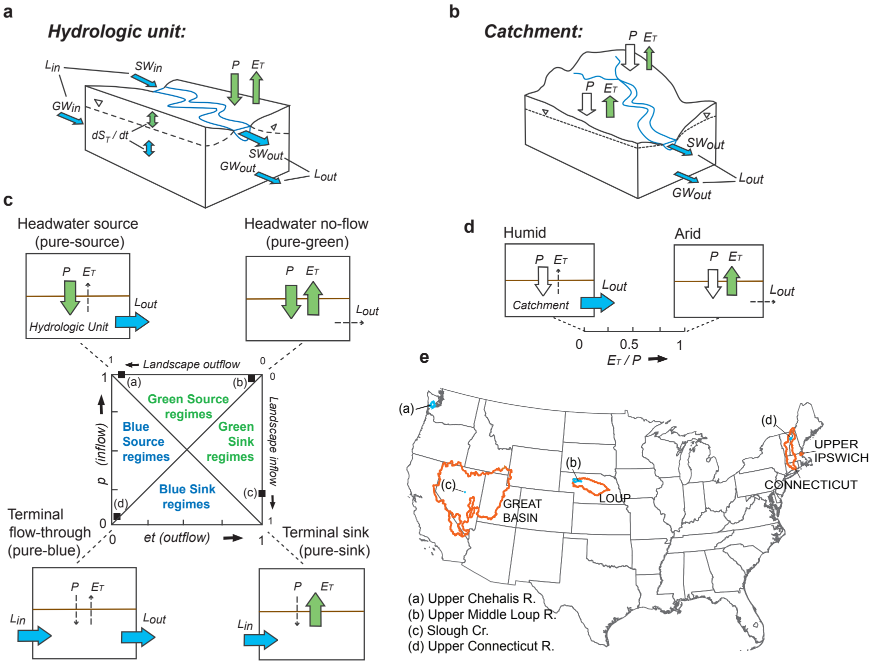

Fig. 1. (a) Hydrologic unit, and **(b)** catchment, showing land–atmosphere (or green) fluxes (precipitation, evapotranspiration; P, E_T), and landscape (or blue) fluxes (groundwater + surface-water flows; L_{in}, L_{out}), at boundaries. Double arrows show change in green (unsaturated) and blue (saturated) storage; their sum equals change in total water storage (dS_T/dt) during a time step of interest. Catchment P influxes, defined by Falkenmark and Rockström (2004) as undifferentiated (neither green nor blue), indicated by white arrows. Internal soil moisture/groundwater/surface-water exchanges not shown. **(c)** A hydroclimatic regime is defined by the 2-D, (*et, p*) plotting position on central regime space; see Table 2 for et and p definitions. End-member regimes shown by sketches at corners of regime space. Example regimes a, b, c, and d: see Table 1. **(d)** Catchment hydroclimatic regime, defined by 1-D position on E_T/P axis. **(e)** Locations of example regimes, Table 1 and Fig. 2.

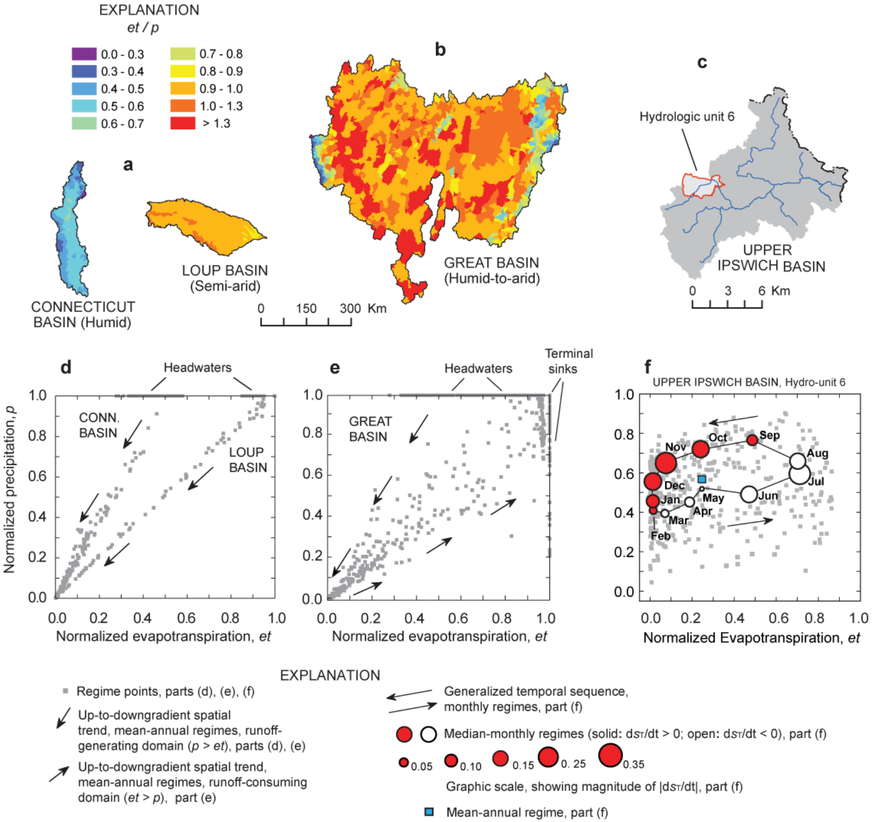

Fig. 2. Spatial variation of hydroclimatic regimes (1896–2006), shown by maps **(a, b)** of hydrologic-unit evapotranspiration ratio (et/p) and hydroclimatic regime scatter plots **(d, e)** of selected USA basins: Connecticut River Basin, New England ($n = 349$); Loup River Basin, Nebraska ($n = 150$); and Great Basin, intermountain USA ($n = 908$). Temporal variation of monthly ($n = 420$) median monthly ($n = 12$), and mean-annual ($n = 1$) hydroclimatic regimes (1961–1995) for hydrologic unit 6, Ipswich River Basin, New England, **(c, f)**.

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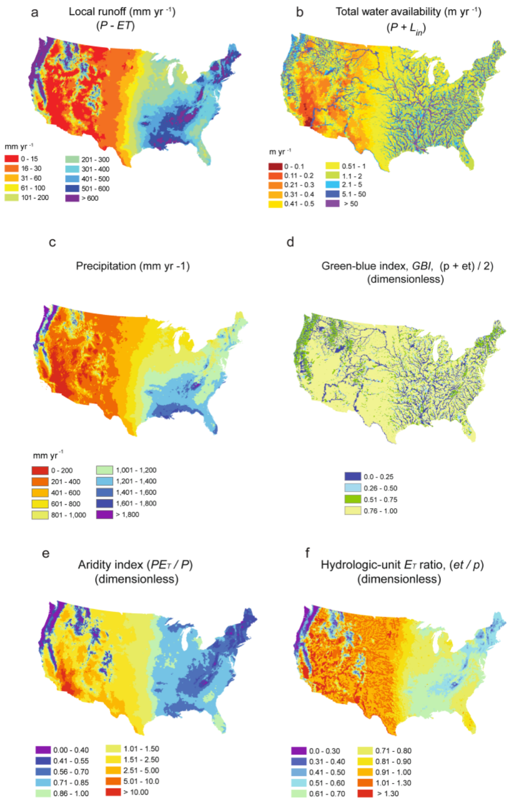

Fig. 3. Classical **(a, c, e)** and newly introduced **(b, d, f)** indicators of terrestrial water availability for 53 400 networked hydrologic units of the conterminous USA, on a mean-annual basis for 1896–2006. See text and Table 2 for indicator definitions. **(a)** Local runoff ($\text{mm}\,\text{yr}^{-1}$), **(b)** Total water availability ($\text{m}\,\text{yr}^{-1}$). **(c)** Precipitation ($\text{mm}\,\text{yr}^{-1}$), **(d)** Green-blue index (dimensionless). **(e)** Aridity index (dimensionless), and **(f)** hydrologic-unit evapotranspiration ratio (et/p, dimensionless).

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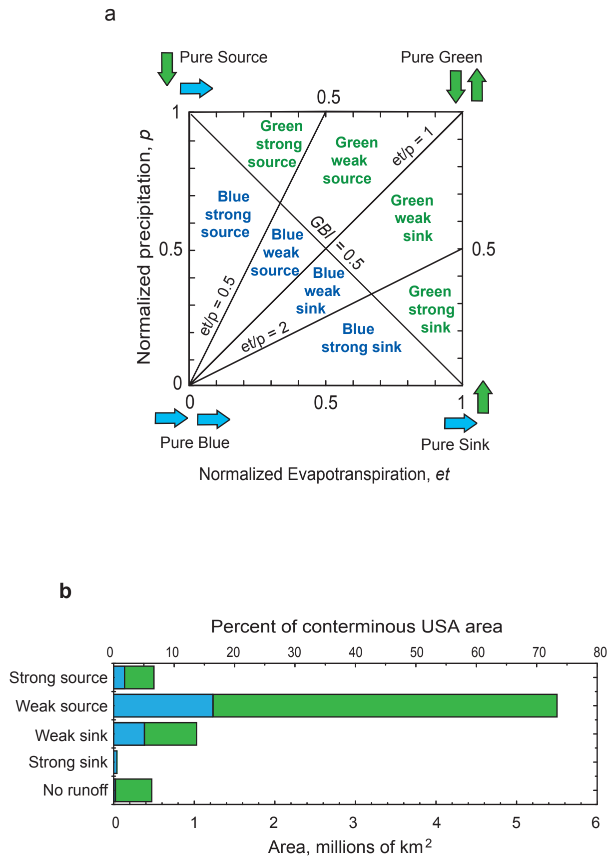

Fig. 4. **(a)** Hydroclimatic regime classification, based on indicators of local climate (hydrologic-unit evapotranspiration ratio, et/p) and relative magnitude of green and blue fluxes (green-blue index, GBI); **(b)** Areas of conterminous USA covered by regime classes of **(a)**, and by area considered to have zero runoff ($0.99 < \mathrm{et}/p < 1.01$).