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Practice on the Watershed Hydrological Experimental System Reconciling Deterministic and Stochastic Subjects Based on the System Complexity: 1. Theoretical Study

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<http://dx.doi.org/10.5772/intechopen.78721>

Abstract

This is the first of a two-part series on the watershed hydrological experimental system (WHES). Since the foundational stage and developmental stage of hydrological basin study with a duration of more than ca. one century, facing with the changing environment and, the declined risk of field study while the catchment hydrology is trapped in a theoretical impasse, a third phase of renovation on hydrological experiments seems ready to come out inevitably. Learned from Chinese decades' experiences on the field basin study for the question of what is wrong with the status quo, our exploratory idea is reported in this part. From the viewpoint of general system theory based on the paralleled concepts of the ancient Chinese and the Western, it is considered that the adequate method should face the characters of the complex dynamic system instead of previous static, linear system. From the viewpoint of another philosophical paralleled concept of the Middle Way, it should also face the operation and organizing of the mesoscopic systems for the organized complexity. Then, a framework of WHES is suggested with its organization based on the strategy of constrain complexity and add complexity and on the strategy of manipulation including the artificial-natural and controlled-natural objects. Such a trial framework, the Chuzhou WHES, is reported including the suggested critical zone experimental block (CZEB) instead of the experimental basin (EB) in the last decades.

Keywords: general system, hydrology system, watershed hydrology, hydrological experimentation, experimental basin, critical zone experimental block, eight trigrams, Tai-Chi Tu

1. Introduction

The most difficult is that the hydrology science perhaps cannot take the natural objects to laboratory for experimental studies, but the development of hydrology will depend mostly on the field observations and experiments; even the foundation of scientific hydrology recognized by UNESCO in 1974 is not from the work in laboratory but from the two field basin studies in France [1]. The first modern basin studies commenced in Switzerland at Emmental during 1890s; after that, a multitude of basin studies have developed from many parts of the world since the early twentieth century. Following it, a period of rapid development of hydrological basin studies was resulted from the International Hydrology Decade (IHD) Representative and Experimental Basin Program 1965–1974; during this period, it is estimated that ca. 3000 experimental basins (EBs) have been conducted [2]. If we designate the first phase of basin study until ca. the middle twentieth century as the stage of foundational and the second phase during/after the IHD as the stage of developmental, which has been going on for more than five decades up to now, a third phase of renovation seems ready to come out inevitably. A paper coauthored by 12 scientists pointed out that “Yet, most field experiments and observations in watershed science to date, remain largely descriptive..., have not set out to seek fundamental truth or understanding (nor test any formal theory or hypothesis per se)” [3] while Sivapalan alarmed that “catchment hydrology is trapped in a dead-end track, a theoretical impasse” [4], but the field study also meets its risk of decline, more complicated challenges, as Burt and McDonnell asked: “Field work: A dying art?” [5].

Question was then raised that “What’s wrong with the status quo” [3]? Yes, there are many objective causes to look for, e.g., “many times things do not work out, weather does not cooperate,” “field studies can be difficult to publish in international journals if they are seen as case studies” [5]. “There has been a movement away from field work and towards an almost complete dependence on modeling,” as “computing power has become less expensive and field work more expensive (and risky, compared to model approaches)” [6]; this impacts researchers to flinch from field study rather modeling. However, to remind of especially the inherent objective roots have the significance. Learned from Chinese decades’ experiences in their field basin studies with zigzagging process [7] especially those based on the concept of experimental basin, the inherent defects have been summarized mainly as the following: (1) designs of the experimental basins have been limited by the black box concept, as well as by many misconceptions (e.g., the linearity, nonheterogeneity, additivity of hydrologic systems, etc.), (2) operation has been substantially bounded by the hydraulic conception of these watersheds as isolated hydrological systems, (3) the studies of experimental basin are focused just on the surface hydrology, and (4) all of these watershed studies monitor only total runoff at the stream-outlet, and the subsurface responses of the watershed are only estimated by hydrograph separation [7, 8].

After the first stage of foundational and the second stage of developmental, if it reveals that experimental watershed hydrology is “inevitably going into a third phase of transition and innovation [8]”? While the planet moves to a new geologic era of Anthropocene [9], what faced is a changing nature of great transition with anthropogenic perturbation, replumbing of the hydrologic cycle [10], and natural climate oscillations. Aimed at the substantial progress in hydrologic science toward “a new unified hydrologic theory” as Sivapalan suggested [4], the answer will certainly be Yes. For this purpose, it, however, “ultimately depends on supporting new experimental work, new field observations, and new data collection networks” [11]. But, what shape will these new experiments and networks take? Twofold is reported here: our exploratory idea and practical tests.

2. Dialog with the hydrological nature

The hydrological experimentation appears as a dialog with the hydrological nature via designed objects aimed at knocking up its hiding doors of “black boxes” involved in for her true features. However, such a dialog seems not easy, it depends mostly on the adequate *method of questioning*, i.e., on the designed objects and the keys for it. Facing with the inevitable transition phase of the experimental watershed hydrology, it appears worth to have a fundamental rethinking on our previous methods of dialog, which seems challenged, sometimes having a successful beginning but becoming increasingly inadapted with the dynamic nature. In this paragraph, we will report the following: (1) from the viewpoint of *general system theory* based on the paralleled concepts of the ancient Chinese and the Western, it is considered that the adequate *method of questioning* should face with the characters of the complex dynamic system instead of previously the static, linear system, (2) from the viewpoint of *the philosophy of the Middle Way* (“golden mean”), based also on the paralleled concepts, it is considered that the adequate *method of questioning* should also face with the operation and organizing of the mesoscopic systems of organized complexity, (3) from these considerations, a suggested framework of *watershed hydrological experimental system* (WHES) is reported.

2.1. The quest for the watershed hydrological experimental system

2.1.1. What sort of system the watershed hydrology is?

A system is in general a set arrangement of things so related or connected as to form a unity or organic whole, also in interaction with environment [12]. For watershed hydrology, it is essentially an open system, it is bound up with the continuous exchanges, inflow and outflow, materials and energies to maintain in a so-called steady state. The fundamental characters of it consist of twofold: (a) complexity of various constituents of the system includes mainly the components which are correlated each other in the way of nonlinear and nonsymmetric and (b) complexity of the system itself includes mainly the evolution mechanism, never being in a state of dynamic equilibrium but always in changing with also the self-organization mechanism, etc.

So the watershed hydrological experimental system (WHES) is defined as an experimental system, which is designed to dialog with the complex watershed hydrological nature, to drive

opening of various door of their black boxes aimed at revealing mechanisms hidden deep in the system.

2.1.2. Main components of the watershed hydrological experimental system: the Capra's parallels-1

In a radical manner, the WHES is a system of material, however refer to operation manner it is manifested itself in three aspects: (a) *Mass*. It is the *material aspect* involving “rock, soil, water, air, and living organisms” according to NRC of USA on 2001 for the components of the critical zone [13]. Magically, it happens to coincide with the ancient Chinese philosophy for nature 1000 years ago, the so-called “*Five-Xing*,” which holds the five fundamental elements from the Earth nature (“Jin,” “Mu,” “Shui,” “Huo,” and “Tu”) [8]. (b) *Energy and force*. It is the *driven aspect* including external solar energy from its environment, and various inherent forces, gravity, surface tension, intermolecular forces, capillary force, etc., from material system internally itself. (c) *Information*. It is the *philosophical aspect* including organization, entropy, gene, etc. [8]. This living open system of structural dissipative processes and irreversible evolution tends to increase its entropy spontaneously and go towards disorder, even the exchange of entropy fluxes across its boundaries is continuous [14]. However, the role of feedbacks of this nonlinear system will promote “self-organization” as energy dissipates, providing opportunities for dissipating energy to act again within the system towards the direction of order. “Conservation without evolution is death. Evolution without conservation is madness” [15, 16]. The material system with “*Five-Xing*” can be so arranged following the Chinese general philosophical imagine thinking, the archetypal symbols of “eight trigrams” for all cosmic and human situations [8], every trigram is composed with three lines, solid (“*Yang*”) or broken (“*Yin*”). Such “*eight trigrams*” corresponding to the “*Five-Xing*” in different weights (shown later) can also be the image thinking of the WHES, schematically shown in **Figure 1** (left) which is quoted from Capra’s book [17]. The “parallels” between modern physics and eastern mysticism has been explored firstly by him, and it is even vaguely similar to the meson octet (**Figure 1**, right). “The eight trigrams are symbols standing for changing transitional states; they are images that are constantly undergoing change. Attention centers not on things in their state of being—as is chiefly the case in the Occident- but upon their movements in change” (Richard Wilhelm, from [17]). “In modern physics, we have come to see the ‘things’ of the subatomic world in very much the same way, laying stress upon movement, change, and transformation and regarding the particles as transient stage in an ongoing cosmic process [17].”

2.1.3. Boundary and environment of the watershed hydrological experimental system

It was suggested that in addition to the three operation manners: mass, energy, and information, manifested by the material system itself, there should have the fourth subjective component [12], i.e., the view of the observer. It is true e.g., in our case, for the boundary of the watershed system to be studied, it depends actually on what is the purpose of studying and largely on the view of point for the watershed system as well. During the first and second stages of basin study aforementioned, the boundary of the WHES is limited mostly by the surficial watershed, and it appears as the *narrow system of interest (NSI)* according to Yan et al. [12] as shown schematically in **Figure 2**. It holds relevantly an *around environment*, and a *wider environment* as well. For the new stage, it will be inevitably renovated into a *wider system of*

Figure 1. The eight trigrams are symbols with opposite coupled “Yin” and “Yang” lines interchanged, standing for changing transitional states. It appears as an image of the WHES (left). This pattern is even vaguely similar to the meson octet with different charges including π^+ , π^0 , π^- , κ^+ , κ^0 , κ^- , $\bar{\kappa}^0$, and η (right) [17].

Figure 2. Development of the system boundary, around environment, and wider environment of the watershed hydrological experimental system from its previous stages I and II to the renovation stage III (sketch following Yan et al. [12] with explanations for our systems).

interest (WSI) [12], i.e., taking the critical zone as its system boundary with a much wider environment involving the Earth spheres.

2.1.4. The image thinking for the system evolution: the Capra's parallels-2

As an open, dynamic, and evolving WHES, all of its system components (“eight trigrams”) are never just the aggregate of heaps but are correlated with each other, and are merely in the transitional stages of hydrological process. “The eight trigrams therefore are not representation

of things as such but of their tendencies in movement" [17]. In fact, the changing items revealed in the schematic eight trigrams (left of **Figure 1**) are twofold, i.e., internally between different trigrams showing by lines within opposite "Yin" and "Yang," they are standing in interrelations, and externally between the system and the environment, they are standing in interrelations as well. According to the Chinese saying, it seems that "pulling one hair, the whole body is effected," e.g., a change of soil moisture even partly in the watershed will result in the changes of surface and subsurface runoff generation, the groundwater recharge, the land evapotranspiration, the living organisms, and perhaps the far-sited outlet discharge.

It was illustrated by another symbol called "*Tai-Chi Tu*" or "*Diagram of the Supreme Ultimate*." It is generated by a symmetric arrangement of dark Yin and bright Yang with cyclic interplay, with fishlike image in opposition, coordination, conjunction, and in blended harmony of Yin and Yang. Such "archetypal pair of nature is the grand leitmotiv that permeates Chinese culture" [17]. Two dots imply the inherent connections of the primordial pair of opposites Yin and Yang and symbolize the idea that both contain always the "seed" of the opposite sides. The curved interface can be derived mathematically from periodicity, it also seems to be "the closest analogy to S-matrix Theory in Eastern Thought" [17] while the S-matrix Theory is "a framework which seems to be most appropriate for the description of hadrons and their interactions" [17]. Fritjof Capra used *Tai-Chi Tu* on the cover of his book "The Tao of Physics: an exploration of the parallels between modern physics and Eastern mysticism" with which over 1 million copies was sold worldwide during its third edition (**Figure 3a**). In our case, it can be revealed for different sorts of WHES, or for subsystems, e.g., reconciliations of the WHES and the environment (**Figure 3b**). It is also being used recently as the book cover (**Figure 3c**) on the theory of *irregularities* [18], which is closely related to the rationale of our WHES. Niels Bohr was well aware of the parallel between his concept of complementarity and Chinese thought, when he was knighted, he had to choose a suitable motif for his coat-of-arms, his choice of feel on the Chinese symbol of *Tai-Chi* representing the complementary relationship of the archetypal opposites Yin and Yang. In choosing this symbol for his coat-of-arms, he also put together the inscription *Contraria sunt complementa* (**Figure 3d**) [17]. In fact "opposites are complementary" just describes a rationale of the WHES as well.

"*Tai-Chi Tu*" (**Figure 3**) and the "*eight trigrams*" (**Figure 1** left) are always coupled, the *eight trigrams* revolved around the *Tai-Chi* including four couples oppositely distributed symmetrically to the circle center of *Tai-Chi* with their trigram lines in contrary (full or broken) with each other as shown in **Figure 3e** (numbers 1 and 8; 2 and 7; 3 and 6; and 4 and 5). The *eight trigrams* are also related to the five materials of system described both by NRC and the *Five-Xing* with different weights (**Figure 3e**). The peripheral arrangement of "*eight trigrams*" is strictly made according to the philosophy of *Five-Xing* i.e., in mutual promotion and restriction to each other to maintain dynamic balance of the system, which in fact are the initiator of the complexity and irregularity of the watershed hydrological system. However, the important parameter *time* of this coupled "*Tai-Chi Tu*" and the "*eight trigrams*," which is the diagram of imagine thinking for the watershed hydrological system and also that of WHES, lies deep hidden, resulted from the philosophical concept of *time*. Traced to the ancient Chinese concepts on time and space since 2000 years ago, OuYang S.C and Lin Y. suggested that "Time dwells in the rotational movements of materials so that it cannot exist independently outside the materials," "time is an attribute of materials so that it does not occupy any material dimension," "time is parasitic on

Figure 3. The image thinking for the system evolution based on the ancient Chinese philosophy, the “Diagram of the Supreme Ultimate” (Tai-Chi Tu) and the “Eight Trigrams” (Bagua). (a) The Tai-Chi Tu Fritjof Capra used on the cover of his book [17], (b) system concept for the experimental catchment of the previous stages and the suggested new stage, (c) the Tai-Chi Tu, which OuYang and Lin used on the cover of their book of *irregularities* [18], (d) the Tai-Chi Tu Niels Bohr used on his coat-of-arms during he was knighted, put together with the inscription *Contraria sunt complementa* for his theory, (e) the coupled diagram of the Tai-Chi Tu and Eight Trigrams (Bagua). The eight trigrams are related to the five materials of system with different weights, it forms four couples with their peripheral arrangement following the philosophy of *Five-Xing*, in mutual promotion and restriction to each other, and (f) schematically showing the hidden parameter time, it also reveals the unceasing moving of materials and the unceasing evolution of system as well.

the changes of materials,” “so that as long as there is material, the material will have to move” [19]. For the coupled “Tai-Chi Tu” and the “eight trigrams,” time is in fact hidden in the continuous movement and evolution as schematically shown in **Figure 3f**.

2.1.5. The mathematical descriptions for the system evolution: the Bertalanffy’s differential equations

The concept of changing evolution interrelated between the system components and between the system and its environment as well can be revealed by the combined *eight trigrams* and *Tai-Chi*; they are bound up with the continuing exchanges for maintaining their steady state. Such an image thinking for the system concept of interrelations was illustrated mathematically by Ludwig Von Bertalanffy [19] and discussed by Yan et al. [12].

Suppose there are n elements in a given system, $X_i (i = 1, 2, \dots, n)$, denoting some measure of elements X_i by Q_i for a finite number of elements, and in the simplest case, while dQ_i/dt is continuous, then the interaction between system elements can be described as follows:

$$\begin{aligned} \frac{dQ_1}{dt} &= f_1(Q_1, Q_2, \dots, Q_n) \\ \frac{dQ_2}{dt} &= f_2(Q_1, Q_2, \dots, Q_n) \\ &\vdots \\ \frac{dQ_n}{dt} &= f_n(Q_1, Q_2, \dots, Q_n) \end{aligned} \quad (1)$$

It follows that the change of any measure Q_i , i.e., $\frac{dQ_i}{dt}$, therefore, is a function of all Q 's, from Q_1 to Q_n , conversely, change of any Q_i in the right side of above equation will introduce the change of other elements ($\frac{dQ_j}{dt}$) and of the system as a whole. It also reveals that not only the Q_1 , acts on Q_j , i.e., Q_1 is the cause and Q_j is the effect, but also Q_j will act on Q_1 that also existed, they are in *causation*. It means a *feedback*, a *cycle causation*, e.g., the soil and the plant in our system. Furthermore, such an interaction of causation and feedback existed not only for several elements of the system but also for all of the elements, it in fact reveals the systematicness and complexity [12, 19].

The foregoing considerations are a set of n simultaneously first-order differential equation called dynamic equations or equations of motion of the system [19]. In order to avoid expressing it in partial differential and integro-differential equations, the above equation abstracts from spatial and temporal conditions, the previous history of the system, etc., even so, it is quite useful for discussing several general system properties [19].

2.2. The middle-ground perspective for the watershed hydrological experimental system

2.2.1. System categories by complexity

In his frontier paper of 1948 on "Science and complexity" [20], Warren Weaver first proposed three terms on complexity: "*Problem of simplicity*," refers mostly to the physical sciences for study problems, which involved two variables or at most three or four; "*Problems of disorganized complexity*," referred as "a problem in which the number of variables is very large, and one in which each of the many variables has a behavior, which is individually erratic, or perhaps totally unknown"; and what he emphasized was the *middle region*, the "*Problems of organized complexity*," with moderate number of variables involved, the really important characteristic of the problems of this middle region "lies in the fact that these problems, as contrasted with the disorganized situations with which statistics can cope, show the essential feature of *organization*" [20]. Later on 1975, Weinberg described these terms as "*organized simplicity (mechanisms)*," "*unorganized complexity (aggregates)*," and "*organized complexity (complex systems)*" [21] as shown in the II, I, and III of **Figure 4a**, respectively. Dooge emphasized this *middle region* as *intermediate systems*, and he pointed out that "most problems arising in catchment hydrology fall in the category of complex systems with some degree of organization," and "a theory of complexity based on the concept of reality as intermediate between determinism and randomness" has emerged [22].

As for the basin studies in China within last decades, it has been conducted mostly by using of the representative basin (RB) and experimental basin (EB) proclaimed by the first IHD more than 50 years ago, and by using of some kinds of artificial physical models e.g., the soil column. It appears that the important *intermediate system* (III in **Figure 4b**) described by Weaver and Dooge is actually a vast gap in between the two extremes, "*unorganized complexity (aggregates)*" and "*organized simplicity (mechanisms)*" (I and II in **Figure 4**, respectively) for the watershed hydrological experiments [14, 8].

Figure 4. (a) A schematic representation of the complexities adapted from Weinberg [21], Dooge [22], and Sivapalan [4] and (b) there is a gap between the two extremes in watershed hydrological experiments with mostly natural EBs and artificial physical models.

2.2.2. The middle-ground perspective: one of another parallels

For the intermediate, it seems hackneyed, e.g., the story of “Boucle d’or les trios ours”; however, for its scientific solution, it seems inevitably to contact with the philosophical concepts about it. In fact as said early by Aristotle, he termed “the golden mean between two extremes of character” in Book IV of his *Ethics*. Comparing with *Dichotomy* (*dimidiata thinking*) in Western philosophy, the Chinese philosophical mode can be illuminated by the middle-ground perspective, the *mid-view thinking*, with core concept of “holding the two extremes and using the middle impartial,” “using the middle impartial for the understanding of the two extremes” [23]. In fact, it happens as a general mode for treating everything both socially and scientifically, “too tight a string will easily be broken while too loose will bring no music” as the saying goes. Parallely, there is also a central concept of “*mid-view thinking*” in Buddhism [24].

Down to watershed hydrological experiments, the intermediate gap (**Figure 4b**) between the deterministic and stochastic extremes is actually a strategic weakness of it; perhaps it may hamper the progress for getting a “unified theory of hydrology at the catchment scale” as Sivapalan has described [4]. It is, thus, very desirable to fill up such a gap, to have new intermediate experimental entities for the watershed music based on the *middle-ground-perspective* (MGP) concept. For watershed hydrological experiments, here we refer the entities of deterministic paradigm as the micros (*Micro*), that of stochastic the macros (*Macro*), in between the mesos (*Meso*), from MGP concept; three characters of this intermediate system can be specified as following: (1) character of *Trichotomy*: MGP viewed: these are the hierarchies of the whole system, i.e., the *Meso* contains both the information of *Micro* and *Macro*, *Meso* is composed by *Micro* but also is the subsystem of *Macro*; (2) character of intermediate: *Meso* system acts as the bridging

between Micro and Macro, bridging not just means a passageway as current concept revealed, but intermediary and reconciliation independently; and (3) character of *Hypercycle*: as a manifestation of both self-organization and feedback, it composed of four interrelated cycles, i.e., $Micro \leftrightarrow Meso$, $Micro \leftrightarrow Macro$, $Meso \leftrightarrow Macro$, and $Micro \leftrightarrow Meso \leftrightarrow Macro$ (**Figure 5**) [25].

2.2.3. Target of the watershed hydrological experimental system (WHES) and its setting

Learned from the field experiments on watershed hydrology since 1953 in China [7], great efforts have been exerted for “getting right answers [11]” on engineering hydrology, facing with the changing environment since then and lots of new raised water problems coupling with misconceptions, and “in an era of largely model-only research” [5], it needs to have further understanding on scientific hydrology for “the right reasons [11].” The WEHS will specifically target the tests of outrageous hydrological hypotheses, and the generation of theories as Burt and McDonnell [5] and Sivaplan [4] have called upon.

We can take a diagonal in the space of complexity versus randomness of **Figure 4a**, and replotting it in **Figure 6a** and **b** with arbitrary points L, A, C, and N (**Figure 6b**) for the sake of discussions later. Aforementioned natural experimental watersheds are falling in the region I (**Figures 4** and **6**), represented by N in **Figure 6b**; it possess main characteristics of an adaptive complex system, and it is defined in **Figure 5** as the “macro.” In addition, L1 and L2 in **Figure 6b** are in the region II with lowermost randomness and complexity, which is also defined in **Figure 5** as the “micro.” Evidently, the watershed as a whole cannot be understood directly from individual parts of its own, i.e., from the “micro” leap forward to the “macro.” The requirement of the intermediate “meso” system is then emerged as have discussed. So the questioning of strategy of setting WHES is then shifted to the “meso” system.

2.2.4. Strategy of “constrain complexity”

There is a particular difficulty raised to the hydrologists that no possibility for taking the research entity, natural catchment, as a whole to their laboratory for experimental research as many other natural science did, the only way out is to work on the EBs in the field, which in

Figure 5. Mechanism of hypercycle among micro, meso, and macro based on the *middle-ground-perspective* of system [25].

Figure 6. (a) Re-plotting diagonal in the space of complexity versus randomness of **Figure 4a**, (b) the organization of the WHES, and (c) different treatments for the WHES.

fact has been used for decades worldwide. However, as McDonnell coauthored by 11 hydrologists pointed out that “Yet, most field experiments and observations in watershed science to date, remain largely descriptive” [3]. It gives rise to assuming that the impact of the complexities existed inherently within natural watersheds even in different scales? Very likely, yes. The source of complexity very likely is attributed to the materials composing the entity system (five materials provided by NRC, USA, and the *Five Xing* of ancient China) as have argued in a book related to postmodern science that “irregularity just is the basic attribute of materials [26].” By the way, one of our works suggested that the existence of vadose zone appears as the main complexity source to watershed hydrology [27]. It follows that the inherent complexities of natural catchment cannot be avoided except moving away its constituent materials. Nevertheless, making constrains for the complexity seems not impossible, if so, the N in **Figure 6b** could be moved apart from that position with a higher complexity to a lower complexity at e.g., C or even A as shown in **Figure 6b**. For this purpose, several possibilities are suggested under the prerequisites of keeping conformance with the main characteristics of complex system, i.e., taking system theory as the framework. The idea of “constrain complexity” appeared first in the paper of Sivapalan ([4], p. 206; **Figure 6**).

2.2.4.1. Hierarchical subsystems

Classic reductionist framework prefers that the phenomena can be explained completely in terms of relations between other more fundamental phenomena, and to reduce explanations to the smallest entities. It appears as the method of explaining macroscopic properties in terms of microscopic components. General system theory is opposite to such kind of approaches, simply

because of the basal principle: “*The whole is more than the sum of its parts*” [19]. It can be shown also from Bertalanffy’s differential equations if we take its simplest case with two inputs Q_1 and Q_2 , after developing $\frac{dQ_1}{dt}$ and $\frac{dQ_2}{dt}$ in Taylor series, the results will not obey linear additive but a series of higher order terms left, it gives the index to self-organization and feedback mechanisms, which is not explainable from the characteristics of isolated smallest parts. It was also remarked sharply early by Toffler that “One of the most highly developed skills in contemporary Western civilization is dissection: the split-up of problems into their smallest possible components. We are good at it. So good, we often forget to put the pieces back together again...In this way we can ignore the complex interactions between our problem and the rest of the universe” [28].

The framework suggested here is based on two essential features of the organized complex system: (1) the concept of *hierarchical order*. It is obviously “a mainstay of general system theory,” “it is intimately connected with those of differentiation, evolution, and the measure of organization,” and “the hierarchical order and dynamics may be the very same” [19]. In graph theory, hierarchical order can be expressed by “trees,” (2) the existence of complex interactions as described by Toffler. It is also the key characteristic of complex system. “A system or ‘organized complexity’ may be circumscribed by the existence of ‘strong interactions’ or interactions, which are ‘nontrivial’ i.e., nonlinear” [19].

Here, the suggested subsystem framework, the hierarchical order, is similar to a sort of the reductionism framework, i.e., the “hierarchical reductionism” introduced by Richard Dawkins to describe the opinion that complex system can be described with a hierarchy of organizations, each of which is *only* described in terms of objects one level down in the hierarchy [29]. However in our case, not only the level down but feedbacks as Robert Ulanowicz had suggested that “science must develop techniques to study ways in which larger scales of organization influence smaller ones, and also ways in which feedback loops create structure at a given level, independently of details at a lower level of organization” [30]. In order to illustrate the difference between “hierarchical reductionism” and classic reductionism, a schematic diagram of a system is used following Yan [12] as the S in **Figure 7**, it is composed with hierarchically different subsystems S1s, S2s, S3s, etc., while the classic reductionism composes the splitting elements of natural system, i.e., instead of these interrelated subsystems but the different elements in series (Es in **Figure 7**). Hierarchical subsystems will have lower complexities hierarchically compared with the holistic system S as in **Figure 7**. We take this as the way of constrain complexity, it is schematically shown as the A in **Figure 6b**, A is interacted with both C, N of higher levels and L of lower levels, and with feedbacks as well.

2.2.4.2. Reduce the number of system elements

Referring to Bertalanffy’s differential equations aforementioned, another way for constrain complexity is trying to reduce the number of elements of the hierarchical subsystems, i.e., the n in his equations. There may be several choices: (1) reduce the number of inflow and/or the number of outflow (I and O in **Figure 7**), (2) reduce the variabilities of some of its elements, e.g., making some or all of the inflow process, e.g., that of water amount and water hydrochemistry of hierarchical subsystems in regular type or in organized patterns, (3) reduce the number of effective parameters from the around environment (**Figure 2**) of hierarchical subsystems, etc.

Figure 7. A schematic diagram of a system (adapted from Yan [12], revised).

2.2.5. Strategy of “add complexity”

The artificial physical model e.g., the soil column, is another extreme measure that the current hydrological experimentation studies go for, as shown schematically by L2 in **Figure 6b**. In fact, it is the measure with which many fundamental laws in hydrology; e.g., the Darcy’s law and Fick’s law were derived from, i.e., in small-scale physics and in simplifications, which is very different from real natural behaviors. Blöschl clearly noted that “in the Darcy example, the geometry of soil pores is far more complex than a bundle of tubes,” “but at larger scales where the equations apply the media are considered uniform.” [31]. Beven and Germann challenged the Richards equation that “may be predicated on the wrong experimental method for natural conditions” [32]. Sivapalan pointed out that “However, it is often overlooked that the constituent process theories are essentially derived at the laboratory or small scales. They are underpinned by assumptions of homogeneity, uniformity, and time invariance of various flow paths, over the land surface and in channels, and through soils and vegetation” [4]. Despite all of these recognitions, however, modern approaches for modeling hydrologic systems still have to use these problematic equations and “go further and further down the rabbit hole of model uncertainty estimation” [5]. Aimed at tests of outrageous hydrological hypotheses, and the generation of theories [4, 5], it needs to take the upward approach defined by Klemes as “attempts to combine, by mathematical synthesis, the empirical facts and theoretical knowledge available at a lower level of scale into theories capable of predicting events to be expected at a higher, in our case at a hydrological level” [33]. As an example following his idea, for the “10 different formulas for estimating infiltration” [4], the experimentation was extended from the classic one-dimensional scale to two- and three-dimensional scales, i.e., from the lower level schematically as L2 in **Figure 6b** extended to e.g., L1, etc., and it reveals the “add complexity.” In our work, the different phenomena got from three-dimensional infiltration experiments were then used to the explanation of one of the generation mechanisms of surface runoff [27].

2.2.6. Strategy of manipulation

Remember the warning from Werner Heisenberg that, “what we observe is not nature herself, but nature exposed to our method of questioning,” as we have experienced that for achieving our goal of watershed hydrological experimentation, tests of outrageous hydrological hypotheses, and for the generation of theories, it appears very difficult to rely *only* upon the natural EBs even in small scale due to its inherent complexities. However, the natural EBs are indispensable for achieving the goals. A possible solution for this knot maybe taking some actions that are compelling instead to let it be. What follows that the way of constrain complexity and add complexity is never just for the *natural* entities but also for the *manipulated natural entities*. It may have two ways as experienced:

1. **Artificial-natural.** Starting with the artificial entity, an artificial subsystem of a watershed following different designs, with/without plant systems, maybe a slope, or several combined slopes, or a catchment with slopes. Making artificial boundaries including the bottom and the surface and subsurface dividers, using filling soil or undisturbed soil to form both unsaturated zone and saturated zone. After many years of operation, such an artificial entity approaches gradually to the natural conditions including the promotion of both the physical and chemical features of soils and the ecosystem beneath the ground surface. Here, we term it as the *artificial-natural*, from artificial approaches to natural, e.g., the hydrohill, soil of 1 m in depth was filled up at 1978, equipped and operated at 1982, in the meantime after decades' of exposure under natural rainfalls, it's unsaturated zone can be treated as almost the natural entity. Further step of manipulation is to making around environment e.g., the rainfall input and even the microclimate to be partly controlled.
2. **Controlled-natural.** Starting with a selected natural EB with natural bedrock and deposit, the artificial controls are then made to it including its bottom and surroundings aimed at reducing its surface and/or subsurface inputs and outputs. Here, we term it as the *controlled-natural*, the natural to be controlled, e.g., the Nandadish, and it will be described in detail later.

It may come down to a point that for tapping their potential, both the strategy of *constrain complexity* and *add complexity* based on the middle-ground perspective still needs to have the wind at their back, the measures of manipulation.

3. Organization of the watershed hydrological experimental system (WHES)

3.1. Requirements of the WHES

It can be summarized based on discussions aforementioned as follows: (1) need all scales including the two extremes of pure natural and pure artificial entities, and various intermediate entities; (2) need both downward or top-down approach and upward or bottom-up approach [33], and it could be realized by strategies of constrain complexity and add complexity, respectively; (3) need the measures of manipulation for both natural and artificial entities; (4) need parallel entities of different coverages especially the plant ecosystems; and (5) need an

extension of WHES. As have experienced that for identification, evaluation, and quantification of the interactions between hierarchical subsystems, it needs working on the molecular level and nuclear level for both water and its material mediums, i.e., their isotopic and hydrochemical processes. So the role of it is not merely for getting reference data but for opening another door for the understanding of the hierarchical subsystems.

3.2. Organization and treatment of the WHES

As schematically shown in **Figure 6b**, it includes three levels with both complexity and randomness from high to low, and an extension part:

1. High level: composed by pure natural EBs, the “macros” of WHES represented by N in **Figure 6b**
2. Intermediate level: composed by intermediate chain, the “mesos” of WHES represented by C and A in **Figure 6b**: the controlled-natural entities and the artificial-natural entities, respectively.
3. Low level: composed by pure artificial chain, the “micros” of WHES represented by L1, L2 in **Figure 6b**.
4. Extension of WHES: the laboratory for geochemical processes by water tracing for all entities.

There are different treatments for different organization levels of WHES as shown in **Figure 6c**. Only the “micro” level of WHES is linear, and a small part of the “meso” level, which is very close to the “micro” level is quasilinear or linearizable, these two parts can be treated by Newtonian dynamic methods. For the large-scale river basin, it belongs to the hydrometric monitoring network (HN) (**Figure 6b**), statistics will be the dominate method. In most of the intermediate chain, the “meso” level of WHES (**Figure 6b**) should be treated by nonlinear dynamic methods.

3.3. The WHES of Chuzhou hydrology laboratory

The idea for the necessity of an experimental system for watershed hydrology [7, 34] was summarized from the decades working on field basin studies since the operation of the first hydrological experimental station in China, the Bluebrook, which was established in 1953 [35]. The dream of a WHES finally came to reality with the establishment of the Chuzhou hydrology laboratory (CHL) in 1978 by the Nanjing Hydraulic Research Institutes of the Chinese Ministry of Water Resources on the basis of the Chengxi Runoff Experimental Station established on 1962 with three experimental watersheds. This Chuzhou WHES was designed including both artificial and natural entities of different scales as shown in **Figure 8a**, within which, most of them have established, few of them are in modified and renewed after an interruption of many years. This WHES is settled in a natural Bloomhill (Hua-Shan) watershed (**Figure 8b**), with surficial drainage area of 82.1 km² since 1962, 80.0 km² since 1998 due to a hydraulic engineering. This basin is situated at the upstream area of a river named as the *Western Stream of Chuzhou*, which was described in an ancient poem of Tang Dynasty by Wei Ying-Wu (737–792) which most Chinese pupil can recite. In the meantime within such a

Figure 8. (a) Organization of the Chuzhou WHES of the CHL. ND—Nandadish, GC—Gaocong, WY—Wangying, HW—Huangwa, SCH—Sanchahe, HZS—Huzhuangsan (outlet of the Bloomhill watershed), L1 to L4—lysimeters, area—surficial drainage area and (b) the natural Bloomhill (Hua-Shan) watershed within which the Chuzhou WHES is settled all ad.

traditional cultural atmosphere, the reborn CHL together with WHES is in the process of emotional renovation.

3.4. What is CZEB

The “critical zone” (CZ) is defined by the National Research Council of US in 2001 as “the heterogeneous, near-surface environment in which complex interactions involving rock, soil,

Figure 9. A conceptualized critical zone experimental block (CZEB) [8].

water, air, and living organisms regulate the natural habitat and determine availability of life sustaining resources” [13]. Later in 2005, in a report of a workshop, it was further defined as an extending from “the vegetation canopy to the zone of groundwater” [36], or “the bedrock to the atmosphere boundary layer” [37]. Critical zone becomes one of the most compelling research areas in earth sciences in the twenty-first century [14].

Aforementioned that if we designate the first phase of basin study until ca. the middle twentieth century as the stage of foundational and the second phase during/after the recommendation of EB of IHD since 1965 as the stage of developmental, a third phase of renovation seems ready to come out inevitably. What we suggested is the concept of critical zone experimental block (CZEB) [8], focusing on the fact that the natural watershed hydrological system itself, running on the principle of holism is an extending from watershed surface to its underground deposit layers, never just the dissected watershed surface laterality. The suggested CZEB geologically is a monolith block, with its surface, the watershed, bounded by topographical water divides (**Figure 9**) [8], it is actually an experimental “block” within the critical zone with a surface drainage basin (the watershed). It is a dynamic ecosystem coupled with various supporting systems but using hydrological processes as the unifying theme. It is a living, breathing, evolving boundary layer where rock, soil, water, air, and living organisms interact [38]. The CZEB is the watershed hydrological experimental study in the CZ observatory framework. As “the critical zone observatory network is the only type to integrate biological and geological sciences so tightly” [37]; following this, the CZEB network will perhaps be the network to integrate the hydrological, biological, and geological sciences so tightly as well.

3.4.1. The boundaries of CZEB

Top: if the mean evaporation surface of the canopy is $h(m)$ above the mean ground surface, then the top boundary of a CZEB is defined as $H(m)$, where $H \geq (1.5-2.0) \times h$ with coefficients of h

varying according to the vegetation, 1.5 for crops and grasses, 2.0 for woods, and forest. This is mainly for the purpose of energy budget and eddy covariance flux observations. H is just the lower part of the atmosphere boundary layer.

Bottom: the three cases are discussed below:

Case I: bedrock is situated at a relatively shallow depth from the ground surface while the regolith is shallow, too. The bottom boundary is defined as the geological boundary (Figure 10a).

Case II: bedrock is deep. The bottom boundary is defined as the plane where the tritium content of groundwater approaches zero or the detection limit of ± 0.7 TU (the “tritium naught line” (TNL) [39]), which is same as that of Case III (Figure 10b).

Case III: there are stratified alluvia, potentially with multiple aquifers with aquicludes and aquitards, common in flat plain areas with thick deposit and deep bedrock, up to hundreds of meters or more. Groundwater recharge to the river can be separated into sensitive, active, and passive zones. In this case, the bottom boundary of CZEB is defined as the bottom of the active recharge zone, which is also the plane of TNL (Figure 10c).

Figure 10. Boundaries of CZEB [8].

Lateral sides. There are two parts:

Part I: above the ground surface up to a height H as described above, delineated according to the surface topographic watershed boundary (**Figure 11a**). The lateral exchanges of water vapor, heat, CO_2 , etc. will be monitored.

Part II: below the ground surface, it is in general defined arbitrarily except in the case of existing geological boundaries. (1) Case I: for a general CZEB, the lateral exchanges as shown schematically in **Figure 9** are subjected to monitoring including water tracing, (2) Case II: for the setting of a *controlled-natural* entity as described above, it needs to close all the underground surroundings until bedrock aimed at *constrain complexity* by using of engineering methods; e.g., in Nandadish, it is ready to use steel sheet piling following its surficial boundary perpendicularly until bedrock.

3.4.2. The functioning of CZEB

3.4.2.1. Interfaces and compartment zones

CZEB encompasses “the near-surface biosphere and atmosphere, the entire pedosphere [8], and the surface and near-surface portion of the hydrosphere and lithosphere” [14]. Within the CZEB, various processes including hydrologic, atmospheric, lithospheric, geomorphic, and geochemical processes are coupled and dynamically interrelated. To simplify the organization of various interfacing processes throughout the CZEB, compartment zones can be broadly separated as follows [14]:

1. The zone aboveground surface, the “aboveground vegetation zone.”
2. The unsaturated zone, the “belowground root zone and the deeper vadose zone.”
3. The saturated zone, the “saturated aquifer zone.”

This layering has a general trend of increasing density with depth, has a dampening effect on state variables with depth, and an increase in distance to energy input at the soil surface [36]. There is also “an overall trend of increasing characteristic response time” [14, 40].

3.4.2.2. The “reactors” of CZEB

Each zone will behave as a “feed-through reactor” according to Anderson et al. [41]. It follows then that there are three feed-through reactors coupled together in the CZEB (**Figure 11**), with probably different rates and residence time of materials.

1. Reactor I. The first zone is the aboveground surface zone, which also contains above-ground vegetation up to its interface with atmosphere (**Figure 11**). Evaporation and plant transpiration may account for 50% or more of the total local precipitation and, use up to ca. 50% of the total solar energy.
2. Reactor II. The second zone is the unsaturated zone, extending from the soil surface to the upper surface of the groundwater table. It consists of the whole soil profile: the O horizon (humus), A horizon (topsoil), B horizon (subsoil), and C and potentially D horizons

Figure 11. (a) Functioning of the CZEB, (b) the schematic “reactors” corresponding to CZEB, and (c) general monitoring parameters for the CZEB.

- (Figure 11a). The unsaturated soil zone has been recognized as “the most complicated biomaterials on the planet” [14, 27].
3. Reactor III. The third zone is the saturated zone, extending from the groundwater table down to bedrock, including the capillary fringe (Figure 11). There are two general cases for CZEB, phreatic groundwater and confined aquifers.

3.4.2.3. Functioning of reactors

1. Reactor I includes hydrometeorological and ecohydrological processes, reactor II includes hydropedological and hydroecological processes, while the reactor III is more exclusive for hydrogeological processes.
2. There is an overall trend of decreasing operation rates from reactors I to III.
3. Each reactor has its own lateral flux exchanges L_{ex} via the CZEB lateral boundaries (Figure 11b). Reactor I has vertical fluxes exchange V_{ex} with atmosphere via the upper boundary of CZEB while reactor III has V_{ex} with deep aquifers and/or deep circulation via the bottom boundary of CZEB (Figure 11b). Fluxes include all material and immaterial components.
4. Reactors are closely coupled within the boundaries of CZEB. There are flux exchanges W_{ex} (blue arrows in Figure 11b) between reactors I and II and, and between II and III within the CZEB. There are flux channels MC (Figure 11b) through I to III for materials, and flux channels IMC (Figure 11b) through I to III for nonmaterials.

5. The MC appears similar to blood vessel system and IMC to meridians and collaterals of the human body from the Chinese art of acupuncture.
6. The general monitoring parameters in reactors are shown schematically in **Figure 11c**.

A trial for CZEB is included in the Chuzhou WHES, i.e., the Nandadish, which will be described in detail later.

4. Conclusions

The hydrological experimentation is actually a dialog with the hydrological nature; however, such a dialog seems not easy, it depends mostly on the adequate *method of questioning*, i.e., on the designed objects and the keys for it. If we designate the first phase of basin study until ca. the middle twentieth century as the foundational stage and the second phase during/after the IHD since 1965 as the developmental stage, which has been going on for more than five decades up to now, a third phase of renovation seems ready to come out inevitably. Facing with this transition of the experimental watershed hydrology, it appears worth to have a fundamental rethinking on our previous methods of dialog, which seems challenged, sometimes having a successful beginning but becoming increasingly inadapted with the dynamic nature. The inherent defects of the field basin studies have been summarized from Chinese decades' experiences in their basin studies with zigzagging process especially those based on the concept of experimental basin system.

Facing with the hydrological complex dynamic system, a framework of *watershed hydrological experimental system* (WHES) is suggested, which is raised from both the viewpoints of the *general system theory* based on the paralleled concepts of the ancient Chinese and the Western, and that of the Middle-ground perspective philosophy on the *Middle Way* ("golden mean") that is also based on the paralleled concepts. Thus, the WHES is defined as an experimental system that is designed to dialog with the complex watershed hydrological nature, to drive opening of various doors of their black boxes aimed at revealing mechanisms hidden deep in the system.

Three strategies have been developed for the WHES: the strategy of *constrain complexity* for the natural watershed, which is the downward or top-down approach, the strategy of *add complexity* for the physical model, which is the upward or bottom-up approach, and the strategy of *manipulation* for the operation of both ways including the so-called *artificial-natural* and the *controlled-natural*. In fact the suggested WHES is trying to reconcile the deterministic and stochastic extremes, "opposites are complementary" as the basic Chinese philosophy have revealed.

As a trial of it, the Chuzhou WHES is ongoing. Most problems involved in WHES fall in the category of complex systems with some degree of organization. It includes three levels with both complexity and randomness from high to low, and an extension part: (1) high level: composed by pure natural EBs, defined as the "macros" of WHES, (2) intermediate level: composed by intermediate chain, the "mesos" of WHES, it includes both the controlled-natural entities and the artificial-natural entities, (3) low level: composed by pure artificial chain, the "micros" of WHES, and (4) extension of WHES: it is the laboratory for geochemical processes by

water tracing for all entities. It is the “nucleus” of WHES, an essential condition of it. Different organization levels of WHES will have different treatments; only the “micro” level of WHES is linear, a small part of the “meso” level close to the “micro” level is quasilinear or linearizable, and these two parts can be treated by Newtonian dynamic methods. Most of the intermediate chain, the “meso” level of WHES, should be treated by nonlinear dynamic methods.

Trying to improve the current idea on the research platform of hydrological experimental basin (EB), which is widely used since IHD of 1965, a CZEB within the Chuzhou WHES was suggested. The boundary and functioning of it are discussed including its interfaces and three compartment zones: aboveground vegetation zone, belowground unsaturated zone including root zone and deeper vadose zone, and the saturated aquifer zone. These zones can be treated as three coupled feed-through reactors. Such CZEB is a watershed hydrological experimental study in the CZ observatory framework.

Acknowledgements

This review is a commemoration of the 65th anniversary of the Chinese basin study and the 37th anniversary of the establishment of the Chuzhou Hydrology Laboratory (CHL). The senior author (W-Z Gu) has been fortunate to render his services to the both from their beginning; with grateful heart, he is indebted to a number of people including colleagues, experts, professors, and local peasants, who have helped, succored, supported to make this possible. We are very grateful for those who have made numerous efforts for the reborn renovation of the CHL after a long abandonment and for its leaping forward from manual to digital: Academician Jian-Yun Zhang, Prof. Jiu-Fu Liu, and many other experts in the Chinese Ministry of Water Resources. We also thank many foreign experts who have encouraged, helped, taught, and guided our work over the years especially during our difficulty, including Jeffrey McDonnell, Keith Beven, Henry Lin, Mebus Geyh, Carol Kendall, Vance Kennedy, Norman Peters, Michael Sklash, А.И. Шикломанов, Joel Gat, Verhagen B, and Klaus Froehlich. We also acknowledge many colleagues in the CHL for their hard work in the field.

This work was supported by the grants from the National Key R&D Program of China (No. 2017YFC0403500) and the National Natural Science Foundation of China (Nos. 91647203, 91647111, and 51609145).

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