

1 **AMS 100<sup>th</sup> Anniversary Monograph**

2 **Chapter 14: 100 YEARS OF PROGRESS IN HYDROLOGY**

3  
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64 **Abstract**

65 The focus of this chapter is progress in hydrology for the last 100 years. During this period, we  
66 have seen a marked transition from practical engineering hydrology to fundamental developments  
67 in hydrologic science, including contributions to Earth system science. The first three sections in  
68 this chapter review advances in theory, observations, and hydrologic prediction. Building on this  
69 foundation, the growth of global hydrology, land-atmosphere interactions and coupling,  
70 ecohydrology, and water management are discussed, as well as a brief summary of emerging  
71 challenges and future directions. Although the review attempts to be comprehensive, the chapter  
72 offers greater coverage on surface hydrology and hydrometeorology for readers of this American  
73 Meteorological Society (AMS) Monograph.

## 74 **1 Introduction: From Engineering to Hydrologic Science**

75 The development of ancient civilizations along the Nile, Tigris-Euphrates, Indus, and Huang-Ho  
76 rivers is not an accident—proximity to water for drinking, sanitation, agriculture, and navigation  
77 enriched their livelihoods. Soon after these civilizations were established, they began to measure  
78 and manage water, including constructing flood control dams, collecting stream gauge  
79 information, and building irrigation canals (Noaman and El Quosy, 2017; Harrower, 2008;  
80 Chandra, 1990). There is evidence to support that these ancient civilizations understood the  
81 concept of the hydrologic cycle, including precipitation as the source of groundwater recharge  
82 through infiltration, and the role of solar radiation in evapotranspiration (Chow, 1964; Chandra,  
83 1990). As summarized by Baker and Horton (1936), there were competing theories of the origin  
84 of springs and rivers by ancient philosophers from Aristotle, Vitruvius, and Ovid to Seneca, who  
85 described “Forms of Water” in his “Questions Naturalis”.

86

87 Many of these ideas remained in place until the Renaissance, when Leonardo da Vinci (ca. 1500)  
88 classified hydrologic processes using hypothesis-driven science, including the hydrologic cycle  
89 (Pfister et al. 2009). Almost 200 years later during the Scientific Revolution in the 16th and 17th  
90 centuries, the French writer Pierre Perrault was the first to take a quantitative approach to  
91 understanding the nature of the hydrologic cycle (Deming, 2014). In England, astronomer  
92 Edmond Halley also studied the hydrologic cycle. However, French Academy member Edme  
93 Mariotte was the first to quantitatively demonstrate a fundamental concept of hydrogeology, which  
94 is that precipitation and infiltration ultimately comprise streamflow (Deming, 2017). Mariotte  
95 also made fundamental contributions to hydrostatics and applied this knowledge to engineer the  
96 water supply at Versailles. Clearly from ancient times through the Scientific Revolution, advances

97 in hydrologic science were often made by polymaths observing and testing their knowledge to  
98 support water management.

99

100 To meet the needs of flood design, land and forest management, and economic efficiency, national  
101 governments established programs for measuring and analyzing rainfall. In the U.S., this function  
102 was carried out by the U.S. Weather Bureau, which became the National Weather Service (NWS)  
103 in 1970. The Weather Bureau conducted rainfall analyses that supported road building and the  
104 design of engineering structures such as sewers and dams. For example, since the late 19th  
105 century, civil engineers have utilized the so-called rational method (Kuichling, 1889) for roadway  
106 drainage design. A related method from the United States Department of Agriculture (USDA)  
107 Natural Resources Conservation Service (NRCS; formerly Soil Conservation Service, SCS),  
108 known as the SCS Runoff Curve Number method (Mockus, 1972), can also be used. These  
109 methods rely on “design storms” of a known intensity for a given return period and duration. In  
110 the U.S., design storm intensities are derived using intensity-duration-frequency information  
111 similar to Figure 1 below, which is based on Weather Bureau Technical Paper-40 (Hershfield,  
112 1961a). Typical return periods include 25, 50 or 100 years depending on the importance of the  
113 roadway. Even today, such rainfall analyses underpin the design of important structures such as  
114 detention basins, roadways, bridges, and dams, and these maps continue to be periodically updated  
115 by the NWS (e.g., Bonnin et al. 2006).

116

117 The focus of this chapter is progress in hydrology for the last 100 years. As with any effort to  
118 track the progress of a field over a century, it is not quite possible to document all the advancements  
119 made across all sub-disciplines. However, to make our review scoped appropriately for this

120 American Meteorological Society (AMS) Monograph and its readers, we provide greater focus on  
121 the theoretical underpinnings of surface processes, the atmosphere above and the interactions  
122 within the land-atmosphere interface. During the last 100 years, we have seen a marked transition  
123 that has improved practical applications of hydrology through fundamental advancements in  
124 hydrologic science, including contributions to Earth system science (Sivapalan, 2017). As first  
125 described in Chow (1964) and later proposed and extended by Sivapalan and Blöschl (2017) and  
126 shown in Figure 2, hydrology first progressed through the Empirical Era (1910-1930), to the  
127 Rationalization Era (1930-1950), to the Systems Era (1950-1970). These periods were followed  
128 by the Process Era (1970-1990), the Geosciences Era (1990-2010), and finally by the current Co-  
129 evolution Era (2010-2030). As noted in the figure, the foundations of networks, experimental  
130 basins, operations research, high performance computing, remote sensing, and big data have  
131 advanced hydrological understanding. At the time of the founding of the AMS, there was a single  
132 journal—Monthly Weather Review (MWR)—that served as an outlet for hydrologic science in the  
133 AMS community. In the first several decades of this period (1919-1959, Empirical to  
134 Rationalization Eras), MWR articles reflect the emergence of quantitative hydrology from  
135 empirical observation (as will be discussed in Section 2 below). Examples include discussions of  
136 floods (Henry, 1919; Henry 1928; Nagler, 1933), rainfall-runoff relationships (Fischer, 1919;  
137 Shuman, 1929; Zoch, 1934), and even the potential of seasonal rainfall prediction based on snow  
138 pack (Monson, 1934). Later, MWR articles (1960-2000; Systems to Process and Geosciences  
139 Eras) became less focused on basic hydrology, partly due to the emergence of hydrology journals  
140 including the Hydrological Sciences Journal (established in 1956), the Journal of Hydrology  
141 (established in 1963), and AGU’s Water Resources Research (WRR; established in March 1965).  
142 Another factor in the change in hydrology focus for MWR articles in this period is related to the

143 establishment of the Journal of Applied Meteorology (JAM) in 1962, along with the emergence of  
144 hydrometeorology and hydroclimatology, which culminated with the introduction of the Journal  
145 of Hydrometeorology in 2000. Classic examples from MWR include Rasmusson's (1967; 1968)  
146 water vapor budgets, Lettau's (1969) evaporation climatology, Manabe et al.'s (1969) bucket  
147 model and Priestley and Taylor's (1972) evaporation formulation. Examples from JAM include  
148 the albedo model of Idso et al. (1975), Adler and Negri's (1988) infrared rainfall technique,  
149 Nemani et al.'s (1989) satellite-based surface resistance methodology, Dorman and Sellers (1989)  
150 Simple Biosphere Model parameter climatologies, Beljaars and Holtlag's (1991) land surface flux  
151 parameterization, Daly et al.'s (1994) topography-based precipitation analysis methodology, and  
152 Hsu et al.'s (1997) neural network based satellite precipitation estimation.

153

154 An article in WRR's recent 50th anniversary issue by Rajaram et al. (2015) identified the  
155 topics covered by the top 10 most highly cited papers of each decade since 1965. These topics  
156 mirrored the evolution of topics in MWR and JAM, from infiltration and evapotranspiration  
157 formulations, to land surface hydroclimatological models and data assimilation. In addition to the  
158 evolution of scientific topics, progress in hydrology during this period is marked by the  
159 establishment of Hydrology as a science rather than an "application" (e.g., Klemesš, 1988). The  
160 so-called Eagleson "Blue Book" (National Research Council, 1991; Eagleson, 1991) was a  
161 bellwether moment in hydrology, because it helped define hydrology as a distinct geoscience, and  
162 recommended the establishment of research and educational programs in hydrology, hence the so-  
163 called "Geosciences Era" from 1990-2010 (Sivapalan and Blöschl, 2017).

164

165 Since JHM was initiated in 2000, the growth and impact of hydrologic research both within the  
166 AMS community (e.g., Figure 3), and overall (Clark and Hanson, 2017) has been substantial. In  
167 this monograph chapter, we will review progress in hydrology for the last 100 years, including  
168 theory, observations, and forecasting. Major themes such as the emergence of global hydrology,  
169 coupled land-atmosphere modeling including hydrometeorology and hydroclimatology,  
170 dynamical hydrologic prediction, and water resources management and water security will be  
171 reviewed. Finally, we look forward with a discussion of future directions.

## 172 **2 The Evolution of Hydrologic Understanding**

173 As noted in Chapter 1 of the Handbook of Hydrology (Maidment, 1993), quantitative hydrology  
174 emerged in the 1850s with Mulvaney's (1851) time of concentration concept, and Darcy's (1856)  
175 law of groundwater flow. Surface water flow equations developed shortly thereafter by Saint-  
176 Venant (1871) and Manning (1891) underpin today's routing schemes. Infiltration models from  
177 Green and Ampt (1911) to Horton (1933) provide a physical basis for rainfall-runoff modeling that  
178 further advanced hydrologic science. In this section, we focus on advances in hydrologic theory  
179 over the past 100 years in 6 key areas: (1) precipitation; (2) evaporation; (3) infiltration and soil  
180 water movement; (4) groundwater; (5) streamflow and routing; and (6) hydrogeomorphology.

### 181 *a. Precipitation*

182 In the previous section, we described widely-used concepts such as precipitation intensity-  
183 duration-frequency curves for engineering design for structures such as roadways, sewers and  
184 dams. Accordingly, from the hydrology perspective, key theoretical developments with respect to  
185 precipitation were initially focused on estimating precipitation extremes, including statistical



186 techniques and the design of rainfall measurement networks. The reader is referred to Chapter 12  
187 of this Monograph for a more detailed treatment of advances in observing and modeling mesoscale  
188 precipitation processes. In this section, we focus on advances in precipitation estimation for  
189 hydrometeorological and hydroclimatological applications.

190

191 A fundamental concept in the estimation of rainfall intensities for high-hazard structures such as  
192 dams is the Probable Maximum Precipitation (PMP; Hershfield, 1961b; WMO, 2009) which is  
193 defined as “theoretically, the greatest depth of precipitation for a given duration that is physically  
194 possible over a given storm area at a particular geographical location at a certain time of the year.”  
195 The general procedure for calculating PMP relies on estimating maximum precipitable water,  
196 convergence rate, and vertical motion, and there are numerous reports available produced by the  
197 NWS from 1963-1999 that provide PMP estimates for the U.S.  
198 (<http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html>). Unfortunately, these efforts have been  
199 discontinued due to lack of funding. Despite this, PMP estimation is still an active area of research,  
200 and recent publications suggest that PMPs are changing along with climate (Kunkel et al. 2013;  
201 Chen et al. 2017).

202

203 Around the same time, the design of precipitation networks became a focus, including Dawdy and  
204 Langbein (1960), Peck and Brown (1962), and Peck (1980), who recognized the role of topography  
205 in areal precipitation estimation. Rodríguez-Iturbe and Mejía (1974a,b) further studied point-area  
206 relationships and rainfall network design. These works ultimately led to the highly-cited work of  
207 Daly et al. (1994), who use observed precipitation and temperature gradients with topography to  
208 provide gridded precipitation products for CONUS.

209

210 Beyond these studies, major advances in the simulation of precipitation time series as spatially  
211 correlated random fields led to further advancements in stochastic hydrology. Understanding the  
212 space-time structure of precipitation allowed hydrologists to simulate precipitation over areas of  
213 interest, such as watersheds or river basins. Examples include Huff and Changnon (1964);  
214 Amorocho and Wu, (1977); Waymire, Gupta and Rodriquez-Iturbe (1984); Georgakakos and Bras,  
215 (1984); Eagleson et al. (1987); Foufoula-Georgiou and Lettenmaier (1987); Sivapalan and Wood  
216 (1987) and Foufoula-Georgiou (1989). This work complemented studies that identified the fractal  
217 and ultimately multiscaling structure of precipitation (e.g., Zawadzki, 1987).

218 *b. Evapotranspiration*

219 Evapotranspiration (ET) represents the combination of open water, bare soil, and canopy surface  
220 evaporation and transpiration. Theoretically, ET represents a turbulent flux of water vapor from  
221 the earth's surface to the atmosphere resulting from the phase change of liquid water. This phase  
222 change means that ET is coupled to the surface energy balance via the latent heat of vaporization,  
223 and therefore the transfer of energy from the surface to the atmosphere due to evapotranspiration  
224 is also referred to as the latent heat flux. If the phase change is from solid to vapor, then this energy  
225 transfer must also include the latent heat of sublimation. ET can be estimated as the product of  
226 the kinematic turbulent flux of water vapor ( $w'q'$ ), and the density of air. This is the concept  
227 behind the eddy covariance measurement technique, as will be discussed further in section 3.f.  
228 below.

229

230 Given that ET is a dominant term in the terrestrial water budget, there have been many efforts  
231 designed to estimate this term with limited meteorological information. An important concept in  
232 ET estimation is that of potential evaporation (PE), which is defined as “the quantity of water  
233 evaporated per unit area, per unit time from an idealized, extensive free water surface under  
234 existing atmospheric conditions” (Maidment, 1993, p. 4.2). This concept effectively represents  
235 atmospheric “evaporative demand”. A closely related concept is that of reference crop ET  
236 (denoted  $E_{To}$ ), which is the rate of ET from an idealized grass crop with a fixed height, albedo,  
237 and surface resistance. In order to obtain actual ET from potential or reference ET, PE or  $E_{To}$   
238 are multiplied by a series of coefficients representing specific crops and stress factors (Allen et al.  
239 1998; Doorenbos and Pruitt, 1977).

240

241 In general, the methods for PE estimation can be classified as (1) temperature-dependent methods  
242 or (2) combination methods. The original, and still widely-used temperature dependent method  
243 was developed by Thornthwaite (1948). This method has been shown by numerous authors to  
244 overestimate the sensitivity to air temperature changes (e.g., Milly and Dunne, 2016), and  
245 alternative temperature-based methods have been shown to behave more like combination methods  
246 (e.g., Blaney and Criddle, 1950; Hargreaves and Samani, 1985).

247

248 The foundation of combination methods is Penman (1948), who combined the energy balance  
249 approach with an aerodynamic approach to derive an estimate of  $E_{To}$  based on an implicit  
250 assumption of measurement height and roughness length (Thom and Oliver, 1977). Monteith  
251 (1965) generalized the Penman equation, by calculating leaf resistances in series with the  
252 aerodynamic resistance employed by Penman. This led to a generalized form of the reference

253 crop ETo equation now known as the Penman-Monteith equation. Priestley and Taylor (1972)  
254 found that ETo could be approximated quite accurately using a simplified form of Penman's  
255 equation requiring only the available energy (=net radiation minus ground heat flux) and a  
256 coefficient that changes depending on humid or arid climates, as defined by relative humidity.  
257 The most general form of the Penman-Monteith equation utilizes both aerodynamic and canopy  
258 resistances in series, where the canopy resistance (or its inverse, the conductance) can be calculated  
259 using a Jarvis (1976) approach, which depends on both leaf area and soil moisture (e.g., Lhomme  
260 et al. 1998). A comprehensive summary of ET theory and methods is given in Brutsaert (1982)  
261 and Dolman (2005).

262

263 Modern approaches to estimating actual ET fall into three categories: energy balance (e.g., Su et  
264 al. 2009; Anderson et al. 1997; 2011), combination (e.g., Penman-Monteith or Shuttleworth-  
265 Wallace, 1985) and complementary approaches (e.g., Bouchet, 1963), or combinations thereof  
266 (e.g., Mallick et al. 2013), and the choice and performance depends primarily on the availability  
267 of required data (Mueller et al. 2013). Most modern land surface models used in climate models  
268 (as will be discussed in Section 6 below) calculate ET using a Jarvis-based energy balance  
269 approach or a coupled photosynthesis-canopy conductance energy balance approach (Ball et al.  
270 1987), as discussed in the review by Wang and Dickinson (2012).

### 271 *c. Infiltration and Soil Water Movement*

272 In the Empirical era, infiltration estimation was primarily focused on estimating losses for runoff,  
273 and this led to the work of Green and Ampt (1911), which was later shown to be consistent with  
274 theory and observations, with some updates to account for antecedent moisture conditions (Mein

275 and Larson, 1973). It was also shown to be an expression of the Time Condensation  
276 Approximation (TCA; Sivapalan and Milly, 1989). Horton (1933) further investigated infiltration,  
277 and found that a time-varying infiltration capacity can be used to better estimate infiltration excess  
278 runoff than the so-called “rational method”. In Horton’s work, estimating “effective rainfall”,  
279 which is the infiltrated water available to plants, was another major objective. Philip (1957)  
280 derived a series solution for infiltration into a vertical, semi-infinite homogeneous soil surface, and  
281 since that time, this approach has largely been replaced by numerical solution of the governing  
282 equation for soil water movement as described below.

283  
284 Richards (1931) derived an equation for capillary conduction of liquids through porous mediums,  
285 which combines Darcy’s law applied to unsaturated media with the continuity equation. The  
286 “Richards equation” is the foundation for predicting both infiltration and soil water movement,  
287 and soil moisture specifically. There are a number of works geared towards the proper form of  
288 this equation for numerical solutions (e.g., Celia et al. 1990; Zeng and Decker, 2009), in addition  
289 to various functional forms for the required soil water characteristic curves, which are nonlinear,  
290 hysteretic, and a function of soil texture (e.g., Brooks and Corey, 1964; Clapp and Hornberger,  
291 1978; Rawls et al. 1982; van Genuchten, 1980). The Richards equation is the basis for many of  
292 today’s hydrological and land surface models (e.g., Downer and Ogden, 2004; Lawrence et al.  
293 2011), although there are still challenges to its application and solution (Farthing and Ogden,  
294 2017).

295 *d. Groundwater*

296 As with other aspects of the hydrological cycle, early efforts to characterize groundwater focused  
297 on mapping groundwater resources. The US Geological Survey (USGS) was a pioneer in this area,  
298 and the foundational work of Meinzer (1923) defined groundwater provinces as well as the basic  
299 principles of groundwater occurrence and movement. As with soil water movement, groundwater  
300 flow in saturated porous media is governed by Darcy's (1856) law. Combining this constitutive  
301 relation with the continuity equation led to key theoretical developments in describing  
302 groundwater motion, e.g., Theis (1935), Hubbert (1940), Jacob (1940), and Hantush and Jacob  
303 (1955). Texts such as Bear (1972) and Freeze and Cherry (1979) provide more in-depth  
304 treatments of the topic. A breakthrough in the recognition of the role of groundwater in runoff  
305 generation came from Dunne et al. (1975), who showed that saturated areas intersecting the surface  
306 produced instantaneous runoff known as "saturation excess" in contrast to the Hortonian  
307 "infiltration excess" runoff produced when rainfall exceeds the infiltration capacity. This led to  
308 the observation that these saturated areas could be approximately represented via a topography-  
309 based drainage index, which led to to the so-called TOPMODEL concept for parameterizing  
310 saturated areas (Beven and Kirkby, 1979). Later, Yeh (1986) formalized inverse approaches for  
311 identifying parameters for groundwater hydrology that are now commonly used in groundwater  
312 modeling.

313  
314 These theoretical developments were later translated into numerical models, the most prevalent  
315 being the USGS MODFLOW (Trescott et al. 1980; McDonald and Harbaugh, 2003). In the last  
316 20 years, there has been a push to include representations of groundwater flow in land surface  
317 models, ranging from simple treatments based on the TOPMODEL concept (e.g., Famiglietti and

318 Wood, 1994; Koster et al. 2000a; Niu et al. 2007) to more complex treatments based on  
319 groundwater flow models (e.g., Maxwell and Miller, 2005; Fan et al. 2007; Miguez-Macho et al,  
320 2007).

321 *e. Streamflow and Routing*

322 The theory of surface water flow has been well-known since Saint-Venant (1871) derived the  
323 shallow water equations (also known as the Saint-Venant equations) based on the conservation of  
324 mass and momentum (i.e. the Navier-Stokes equations). Depending on which terms in the Saint-  
325 Venant equations are retained, the equations may be reduced to “kinematic wave” (e.g., Lighthill  
326 and Whitham, 1955; Feldman, 2000; Getirana et al. 2012) or “diffusion wave” approximations  
327 (e.g., Julien et al. 1995). The full 1-D equations are known as “dynamic wave” (e.g., Brunner,  
328 2016), and are computationally intensive to solve, and cost-accuracy tradeoffs remain even for  
329 approximations to these equations (Getirana et al. 2017). The velocity of flow in open channels  
330 was described by Manning (1891), who re-developed an earlier relationship by Gauckler (Hager,  
331 2001) in which velocity is related to slope, roughness and cross sectional area. Combining the  
332 velocity formulation with the Saint-Venant equations allows for the prediction of streamflow in  
333 open channels as well as overland flow on hillslopes (e.g., Chow, 1959).

334  
335 Routing refers to the prediction of changes in the height (stage) and volumetric flow rate  
336 (discharge) of water (i.e. the hydrograph) as it moves over a hillslope or through a river channel  
337 or a reservoir (Woolhiser and Liggett, 1967). Hydraulic or distributed routing refers to solving  
338 both the continuity and momentum equations, while hydrologic or lumped routing refers to the  
339 continuity equation alone. One of the first approximate techniques to transform rainfall as a runoff

340 response was Sherman's (1932) unit hydrograph. This technique allows the computation of a  
341 hydrograph by convolving the excess rainfall with a response function that could be derived for  
342 each watershed (e.g., Dooge, 1959). This approach is still in use in engineering hydrology (e.g.,  
343 Feldman, 2000), although the most prevalent hydrologic routing technique is the Muskingum  
344 (McCarthy, 1940) or its extension, the Muskingum-Cunge (Cunge, 1969; Todini, 2007) method.

345

346 In addition to overland flow routing described above, there is also the concept of subsurface flow  
347 routing, which is an approximation to unsaturated and saturated groundwater flow (as described  
348 above). As discussed by Tague and Band (2001), the TOPMODEL (Beven and Kirkby, 1979)  
349 approach can be described as an "implicit" routing approach in contrast to "explicit" approaches  
350 such as Wigmosta et al. (1994). The developing National Water Model, based on the WRF-Hydro  
351 system (Gochis et al. 2015), currently uses a configuration that includes explicit subsurface  
352 routing, diffusive wave surface routing and Muskingum-Cunge channel routing.

### 353 *f. Hydrogeomorphology*

354 Hydrogeomorphology "focuses on the interaction and linkage of hydrologic processes with  
355 landforms or earth materials and the interaction of geomorphic processes with surface and  
356 subsurface water in temporal and spatial dimensions" (Sidle and Onda, 2004). Eminent  
357 hydrologists including Horton, Langbein (Dooge, 1996), Freeze and Harlan (1969), Dooge (1973),  
358 Beven and Kirkby (1979) have clearly recognized the linkages between the landscape and  
359 hydrologic processes. During the so-called "systems era" (1950-1970), the full integration of  
360 hydrologic theories and processes was explored and led to the Freeze and Harlan "blueprint" for  
361 hydrologic modeling, as discussed recently by Clark et al. (2017). As we progressed to the process



362 era (1970-1990), hydrogeomorphological work focused on the search for universal laws (Dooge,  
363 1986), the linkages between climate, soil and vegetation (Eagleson, 1978a-g), and scaling and  
364 similarity (Wood et al. 1988; Blöschl and Sivapalan, 1995).

365

366 As discussed in Peters-Lidard et al. (2017), one outcome of this era is the Representative  
367 Elementary Area (REA) concept (Wood et al. 1988; Fan and Bras, 1995), which found that the  
368 rainfall-runoff process behaved in a much simpler manner at the roughly 1 square kilometer scale.  
369 Later extensions to the concept include the Representative Elementary Watershed (REW)  
370 introduced by Reggiani et al. (1998, 1999, 2000, 2001) and the Representative Hillslope (RH;  
371 Troch et al. 2003; Berne et al. 2005; Hazenberg et al. 2015). The REA/REW approach is  
372 conceptually similar to Reynolds averaging, and assumes that the physics are known at the smallest  
373 scale considered (e.g. Miller and Miller, 1956). In another parallel, fluxes at the boundaries of  
374 model control volumes require parameterization (i.e. “closure”), with assumptions that are  
375 typically ad-hoc, and may include sub-grid probability distributions, scale-aware parameters, or  
376 new flux parameterizations.

377

378 Explicit “Newtonian” modeling of hillslopes at “hyper-resolutions” (Wood et al. 2011), or with  
379 clustered 2-D simulations (e.g., the HydroBlocks of Chaney et al. 2016), may render the  
380 REA/REW approach obsolete, although hydrogeomorphological connections continue to be  
381 explored. For example, Maxwell and Condon (2016), found that the interplay of water table depths  
382 with rooting depths along a given hillslope exerts different controls on evaporation and  
383 transpiration, linking the water table dynamics with the land surface energy balance. Further, the  
384 concept of catchment co-evolution and “Darwinian” hydrology (Sivapalan, 2005; McDonnell et

385 al. 2007, Thompson et al. 2011; Harman and Troch, 2014) has extended scale and similarity  
386 concepts to synthesize catchments across scales, places and processes, ushering in the “Co-  
387 evolution Era”.

### 388 **3 Advances in Hydrologic Observations**

389 Moving from point to areal estimates of hydrologic states and fluxes has revolutionized hydrologic  
390 science. Advances in precipitation estimation from gauges to radars to satellites, combined with  
391 similar advances in observing snow packs, soil moisture, terrestrial water storage,  
392 evapotranspiration, and stream stage and discharge, have enabled continental and global-scale  
393 hydrology. Famiglietti et al. (2015) provide an overview of the advantages of satellite based  
394 observation, including global coverage, near-continuity across space and time, and consistency of  
395 measurements from a given instrument. Taking the other side of the argument, Fekete et al. (2015)  
396 describe the shortcomings and dangers of over-reliance on remote sensing, including errors  
397 associated with mis-calibration of remote sensing retrieval algorithms, coarse spatial resolution  
398 relative to in situ measurements, inconsistencies associated with technology/instrument changes,  
399 and termination of long term in situ measurement locations incorrectly perceived to have been  
400 made obsolete by remote sensing.

#### 401 *a. Precipitation*

402 Rain gauges, disdrometers and radars have long been conceptualized as the data reference for  
403 precipitation studies. The use of standardized rain gauges has been documented as early as the 15<sup>th</sup>  
404 century in Korea, so it is not surprising that for a long time in history they have been considered  
405 as indispensable for precipitation science (Tapiador et al. 2011). In fact, rain gauges are still

406 considered the privileged source of reference data for precipitation estimates as they provide a  
407 direct physical record of the hydrometeors (cf. Kucera et al. 2013). Most of the global datasets of  
408 precipitation such as the Global Precipitation Climatology Project (GPCP; Adler et al. 2003, 2012,  
409 2017), or the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and  
410 Arkin, 1997; Xie et al. 2003) include them in one way or another, and they are still used to calibrate  
411 and tune climate models. The same applies to other climate data records from multi-satellite  
412 observations (Ashouri et al. 2015). Disdrometers—modern instruments that estimate not only the  
413 total precipitation but also the drop size distribution (DSD)—are also becoming increasingly  
414 important part of ground instrumentation systems. Disdrometers are direct in that they respond to  
415 individual drops, but they have a fairly small sampling area (tens of square centimeters), which  
416 affects the representativeness of the measurements (Tapiador et al. 2017).

417

418 In contrast, ground-based radars sample a large volume but provide an estimate of the precipitation  
419 based on the backscattered echo, an indirect observation which relates to total rainfall through the  
420 DSD. In recent times, exploiting the radar transmit/receive polarization state has enhanced radar  
421 capabilities by discriminating the phase of the hydrometeors (Bringi et al. 1990). These three  
422 ground observations of precipitation (gauges, disdrometers and radars) were the primary input for  
423 hydrologic models for many years.

424

425 However, beginning with the inception of operational passive microwave imagery onboard the  
426 operational Defense Meteorological Satellite Program (DMSP) low Earth-orbiting (LEO) satellites  
427 in 1987, and continuing with the joint NASA-JAXA Tropical Rainfall Measuring Mission  
428 (TRMM) in 1997 (Simpson et al. 1988), a shift towards a blended or merged use of both ground-

429 and satellite-based precipitation estimates was initiated (Adler et al. 2000; Huffman et al. 2007,  
430 Joyce et al. 2004, Behrangi et al. 2009; Kidd and Huffman 2011). With microwave-based  
431 precipitation observations onboard multiple LEO satellites, complemented by the fast-refresh  
432 capabilities (30-minutes or less) of operational geostationary visible and infrared imaging sensors,  
433 improved global precipitation was enabled at spatial and temporal scales relevant to hydrological  
434 models and applications (Hossain and Lettenmaier, 2006; Nguyen et al. 2017; Nguyen et al. 2018).  
435 TRMM demonstrated the first spaceborne precipitation radar (Iguchi et al., 2000), and algorithms  
436 that fused passive and active measurements for global precipitation estimation over tropical and  
437 subtropical regions (Kummerow et al., 2000). TRMM was key to improving our understanding  
438 of the water cycle and the role of latent heat in the Earth system (Tao et al., 2016). The role of  
439 TRMM in improving our knowledge of the structure (and thus of the physics) of hurricanes cannot  
440 be underestimated (Hawkins and Velden, 2011).

441  
442 More extensive global coverage at higher latitudes (i.e., poleward of TRMM's limited 35-degree  
443 latitude coverage) culminated with the launch of the joint NASA-JAXA Global Precipitation  
444 Measurement (GPM) core observatory in 2014 (Skofronick-Jackson et al. 2017). GPM's dual  
445 frequency precipitation radar and higher orbit inclination expands the measurements to more over-  
446 land regions where much of the water cycle is driven by frozen precipitation processes (Houze et.  
447 al., 2017).

448  
449 Regarding the future of precipitation estimation from space, the direction in the US points to small  
450 systems such as Cubesats (Peral et al. 2018), with an emphasis on understanding the interplay  
451 between aerosols and precipitation; aqueous chemistry; and a better understanding of convection.

452 Such topics are those favored by the National Academies Decadal Survey of Earth Sciences and  
453 Applications from Space (2018), and therefore will be likely the drivers of future missions.

454

455 *b. Snowfall*

456 Quantification of frozen precipitation has been especially difficult in the past. Indeed,  
457 instrumentation designed to remotely sense snowfall water equivalent (SWE) rates, for example,  
458 be it via weighing gauge, radar, or disdrometer have all addressed the challenges to deal with  
459 maintenance, calibration, point-to-area representativeness, measurement error, wind, etc., in  
460 addition to the irregular shapes, sizes, and bulk density of snowfall (Tapiador et al. 2012)

461

462 There are ways to retrieve SWE rates over larger areas using combinations of polarimetric radar,  
463 disdrometer and weighing gauge data (Brandes et al. 2007; Huang et al. 2010), however doing so  
464 is tedious and case specific (Tapiador et al. 2012). The advent of the GPM core observatory, with  
465 its enhanced capabilities over TRMM and the ability to measure the solid phase over the whole  
466 planet has opened a new phase for hydrology.

467 *c. Snowpack*

468 Observations of snowpack properties, such as Snow Covered Area (SCA)/Snow Cover Extent  
469 (SCE), snow depth and Snow Water Equivalent (SWE), prove challenging due to the considerable  
470 variability at fine spatial scales (e.g., Blöschl, 1999; Erickson et al. 2005; Dozier et al. 2016).  
471 Ground-based measurement of SCA is labor-intensive, although tower-mounted imaging is still a  
472 useful verification technique, and new approaches such as low-cost temperature sensors can be

473 used to monitor seasonal SCA (Lundquist and Lott, 2010). Remote sensing of SCA was among  
474 the first applications of satellite data (as discussed in the review by Lettenmaier et al. 2015), and  
475 today, the spatial and temporal evolution of SCA is monitored with multiple satellites, including  
476 30-meter resolution Landsat (Rosenthal and Dozier, 1996), 500-m resolution Moderate Resolution  
477 Imaging Spectroradiometer (MODIS; Hall et al. 2002; Painter et al. 2009), and 1000-m resolution  
478 Advanced Very High Resolution Radiometer (AVHRR; Ramsay, 1998; Romanov et al. 2000).  
479 These datasets have been used to construct a Climate Data Record of northern hemisphere SCA  
480 from 1966-present (Estilow et al. 2015).

481  
482 Ground-based observations of snow depth can be obtained through intensive depth probe sampling  
483 (Elder et al. 1991), photographs (Tappeiner et al. 2001; König and Sturm, 1998), and snow pits  
484 (e.g., Cline et al, 2004) along with ground-based and airborne radar (Machguth et al. 2006) and  
485 lidar (Deems et al. 2013). Ground-based measurement of SWE is done through snow pillows with  
486 pressure transducers (Beaumont, 1965). Routine airborne SWE monitoring is conducted over  
487 CONUS using gamma ray sensing (Carroll and Carroll, 1989; Carroll, 2001). Satellite-based  
488 monitoring of snow depth has been demonstrated with passive microwave sensors (Chang et al.  
489 1987; Kelly et al. 2003; Kelly, 2009), despite issues of signal saturation for  $SWE > 200\text{mm}$  and loss  
490 of signal in heavily forested areas (Vuyovich et al. 2014). To overcome some of the limitations of  
491 the passive microwave approach, the community generally favors an integrated approach among  
492 multiple satellite sensors (Frei et al. 2012). Alternatives that have been shown to work well in  
493 mountainous regions such as lidar (Painter et al. 2016) and Ka- and Ku-band radar (Hedrick et al.  
494 2015; Liao et al. 2016) are recommended in the most recent National Academies Decadal Survey

495 of Earth Sciences and Applications from Space (National Academies of Sciences Engineering and  
496 Medicine, 2018).

497 *d. Soil moisture*

498 Soil moisture is significant in its roles as an atmospheric lower boundary condition, a regulator of  
499 near-surface temperature, evapotranspiration, and photosynthesis, an influence on flash flooding  
500 and surface runoff, an indicator of wetness conditions and drought and as the water available to  
501 shallow rooted plants. As discussed in Walker et al. (2004), Robinson et al. (2008), and Peng et  
502 al. (2017), there are many techniques to measure soil moisture with ground instruments, including  
503 gravimetric methods (e.g., Vinnikov and Yeserkepova, 1991), time domain reflectometry (e.g.,  
504 Robinson et al. 2003), capacitance sensors (e.g., Bogaen et al. 2007), neutron probes (e.g.,  
505 Hollinger and Isard, 1994), electrical resistivity measurements (e.g., Samouëlian et al. 2005), heat  
506 pulse sensors (e.g., Valente et al. 2006), and fiber optic sensors (e.g., Garrido et al. 1999). One of  
507 the first efforts to compile ground-based soil moisture into a global database was Robock et al.  
508 (2000). More recently, this effort has been expanded by Dorigo et al. (2011), and over the U.S.  
509 there is a comprehensive data collection effort described by Quiring et al. (2016). As described by  
510 Crow et al. (2012), several in situ networks have been established and expanded with the goal to  
511 evaluate satellite-based soil moisture products. While these networks are primarily focused on in  
512 situ sensors, an exciting development for measuring intermediate-scale soil moisture is via cosmic-  
513 ray neutrons (Zreda et al. 2008). This has led to the development of the Cosmic-ray Soil Moisture  
514 Observing System (COSMOS) soil moisture network, which has expanded from the US to provide  
515 some international coverage.

516

517 Remote sensing of soil moisture is possible because soil moisture changes the surface emissivity  
518 and backscattering properties in microwave frequencies (Schmugge et al. 1974; Njoku and Kong,  
519 1977; Dobson et al. 1985). Surface roughness, vegetation and the presence of rainfall confound  
520 the retrieval of soil moisture. Both active and passive microwave respond to soil moisture signals  
521 from a shallow surface layer, with the 1.4 GHz (L-band) penetrating to about 5 cm, and less at  
522 higher frequencies. Soil moisture products have been generated from numerous sensors, from the  
523 Scanning Multichannel Microwave Radiometer (SMMR) sensor on board Nimbus (launched in  
524 1978) to the most recent ESA Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al. 2016)  
525 launched in 2009, and the NASA Soil Moisture Active and Passive (SMAP) mission (Entekhabi  
526 et al. 2010) launched in 2015. Retrieval algorithms vary from the SMAP single and dual channel  
527 algorithms (O'Neill et al. 2015) and Land Parameter Retrieval Model (LPRM) (Owe et al. 2001;  
528 Owe et al. 2008), to the L-band Microwave Emission of the Biosphere (L-MEB) model (Wigneron  
529 et al. 2003) of SMOS. Radiometers and scatterometers have been shown to provide highly  
530 correlated and somewhat complementary information (de Jeu et al. 2008), and radiometer  
531 algorithm performance has been shown to depend strongly on vegetation and roughness  
532 parameterizations (Mladenova et al. 2014). Recent attention has focused on providing both long  
533 time series soil moisture data records (Dorigo et al. 2017) and fine spatial scale soil moisture  
534 information (Peng et al. 2017) from multiple platforms using a variety of approaches. These  
535 approaches are increasing the relevance of remotely sensed soil moisture for drought assessment,  
536 agriculture, and vadose-zone hydrology (Mohanty et al. 2017).



537 *e. Terrestrial water storage*

538 Terrestrial water storage refers to the all the water stored in and on a column of land, i.e., the sum  
539 of groundwater, soil moisture, surface waters, snow, ice, and wet biomass. It is the freshwater that  
540 enables life on land. It is also one of the four terms in the terrestrial water budget, i.e.,

541

$$542 \quad dS = P - ET - Q \quad (1)$$

543

544 where  $dS$  is the change in terrestrial water storage,  $P$  is precipitation,  $ET$  is evapotranspiration, and  
545  $Q$  is runoff from a given study area. Defining that study area as a watershed, river basin, or other  
546 closed hydrologic unit facilitates the application of equation 1. Of the four terms,  $dS$  and  $ET$  are  
547 the most difficult to measure, and over the years many researchers have chosen to assume that  $dS$   
548 is negligible in order to close the water budget or to infer  $ET$  – an increasingly dubious assumption  
549 as the study period shortens. Mintz and Serafini (1992) recognized the importance of  $dS$  and were  
550 among the first to account for it in a water budget analysis. Nevertheless, due to the difficulty of  
551 obtaining coincident measurements of all the terrestrial water storage components, only a few  
552 studies paid serious attention to the left side of equation 1. In particular, Yeh et al. (1998) and  
553 Rodell and Famiglietti (2001) assessed variations in terrestrial water storage using in situ  
554 observations of groundwater, soil moisture, snow depth, and reservoir storage from Illinois. They  
555 showed that the interannual variations in groundwater and terrestrial water storage in Illinois were  
556 of the same order of magnitude as those of soil moisture, thereby casting doubt on studies that  
557 relied on the assumption of  $dS$  equaling zero over the course of an annual cycle. Despite advances  
558 in hydrogeophysics (Binley et al. 2015), direct measurement of this term has been most successful  
559 from the vantage point of space.

560

561 Our ability to measure terrestrial water storage changes from space is somewhat serendipitous. In  
562 the 1980s and 1990s, geodesists, who measure the precise shape of the Earth and its gravity field,  
563 had been searching for a way to improve space based gravity measurement. The first satellite  
564 dedicated to this purpose, Lageos, looked like a silver-colored ball; it was an uninstrumented,  
565 mirrored sphere used for laser ranging from Earth's surface. By measuring departures from its  
566 predicted orbit, the geodesists could map irregularities in Earth's static gravity field. Yoder et al.  
567 (1983) inferred that Lageos and other satellites were also sensitive to temporal variations in the  
568 gravity field caused by atmosphere and ocean circulations and the redistribution of water on the  
569 land. Geodesists proposed that in order to measure those orbital departures with enough precision  
570 to quantify mass changes with a useful degree of accuracy, the measurements would have to be  
571 made by another, co-orbiting satellite (Dickey et al. 1997). Thus was born the Gravity Recovery  
572 and Climate Experiment (GRACE) satellite mission, developed jointly by NASA and two German  
573 agencies. GRACE, which launched in 2002 and continued operating until 2017, used a K-band  
574 microwave system to measure the distance (~100-200 km) between two identical, co-orbiting  
575 satellites, with micron level precision. Over the course of each month, these measurements were  
576 used to produce a new map of Earth's gravity field that was accurate enough that month to month  
577 changes in terrestrial water storage could be estimated, after using ground based measurements  
578 and models to remove the effects of atmospheric and oceanic mass changes (Wahr et al. 1998;  
579 Tapley et al. 2004).

580

581 Hydrologists were slow to embrace GRACE due to its data being much different from anything  
582 they had previously seen. In particular, relative to other remote sensing measurements the spatial

583 resolution of GRACE is extremely low – on the order of 150,000 km<sup>2</sup> at mid-latitudes (Rowlands  
584 et al. 2005; Swenson et al. 2006). GRACE only provided month to month changes in terrestrial  
585 water storage with a multi-month time lag, whereas most remote sensing systems provide  
586 instantaneous observations with latencies that range from a few hours to a week. Finally, GRACE  
587 provides no information on the vertical distribution of the observed terrestrial water storage  
588 changes, leaving it to hydrologists armed with auxiliary data and models to determine how much  
589 each of the water storage components contributed to an observed change. As a result of these  
590 unusual characteristics GRACE data have been misinterpreted and misused by researchers in  
591 numerous instances, which has caused others to dismiss GRACE entirely (e.g., Darama, 2014;  
592 Alley and Konikow, 2015; Sahoo et al. 2016).

593  
594 Nevertheless, because satellite gravimetry is currently the only remote sensing technology able to  
595 discern changes in water stored below the first few centimeters of Earth’s surface, GRACE caused  
596 a revolution in water budget hydrology. Among the highlights, GRACE enabled closure of the  
597 terrestrial water budget and estimation of evapotranspiration as a residual (Rodell et al, 2004;  
598 Swenson and Wahr, 2006; Rodell et al. 2011), determination of ice sheet mass changes (Luthcke  
599 et al. 2006; Velicogna and Wahr, 2005; 2006), ablation of major glacier systems (Tamisiea et al.  
600 2005; Chen et al. 2007; Luthcke et al. 2008), estimation of groundwater storage changes (Rodell  
601 et al. 2007) and trends (Rodell et al. 2009; Richey et al. 2015), enhanced drought monitoring  
602 (Houborg et al. 2012; Thomas et al. 2014), effects of terrestrial water storage changes on sea level  
603 (Boening et al. 2012; Reager et al. 2016), and improved understanding of seasonal and interannual  
604 variability of and human impacts on the global, terrestrial water cycle (van Dijk et al. 2014;  
605 Humphrey et al. 2016; Rodell et al. 2018). By 2010 the importance of GRACE to multiple

606 disciplines became so clear that NASA promoted the GRACE Follow On mission ahead of several  
607 other missions which had been recommended by the 2007 Decadal Survey in Earth Sciences  
608 (National Research Council, 2007). GRACE Follow On launched successfully on 22 May 2018.  
609 While it will provide only a small improvement in resolution and accuracy over GRACE, it will  
610 ensure continuity of the terrestrial water storage data record.

611 *f. Evapotranspiration*

612 Measuring actual evapotranspiration (ET) directly is difficult, and as discussed above, reviews of  
613 theory and methods can be found in Brutsaert (1982) and Dolman (2005). The original  
614 measurement techniques included evaporation pans and weighing lysimeters, and more recent  
615 approaches include energy balance/bowen ratio, eddy covariance, sap flow, isotopes, and  
616 fluorescence (e.g., Wilson et al. 2001; Shuttleworth, 2007). For a handy reference summarizing  
617 these techniques, see Shuttleworth (2008). Networks of flux stations (FLUXNET; Baldocchi et  
618 al. 2001) are now prevalent, and approaches to postprocess these observations to address the  
619 closure problem (e.g., Twine et al. 2000) are required for comparisons among different approaches.  
620 Further, because the spatial footprint or “fetch” of these ground-based measurements is limited,  
621 empirical “upscaling” approaches (e.g., Jung et al. 2009) are required to produce gridded  
622 observations for global hydroclimatological analysis (e.g., Jung et al. 2010).

623

624 Remote sensing of ET is based on a number of techniques that depend on temperature, as  
625 summarized by Kalma et al. (2008). Popular variants of these techniques include Surface Energy  
626 Balance Algorithm for Land (SEBAL; Bastiaanssen et al. 1998), Surface Energy Balance System  
627 (SEBS; Su, 2002), Mapping Evapotranspiration with Internalized Calibration (METRIC; Allen et

628 al. 2007), Simplified Surface Energy Balance (SSEB; Senay et al. 2011), Atmosphere-Land  
629 Exchange Inverse (ALEXI; Anderson et al. 2011). Other remote-sensing based methodologies  
630 augment the temperature signal with weather model data and vegetation information from MODIS  
631 to apply the Penman-Monteith approach (e.g., Mu et al. 2011), or augment the temperature signal  
632 with other remote sensing data, soil water, interception, and stress accounting and apply a  
633 Priestley-Taylor approach (e.g., Global Land surface Evaporation: the Amsterdam Methodology—  
634 GLEAM; Miralles et al. 2011; Martens et al. 2017). Vinukollu et al. (2011) provided the first ever  
635 moderate resolution estimates of ET on a global scale using only remote sensing based inputs. The  
636 recent GEWEX LandFlux project evaluated multiple global ET products, ranging from models to  
637 remotely sensed, and found that no single approach outperformed the other (e.g., McCabe et al.  
638 2016).

639 *g. Surface water stage and discharge*

640 In traditional hydrology, discharge (streamflow) at a stream location is considered a functional  
641 integration of the various surface and sub-surface hydrologic processes that occur in the area  
642 draining through that point. Measurement of this hydrologic variable forms the cornerstone of  
643 calibration and validation of hydrologic models, development of flow routing schemes and  
644 assessment of flow forecasting skill. In more recent times, as process-based understanding  
645 improved in hydrology, the importance of streamflow as a relatively easy to measure descriptor  
646 (using stage discharge relationship) only increased further. This is because streamflow can also  
647 exhibit signatures of the mechanistic role played by land cover change (deforestation), land-surface  
648 interactions, surface-groundwater interactions, climate and weather change, drought and fluvial  
649 processes, and of course water management (see section 5).

650

651 Governments of the developed world have built extensive networks of river and stream gauges to  
652 track the flow (Hannah et al. 2011). For example, the Global Runoff Data Centre (GRDC) archives  
653 data from more than 9200 gauges worldwide, and the US Geological Survey (USGS) collects real-  
654 time streamflow data at nearly 10,000 locations within the United States. Such streamflow data  
655 records have played a vital role in the continued development of hydrologic, land-surface, climate  
656 and earth system models today.

657

658 A key limitation of conventional streamflow monitoring using stage discharge relationship is two-  
659 fold. First, such networks do not exist in developing countries of the world where most often there  
660 are no records of streamflow in rivers along the reach. Even if records were maintained, they are  
661 usually not shared openly as is the norm in developed countries (Hossain et al. 2014). Second,  
662 point-based stage monitoring of discharge is able to only capture the flow that passes through a  
663 one-dimensional point. Such measurements do not capture the two-dimensional exchange of water  
664 mass that can occur laterally, especially in wetlands, floodplains and braided rivers. In response to  
665 the first limitation, remote sensing community has been using satellite radar altimeters that were  
666 originally designed for ocean monitoring, to build a steady record of river heights (Birkett, 1998;  
667 Gao et al. 2012) and lake and reservoir elevations (Birkett et al. 2011). For both limitations,  
668 scientific community is now eagerly awaiting a proposed satellite mission, the Surface Water  
669 Ocean Topography (SWOT; Alsdorf et al. 2007), scheduled for launch in 2021, SWOT mission  
670 will provide the community with a more spatially distributed estimate of the flow in water bodies.  
671 With its global sampling from space of water elevation, its temporal change, and its spatial slope  
672 in fluvial environments, as well as across lakes, reservoirs, wetlands, and floodplains,

673 (Biancamaria et al. 2016), SWOT measurements are expected to contribute to the further  
674 understanding of global scale hydrology.

## 675 **4 Hydrologic Prediction Across Scales**

### 676 *a. Background*

677 Hydrologic forecasting is one of the earliest applications of hydrologic theory, with deep roots in  
678 engineering, and particularly civil engineering in support of water systems management (Anderson  
679 and Burt, 1985). The need to anticipate and respond to hydrologic variability and the associated  
680 impacts on water uses and hazards has motivated the practice of hydrologic forecasting for much  
681 of the last century, and it is now a valuable part of operational services in most of the world's  
682 nations (Emerton et al, 2016; Adams and Pagano, 2016). Hydrologic forecasting applications most  
683 often target time scales from minutes to seasons, and focus not only on extreme events (droughts  
684 and floods), but also the entire spectrum of hydrologic variation in which even moderate departures  
685 from normal can affect water operations, management and planning across a broad range of  
686 sectors. Over the last century, scientific and technological advances have driven a steady growth  
687 in forecast capabilities, culminating in a modern landscape of forecasting in which the advent of  
688 high performance computing, broadband connectivity, and global high resolution geophysical  
689 datasets are transforming long-held traditional paradigms of operational prediction.

690 The concept of seamlessness (of models, data, methods and information products across space and  
691 time) is commonly touted as a development objective for hydrological forecasting systems as well  
692 as weather and climate forecasting systems (Wetterhall and Di Giuseppe, 2017; Hoskins, 2013).  
693 Yet for hydrologic forecasting, the strong foundation of engineering pragmatism coupled with

694 limitations in methods, tools, data and scientific understanding have produced a fragmented,  
695 rapidly evolving variety of approaches and operational practices. Forecast products and services  
696 have traditionally been distinct along lead time scales and space scales – from the localized  
697 minutes-to-hours ahead phenomenon of flash flooding, to river stage and flow prediction at the  
698 river basin scale over periods of hours to days, to long range seasonal runoff and drought prediction  
699 which may span multiple river basins and focus on time-space-averaged predictands (e.g., seasonal  
700 snowmelt runoff). The dominant hydrologic processes, and the applicability of data, models and  
701 methods in each area are different, hence the operational pathways toward harnessing  
702 predictability have also differed, leading to multiple views on forecasting development strategies.  
703 For example, despite substantial progress in groundwater modeling (as noted above in Section 2d)  
704 and understanding interactions between surface water and groundwater (Brunner et al. 2017),  
705 groundwater level short-to-medium range forecasting relies to a greater extent on statistical and  
706 machine learning techniques (e.g., Daliakopoulos, et al. 2005) than on process based modeling  
707 (e.g., Prudhomme et al. 2017). Most surface-water hydrologic forecasting efforts supporting water  
708 management include only simplified representations of groundwater, if any.

709 Efforts to develop a spatially and temporally seamless paradigm over the last 15 years have yielded  
710 a proliferation of medium-to-high resolution applications of hydrologic models for continental to  
711 global-extent prediction – a trend resulting from the ready availability of high performance  
712 computing (HPC) resources, the ease of sharing models and methods, the accessibility of  
713 continental and global meteorological, hydrological, and extensive geophysical attributes datasets,  
714 including those derived from satellite-based remote sensing. This development has paralleled the  
715 migration of hydrology as a discipline taught in engineering schools towards an application of the  
716 geosciences, and a reframing of hydrologic forecasting from an engineering practice supporting



717 water resources management toward the view of prediction as an Earth Science grand challenge.  
718 Today the fit-for-purpose traditional forecasting practice and the fledgling Earth Science  
719 prediction science co-exist, with the latter clearly on the rise. It is therefore timely to review the  
720 evolution of hydrologic modeling and forecasting for major phenomena, the better to understand  
721 the opportunities and challenges as new forecasting approaches arrive. In this section, we focus  
722 primarily on hydrometeorological prediction.

723 *b. Seasonal forecasting*

724 Hydrologic forecasts at seasonal scales (with multi-month lead times and predictand durations)  
725 predate the use of computers in hydrology (which began in the 1960s) by decades. The earliest  
726 seasonal operational forecasts, which are still today among the most economically valuable, were  
727 for peak seasonal runoff, as driven by phenomena such as snowmelt or monsoon season rainfall.  
728 Statistical methods have long been used to relate estimates of watershed variables including  
729 snowpack and accumulated moisture from rainfall (and in the last 25 years, climate indices and  
730 forecasts) to future runoff, often achieving high skill ( $r^2 \sim 0.9$ ). In the US, the Department of  
731 Agriculture's SCS, now NRCS, began the practice in the mid-1930s, and was joined in 1944 by  
732 the NWS in issuing forecasts (Pagano et al, 2014; Helms et al, 2008). For most of their history,  
733 seasonal predictions have been probabilistic, providing a range of uncertainty, and currently help  
734 to inform water allocation decisions in major reservoir systems.

735 The development and adoption of computer-based conceptual catchment hydrology models in the  
736 late 1960s and early 1970s (e.g., Burnash, 1973) enabled a new 'dynamical' approach to seasonal  
737 hydrologic forecasting, now called 'Ensemble Streamflow Prediction' (ESP: Day, 1985; Wood et  
738 al, 2016). ESP involves running a real-time continuous hydrologic model simulation to estimate

739 current watershed conditions, and then using these moisture states to initialize forward simulations  
740 based on a sample of historical weather sequences to project watershed conditions ahead into the  
741 forecast period. Different forms of ESP provide the central method used operationally in countries  
742 around the world, and ESP complements statistical volume forecast techniques by providing  
743 ensembles of streamflow sequences, often at the daily or sub-daily time step used in the hydrology  
744 model, from which a range of predicted variables of interest can be calculated (such as daily peak  
745 flow magnitude, timing and probabilities). Such streamflow sequences are commonly used to  
746 estimate runoff volume probabilities or input directly into reservoir operations models to calculate  
747 probabilities of future system states and outputs, given specific release policies (eg, Kistenmacher  
748 and Georgakakos, 2015).

749 In the early 2000s, ensemble seasonal hydrologic forecasting began to attract attention in the land  
750 surface modeling research community (Wood et al, 2002; Luo and Wood, 2008; Wood and  
751 Lettenmaier, 2006), leading to the development of LSM-based national, continental and global  
752 scale forecasting systems using ESP in addition to alternatives involving downscaled climate  
753 forecast model outputs (Duan et al, 2018). These large-domain LSM-based seasonal forecast  
754 systems, however, often lack several critical elements that increase skill in the traditional,  
755 operational lumped-model seasonal forecast issued from regional or small national centers. In  
756 particular, such centers perform comprehensive model calibration as well as data assimilation  
757 (mostly manual) to reduce and correct initial hydrologic state errors and thereby improve forecasts.

758 The practice of using parameter estimation and optimization to support the use of low-dimensional,  
759 agile conceptual models in gaged basins and for streamflow forecasting has spurred extensive  
760 research and practical successes, yielding widely-used techniques such as the Shuffled Complex  
761 Evolution (SCE; Duan et al, 1992) method, and leading to innovative multi-method packages (e.g.,

762 Mattot, 2017) and theoretical advancement toward joint parameter-state estimation approaches  
763 (e.g., Vrugt et al, 2006). Research into hydrologic model data assimilation has also provided a  
764 broad range of promising variational and ensemble techniques that have been shown in watershed-  
765 scale research applications to benefit not only simulation but also forecasting (Liu et al. 2012).  
766 These parameter estimation and DA practices remain less developed and effective for large-  
767 domain, regional to national scale LSM-based hydrologic prediction systems. This is due in large  
768 part on the inability of such methods in large-domain applications to rely directly on watershed  
769 observations such as gaged streamflow, versus on remotely sensed hydrologic variables such as  
770 soil moisture or snow cover. Regional parameters, may be estimated through schemes that either  
771 assign or calibrate relationships between terrain attributes and model parameters (e.g., Samaniego  
772 et al, 2010), or leverage similarity concepts or proximity to transfer parameter values estimated in  
773 well-gaged locations to ungaged locations (Wagener and Wheater, 200). Both techniques are  
774 critical important to the success of large-domain hydrologic forecasting, and are active areas of  
775 current research.

776 The heightened profile of seasonal hydrologic prediction in a research context has also spurred a  
777 new research thrust into quantifying seasonal hydrologic predictability and frameworks for the  
778 attribution of prediction skill to sources including initial hydrologic conditions (IHCs; primarily  
779 soil moisture and snow water equivalent) and future meteorological variability (Wood and  
780 Lettenmaier, 2008; Paiva et al, 2012; Mahanama et al, 2012; Wood et al, 2016). The strong role  
781 of IHCs in seasonal forecast skill argues that continued development of watershed modeling,  
782 observational monitoring and data assimilation is critically important. To enhance skill at longer  
783 lead times and for seasons in which the role of climate variability is large, however, sub-seasonal

784 to seasonal climate forecasting inputs for hydrologic prediction offer a compelling area of  
785 investigation (see Wetterhall et al, 2016).

786 *c. River Flood forecasting*

787 Modern river flood forecasting traces back to the development and application of computer-based  
788 watershed models in the late 1960s and 1970s (e.g., Crawford and Linsley, 1966), and the  
789 techniques employed reflect the engineering heritage as well as limitations of the early decades of  
790 computer use. The capability began with discrete event forecasting based on relatively simple,  
791 empirical or statistical models, the earliest of which were essentially graphical in nature --  
792 capturing observable relationships between rainfall, soil wetness, and future runoff for short lead  
793 times. Early techniques such as the use of antecedent precipitation index (API) models (Fedora  
794 and Beschta, 1989; O'Connell and Clarke, 1981) still exist operationally in parts of the world  
795 today, but have for decades been superseded by forecasting based on continuous watershed  
796 models.

797 The same models and software systems that brought dynamical (model-based) methods to the  
798 seasonal forecast context were among those used in the continuous river flood context, including  
799 the NWS River Forecast System (Anderson, 1972), which centered on conceptual snow and soil  
800 moisture accounting models within a system providing broad array of analytical and interactive  
801 techniques, e.g., for model calibration, state updating and post-processing. Some national-scale  
802 operational forecasting capabilities in the US and elsewhere (Pechlivanidis et al, 2014; Emerton et  
803 al, 2016) still rely heavily on such continuous conceptual model-based approaches, run in regional  
804 or national river forecasting centers. The most common application of these models remains  
805 relatively low-dimensional, favoring lumped discretization of small watershed areas (on the order

806 of 10-500 km<sup>2</sup>), enabling manual effort to be applied for calibrating models and for updating their  
807 inputs, states, and outputs in real-time during the forecasting workflow.

808 With the strengthening connection of the operational forecasting to Earth Science, the vastly  
809 improved geophysical datasets described above and the rapid advances in computing resources,  
810 the last decade has seen an unprecedented expansion in the range and complexity of modeling  
811 approaches currently being implemented for river forecasting at short to medium ranges (out to  
812 several weeks). The development and deployment of distributed ‘macroscale’ (order 100 km<sup>2</sup>  
813 spatial resolution) hydrology models in the 2000s for continental and global scale domains as part  
814 of land data assimilation systems (LDAS; Mitchell et al, 2004; Rodell et al, 2004) was a notable  
815 step toward a broader convergence between parameterization approaches in watershed-scale  
816 hydrological models and global-scale land surface models (LSMs) used in coupled climate models  
817 and as initial conditions for NWP. These large-domain LSMs were operationalized in research  
818 and agency settings for monitoring and prediction applications (Wood and Lettenmaier, 2006;  
819 Thielen et al, 2009; Alfieri et al, 2013), adopting techniques such as ESP from traditional seasonal  
820 forecasting. At the watershed scale, high resolution distributed process-oriented models also were  
821 implemented for forecasting applications, primarily at a local scale (Westrick et al, 2002).

822 Today, traditional river flood forecasting using conceptual models is joined by two new major  
823 operational river forecasting paradigms that leverage scientific advances and technical strategies  
824 from the field of Earth System Modeling (ESM). One is the application of very high-resolution  
825 watershed models (order 100m horizontal resolution) for national to continental domains,  
826 incorporating explicit hydrologic vertical and lateral fluxes at the model grid scale. Such  
827 computational demanding modeling is enabled by HPC and code parallelization, in some cases  
828 resourcing 1000s of cores, and places a new emphasis on the need to resolve long-standing

829 hydrologic modeling challenges. In particular, the vast increase in the distributed parameter space  
830 coupled with the cost of simulation has underscored the need for efficient parameter estimation  
831 and regionalization approaches. A recent example of such an approach is the NWS National Water  
832 Model (NWM; Figure 5), which produces distributed, deterministic river flood predictions and  
833 other hydrometeorological outputs for every 250m of the US (Salas et al, 2018).

834 A second major paradigm to emerge centers on the development and application of ensemble  
835 techniques for forecasting (Duan et al, 2018), using either conceptual or intermediate scale  
836 hydrologic models, with the objective of ‘Completing the Forecast’ (National Research Council,  
837 2006) -- i.e., providing forecasts with uncertainty estimates that can be used for risk-based  
838 decision-making. In the last 15 years, ensemble prediction has made great strides in the US and  
839 internationally, facilitated in part by the international Hydrologic Ensemble Prediction Experiment  
840 (HEPEX; Schaake et al, 2007) launched in 2004. A key challenge in the ensemble prediction  
841 context is the provision of probabilistic forecasts that are as accurate (sharp) as possible while  
842 maintaining statistically reliable spread (uncertainty) (Werner et al, 2016). Ensemble river  
843 prediction systems now co-exist with traditional forecasting systems in a number of countries;  
844 examples include the US NWS Hydrologic Ensemble Forecast Service (HEFS; Demargne et al,  
845 2014) and the European Flood Awareness System (EFAS; Thielen et al, 2009), which coordinates  
846 with national hydrometeorological services to provide forecast services across Europe.

#### 847 *d. Flash flood forecasting*

848 Flash flooding is one of the most damaging water-related hazards, particularly from a human life  
849 standpoint (with over 100 lives lost per year), but for most of the last century and in many countries  
850 today, the responsibility for forecasting of flash floods has been carried out by meteorological

851 rather than hydrological services. This organization follows from both the distributed nature of  
852 flash flooding, in that deadly torrents of water can be generated on small creeks and washes that  
853 were not explicitly modeled in traditional river flood prediction systems, and the fact that flash  
854 flooding is proximally driven (far more than river flooding) by meteorological events, rather than  
855 a combination of rainfall inputs and subsurface fluxes (eg baseflow, interflow). For decades, flash  
856 flood watches and warnings have been a central alert category of the NWS, but were undertaken  
857 by weather forecast offices (WFOs) rather than RFCs, and issuing products describing areas or  
858 regions of risk (polygons on a map), rather than explicit locations with a quantitative high flow  
859 forecast.

860 Such products were originally generated from meteorological forecast maps alone, and have  
861 steadily improved in the last four decades. Progress in several foundational scientific and technical  
862 areas have driven these advances. Rainfall monitoring has benefited from improvements in the  
863 quality of multi-sensor products and objective analysis techniques, and forecasting has leveraged  
864 higher resolution and more accurate NWP. Improved satellite-based description of terrain and  
865 landcover have enabled hyper-resolution digital elevation models (DEMs) and runoff routing  
866 schemes. Hydrologic simulation has evolved from lumped, conceptual models to the development  
867 and implementation of ever-finer resolution distributed hydrologic models (Wigmosta et al, 1994;  
868 Bierkens et al, 2015) that can make use of distributed meteorological inputs.

869 The first of such distributed hydrology models to be applied operationally on large domains were  
870 intermediate scale, as exemplified by the the 1/8th degree multi-agency National Land Data  
871 Assimilation System (NLDAS) project LSMs, beginning in 1998 (Mitchell et al, 2004) and the 4-  
872 km NWS Hydrology Laboratory Research Distributed Hydrologic Model (HL-RDHM; Koren et  
873 al, 2004). At a finer resolution, the 1-km distributed NWS Flooded Locations and Simulated

874 Hydrographs (FLASH) system in 2012 also began providing 1-km, 5-minute channel estimates of  
875 flash flood risk, based on the percentiles of simulated and routed flow relative to a background  
876 climatology (Gourley et al, 2014). Since 2016, the 250-m National Water Model (NWM) has  
877 issued quantitative 0-2 day channel lead flow predictions for a channel network defined by the  
878 USGS NHDPlus hydrography dataset, which includes 2.7 million river reaches.

879 Flash flood forecasting has commonly taken the form of ‘Flash Flood Guidance’ (FFG; Carpenter  
880 et al, 1999; Georgakakos 2006), in which models -- initially lumped and more recently gridded --  
881 are used to estimate the quantitative capacity of the soil to absorb rainfall, which when combined  
882 with estimates of observed and forecasted precipitation, characterizes flood risk. In the distributed  
883 model context, where local calibration of runoff is not possible, a ‘threshold frequency’ concept is  
884 applied in which modeled flows above a certain frequency threshold (e.g., 2 year return period)  
885 relative to past model simulations are indicative of flood risk (Reed et al, 2007). Currently both  
886 lumped and gridded FFG approaches inform operational flash flood watch and warning products,  
887 and the practice has been promoted for international adoption by the World Meteorological  
888 Organization (WMO).

889 The WFO areal alerts and the NWM data products represent the diversity of strategies for flash  
890 flood forecasting, from local assessment resulting from experts integrating hydrometeorological  
891 information, to the automated outputs of a very high resolution LSM. Globally, development is  
892 underway to create fine-resolution, real-time distributed flood risk maps with low latency by  
893 merging satellite-based estimates of land inundation, river level altimetry, NWP and global NWP  
894 model runoff, and even real-time social media streams (ie, Twitter alerts) (Westerhoff et al, 2013).



895 *e. The realization of a hydrologic prediction science*

896 The nascent applications of LSMs and complex watershed models in prediction applications have  
897 unleashed great scientific and pragmatic enthusiasm for a new era of Earth System prediction that  
898 includes hydrological fields as well as more common meteorological ones. Yet the ease at which  
899 data streams can be connected to models, generating real-time outputs that can be called  
900 ‘forecasts’, belies the substantial difficulty in producing not just distributed model output, but  
901 actionable, high quality predictions at the local scales required for water and emergency  
902 management. Myriad, long-standing scientific challenges in hydrologic modeling remain  
903 unsolved (Clark et al, 2017), and are compounded by technical challenges that arise particularly  
904 in the operational forecasting context. Operational river forecasters grapple with these challenges—  
905 e.g., erratic or degraded data streams, model deficiencies, model state and input uncertainties—on  
906 a daily basis, and have a deep, first-hand understanding of the adequacy of hydrological methods  
907 to overcome them. Welles et al. (2007) highlighted the role that objective verification measures  
908 should play in adopting forecast process improvements. Essential techniques include parameter  
909 estimation (or model calibration, e.g., Welles and Sorooshian (2008)), meteorological forecast  
910 downscaling and bias correction, hydrologic data assimilation, hydrologic forecast post-  
911 processing, and accounting for and integrating water management – all of which reduce errors in  
912 model predictions.

913 Fortunately, the gap between the Earth System prediction research community and the operational  
914 river forecasting community is narrowing. The view that current operational methods are ad hoc  
915 or (in the case of model calibration) theoretically unsound, a way of ‘getting the right answer for  
916 the wrong reasons’, is waning as the ESM community begins to understand the role of such  
917 methods and forecasting-related challenges are re-articulated in the language of science. For all

918 the advances of the last decade, modern hydrological models run in a fully-automated, ‘over-the-  
919 loop’ paradigm, without effective, objective counterparts to traditional techniques described  
920 above, often still fail to generate outputs matching the actionable quality of those created by  
921 simpler models using traditional approaches (Smith et al, 2004; Reed et al, 2004; Smith et al. 2013;  
922 Beven et al, 2015). Today, national and global-scale hydrologic forecasting system  
923 implementations successfully reflect large-scale variability but do not bear scrutiny at the local  
924 watershed scale, where river flood impacts are most relevant. To make global scale approaches  
925 usable locally, the Earth System prediction research community must continue to pursue scientific  
926 understanding and methods to improve engineering-based techniques in three key areas: model  
927 parameter estimation, hydrologic data assimilation of observations of all types, and representing  
928 human impacts on the hydrologic cycle.

929 Fortunately, over the last 15 years, a shift in perspective is leading to greater integration of  
930 traditional communities of practice and land surface modeling research. The international, multi-  
931 agency HEPEX initiative has fostered collaboration between communities of hydrologic research  
932 and practice, and promoted the recognition of operational hydrologic prediction as a coherent  
933 scientific sub-discipline rather than an engineering activity. Research funding in the US and  
934 elsewhere has increasingly supported collaborations with operational entities, and sessions on  
935 applied hydrologic prediction in national and international scientific conferences have greatly  
936 expanded. As this integration between traditional operational and research communities grows,  
937 an improved understanding of tradeoffs and limitations in forecasting system components is  
938 beginning to lead to more informed choices as Earth System research strives to create next  
939 generation prediction systems that provide actionable information at local scales.

940 From a stakeholder perspective as well, the landscape of hydrological forecasting is changing  
941 dramatically. For most of the last century, for a given river location, at most one deterministic  
942 flood forecast was available from the regional forecast center, using a locally tailored conceptual  
943 watershed model. Today, multiple forecasts for a given US location can be viewed and  
944 downloaded, including one from the NWM and additional ensemble predictions from global  
945 forecasting systems run outside of the US. For some of these systems, the runoff is even extracted  
946 from the land surface models of coupled global models (e.g., NWP systems), rather than from  
947 offline LSMs (Gaborit et al, 2017). These developments are ushering in a hydrologic forecasting  
948 future that is marked by an expansion from local and regional forecasting approaches toward  
949 national, continental, and global scale hydrologic prediction systems, run in centralized over-the-  
950 loop modes.

951 Improvements in forecast quality will come through a range of advances: better earth system  
952 modeling (including coupled NWP and climate prediction) and creative, efficient solutions for  
953 representing space-time heterogeneity (e.g., Peters-Lidard et al, 2017); improved observational  
954 data through data fusion and assimilation of satellite-based observations as well as non-traditional  
955 observations from social media; the adoption of reliable uncertainty frameworks; and the use of  
956 increasingly sophisticated statistical techniques (e.g., deep learning) merged in hybrid frameworks  
957 with dynamical modeling. The overarching scientific and community challenge facing the field  
958 today is the need to connect local knowledge and information to large-domain approaches, and in  
959 turn to make national to global system predictions relevant locally. With greater integration of the  
960 entire hydrologic prediction community -- including those in research, in operations, and  
961 stakeholders -- this challenge can be surmounted.

## 962 5 The Emergence of Global Hydrology

### 963 a. Key Milestones

964 As people gained the ability to travel more quickly and routinely across continents and around the  
965 world in the 20th century, it was inevitable that they would come to recognize the global  
966 connectivity of Earth's physical processes and systems, including the water cycle. Voeikov (1884)  
967 and Murray (1887) had the foresight to assess worldwide, terrestrial precipitation, evaporation,  
968 and runoff well before global scale meteorological measurements began to be collected  
969 systematically. Murray's (1887) global terrestrial precipitation estimate is particularly impressive,  
970 being only about 5-10% larger than the average of estimates from the 2000s (Figure 6a).  
971 Fritzsche's (1906) global terrestrial precipitation estimate was even better, but most studies  
972 misestimated evapotranspiration and/or runoff until Lvovich's (1972) published values that remain  
973 very close to the most modern estimates. Brückner (1905) and Fritzsche (1906) provided the first  
974 global ocean precipitation and evaporation estimates. Amazingly, they were only about 10%  
975 below modern estimates (Figure 6b). Mather (1969) and Baumgartner and Reichel (1973; 1975)  
976 were the first to hit the mark with both ocean evaporation and precipitation, based on recent  
977 estimates. Baumgartner and Reichel's (1975) and Budyko and Sokolov's (1978) land and ocean  
978 flux estimates, with some updates from Chahine (1992) and Oki (1999), continued to be used as  
979 benchmarks until Oki and Kanae (2006) and Trenberth et al. (2007) delivered updated global water  
980 balance assessments.

981  
982 A decade after Baumgartner and Reichel's (1975) comprehensive treatise on the global water  
983 balance, Eagleson (1986) announced the "Emergence of Global-Scale Hydrology" and evaluated  
984 the state of global hydrological modeling at that time. Chahine (1992) helped to establish the

985 global hydrology community in his review paper on the hydrological cycle and its influence on  
986 climate, declaring that, "In the short span of about 10 years, the hydrological cycle has emerged as  
987 the centrepiece of the study of climate, but ... rather than fragmented studies in engineering,  
988 geography, meteorology and agricultural science, we need an integrated program of fundamental  
989 research and education in hydrological science." Other important milestones included Berner and  
990 Berner's (1987) thorough physical and chemical description of the water cycle, and Mintz and  
991 Serafini (1992) recognizing the importance of water storage in the land when they published a  
992 global, monthly climatology of world water balance.

993

994 *b. Remote Sensing of the Global Water Cycle*

995 In 1958 NASA's Explorer 1 satellite launched and provided imagery of clouds and snow cover  
996 that revolutionized the way scientists thought about the water cycle. Other satellites soon began  
997 to improve our ability to observe Earth from space, and in 1972 the Blue Marble photograph from  
998 Apollo 17 inspired a new generation of Earth scientists and conservationists. During that seminal  
999 period of space exploration, the study of hydrology at continental to global scales began to  
1000 accelerate. The difficulty in extrapolating limited point observations to those scales soon became  
1001 clear, which was one of the motivations for satellite remote sensing of the global water cycle, and,  
1002 more broadly, the entire Earth system (Famiglietti et al. 2015).

1003

1004 The first several satellites that were useful for studying the water cycle were not designed for that  
1005 purpose. The TIROS-1 satellite delivered fuzzy, black-and-white images of Earth in 1960, which  
1006 elucidated the large-scale patterns of cloud and snow cover. The NASA/USGS Landsat series of  
1007 satellites, which began in 1972, has provided increasingly higher resolution imagery that has been

1008 useful for delineating and monitoring the extent of snow cover, glaciers, surface water bodies,  
1009 different types of vegetation and land cover, and irrigation, and for estimating evapotranspiration.  
1010 The first satellite in NOAA's Geostationary Operational Environmental Satellites (GOES) series  
1011 was launched in 1975, providing visible and infrared imagery that have been essential for weather  
1012 forecasting and similarly valuable for hydrometeorological studies. As described in section 3,  
1013 satellite remote sensing now enables global scale observation of precipitation, soil moisture,  
1014 terrestrial water storage, snow cover depth and snow water equivalent, evapotranspiration, lake  
1015 elevation, and soon river discharge. The integration of these capabilities has transformed research  
1016 on the global water cycle. Lettenmaier et al. (2015) provides a detailed overview of the  
1017 contributions of remote sensing to hydrologic science, while McCabe et al. (2017) describes future  
1018 prospects in this area.

1019

### 1020 *c. Global Scale Hydrological Modeling*

1021 Global modeling of the water cycle is motivated by multiple considerations. For one, we cannot  
1022 currently observe the water cycle globally with adequate resolution, accuracy, and continuity.  
1023 While remote sensing can provide global coverage, the observations themselves typically are  
1024 derived using retrieval algorithms that have to be calibrated and require simplifying assumptions,  
1025 both of which introduce error. Second, global models can be used to investigate different climate  
1026 change or paleoclimate scenarios and test sensitivities to natural properties and anthropogenic  
1027 influences. Third, our proficiency in modeling the water cycle at the global scale provides insight  
1028 into our understanding of the Earth system. Fourth, global land surface models can be coupled to  
1029 Earth system models or used to integrate data from multiple observing systems. Finally, running

1030 a hydrological model at the global scale complements remote sensing or in-situ observing systems  
1031 that are limited by both cost and technology in their ability to provide continuous spatial and  
1032 temporal coverage. Such models, which range from extremely simple water budget equations to  
1033 physically-based, coupled land-atmosphere-ocean models comprising tens of thousands of lines of  
1034 code, have their own weaknesses. In particular, they are constructed using our sometimes-flawed  
1035 understanding of physical processes, they rely on their own simplifying assumptions, and their  
1036 accuracy is limited by that of the input parameters and meteorological variables. Nevertheless,  
1037 global hydrological models have supported a huge number of water cycle studies over the years,  
1038 and they enable sensitivity studies and the analysis of scenarios that could never be tested in the  
1039 real world.

1040  
1041 Global hydrological models were originally developed in order to improve the lower boundary  
1042 condition for atmospheric models. One of the first was Manabe's (1969) "bucket model", which  
1043 he incorporated into the Geophysical Fluid Dynamics Laboratory's general circulation model,  
1044 yielding estimates of the global rates of land surface evaporation. By the mid-1980s, it was  
1045 understood that simplistic land surface representations were creating systematic errors in simulated  
1046 evapotranspiration and hence the overlying atmosphere, leading to the development of more  
1047 sophisticated schemes (Dickinson, 1984). In particular, the Simple Biosphere model (SiB; Sellers  
1048 et al. 1986) and the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al. 1986)  
1049 enabled simulation of the transfers of mass, energy, and momentum between the atmosphere and  
1050 the land surface. Thirty-two years later elements of SiB and BATS, the first soil-vegetation-  
1051 atmosphere transfer schemes, are obvious in the code of many modern land surface models.  
1052 Incorporating the influence of topography on runoff generation and other processes was one of the

1053 next key milestones (Famiglietti and Wood, 1991) along with ways to represent such spatially and  
1054 vertically distributed processes statistically (Famiglietti and Wood, 1994). Around the same time,  
1055 Koster and Suarez (1992) demonstrated a “tiling” approach to modeling multiple different  
1056 vegetation types within a single grid pixel. An explosion of new land surface models ensued,  
1057 which brought about the need for model intercomparison projects. The Global Soil Wetness  
1058 Projects (GSWP) 1 & 2 (Dirmeyer et al. 1999; 2006a) focused on soil moisture and included 10  
1059 and 15 models, respectively, each with their own unique set of advances and simplifications. The  
1060 Water Model Intercomparison Project (WaterMIP; Haddeland et al. 2011) emphasized water cycle  
1061 fluxes and included five coupled models as well as six offline (land only) models.

1062

1063 Owing to exponential increases in computing power, incremental improvements in our  
1064 understanding of water and energy cycle processes, and the availability of more accurate and  
1065 higher resolution forcing and parameter datasets, many global land surface models now run  
1066 routinely (e.g., Alcamo et al. 2003; Rodell et al. 2004) and most weather forecasting agencies have  
1067 implemented advanced land surface modules into their operational systems. Software packages  
1068 like the Land Information System (LIS; Kumar et al. 2006) now allow non-expert users to  
1069 configure and run multiple land surface models for both scientific and practical applications. A  
1070 handful of land surface models have benefitted disproportionately from a community development  
1071 approach and/or implementation by multiple operational agencies that foster their continued  
1072 improvement. Examples include Noah Multiparameterization (Noah-MP; Niu et al. 2011), the  
1073 Community Land Model (Oleson et al. 2010), and the Joint UK Land Environment Simulator  
1074 (JULES; Best et al. 2011). Kumar et al. (2017) concluded that this may be causing a convergence  
1075 of the output from different models.



1076 *d. Community Water Cycle Research Initiatives*

1077 In addition to these individual efforts, the Global Water and Energy Cycle Experiment (GEWEX)  
1078 and other international programs have facilitated community initiatives aimed at improving  
1079 understanding of the global water cycle and its components. Kinter and Shukla (1990) suggested  
1080 a framework for utilizing ground and space based observations during the first phase of GEWEX  
1081 towards the goal of improved understanding of the global water and energy cycles. Sub-projects  
1082 within GEWEX have included global hydrology as an explicit component, such as the Global Soil  
1083 Wetness Project (GSWP) phases 1 & 2, LandFlux, the Coordinated Enhanced Observing Period  
1084 (CEOP), and the GEWEX Hydroclimatology Panel (GHP). The International Geosphere-  
1085 Biosphere Programme (IGBP; 1987-2015) similarly included projects relevant to global water  
1086 cycle and water resources research, such as the Integrated Land Ecosystem-Atmosphere Processes  
1087 Study (iLEAPS) and the Global Water System Project (GWSP). However, the Intergovernmental  
1088 Panel on Climate Change (IPCC), which is perhaps the best known international community Earth  
1089 science initiative, has focused largely on ground and near surface air temperature variations and  
1090 trends, and while water cycle impacts have been considered secondarily. Further, a persistent  
1091 obstacle for studies that is conceived within GEWEX and other community initiatives is that the  
1092 initiatives themselves typically have little or no funding to support the research. NASA's Energy  
1093 and Water Cycle Study (NEWS) program has sought to overcome that issue and combine  
1094 integrative community research with funding support, towards the goal of quantifying water cycle  
1095 consequences of global climate change. Another example of that approach was the European  
1096 Union's Water and Global Change project (EU-WATCH; 2007-2011), which aimed to bring  
1097 together scientists from the hydrology and related communities to improve quantification and  
1098 understanding of global hydrological processes.

1099

1100 *e. Recent Advances in Global Water Cycle Science*

1101 Many of the major advances in global water cycle science in the 21<sup>st</sup> century have involved (1)  
1102 assessing changes in the water cycle and the distribution of water resources, (2) science enabled  
1103 by satellite remote sensing; and/or (3) science enabled by data integrating numerical models with  
1104 ever increasing spatial resolution and sophistication of process representation. Regarding the first,  
1105 Vörösmarty et al. (2000) used climate model predictions together with hydrologic and  
1106 socioeconomic information to assess the vulnerability of water resources to climate change and  
1107 population growth, with startling results. Many related studies followed, including Vörösmarty et  
1108 al.'s (2010) reassessment that also considered threats to biodiversity. Allen et al. (2002) analyzed  
1109 variability of the hydrological cycle during the 20th century in order to evaluate the range of  
1110 possible 21st century changes. Milly et al. (2002) reported an increasing risk of great floods due  
1111 to climate change. Bosilovich et al. (2005) and Held and Soden (2006) analyzed climate model  
1112 output to identify evidence of “intensification” of the water cycle, which refers to the prediction  
1113 of more intense and rapid cycling of water fluxes in a warming environment. Milly et al. (2008)  
1114 warned that water management, which has heretofore relied on the assumption of stationarity –  
1115 natural systems fluctuating within an unchanging range of variability – is imperiled by both direct  
1116 human disturbances and climate change. Brown and Robinson (2011) used a combination of  
1117 ground, airborne, and satellite datasets to estimate that March and April northern hemisphere snow  
1118 cover extent decreased at a rate of ~0.8 million km<sup>2</sup> per decade during 1970–2010. GRACE has  
1119 been used in combination with other data sources to quantify groundwater depletion around the  
1120 world (Rodell et al. 2009; Wada et al. 2012; Döll et al. 2014; Richey et al. 2015; Chen et al. 2016;

1121 Rodell et al. 2018). Nevertheless, Reager et al. (2016) used GRACE data to show that there was  
1122 a net increase in non-frozen terrestrial water storage during 2002-2014, which reduced the rate of  
1123 sea level rise by 15%. Rodell et al. (2015) used an objective optimization approach to combine  
1124 ground and space based observational datasets with data integrating model output, covering the  
1125 first decade of the millennium, while simultaneously closing the water and energy budgets at  
1126 multiple scales. The result was a physically, spatially, and temporally consistent set of estimates  
1127 of the major fluxes and storages of the water cycle at continental, ocean basin, and global scales  
1128 (Figure 7). This analysis is useful as a baseline for assessing future changes in the water cycle and  
1129 for global model evaluations. Other projects have produced global water cycle accountings  
1130 through the assimilation of data into global coupled or offline models (e.g., Rienecker et al. 2011;  
1131 van Dijk et al. 2014; Gelaro et al. 2017; Zhang et al. 2018).

1132  
1133 Modeling improvements and the unprecedented availability of satellite-based observations have  
1134 benefitted global water cycle science enormously, but questions and uncertainty remain. For  
1135 example, while many have predicted an increasing occurrence of drought in a warming  
1136 environment, Sheffield et al. (2012) reported no significant change in drought over 60 years,  
1137 setting off an intense debate in the hydroclimate community. Similarly, when Jasechko et al.  
1138 (2013) used an isotope analysis to estimate that transpiration accounts for 80-90% of  
1139 evapotranspiration globally, the community responded with a slew of alternate interpretations and  
1140 analyses (e.g., Sutanto et al. 2014; Coenders-Gerrits et al. 2014).

1141  
1142 Future breakthroughs in global water cycle science will continue to be fueled by advances in  
1143 remote sensing and modeling. Expansion of remote sensing data records is already enabling  
1144 studies of global change that are less dependent on the sparse network of in situ observations. By

1145 2030, many of these records will be long enough to generate climatologies and to identify trends.  
1146 This is already happening with soil moisture (e.g., Owe et al. 2008; Dorigo et al. 2012) in addition  
1147 to snow cover. While there are serious concerns about the decline of ground based networks that  
1148 are crucial for both long term temporal continuity and calibration of remote sensing retrievals  
1149 (Fekete et al. 2015), an optimistic perspective is that implementation of advanced observational  
1150 approaches, including measurements using signals of opportunity and remote sensing from  
1151 cubesats and unmanned aerial vehicles, will fill gaps and provide a more complete view of the  
1152 water cycle (McCabe et al. 2017).

## 1153 **6 Coupling of Hydrology with the Atmosphere and Ecosystem**

1154 By redistributing surface and subsurface moisture in space and time, hydrological processes have  
1155 an important control over evapotranspiration at the surface and moisture available to plants. Hence,  
1156 hydrological science plays a critical role in understanding and modeling land-atmosphere  
1157 interactions and ecohydrology, the topics of this section discussed below.

### 1158 *a. Coupling of Hydrology with the Atmosphere: Land-atmosphere interactions*

1159 Land and atmosphere can interact through exchanges of water, energy, momentum, and  
1160 biogeochemistry that are influenced by many processes across a wide range of temporal and spatial  
1161 scales. Understanding and modeling surface fluxes of precipitation, evapotranspiration, sensible  
1162 and latent heat, momentum, and aerosol particles and trace gases, as well as the processes that  
1163 control these fluxes are all important for advancing the study of land-atmosphere interactions. In  
1164 the context of this monograph on progress in hydrology, this section focuses mainly on land-  
1165 atmosphere interactions related to soil hydrological processes such as soil moisture, groundwater,

1166 and lateral flow. We note however that the land surface can interact with the atmosphere  
1167 importantly through surface albedo, surface roughness, and biogeochemical processes that  
1168 influence the net energy input to land and surface flux exchanges.

1169

1170 Traditionally, hydrological science has focused on understanding the hydrologic response to  
1171 atmospheric forcing, as mediated by the landscapes at watershed and basin scales, while  
1172 atmospheric science has focused on understanding atmospheric dynamical and physical processes  
1173 that are influenced, to some degrees, by the surface fluxes. Hence, in hydrology, the atmosphere  
1174 was considered an external forcing and provided as an input to hydrologic modeling while in  
1175 atmospheric modeling, land surface processes were ignored or simplified to provide lower  
1176 boundary conditions for atmospheric general circulation models (GCMs). For example, Manabe  
1177 (1969) developed a bucket model to represent surface hydrology in GCMs, which allows time-  
1178 evolving surface evapotranspiration to be calculated as lower boundary conditions for GCMs.

1179

1180 The need to improve the lower boundary conditions in GCMs became more recognized in the  
1181 1980s from studies that investigated the atmospheric response to land surface conditions (Shukla  
1182 and Mintz 1982; Rowntree and Bolton 1983; Mintz 1984) and impacts of deforestation on climate  
1183 (Dickinson and Henderson-Sellers 1988). Efforts to develop land surface models with more  
1184 physically based representations enabled the role of the land surface on climate to be better  
1185 understood. For example, including a physical representation of soil moisture variability in a fully  
1186 coupled ocean-atmosphere-land model, Delworth and Manabe (1993) noted that the presence of  
1187 an interactive soil moisture reservoir increases the variance and adds memory to near surface  
1188 atmospheric variables such as humidity. Studies of precipitation recycling in the 1990s using

1189 gridded observations and analyses further established the role of the land surface in providing  
1190 important sources of moisture for continental precipitation in certain regions (Brubaker et al. 1993;  
1191 Trenberth 1999). Advances in modeling such as development of the Biosphere-Atmosphere  
1192 Transfer Scheme (BATS) (Dickinson et al. 1986) and the Simple Biosphere Model (SiB) (Sellers  
1193 et al. 1986) and observations such as the First International Satellite and Surface Climatology  
1194 Project (ISLSCP) Field Experiment (FIFE) (Sellers and Hall, 1992) and the Boreal Ecosystem  
1195 Atmosphere Study (BOREAS) (Sellers et al. 1995) provided impetus for studying land-atmosphere  
1196 interactions. Readers are referred to Garratt (1993), Entekhabi (1995), Eltahir and Bras (1996),  
1197 and Betts et al. (1996) for reviews of advances in land-atmosphere interaction research through the  
1198 1990s.

1199  
1200 With increasing availability of in-situ and remotely sensed observations, gridded global and  
1201 regional analyses and land data assimilation products, more complex modeling tools, and larger  
1202 and faster computers, studies of land-atmosphere interactions have advanced more rapidly since  
1203 the 2000s. More specifically, the role of soil moisture on precipitation, or soil moisture-  
1204 precipitation feedback, has been investigated extensively using observations and modeling. GCM  
1205 experiments (Koster et al. 2000b) and observations (Yoon and Leung 2015) showed that in some  
1206 mid-latitude continental areas during summer, the impacts of the oceans on precipitation can be  
1207 small relative to the impacts of soil moisture, suggesting that soil moisture memory may provide  
1208 important predictability for summer precipitation from weather to seasonal time scales.

1209  
1210 Locally, soil moisture can influence precipitation through its impacts on the lower level moist  
1211 static energy (MSE) and the partitioning of surface energy flux between sensible and latent heat

1212 fluxes (Betts et al. 1996; Schär et al. 1999). Wetter soils increase the evaporative fraction (EF  
1213 defined as the ratio of latent heat flux to the sum of the latent and sensible heat fluxes) to moisten  
1214 the atmospheric planetary boundary layer (PBL) and lower the levels of lifting condensation and  
1215 free convection, which may trigger convection and enhance precipitation (Findell and Eltahir  
1216 2003). Conversely, sensible heat flux is enhanced relative to latent heat flux over drier soils to  
1217 deepen the PBL and dilute the moist static energy within the PBL. As the PBL grows, more  
1218 rigorous entrainment of drier air from above the PBL further reduces the MSE within the PBL and  
1219 reduces the likelihood of convective triggering and precipitation. Changes in cloud cover may  
1220 further enhance the positive soil moisture-precipitation feedback as increased formation of  
1221 convective clouds over wetter soils may increase the net radiation at the surface if the reduction of  
1222 outgoing longwave radiation by the high clouds overcompensates for the reduction of solar  
1223 radiation due to cloud cover, thus increasing the MSE and convection (Schär et al. 1999; Pal and  
1224 Eltahir 2001).

1225  
1226 Importantly, the sign of the soil moisture-precipitation feedback may depend not only on the  
1227 partitioning of the surface fluxes, which depends on soil moisture (i.e., surface control), but also  
1228 on the atmospheric conditions that determine the levels of lifting condensation and free convection  
1229 (i.e., atmospheric control). The more rapid growth of the PBL over drier soils may allow the PBL  
1230 to reach the level of free convection and trigger convection and precipitation while convection is  
1231 prohibited over wetter soils because the level of lifting condensation may never reach the top of  
1232 the shallow PBL, despite enhanced moisture and MSE by the increased latent heat flux over wetter  
1233 soils (Findell and Eltahir 2003). Soil moisture can also influence atmospheric circulation through  
1234 changes in the thermal gradients near the surface that induce sea level pressure gradients. Changes

1235 in sea level pressure can influence mesoscale circulation such as the Great Plains low level jet  
1236 (Fast and McCorcle 1990) and large-scale circulation systems such as the monsoon systems (e.g.,  
1237 Douville et al. 2001). As soil moisture affects convection, it can also induce changes in the large-  
1238 scale circulation through its impacts on convection and latent heating in the atmosphere.

1239

1240 To quantify the strength of land-atmosphere coupling, Koster et al. (2004; 2006) designed the  
1241 Global Land-Atmosphere Coupling Experiment (GLACE) that provided an ensemble of GCM  
1242 simulations following the same simulation protocol. In GLACE, each GCM was used to perform  
1243 16 simulations in which soil moisture varies in each simulation based on the precipitation produced  
1244 by the model (i.e., land-atmosphere interactions are active). In another set of 16 simulations,  
1245 geographically varying time series of subsurface soil moisture was forced to be the same across  
1246 the simulations (i.e., land-atmosphere interactions are disabled). Comparison of the intra-ensemble  
1247 variance of precipitation between the two sets of simulations yields an estimation of land-  
1248 atmosphere coupling strength for each model. Since GCM representations of atmospheric and land  
1249 surface processes vary, results from an ensemble of 12 GCMs that participated in GLACE provide  
1250 a more robust estimate of land-atmosphere coupling strengths. Koster et al. (2004) identified the  
1251 central U.S., the Sahel, and India as hotspot regions of land-atmosphere coupling (Figure 8).  
1252 However, the use of 12 GCMs in GLACE also reveals large uncertainty in model estimates of  
1253 land-atmosphere coupling strengths (Koster et al. 2006; Guo et al. 2006).

1254

1255 The GLACE experiments motivated many follow-on studies to estimate the land-atmosphere  
1256 coupling strength using observations and modeling experiments. For example, using long-term in-  
1257 situ measurements from the U.S. Department of Energy Atmospheric Radiation Measurement



1258 (ARM) Program in the Southern Great Plains and FLUXNET sites in the U.S. and Europe  
1259 (Baldocchi et al. 2001), Dirmeyer et al. (2006b) compared the local covariability of key  
1260 atmospheric and land surface variables similar to Betts (2004) in model simulations and in-situ  
1261 measurements. They found that most models do not reproduce the observed relationships between  
1262 surface and atmospheric state variables and fluxes, partly due to systematic biases in near-surface  
1263 temperature and humidity. Despite the large inter-model spread and biases in individual models,  
1264 the multimodel mean captures behaviors quite comparably to that observed. The international  
1265 Global Energy and Water Exchanges project (GEWEX) Global Land–Atmosphere System Study  
1266 (GLASS) panel has formed the Local Land–Atmosphere Coupling (LoCo) project to focus on  
1267 understanding and quantifying these processes in nature and evaluating them with standardized  
1268 coupling metrics (Santanello et al. 2018).

1269

1270 With availability of global surface soil moisture and precipitation data from satellites, Taylor et al.  
1271 (2012) evaluated the soil moisture-precipitation feedback, focusing particularly on the least well  
1272 understood aspect of the feedback loop – the response of daytime moist convection to soil moisture  
1273 anomalies. They analyzed the location of afternoon rain events relative to the underlying  
1274 antecedent soil moisture using global daily and 3-hourly gridded soil moisture and precipitation  
1275 data at  $0.25^{\circ} \times 0.25^{\circ}$  resolution to determine whether rain is more likely over soils that are wetter or  
1276 drier than the surrounding areas. Across all six continents studied, they found that afternoon rain  
1277 falls preferentially over soils that are relatively dry compared to the surrounding area, implying  
1278 that enhanced afternoon moist convection is driven by increased sensible heat flux over drier soils  
1279 and/or increased mesoscale variability in soil moisture, and hence a negative soil moisture-

1280 precipitation feedback. In contrast, a positive feedback dominates in six global weather and climate  
1281 models analyzed, which may contribute to the excessive droughts simulated by the models.

1282

1283 The challenge of modeling land-atmosphere interactions was elucidated by Hohenegger et al.  
1284 (2009), who compared cloud resolving simulations at 2.2 km grid spacing in which deep  
1285 convection is explicitly resolved with simulations at 25 km grid spacing with a cumulus  
1286 parameterization. In their 2.2 km simulations with cumulus parameterization turned off, dry initial  
1287 soil moisture conditions yield more vigorous thermals that more easily break through the stable air  
1288 barrier. In contrast, a stable layer setting on top of the PBL that develops over wet initial soil  
1289 inhibits deep convection. Hence the 2.2 km simulations produce a negative soil moisture-  
1290 precipitation feedback, but in the 25 km simulations with parameterized convection, deep  
1291 convection is much less sensitive to the stable layer on top of the PBL because of the design of the  
1292 convective parameterization so simulations initialized with wet soil moisture produce stronger  
1293 convection and a positive soil moisture-precipitation feedback. These results highlight the  
1294 sensitivity of land-atmosphere interactions to model resolution and convection parameterizations.

1295

1296 Land-atmosphere interactions in weather and climate models are also sensitive to representations  
1297 of land surface processes. With advances in land surface modeling incorporating more complete  
1298 hydrological processes, the role of surface water-groundwater interactions on land-atmosphere  
1299 interactions has been studied using models that include representations of groundwater table  
1300 dynamics (e.g., Anyah et al. 2008; Yuan et al. 2008; Jiang et al. 2009; Leung et al. 2011; Martinez  
1301 et al. 2016). These studies found that groundwater table variations can induce soil moisture  
1302 anomalies that subsequently influence ET and precipitation through land-atmosphere interactions.

1303 Integrated hydrology model featuring land surface models coupled to detailed three-dimensional  
1304 groundwater/surface-water models have also been used to investigate the role of groundwater  
1305 dynamics and land-atmosphere feedbacks (e.g., Maxwell and Miller 2005). Applying such models  
1306 to the southern Great Plains, Maxwell and Kollet (2008) found very strong correlations between  
1307 groundwater table depth and land surface response in a critical zone between 2 and 5 m below the  
1308 surface, which could then influence land-atmosphere interactions. Miguez-Macho and Fan (2012)  
1309 found that groundwater can buffer the dry season soil moisture stress in the Amazon basin, with  
1310 important effects on the dry season ET. With the long memory, groundwater table can potentially  
1311 provide an important source of predictability for precipitation and other water cycle processes.

1312

1313 Besides groundwater dynamics, the impacts of lateral flow on land-atmosphere interactions have  
1314 also been investigated using detailed hydrology models, as lateral flow is typically ignored in one-  
1315 dimensional land surface models used in weather and climate models. Subsurface lateral flow can  
1316 have important effects on ET and the partitioning of ET between transpiration and bare ground  
1317 evaporation through spatial redistribution of soil moisture and groundwater table. Using a  
1318 continental-scale integrated hydrology model, Maxwell and Condon (2016) found that including  
1319 lateral subsurface flow in models increases transpiration partitioning from 47% to 62% over the  
1320 conterminous U.S. With integrated hydrology coupled to atmosphere model in regional domains,  
1321 the impacts of groundwater dynamics and lateral flow have been investigated in recent studies. In  
1322 idealized simulations, terrain effects dominate the PBL development during the morning, but  
1323 heterogeneity of soil moisture and water table can overcome the effects of terrain on PBL in the  
1324 afternoon and influence the convective boundary layer strongly in wet-to-dry transition zones  
1325 (Rihani et al. 2015). In case studies of strong convective precipitation events, modeling using

1326 coupled atmosphere-integrated hydrology model shows that groundwater table dynamics can  
1327 affect atmospheric boundary layer height, convective available potential energy, and precipitation  
1328 through its coupling with soil moisture and energy fluxes (Rahman et al. 2015). Recognizing the  
1329 importance of subsurface processes on land-atmosphere interactions, groundwater dynamics are  
1330 now commonly included in land surface models used in climate models, but lateral subsurface  
1331 flow is still mostly ignored (Clark et al. 2015) though some efforts have begun to introduce  
1332 parameterizations of lateral flow in land surface models (e.g., Miguez-Macho et al. 2007; Maquin  
1333 et al. 2017).

1334

1335 Research over the last few decades has greatly advanced understanding and modeling of land-  
1336 atmosphere interactions. The impacts of initial soil moisture conditions on weather forecast skill  
1337 (e.g., Trier et al. 2004; Sutton et al. 2006) and seasonal forecast skill (e.g., Fennessy and Shukla  
1338 1999; Douville and Chauvin 2000; Ferranti and Viterbo 2006; Della-Marta et al. 2007; Vautard et  
1339 al. 2007; Koster et al. 2010; Hirsch et al. 2014) through land-atmosphere interactions have been  
1340 demonstrated. Land-atmosphere interactions have also been found to have important effects on  
1341 extreme events such as droughts (Hong and Kalnay 2000; Schubert et al. 2004) and floods  
1342 (Beljaars et al. 1996) as soil moisture anomalies and precipitation anomalies may be amplified  
1343 through positive soil moisture-precipitation feedback (Findell et al. 2011; Gentine et al. 2013; Ford  
1344 et al. 2015; Guillod et al. 2015a;b; Taylor, 2015; Hsu et al. 2017). Land-atmosphere interactions  
1345 can also contribute to summer heat waves (Fischer et al. 2007) as anomalous warm temperatures  
1346 reduce soil moisture through enhanced ET, and drier soils may subsequently intensify and prolong  
1347 the heat waves.

1348

1349 Understanding land-atmosphere interactions is also important for understanding the impacts of  
1350 land use land cover change (LULCC). Based on global observations of forest cover and land  
1351 surface temperature, forest losses have been shown to significantly alter ET and amplify the diurnal  
1352 temperature variation and increase the mean and maximum air temperature (Alkama and Cescatti  
1353 2016). Consistent findings are obtained using modeling, showing that conversion of mid-latitude  
1354 forests to cropland and pastures increases the occurrence of hot-dry summers (Findell et al. 2017).  
1355 The impacts of afforestation in the mid-latitude on climate has also been studied, with results  
1356 showing the important control of soil moisture on the response (Swann et al. 2012). In water-  
1357 limited region in which latent heat flux is not able to compensate for the increase in surface  
1358 temperature due to increase in solar absorption by the darker forest, afforestation can lead to large  
1359 warming. The latter can induce changes in remote circulation and precipitation by perturbing the  
1360 meridional energy transport that shifts the tropical rainbelt. Irrigation can have important effects  
1361 on precipitation locally through its impacts on soil moisture, ET, and surface cooling (e.g.,  
1362 Kueppers et al. 2007; Bonfils and Lobell 2007), and remotely through its impacts on atmospheric  
1363 moisture transport (e.g., DeAngelis et al. 2010; Lo and Famiglietti, 2013; Yang et al. 2017).

1364

1365 Land-atmosphere interactions can also play an important role in modulating the impacts of global  
1366 warming. For example, land-atmosphere interactions can enhance interannual variability of  
1367 summer climate such as summer temperatures because climate regimes may shift as a result of  
1368 greenhouse warming. The latter can create new wet-to-dry transitional climate zones with strong  
1369 land-atmosphere coupling (Seneviratne et al. 2006), and GCMs provided some evidences that  
1370 land-atmosphere interactions will be enhanced in a warmer climate (Dirmeyer et al. 2012). Climate  
1371 models projected increase in global aridity in the future. This response has been attributed to the

1372 larger warming over land relative to the ocean, which increases the saturation vapor deficit over  
1373 land as moisture over land is mainly supplied by moisture evaporated from the ocean surface,  
1374 which increases at a lower rate due to the smaller warming (Sherwood and Fu 2014). However,  
1375 the GLACE-CMIP5 experiments show that the increase in aridity under global warming can be  
1376 substantially amplified by land-atmosphere interactions through changes in soil moisture and CO<sub>2</sub>  
1377 effects on plant water use efficiency (Berg et al. 2016).

1378  
1379 In summary, land-atmosphere interactions have important implications to weather and climate  
1380 forecast skill, understanding and predicting extreme events including floods, droughts, and heat  
1381 waves, and projecting future changes in surface climates such as surface temperature variability  
1382 and drought and aridity over land. Although both complexity and resolution have increased over  
1383 time, models still struggle to reproduce the observed surface fluxes (Dirmeyer et al. 2018),  
1384 suggesting more efforts needed to improve modeling of the behaviors of the coupled land-  
1385 atmosphere system. Coordinated modeling experiments such as GLACE, GLACE-2, and GLACE-  
1386 CMIP5 have provided valuable insights on land-atmosphere interactions and their role in  
1387 predictability and climate change impacts. Coordinated efforts to design experiments such as  
1388 CAUSES (Clouds Above the United States and Errors at the Surface; Morcrette et al. 2018)  
1389 focusing particularly on understanding model biases, combined with more systematic use of  
1390 process-oriented diagnostics and designing observing approaches targeting the data needs for  
1391 characterizing land-atmosphere interactions (e.g., Wulfmeyer et al. 2018) could prove useful for  
1392 advancing understanding and modeling of land-atmosphere interactions. Cloud resolving and  
1393 large-eddy simulations constrained by observations could provide detailed information for

1394 improving understanding of the complex processes involved in land-atmosphere interactions in  
1395 different climate regimes.

1396

1397 *b. Coupling of Hydrology with Ecosystems: Ecohydrology*

1398 Ecohydrology is the study of the interactions between ecosystems and the hydrological cycle (e.g.  
1399 Porporato and Rodríguez-Iturbe 2002). Building upon theory and approaches from both hydrology  
1400 and ecology, ecohydrology is an extension of the study of the water cycle to include its impacts  
1401 and feedbacks with other ecosystem processes such as biogeochemistry, plant ecology, and climate  
1402 (Hannah et al. 2004). Though this discipline arose from hydrologic and ecosystem science that  
1403 dates back more than a century (Rodríguez-Iturbe 2000, Vose et al. 2011), the explicit focus on  
1404 understanding the processes that couple and feedback between hydrology and vegetation has  
1405 allowed ecohydrology to make significant advances. This relatively young discipline (e.g.  
1406 Zalewski 2000) has in common amongst these advances the theme of integrated, multi-disciplinary  
1407 research focused on the interactions between the biota and the hydrologic cycle.

1408

1409 Ecohydrology has benefitted science and society through improved understanding of the  
1410 hydrologic cycle, ecosystem function, and how climate change, management, and disturbances  
1411 impact resources of human value (e.g. Adams et al. 2012; McDowell et al. 2018). Because of the  
1412 inherent interdisciplinary nature of ecohydrology, it has resulted in significant knowledge gains in  
1413 fields ranging from biogeochemistry to plant physiology to climate impacts. Ecohydrological  
1414 research spans from arid environments where water-ecosystem coupling is strongly evident in part

1415 through water scarcity (e.g. Newman et al. 2006), to humid environments where ecohydrological  
1416 conditions result in ecosystems sustaining high biomass and stature (e.g. Brooks et al. 2010).

1417  
1418 Ecohydrology is rooted strongly in observations of both hydrologic and ecosystem parameters that  
1419 respond to each other. Classical hydrologic measurements such as streamflow, precipitation, and  
1420 evaporation remain a central component of ecohydrology as they are in hydrology, but are often  
1421 coupled with measurements of plant water sources, transpiration, and ecosystem biogeochemical  
1422 fluxes to better understand the interacting systems. A frequent focus is on vegetation-hydrology  
1423 feedbacks with the goal of understanding where and how plants obtain water, and how such water  
1424 acquisition subsequently impacts the local water cycle (e.g. Brantley et al. 2017). A global review  
1425 of depth of plant acquisition of water revealed a wide range of rooting depths, with a surprisingly  
1426 large fraction derived from groundwater (Evaristo and McDonnell 2017, Fan et al. 2017, Figure  
1427 9). In addition to a large groundwater support of plant transpiration (Figure 9), ecohydrology has  
1428 also revealed an additional surprise, that plants use water that is from a distinct pool from the  
1429 source of stream water (e.g. McDonnell 2017). The two water worlds hypothesis that has emerged  
1430 from these observations has yielded significant improvements in our understanding of ecosystem  
1431 function (Berry et al. 2018) and has major implications for how we understand, model, and manage  
1432 catchment hydrologic cycles. This observation fundamentally improves our knowledge of the  
1433 hydrologic cycle and its control, and simultaneously informs us on vegetation function.

1434  
1435 One focal area of ecohydrology has been to understand how management of ecosystem properties  
1436 impacts subsequent ecohydrological processes across all terrestrial ecosystems (Wilcox 2010).  
1437 Ecohydrological management applies to estuaries and coastal waters (Wolanski et al. 2004) to the



1438 management of forests to maximize water-based resources (Ford et al. 2011). There is a long-  
1439 history of investigation into run-off responses to forest harvest (e.g. Bosch and Hewlett 1982;  
1440 Beschta et al. 2000; Holmes and Likens 2016), much of which falls into the category of  
1441 ecohydrology due to the coupled nature of the investigation into the interactions of hydrology and  
1442 vegetation disturbance. Ecohydrology of agricultural and other managed lands is also a critical  
1443 issue given our growing demand for food and fuel production, and the tight coupling between  
1444 hydrology and crop yields (Hatfield et al. 2011). Future land-management can benefit from  
1445 ecohydrological knowledge and forecasts, to better mitigate the consequences of warming  
1446 temperatures, drought, and associated disturbances on both ecological and hydrological functions  
1447 of human value e.g. crop production, water yields, and energy supply (Vose et al. 2011; McDowell  
1448 et al. 2018).

1449  
1450 Our changing climate has provided large impetus to understand how ecohydrological functions  
1451 may change under future conditions (Vose et al. 2011; Wei et al. 2011). Rising temperature is  
1452 forcing greater evaporative demand (e.g. Trenberth et al. 2014), resulting in greater water stress  
1453 for ecosystems (Williams et al. 2014). Integration of hydrologic formulations such as Darcy's law  
1454 into ecohydrologic frameworks suggests that vegetation stature must decline under increasing  
1455 evaporative demand, even with no change in the frequency of precipitation droughts (McDowell  
1456 and Allen 2015); this theory is supported by experimental, observational, and simulation evidence  
1457 (Allen et al. 2015; Bennett et al. 2015). However, rising carbon dioxide is also increasing water  
1458 use efficiency (but not growth e.g. Peñuelas et al. 2011; Van Der Sleen et al. 2014), resulting in a  
1459 shift in the balance of carbon uptake per water consumed that has significant potential hydrologic  
1460 impacts on soil water content and streamflow (though climate and land use may have larger

1461 impacts; e.g. Piao et al. 2007). Thus, ecohydrologic approaches will be valuable for understanding  
1462 the net impacts of future global change on the hydrologic cycle and its feedbacks with ecosystem  
1463 functions.

1464

1465 Vegetation disturbances, and their dependence and feedbacks upon hydrology, have become an  
1466 important ecohydrology research focus in recent years (e.g. Adams et al. 2010). Watershed-scale  
1467 measurements and process modeling are revealing both increasing and decreasing streamflow  
1468 responses to vegetation loss via disturbance (reviewed in McDowell et al. 2018). Multiple possible  
1469 ecohydrologic impacts and feedbacks appear to be underlying these variable responses of  
1470 disturbances on hydrology. The removal of transpiring vegetation by wildfire, logging, or insect  
1471 outbreaks are expected to increase streamflow due to reductions in net transpiration from the  
1472 ecosystem, however, shifts in interception and albedo can allow net infiltration responses to go in  
1473 the opposite direction, resulting in complex streamflow responses to disturbances (e.g. Molotch et  
1474 al. 2009; Adams et al. 2012; Bennett et al. 2018). Other global change factors that are a growing  
1475 focus of ecohydrological research include the impacts of invasive species and land-use change  
1476 (Vose et al. 2011).

1477

1478 Models play a large role in our understanding and prediction of ecohydrology. Next-generation  
1479 models of the coupling of water, vegetation and biogeochemistry are emerging that capitalize on  
1480 the simulation strengths from each discipline. For example, inclusion of rigorous plant hydraulics  
1481 knowledge from empirical physiology work has allowed much improved representation of plant  
1482 transpiration and its dependence on rooting depth (e.g. Mackay et al. 2015), and can now be fully  
1483 coupled to photosynthesis (Sperry et al. 2017). Such models are now being employed to

1484 understand how regional drought kills trees (e.g. Johnson et al. 2018). Likewise, the growing  
1485 frequency and severity of terrestrial disturbances, such as insect outbreaks and wildfires, have  
1486 driven significant ecohydrological advancement in recent years. The ecohydrologic consequences  
1487 of these disturbances are large, including vegetation removal, accelerated sediment transport, and  
1488 changes in the timing and amount of water yields (Adams et al. 2010; Penn et al. 2016; McDowell  
1489 et al. 2018; Bennett et al. 2018). Using process models, we can better understand how disturbances  
1490 impact the water cycle (Bearup et al. 2016).

1491  
1492 Representation of hydrology in Earth System Models remains challenged by integration of  
1493 hydrologic and land-surface processes (Clark et al. 2015) and thus an ecohydrologic approach is  
1494 required to advance model representation. This is particularly true under a non-stationary climate,  
1495 in which the feedbacks and interactions between climate, hydrology, and vegetation are complex  
1496 and difficult to test. An important component to bridging the gap between modeling hydrology  
1497 and ecosystems is the use of ecohydrological benchmarks (Kollet et al. 2017). For example, the  
1498 most rigorous tests of Earth System Models will require not only hydrologic benchmarks (e.g.  
1499 streamflow, soil water content) but also of vegetation function (e.g. transpiration, growth).  
1500 Utilization of new tools such as the International Land-Atmosphere Modeling Benchmarking  
1501 (ILAMB; Hoffman et al. 2017) and the Protocol for the Analysis of Land Surface Models (PALS)  
1502 Land Surface Model Benchmarking Evaluation Project (PLUMBER; Best et al. 2015) should  
1503 greatly accelerate both the rate and knowledge gained through benchmarking of both water and  
1504 non-water parameters simulated by models. Ultimately, benchmarking against multiple data-  
1505 constraints crossing multiple biogeochemical cycles (e.g. water, carbon, nutrients) forces models

1506 to get the right answers for the right reasons, and is thus a powerful direction forward for  
1507 ecohydrological modeling (e.g., Nearing et al, 2016).

1508

1509 The interactions between hydrology and biogeochemistry, specifically the water, carbon, and  
1510 nutrient cycles, are a central component of ecohydrology. Nutrient availability, for example, is  
1511 critical to growth of aquatic biota, soil microbes, and vegetation, and is simultaneously highly  
1512 responsive to the hydrologic cycle (Liu et al. 2008; Wang et al. 2015). The movement of nutrients  
1513 such as nitrogen across land-water gradients is of growing concern, particularly with land-cover  
1514 and climate changes (Burt et al. 2010). Such changes can have cascading impacts on trophic  
1515 systems and water quality (Krause et al. 2011). Disturbances are particularly threatening to impact  
1516 the nitrogen and other elemental cycles (Sollins and McCorison 1981), and thus a strong need for  
1517 integrated research for prediction and mitigation is required under a future disturbance-regime  
1518 (McDowell et al. 2018).

1519

1520 Future ecohydrological research will benefit hydrology not only in addressing the linkages  
1521 between vegetation, nutrient cycles, and water, but through an explicit focus on understanding  
1522 ecosystem/watershed scale mechanisms driving our observations. To achieve this, ecohydrology  
1523 must continue to utilize cutting-edge techniques including remote sensing (described in section 3  
1524 of this paper), fine and coarse-resolution models, and advanced monitoring and experimental  
1525 techniques. The long-history of cause-and-effect experiments (e.g. catchment disturbances) must  
1526 continue to play a strong role, but can be refined to address future ecohydrological threats such as  
1527 wildfires, insect outbreaks, and climate warming. With these advances, we can expect

1528 ecohydrology to continue to advance our knowledge and mitigation options for water and non-  
1529 water resources of human value under increasing future pressure.

## 1530 **7 Water Management and Water Security**

### 1531 *a. The Origins*

1532 As already noted in the first section, the concept of the hydrologic cycle appears to have been  
1533 known since ancient civilizations. As population increased, so did the demand for a steady and  
1534 reliable source of water. Water as a resource has thus been artificially ‘managed’ ever since there  
1535 was such demand for mankind. However, until the advent of hydrology as a proper scientific  
1536 discipline, most water management practices around the world were relatively ad hoc and lacked  
1537 sound hydrologic principles. For example, in ancient India, the amount rain in an area was recorded  
1538 for each year and used as a proxy for estimating food production and taxation rate for the following  
1539 year (Srinivasan, 2000). In Sri Lanka, giant-sized reservoirs were built in the 1st century B.C.  
1540 during the reign of King Wasabha (67 – 111 BC). According to historical records, the king built  
1541 11 large reservoirs and two irrigation canals of what is known today as perhaps the world’s oldest  
1542 and surviving rainwater harvesting project (de Silva et al. 1995). Thus, the history of hydrology  
1543 in water management is long and has always been driven by societal needs for maintaining a steady  
1544 supply of water.

### 1545 *b. Water Management Today*

1546 Today, water management owes its foundation to pioneers who developed hydrology as a science  
1547 during early 20<sup>th</sup> century. One particular pioneer who must be mentioned for his seminal role in

1548 spurring water management is Robert Horton, who performed scientific investigations to solve  
1549 real-world problems. Horton (1940) had written about infiltration and runoff production that is  
1550 commonly used today to express runoff generation process from precipitation in many of today's  
1551 watershed management models. He had also written on erosion, geomorphology, basin response –  
1552 all of which have directly contributed to the evolution towards physical hydrology-based  
1553 engineering design of water management systems.

1554

1555 In the current computer-era, the first use of digital computing in hydrology, although driven  
1556 primarily by scientific investigations, was in the Stanford Watershed Model (Crawford and  
1557 Linsley, 1966) and the MIT Catchment Model (Harley, 1971). These computer models offered  
1558 hydrologists and water managers, an opportunity to look at the complex behavior of a river basin  
1559 more holistically for decision making. Since these early computer models, there have been  
1560 numerous others developed for hydrologic prediction in water management decision making for  
1561 flood management (Abbott et al. 1986), irrigation management (Singh et al. 1999), reservoir  
1562 operations (Yeh, 1985), water quality management (Abbaspour et al. 2007). For a historical  
1563 overview of current computer models used for watershed management, Singh and Woolhiser  
1564 (2002) provide a very comprehensive review.

1565

1566 With the advent of 'Dynamic Hydrology' (Eagleson, 1970) as a discipline, hydrology evolved  
1567 after the 1980s as a more inter-disciplinary topic with closer links to atmospheric science,  
1568 groundwater science, plant biology, and climate (see sections 2 and 5). Land-atmosphere  
1569 interactions were recognized of their importance and land surface hydrologic (computer) models  
1570 were developed. These models, such as the Variable Infiltration Capacity (VIC) model (Liang et

1571 al. 1994), Noah (Chen et al. 1996; Ek et al. 2003), Noah-MP (Niu et al. 2011), and the Common  
1572 Land Model (CLM; Dai et al, 2003) to name a few, opened doors for water managers to explore  
1573 the role of climate and weather on water management. Unlike traditional hydrologic models, the  
1574 atmospheric forcings are integrated with the land's response through energy and water fluxes. Such  
1575 land surface models, including those that are coupled with water management models (e.g.,  
1576 Haddeland et al. 2006; Hanasaki et al. 2006; Voisin et al. 2013), have thus been used in identifying  
1577 best practices for land or irrigation management (Pielke et al. 2011; Ozdogan et al. 2010), water  
1578 development and adaptation policy for climate change (Kundewicz et al. 2008), and reservoir  
1579 management (Hamlet, 2011), just to name a few.

1580

1581 Most recently, with the advent of remote sensing from ground or space platforms (section 3) that  
1582 can now provide estimates of key hydrologic variables on a global scale, hydrology has begun to  
1583 experience much broader and more global application in water management. This is primarily  
1584 because remote sensing from satellites is the only way to monitor changing fluxes of the water  
1585 cycle in difficult or ungauged regions of the world. In what follows next, water management is  
1586 broken down thematically into societal application topics.

### 1587 Reservoir Management

1588 Dams and artificial reservoirs are built to trap a sufficiently large amount of water from the  
1589 hydrologic cycle to make up for a shortfall when demand for water exceeds the variable supply  
1590 from nature. Using advancements in hydrologic science, much is now known about the  
1591 management of post-dam effects on aquatic ecology (e.g., Ligon et al. 1995; Richter et al. 1996;  
1592 Zhang et al. 2019), geomorphology (e.g., Graf, 2006), floods (e.g., Wang et al. 2017) and droughts  
1593 (e.g., Wan et al. 2017), and sediment trapping by reservoirs (Graf et al. 2010). Such understanding

1594 has consequently improved water management practices for regulated river basins. Yeh (1985)  
1595 provides a thorough review of the progress of quantitative water management practices that remain  
1596 a cornerstone for practitioners today even after three decades.

1597

1598 In designing a dam's physical dimensions, the inflow design flood (IDF) is a major parameter that  
1599 is derived from analyzing probability of occurrence of flood and precipitation events using  
1600 historical hydrologic records (Hossain et al. 2010). Also, most of the large dams, especially the  
1601 hazardous ones located upstream of population centers, are often designed considering the standard  
1602 Probable Maximum Flood (PMF) (Yigzaw et al. 2013). PMF, by its definition, is the hydrologic  
1603 response as flow to the previously introduced concept of Probable Maximum Precipitation (PMP).  
1604 WMO (2009) suggests several methods for PMP estimation: statistical method, generalized  
1605 method, transposition method, and moisture maximization method (Rakhecha and Singh, 2009).  
1606 Ever since the wider availability of numerical atmospheric models and reanalysis data of the  
1607 atmosphere, the dam design and reservoir management community is increasingly marching  
1608 towards more atmospheric science-based approaches to predict changing risks associated with  
1609 PMP and PMF (Chen and Hossain, 2018; Rastogi et al. 2017; Chen et al. 2017; Rouhani and  
1610 Leconte, 2016; Ohara et al. 2011).

1611 Remote Sensing Applications in Water, Food and Disaster Management

1612 As indicated in section 3, from the early days of satellite precipitation remote sensing driven mostly  
1613 by weather and climate science (Griffith et al. 1978; Arkin and Meisner, 1987) to the modern era  
1614 of Global Precipitation Measurement (GPM) mission (Hou et al. 2014), the scientific community  
1615 has made great strides in reducing uncertainty and improving resolution. Consequently, this has  
1616 opened up a diverse set of applications over the last decade. The global nature of coherent and



1617 more accurate satellite precipitation products have now improved water management in river  
1618 basins where rainfall is abundant but in situ measurement networks are generally inadequate.  
1619 Building on the success of past satellite remote sensing missions for precipitation, we can now  
1620 perform global-scale runoff/flood prediction (Wu et al. 2012; 2014), monitor drought/crop yield  
1621 (Funk and Verdin, 2010; McNally et al. 2017), provide irrigation advisory services (Hossain et al.  
1622 2017), monitor landslide risks (Kirschbaum et al. 2012). Remote sensing applications and decision  
1623 support system have also been utilized in monitoring water supplies stored in snowpacks, drought  
1624 impacts on agricultural production and groundwater depletion (Schumann et al. 2016).

1625

1626 Transboundary flood forecasting is another area that has recently benefited from application of  
1627 hydrologic prediction driven by remote sensing, particularly in developing countries (Hossain and  
1628 Kaityar, 2006). This is because in transboundary river basins, the lack of knowledge about the real-  
1629 time hydrological state of the upstream nations makes floods more catastrophic than other places.  
1630 Bakker (2009) has shown that the number of the international river basin floods (i.e.,  
1631 transboundary flood) is only 10% of the total riverine floods. With this small number of  
1632 occurrences, transboundary floods are responsible for 32% of total casualties, and the affected  
1633 individuals could be high as 60%. UN-Water (2008) reported that 40% of the global population  
1634 lives in the 263 shared or transboundary lake or river basins. For transboundary basins, flood  
1635 forecasting based on satellite remote sensing and hydrologic models has become one of the most  
1636 economic and effective ways to mitigate floods (Wu et al. 2014). Given the plethora of satellite  
1637 nadir altimetry sensors that can now measure river levels (JASON-3, Sentinel 3A, 3B, IceSat-2,  
1638 AltiKa), it appears that altimetry usage with conventional flood forecasting systems will further  
1639 improve the management of floods. The impacts of food security are felt most seriously in

1640 developing countries where people practice subsistence farming. This is where accurate  
1641 monitoring of growing season conditions can significantly help mitigate the effects of food security  
1642 in the developing world. These assessments are now being done using remotely sensed monitoring  
1643 data for precipitation, crop water requirements, and vegetation indices, using hydrologic models  
1644 and monitoring systems (Budde et al. 2010). For example, MODIS satellite data is now used in  
1645 developing vegetation indices that provide consistent spatial and temporal comparisons of  
1646 vegetation properties used to track drought conditions that may threaten subsistence agriculture  
1647 (Budde et al. 2010).

1648 *c. Emerging Issues*

1649 The current trend of expanding human settlements, economic activity, population increase and  
1650 climate change mean that water will continue to get redistributed and artificially managed to the  
1651 extent that there will be no pristine river basin left today without the human footprint caused by  
1652 water diversions, barrages, dams and irrigation projects (Zarfl et al. 2014; Kumar, 2015). The  
1653 evidence is already there. For example, the United States Geological Survey (USGS) records  
1654 indicate an increase in irrigation acreage from 35 million acres (1950) to 65 million acres (in 2005)  
1655 in the US alone (Kenny et al. 2009). The latter is equivalent to a withdrawal of 144 million acre-  
1656 feet (or 177 km<sup>3</sup>) of surface and ground water per year. Similarly, there are about 75,000 artificial  
1657 reservoirs built in the US alone during the last century with a total storage capacity almost equaling  
1658 one year's mean runoff (Graf, 1999). Around the world, the number of impoundments in populated  
1659 regions is more staggering and exploding due to needs for economic development (Zarfl et al,  
1660 2014).

1661

1662 Studies now clearly show that the regulation of rivers by dams built by upstream nations and the  
1663 ensuing lack of connectivity between river reaches or the increased time water remains stagnant  
1664 (in reservoirs) will be most severe in the mid-21<sup>st</sup> century (Grill et al. 2015). However, the impact  
1665 on availability of freshwater, which also drives food and energy production, cannot be monitored  
1666 and managed by downstream nations of such transboundary river basin using conventional  
1667 approaches to water management. .

## 1668 **8 Future Directions**

1669 As we move forward in the 21<sup>st</sup> century, the expansion of human settlements, economic activity  
1670 and increasing population mean that water availability will continue to increase in importance. As  
1671 already evident in the previous sections, scientists, engineers, planners and decision makers will  
1672 be dealing more and more with a ‘human-water cycle.’ This ‘human-water cycle’ will represent  
1673 active interplay between humans and nature, therefore inviting new and exciting dimensions to  
1674 hydrology in the coming decades (Wheater and Gober, 2015). Within hydrologic science, there is  
1675 increasing recognition of the co-evolution of natural and anthropogenic landscape features and the  
1676 hydrological response of catchments, and this concept has been termed ‘catchment coevolution’  
1677 (Sivapalan and Blöschl, 2017), with the co-evolution era projected from 2010-2030. Advances in  
1678 hydrologic modeling will continue, supported by more observational data available to constrain  
1679 the model, improved understanding of hydrologic processes and incorporation of key processes  
1680 and new approaches, and comprehensive benchmarking of models (Clark et al. 2015). Coincident  
1681 with these trends, is the new era of ‘big data’ in which computational and theoretical advances are  
1682 ushering in new learning opportunities, as discussed in Peters-Lidard et al. (2017). Combining big

1683 data with new observational platforms, as described in McCabe et al. (2017), will yield important  
1684 new insights and societal benefits.

1685

1686 In the 50-year anniversary celebration of WRR, Alberto Montanari et al. state that “Water science  
1687 will play an increasingly important role for the benefit of humanity during the next decades, as  
1688 water will be the key to ensuring adequate food and energy resources for future generations”  
1689 (Montanari et al. 2015). They go on to exhort the community that the “target for hydrology in the  
1690 21st century must be ambitious. There are relevant and global water problems to solve and there  
1691 is a compelling need to ensure sustainable development of the human community.”

1692

1693 We are already witnessing some of this ‘ambition’ to solve grand challenge societal problems  
1694 through the assimilation of climate, weather, numerical modeling and remote sensing into tangible  
1695 solutions for society. Some of the most exciting prospects for advancing hydrologic science exist  
1696 at the interfaces with other scientific disciplines, for example: plant biology and ecology for crop  
1697 yield and ecosystem modeling; oceanography for estuarine process modeling; biogeochemistry for  
1698 understanding the interactions between carbon and water cycles; and socio-economics for  
1699 integrating human and water systems (Vogel et al. 2015). All of these advances will likely  
1700 converge to improve understanding and modeling of the earth system, leading to improvements in  
1701 weather and climate predictions that exploit land memory from a spectrum of interconnected  
1702 processes of surface and subsurface hydrology, vegetation, biogeochemistry, and human activities  
1703 (e.g., irrigation). In the climate projection arena, Bierkens (2015) posits that physically-based  
1704 continental earth system models (PBCESMs) will converge to support integrated assessments,  
1705 including, for example, groundwater (e.g., Fan, 2015). For example, in the water management

1706 area, there now exists operational satellite remote sensing-based transboundary flood forecasting  
1707 systems that provide valuable updates of flood risk around the world (Wu et al. 2014; Alfieri et al.  
1708 2013) .

1709

1710 However, the human-water cycle is not the only area that needs to experience growth for the future  
1711 of hydrology. In a recent review of progress and future directions for hydrologic modeling, Singh  
1712 (2018) cites other areas that need to be studied, such as: Hydrologic impacts of hydraulic  
1713 fracturing; Transport of biochemical and microorganisms in the soil; Hydrology of hurricanes and  
1714 atmospheric rivers; and Socio-hydrology. The review goes on to state that “For management of  
1715 hydrologic systems, political, economic, legal, social, cultural, and management aspects will need  
1716 to be integrated....” where “both hydrologic science and engineering applications are equally  
1717 emphasized.”

1718

1719 At the fundamental process level, studies involving isotopes have revealed a complexity of the  
1720 movement and distribution of water particles in time and space where many of the dynamic  
1721 connections and disconnections of water stored in the ground remain unexplained today  
1722 (McDonnell, 2017). For example, at the hillslope scale, the movement of water is often  
1723 compartmentalized. Runoff from snowmelt can often be from precipitation snowpack that  
1724 occurred several years earlier. There is clear evidence that plants often remove water through  
1725 transpiration from immobile pools underground that are not tightly coupled to the infiltration and  
1726 groundwater recharge processes being modeled today (Brooks et al. 2010). With such process-  
1727 based questions on hydrology remaining unexplained today, McDonnell argues that future

1728 directions in hydrology should also require thinking of newer frameworks that can track both flow  
1729 and the age of water.

1730

1731 One likely direction toward which hydrology seems to be already evolving is in the area of  
1732 ‘nexus’ of resources or themes – such as food-energy-water (the FEW nexus) or climate-energy-  
1733 water (the CEW nexus) and even the sociology-hydrology nexus (Socio-hydrology). There is no  
1734 doubt that the future direction of hydrology will be increasingly more multi and inter-disciplinary  
1735 and draw in fields that have traditionally never interacted with hydrology. For example, freshwater  
1736 access and nutrition are the foundation pillars of public health. Lack of safe water and sanitation  
1737 access and malnutrition are intricately linked to water and food security – and can be critical factors  
1738 behind child mortality and morbidity anywhere. In order to tackle challenges due to compounding  
1739 factors of lack of sanitation/safe water and nutrition, health management will need to partner  
1740 closely with agricultural and water management and naturally require strong collaboration from  
1741 the hydrologic community.

1742

1743 In addressing the ensuing challenges for managing the water, piecemeal approach to hydrology  
1744 research or investigation will not suffice anymore. To keep water management practices timely  
1745 and relevant, hydrologic research will most likely be converted into language that encourages  
1746 uptake by policy makers, practitioners and the public in the real-world out of sheer necessity in  
1747 the 21<sup>st</sup> century (Cosgrove and Loucks, 2015; Wheeler and Gober, 2015).

1748

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3372 Figure 3. Number of publications per year in the Journal of Hydrometeorology since inception in  
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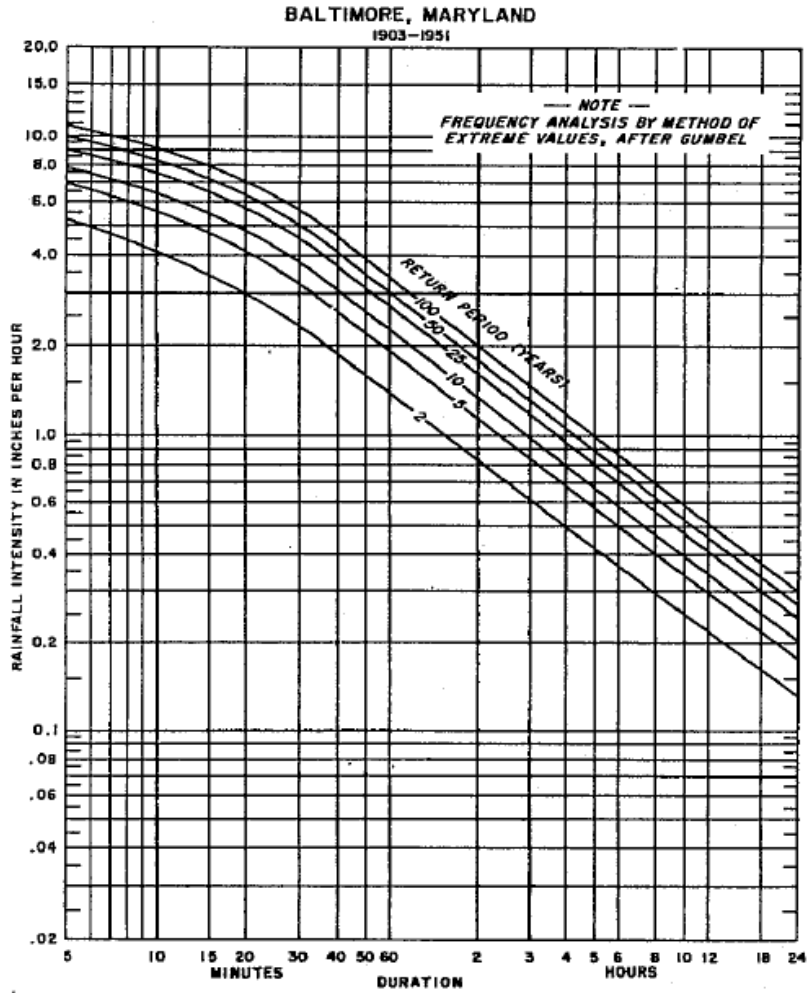
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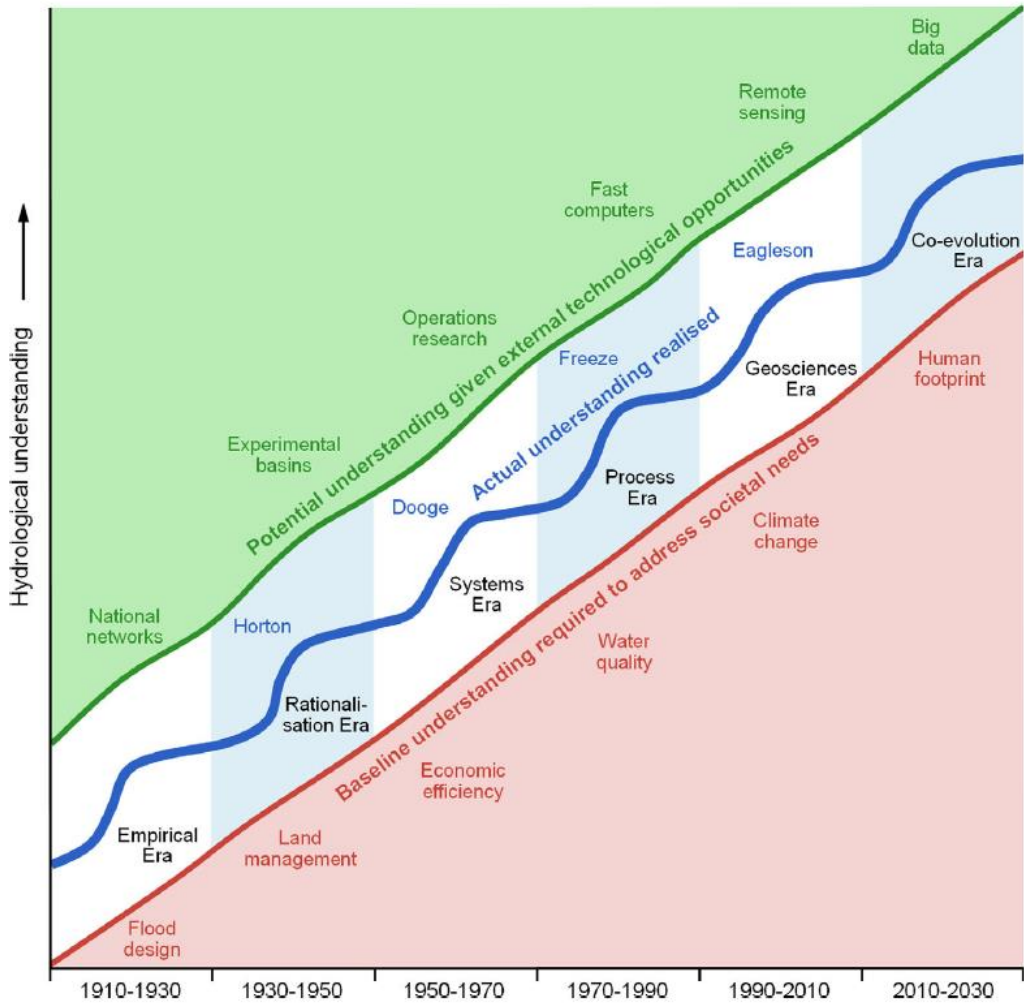
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3412 1961a).

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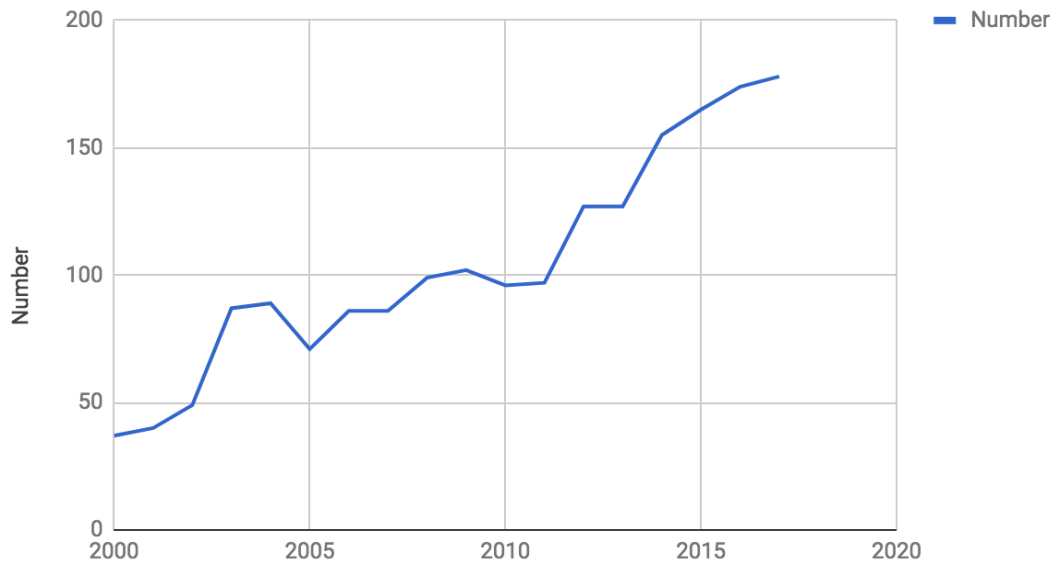


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3415 Figure 2. Staircase growth of hydrological understanding sandwiched between baseline  
 3416 understanding required to address societal needs and potential understanding given external  
 3417 technological opportunities. Names in blue epitomize dominant paradigms of the eras. (From  
 3418 Sivapalan and Blöschl, 2017)

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### JHM Publications per Year



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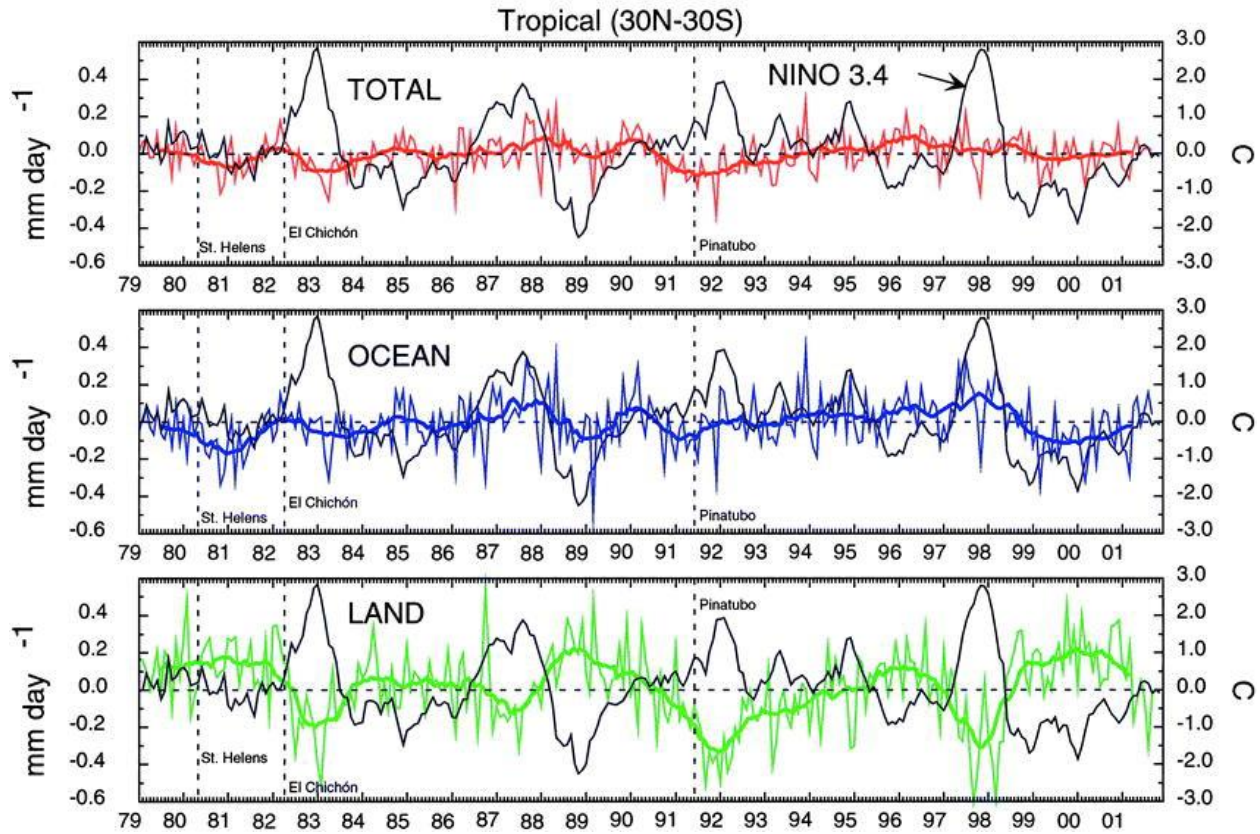
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# Global Precipitation Climatology Project (GPCP)

Time series of rainfall anomalies from 1979 to 2001

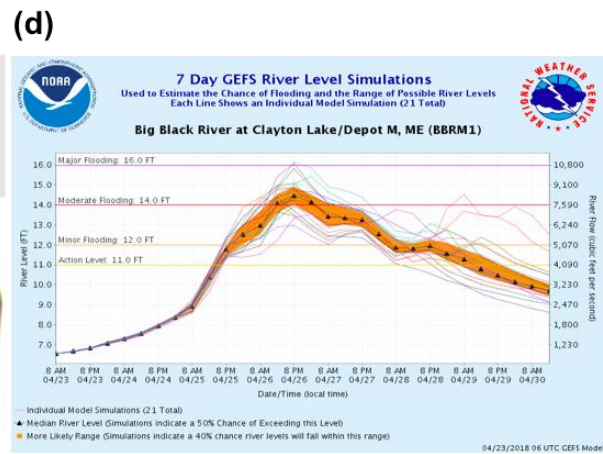
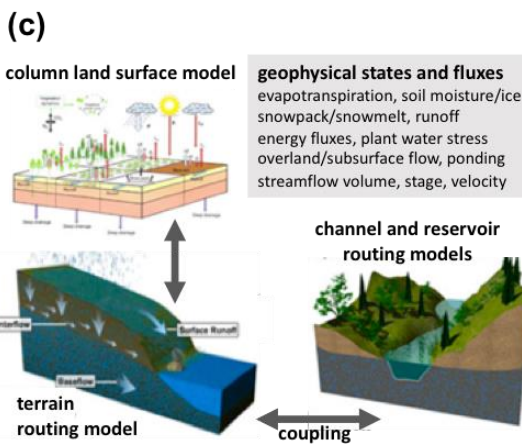
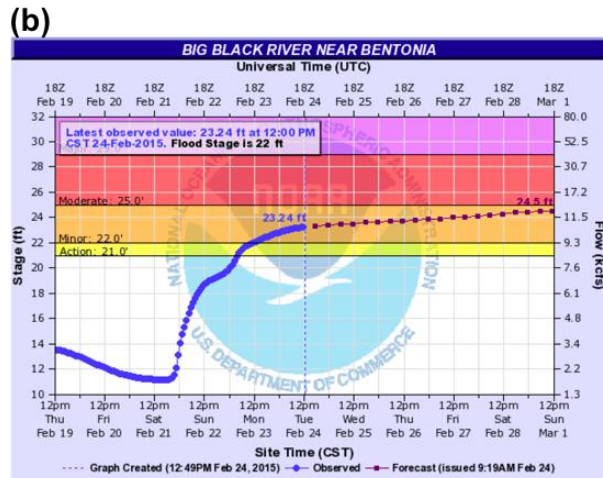
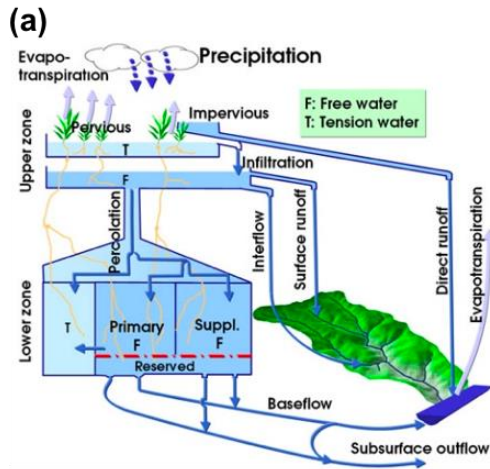


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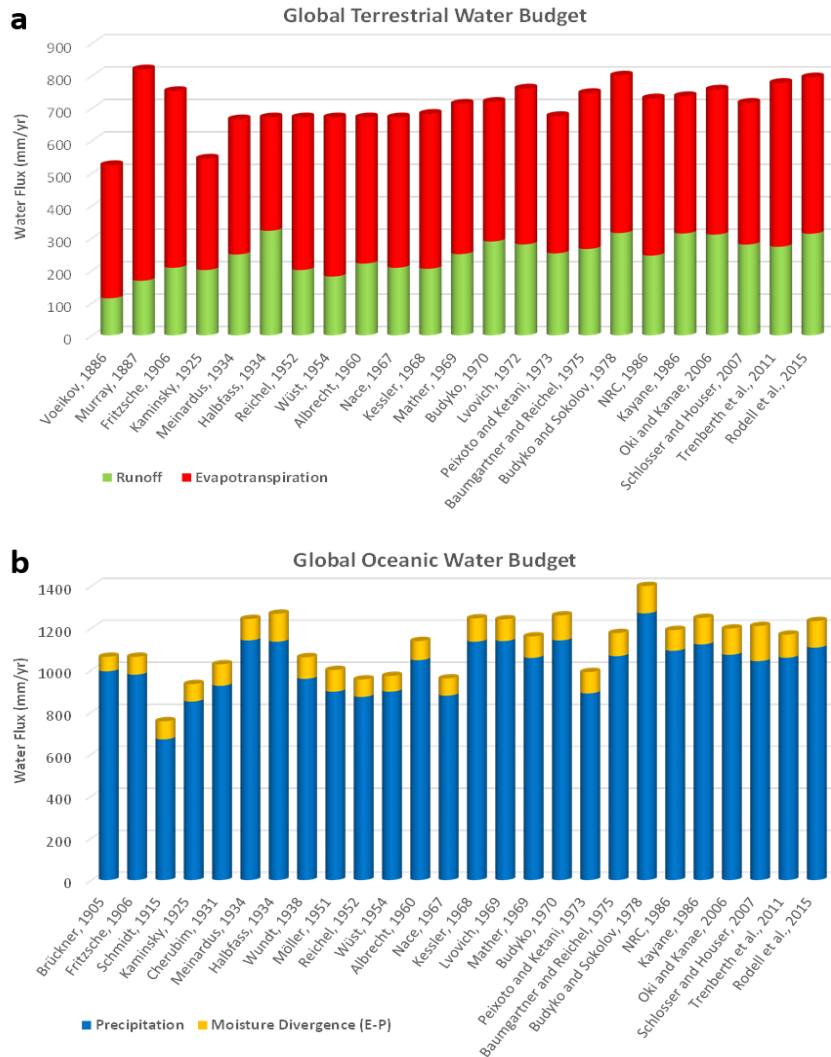
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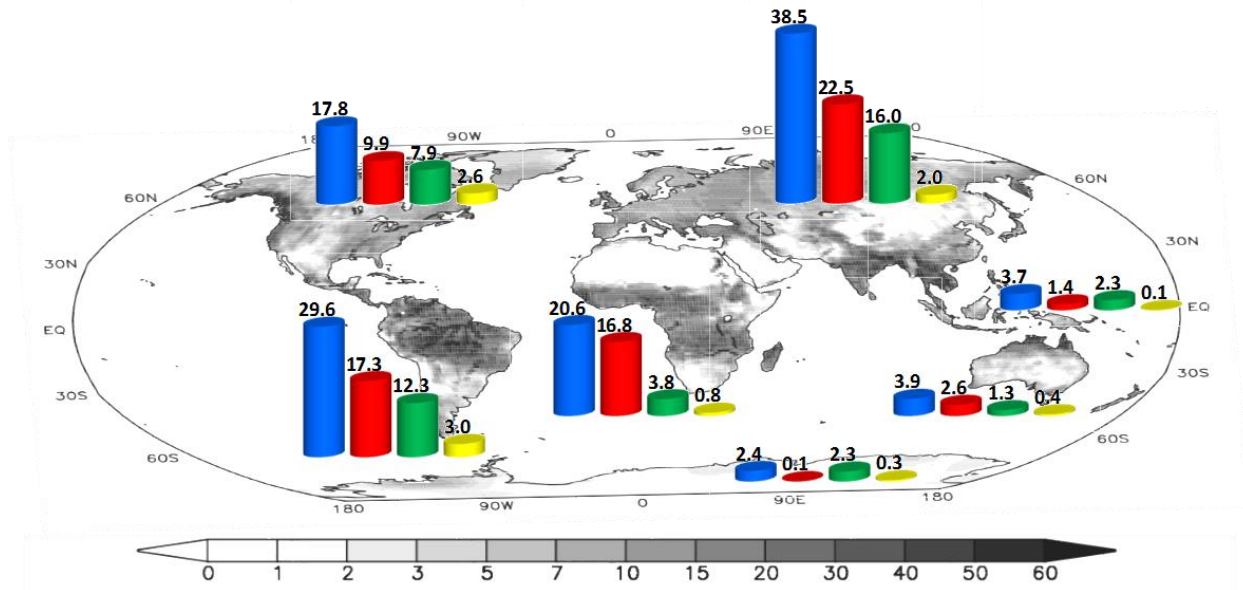
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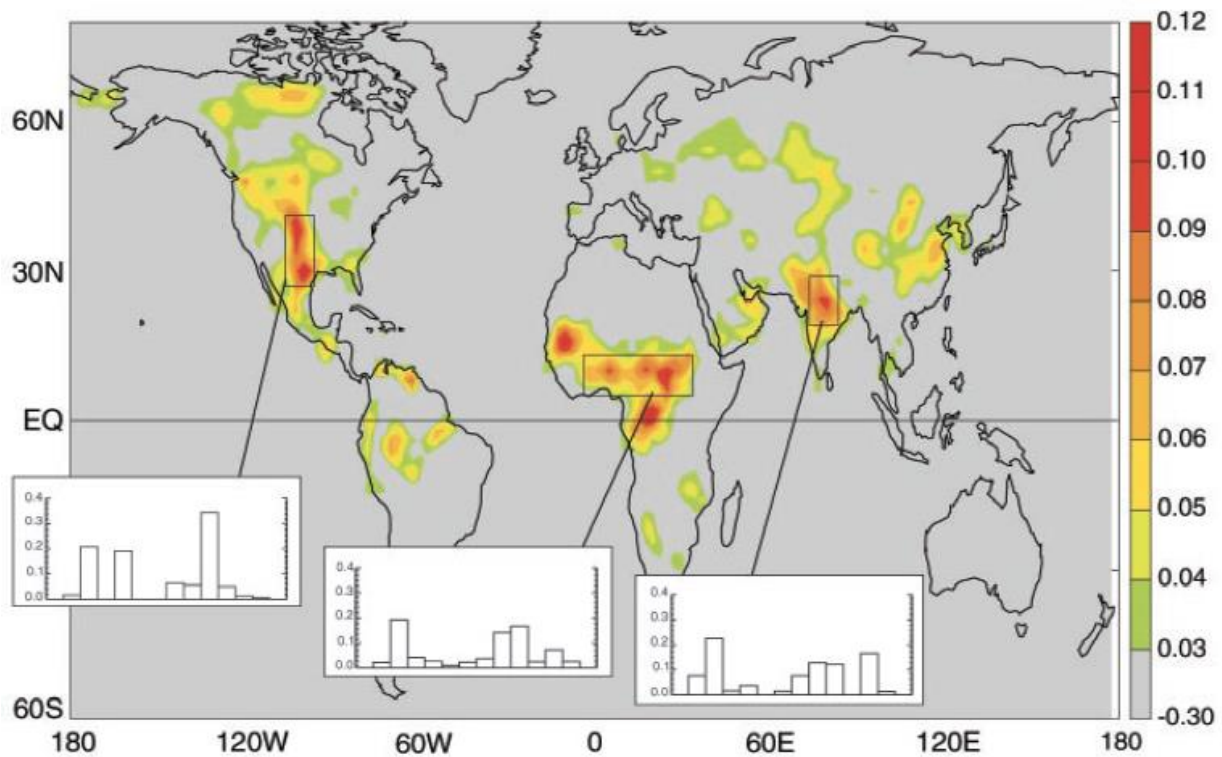
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### Land-atmosphere coupling strength (JJA), averaged across AGCMs

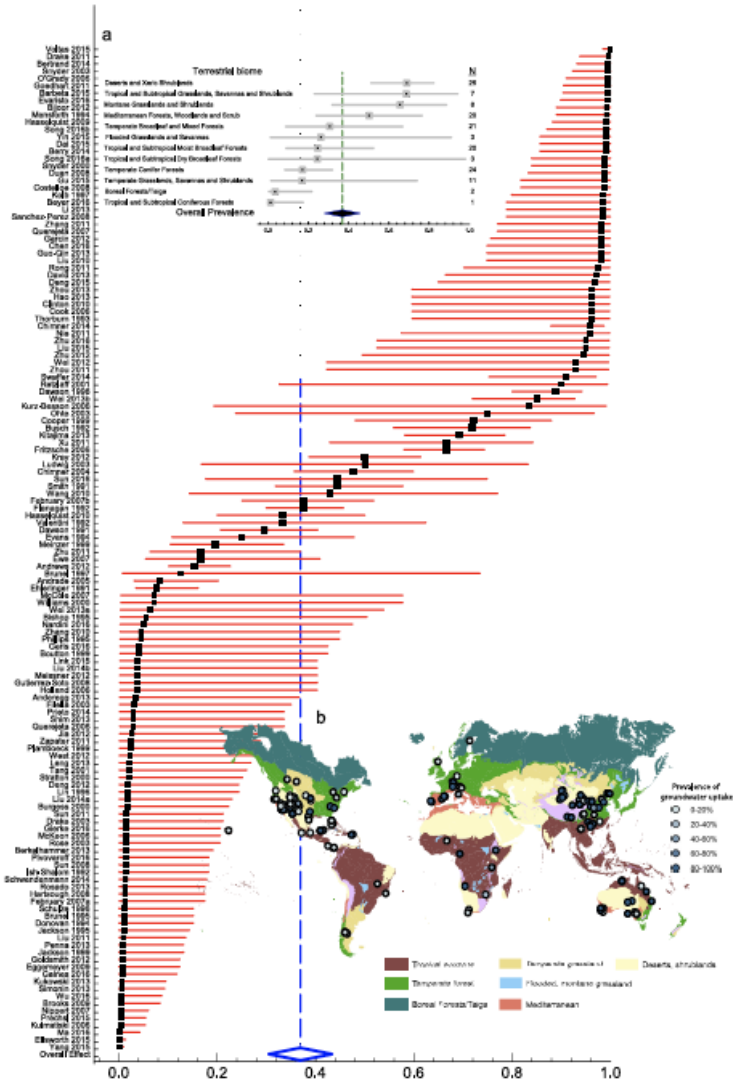


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