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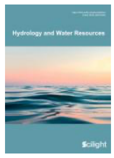

Article

Hydrology and the Water Balance: From 1990 of Klemes and Eagleson to Today

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Abstract: The general structure of hydrologic sciences is discussed in relation to a formulation of the water balance based on ecological optimality and spatio-temporal scaling of flow and transport over disordered networks. The basic physical controls on the function of Earth's vegetation are discussed. The paper addresses how the curriculum of hydrology can be improved through addressing the components necessary to understand optimal approaches to solve the water balance equation and related hydrological problems. The implications for the past, and future status of hydrology are considered in light of what progress the community has actually made in solving the water balance. The arguments are evaluated by comparing new water balance results with existing theory and with continental-scale evapotranspiration measurements.

Keywords: scaling; ecological optimality; water balance; similarity theory

1. The Structure of Hydrologic Sciences

What is known about the behavior of the atmosphere in weather and climate, wind and rain, is most reliably derived from the thermodynamics of phase changes and, e.g., mixing, together with how the dynamical laws of turbulence over a curved and rotating surface drive the associated phenomena of (sensible, radiative, and latent) thermal energy, together with momentum and moisture transfer (e.g., [1,2]). Despite the extreme difficulties associated with solving such equations, it is generally acknowledged that there is no viable shortcut.

What is known about the behavior of the subsurface is most reliably derived from the transport of water, air, and solutes over disordered networks [3,4]. Because real networks are heterogeneous, the most accurate treatment of such transport employs percolation theory [3,5,6], which addresses large heterogeneity. The reason is simple; if two widely different electrical/hydraulic resistors are connected in parallel, the smaller one controls the current/flow, but when connected in series it is the larger of the two that dominates. Percolation theory carries this argument to a logical conclusion for an entire network of resistors. The controlling resistance for an entire network is the smallest possible value of the largest resistance on a path with no breaks. This value is then the bottleneck resistance, since it corresponds to the largest possible value of the smallest pore throat on such a path, and is found using the critical bond probability for percolation. Since, in three-dimensional media, the critical percolation probability tends to be so low (as small as 10%), the dominant flow is controlled by a small subset of the entire range of resistances far into the tail of the distribution. The result quantifies both preferential flow and the long-tailed solute arrival time distributions that are the rule, not the anomaly, in porous media [7]. Perturbation theory [8,9], derived for a medium in which the spread of local hydraulic conductance values is small compared with the mean or median conductance, generates effective hydraulic conductivities related in lowest order to the median conductance, while it is does not support derivation of the typically observed non-Gaussian transport [7].

This is not to say that disorder has no role in the atmosphere, or that chaos and turbulence are impossible in the subsurface; it is merely a statement about the dominant difficulties posed to scientists in addressing the land surface-atmosphere interaction in Earth's climate system, which involves as well the physiology, physics, and chemistry of the living and adapting, directed networks of plants at the Earth's surface, and which connect the atmosphere with the subsurface. Adding in bodies of water, such as rivers, contributes turbulence to the mix. We also do not say that all the problems of porous media and hydrology are solved by substituting a more accurate and better suited approach to the physics; rather, we argue that a decision to use an inferior basis to address the physical components of a complex model will degrade its relevance everywhere.

2. The Status of Hydrologic Science Research According to Vit Klemes

Unfortunately for the success of the community in actually solving problems at the land-atmosphere boundary, the fundamental science necessary to treat the subsurface is mostly ignored or unknown. The incomplete and inaccurate nature of this understanding is still holding our science hostage in its theoretical status before the Eagleson Report [10] at a time when its problems were described as follows by Klemes [11] (written in his role as president of IAHS).

> *"In practice, hydrology is regarded mostly as a technological discipline rather than a science; this attitude is responsible for much bad science in hydrology which, in turn, has led to much bad technology in applied disciplines."*

Klemes [11] saw two primary barriers to progress: (1) that the science was regarded as complete (except for the details), (2) that the connection between science and technology (how to change what can be observed) was drawn in a statistical fashion.

Speaking to the first, he wrote, "The pressure to find immediate solutions to all the pressing water-related problems has created a vast body of hydrological technology which is mostly empirical and has very thin scientific underpinnings, but is often presented as a body of hydrological science. Since it offers "solutions" to almost any practical problem, hydrology is often regarded as a virtually closed science where not much more research is needed" [11].

To the second problem, Klemes [11] added, "Suspended between a technology he [the hydrologist] does not practice and a science for which he has not been trained [transport over disordered networks], his 'research' is naturally guided to performing elaborate pirouettes on the high wire of techniques connecting the two distant poles [technology and science] and holding him in place. Seeing the long distance separating him from both of them, he clings to the wire and before long becomes an expert in random number generation, nonparametric optimization of parameters, second-order convergence of kriged Thiessen polygons…"

To translate the first paragraph to the present day, all that one needs to perform is to assume falsely that the scientific basis is established in continuum descriptions of the soil, with bundles of capillary tubes describing the flow and transport, and heterogeneity addressed with perturbation theory (stochastic methods) or brute-force numerical methods. To translate the second paragraph to the present-day, one can most parsimoniously substitute AI and machine learning for the connections, although several other substitutions would work as well.

Overall, the status of hydrology has not changed significantly. In fact, there appears to have been a conscious decision to retreat from whatever moderate successes had resulted from the introspection in [10]. In particular, two of the leading figures in catchment hydrology (Sivapalan and Bloeschl) have stated [12], "A few decades ago we even (!) went through a period of self-criticism, concerned that we were too beholden to engineering applications to be a true science ([11], p. 3), and responded to calls to rebrand our science as a geoscience (National Research Council [10])." "[We find that] progress in hydrological understanding is brought about by changing societal needs and technological opportunities."

We emphasize that the final message of both [11,13] is that hydrologists, who had (have) been "constantly trying to find better ways to manage water", should say simply, "Enough is enough—our task is constantly to seek better solutions to the water balance equation". The water balance equation, of course, reads $P = ET + Q$, and to be able to solve it implies merely that the evapotranspiration, ET can be predicted in terms of the climate variables potential evapotranspiration, PET, and precipitation P, with the variability in ET for specific P and PET relatable to specific catchment characteristics. Q, of course, follows from $P - ET$. But solutions to this problem are rarely even attempted, as it appears to be simply too difficult.

The concept extends to education, as pointed out by [14]. "Hydrology will develop only through changes in the way we *educate hydrologists*". That education needs to be "founded on the basic sciences of geology, physics, mathematics, chemistry, and biology" [14]. While certainly neglect of any of these subjects is critical, yet, since the soil is arguably the center of the critical zone, the lesson from complexity/physics that even the bouncing of a floppy basketball is better predicted using a set of difference equations discretized at a time scale equal to the inverse of the basketball's fundamental vibrational frequency, would surely not be lost on physicists cognizant of the necessity to treat the soil as a network, using difference equations discretized at the pore scale.

Thus, we argue that the two fundamental perspectives from physics that frame the critical zone are the study of environmental fluid dynamics at the top of the zone, and that of networks and percolation at its bottom, and that both need to be required parts of the hydrology curriculum. Only then would it be possible to address the full complexity of this critical anchor of the biosphere.

3. The Proposed Solution of the Water Balance and the Eagleson Report (NRC, 1991)

The Eagleson Report [10] agrees substantially with [11], to wit, "(its) pragmatic focus has left fundamental hydrologic science lagging behind in comparison with other geosciences. The result is a scientific and educational base in hydrology that is incompatible with the scope and complexity of many current and emerging problems. Questions of scaling, equilibrium, stability, teleconnections, and space-time variability demand a renewed emphasis on fundamental hydrologic research." (From the Foreword, by Frank Press).

In its treatment of the water balance, "Opportunities in the Hydrologic Sciences" [10] states explicitly (pp. 65–66),

"In plant dynamics it is known that the abundance of species and their spatial distribution are related to environmental conditions called ecological optima. A natural speculation is that these conditions are the preferred operating domain of the climate-soil-vegetation system. The key question relates to what the optimality criteria are that direct the functioning of this system. Where water is the driving force of the system, a logical hypothesis is that the optimality criteria are related to the key hydrologic variables. Among the exciting scientific challenges are the search for the optimality criteria under different types of constraints and the mathematical representation of these criteria. The fluxes of the key biological variables (e.g., biomass growth) are also intertwined with the operating chemical processes (e.g., carbon assimilation), which in turn are linked to hydrologic processes (e.g., transpiration). From such relations it is clear that hydrology is a fundamental structural component of the biogeochemical cycles."

From the abstract of [15]

"We propose a theoretical framework for predicting characteristics of the water cycle from scaling relationships. In this framework, the ecosystem net primary productivity [NPP] is expressed in terms of soil formation and vegetation growth, which is mathematically optimized with respect to the water partitioning, generating directly the value ET/P. The mathematical optimization is based on the general ecological principle that dominant ecosystems tend to be those that, for any given conditions, maximize conversion of atmospheric carbon to biomass. It is shown that application of the results of mathematical optimization to water-limited ecosystems is possible by applying the optimization only to a vegetation covered portion of the surface. For energy-limited ecosystems, the optimization can be applied only to a portion of the precipitation equal to PET, assuming that the remaining P simply runs off."

Although the close connection between this abstract and the statement of [10] was not recognized in [15], the implications of the relevance of the hydrologic optimization for delivering maximum *NPP* underlying that solution were later exploited in [16] to calculate precipitation elasticity of streamflow (*Q*), defined as $\varepsilon_P \equiv (P/Q)(dQ/dP)$, *NPP* [17], and species richness [18]. Here, only the new comparison of the resulting prediction of the water balance at continental scales with observation will be shown.

4. Combining the General Approach of Klemes (1988) and the Specific Ideas of the Eagleson Report (NRC, 1991)

Scaling laws of percolation were employed to find vegetation growth rates and soil formation rates in terms of the fluxes *ET* and *Q*, respectively. The justification for applying percolation scaling was given in the tendency for water flow, and thus solute transport [19] to be dominated by the critical percolation (preferential flow) path at any length scale, thereby addressing the following questions from page 67 of [10], "How does one contend with the scale issues that are so pervasive in hydrologic phenomena? Is there hope for unifying relationships across scales?" The validity of these scaling relationships was shown in Figure 4 of [20] to hold to length and time scales constituting a Wilson cycle in tectonics. The same scaling relations were then applied [15] to find a maximum value of *NPP*.

Given that plants cannot grow without soil (which requires that some water pass by the plants to create soil), nor can they grow without water (which requires them to take some of the water delivered by *P*), there must be a maximum plant growth and productivity for $0 < ET < P$. If the functional form of *NPP* (*ET*) is known, this maximum may be found by setting the derivative of *NPP* with respect to *ET* equal to zero.

Using the predicted result from percolation that *NPP* should be proportional to the evapotranspiration to the 1.9 power (the mass fractal dimension of large percolation clusters in two dimensions) as well as to the soil depth, itself proportional to $(P - ET)^{1.15}$, one has, $NPP \approx ET^{1.9}(P - PET)^{1.15}$. The result of the procedure outlined led to [15] Equation (1a) for *ET*/*P* in water-limited systems,

$$\frac{ET}{P} = \left[1 - (1 - 0.623)\frac{P}{PET}\right], \tag{1a}$$

and Equation (1b) in energy-limited systems,

$$\frac{ET}{P} = 0.623\frac{PET}{P}. \tag{1b}$$

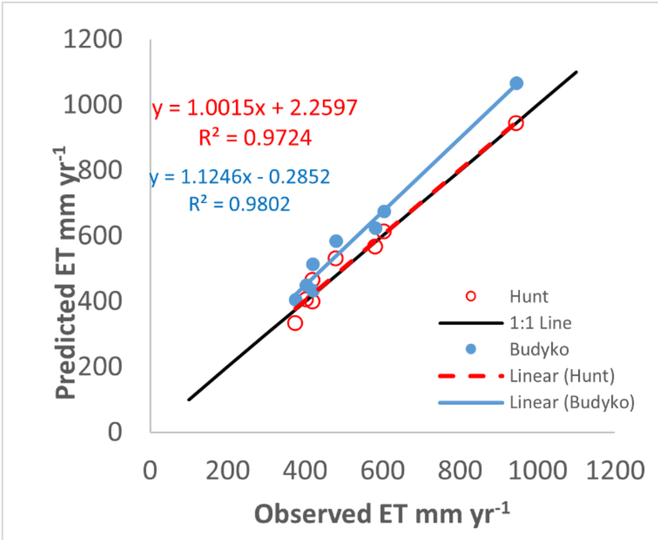
Each result reduces to $ET = 0.623\ P$ valid for ecosystems limited by neither energy nor water and for the case when plant roots are confined nearly to a plane (two-dimensional 2D domain), but with a (relatively) small thickness. This value is derived from universal percolation exponents, thus is not adjustable, and applies to systems that are neither energy nor water limited. In [15] it was argued that the 2D result was a necessary outcome for the case that horizontal dimensions of the ecosystem root zone are much larger than the vertical. At continental scales where horizontal dimensions are 10^7 as large as the vertical (equivalent to a square centimeter of gold film a few atoms thick), this assumption should be valid. Accordingly, at least for large spatial scales the parameter-free Equations (1a) and (1b) are absolute predictions. Their applicability to small catchments, even with very thin soils, would carry the additional complication that storage changes are neglected, but at scales smaller than continental, a 3D solution may be preferred [15]. At the continental scale, however, as particularly for longer periods of time [21] it is reasonable to neglect the storage term in the water balance, the 2D solution should be preferred. It should be emphasized that Equations (1a) and (1b) were used without modification to calculate the consequences of the new theory for streamflow elasticity, net primary productivity, and species richness cited [16-18].

Substitution of Equations (1a) and (1b) into the proportionality of *NPP* to $ET^{1.9}$ with use of a single adjustable proportionality factor predicts *NPP* as a function of *P* and *PET* [16]. A regression of the prediction on the data for the entire continent of Asia from Budyko's Climate and Life [22] yielded [16] an R^2 value of 0.96. The adjustable parameter then acquires the interpretation as universal ecosystem photosynthetic efficiency. Equations (1a) and (1b) also gave accurate predictions of median streamflow elasticity as a function of aridity index, and, pending common assumptions of the variability in annual storage changes, also streamflow elasticity variability.

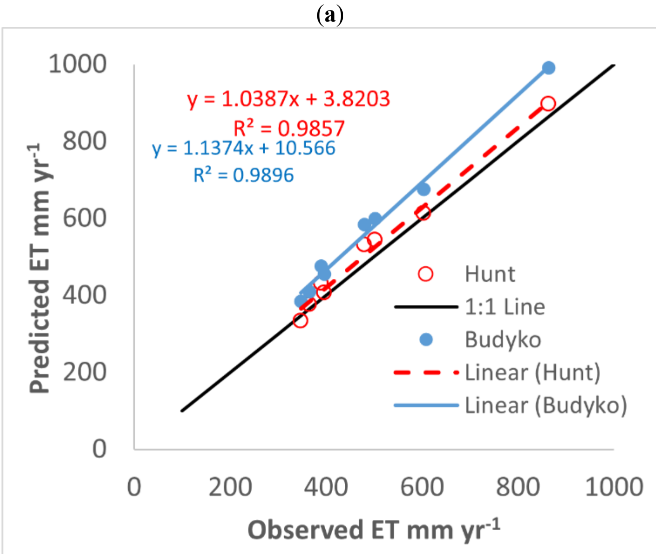
It was further shown [18] that with the use of a universal conversion of *NPP* to species richness, the same theoretical framework also accurately predicts the variability of tree species numbers across northern America. The specific procedure to address the range in tree species numbers at a given *PET* involved substitution of the bounds on *P* values associated with each *PET* into Equations (1a) and (1b) and then multiplying the associated predictions for *NPP* by the universal conversion factor.

Now, on continental landscape scales, it is shown in Figure 1 that the water balance predictions derived from Equations (1a) and (1b) are significantly better than those of the Budyko formalism [23].

The root-mean squared error (RMSE) values from the Budyko function for the three comparisons of Figure 1 are 75, 84, and 90 mm yr^{-1}, respectively, while the RMSE values from the comparisons with [15] are 30, 31 and 47 mm yr^{-1}, respectively. Since the experimental mean *ET* values (indicated by overline) are somewhat larger than 500 mm yr^{-1}, the relative RMSE error for the comparisons with the Budyko function of [23] constitute nearly 16% ($\mathrm{RMSE}(ET)/\overline{ET} = 0.16$) of the mean, but those from percolation theory [15] only about 7%. Note, however, that the high values of R^2 achieved by Budyko [23] imply that the error of Budyko is largely systematic, rather than random, as is also apparent visually. There are two reasons that these findings are of significance: (1) Comparison with results for precipitation elasticity of streamflow ε_P, [16] verified a theoretical problem with the Budyko formalism, (2) Considered together with the comparison of [21] with Model Parameter Estimation Experiment (MOPEX) data for *ET* [24], we can better determine the level of (random) experimental uncertainty.



(**a**)



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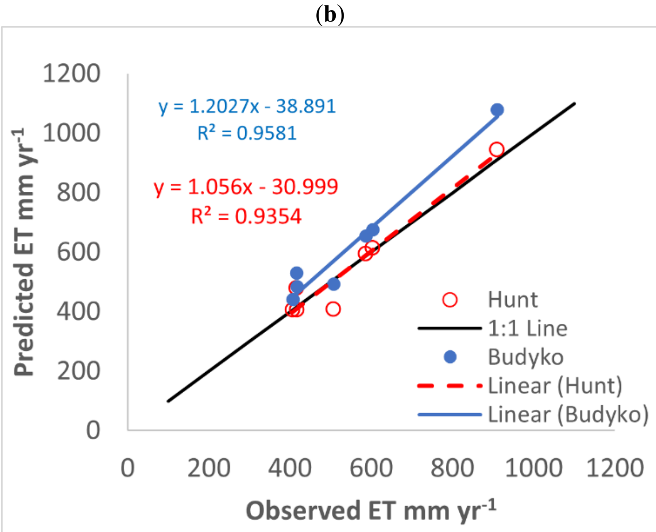

(**c**)

Figure 1. (**a**). Scatter plot of observed [25] and predicted continental *ET* values using Equations (1a) and (1b) from percolation theory [15]. The predicted *ET* values use *P* data from [25] and *PET* values from [26]. The predictions of the Budyko [23] model are given for comparison. Both methods perform best with Priestley-Taylor (PT) estimates of *PET*, already noted in [27] as being the most accurate treatment of PET. (**b**). Identical, except the data set from [28] is substituted for [25]. (**c**). Identical, except the data set from [29] is used.

We start with ε_P. For an aridity index AI(=*PET*/*P*) greater than 1 (arid regions), observations [30,31] delivered in nearly all cases a median value of ε_P almost exactly 2. Equation (1a), which does not account for any storage change, yields exactly $\varepsilon_P = 2$, since $Q \propto P^2$. Yet, particularly in the limit of large AI, the mean elasticity values are larger than the median values. Hunt et al. (2023) investigated the effects of a change in storage on Equation (1). The non-linear behavior of the predicted ε_P (ΔS) yields an asymmetric distribution of ε_P values, with the mean value > 2. But the Budyko [23] phenomenology, since it does not account for storage changes, ΔS, can be interpreted as generating a median value of ε_P ($\Delta S = 0$). Since its prediction for ε_P approaches 4 in the limit of large AI, its functional dependence of ET(AI) must generate Q^4 in this limit. Notably, however, this prediction more nearly tracks the trend of the mean, than the median values of ε_P, overestimating the influence of *ET* under conditions that minimize the impact of storage changes. This interpretation is in accord with the data for *ET* in Figure 1 here, namely that the Budyko phenomenology overestimates *ET* for AI > 1 and large *ET*, at least on the continental scale, where annual changes in storage are expected normally to be negligible. The ameliorating effects of storage may be possible to accommodate in this framework using dimensional analysis as discussed elsewhere [32], though it would not change the present inferences.

Secondly, the typical Budyko RMSE of magnitude nearly 16% of the mean *ET* is generally in accord with the quantitative estimates of uncertainty from [21], who found that nearly all the data lay within about 10% of the Budyko curve. However, in the comparisons here, a significant share of the RMSE appears to be due to systematic, rather than random, error. While we certainly do not wish to diminish creative freedom in framing scientific narratives, our findings suggest that the title of [21], '*Interdependence of climate, soil, and vegetation as constrained by the Budyko curve*', may be misleading. The implied direction of causality is reversed: it is not the Budyko curve that constrains the land surface system, but rather the system that gives rise to the observed Budyko-like behavior. This inference is further supported by our comparison, which reveals a narrower range of *ET* values at the continental scale—pointing to the presence of more selective physical constraints than a purely mathematical fit would suggest.

To underscore the significance of Equations (1a) and (1b) in general and the coefficient 0.623 in particular, it is worth pointing out that many generic features of the Budyko curve can be derived from dimensional analysis, complete similarity theory, and the hydrologic balance. So, to what extent Equations (1a) and (1b) are outcomes from such dimensional considerations with minimal constraints instead of new physics routed in percolation theory is worth commenting on. To do so, the Budyko curve is now derived from the Buckingham Pi theorem subject to hydrologic balance constraint. The starting point is to assume $ET = f(PET, P)$.

There are two dimensions here (water depth and time) and 3 variables (*ET*, *PET*, and *P*). Hence, depending on choices of repeat variables, say *P* to be consistent with Budyko's original work, the Buckingham-Pi theorem leads to two dimensionless groups defined by

$$\pi_1 = \frac{ET}{P};\ \pi_2 = \frac{PET}{P} = \text{AI}; \text{and}\ \pi_1 = G(\text{AI}), \tag{2}$$

where $G(.)$, in principle, must be determined from experiments. If one invokes complete similarity, it follows that as AI → ∞, $G(.)$ must asymptotically approach a constant c_1. The numerical value of c_1 can also be determined from the hydrological balance constraint whereby in the absence of storage in the soil, long-term runoff cannot be generated in very arid ecosystems so that $G(.) \rightarrow 1$ when AI → ∞. At the other extreme, $G(.)$ can be derived for an isolated system with a saturated atmosphere whereby both *ET = 0*, *PET = 0*, and thus $G(.) \rightarrow c_2$ AI. To determine c_2 it is assumed that the available energy is the only driver for *ET* and *PET*. Moreover, it may be conjectured that *PET* is given by the available energy (imbalance between net radiation and soil heat flux) and *ET* is given by the equilibrium evaporation. Thus,

$$c_2 = \frac{\Delta}{\Delta + \gamma} \tag{3}$$

Where Δ is the slope of the saturation vapor-pressure temperature curve given by the Clausius-Clapeyron equation and γ is the psychrometric constant. For air temperatures between 15–33 °C, c_2 is between 0.62 and 0.813 [33,34]. For the greater part of the Cenozoic before the Pleistocene, Earth's temperature has varied between these temperatures [35] and is currently near 15 °C. As noted, ref. [15] proposed two root models, one related to the 2D percolation topology and mass fractal dimensionality (and used in most of the previous publications), and one which assumes the 3D percolation topology for the root mass. For Equation (2), the 2D value is in close correspondence with Brutsaert result for 15 °C, while the 3D result of 0.813 is what was obtained for 33 °C [33,34].

Equations (1a) and (1b) go beyond satisfying these elementary dimensional constraints (see [32]) because they predict the form of $G(.)$ in each of the two AI regimes using entirely different theoretical tactics and assumptions.

A partial integration of these ideas is made possible by considering the best fit functions for the water balance given by [36,37], as well as the ecohydrological optimization of the process model of [38]. Nijzink and Schymanski [38] reported that their results with the largest ET corresponded most closely to the Choudhury [39] function with parameter 1.49, which [36] reported was the best-fit function for their Fluxnet data. In [37], it was reported that their data fit the Fu model [40] with parameter 2.24 best. As it turns out these functions are indistinguishable from each other and agree closely with Equation (1b) here, but not Equation (1a). We present the results together with the result for AI << 1 from [33,34] in Figure 2. Although purely geometrically, Equation (1a) is the only possible way to join the purely physical result [33,34] with the best-fit functions, a different overall functional appearance could have been generated if a larger latitude of functional forms had been applied in the best-fit search, in particular if the percolation-optimality option had been included, but without specifying the constant. However, if the low AI condition from [33,34] were included in the best-fit search, it would be difficult to see how another function could succeed.

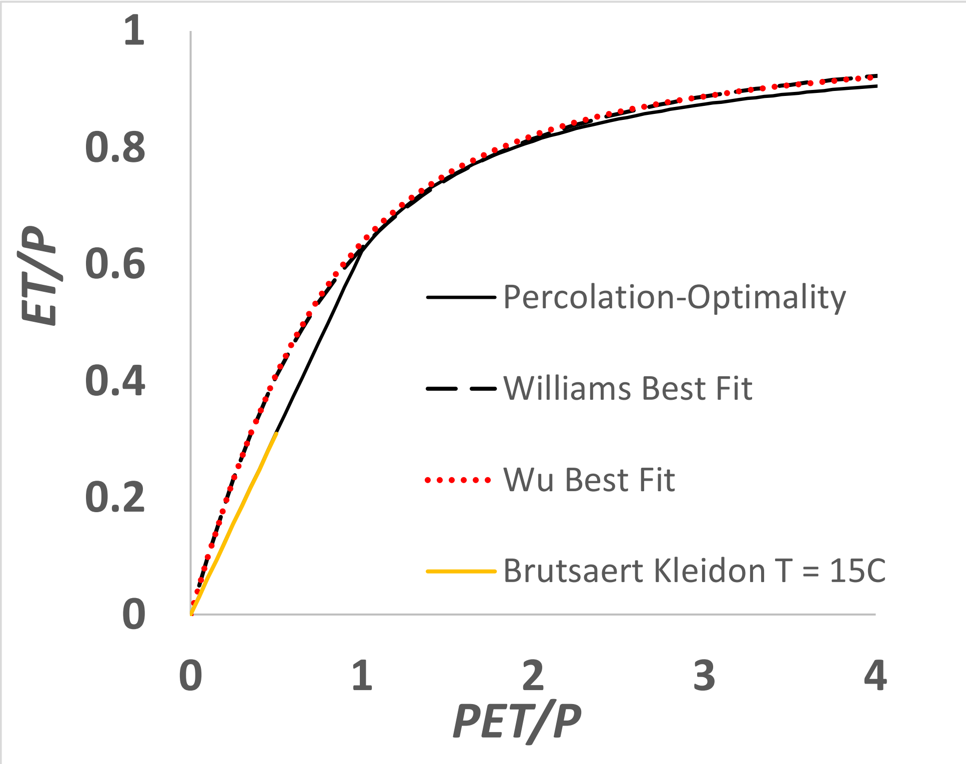

Figure 2. Integration of best fit water balance functions from the literature with Equation (3) [33,34] for the AI << 1 limit at T = 15 °C compared with percolation-optimality.

5. Conclusions

We conclude that, at least as regards the central problem of hydrology [41], it is not true that societal needs and technological advances have guided the relevant theoretical breakthroughs [12]. What societal needs have driven, amount to new phenomenological results for the water balance, including parametric equations, which contain mathematical parameter fields with no demonstrated relation to catchment characteristics [42–44]. Instead of addressing the theoretical shortcomings of what is simply a geometric mean [23] of two early 20th Century guesses of the functional form of ET (P, PET), one of which systematically overestimates ET, the other of which underestimates it, the community has continued mostly along two paths: (1) to continue to use Budyko, as though it had "become scientific fact... [by a] proper number of citations in the literature" [11] or (2) adopted parametric equations in the service of "finding quick fixes to water management problems" [11]. In fact, we find here using continental scale observations of ET, that the discrepancies between [23] and observation average over 50-year time periods that were attributed mainly to experimental error [21], probably represent a significant defect in the phenomenology, one which generated related problems in understanding precipitation elasticity of streamflow [16]. This is not a criticism of generating the phenomenology in the first place; rather, it is encouragement to develop the will to say, "Enough is enough," as Klemes [11] did. Budyko's phenomenology has served a useful purpose [23], e.g., in testing Manabe's [45] land-surface model for accuracy, but better theory is now available.

The apparent equivalence of the result of the ecological optimality adopted and the constraints proposed by [33,34] could have two very different interpretations: (1) that we achieved the right results for the wrong reasons or, (2) the various components/laws of the hydrologic balance are so interdependent that the temperature relaxes to a state that produces the smallest discrepancy with the optimality.

Overall, we find that the careful choice of appropriate theoretical procedures and the systematic application to problems from flow and conservative solute transport through reactive solute transport, chemical weathering, and soil formation [3] all the way to their practical application to the maximization of net primary productivity of ecosystems [15] provides a step in a new direction with a basis for continued exploration. For, we do not imagine that this step is the end result, but a trigger for new ways of thinking and educating.

Author Contributions

A.H.: ecohydrological conceptualization, writing; G.K.: physical conceptualization, writing; J.V uncertainty effects, writing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

No new data were used in this study. The PET data were digitized from [26]. ET and P data were not obtained directly from their sources [25,28,29], but from a table in Thomas, G., & Henderson-Sellers, A. (1992). Global and continental water balance in a GCM. *Climatic Change*, 20(4), 251–276 [46].

Conflicts of Interest

The authors declare no conflict of interest.

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