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The role of catchment classification in rainfall-runoff modeling

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Abstract

A sound catchment classification scheme is a fundamental step towards improved catchment hydrology science and prediction in ungauged basins. Two categories of catchment classification methods are presented in the paper. The first one is based directly on physiographic properties and climatic conditions over a catchment and regarded as a Linnaean type or natural classification scheme. The second one is based on numerical clustering and regionalization methods and considered as a statistical or arbitrary classification scheme. This paper reviews each category including what has been done since recognition of the intrinsic value of catchment classification, what is being done in the current research, as well as what is to be done in the future.

1 Introduction

While "diversity is nature's principal theme" (Gould, 1989), human beings have been craving for the least variability and order (Wagener et al., 2007). There exists an order in any seemingly chaotic and turmoil process or system, which needs to be discovered or unveiled. One approach to discern order in a heterogeneous world is through the means of classification (Gould, 1989; Wagener et al., 2007). Classification systems such as taxonomy, nomenclature, categorization and organization all lead to name and organize entities or organisms into groups on the basis of properties or relationships they have in common (Grigg, 1965).

Classification has been considered as a fundamental step towards improved catchment hydrology science (Gottschalk, 1985; McDonnell and Woods, 2004; Vogel, 2005; Wagener et al., 2007). The need for classification in the field of geography has been identified by Grigg (1965) as follows:

1. to give names to things;
2. to transmit information;

3. to make inductive generalization.

While geographers require names for similar features of the earth's surface that occur repeatedly (Grigg, 1965), hydrologists need names for catchments that have similar characteristics and can transmit similar knowledge or information.

Catchment classification has been traditionally carried out via Linnaeus-type (Linnaeus, 1766) analysis, mainly represented by hierarchical approaches. Similar to what has been implemented in the field of ecology, statistical classification has gradually seen its growth and become an essential component contributing to catchment classification.

This papger is organized into two parts. Section 2 is a review of methods directly based on physiographic properties and climatic conditions over a catchment. These methods are regarded as Linnaean or natural classification. Section 3 provides an overview on the current numerical clustering and regionalization methods. They are regarded as statistical or arbitrary classification.

2 Linnaean catchment classification (LCC)

Classification is a benchmark for most scientific disciplines as Grigg (1965) put it, "the state of classification is a measure of the maturity of a science". Hydrology, as a discipline of science, is still young if compared to biology. A scientific and globally agreed classification system in hydrology has yet to be delivered (Wagener et al., 2007).

Many hydrological regions have been delineated or divided based on administrative boundaries which may cut across geologic, climatic and topographic boundaries (Mosley, 1981). Simple division of areas cannot be of use for the purposes of hydrological prediction. Isolines were probably the earliest attempt to extract some similar features of an area and used as a common method of regionalization to classify regions into runoff zones (Gottschalk, 1985). An isoline joins points of the same value and forms a continuous line which can be of equal altitude (contour lines), temperature (isotherms), barometric pressure (isobars), wind speed (isotachs), wind direction (isogon) and so forth. An isoline map is therefore regarded as a sort of thematic map. In the case of hydrology, an isoline map is a prototype classification that is based on a continuous variation of landscape features. Grigg (1965) points out the difference between the classification of objects and areas, where the former is based on not only the properties but also the functions and relationship that the objects have in common and the latter based only on the properties. Classification of objects that are based on function and relationship is most important for hydrologists since the ultimate goal of classification is to make inductive generalization of objects. An isoline map, apparently, cannot suffice such purpose.

Fortunately, hydrologists are by no means "the frog in the shallow well". Many wonderful systems, such as organism classification in biology, element classification in chemistry, soil classification in pedology and regionalization in geography, already exist for hydrologists to study and emulate. They have been recognized by many hydrologists as classification systems that can be adopted in hydrology, even though some of them have been subject to criticism.

2.1 LCC – What's been done

2.1.1 Linnaean classification and nomenclature

Looking back into the great 18th century, Carl Linnaeus, a Swedish botanist, physician and zoologist, laid the foundations for the modern taxonomic research (Ereshefsky, 2001). The original Linnaean system classified organisms within a hierarchy, starting with three *Kingdoms* followed by *Classes*, *Orders*, *Genera* and last *Species* (Freer, 2003). Linnaean nomenclature can identify every species with only two names without any ambiguity. Systems of classification and binomial nomenclature have a revolutionary effect on the study of all living organisms. Linnaean hierarchical classification system offered clear and simple rules for constructing classifications and became the basis for almost all subsequent systems of classification and nomenclature (Freer, 2003). It contributed to understanding of the morphological similarities among species while also providing powerful evidence for common origins.

2.1.2 Periodic table of chemical elements

Another celebrated classification system is the periodic table of chemical elements and the credit goes to Dmitri Mendeleev from Russia and Lothar Meyer from Germany (Brown et al., 2008). Unlike the top-down hierarchical classification system in biology, the periodic table is based on the recurring trends of the properties of the elements. A group is a vertical column, while a period is a horizontal row in the periodic table of the elements. The elements in the same group usually have very similar properties and exhibit a clear trend in properties with increasing atomic number down the group (Brown et al., 2008). The periodic table is a useful classification framework to systematise chemical elements and predict various forms of chemical behaviour.

2.1.3 Soil classification

Soil classification is another area where classification has played significant roles. Soil classification sees its most application in agriculture due to the fact that soil is the nature medium for the growth of land plants that supply food, fibers, drugs, and other needs of humans (USDA, 1999). Various purposes lead to a number of soil classification systems. Rossiter (2001) summarises two types of soil classification:

- *natural soil classifications* – soils are grouped by some intrinsic property, behaviour, or genesis of the soils themselves, without direct reference to use, e.g. the World Reference Base (WRB) jointly developed by the International Soil Reference and Information Centre (ISRIC), the International Union of Soil Science (IUSS) and the International Food and Agricultural Organization (FAO). The natural soil classification follows the same line along the Linnaean hierarchical classification system that the differentiating characteristics are used to formulate different levels or hierarchies to group soils.
- *technical soil classifications* – soils are grouped by some properties or functions that relate directly to a proposed use or group of uses, e.g. the HOST (Hydrology

of Soil Types) classification system makes use of the physical properties of soils and groups all UK soil types into 29 hydrological classes; the FCC (Fertility Capability Classification) classification system identifies a number of soil properties essential to the specific requirement of growing crops and divides soils into groups with the critical thresholds of those identified properties (Snchez et al., 1982).

2.1.4 Regionalization and classification in geography

If hydrologists were to borrow ideas from geographers, it is necessary to understand their purposes of regionalization. They are summarised from Grigg (1965) and numerated as follows:

1. for geographers to give widely accepted names or terms to similar features of the earth's surface which occur repeatedly;
2. for geographers to exchange knowledge and pass on to new students of the subject. If similar parts of the earth's surface can be grouped together, then statements can be made about that areal class which are applicable to all the smaller parts within the same class;
3. for geographers to make inductive generalization about the relationship of the regions under study.

There are three types of regions that have been commonly recognized by geographers (Berry and Hankins, 1976):

1. The "region" in the general sense in which the region is given a priori.
2. A homogeneous or uniform region; this is defined as an area within which the variations and covariations of one or more selected characteristics fall within some specified range of variability around a norm, in contrast with areas that fall outside the range. Such a region, unlike that previously described, but like the functional region, is a result of the process of regionalization and is not given a priori.

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3. A region of "coherent organization" or a "functional" region. This region is defined as one in which one or more selected phenomena of movement connect the localities within it into a functionally organized whole.

To throw additional light on regional systems, Grigg (1965) gave ten principles which would be useful in constructing a practical classification system. Amongst them, two principles could be of particular interests to hydrologists:

1. a classification system should be designed for a clear and specific purpose, it hardly serves two or more different purposes equally well. A classification system would lose its precision as instruments of analysis if it attempts to cover a diverse range of goals;
2. a classification system is not absolute, i.e. it would be modified, updated or even completely changed as more knowledge is gained about the objects under study.

A ubiquitous and globally accepted hierarchical classification system or nomenclature in geography has, unfortunately, never been reached in light of many studies and endeavors. Herbertson (1905) is probably the first person who put together regions having the same physical characteristics into similar divisions on a world basis. Being deeply influenced by his doctoral work entitled "The Monthly Rainfall over the Land Surface of the Globe", he used mainly climate and relief as differentiating characteristics to divide the world into six climatic regions, namely, polar region, the cool temperate region, the warm temperate region, the western tropical deserts, the inter-tropical region and the equatorial rainy areas. He believed climate renders the physical earth's surface features and thus can represent various influence on the surface.

2.1.5 Regionalization and classification in hydrology

The regional system in geography has been popularized and adopted as a school of thought in hydrology. Isoline maps that are based on one single earth's surface feature have served as a primitive classification method to classify regions. The first work using an isoline map to formulate a classification scheme was accomplished by

Herbertson (1912) in his paper of "The Thermal Regions of the Globe". The mean annual temperatures of 0°, 10° and 20° are represented with isotherm lines to classify the thermal regions of the World. The emphasis was laid on climate, in particular, temperature. It is a prototype of hydro-climatic classification leading to its development in hydrology.

Herbertson's first classification scheme was criticized by Roxby (1907) who stated a region should be "an area throughout which a particular set of physical conditions prevail" but not one classified by only climate and relief. A set of landscape properties were then used as differentiating characteristics to classify physiographic regions in different parts of the world. Examples of them are listed below (developed from (Gottschalk, 1985)):

1. classify Finland into a number of physiographic regions (Granö, 1925–1928, 1952);
2. classify the former USSR with respect to both topographical and climatic information (Kuzin, 1960);
3. classify the entire Europe into a number of physiographic regions (Kondracki, 1968; Grimm, 1968a,b);
4. hydrological regionalization in New Zealand based on information about precipitation, vegetation, topography, soil types and geology (Toebes and Palmer, 1969).

The above-mentioned studies were undertaken separately and no one general approach was designed. Mosley (1981) commented there was "surprisingly little guidance in the literature regarding the details of regionalization" in hydrology, whereas Sum (1970) delightfully named 1905–1937 "the golden age of regionlism (in geography), for it was during this period the regional concept underwent refinement and received its new images through the hands of Roxby, Unstead and Fleure." It certainly indicates again the maturity of geography and youthfulness of hydrology as a discipline of science in comparison with geography, not to mention biology. Despite of "little guidance in regionalization", Linsley et al. (1975) provided a short note on regionalization: "if the regional approach is used, considerable care should be taken to select streams as nearly similar in hydrologic characteristics as possible. They should have similar vegetal cover, land use, topographic conditions, and geologic characteristics, and large basins should not be grouped with very small basins. They should also have similar rainfall and evapotranspiration regimes". This had certainly pointed out a more comprehensive and practical direction for classification. Till then, regionalization strictly followed the footstep of the Linnaean classification system. Nevertheless, classification in geography and hydrology was no more than a game of mere identification of one and the other properties of the regions (Grigg, 1965). Insufficient attention was paid to the functions, relationships and co-varied behaviour among them. More questions had also been raised as what hydrologic characteristics should be taken into consideration and to what extent the interactions with each other affect the hydrological functions were not mentioned. One obvious reason that hinders the development of hydrologic classification is due to lack of data, in particular, spatially distributed data. The secondary reason lies in the understanding of the causal effects between catchment characteristics and hydrologic behaviour. Hydrologic regionalization surely has a long way to go.

So far, regionlization describes the procedure of grouping individuals into regions under the premise that all individuals that are similar are also contiguous, because a region cannot be formed if individuals are not contiguous (Grigg, 1965; Mosley, 1981). Early work of classification and regionalization was conducted within the context of geography. The actual meaning and usage of the terms of "classification" and "regionalization" have not been clearly defined in the specific field of hydrology. Regionlization having appeared in literature within the context of hydrology (reviewed in Sect. 2.2) does not necessarily apply in one contiguous area. It refers to realisation of proper model parameters by taking advantage of another gauged region or catchment that is similar to the one under study.

2.2 LCC – What's being done

A great deal of effort has recently been put into classification of catchments, especially in the last two decades. They have however been isolated and sometimes buried under vast amount of similar work. It is not until McDonnell and Woods (2004); Wagener et al. (2007) that "a commonly-agreed classification" scheme is officially being discussed within the PUB (Prediction of Ungauged Basins) initiative.

Wagener et al. (2007) has put a lot of effort collecting and reviewing most existing classification methods and concepts, which has provided a brilliant "kick-off" as a way forward (a way that avoids probable redundancy or repetition and hence is more straightforward). A summary based on their work is provided below. Additional work not covered in Wagener et al. (2007) is also reviewed in the following text.

2.2.1 Regionalization

Catchment classification in this paper has been given two categories. The Linnaean catchment classification refers to the systems more or less resembling the Linnaeus-type hierarchical approach using a number of physical catchment properties and climate as differentiating characteristics. It can also be regarded as a natural classification system which has been given the same terminology in the field of geography. The second category is refered to as statistical catchment classification which includes regionalization and statistical clustering methods. Regionalization is put in the second category because it is not directly based on the natural catchment characteristics but the catchment response and model parameters, which are synthetic characteristics fitted with regression procedure. The regional system is thus not reviewed in this section.

2.2.2 Catchment structural similarity

Similarity can be defined with catchment structural characteristics:

1. in the form of a *dimensionless number* such as *stream order* (a hierarchy of stream tributaries, initially developed by Horton (1945) and enhanced by Strahler (1957) to help describe relationships between stream and catchment, also used by biologist to relate species diversity Harrel (1967)); *bifurcation ratio* (originated by Horton (1945), the average ratio between the number of streams of order n and $n+1$, a low ratio indicates a low number of branches and high susceptibility to be flooded due to concentration); *drainage density* (the ratio between square of total length of all streams and total drainage area, the density value corresponds to the shape of a hydrograph); *hillslope Peclet number* Pe (a ratio between the characteristic advective time-scale and the characteristic diffusive time-scale (Berne et al., 2005), it provides estimation of the similarity between hillslopes with respect to the subsurface groundwater flow); *storm speed parameter* (proposed by Ogden et al. (1995). The parameter is obtained by dividing the product of U – the storm speed and t_e – the runoff plane kinematic time to equilibrium by Lp – the length of the runoff plane. It is of particular interest when storm motions play a major role in catchment response and when spatial variability of runoff generation is concerned. The former situation has a strong impact on the shape of the hydrograph and the timing the peak.); G parameter (refer to (Gilfedder et al., 2003), a ratio between t_H – the time factors related to the lateral draining and t_V – the time factors related to the vertical filling of an aquifer. It integrates transmissivity, specific yield, recharge, length and head into one number in order to determine how well a system is likely to cope with a given rate of recharge without discharge to the surface. Hydrogeologically similar catchments in southern Australia were identified using this parameter to handle the dryland salinisation problem.);

2. in the form of *curves of distributions* such as a *hypsometric curve* (first introduced by (Langbein, 1947), an empirical cumulative height frequency curve for the Earth's surface or a catchment. The curve can be shown in non-dimensional or standardized form by scaling elevation and area by the maximum values. The non-dimensional hypsometric curve provides hydrologist and geomorphologist

with a way to assess the similarity of catchments.); *topographic index curve* (the topographic index is conceptualized by (Kirkby, 1975). The index ($\alpha/tan\beta$) is a ratio between α – the drained area per unit contour length and $\tan\beta$ – the slope of the ground surface at the specific location. The locations with the same index value can respond in a hydrologically similar way.);

3. in the form of a *conceptual model* defined as a simplified schematic representation of the subsurface hydrological processes. An example is the HOST (Hydrology of Soil Types) classification system (Boorman et al., 1995) which has been used to group all UK soils into 29 classes and further regionalized a baseflow index;
4. in the form of a *mathematical model* which provides a direct link between structure and response behavior. An example is the study conducted by De Felice et al. (1993) who applied a simple conceptual model to classify catchments. The model uses a variation of the Thornthwaite-Mather method which represents the catchment as two reservoirs in series. His study clearly demonstrated one model parameter β (not fixed as a priori) could encompass the complex geological and morphological characteristics and differentiate catchments from low, medium to high permeability. Within each class, a surrogate value of β could be transfered to a catchment with similar geological and morphological features. The similar catchments identified by β is independent from climatic conditions. Wagener et al. (2007) reviewed this topic in more details and summarised the bottom-up and top-down analysis frameworks;
5. in other forms such as wavelet *spectral analysis*. Schaefli et al. (2006) has proposed a way to study hydrological landscape similarity by analysing spectral properties of observed hydrological time series. The information extracted from frequency domain can be considered as a signature of the catchment response. Prior to its application in hydrology, spectral analysis has been used in ecology for pattern description (Hill, 1973; Usher, 1975; Ripley, 1978).

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2.2.3 Similar hydro-climatic regions

It is not only geographers who have used climate to divide similar regions, hydrologists have also attempted to apply climatic factors to catchment classification. Catchment similarity can be defined based on climate due to the fact that climate has prevailing impact on catchment's hydrologic behaviour. Budyko (1974) proposed a climatic classification based on energy balance and described the climatic condition of each area with a 3-symbol combination (Court, 1976). Budyko's climatic classification is suitable on a large spatial scale as it is based on the balance in the long-term. The climatic dryness index defined as a ratio between average annual potential evaporation and average annual precipitation was used to classify arid regions of the world (UNESCO, 1979). It is only a rough division of regions based on water balance and cannot be used for practical purposes with respect to catchment response. To take into consideration of the seasonal variability, a combination of dimensionless variables including soil and climate properties are advanced by Woods (2006). He proposed three family indices to identify the dominant state of stored water including pore water, frozen water and open water, as the state of dominant storage impacts and is in turn affected by catchment processes and climatic conditions. The limitations to these indices lie in the heavy data demand of soil attributes and the simplifying assumptions the indices are based on.

2.3 LCC – What's to be done

A catchment is an indissoluble bond of landscape, soil, climate as well as human factors. No classification system so far has been designed with all possible characteristics of a catchment, whether it is in a form of hierarchy or a conceptual model. One catchment could be similar to another catchment in some properties, but not all properties. A hierarchical classification system analogous to the biological one is almost impossible as a catchment is such a vital entity, a symbiosis on a multidimensional scale that is more than an association of plants or animals.

It is meaningless to place a catchment in a class if it does not help to understand the one in question, bearing in mind that "a classification system should be designed for a clear and specific purpose" (Grigg, 1965). Nonetheless, a general-purpose hierarchy of catchments may still be the ultimate goal, regardless of its possibility. It could be used for pedagogical purposes to teach and pass the knowledge on as well as to make inductive generalization of a catchment with easy. McDonnell and Woods (2004) believe "a broad-scale catchment hydrology classification system would provide an important organizing principle, complementing the concept of the hydrological cycle and the principle of mass conservation".

A catchment classification system will not be static as more knowledge about the hydrological processes are understood. Any existing system will be subject to change.

Grigg (1965) made pessimistic comment that "Even if (a system of hierarchy and classification) logically possible it is still a formidable task". The statement was perhaps valid in the "punch cards" era, today the reality is different. A distant goal can only be reached with many small and even trivial steps. Perhaps the proper manner to handle it, is to start with the basic process components such as evapotranspiration and baseflow and move gradually to discharge which is the holistic composite response of all processes.

3 Statistical catchment classification (SCC)

Nature disguises itself by its diversity, however, it will not take long before we realise that "nature repeats itself similarly for the same configuration", Bárdossy (2003) Geostatistics lecture note. The similar nature configuration has formed the bases for hydrological regionalization where similar catchments are taken to make inductive generalization of knowledge or information transmission about the other catchments not well documented.

In statistical theory, Gordon (1981) has interpreted classification as a collection of methods for the exploratory analysis of multivariate data. Statistical classification is by no means unique in the field of catchment hydrology, many other fields have explored it in much details. In geography, Grigg (1965) expressed his opinion with regards to the theory of numerical taxonomy “a return to the principles of classification put forward by Michael Adanson before Linnaean. He assumed that all characters are of equal weight and that affinity, the basis of grouping individuals into the same class, is a function of the proportion of features (properties or characters or elements) in common. There is no assumption made about origin.” Ludwig and Reynolds (1988) defines statistical ecology as quantitative methodologies to explore patterns in biotic communities. A classification procedure can be viewed as a reduction of a data matrix of S rows (species) and N columns (SUs-sampling units of variables) into g groups ($g < N$), where the SUs within each of the g groups are more similar to each other than SUs between groups (Green, 1980).

Statistical catchment classification can facilitate extending frequency distribution from information rich to poor catchments (Riggs, 1973). The information refers to streamflow records in the past as well as non-stationary streamflow records in the future within the context of climate change. Transfering the parameters of a hydrological model at an ungauged site is similar to the problem of estimating a streamflow frequency distribution at an ungauged site (Vogel, 2005) and hence could be tackled by statistical catchment classification as well.

3.1 SCC – What’s been done

Information is transfered within similar catchments which can be classified via the methods introduced in Sect. 2. In addition, methods formulated by numerical clustering and regionalization are alternative solutions to information transfer.

3.1.1 Numerical clustering

Numerical clustering is a collection of statistical measures to account for the variability displayed in a data set. Pattern recognition is usually achieved by numerical clustering. From automated speech recognition, text categorization, DNA sequence identification, to catchment classification, numerical clustering has been successfully applied in various areas. Two approaches are commonly used in cluster analysis: (1) supervised and (2) unsupervised clustering. A few examples applied in fields relevant to hydrology are discussed below.

Supervised clustering

Supervised clustering, as its name implies, is a procedure under a specific guidance or supervision. The so called “supervisors”' or “teachers”' provide labeled samples as training sets. The “students” evaluate the objects in the data sets on the basis of the labeled samples. The objects that demonstrate similar features as the training sets will be labeled the same category as the training sets provided by “supervisors” or “teachers”.

Supervised clustering is often used for spatial classification (e.g. land cover) from remotely sensed images. A standard procedure for land cover classification would start with a few selected training sets. They are the cells with given land cover types (provided by “teachers”). Spectral signatures containing multivariate statistics of each cluster are then derived from these specified cells in the image. The cell to classify is assigned to the class with the maximum probability. This procedure is referred to as maximum likelihood. The resulted classification can be reliable if the training cells and the image are both relatively homogeneous (without many mixed cells) (Bárdossy and Samaniego, 2002). A large amount of literature on supervised land cover classification are readily available. Other examples of spatial classification can be found in Fetterer et al. (1994) who assessed sea ice type maps from Alaska Synthetic Aperture

Radar Facility imagery, Ustin et al. (2002) who mapped different plant species, and Bokuniewicz et al. (2003) who used a typological approach to identify locations prone to submarine groundwater discharge.

Unsupervised clustering

In contrary, unsupervised clustering has no explicit "teacher" or "supervisor". According to Duda et al. (2000), unsupervised clustering is an attempt to categorize samples when all we have is a collection of them without being told their category, and is particularly useful for the following reasons:

- collecting and labeling a large set of sample patterns following supervised clustering procedure can be at times extremely costly and/or time consuming;
- if only a few particular groups of samples are of interest, it is unnecessary to label all sample patterns (could be the case of data mining). Supervision is provided to label only the groups of interests;
- for patterns that have inherent temporal variation (patterns slowly change with time);
- to find patterns and sub-patterns may be otherwise ignored under a supervised mode. Major departures from expected characteristics may suggest we alter our prior knowledge of particular features or patterns.

Three types of unsupervised methods, namely (1) hierarchical approach, (2) data partitioning or K-means and (3) hybrid clustering, are discussed below:

Hierarchical approach

A cluster of similar catchments consists of catchments with close distances. The distance is measured in the space of catchment characteristics with a specific distance metrics such as Euclidean and Mahalanobis distances. In this sense, the location of a catchment is identified by its characteristics and the distance from one to another represents their hydrological similarity. Examples include Mosley (1981) and Gottschalk (1985) who identified hydrologically similar regions in New Zealand and Sweden, respectively.

Correlation coefficient ρ_{jk} (see equation below) and Euclidean distance d_{jk} between catchment j and k (see equation below) were used as distance metrics in Gottschalk (1985).

$$\rho_{jk} = \frac{\sum_{i=1}^{p}(x_{ij} - \overline{x}_{ij})(x_{ik} - \overline{x}_{ik})}{[\sum_{i=1}^{p}(x_{ij} - \overline{x}_{ij})^2 \sum_{i=1}^{p}(x_{ik} - \overline{x}_{ik})^2]^{\frac{1}{2}}} \tag{1}$$

$$d_{jk} = \frac{[\sum_{i=1}^{p}(x_{ij} - x_{ik})^2]^{\frac{1}{2}}}{p} \tag{2}$$

where i is the index number of the catchment descriptor x ($i = 1, \ldots, p$)

Catchment pair j and k can be put in one cluster if the distance ρ_{jk} is the highest among all pairs and considered as one element in the next step. Recalculation of clusters can be performed again and new clusters can be identified. The procedure continues till all clusters are put together. To treat a cluster of catchments as one element, Gottschalk (1985) used arithmetic averaging. A common way of displaying the results of clustering is to construct a dendrogram. A dendrogram is a tree-looking diagram to illustrate the arrangement of clusters from the lowest to the highest level.

Data partitioning or K-means

Burn and Boorman (1992) applied K-means algorithm to divide catchments in the UK into K clusters based on their characteristics. The objective O_K expressed below is to minimise the variability in K clusters.

$$O_K = \sum_{k=1}^{K} \sum_{i=1}^{I} \sum_{m=1}^{M} w_m (x_{mi} - C_{mk})^2 \qquad (3)$$

where w_m is the weight assigned to each catchment descriptor, k is the index number of the cluster ($k=1, \ldots, K$), i is the index number of the catchment ($i=1, \ldots, I$), m is the index number of the catchment descriptor x ($m=1, \ldots, M$), and C is the centroid coordinate for the catchment descriptor m within the cluster k.

The K-means algorithm involves three subjective judgments with respect to (1) the identification of global minima, (2) determination of an appropriate number of clusters, and (3) selection of catchment descriptors and associated weights (Burn and Boorman, 1992).

Hybrid clustering

Rao and Srinivas (2006b) tested three hybrid clustering algorithms for estimation of regional flood frequency. The clusters are initially established by hierarchical clustering using single linkage, complete linkage and Ward's algorithm. These clusters are further refined by using the K-means algorithm. The overall performance of the three hybrid algorithms was found to be better than either the hierarchical clustering or the K-means used alone. The combination of Ward's algorithm and K-means was reported to consistently provide good initial estimates of groups of catchments with similar flood responses. Rao and Srinivas (2006b) noted in the conclusion of his study that hierarchical clustering may not always be the best option to initialize K-means algorithm. He also pointed out non-stationarity present in hydrologic time series has made regional flood frequency estimation more complex and uncertain.

The clustering methods mentioned above all assume objects can be divided into ”non overlapping clusters with well-defined boundaries between them” (Rao and Srinivas, 2006a). They are usually referred to as “hard” classification because they do not allow any degree of ambiguity. It is often the case that one object may partially belong to more than one clusters with a certain degree of membership or probability. As a consequence of a vague boundary and a degree of membership, the fuzzy set theory (Zadeh, 1965) provides an option to define a "soft" classifier that can be flexible to cope with "ambiguity". A large amount of fuzzy classification studies can be found in literature. Their major difference lies in the way they handle the data in the training and validating stages as well as the algorithms employed for the allocation phase (Bárdossy and Samaniego, 2002).

Numerical clustering, as described above, is one way to approach pattern recognition and feature classification. It is of great interest to hydrologists because it can be applied in spatial classification of remote sensed images as well as estimation of regional hydrology shared within similar catchments. Most clustering methods are distance based. An important issue is therefore the selection of a proper metric or distance measure. Worth also noting here is that a "hard" homogeneous region is one that all individuals are similar and contiguous, while a "soft" one based on fuzzy set theory can encompass individuals belonging to the region with a degree of membership. Homogeneous regions can be identified and hydrological responses are assumed to be more similar among the catchments within the region than similar to another catchment outside the region. Physiographic characteristics are often used as catchments' attributes to form regions of similar catchments, however, that similarity does not necessarily result in similar catchments' response, which was argued by Burn (1997) with regards to regional flood frequency analysis. Climatic attributes should not be neglected in forming a region of similar flood response. The representativeness of the resulted homogeneous region is highly dependent on the selection of meaningful catchment characteristics.

3.1.2 Parametric regional analysis

In hydrology, the procedure of transferring information in space (catchment-wise) is usually regarded as regional analysis (Riggs, 1973). It is clear that numerical clustering discussed in Sect. 3.1.1 can be used for regional analysis, although identification of a homogeneous region isn't an easy task. Being an alternative solution to remediate the situation of missing streamflow data, parametric regional approaches have been thought of to transfer model variables from gauged to ungauged catchments. Parametric regional approaches, unlike numerical clustering, relate model variables to catchment characteristics with a or a few parametric function(s).

An early regional study was conducted by (Nash, 1960). Two parameter values of the instantaneous unit hydrograph (Nash, 1957) were estimated for an ungauged catchment by using regressional relationship obtained from 60 other gauged catchments in the UK. The parameters were expressed as linear functions of a number of topographic characteristics such as catchment area, slope and length of the main channel. His results were not encouraging as the streamflow prediction at the ungauged catchment was rather poor.

In contrary, James (1972) demonstrated significant correlations between certain model parameters and basin characteristics using the Kentucky Fortran Version of the Stanford Watershed Model IV (Crawford and Linsley, 1966). He further proposed a similar linear regression based approach to be used on an ungauged catchment, that is to relate the values of parameters to measurable catchment characteristics with a regression function. In his study, however, he did not engage in predicting streamflow using the parameters assessed from the regressions.

A similar study was performed by Ross (1970) who estimated a number of parameters of the Stanford Watershed Model using catchment characteristics. Along the same line, Manley (1978) opted for the physically based 17-parameter HYSIM model to simulate flows in the ungauged catchments of the Severn River basin. He favored a physically based model for prediction in ungauged basins over the conceptual models due to the fact that "most of the (HYSIM model) parameters were based on field observations, or could be related to field observation". In addition to the ability to model an ungauged basin, he also argued that a physically based model is able to (i) use climate data to simulate events which are more extreme than those in the flow records on which the model is calibrated, provided the dominant hydrological processes are realistically defined; (ii) utilize data on basin type and topography to fix many of the parameters; and (iii) produce good starting estimates for the calibration process, if values of the parameters can be obtained from field measurements. Manley (1978) worked with a great deal of energy and determination although the time and cost invested are unproportional to the outcome and hence far from being practical.

Regardless of physically based or conceptual models, the essence of a regional approach is premised on the deterministic relationship between model parameters and catchment characteristics in a certain region (James, 1972). The same applies to regional streamflow distribution as it is believed that distribution function is closely related to the catchment characteristics such as size, topography, surficial geology and climate (Riggs, 1973).

Regional analysis of streamflow can be implemented in two different procedures. The first procedure is used to estimate discharge with a certain return interval Q_T. It is calculated by a product of the catchment characteristics $C_1 \cdots C_n$ to a certain extent expressed by their power functions.

$$Q_\mathrm{T} = a_0 \cdot C_1^{a_1} \cdot C_2^{a_2} \cdots C_n^{a_n} \tag{4}$$

$$\log(Q_\mathrm{T}) = \log(a_0) + a_1 \log(C_1) + a_2 \log(C_2) + \cdots + a_n \log(C_n) \tag{5}$$

where $a_0 \cdots a_n$ are the regression coefficients.

An early application of this procedure can be found from Benson (1962, 1964). A very comprehensive study on different regions across the US was performed by Thomas and Benson (1970). Over 20 catchment characteristics were considered to regionalize high, medium and low flows. Results of the regression analyses indicate that streamflow can be defined more accurately in the humid Eastern and Southern regions than in the more arid Western and Central regions, that medium flows can be more accurately defined than high flows, and that low flows can be only weakly defined. Standard deviations of monthly and annual flows were found to be significantly related to catchment characteristics (Thomas and Benson, 1970).

The relevant catchment characteristics need to be selected according to their significance relevant to the flow characteristics (Riggs, 1973). Riggs (1973) collected 10 published regional flood frequency regressions and found that 4 catchment characteristics were the most commonly used ones, namely, (1) drainage area (10/10 times), (2) main-channel slope (5/10 times), (3) percentage of basin area covered by lakes and swamps (5/10 times) and (4) mean annual precipitation (4/10 times). The characteristics that were used in two out of the 10 studies of regional flood frequency are T-year 24-hour rainfall, elevation, number of thunderstorm days and geographical factor. The characteristics that appeared in only one study are mean annual runoff, average degrees below freezing in January, orographic factor, main channel length, ratio of runoff to precipitation, mean annual snowfall, average number of wet days per year and shape factor. All these catchment characteristics are, to some extent, "crude indices" and should be selected on the basis of prior knowledge or the system (Riggs, 1973). It is perhaps more appropriate to call the catchment characteristics as catchment descriptors (CDs). Pandey and Nguyen (1999) provides a comparative study on nine parameter estimation methods, namely ordinary least square, weighted least squares using variance as weight, weighted least squares using Taster's weight, least absolute value regression, robust regression, generalized least squares, nonlinear optimization minimizing the sum of the squared errors, nonlinear optimization minimizing the relative errors and nonlinear optimization minimizing the least absolute deviations.

The first procedure is of limited interest since only a limited number of Q_T can be estimated. In many cases, a regional peak flow frequency curve is needed. The second procedure is established to estimate the parameters of a pre-defined distribution curve (mean and variance for a 2-parameter distribution and skewness in addition for a 3-parameter distribution to specify the location, scale and shape of a curve). The same catchment characteristics are used to formulate the regression function of the two or three distribution function parameters. A flow frequency curve can be obtained in this way.

Either with frequency study or prediction of streamflow, application of regional analysis to low flow was reported as least successful (Riggs, 1973). He suspected it is due to the greater dependence of low flows on catchment characteristics that are imperfectly known and that cannot be described by simple indices.

All methods so far have attempted to figure out this relationship no matter how it is formulated, physically or conceptually, and in a linear or non-linear form. It is interesting to see that the focus has never been shifted from what James (1972) pointed out: "The question of how to interpret the relation between characteristics and parameters to estimate parameter values for the larger watershed is left open by this research design." Section 3.2 provides a brief review on many studies recently conducted following this direction.

3.2 SCC – What's being done

A large number of regional studies have been undertaken since 1970's and the number has been on the rise due to the increasing demand to estimate the impact of rapid climate and land use change. The reviewed studies below are arranged by the year of publication. Many interesting studies could not be reviewed here due to their unavailability or inaccessibility to the author, e.g. material published in languages outside the author's linguistic competence.

Abdulla and Lettenmaier (1997a,b)

VIC-2L – a two-layer Variable Infiltration Capacity land surface hydrologic model for prediction of monthly discharge, 40 catchments ranging from 160 to 7000 km^2 distributed throughout the Arkansas River basin of the south central US. Values of nine model parameters were first obtained by using two optimization methods. These optimal parameter values were then related to 10 distributed land surface characteristics and 12 meteorological variables. The method was tested by comparing simulations using the regional (regression equation) parameters for six catchments not in the parameter estimation set. The model performance using the regional parameters was good for most of the calibration and validation catchments, which were humid and semi-humid. The model did not perform as well for the arid to semi-arid catchments. A grid network version of the VIC-2L model was used in the second study to simulate monthly flow. In the first application, gridded parameter fields were linearly interpolated from locally estimated parameters at a set of the same 40 catchments. In the second application, the model was run using the parameters transferred to the large area grid from the gauged catchments via regression of the locally estimated parameters on catchment soils, topographic and climatological characteristics. Generally, the simulations based on the regional regression transfer scheme performed significantly better than those based on the interpolated parameters. However, the predicted actual evapotranspiration and its seasonal cycle were relatively insensitive to the regional parameter estimation schemes.

Post and Jakeman (1999)

IHACRES – a lumped conceptual rainfall-runoff model, based on unit hydrograph principles (Jakeman et al., 1990). for prediction of daily discharge, 16 small (less than 1 km^2) catchments in the Maroondah region of Victoria, Australia. Six catchment descriptors were found to be important in defining catchment hydrologic response. They are area, drainage density, elongation, gradient of the channel, slope and wetted area. The model was calibrated first. Afterwards, six most appropriate regression functions were obtained to quantify the relationships and predict the daily streamflow of each catchment, as if it were ungauged for streamflow. The most appropriate regression functions were searched by trial and error from combinations of different catchment descriptors and function forms such as square root, square, *ln*, and inverse transformations. Some of the relationships between the model parameters and landscape attributes are well defined, while others are poor (R^2 ranges from 0.37 to 0.94). As a result, the predictions of daily streamflow also vary in quality. Improvement of these results can be obtained through better understanding of the controls on hydrologic response as well as inclusion of a large number of catchments representing a broad range of features.

Seibert (1999)

HBV model for prediction of daily discharge, 11 catchments ranging from 7 to 950 km^2 located in the NOPEX area in central Sweden. A fuzzy measure, which allowed to combine different objective functions, was used to determine optimised parameter sets. Four widely available characteristics are selected, namely, drainage area (km^2), forest area (%), area of field or meadow (%) and lake area (%). Four different two-parametric regression functions (linear, exponential, power and log) were fitted to the relationships. 6 out of 13 model parameters could be well related to catchment descriptors. Some relationships that had been expected were found only partly or contrary. Loose or unexpected relationships could be partly explained by parameter uncertainty due to interrelations between model parameters. This is the so called "equifinality" problem (Beven and Freer, 2001) that complicates the regionalisation of model parameters because optimised parameter values may vary by chance within a range of values. Reduction of uncertainty could potentially improve the relationships. One method proposed to reduce parameter uncertainty is to include additional data beyond observed runoff into the calibration procedure.

Merz and Bloeschl (2004)

11-parameter lumped conceptual model for prediction of daily flows, 308 Austrian catchments ranging from 3 to 5000 km^2. The model is calibrated using a 5-term compound objective function. Afterwards, a linear regression function is obtained for each parameter and catchment descriptor. Using the preset or globally averaged parameters produces the worse regionalization results. Using multiple regressions improves the results, which suggests catchment descriptors do contain valuable information, in particular, spatial variability, that can be used to improve parameter estimates (with median Nash-Sutcliffe efficiency of 0.53 for both calibration and validation using optimised local regression). However, they note that there is no tight relationship between the parameters and any of the descriptors and the underlying hydrological relationship seems to be weak (the coefficients of determination R^2 is only up to 0.27, most of them are less than 0.10). Using the averaged parameter values of immediate upstream and downstream (nested) neighbors performs best (with median Nash-Sutcliffe efficiency of 0.57 for calibration and 0.56 for validation). In addition, they tested kriging methods which perform slightly poorer than the averaging method using immediate neighbors. They further conclude that catchment descriptors are not representative of the real physical controls on the water balance dynamics, instead, spatial proximity may be a good surrogate. In general, the relatively low Nash-Sutcliffe model efficiency could be due to some low-quality data and insufficiently optimised model structures for individual catchments.

Many more regional studies with varying success and experiences have been reported, including: Servat and Dezetter (1993) developed multiple non-linear regression equations for two models to assess daily flow in 20 catchments in the northwestern Ivory Coast; Sefton and Howarth (1998) calibrated IHACRES model on 60 catchments in England and Wales, and then related a set of dynamic response characteristics (DRCs) to physical catchment descriptors (PCDs) indices (topography, soil type, climate and land cover); Xu (1999) performed a regional study with multiple linear regression using MWB-6 (Xu et al., 1996) (a monthly water and snow balance model) on 26 Swedish and 24 Belgian catchments.

The regional studies mentioned above all follow a two-step procedure, that is to calibrate the hydrological model and obtain optimal parameter values in the first step and formulate the regression functions between catchment descriptors and model parameters and obtain the relationship in the second step. They all focus upon selection of an appropriate objective function, an efficient optimization procedure as well as a suitable regression form. Gradually, the focus has shifted and a one-step multiple regression approach has evolved. The one-step multiple regression approach acknowledges the fact that many equally good parameter sets lead to equivalent model performance and therefore does not separate the two steps of model calibration and multiple regression. It can help reduce the number of feasible parameter space and hence strengthen the relationships. The one-step approach is made possible thanks to rapid development in computing power.

Fernandez et al. (2000)

abcd model – a 4-parameter monthly water balance model, 33 catchments in the Southeastern US ranging from 155 to 39 847 km^2. The model performance is evaluated with the objective function described in Equation 6. The model is not calibrated independently from the catchment descriptors but with an integrated objective function O_F (see equation below) simultaneously taking into consideration of both the performance of the multiple regression and the goodness-of-fit R_i^2 between predicted discharge $\hat{Q}_t$ and observed discharge Q_t at the time step t.

$$R_i^2 = \sum_{t=1}^{n} (\ln(Q_t) - \ln(\hat{Q}_t))^2 \tag{6}$$

$$O_{\mathrm{F}} = \frac{1}{N}\sum_{i=1}^{N} R_i^2 + \frac{1}{4}(R_a^2 + R_b^2 + R_c^2 + R_d^2) \qquad (7)$$

where i is the index number of a catchment, $i=1, \ldots, N$, and R_x^2 is the coefficient of determination of the regression function of the model parameter *a, b, c, d*.

The generalized reduced gradient nonlinear algorithm is used to optimize 30 × 4 = 120 variables (30 catchments used for calibration). The regression relationships are found to be nearly perfect. These optimized relationships are tested with 3 other catchments. The results do not show any improvement from the traditional 2-step approach. The loss of model performance from calibration to validation catchments with the proposed one-step approach is almost the same as with the two-step approach. It must be pointed out that their study uses several catchment descriptors which require analysis of discharge data. The study is intended on formulation of the one-step approach but not its implementation in ungauged catchments. Based on these results, they believe multivariate regression analysis is not able to uncover basic physical laws and therefore regional studies will not advance unless the basic relationships between catchment characteristics and model parameters are formulated correctly. They also point out one way to tighten the relationships is to reduce model uncertainty and the large feasible parameter space.

Hundecha and Bárdossy (2004)

HBV-IWS model, 45 catchments selected from the Rhine River Basin ranging from 400 to 2100 km^2. An aggregated objective function O_{H} is established to maximize the model performance in the form of the Nash-Suctliffe efficiency coefficient R_i^2 (see equation below) for all catchments ($i=1, \ldots, N$) and punish the individual catchment with the worst model performance (see equation below).

$$R_i^2 = 1 - \frac{\sum_{t=1}^{n} Q_t(\hat{Q}_t - (Q_t))^2}{\sum_{t=1}^{n} Q_t(\hat{Q}_t - (\overline{Q}_t))^2} \tag{8}$$

$$O_\mathrm{H} = \sum_{i=1}^{\mathrm{N}} R_i^2 + N \cdot \min(R_i^2) \tag{9}$$

where $\overline{Q}$ is the mean observed discharge.

Soil properties and land use are related to the model parameters according to their relevance to the processes of runoff generation and runoff response. Instead of calibrating the model parameters, the linear coefficients relating the model parameters and catchment descriptors are calibrated. The generalized reduced gradient nonlinear algorithm is used to find the optimal solution. In this way, the regional study can be performed in one step. The relationships established with 30 catchments are tested with up to 15 other catchments. Most of them obtain a Nash-Suctliffe efficiency above 0.8. With these relationships, the method is further implemented to study the impact on streamflow under three different future land use scenarios.

3.3 SCC – What's to be done

The multiple regression regional analysis is just coming to bloom, nevertheless, some people have doubted how long it would really last and if at all it would actually come to bloom. Kuczera and Mroczkowski (1998) believed that ”poor parameter identifiability may result in considerable uncertainty in the prediction of fluxes including the streamflow flux used in calibration and, perhaps more importantly, virtually makes impossible attempts to regionalize model parameters for the purpose of application to ungauged catchments.” Merz and Bloeschl (2004) came to the conclusion that “there is no tight relationship between the (model) parameters and any of the (catchment) attributes.” McIntyre et al. (2005) admited “that regression has proven to be a useful tool for making predictions of runoff in ungauged catchments”, but pointed out “that the need to neglect or greatly simplify the interdependencies between model parameters and the neglect of errors in the catchment descriptors, leads to the view that further effort at refining the application of regression techniques may not be the optimum way forward."

In addition to the problems of parameter interdependencies and input errors, a regression function pre-defined between model parameters and catchment descriptors is usually subjective and arbitrary. One can also argue that a priori function is neither able to represent the highly complex hydrological processes nor consider the interdependences amongst model parameters. Nevertheless, regression-based methods may still play important rolls in the future because a regression function can help to understand and quantify the relationship between model parameters/streamflow and catchment descriptors. Even if relationships between catchment characteristics and model parameters will not lead to the best predictions in ungauged basins, studies of these relationships are still useful to improve the physical basis of conceptual models (Seibert, 1999). Alternatives to regression type methods are already on the way and yet to become as popular as the former type.

3.3.1 Canonical correlation analysis

Hundecha et al. (2007) has tested a new approach based on the former work of (Ouarda et al., 2001) and (Hundecha and Bárdossy, 2004) where the relationships between catchment descriptors and model parameters are not defined with multiple regression functions but a linear canonical correlation (see equation below).

$$V = \sum_{i=1}^{n} a_i X_i = a' X \tag{10}$$

$$W = \sum_{j=1}^{r} b_j Y_j = b' Y \tag{11}$$

where V and W are canonical variables with corresponding linear coefficient vectors a

and b, X represents catchment physiographic-climatic descriptors (i=1, ..., n), and Y represents model parameters (j=1, ..., r).

Vectors $\boldsymbol{a}$ and $\boldsymbol{b}$ can be identified by performing a canonical correlation analysis to obtain maximum correlation coefficients between V and W. Catchment descriptors X are replaced by canonical variable V. Catchment locations can be identified with their canonical coordinates a. The spatial structure of the model parameters is considered in the canonical space. The model parameter values are optimized with a parametric and a non-parametric approach. The parametric approach assumes a priori spatial structure of each parameter with a predefined variogram and the model is optimized such that the objective function O_H (see Eq. 9) is maximized and the variograms are best fitted. In contrary, the non-parametric approach does not assume any variograms functions. In addition to maximize the O_H, Lipschitz and monotonic conditions are imposed on each parameter. In other words, the objective is not only to maximize the model performance but also require that model parameters display similar values if the catchments are close to each other (Lipschitz condition) and the difference in parameter values increases as the distance between the catchments increases (monotonic condition). The distance in this context is a Euclidean distance measured in the canonical space. The theoretical variogram for each parameter is manually fitted to the experimental variogram obtained after the non-parametric optimization. Both approaches obtained improved results reported in Hundecha and Bárdossy (2004). Canonical correlation analysis has its limitation in that it only accounts for a linear transformation.

3.3.2 Ensemble predictions of runoff in ungauged catchments

McIntyre et al. (2005) treats the relationships between catchment descriptors and model parameters as a response surface of likelihood. Discharge at an ungauged catchment $\overline{Q}(t)$ can be estimated using a weighted average of discharge $Q_{i,j}(t)$ obtained from a certain candidate model on a specific gauged donor catchment. An explicit assumption in the ensemble predictions lies in a Gaussian-type noise, in other words, each individual prediction shall be independent so that the structural errors can be averaged out. This would require a large number of model simulations with different model structures and parameter values.

$$\overline{Q}(t) = \sum_{j=1}^{S} \sum_{i=1}^{N} Q_{i,j}(t) \times W_{i,j} \tag{12}$$

$$W_{i,j} = \frac{P_{i,j} B_j}{\sum_{j=1}^{S} \sum_{p=1}^{Pa} P_{p,j} B_j} \tag{13}$$

5 where i is the index number of the candidate model (i=1, ..., N), j is the index number of the donor catchment (j=1, ..., S), $P_{i,j}$ is rescalled Nash-Sutcliffe efficiency values, B_j is rescalled values for measuring catchment dissimilarity, and $W_{i,j}$ is the posterior likelihood given to the ith candidate model originating from the jth gauged donor catchment ($\sum W = 1$).

3.3.3 Catchment pooling

Catchment pooling, as its name implies, collects catchments on the basis of their hydrological similarity. Examples of this approach include the region of influence (ROI) approach (Burn, 1990), hybrid-cluster analysis (Rao and Srinivas, 2006b), fuzzy-cluster analysis (Rao and Srinivas, 2006a), and site-similarity approach (Kay et al., 2006).

3.3.4 Local variance reduction

Bárdossy et al. (2005) proposed application of a local variance reduction method to regional streamflow prediction. The method assumes that a distance defined on the space of catchment descriptors can be used to find a most similar observed case. The subset of independent catchment response of the most similar case can be used for prediction. It was along the same line of thought, Bárdossy (2007) suggests further research be extended to model parameters to understand why some catchments show a similar behavior by sharing good parameter sets for a given rainfall-runoff model. He also suggests further investigation on the questions to what extent the similar behavior depends on (1) the model and (2) the catchment characteristics.

4 Concluding remarks

Methods reviewed in Sect. 2 are not completely independent from the methods reviewed in Sect. 3, although two categories have considerably different bases and serve different purposes. The two might potentially compensate each other and formulate a hybrid catchment classification scheme. The procedures in looking for criteria of hydrological similarity may lead to prolific understanding of the complicated hydrological processes.

Catchment classification is, to some extent, a controversial subject. In part, controversy reflects differences in the purposes for which catchment classifications are made and differences in concepts of hydrology as a scientific discipline. Hydrology is fragmented amongst a broad variety of professions ranging from civil engineers, geographers, soil scientists, ecologists, geologists, meteorologists to hillslop hydrologists and statistical hydrologists. We cannot say that one catchment classification scheme is better than another without reference to the purposes for which both were made. Comparisons of the merits of various schemes made for different purposes can be useless. When many different disciplines claim hydrology, it will become almost impossible to reach a general-purpose catchment classification scheme. In this case, a venn diagram could be drawn to show the various interests of different disciplines, only the region of a common interest, if there is any, could be the basis to design a general-purpose classification scheme. In any case, the system of classification needs to be devised with a specific purpose in mind (Grigg, 1965). A more coordinated and harmonized approach is desired to replace the generally existing piecemeal approach to cope with the formidable task of catchment classification.

James (1972) encouraged the followers by saying "For the moment, this is a dream. The reality will be realized as the research continues". And it is worth noting Samuel Taylor Coleridge, English poet, critic and philosopher, who wrote in *The Friend* (1828): "The dwarf sees farther than the giant, when he has the giant's shoulder to mount on.", as the mere intention of the text in this paper.

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