DOKUZ EYLÜL UNIVERSITY
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SPATIAL OPTIMIZATION OF HYDROLOGIC MONITORING NETWORKS ON RIVERS

by
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İZMİR

SPATIAL OPTIMIZATION OF HYDROLOGIC MONITORING NETWORKS ON RIVERS

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Ph.D. THESIS EXAMINATION RESULT FORM

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"He who does not look back from where he came from, will never reach his destination." - *Anonymous*

Cem Polat ÇETİNKAYA

SPATIAL OPTIMIZATION OF HYDROLOGIC MONITORING NETWORKS ON RIVERS

ABSTRACT

Efficient water resources planning and management must take into account multiple users, multiple criteria, and multi objectives. Due to this complexity of recent water management problems and solutions, better analytical tools and methodologies are required to identify and evaluate alternative solutions for managing water resources systems. Accomplishment of this requirement depends essentially on information gathered on natural and environmental processes so the success of sustainable water resources management depends on monitoring activities.

Many countries have developed extensive streamflow gauging networks and expanded them to multi-site monitoring. Such a development has led to accumulation of significant amounts of data to eventually raise the questions whether they produce the expected information, and whether monitoring should be continued ever whereas it is constrained by increasing budgetary restrictions. These questions have led monitoring agencies to assess their current networks for efficiency and cost-effectiveness and, to consolidate the networks while increasing their information productivity.

The presented study is initiated in respect of the above questions to critically examine various methodologies to assess existing networks for possible consolidation. The study also aims to develop some guidelines for consolidation (reduction) of a monitoring network. The investigation for such a methodology has resulted in the use of multi criteria decision making methodologies (MCDM). Consequently, the method of stream orders, a dynamic programming approach and two MCDM methods; analytic hierarchy process and reference point approach are presented. The proposed study is particularly focused on the assessment of the "performance" of the existing networks. Upon the need expressed by the *Electrical Works Authority* (EIE) towards assessment of the performance of their monitoring practices, the introduced methods are applied to Gediz River Basin. The results are evaluated with respect to the ten operational and three non-operational stations and the answer to the question “which are those three stations to be closed?” is searched. It is concluded that in most of the cases the non-operational three stations are the ones to be removed from the network. Additionally the advantages and disadvantages of the presented methods are discussed. Particular to the network consolidation problem, reference point approach is found more useful than the other methods considering the targets of the study.

Keywords: streamflow monitoring, monitoring network consolidation, network design, multi-criteria decison making, reference point approach.

AKARSULARDAKİ HİDROLOJİK GÖZLEM AĞLARININ ALANSAL OPTİMİZASYONU

ÖZ

Etkin su kaynakları planlaması ve yönetimi birden fazla kullanıcıyı, bir çok kriteri ve amacı gözetmek zorundadır. Bu bağlamda, mevcut su kaynakları problemlerinin çözümünde daha etkin analitik araçların ve metotların kullanımı gerekmektedir. Sürdürülebilir su kaynakları yönetimi doğal ve çevresel süreçler ile ilgili bilginin derlenmesine; yani gözlemlenmesine bağlıdır.

Dünyada birçok ülke akım gözlem ağları geliştirmiş ve havzalarda yaygınlaştırmıştır. Bu gelişim önemli miktarda verinin toplanmasını sağlamış, ancak artan ekonomik kısıtlar yüzünden mevcut gözlem ağlarının beklenen bilgiyi toplayıp toplamadığı ve gözlem etkinliğinin devam edip etmemesi gerektiği sorularını gündeme getirmiştir. Ortaya çıkan bu sorunlar gözlem ağlarını işleten kurumların mevcut gözlem etkinliklerini bilgi içeriği ve ekonomik verimlilik açısından irdelemelerine neden olmuştur.

Sunulan çalışmada yukarıda söz edilen irdelemeye yanıt olabilecek, gözlem ağı daraltılmasında kullanılabilecek değişik metotlar incelenmiştir. Ayrıca, çalışma gözlem ağı daraltılması için rehber oluşturacak temel yaklaşımları da incelemekte ve sorunun çözümü için çok kriterli karar verme metotlarından faydalanmaktadır. Bu kapsamda, akarsu kollarının numaralandırlmasına dayanan kol numaralandırma yöntemi, bundan farklı bir dinamik programlama yaklaşımı ve iki adet çok kriterli karar verme yöntemi (AHP ve referans noktası yaklaşımı) incelenmiştir. Çalışma öncelikle mevcut akım gözlem ağlarının performans değerlendirmesine odaklanmaktadır. Elektrik İşleri Etüt İdaresi (EİE) tarafından belirtilen ihtiyaç da gözönüne alınarak, metotlar Gediz Havzası akım gözlem ağına uygulanmıştır. Sonuçlar halen işletilen 10 ve işletilmeyen 3 adet istasyon için değerlendirilmiş; "hangi üç istasyon kapatılmalıydı?" sorusuna yanıt aranmış ve işletilmeyen üç istasyon birçok durumda işletilmemesi gereken istasyonlar olarak bulunmuştur. Bununla birlikte, uygulanan metotların avantajları ve dezavantajları tartışılmış ve gözlem ağı daraltma problemi için referans noktası yönteminin en uygun yöntem olduğuna karar verilmiştir.

Anahtar sözcükler: akım gözlemi, gözlem ağı daraltılması, gözlem ağı tasarımı, çok kriterli karar verme, referans noktası yaklaşımı.

CONTENTS

CHAPTER ONE
INTRODUCTION

1.1 Information as the Basis for Sustainable Resource Management

Since the second half of the 20th century, the world's fresh water resources have been under pressure, with respect to both quality and quantity, due to rapid industrial development and population growth. Such pressures on available water resources have made it necessary to realize the planning and management of water resources on more effective and efficient grounds, regarding the concept of "sustainability". To this end, a full understanding of how natural processes evolve under natural and man-made conditions is required to increase the efficiency in management and exploitation of water resources (Harmancioglu, 1997).

Efficient water resources planning must take into account multiple users, multiple criteria, and multi objectives. A water management action requires a sound assessment of economic, environmental, political and social impacts. This requirement forces planners, designers, and decision makers to broaden their perspectives and investigate a wider set of alternative solutions to the emerging water resources problems. On the other hand, a final and exact solution to a water resources management problem does rarely exist due to the dynamic nature of water resources systems. Therefore, management plans and projects should be assessed and revised from time to time as initially applied solutions remain obsolete over time (Loucks et. al., 1981).

Due to the complexity of recent water management problems and solutions, better analytical tools and methodologies are required to identify and evaluate alternative solutions for managing water resources systems, where the expertise of different disciplines is also necessary. Accomplishment of this requirement depends essentially on information gathered on natural and environmental processes. Since data collection is the only way to retrieve such information, success of sustainable water resources management and exploitation depends on monitoring activities, which are required to provide reliable data for information production. Accordingly, collection of temporal and spatial data through a monitoring activity has become more important than ever, and it is expected to reflect the variations of natural processes at both the time and the space scales. Since a monitoring activity is time and space dependent, it is a dynamic and iterative procedure, which should be re-evaluated from time to time on the basis of changing demands and objectives in water resources management. Furthermore, the information extracted from observed data must satisfy the needs of improved analytical tools used for multi criteria decision making processes to be utilized for water resources management.

1.2 A Short Review of Data and Information Needs in Water Resources Management

At present, natural and/or man-made environmental problems continue to threaten the sustainable management and use of available surface water in rivers. Until the 70's, hydrometric data collection was focused primarily on the planning, design and operation of particular structures and water systems such as dams, weirs, irrigation schemes etc., so that every monitoring activity has been problem or project-oriented. Recently, however, the accelerated growth of environmental problems related to population growth, urbanization, food production and industrialization, has put broader needs on information availability both in their extent and scale. As mentioned above, the collection of reliable water quality and quantity data in time and space and the management of monitoring networks on rivers have gained increasing importance.

This importance is also underlined in the "Rio Declaration on Environment and Development", known as "Agenda 21", as the major output of the conference held in Rio de Janeiro in 1992. It is stated in Agenda 21 that *"Governments at the appropriate level, in collaboration with national institutions and the private sector and with the support of regional and international organizations, should strengthen the information systems necessary for making decisions and evaluating future changes on land use and management. (...). To do this, they should;*

a. Strengthen information, systematic observation and assessment systems for environmental, economic and social data related to land resources at the global, regional, national and local levels and for land capability and land-use and management patterns;

b. Strengthen coordination between existing sectoral data systems on land and land resources and strengthen national capacity to gather and assess data."

With the above considerations, Agenda 21 has stressed the needs for "informed decision making" for natural resources management and a revision of current monitoring practices which fail to produce the information expected for sound decision making for management.

10 years after the Rio declaration, the final declaration of the "World Summit on Sustainable Development"held in Johannesburg in 2002 has more explicitly underlined the issue as follows:

"27. Support developing countries and countries with economies in transition in their efforts to monitor and assess the quantity and quality of water resources, including through the establishment and/or further development of national monitoring networks and water resources databases and the development of relevant national indicators."

The above statements stress that collection of reliable environmental data is needed to delineate the general nature and trends in characteristics of environmental processes as part of sustainable development and management. For achievement of this goal, data are the essential inputs to activities such as a) environmental impact assessment; b) assessment of general quality and quantity conditions over a wide area or "general surveillance"; and c) modeling of environmental processes.

Another point to be stressed is the fact that data needs undergo changes in time. Environmental problems become more and more varied as the impact of man on the environment changes. Accordingly, information expectations also vary, leading to changes in the nature and types of data needed. As noted earlier, environmental problems had previously been more of a local nature; thus, it was often sufficient to collect data at a single point in space. However, recent problems reflect a significant spatial component so that environmental processes have to be evaluated in both the time and the space dimensions (Icaga, 1998).Accordingly, a monitoring activity for data collection is expected to reflect the spatial variations, temporal changes of environmental processes, and the financial constraints of monitoring agencies. Furthermore, a monitoring program should also adapt to the dynamic changes and impacts by anthropogenic activities for a better understanding of the underlying problems.

The crucial point in all of the above issues is evidently the availability of appropriate and adequate environmental data and the full extraction of information from collected data. (Harmancioglu *et al.*, 1992; Whitfield, 1988):

1.3 Current Status of Water Quantity and Quality Monitoring Networks on Rivers

In general, a monitoring activity should be designed and/or redesigned on the basis of the following questions: a) what is to be measured? b) where should it be measured? c) how can it be measured? and d) when and how often should it be measured? It is obvious that the answers to these questions are time and space dependent and are restricted by the financial constraints. In essence, a monitoring activity is a dynamic and iterative procedure which should be assessed regularly to meet changing information demands on the variability of natural and/or man-made processes in water resources.

In most countries, water quantity monitoring and establishment of streamflow monitoring networks on rivers have been performed primarily for the planning, design and operation of water supply and protection infrastructures and schemes at specific points along a river. However, increases in domestic, industrial and irrigation water demand, or the needs for prevention of droughts and floods, and/or economic considerations have developed the need for a basin-wide "integrated" management of water resources. The need for an integrated approach to river basin management is also strongly emphasized in Rio 1992 Agenda 21 and 2002 Johannesburg declarations and accepted by the participating governments and institutions. The need for integrated management practices also forces policy and decision-makers to evaluate and review the existing streamflow gauging networks to satisfy the enhanced data requirements on water quantity in river basins for better management of the resource. To this end, improvement of the efficiency of existing networks for production of reliable and informative data is an essential task.

Another important issue of recent times is the degradation of water quality in rivers, caused by intense human activities, like industrialization and urbanization. Early in the 70's, water pollution due to human activities arose as an important problem in water resources. Water quality monitoring has gained importance due also to the fact that water pollution has been identified as a cause for water scarcity. Thus, to determine the quality of available water resources, monitoring networks have been established and expanded.

In recent years, problems observed in available water quality data and shortcomings of current monitoring networks have led designers and researchers to focus more critically on the design procedures used. Developed countries have felt the need to assess and redesign their monitoring programs after having run their networks for more than 20 years. Developing countries are still in the process of expanding their rather newly initiated networks; yet they also find it necessary to evaluate what they have accomplished so far and how they should proceed from this point on. In both cases of the developed and the developing countries, the major problem is that there are no universally confirmed guidelines to follow in the assessment and design of water quality monitoring networks. Upon this need, significant amount of research has been initiated to evaluate current design procedures and investigate effective means of improving the efficiency of existing networks (Ward *et al.*, 1990; Chapman, 1992; Harmancioglu *et al.*, 1992; Adriaanse et al, 1995; Ward, 1996; Timmerman *et al.* 1996; Niederlander *et al.*, 1996; Dixon & Chiswell, 1996; Icaga, 1998). In essence, the problem is also similar for water quantity monitoring networks. Many countries have developed extensive streamflow gauging networks and expanded them to multi-site monitoring. Such a development has led to accumulation of significant amounts of data to eventually raise the questions whether all these data are needed, whether they produce the expected information, and whether monitoring should be continued ever whereas it is a costly activity constrained by increasing budgetary restrictions. These questions have led monitoring agencies to assess their current networks for efficiency and cost-effectiveness and, in most cases, to consolidate the networks while increasing their information productivity.

1.4 Objectives and Scope of the Study

In the view of the above-mentioned problems related to monitoring of water quality and quantity on rivers, most countries have started to assess and redesign their existing networks. Turkey, as a typical developing country, has established its water quantity monitoring networks since late 30's and water quality monitoring networks since the 70's. The government makes the investments for these networks, and the monitoring agencies have taken monitoring activity as one of their official tasks. Recently, these agencies have commenced to question the performance of their networks for their efficiency and cost-effectiveness and to assess whether the available data produce the expected information for decision making. With respect to cost-effectiveness, there has been no major concern as the government has paid for gauging activities; recently, however, the government has foreseen a reorganization of all nation-wide activities, as dictated by increasing economic pressures (Harmancioglu *et al.*, 1994; Harmancioglu, 1997). As noted in the previous section, the major question raised has been whether basin networks can be consolidated to cut down excessive costs while increasing their information productivity. The presented study is initiated in respect of this question to critically examine various methodologies to assess existing networks for possible consolidation. To this end, the study serves:

a) to examine, revise and adapt the previous methodologies such as those proposed by Lettenmaier *et.al.* (1984) and Sanders *et.al.* (1983) in assessing and redesigning an existing streamflow monitoring network with respect to monitoring sites;

b) to search and examine the application of new methods related with multi-criteria decision making (MCDM) processes such as the *"Analytic Hierarchy Process (AHP)"* and *"Reference Point Approach"* and obtain a "ranking" methodology for sampling sites by emphasizing their importance within the network to assist the network reduction problem;

c) to apply these methodologies to existing streamflow monitoring networks in Turkey upon the need expressed by the *General Directorate of Electrical Power Resources Survey and Development* (EIE) towards assessment of the performance of their monitoring practices.

Lettenmaier *et al*. (1984) proposed a methodology based on dynamic programming as an optimization technique. The method accomplishes the systematic consolidation of a fixed station water quality monitoring network using dynamic programming. The approach they developed uses a hierarchical structure; that is, monitoring stations are allocated to a weighted attribute score, and specific station locations within each subbasin are determined, using a criterion based on stream order numbers. Lettenmaier *et al*. (1984) applied the method to reduce the number of stations in the fixed trend detection baseline network of the Municipality of Metropolitan Seattle. The results of their study helped to consolidate this network from 81 to 47 stations and led to annual savings of about $33,000.

Icaga (1998) applied the above methodology to the case of the Gediz River Basin, where the State Hydraulic Works had operated 47 stations between the years 1990 and 1993 and reduced this number recently to 14 stations. Icaga's study covered an assessment of not only 14 but also other alternative numbers of stations (i.e., 20, 25, 30 stations) to be retained in the existing network. The study has expanded Lettenmaier's methodology by investigating the existing Gediz network with respect to different management objectives and scenarios through allocation of different weights to attributes of stations in the network.

The above methodology was also applied to the Gediz River Basin in two consecutive research projects carried out by Dokuz Eylul University (DEU) Civil Engineering Department and supported by Turkish Scientific and Technical Research Council (TUBITAK) (Harmancıoğlu *et.al.*, 1999, 2003). In both projects, the existing water quality monitoring network in the Gediz Basin was assessed in terms of site selection, sampling frequencies, and sampling costs. In the first project, current sampling sites were analyzed with the entropy method of Information Theory and with Lettenmaier's dynamic programming approach as revised by Icaga. In the second project, Lettenmaier's approach was evaluated and revised again in order to redesign the existing water quality monitoring network. One of these revisions was related to the determination of the number of subbasins, and a method proposed by Sanders *et. al.* (1983) was employed to specify the subbasins. The project also investigated the changes in information produced by the network with respect to particular numbers of stations to be retained in the network.

One of the specific objectives of this study is to adapt the methodology based on Lettenmaier's approach to consolidation of streamflow monitoring networks. The method is almost easily applicable to every hydrologic monitoring network such as streamflow, precipitation, and the similar. Another question addressed through the use of Lettenmaier's methodology is to find "how many stations should be retained in a redesigned monitoring network?" This problem is addressed by investigating different numbers of retained station combinations with respect to their information productivity.

The study also aims to develop some guidelines for consolidation (reduction) of a monitoring network by using an easily applicable methodology. The investigation for such a methodology has resulted in the use of multi criteria decision making methodologies, taking into account the basic concepts of information production from available data. The impetus for selection of these methodologies has been derived from the consideration that multiple basin management and monitoring objectives require a decision analysis (DA). Since a network reduction problem is essentially a multi-criteria decision making problem (MCDM), the use of MCDM methods has been found more suitable for producing accurate decisions on reduction of the number of stations to be retained in a network. It must be noted here that the presented study is the first in literature to use MCDM within this context. An earlier study by Ning & Chang (2002) has used the methodology in a limited context to only specify monitoring objectives.

One of the specific objectives of the study as mentioned earlier is to apply the methodologies to existing streamflow monitoring networks in Turkey upon the need expressed by the *General Directorate of Electrical Power Resources Survey and Development* (EIE) towards assessment of the performance of their monitoring practices. EIE of Turkey essentially wants to optimize the currently running streamflow monitoring networks in terms of monitoring sites. The driving force for the assessment of EIE’s monitoring program is the agency’s considerable expenditure on monitoring activities. On the other hand, requirements for integrated basin management also introduce new demands on the existing streamflow monitoring networks to fulfill several different functions under different constraints. To this end, the proposed study is expected to contribute to solution of the above-mentioned challenges to assess in particular the “performance” of the existing networks.

The proposed study foresees the spatial optimization of existing streamflow monitoring networks on rivers with respect to only the monitoring sites within a network, and temporal optimization is out of the scope of this investigation. It is also intended herein to evaluate the performance of existing monitoring networks by generated alternative monitoring scenarios with respect to different basin management objectives.

1.5 Outline of the Study

The dissertation is arranged in six chapters. The first chapter introduces the current aspects of water monitoring networks and summarizes the general objectives and the scope of the study.

Chapter 2 is a general overview on the design methodologies previously used in hydrometric network design. The chapter also focuses on the shortcomings of the available methods in the literature.

Chapter 3 is based on the methods employed within the context of the study. First, a basic approach based on stream order numbering is presented and discussed. The next method explored bases on a dynamic programming approach used for network consolidation. This approach is also useful to determine the change of information content of the network with respect to the number of stations retained. The last two approaches, analytic hierarchy process (AHP) and reference point approach, introduced are in the realm of multi-criteria decision making process (MCDM) and adapted to the network reduction and performance assessment problem in the context of this study. Those both approaches are widely discussed with pros and cons and their adaptation is realized in this chapter.

Chapter 4 focuses on the application of the presented methods to Electrical Works Authority’s streamflow gauging network of Gediz River Basin. The results are evaluated with respect to the 10 operational and 3 non-operational stations and the answer to the question “which are those three stations to be closed?” are searched. Furthermore, the change of information content with respect to the number of stations to be retained in the network is explored with dynamic programming approach. Additionally, the MCDM methods introduced are used for the performance assessment of the 13 station network.

Chapter 5 discusses the advantages and disadvantages of the presented methods. This chapter also focuses on the question “which method is more useful in which situation?”.

Chapter 6 is a general discussion on the results obtained and the lessons learned from the study.

CHAPTER TWO
REVIEW OF PREVIOUS STUDIES ON HYDROLOGIC NETWORK DESIGN

2.1 General Overview

Problems observed in available data and shortcomings of current hydrometric networks have led researchers to focus more critically on the design methodologies used. In addition, recent advances in sampling and analysis techniques for water quality and quantity have also led to the expansion of networks, and thus to a growth in economic features of monitoring. Accordingly, researchers have started to question both the efficiency and the cost-effectiveness of existing networks with regard to design methodologies used (Icaga, 1998).

The first data collection procedures for water quantity foresaw the gauging of major streams at potential sites for water resources developments. Networks have then been expanded to cover the gauging of tributaries of main rivers at upstream regions of basins, and the operational purposes of gauging stations have become varied to cover not only the assessment of water potential but also other specific goals such as flood protection, basin modeling, water quality and sediment transport assessments, and the similar. The approach in initiating water quality observations has been practically similar, namely to collect data at potential sites for pollution problems. Thus, the early water quality monitoring practices were often restricted to what may be called "problem areas", covering limited periods of time and limited number of variables to be observed. However, water quality-related problems have intensified so that the information expectations to assess the quality of surface waters have also increased. The result for both water quantity and quality has been an expansion of monitoring activities to include more observational sites. These efforts have indeed produced plenty of data; yet they have also resulted in "data-rich information-poor" and "expensive" networks, as information expectations have not always been met (Harmancioglu et al., 1992).

2.2 Review of Network Design Methodologies

The above considerations have eventually led to the realization that a more systematic approach to monitoring is required. Following up on this need, monitoring agencies and researchers have proposed and used various network design procedures either to set up a network or to evaluate and revise an existing one. Significant amount of research has been initiated to evaluate current design procedures and investigate effective means of improving the efficiency of existing networks (Ward et al., 1990; Chapman, 1992; Harmancioglu et al., 1992; Adriaanse et al, 1995; Ward, 1996; Timmerman et al. 1996; Niederlander et al., 1996; Dixon and Chiswell, 1996). In all these studies, allocation of station locations is considered as the initial and the most crucial step of the network design process. Early considerations on this matter led to problem-oriented selection procedures for particular sites. Later, as new objectives of monitoring developed, several sites had to be observed. The basic problem with multi-site monitoring is the realization of representative sampling. This means to select the sampling points in such a way that the river reach investigated is best represented by these sites. If this approach can be realized, then the variability of data along the reach may be assessed and further, information transfer among sites may be effectively carried out. However, most of the existing networks reflect shortcomings related to representative sampling so that the issue is still investigated to improve the network designs (Harmancioglu & Singh, 1990).

Schilperoot & Groot (1983) stressed that a monitoring network should be based on the water system to be monitored and on the monitoring objectives. They stated that a clear definition of objectives is required for efficient monitoring. They also referred to the complicated nature of such a definition due to the presence of numerous different objectives, which included the estimation of the present state of quality, detection of long term trends, detection of standard violations, and modeling studies.

Sanders et al. (1983) consider the problem of selecting sampling sites at two levels: macrolocation and microlocation. Microlocation relates to representative sampling at a point and requires an analysis of complete mixing within a river reach. Statistical methods (e.g., regression analyses, two-way analysis of variance) are proposed for microlocation purposes. Sanders et al. (1983) claim that, in practice, microlocation and representative sampling with respect to station location are not sufficiently evaluated by monitoring agencies. On the other hand, macrolocation encompasses the identification of sampling reaches in a river basin when the intent is to allocate monitoring sites along the entire basin. The method proposed by Sanders et al. (1983) is originally based on Horton's (1945) stream ordering procedure to describe a stream network. Horton assigns each unbranched small tributary the order of one, a stream made up of only first order tributaries the order of two, and so on. Later, Sharp (1970) used Horton's approach to measure the uncertainty involved in locating the source of pollutants observed at the outlet of a network. Then, Sanders et al. (1983) followed Sharp's procedure by selecting sampling sites on the basis of the number of contributing tributaries. Next, they modified the same method for water quality by considering the pollutant discharges as external tributaries.

Tirsch, & Male (1984) indicated that the early practices of water quality sampling started at sites of easy access or often at streamflow gauging points without any systematic approach to selection of sampling locations. The number of these sites has increased in time to include stations “at points of interest” such as those located at upstream and downstream of highly industrialized or highly populated areas, areas with point pollution sources, or areas of intensive land use. Researchers emphasized that such non-systematic approaches in the selection of sampling sites are still valid, especially in developing countries where monitoring efforts have not yet evolved into a network. Tirsch, & Male (1984) propose a multivariate linear regression model where the corrected regression coefficient of determination between sampling stations is considered as a measure of monitoring precision. The monitoring precision changes with the addition or deletion of some number and location of stations within a basin. Similarly, Whitlatch (1989) examines the spatial adequacy of NASQAN (USGS) water quality data by testing the differences between two sample means as a direct method and then by regression analyses between water quality variables and basin characteristics.

These approaches, although each may produce a rather different system of stations, work pretty well in initiating a network when no data or very limited amounts of data are available. It must be noted that, by applying these methods, one may roughly specify the appropriate sampling sites. To pinpoint the locations more precisely, microlocation and representative sampling considerations will have to be followed. As a case study for Sanders' methodology, allocation of sampling sites in the Gediz River in Turkey is realized through a number of studies (Alpaslan, & Harmancioglu, 1990; Harmancioglu et al., 1992; Harmancioglu et al., 1994; Cosak, 1999). The results of these investigations have shown that macrolocation by Sanders' approach divides the basin into equal subbasins with respect to the number of tributaries or discharges. A comparison between the existing network in the Gediz basin and that delineated by such macrolocation discloses that the two do not coincide. The reason for this difference is that the existing network is established on the basis of particular project needs so that it does not reflect the quality and quantity conditions within the entire basin. As a result of these investigations, it is concluded that Sanders' method (Sanders et al., 1983) may be effectively used to allocate station locations by considering all the polluting sources or discharges within the basin (Icaga, 1998).

Dixon et.al. (1999), presented a method for optimizing the selection of river sampling sites. The authors discussed sampling procedures which used a geographical information system (GIS), graph theory and a simulated annealing algorithm. Dixon et. al. (1999) applied the methodology to three case studies with different monitoring practices. The spatial optimization of sampling sites by the simulated annealing methodology was shown to be adaptable to a variety of practical situations. Dixon et. al. (1999) indicated that the method proposed by Sharp (1971) had no proof that it really finds the topological optimum and claimed that their methodology is superior.

Ward & Loftis (1986) stress that information expectations from a monitoring system must be defined in statistical terms and that these "expectations are to be in line with the monitoring system's statistical ability to produce the expected information”. This implies that one can infer on the types of data needed to perform the statistical methods which, in turn, will eventually lead to the expected information. Then, the selection of sampling strategies (sampling sites, variables, frequencies, and duration) can be realized by starting off with such a statistical approach.

Moss (1989) has emphasized that network design should be realized with a combined approach based on hydrology, optimization techniques, decision theory and data analysis methods. In particular, he states that networks should produce data that permit the application of statistical data analysis techniques. Since such considerations are not taken into account in current design methodologies, it is often very difficult to assess the information conveyed by existing networks.

Some researchers stress the use of optimization techniques in selection of sampling sites (Reinelt et al., 1988, Palmer & MacKenzie, 1985, MacKenzie et al., 1987, Dandy & Moore, 1979). In such design procedures, two requirements are expected to be fulfilled by the network: cost-effectiveness and statistical power. The latter is often investigated by analysis of variance (ANOVA) techniques, and optimization methods are used to maximize the statistical power of the network while minimizing the costs.

Lettenmaier et al. (1984) proposed a methodology based on dynamic programming as an optimization technique. The method used accomplishes the systematic consolidation of a fixed station water quality monitoring network using dynamic programming. The approach they developed uses a hierarchical structure; that is, monitoring stations are allocated to a weighted attribute score, and specific station locations within each subbasin are determined, using a criterion based on stream order numbers. Lettenmaier et al. (1984) applied the method to reduce the number of stations in the fixed trend detection baseline network of the Municipality of Metropolitan Seattle. The results of their study helped to consolidate this network from 81 to 47 stations and led to annual savings of about $33,000.

Icaga (1998) applied the above methodology to the case of the Gediz River Basin, where the State Hydraulic Works (DSI) operated 47 stations between 1990 and 1993 and reduced this number recently to 14 stations. Icaga's study also covered an assessment of not only 14 but also other alternative numbers of stations (i.e., 20, 25, 30 stations) to be retained in the existing network. The study has expanded Lettenmaier et al.'s (1984) methodology by investigating the existing network on Gediz River with respect to different management objectives and scenarios through the allocation of different weights for the determined attributes.

Icaga's approach was applied to the Gediz River Basin in two consecutive research projects, which were carried out by DEU Civil Engineering Department and supported by Turkish Scientific Research Committee TUBITAK (Harmancıoğlu et.al., 1999a, 2003). In both projects, the existing water quality monitoring network in Gediz Basin was investigated in terms of site selection, sampling frequencies and sampling costs. In the first project, the current sampling sites were analyzed both by the entropy method of Information Theory and by Lettenmaier's dynamic programming approach revised by Icaga (1998). In second project, Lettenmaier's approach was evaluated and revised again in order to redesign the existing water quality monitoring network in the case study area. One of these revisions related to the determination of subbasins. A method proposed by Sanders et. al. (1983) was utilized to divide the basin into subbasins. In the same project, the change of information with respect to the number of stations to be retained in the network was investigated on the basis of entropy (information) theory.

Harmancioglu & Alpaslan (1992) proposed the use of the entropy concept of Information Theory to decide upon the required numbers and locations of stations within a monitoring network. Entropy methodology allows deciding on the reduction of the number of monitoring stations when the information they produce is redundant or addition of new sampling sites at locations where additional information is required. This methodology is later applied to site selection problems in Gediz and Sakarya River basins in Turkey (Harmancioglu et al., 1994; Ozkul et al, 1995).

Following along the same line, Ozkul (1996) applied the entropy principle to assess spatial frequencies of water quality observations along the Mississippi River in Louisiana, USA, for basin segment 07. The methodology used resulted in a spatial orientation of sampling stations where the redundant information among these stations was minimized by an appropriate choice of the number and locations of monitoring stations.

Ozkul et. al (2000) extended the work of Harmancioglu & Alpaslan (1992) by improving and clarifying the previous applications of the method. They corrected the definition of multivariate entropy and, hence, the computations based on it, and revised the approach used in assessment of spatial frequencies. This latter study developed an entropy-based methodology for the evaluation of combined spatial/temporal design features so that it advanced a step further in applying the entropy method for network assessment purposes.

Mogheir & Singh (2002) developed a methodology for the design of an optimal groundwater monitoring network again by using the entropy theory. They applied entropy measures to describe the spatial variability of synthetic data that can represent spatially correlated groundwater quality data. Their application involved information measures such as transinformation, the information transfer index, and the correlation coefficient. These measures are computed using discrete and analytical approaches.

Mogheir et. al (2004 b) extended the previous work of Mogheir et. al (2004 a), where the authors used the entropy theory to describe the spatial variability of groundwater quality data sets. The methodology was applied to sets of chloride observations obtained from a network of groundwater quality monitoring wells in the Gaza Strip, Palestine.

Mogheir et. al (2005) further assessed the monitoring cycle in the Gaza Strip on the basis of the entropy theory. This article also proposed a flowchart to identify the relation between objectives, tasks, data and sampling activities within a monitoring network.

One may refer to Dixon & Chiswell (1996) or to Harmancioglu et al. (1999b) for an extensive review of design procedures and methodologies either proposed or practiced in hydrometric network design.

2.3. Shortcomings of Current Design Methodologies

Although researchers have proposed various techniques, there are still problems in the design of the hydrometric monitoring networks so that the issue remains unresolved. First of all, statement of objectives and the actual technical design of networks are still in discussion due to the dynamic nature of the network re-design problem. At the current state of matters, there are no definitely prescribed and widely accepted standard procedures to solve the above problems (Harmancioglu et. al., 1999b).

Deficiencies related to current design procedures are primarily associated with an imprecise definition of information and value of data, transfer of information in space and time, and cost-effectiveness. The major difficulty associated with these current design methods is related to the lack of a precise definition for “information” (Harmancioglu et al., 1992; Harmancioglu et al., 1994; Harmancioglu et. al., 1999b).

The current design methods also have a difficulty in the definition of the value of data. In every design procedure presented in literature, the ultimate goal is an “optimal” network both in space and time while the “optimality” means that the network must meet the objectives of the data gathering at minimum cost. While costs are relatively easy to assess, the major difficulty arises in the evaluation of benefits because such benefits are essentially a function of the information produced through the data collected. However, how this information might be assessed in quantifiable terms still remain unsolved (Harmancioglu et. al. 1999b).

Another deficiency of the methods proposed for network design or redesign is that decision makers are not involved or are involved to a limited extent in application of the methodologies. In this case, researchers experience difficulties in having their designs approved by the decision makers. This problem is partially due to the fact that current methodologies do not sufficiently reflect decision makers' preferences or the actual decision making process.

In conclusion, it must be stated that, despite the presence of numerous methods developed and used in hydrometric network design and redesign, problems still remain in their application and the assessment of results they produce. The presented study aims to focus on these deficiencies to solve at least some of the main problems.

CHAPTER THREE
APPLIED METHODOLOGIES

3.1 General

Consolidation of a sampling network requires first the delineation of objectives and criteria for comparing the worth or the significance of stations. These criteria, which essentially relate to station attributes, are used in ordering or priority listing of stations. Once such criteria are set and ordering is accomplished, the n highest ranked stations to be retained in the reduced network can be selected. The criteria or attributes to be used for ordering stations are essentially based on data and information requirements of river basin management objectives, which can as well be employed to define the objectives of a monitoring network. However, in most cases, objectives of monitoring networks are not clearly identified; and, in case of multi-objective monitoring activities such as stream flow gauging, multiple objectives may be in conflict with each other.

Another issue to be stressed here is the dynamic nature of environmental processes in terms of water resources, which may require a re-definition of monitoring objectives as different problems emerge in time. Therefore, any methodology utilized to evaluate the performance of a monitoring network should be easily applicable and flexible, while monitoring performance should be reassessed from time to time.

On the other hand, in large river basins, management problems encountered and monitoring objectives may vary in different parts of the basin so that each monitoring station should fulfill an objective specific for its location or command area rather than meet a global monitoring objective for the entire basin. Therefore, a station ranking method should also serve to evaluate such cases.

In the following sections, some of the methodological approaches used in this study to cover design and re-design of monitoring networks will be discussed in theoretical terms. The first two methods, i.e., stream ordering and dynamic programming approaches, are well-known techniques, previously applied to solve particular network design problems. The last two approaches introduced are in the realm of multi-criteria decision making methodologies. The first approach is utilized for ranking different stations with respect to weights and attributes assigned to stations in the network. This methodology allows the consideration of general monitoring objectives for the entire monitoring network, based on to the possible preferences of a single decision maker such as EIE. The second multi-criteria methodology is based on a reference point approach; hence an aspiration level is taken into account instead of weights.

3.2 Method of Stream Orders

This method is originally based on Horton's (1945) stream ordering procedure to describe a stream network. Horton assigns each un-branched small tributary the order of one, a stream made up of only first order tributaries the order of two, and so on. Later, Sharp (1970) used this procedure to measure the uncertainty involved in locating the source of pollutants observed at the outlet of a network. Sharp's (1971) work described the design of a monitoring network to identify sources of stream standard violations by using a trade-off between uncertainty and the intensity of sampling. Sanders et. al. (1983) followed Sharp's procedure by selecting sampling sites on the basis of the number of contributing tributaries. Next, they modified the same method by considering the pollutant discharges as external tributaries. A similar approach can be used via replacing the numbers of tributaries by measures of pollutant loadings (Ozkul et. al., 2003).

Each of the three ordering procedures used by Sanders et. al. (1983) may produce a rather different system of stations; yet, all work pretty well in initiating a network when no or very limited amounts of data are available. It must be noted that, by applying these methods, one may roughly specify, or macro-locate, the appropriate sampling sites. To pinpoint the locations more precisely, microlocation and representative sampling considerations will have to be followed (Sanders et. al, 1983; Harmancioglu et. al. 1999b).

The stream ordering approach systematically locates sampling sites so as to divide the river network into sections which are equal with respect to the number of contributing tributaries (Fig. 3.1). Stream ordering is the first step of the method, where each exterior tributary or link contributing to the main stem of the river, (one which has no other tributaries or one with a certain minimum mean flow) is considered to be of first order. Ordering is carried out along the entire river such that a section of the river formed by the intersection of two upstream tributaries will have an order described as the sum of the orders of the intersecting streams. At the mouth of the river, the magnitude (order) of the final river section will be equal to the number of all contributing exterior tributaries (Sanders et. al, 1983; Harmancioglu et. al, 1999b).

Next, the river is divided into hierarchical sampling reaches by defining centroids for each reach. The major centroid which divides the basin into two equal parts is found by dividing the magnitude of the final stretch of the river by two. Accordingly, the major centroid where a first hierarchy station is to be placed is located in that link whose magnitude is closest to:

$$M_{ij} = [(N_o + 1)/2] \tag{3.1}$$

where M_{ij} defines the first-hierarchy location, with M denoting the magnitude (order) of the link; i, the hierarchical level of the station to be placed on that link; and j, the order of that station within the ith hierarchical level (e.g., M_{11} indicates the first station at the first hierarchical level and M_{12}, the second station of the same hierarchy). N_o stands for the total number of exterior tributaries at the most downstream point of the basin where station M_{11} is located. M_{12} (or the stream number closest to it) divides the total basin into two equal parts for which new centroids may be found.

It must be noted in the above procedure that a link determined at a given hierarchy does not necessarily have the value of M_{ij} since a link of that number may not exist. In this case, the link closest in magnitude is selected as the centroid. When this link is specified, a sampling location is placed at its downstream junction. Although Sanders et al. (1983) locate the station M_{ij} at the downstream point of the reach that has the corresponding stream order number, it may be allocated to any site along that reach, considering such local factors as the accessibility of the site. It must also be noted here that the squared brackets in Eq. (3.1) indicate a truncation of the enclosed value to an integer value.

As noted above, M_{12} divides the total basin into two equal parts where new centroids may be determined. For the upstream part, the first station with the second hierarchical order is found by:

$$M_{21} = [(M_{12} + 1) / 2] \tag{3.2}$$

which is the magnitude of the link that divides the region upstream of M_{12} into two equal areas with respect to their drainage density. Essentially, Eq. (3.2) applies the same procedure as in Eq. (3.1) by replacing N_o with M_{12}.

For the downstream portion of M_{12}, one can either renumber the tributaries, or alternatively, the centroid may be found as the location with an order closest to either:

$$M_{ij} = [(M_d - M_u + 1) / 2] \tag{3.3}$$

or,

$$M'_{ij} = Mu + M_{ij} \tag{3..4}$$

with, i being the hierarchy order; j, the order of the station; M_d, the order where the basin is divided on the downstream side; and M_u, the order where the basin is divided on the upstream side. This procedure locates stations at the second hierarchical levels as M_{21} and M_{22} so that two more sampling locations are added to the system, which now has four stations altogether at the first and second hierarchical levels (Sanders et. al, 1983; Harmancioglu et. al, 1999b).

Next, new stations may be allocated upstream and downstream of both M_{21} and M_{22} to constitute stations at the third hierarchical level. This is accomplished by applying the same procedure described in Eqs. (3.1) through (3.4). Eventually, four new locations will be designated at the third hierarchical level so that the network now comprises eight stations altogether.

Having specified the third-hierarchy stations, the same procedure is applied to select higher order hierarchy locations, if necessary. Here, hierarchy levels indicate sampling priorities so that increasing hierarchies show decreasing levels of sampling priorities. How far the hierarchical divisions should be continued depends on economic considerations and information expectations from sampling at each hierarchy (Sanders et. al, 1983; Harmancioglu et. al, 1999b; Ozkul et. al, 2003).

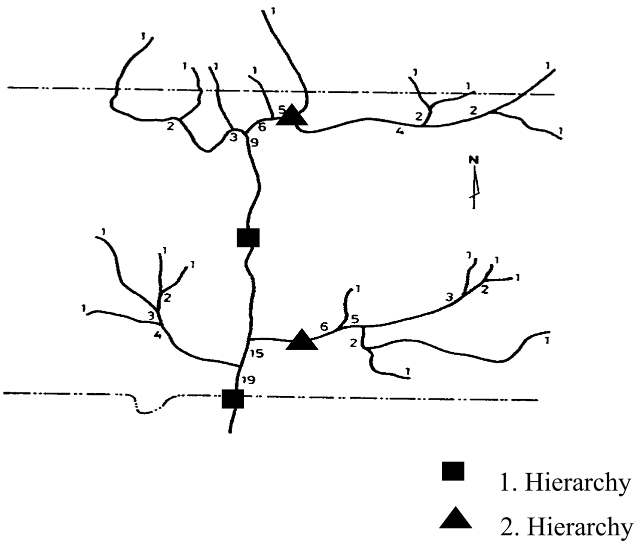


Figure 3.1 Stream order numbers and delineation of centroids, i.e. hierarchical levels, for a hypothetical basin.

3.3 Lettenmaier’s (1984) Dynamic Programming Approach

In the case investigated by Lettenmaier et al. (1984), the objectives of the Municipality of Metropolitan Seattle had been to protect and enhance swimmability and fishability of the waters within the selected drainage basins. The station retention algorithm described by Lettenmaier et al. (1984) uses a weighted sum of transformed values of the above criteria. The specific values of the criteria associated with the monitoring stations considered for retention are called “station attributes” and are denoted by “*l”* as the attribute index.

Icaga (1998) modified the above methodology by identifying alternative basin water quality management objectives such control of point and/or nonpoint pollution discharges. Through the application of the methodology, the optimum combination of stations in a reduced network for each management objective was derived.

The station allocation algorithm is employed in two steps. First, the basin is divided into subbasins or “primary basins”, and for each primary basin, the algorithm determines the preferred sets of station combinations for each possible number of stations ranging from zero to the pre-existing number of stations. There may be very large numbers of station combinations; therefore, the method based on stream order numbers (Sharp, 1970) is used to limit the number of alternative station configurations within each primary basin. Thus, the preferred sets of station combinations is determined by maximizing the sum of the stream order numbers for each station retained and, for a fixed number of stations, by breaking ties through maximizing the score sums for weighted (transformed) attributes. In the second step, a dynamic program, using primary basins as “stages”, and stations within each primary basin as “states”, determines the combination of station allocations to the various primary basins, resulting in a total network of a given size and the maximum total score. Here, the total score is the sum of station scores within each primary basin for the selected station configurations determined in the first step.

As noted earlier, the main difficulty in the above station selection procedure is that the elimination of any one station may affect some or all of the attributes of the other stations. Within this respect, stations reflect dependence (such as an upstream-downstream kind of relationship), a factor which influences the rank of any one station in the priority listing since its attributes are affected. If one disregards this dependence in the station selection process, he may miss the most important stations and select the less important ones. The optimization algorithm used essentially determines the most significant stations by considering the dependence among stations. This algorithm follows the steps shown in Figure 3.2.

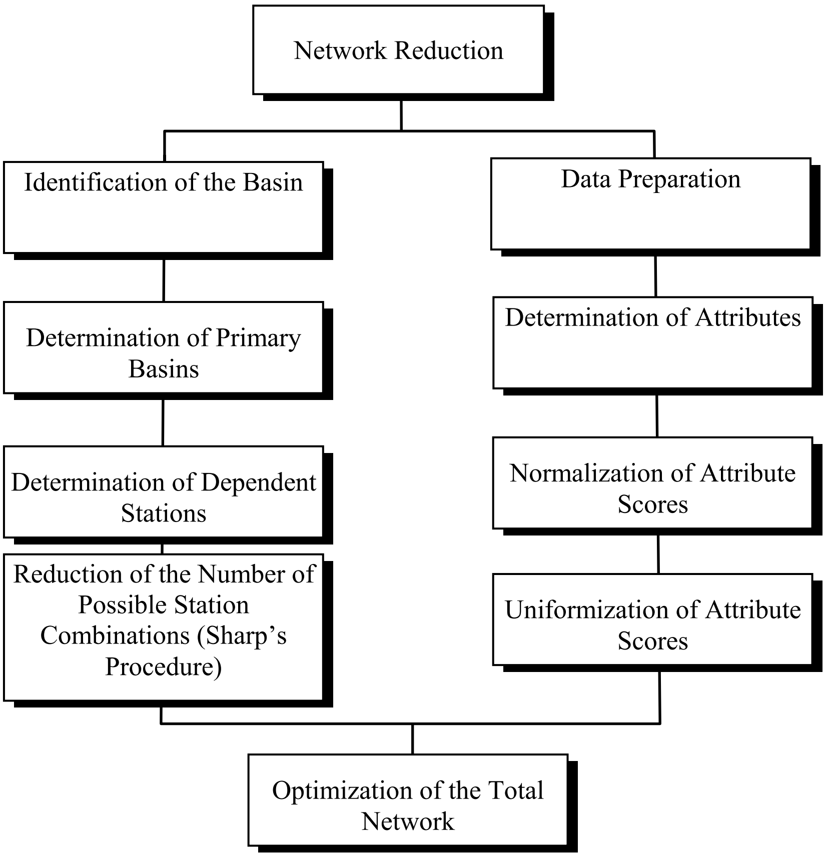


Figure 3.2 Steps of the station allocation algorithm.

The preliminary step covers two tasks:

a) basin identification, where primary basins are selected, dependence among stations is investigated and possible station combinations are determined according to the given reduced size of the network;

b) data preparation, where attributes (*l*) and their scores are determined. For each *l*, the score must be uniformly distributed so that the dominance of the score by any one attribute on the basis of its relative magnitude alone can be avoided. Thus, in this step, scores are normalized (if they are nonnormal) and further uniformized.

Once the above two steps are completed, Sharp's (1970, 1971) procedure is used to reduce the number of alternative combinations of stations. Finally, dynamic programming is used to select the most significant stations for the total network.

3.3.1 Identification of the Basin

3.3.1.1 Determination of Subbasins

The network reduction problem is approached first by dividing the river basin into N subbasins, with k denoting the subbasin index as $k = 1,...,N$. This division does not have to be hydrologic. Basin properties such as topography, geology, meteorology, land use, industry, population density, junctions of tributaries, etc., may be used as criteria for segregating the basin into subbasins. Such criteria assure that stations with similar properties are considered within the same subbasin. One criterion that must be satisfied is that each subbasin must have at least one monitoring station.

Regarding each subbasin k, P_k denotes the pre-existing number of stations in the k^{th} primary basin and R_k, the number of stations to be retained in that subbasin.

3.3.1.2 Alternative Combinations of Stations

If the entire river basin is considered when determining the possible combinations of stations to be retained, the number of alternative combinations can be found as Binomial coefficients $C\ (TP_N;\ TR_N)$:

$$C\,(TP_N\,,\ TR_N\,) = \binom{TP_N}{TR_N} = \frac{TP_N\,!}{TR_N\,!(TP_N - TR_N\,)!} \tag{3.5}$$

where TP_N is number of the pre-existing number of stations in entire basin and TR_N, the number of stations to be retained in the total network. When binomial expansion is used, the number of alternative station combinations increases significantly, depending on TP_N and TR_N.

Once the basin is separated into N subbasins with $k=1,\dots,\ N$, each subbasin will have P_k number of stations, which is a part of the total number (TP_N) of pre-existing stations in the entire basin:

$$TP_N = \sum_{k=1}^{N} P_k \tag{3.6}$$

When TR_N is defined as the resulting total number of stations, the number of stations to be retained in the k^{th} subbasin will be R_k.:

$$TR_N = \sum_{k=1}^{N} R_k \tag{3.7}$$

Then, the number of alternative combinations number will be:

$$C(P_k;\ R_k) = \frac{P_k\,!}{R_k\,!(P_k - R_k\,)!} \tag{3.8}$$

when P_k and R_k values are placed in Eq. (3.5). Since, at the beginning, the number of stations to be retained in the k^{th} subbasin is not known,

$$R_k = 0, 1, 2, \ldots P_k \tag{3.9}$$

so that the total alternative station combinations in subbasin k will be calculated, using Eqs. (3.8).and (3.9) as:

$$TASC_k = \sum_{R_k=0}^{P_k} C(P_k;R_k) = 2^{P_k} - 1 \tag{3.10}$$

where, $TASC_k$ is the total number of alternative station combinations in subbasin k.

Since R_k in any one subbasin k is dependent upon R_k of other subbasins (Eq. (3.7)), the total number of alternative station combinations in the entire basin will be:

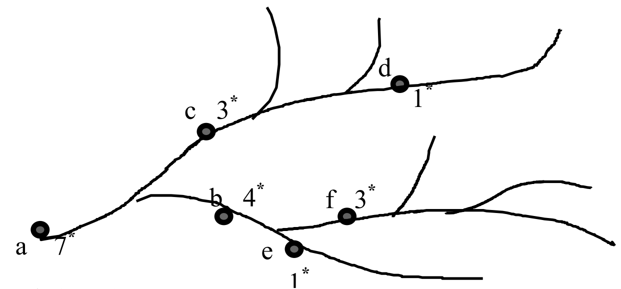
$$TASC = TASC_1 \ x\ TASC_2 \ x \ldots x\ TASC_N \quad \text{or} \quad TASC = \prod_{k=1}^{N} TASC_k \tag{3.11}$$

For example, for the six stations considered in the hyphotetical subbasin of Figure 3.3, $TASC_k$ is equal to $2^6 - 1 = 63$.

It is quite evident that the *TASC* will assume a very high value depending on the $TASC_k$ values. Therefore, it is necassary to decrease the number of station combinations in each subbasin. Lettenmaier *et* al. (1984) suggest the use of the method based on stream order numbers (Sharp, 1970 and 1971) to limit the number of alternative station combinations considered within each subbasin. Figure 3.3 also shows the application of stream order numbers in a hypothetical subbasin. Here, each exterior link of a river reach is numbered as “1”. The stream order number of an interior link is found as the sum of the orders of the upstream exterior links.

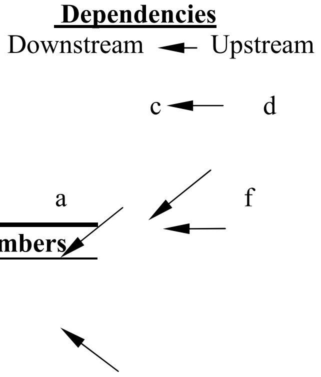
Since R_k, the number of stations to be retained in subbasin k, is not known in advance, alternative station combinations must be determined for varying numbers of R_k (i.e., R_k varying from 0 to P_k).

For example, in Figure 3.3, if the number of retained stations in the hypothetical subbasin will be three ($R_k = 3$), then twenty different station combinations appear such as: *abc, abd, abe, abf, acd, ace, acf, ade, adf, aef, bcd, bce, bcf, bde, bdf, bef, cde, cdf, cef,* and *def.* According to Sharp's procedure, the combinations with the biggest sum of stream order numbers are accepted as the most significant combinations of stations, which, in the hypothetical case, are *abc* and *abf.* The sum of stream order numbers for these two combinations is 14, which is larger than that of other combinations. Accordingly, the method reduces the number of alternative number of combinations from 63 to 8 in the hypothetical basin of Figure 3.3.



Baseline Network (P_k=6)
●Stream location
*Stream order

Station Name	Stream Order Number
A	7
B	4
C	3
D	1
E	1
F	3



R_k	Combination(s)	Sum of Stream Order Numbers
0	-	0
1	A	7
2	Ab	11
3	abc, abf	14
4	Abcf	17
5	abcef, abcdf	18
6	Abcdef	19

R_k: Number of stations to be retained in the primary basin

Figure 3.3 Hypothetical primary basin illustrating the method for selecting candidate stations

3.3.2 Preparation of Data

3.3.2.1 Determination of Attributes for Monitoring Stations

Each station in a monitoring network must be identified with its attributes (l) that comply with management objectives in the basin. Lettenmaier et al. (1984) have defined 8 basic attributes that relate to the management objective of preserving and enhancing swimmability and fishability of the waters in the selected drainage area. Icaga (1998) defined 6 basic attributes related to the management objectives of his case basin. The so-called "station attributes" may be chosen as drainage area, population, irrigation area etc., considering the physical conditions affecting the monitoring station, and the number of observations, length of the observation period, and variables observed in case of water quality monitoring, as factors to represent the characteristics of the station itself.

The above attributes are defined by their numerical values (or scores). These scores are represented by $SR_{j(i)kl}$ with k representing the primary basin index; l, the attribute index; i, the station index within primary basin k; and $j(i)$, index number of the i^{th} station in primary basin k. The determination of the numerical values for some attributes (e.g., drainage area, population, irrigation area, number of samples, and period of observation) is straightforward. For some attributes like observed variables in case of water quality monitoring, appropriate ones must be selected to comply with management objectives. The selection process is also complicated due to the presence of a large number of variables observed at each water quality monitoring station.

Once variables are selected and all attributes $SR_{j(i)kl}$ are identified, the significance of each attribute (or the preference to be given to each) must be specified. This is done by assigning weights w_l to each attribute. The selection of attribute weights is subjective and reflects different management concerns. Essentially, the stations to be allocated within each primary basin are a function of the weights; therefore, the sensitivity of station allocation to different weights may be tested (Lettenmaier et al., 1984).

3.3.2.2 Normalization and Uniformization of Attribute Scores

According to Lettenmaier et al. (1984), it is desirable to specify the scores $SR_{j(i)kl}$ to have an approximately uniform distribution for each attribute (l). If this can be achieved, the dominance of the weighted score by any one attribute on the basis of its relative magnitude alone can be avoided.

The system adopted by Lettenmaier et al. (1984) by Icaga (1998) had the property that the $SR_{j(i)kl}$ were approximately uniformly distributed in the interval (0, 100). The uniformization procedure was realized as follows: for a normally distributed random variable (e.g., attribute), a uniform distribution can easily be achieved by an inverse normal transformation, since the cumulative distribution function of a random variable is, by definition, uniform in the range (0, 1). Alternately, if a variable can be made approximately normal by transformation (e.g., logarithm or power function), a two-step process can be followed to derive a score, which is approximately uniform. Thus, tests for normality should be carried out and normalization for non-normal scores must be made.

3.3.4 Optimization

3.3.4.1 Problem Definition

For the number of stations to be retained in the entire river basin (TR_N), it is necessary to determine the number of stations to be retained in each primary basin (R_k). Accordingly, the number of stations that will be retained in each primary basin should be determined such that the sum of the uniformized attribute data ($SU_{j(i)kl}$) of these stations must be maximum.

For each station combination in primary basin k, the sum of the uniformized attribute data ($SU_{j(i)kl}$) is shown as $TS_{j(i)k}$:

$$TS_{j(i)k} = \sum_{l=1}^{I_N} SU_{j(i)kl} \tag{3.12}$$

where $SU_{j(i)k}$ are the uniformized data at interval (0,100) for attribute l, at the primary basin k and for the i^{th} station; I_N is the number of attributes that will be used in the computations. When weights are assigned to attribute data, Eq. (3.12) becomes:

$$TS_{j(i)k} = \sum_{l=1}^{I_N} (w_l \times SU_{j(i)kl}) \tag{3.13}$$

Eq. (3.13) gives the total attribute value in primary basin k and for $j(i)^{\text{th}}$ station combination. In each primary basin k, there will be different station combinations depending on R_k so that the $TS_{j(i)k}$ values of these station combinations will be different.

For example, for the hypothetical primary basin of Figure 3.3, there are two combinations of stations ($j(3)=2$) for $R_k = i = 3$. Thus, there will be two different $TS_{j(i)k}$ values. If the station allocation procedure results in R_k being 3 for this basin, there must be only one station combination. Accordingly, computations must be carried out with the combination that has a higher $TS_{j(i)k}$ value. Consequently, it is a general logical rule to select those combinations with the highest $TS_{j(i)k}$ values such that:

$$MTS_{j(i)k} = max \ \ TS_{j(i)k} \tag{3. 14}$$

When determining the TR_N number of stations to be retained in the entire basin, the R_k combinations will be those that give the maximum $MTS_{j(i)k}$ attribute values:

$$SMTS = max \sum_{k=1}^{N} \sum_{i=1}^{R_k} MTS_{j(i)k} \tag{3.15}$$

where $SMTS$ is the sum of the $MTS_{j(i)k}$, which give the maximum value for TR_N;;N, the number of primary basins; R_k,, the number of stations to be retained in primary basin k; and $MTS_{j(i)k}$, maximum uniformized total attribute value for $j(i)^{th}$ station combination in primary basin k. When Eq. (3.15) is examined, it is obvious that the problem has two dimensions. Hence, it is not possible to determine the station combinations to be retained in the basin by ranking the $MTS_{j(i)k}$ values from the largest to the smallest and taking the first TR_N value reached. Dynamic programming method is a tool to be used to solve this problem as there are several alternative combinations of maximum total scores $MTS_{j(i)k}$.

3.3.4.2 The Logic of Optimization in a Sequential-Decision Process

Many decision problems have an objective function:

$$V = max \sum_{i=1}^{n} v_i(x_i) \tag{3.16}$$

subject to constraints of the form

$$G \geq g_1(x_1) + g_2(x_2) + \ldots + g_n(x_n) = \sum_{i=1}^{n} g_i(x_i) = q \tag{3. 17}$$

The objective function consists of a series of terms (functions), each of which depends on only one decision variable. Its solution makes use of the independence of the individual terms to consider the decisions represented as a sequential decision process of n stages.

Here, the total return (V) is to be a maximum, whatever the value of q. We define $f_1(q)$ as the best possible solution for stage 1:

$$f_1(q)=max\ (v_1(x_1)) \qquad 0 \leq x_1 \leq q, \qquad 0 \leq q \leq G \tag{3. 18}$$

Such maximization is easy to carry out for all values of q in the range of interest.

Eq. (3.18) defines the optimal policy $x_1(q)$ as a function of the resource q available for a one-stage decision process, and gives the optimal result, $f_1(q)$.

If there were two decision stages in the process, the last of which had been optimized by Eq. (3.18), then, regardless of the quantity of resource x_2 allocated to stage 2, the remaining resource $q - x_2$, after stage 2 decision has been made, should clearly be used in an optimal way, that is, $x_1^*(q - x_2)$, yielding $f_1(q - x_2)$.

The total return is simply the sum of the returns at each stage. This suggests defining the optimum for a two-stage decision process as:

$$f_2(q)=max\ (v_2(x_2)+f_1(q - x_2) \qquad 0 \le x_2 \le q, \qquad 0 \le q \le G \tag{3.19}$$

The solution to Eq. (3.15) gives the optimal policy $x_2^*(q)$ and the optimal return $f_2(q)$ as well as $x_1^*(q - x_2)$ and $f_1(q - x_2)$.

The equations for a three-stage process can be written directly from Eq. (3.19) using the same logic

$$f_3(q)=max\ (v_3(x_3) + f_2(q - x_3) \qquad 0 \le x_3 \le q, \qquad 0 \le q \le G \tag{3.20}$$

The general recursive equation for the k th stage (that is k decisions remaining) is

$$f_k(q) = max\ (v_k(x_k) + f_{k-1}(q - x_k) \qquad 0 \le x_k \le q, \qquad 0 \le q \le G \tag{3. 21}$$

The solution of Eq. (3. 21) gives $x_k^*(q)$ and $f_k(q)$. The preceding solution for the $k-1$ stage gives $x_{k-1}^*(q - x_k^*)$. From this solution, $x_{k-2}^*(q - x_k^* - x_{k-1}^*)$ at stage $k-2$ can be calculated, etc., defining recursively all the x_i^* of the optimal policy as a function of q, the initial quantity of resource. (Hall & Dracup, 1970, Icaga, 1998).

3.3.4.3 Application to the Station Allocation Problem

The objective of the station allocation problem is to find the combination of stations that maximizes the $MTS_{j(i)k}$ corresponding to the determined TR_N (total number of stations which will be retained), so that the objective function of the problem can be determined as:

$$V = max \sum_{k=1}^{N} \sum_{i=1}^{R_k} MTS_{j(i)k} \tag{3. 22}$$

and the constraints of the problem are:

$$\sum_{k=1}^{N} R_k = TR_N \quad ; \quad 0 \leq R_k \leq TR_N \tag{3. 23}$$

$$1 \leq j(i) \leq P_k \quad ; \quad j(i) \neq j(h),\ i \neq h \tag{3. 24}$$

where V is the objective function ; N, the total number of primary basins; R_k, the number of stations which will be retained in primary basin k; k, primary basin index; i, station index within primary basin k; $j(i)$, index number of i^{th} station in primary basin k; TR_N, the total number of stations to be retained in entire basin; and P_k, pre-existing number of stations in primary basin k.

Recursive equations for the above problem are:

stage 1 (k = 1)

$$f_1(d_1; t) = max\ r_1(R_1; a) \tag{3.25}$$

t: $0 \rightarrow d_1$ a:$0 \rightarrow$R1

t = a $0 \leq R_1 \leq TR_N$

stage 2 (k = 2)

$$f_2(d_2 ; t) = \quad max \quad [max\ r_2 (R_2, a) + f_1 (d_1; b)] \tag{3. 26}$$

t : $0 \rightarrow d_2$ $d_2 = d_1 + R_1 \leq TR_N$ a: $0 \rightarrow R_2$ b:$0 \rightarrow d_1$

$t = a + b$

.

.

.

stage N (k = N)

$$f_N(d_N;t) = \max \quad [\max r_N(R_N, a) + f_{N-1}(d_{N-1}; b)] \qquad (3.27)$$

$t : 0 \rightarrow d_N \quad d_N = d_{N-1} + R_N \leq TR_N \quad a: 0 \rightarrow R_N \quad b: 0 \rightarrow d_{N-1}$

$t = a + b$

Here, $f_k(d_k; t)$ is the optimal return (maximum total $MTS_{j(i)k}$) for stage k; $r_k(R_k, a)$, the return function for stage k; R_k, station number which will be retained in primary basin k; TR_N, total number of stations which will be retained; d_k, state variable for stage k; *and* t, a, b are the slack variables.

The computational steps can be arranged to solve the problem given in Eq. (3.21) in the following systematic manner:

For $k = 1, \quad d_1 \leq R_1 \leq TR_N; \quad 0 \leq R_1 \leq P_1$

$$\begin{aligned}
f(1, 0) &= r(1, 0) + 0 \\
f(1, 1) &= r(1, 1) + 0 \\
&\;\;\vdots \\
f(1, d_1) &= r(1, d_1) + 0
\end{aligned}$$

For $k = 2, \quad d_2 = d_1 + R_2 \leq TR_N; \quad 0 \leq R_2 \leq P_2$

$$\begin{aligned}
f(2, 0) &= r(2, 0) + f(1, 0) \\
f(2, 1) &= r(2, 1) + f(1, 0) \\
& r(2, 0) + f(1, 1) \\
f(2, 2) &= r(2, 2) + f(1, 0) \\
& r(2, 1) + f(1, 1) \\
& r(2, 0) + f(1, 2) \\
f(2, 3) &= r(2, 3) + f(1, 0) \\
& r(2, 2) + f(1, 1) \\
& r(2, 1) + f(1, 2) \\
& r(2, 0) + f(1, 3)
\end{aligned}$$

.

.

.

$$\begin{aligned} f(2, d_2) \quad = \quad & r(2, d_2) + f(1, 0) \\ & r(2, d_{2-1}) + f(1, 1) \\ & \ldots\ldots\ldots\ldots\ldots\ldots \\ & r(2, d_2 - d_1) + f(1, d_1) \end{aligned}$$

Finally,

For $k = N,$ $d_N = d_{N-1} + R_N \leq TR_N;$ $0 \leq R_N \leq P_N$

$$\begin{aligned} f(N; d_N) = \; & r(N, d_N) + f(N-1, 0) \\ & r(N, d_N - 1) \quad + \quad f(N-1, 1) \\ & r(N, d_N - 2) \quad + \quad f(N-1, 2) \\ & \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ & r(N, d_N - d_{N-1}) \quad + \quad f(N-1, d_{N-1}) \end{aligned}$$

where, $f()$ represents the total maximum $MTS_{j(i)k}$; $r() = MTS_{j(i)k}$; N is the number of primary basin; and d_N is the step variable.

3.4 Multi-Criteria Decision Making (MCDM) Methods

3.4.1 General

Multi- Criteria Decision Making (MCDM) or Multi-Criteria Decision Analysis (MCDA) is a discipline aimed at supporting planners through the decision making process and provides a structured way to demonstrate the outcomes of their possible decisive actions. MCDM is in the realm of decision analysis (DA), which simply analyzes the way people make decisions or the way people “should” make decisions. As stated in the previous chapters, most water management problems, including monitoring activities, are multiple criteria problems with a complex nature where the criteria often conflict with each other and are variable in time. The main objective of MCDM methods is to help decision makers and analysts organize and synthesize data and information in a way that leads to a more comfortable and confident decision making process and to minimize the post-decision regret (Belton & Stewart, 2002).

Basically, MCDM seeks an answer to the question “Given a set of alternatives and a set of decision criteria, then what is the best alternative?” In general, the main decision problem is how to evaluate and rank the performance of a finite set of alternatives in terms of a number of decision criteria affecting the problem at different hierarchical levels. Many network re-design or reduction problems have the same features; the stations to be retained in the network may be interpreted as “alternatives” while the specifications and the operational purpose of the station might be regarded as “attributes” and “objectives or criteria”, respectively. Once the network reduction problem is identified with the features above, then different MCDM methods can be applied to the problem, and a priority ranking of stations within the network may be obtained.

3.4.2 Basic Aspects of Multi-Criteria Decision Making

According to Zimmerman (1996) and Triantaphyllou (2000), MCDM is divided into multi-objective decision making and multi-attribute decision making, where the latter is also used for MCDM. The main difference between the two methodologies in decision making relates to the concept of decision space, which is considered as being “continuous” in multi-objective decision making and “finite and discrete” in MCDM. Although the terms and/or the names referring to multiple criteria decision analysis methods are widely diverse, most of them have certain aspects in common (Chen & Hwang, 1991; Triantaphyllou, 2000).

First of all, a decision analysis (DA) involves decision makers (DM), decision analysts such as engineers, and “stakeholders” interested in or affected by the decision in progress. A decision-maker (DM) is a person, an organization or any other decision-making entity, which is empowered to make decisions concerning the problem at hand. In most cases, the DM is also responsible for the outcomes of his/her decision. A decision analyst provides advice to the DM and facilitates the decision making progress. The decision analyst’s task is to help the DM find the most appropriate decision alternative(s), based on realistic reasoning through the use of MCDM tools. A stakeholder is a person or a body with an interest in the decision under consideration. The roles of the DM, analyst and stakeholder may overlap, so that they may partially represent the same body, or they may even be a single person (Dietrich & Hämäläinen, 2002).

Another aspect common to different MCDM procedures is the presence of "alternatives" that usually represent different courses of possible actions or actions considered by the decision maker. In most decision making problems, the alternatives are finite and range from several to hundreds.

On the other hand, each MCDM method is represented by multiple "attributes", which may also be referred to as "goals" or "decision criteria". Triantaphyllou (2000) suggests that the criteria may be arranged in a hierarchical manner if the number of criteria is large (e.g. more than a dozen), which means that some criteria may be considered to be the major ones, and some sub-criteria may be related to the major criteria. Along the same line, some sub-sub-criteria may also have to be considered in more complex situations. Furthermore, regarding the multiple criteria issue in MCDM, one should recognize that different criteria represent different dimensions of the problem or choices of alternatives, and different criteria may conflict with each other (Belton & Stewart, 2002).

Another point to be stressed here is the association of different criteria with different units of measure, which is referred to as incommensurability. Although units of attributes have been treated by different means of normalization in MCDM literature, the incommensurable units generally make the multi-criteria decision making problems hard to solve (Triantaphyllou, 2000).

The weights of importance assigned to objectives, attributes or criteria are another aspect common to all MCDM methods. These weights are usually normalized to add up to 1. The general approach used is the capture of those weights by pairwise comparisons such as those in the analytic hierarchy process (AHP), proposed by Saaty (1980), which will be discussed in the following sections.

The basic features of MCDM mentioned above are generally expressed in a matrix format, which is called the “decision matrix”. Triantaphyllou (2000) defines a decision matrix as an (m x n) matrix with a_{ij} elements that indicate the performances of each alternative (A_i, for i =1, 2, 3, ..., m) evaluated according to each criterion C_j (for j= 1, 2, 3, ..., n) with the assigned weights of w_j. Figure 3.4 demonstrates such a decision matrix.

Criteria

	C_1	**C_2**	**C_3**	**......**	**C_n**
Alternatives.	(w_1	w_2	w_3	.....	w_n)
A_1	a_{11}	a_{12}	a_{13}	.....	a_{1n}
A_2	a_{21}	a_{22}	a_{23}	.....	a_{2n}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
A_m	a_{m1}	a_{m2}	a_{m3}	.....	a_{mn}

Figure 3.4 A typical decision matrix (Triantaphyllou, 2000).

3.4.3 The Procedure of MCDM Methods

Belton & Stewart (2002) indicate that most criticisms on MCDM methods focus on the adoption of a stance of “given problem”; that is, at present, MCDM methods are applicable to well-defined problems but do not contribute efforts in defining a problem, which essentially is the case with other classical methods. Accordingly, the set of alternatives and criteria are generally well defined in the application of the MCDM methods. Belton & Stewart (2002) recognize three key steps in the MCDM process as follows:

1- *Problem identification and structuring:* In this phase, the key concerns, goals, stakeholders, actions, uncertainties are defined, and the issues related to the problem are identified. Belton & Stewart (2002) suggest that a general managerial tool such as the SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis may be used. Moreover, this phase is essential for understanding the problem and establishing a common language and basis for the decision analysis.

2- *Model building and use:* This phase is related to the method of relative comparison of the available alternatives, regarding the criteria identified in the problem structuring phase. Construction of a model to represent the preferences of the DM is necessary to facilitate the decision making process. After the relevant criteria and alternatives are determined, the following tasks of this phase cover the attachment of numerical measures to the relative importance of the criteria and identification of the impacts of the alternatives on the criteria. Furthermore, numerical values are specified for ranking the available alternatives as a part of this "model building and use" process. Triantaphyllou (2000) mentions some ranking methods in MCDM such as the weighted sum model (WSM), the weighted product model (WPM), the analytic hierarchy process (AHP) by Saaty (1980), the elimination and choice translating reality (ELECTRE) by Benayoun et.al. (1966), and the technique for order preference by similarity to an ideal solution (TOPSIS) developed by Hwang & Yoon (1981). Some of these ranking models, including the reference point approach, will be discussed briefly in further sections.

3- *Evaluation of results and problem solving:* The decision analysis and ranking of alternative actions may not be sufficient to solve the problem with respect to the decision maker's particular and subjective preferences; hence, MCDM is not solely a compilation of technical and analytical modeling procedures, but it should also support the decision maker in determining the "most wanted (preferred) solution". The ranking approach of MCDM methods enables the revelation of other "close to the best" alternatives. Therefore, the decision maker is able to overview other decision options besides the best but the undesired solution. The decision maker may employ one or more of these options, which is/are closer to his/her preferences. This feature of MCDM provides a more reliable and flexible decision making process for development of an action plan focused on the solution of the problem at hand.

In summary, the main elements of the MCDM process used in decision making cover the determination of relevant criteria and alternatives, specification of their relative numerical preference values, and development of a ranking order for the alternatives.

3.4.4 Some Widely Used Multi-Criteria Decision Making Methods

Determination of the elements a_{ij} of the decision matrix in Fig. 3.4 is the core problem of the decision making process. To this end, several different methods are available in literature. For purposes of this study, some of the basic and common methods and their principles are summarized in the following sections.

3.4.4.1 The Weighted Sum Model (WSM)

The weighted sum model (WSM) is a widely used method in decision making. Based on the definitions of alternatives (A_i), criteria (C_j), the assigned weights (w_j), and the performance value (a_{ij}) of each alternative, the best alternative is the one which satisfies the following expression (Fishburn, 1967; Triantaphyllou, 2000):

$$A_{(best)} = \max(or \min) \sum_{j=1}^{n} a_{ij} w_j \tag{3.28}$$

The WSM is used particularly in single dimensional problems where all the measurement units are the same, but a difficulty emerges when it is applied to multi-dimensional problems. Lettenmaier et al. (1984) used a normalization and uniformization procedure to overcome this problem as explained in the previous sections.

3.4.4.2 The Weighted Product Model (WPM)

The weighted product model is a pairwise comparison model where each alternative is compared to the others by multiplication of a number of ratios. Each ratio is raised to the power of the relative weight assigned to the identified criteria. Equation 3.29 is used to compare two alternatives A_K and A_L (Miller&Starr, 1969; Triantaphyllou, 2000):

$$R(A_K / A_L) = \prod_{j=1}^{n} (a_{Kj} / a_{Lj})^{w_j} \tag{3.29}$$

where n is the number criteria, a_{ij} is the actual value of the i-th alternative in terms of j-th criterion, and w_j is the weight of importance of the criterion.

In case of maximization, alternative A_K is more desirable than A_L if the calculated R value is greater than 1. Hence, the best alternative is the one that is better than all other alternatives.

The structure of WPM eliminates any units of measure so that it can be employed for both the single and the multi-dimensional decision making problems. Another advantage of the method is that, instead of the actual values of a_{ij}, it can also use relative values defined as follows:

$$\frac{a_{Kj}}{a_{Lj}} = \frac{a_{Kj} / \sum_{i=1}^{n} a_{Ki}}{a_{Lj} / \sum_{i=1}^{n} a_{Li}} = \frac{a_{Kj}^{'}}{a_{Lj}^{'}} \tag{3.30}$$

3.4.4.3 The Analytic Hierarchy Process (AHP)

The analytic hierarchy process is developed by Saaty (1980, 1994); it uses a hierarchical value tree for decision aid, where the problems are decomposed into a hierarchical tree of alternatives and criteria. In “value tree” approach, the problem is presented in some connected levels constituted by objectives and criteria (Figure 3.5). The approach is used by many decision making techniques, including the “Elementary Bayesian Decision Theory” (Benjamin&Cornell, 1970), and enables an analytic design for the decision making problem.

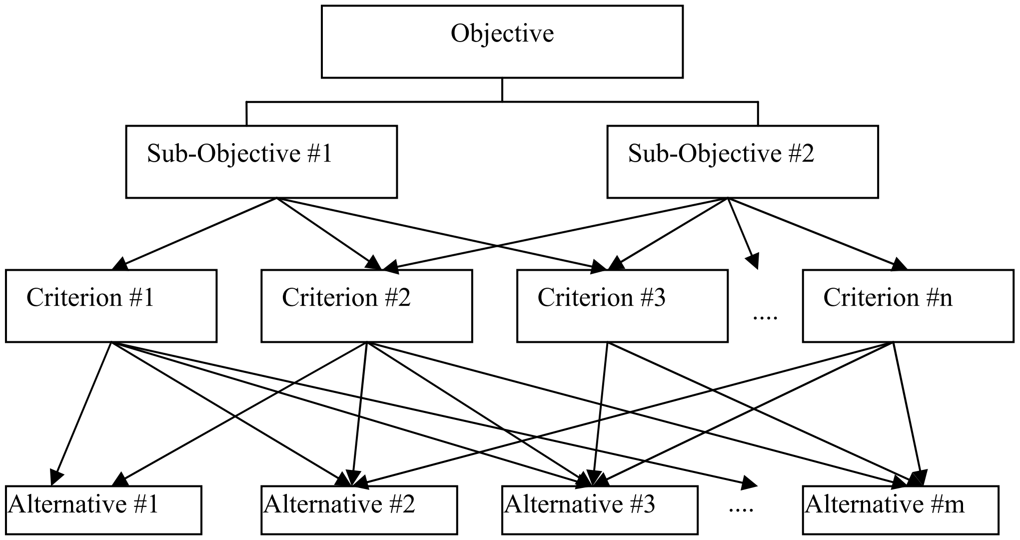


Figure 3.5 An example for a decision value tree.

AHP deals with a decision matrix where the matrix is constructed by using the relative importance of alternatives in terms of each criterion. Although AHP is generally used to elicit weights of criteria through pairwise comparisons by the principal eigenvector approach, it may also be used to process a_{ij} values which are determined. The entry of a_{ij}, in an (m x n) decision matrix represents the relative value of alternative A_i in terms of the criterion C_j. The sum of a_{ij} for the j-th criterion is equal to 1, which is obtained through the division of each a_{ij} by the sum of a_{ij} for j-th criterion. Then, in the case of maximization, the best alternative is determined by Eq. (3.28) (Triantaphyllou, 2000).

It is clear that a similarity between AHP and WSM exists, but AHP uses relative values instead of actual ones; therefore it can be used in multi-dimensional decision making problems as well.

3.4.4.4 The Reference Point Method

Reference Point Methods are basically based on achieving satisfactory levels of the performance of each alternative on each criterion. The approach needs each criterion to be associated with an attribute defined on a measurable scale, and the values of the attributes corresponding to m criteria for an alternative A_i are to be computed. Next, the decision maker is asked to express value judgements in terms of “goals” or “aspiration levels” for each criterion, defined in terms of desirable levels of performance for the corresponding attribute values. On the other hand, if the aspiration levels are hard to determine at this phase, one may also consider the worst stance of each criterion or attribute value. It is obvious that the attribute values and reference points (or goals) indicate a point or a vector in a multi-dimensional decision space; therefore, the performance of the attribute value is determined through the scalar “distance” to the aspiration level or point. In a maximization case, the minimum distance to a reference point is desired; on the contrary, the maximum distance to the worst stance is required for the minimization case.

The scalar difference between the performance of an alternative and a reference point (Figure 3.6) is generally measured by the Euclidian distance, which may be formulated as follows for two points in a space A and B with coordinates A (x_a, y_a) and B(x_b, y_b) in a two dimensional space:

$$D_{A-B} = \left[(x_B - x_a)^2 + (y_B - y_A)^2 \right]^{1/2} \tag{3.31}$$

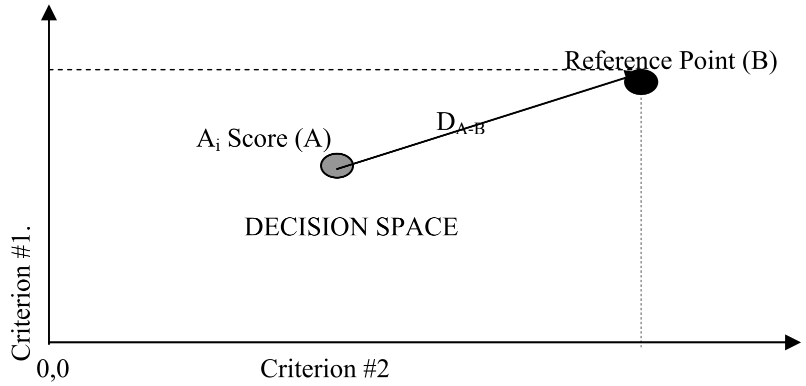


Figure 3.6 Measurement of the distance between an alternative and the reference point in a two dimensional decision space.

For further details, applications and reading on theory of reference point approach, one may refer to Wierzbicki (1980, 1999) and Belton & Stewart (2002).

3.4.5 Elicitation of the Weights of Decision Criteria

Another crucial step in MCDM is the determination of relative weights of attributes or decision criteria. In many cases, it is clear that not all the criteria considered have the same importance, as one or more of them are more desirable than the others in qualitative terms. Generally, in multi-criteria decision making problems, this information cannot be expressed in terms of absolute values; therefore, decision makers are forced by the decision analyst to express their preferences in verbal statements, such scoring one criterion over another or making pairwise comparisons through the use of a scale. Regarding this difficulty in quantifying weights, many decision making methods attempt to determine the relative importance of the decision criteria (Triantaphyllou, 2000; Belton & Stewart, 2002).

3.4.5.1 Pairwise Comparisons

Pairwise comparisons can be used to asses the relative importance of each alternative in terms of each criterion. The pairwise comparison approach simply demands from the decision maker to express his/her opinion and preferences in a linguistic phrase such "A is more important than B" or "A has the same importance as C". These verbal statements are later quantified through a defined scale. Generally, the scales are constructed for a one-to-one mapping between the set of discrete linguistic choices of the decision maker. Such scales are based on two major approaches. The first approach is based on linear scales as in AHP proposed by Saaty (1980), and the second one is the exponential scale introduced by Lootsma (1988). Such scales identified are based on some psychological theories; but it should be stated here that the pairwise comparisons become impractical when the number of entities becomes large, e.g., if the number of entities are 100, then the decision maker shall make 4950 pairwise comparisons, which may lead to some inconsistencies (Triantaphyllou, 2000). In the following section, weight elicitation through the eigenvalue approach proposed by Saaty (1980) in AHP will be introduced.

3.4.5.2 Weight Elicitation through the Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is based on paired comparisons and the use of ratio scales in preference judgements. The AHP uses a principal eigenvalue method to derive priority vectors (Saaty & Hu, 1998). The decision maker is asked to identify the ratio of attributes' weights through the use of a linear scale proposed by Saaty (1980) as shown in Table 3.1. The upper limit of the scale is set to 9; regarding the fact that most individuals cannot simultaneously compare more than seven (plus or minus two) objects (Miller, 1956; Triantaphyllou, 2000).

Table 3.1 Scale of relative importances according to Saaty (1980).

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective(s)
3	Weak importance of one over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed
Reciprocals of above nonzero	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	

In AHP, the decision maker is asked to define the r_{ij} ratio of attribute (objectives, alternatives) weights as:

$$r_{ij} = \frac{w_i}{w_j} \tag{3.32}$$

Fixed values of r_{ij} associated with verbal statements of Table 3.1 are used for purposes of comparison.. Clearly, the selection of the comparison scale has an effect on the result; hence, the scale should be selected with careful attention. The AHP method presents the results of paired comparisons in the comparison matrix A as defined below:

$$\mathbf{A} = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nn} \end{bmatrix}$$

where the elements r_{ii} on the diagonal are assumed to be 1. Moreover, in the comparison process, only upper triangular matrix is demanded from the decision maker, and the lower triangular part is defined as

$$r_{ij} = \frac{1}{r_{ji}} \tag{3.33}$$

The weights w_i are estimated by normalising the elements of the eigenvector corresponding the largest eigenvalue of the matrix A. For n weights (values), the decision-maker makes n(n-1) estimates; and a consistent weighting procedure should possess the property that any r_{ij} is equal to the multiplication of r_{ik} and r_{kj} of the ratio of the k-th activity over the i-th and the j-th (Eq. 3.34):

$$r_{ij} = r_{ik} \times r_{kj} \qquad \text{for i, j, k} = 1, 2, 3, \ldots\ldots, \text{n} \tag{3.34}$$

Since the matrix A has rank 1 and λ = n is its nonzero principal right eigenvalue, then the following equation can be written:

$$A \times \text{x} = \text{n} \times \text{x} \tag{3.35}$$

where x is a principal right eigenvector. Considering Eq. 3.32; Eq. 3.35 takes the form of;

$$\sum_{1}^{n} r_{ij} w_j = \sum_{j=1}^{n} w_i \quad \text{or} \quad AW = nW \qquad \text{for i} = 1, 2, 3, \ldots\ldots, \text{n} \tag{3.36}$$

where n is the number of elements to be compared.

In real life applications, the pairwise comparisons are not perfect, and the ratio r_{ij} may deviate from the real values; this situation leads Eq. (3.34) to an inequality. Considering the matrix A, it is now a “perturbation” of the consistent case, and the maximum eigenvalue is close to but greater than n with the slight change of r_{ij} ratios (Triantaphyllou, 2000). Saaty (1980) claims that one should find an eigenvector corresponding to the maximum right eigenvalue $\lambda_{\max}$ as in Eq. (3.37) to find the weights in such a non-consistent situation,.

$$AW = \lambda_{\max} W, \qquad \text{where } \lambda_{\max} \geq n \tag{3.37}$$

Saaty proposed to estimate the reciprocal right eigenvector W by multiplying all elements in each row of matrix A and taking the n-th root. An average perturbation value is then given by consistency index, CI as:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{3.38}$$

Then, the inconsistency of the weight estimates w_i given by the decision maker can be measured by the consistency ratio index, CR:

$$CR = \frac{CI}{RCI} \tag{3.39}$$

Here, RCI (Table 3.2) denotes the average random consistency index obtained from a sample of size 500 of randomly generated reciprocal matrices with entries derived from the scale 1/K, 1/(K+1),..., 1,..., K-1, K, where K is a positive constant giving the bounds for the real weights. If this approach yields a CR value greater than 10 %, then a re-examination of the pairwise judgments is recommended until a CR less than or equal to 10 % is obtained (Triantaphyllou, 2000). Dietrich & Hämäläinen (2002) indicate this ratio as 20 %.

Table 3.2 RCI values of sets of different orders n (Triantaphyllou, 2000).

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Re-examination of the inconsistent matrix is realized through partial evaluation of pairwise judgments, i.e, the decision maker is initially forced to re-evaluate the highest preference comparison. If the decision maker does not change his value of relative importance, one considers the second highest inconsistent judgment and repeats the process until a near consistent matrix is reached (Saaty, 2003).

Another issue to be stressed in application of the AHP method is the "rank reversal" phenomenon. In the method, a change in the set of alternatives (i.e, deleting one or more alternatives) may alter the existing order between the alternatives, even if the original valuations are not changed. The rank reversal effect is widely seen as a result of the normalisation of values, where the sum of values under an attribute equals 1. The rank reversal effect can be avoided by using value functions and normalisation where the value of "1" is given to the best alternative, 0 to the worst alternative, and others are rated in between (Dietrich & Hämäläinen, 2002).

More readings and discussions on the AHP method are available in Belton & Stewart (2002), Saaty (1980, 1983, 1987, 1990, 1994, 2003, 2006), Saaty & Hu (1998), Belton & Gear (1983), Salo & Hämäläinen (1997) and Triantaphyllou (2000).

3.4.5.3 Determination of Weights in a Decision Value Tree

In a decision value tree (Fig. 3.5), there are two ways to determine the weights; a) *non-hierarchical weighting*, where the weights are defined only for the attributes, and b) *hierarchical weighting*, where the weights are defined for the each hierarchical level separately and than multiplied down to get the corresponding lower level weights.

In non-hierarchical weighting, upper-level weights (objective weights) are not demanded from the decision maker, but they may be calculated as a sum of the lower level weights. In the WSM method explained in section 3.4.4.1, only the attribute weights are used to determine the overall value of the alternatives, as the weights of the objectives are used only when interpreting the results of the analysis.

3.4.6 Application of MCDM Methods to Monitoring Network Reduction Problem

As indicated in the previous sections, many network re-design or reduction problems have some common features with those that can be solved through the use of MCDM methods. The outcome of the application of a multi-criteria decision making method to a network reduction problem gives a hierarchical ranking of the operational and non-operational stations in a network in terms of defined monitoring objectives and station attributes. This situation provides a valid decision making ground for the planners (e.g., monitoring agencies like EIE) to assess the operational state of a monitoring station.

The overall "objective" of the network problem may be set as "reduction of the monitoring network", or "performance assessment of operated stations", in terms of criteria such as "data extraction for statistical analysis", "assessment and management of floods", "assessment of available water potential", "data collection for hydrological modeling purposes" etc. The stations (operational or not) in the network may be interpreted as "alternatives" while the specifications of the stations such as the presence of limnigraphs, operational periods, online satellite connection etc., and some parameters of the collected data such as the coefficient of skewness or variation of floods might be regarded as "attributes". Once the network reduction problem is identified with the features mentioned above, the application of a MCDM method is easily handled.

3.4.6.1 Selection of Attributes Representing Monitoring Stations

Each station in a monitoring network must be identified with its attributes that comply with basin management objectives and the relevant operational criteria of the network. These attributes may be selected as the drainage area, population addressed, and irrigation area, etc., considering the physical conditions that affect the monitoring station. Number of observations, length of the observation period, and similar attributes may be selected to define station specific characteristics.

The selection of attributes is an important step in the network reduction process, as the attributes of the stations can be interpreted as performance indicators. The selected attributes should reflect a general perspective for the entire network considered and must also indicate the main characteristics of the station, including the information extracted at that location on the basis of collected data. For instance, if a decision-maker wants to reduce the number of stations in a streamflow gauging network the general objective of which is “assessment of the water potential for a reservoir construction”, then the selection of long-term mean discharges at stations as an attribute to be maximized may lead to the preservation of more downstream stations, where construction of a dam is not desired. However, in that case, the selection of attributes such as the “operational period”, “sampling interval”, “continuity of records”, etc., may give better results, since better or optimum values of such attributes are related with the quality of the extracted information from collected data. Similarly, for a monitoring objective such as “production of information for flood prevention”, selection of an attribute indicating the number of historical flood hazards which have occurred at the station location conveys more information about the issue than that provided by the highest instant peak flow observed.

On the other hand, the selected attributes should be general for all stations instead of being specific to each, and the selected attribute should be easy to compute for each station in the network. This asset permits a comparison among the stations, which actually is the sense of network reduction procedure.

3.4.6.2 Application of the AHP Method to Network Reduction Problem

The AHP method can be applied to the network reduction problem in two ways: a) A decision matrix (Fig. 3.7) can be constructed by regarding solely the values of "attributes" defined for the stations, or b) through structuring the network reduction problem in a decision value tree containing the above considered criteria and attributes, while considering the stations as alternatives (Fig. 3.8). In both ways, the weights of the attributes and criteria can be elicited through pairwise comparisons explained in the previous sections.

In the decision matrix approach, only the attributes of stations are identified and considered as "performance indicators". Such an evaluation of the problem is the simplest way of decision making for network reduction and can be used as a measure of performance for each station in the network considered.

	Attribute #1 (w_1)	***Attribute #2 (w_2)***	**…**	***Attribute #j (w_j)***
Station #1	S_{11}	S_{12}	…..	S_{1J}
Station #2				
⋮	⋮	⋮	⋮	⋮
Station #i				S_{IJ}

Figure 3.7 Decision matrix for the network reduction problem.

In order to determine the relative scores (S_{ij}) of the attributes for each station, a normalization procedure as explained in Section 3.3.4.3 should be carried out. Then, the matrix ***W*** (j x 1), whose elements correspond to the weights of each attribute, is to be multiplied with the decision matrix ***S*** (i x j) to obtain the product matrix ***P*** (ix1) which indicates the ranking of the stations in terms of the selected attributes (Eq. 3.40):

$$S \times W = P \tag{3.40}$$

In the decision value tree approach, the computations are more complex, and the relative weights of the identified criteria and attributes should be identified for each hierarchical level as in Figure 3.8.

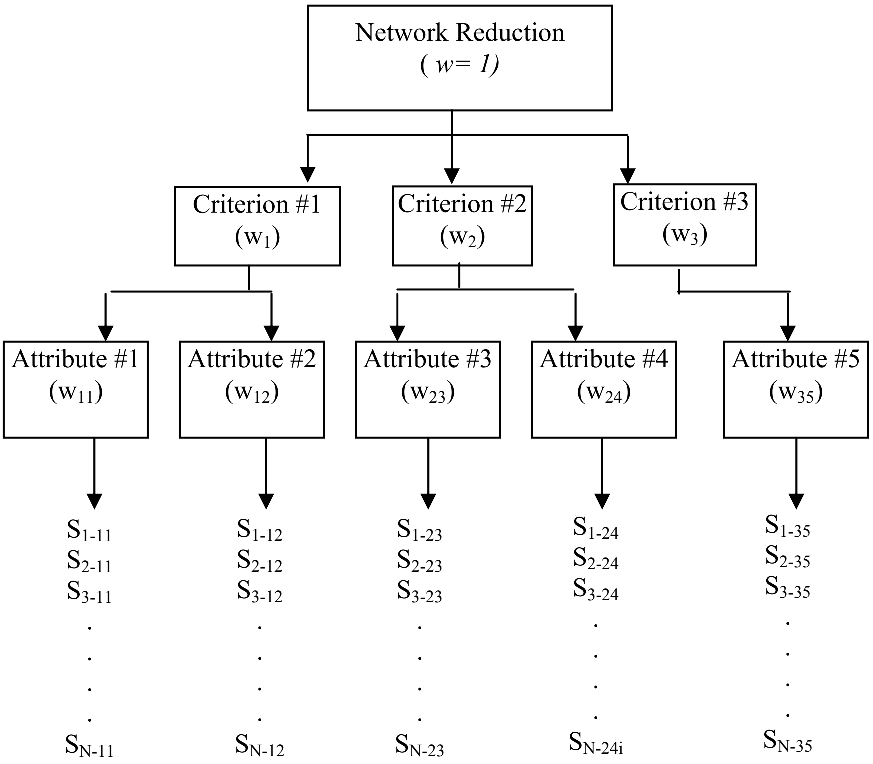


Figure 3.8 Hierarchical structure of the network reduction problem in a decision value tree ($S_{i\text{-}jk}$ values correspond to the normalized values of the attributes for each station in the network).

In Figure 3.8, the network reduction problem is structured in a hierarchical manner through the use of a decision tree. The top level of the tree indicates the overall objective of the action, whereas the level below identifies the criteria such as the "assessment of water potential", "detection of trends" etc. Each criterion is measured by some defined attributes. For example, "operational period", "number of measured data", "availability of a limnigraph at the station" are attributes that are related with the criterion of "data collection for hydrological modeling purposes".

The weight (w) elicitation process in Figure 3.8 can be fulfilled by the AHP method for all levels, or even by different methods such as direct rating, SWING, SMART etc. (Belton & Stewart, 2002).

The ranking procedure starts from the bottom level of the hierarchy, and the final ranking of the alternative, i.e. the stations, is obtained through the multiplication of the related weights for each level by the rankings obtained for each station (Fig. 3.9).

The final product of the multiplication chain shown in Fig. 3.9 defines the priority ranking of the stations in the network. A higher r_i value indicates that this station outranks the other stations below, hence it is more desirable to retain it in the network.

3.4.6.3 Application of the Reference Point Approach to Network Reduction Problem

Similar to AHP, application of the reference point approach to the network reduction problem aims to obtain a ranking among the stations in the network in terms of their performances. The performance of a station is again measured by the assessed values of attributes and criteria as in the AHP method;, but, in the reference point approach, an aspiration level for the criteria or objectives is identified, and the performance of the alternatives are measured by the distance to that reference point, which is indicated by the decision maker. The main advantage of the reference point approach is that one does not need to elicit any weights to the attributes or the criteria. This advantage stems from the definition of "distance" (Eq. 3.31 and Fig. 3.6); any reference point defined has the same weight as the criterion value computed. Hence, it is a common multiplier which changes only the extent of the decision space.

$$\begin{array}{c|cc|} & \text{Attribute 1} & \text{Attribute 2} \\ \hline \text{Station 1} & S_{1\text{-}11} & S_{1\text{-}12} \\ . & . & . \\ . & . & . \\ . & . & . \\ . & . & . \\ \text{Station N} & S_{N\text{-}11} & S_{N\text{-}12} \end{array} \times \begin{vmatrix} w_{11} \\ w_{12} \end{vmatrix} = \begin{array}{c|c} & \text{Criterion 1} \\ \hline \text{Station 1} & r_{11} \\ . & . \\ . & . \\ . & . \\ . & . \\ \text{Station N} & r_{N1} \end{array} \Rightarrow$$

$$\begin{array}{c|cc|} & \text{Attribute 3} & \text{Attribute 4} \\ \hline \text{Station 1} & S_{1\text{-}23} & S_{1\text{-}24} \\ . & . & . \\ . & . & . \\ . & . & . \\ . & . & . \\ \text{Station N} & S_{N\text{-}23} & S_{N\text{-}24} \end{array} \times \begin{vmatrix} w_{23} \\ w_{24} \end{vmatrix} = \begin{array}{c|c} & \text{Criterion 2} \\ \hline \text{Station 1} & r_{12} \\ . & . \\ . & . \\ . & . \\ . & . \\ \text{Station N} & r_{N2} \end{array} \Rightarrow$$

$$\begin{array}{c|c|} & \text{Attribute 5} \\ \hline \text{Station 1} & S_{1\text{-}35} \\ . & . \\ . & . \\ . & . \\ . & . \\ \text{Station N} & S_{N\text{-}35} \end{array} \times w_{35} = \begin{array}{c|c} & \text{Criterion 3} \\ \hline \text{Station 1} & r_{13} \\ . & . \\ . & . \\ . & . \\ . & . \\ \text{Station N} & r_{N3} \end{array} \Rightarrow$$

$$\begin{array}{c|ccc|} & \text{Criterion 1} & \text{Criterion 2} & \text{Criterion 3} \\ \hline \text{Station 1} & r_{11} & r_{12} & r_{13} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ \text{Station N} & r_{N1} & r_{N2} & r_{N3} \end{array} \times \begin{vmatrix} w_{1} \\ w_{2} \\ w_{3} \end{vmatrix} = \begin{array}{c|c} & \text{Objective} \\ \hline \text{Station 1} & r_{1} \\ . & . \\ . & . \\ . & . \\ . & . \\ \text{Station N} & r_{N} \end{array}$$

Figure 3.9 Calculation of station rankings for the decision value tree in Figure 3.8 in terms of defined objective and criteria.

Regarding the hierarchical problem structure in Fig. 3.8, many attributes may be associated with criteria defined and such criteria are subject to decision making in terms of the overall objective. In that case, the reference point approach is based on performance assessment of a monitoring station in terms of the relevant criterion. The performance value of a monitoring station is to be computed through the related attribute values, where a summation of the attribute values (a_{ij}) for each criterion can be used. Therefore, the selected attribute values should improve the stations' performance when they are maximized. That is, if one decides to use "the number of days without any observation" as an attribute, where the minimum is more desirable, he/she should define that attribute in a different way such as "the number of days with observation", or "the ratio of the days with observation to the overall operational period", which are more desirable when maximized. Another point to be stressed here is the common deficiency of the sum models, which is referred to as "incommensurability" or the association of different criteria with different units of measure. A normalization and uniformization of attribute units are needed, and to that end, the approach used by Lettenmaier et.al. (1984) and Icaga (1998) is adopted.

The station attribute values computed should be approximately uniformly distributed on the interval (0, 1); hence, for a normally distributed random variable (e.g., attribute), a uniform distribution can be easily attained by an inverse normal transformation, since the cumulative distribution function of a random variable is, by definition, uniform in the range (0,1).

The normalization of a skewed distribution can be realized by a Box-Cox transformation, where the transformation of skewed x_i values can be realized by:

$$y_i = \frac{x_i^{\lambda} - 1}{\lambda} \quad \text{for} \qquad \lambda \neq 0 \qquad (3.41)$$

where y_i are the transformed data; x_i, the original skewed data, and λ, a parameter value to be estimated by trial and error such that y_i have a zero or close to zero coefficient of skewness (McMahon & Mein 1986, p. 47).

Next, the normalized attribute values may be transformed once more to have a uniform distribution function for the interval (0, 1) through the use of Probability-Integral Transformation described below:

> *Theorem : Probability -Integral Transformation.*
> *Let the random variable X have the cumulative distribution function F_x. If F_x is continuous, the random variable Y produced by the transformation $Y = F_x(X)$ has the uniform probability distribution over the initial interval (0, 1).*
>
> *Proof:*
> *Since $0 \leq F_x(x) \leq 1$ for all x, we have $F_y(y) = 0$ for $y \leq 0$ and $F_y(y)=1$ for $y \geq 1$. For $0 < y < 1$, define u to be the largest number satisfying $F_x(u) = y$. Then $F_x(X) \leq y$ if and only if $X \leq u$, and it follows that*
>
> $$F_y(y) = P\,[F_x(X) \leq y\,] = P\,(\,X \leq u\,) = F_x(u) = y$$
>
> *which is the uniform distribution.*(Gibbons & Chakraborti, 1992, p.26).

According to this theorem, the cumulative distribution function *F(x)* of attribute values, which are normalized, becomes equal to the cumulative distribution function *F(y)*. Thus,

$$F(\,x\,) = \int f(\,x\,)\,dx = P(\,X < x\,) \tag{3.42}$$

where, *F(x)* is the cumulative function of normal distribution; *f(x)*: probability density function of normal distribution; *P(X<x)*: probability of $X < x$, and

$$F(y) = \int f(y)\,dy = P(Y < y) = \frac{y-a}{b-a}\,, \qquad a \le y < b \tag{3.43}$$

where, F(y) is the cumulative function of uniform distribution; f(y): probability density function of uniform distribution ; and P(X<x): probability of X < x.

The cumulative function *F(x)* is standardized as *F(z)* using the transformation:

$$z = \frac{x-\mu}{\sigma} \tag{3.44}$$

where, *z* is the standardized normal data; *x*: attribute data; μ: arithmetic mean; and σ: standard deviation. After this transformation, the standardized cumulative normal distribution function *F(z)* becomes equal to the cumulative uniform distribution function *F(y)* according to the Probability-Integral Transformation theorem:

$$F(z) = F(y) = \frac{y-a}{b-a} \tag{3.45}$$

and then,

$$y = (b - a)\; F(z) + a \tag{3.46}$$

is obtained. By replacing the values b = 1 and a = 0, as the limits of the uniform distribution, we can obtain:

$$y = F(z) \tag{3.47}$$

where, *y* is the uniformized data of *x,* which is attribute value with normal distribution function, and *F(z)*: standardized cumulative normal distribution function of *x*.

After the normalization and uniformization processes defined above, the attributes have values between 0 and 1 and have no units, thus the sum of the attributes are easy to obtain. Recalling Fig. 3.6, a "score" (SC_{im}) of the m-th criterion associated with n number of attributes can be obtained for the i-th monitoring station through the summation of uniformized j-th attribute values (au_{ij}) as follows:

$$SC_{im} = \sum_{j=1}^{n} au_{ij} \tag{3.48}$$

The reference level for the m-th criterion is the number of the attributes associated, as none of the attributes may have a uniformized value more than 1, and a "super station" which fulfils all for the m-th criterion has the SC_{im} value as n.

The number of the criterion identifies the dimension of the decision space; e.g., if only three criteria are introduced, the reference point has three dimensional coordinates $\{n_1, n_2, n_3\}$ corresponding to the number of attributes associated with each criterion. In that phase, it is obvious that each i-th station is represented by a single point with the coordinates $\{SC_{i1}, SC_{i2}, SC_{i3}\}$ in the three dimensional space (Fig. 3.10). Therefore, the performance of the monitoring station is measured by the distance (Eq. 3.31) to the reference point, where the closer the station is to the reference point, the better is the performance so that it dominates the other stations. Accordingly, the monitoring stations can be prioritized from the minimum to the maximum distance.

On the other hand, the reference point approach allows evaluating the stations with respect to their specific operational objective; e.g, if a monitoring station is operated only for one objective such as the "assessment of water potential", then its performance can be measured in terms of the decision space of the related objective. Thus, the performance of the station can be measured with respect to its purpose, irrespective of the influence of the operational purposes of other stations. This feature enables an independent evaluation of a station's performance and the detection of stations which fulfill their operational purpose more properly than the others within the network.

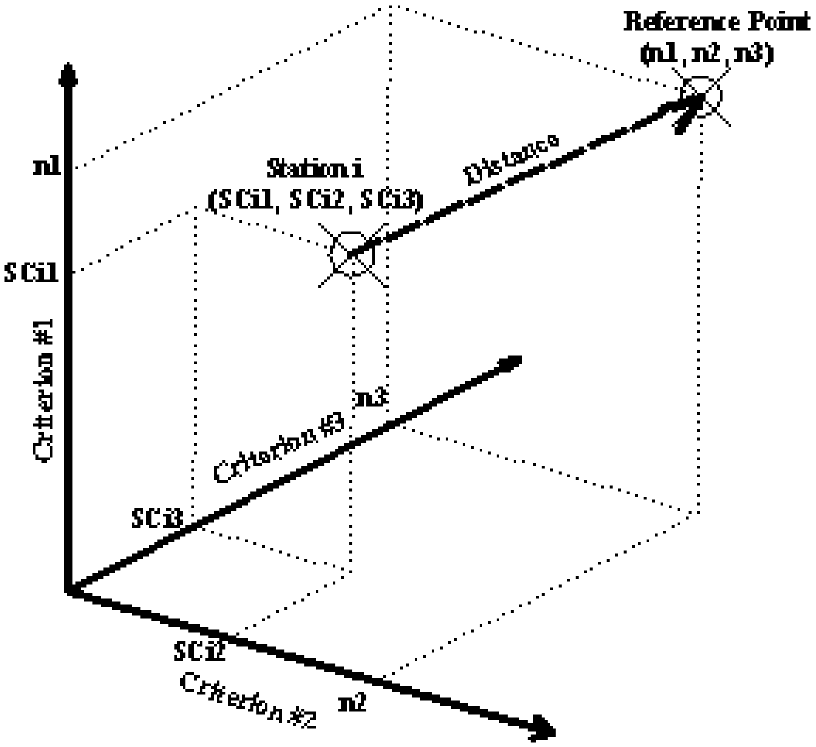


Figure 3.10 Presentation of the reference point and the performance of a monitoring station in the three dimensional decision space.

CHAPTER FOUR
APPLICATION OF METHODS TO GEDIZ RIVER BASIN

4.1 Gediz River Basin

Gediz River basin is located in West Anatolia between the Aegean Sea to the west, Kucuk Menderes basin to the south, and Bakircay river basin to the north. The length of the river is 276 km, and the total drainage area is around 17 000 km^2. The main tributaries are Deliinis, Selendi, Demirci, Nif, Alasehir and Kumcay streams. Adala, Ahmetli, Menemen, Akhisar, Manisa and Alasehir plains make up the lower Gediz plains, which are subject to extensive agricultural practices with large irrigation schemes covering an area of about 110 000 hectares.

The climate of the Gediz River Basin is typically Mediterranean with hot and arid summers and warm and rainy winters. The annual precipitation for the region changes from 492 mm (Salihli) to 726 mm (Manisa), with the average being 635 mm. 75 % of the annual precipitation occurs during the five months between November and March.

4.2 The Current Streamgaging Network in the Gediz Basin

In Turkey, nation-wide streamflow gauging networks are operated by two state organizations: Electrical Works Authority (EIE) and State Hydraulic Works (DSI). Each organization has its own independent network of streamflow gauging stations (SGS). Both the EIE and the DSI networks aim to collect streamflow information for small and/or large-scale projects at specific cross-sections of rivers. The monitoring activity in these networks is realized for two main goals: a) collection of data for the statistical analysis of hydrologic phenomena (e.g. floods & droughts); and b) determination of basin water potential and the long-term mean discharge at any specific cross-section of a river.

DSI and EIE both have SGS monitoring networks in the Gediz River Basin. Streamflow gauging in the basin was initiated in 1938 by EIE in order to obtain data for the planning and construction of the Demirkopru Dam. In 1941, EIE started to operate two more SGS and developed the network until 1978. At present, some of these stations are closed so that only 10 SGS of EIE have remained operational (EIE, 2003). DSI started its streamflow monitoring network in 1968 at Muradiye, 9 km away from the city of Manisa. DSI operated 20 SGS in Gediz River Basin, but most of them are closed at present. Recently, DSI has initiated a flood warning project called TEFER, which includes online streamflow monitoring stations and an early flood warning system. Currently, 6 TEFER stations are operational in Gediz; however the data collected are not made available to users due to legal and institutional constraints imposed by the TEFER project.

DSI streamflow gauging activity has mainly focused on small tributaries, where data are needed for small and medium scale water resources development plans, while EIE focused mainly on gathering data for determination of water potential and statistical analyses of hydrologic phenomena, e.g. floods & droughts. DSI's SGS monitoring network is excluded from the context of this study since it lacks data for recent years and since the locations of its stations are generally on small tributaries.

Table 4.1 lists both the operational and the closed EIE SGS along the Gediz River. SG Stations, 501, 502, 503, 504, 506, 508 and 521 are neglected in the optimization analyses due to significant amounts of missing data and the short records of streamflow observations. Accordingly, the number of stations considered in the current study is reduced to 13.as shown in Figure. 4.1. Some of the stations listed in Table 4.1 do not show in Figure 4.1 since the numbers of these stations were changed by EIE although their locations remained the same. Optimization of the EIE network as presented in Figure 4.1 is the primary concern of the case study presented herein.

Table 4.1 EIE streamflow gauging stations in the Gediz Basin (EIE, 2003)

SGS NO	Location and Station Name	Operational Start Date	Operational End Date	Area (Km^2)	Elevation (m)
501	GEDIZ River-KIZKOPRUSU	01.03.1938	31.03.1960	5675.2	150
502	GEDIZ River.-KOPRUBAŞI	14.09.1941	18.07.1960	1182.4	652
503	DELINIŞ Creek -SELMANHACILAR	18.10.1941	14.04.1960	528.8	484
504	SELENDI Creek.-SELENDI	19.10.1941	12.04.1960	530.4	420
506	GORDES Creek.-HACIHIDIR	04.11.1951	08.04.1964	826.0	306
507	ALAŞEHIR Creek.-TAYTAN KOP.	06.11.1951	01.11.1968	2512.8	93
508	GEDIZ River -TATAROCAGI	08.11.1951	29.05.1952	9214.8	63
509	MEDAR Creek.-KAYALIOGLU	10.11.1951		901.6	77
510	KUM Creek.-KILLIK	11.05.1951		3184.8	55
512	KUM Creek.-COMLEKCI	21.03.1952	28.02.1957	1092.0	125
513	NIF Creek.-BETON KOPRU	21.04.1955	01.11.1974	690.4	52
514	SELENDI Creek.- DEREKOY	12.04.1960		689.6	344
515	DELINIŞ Creek.-TOPUZDAMLARI	14.04.1960		739.6	376
516	GEDIZ River.-GEDIZ KOP.	24.06.1960	01.10.1969	3265.2	376
517	DEMIRCI Creek.-SARAYCIKHAMAMI	26.06.1960	01.06.1970	757.6	269
518	GEDIZ River.-MANISA KOP.	09.02.1962		15616.4	23
519	KUM Creek.-KEMIKDERE	01.01.1963	01.10.1964	3180.0	71
520	GORDES Creek.-COMLEKCI	01.10.1968	01.10.1978	1470.4	120
521	DERBENT Creek.-HACILILAR KOP.	18.11.1968	10.04.1969	544.4	181
522	DEMIRCI Creek.-BORLU KOP.	01.06.1970		818.8	245
523	GEDIZ River.-ACISU	01.10.1969		3272.4	373
524	MURAT Creek.-SAZKOY	01.10.1972		176.0	790
525	YIGITLER Creek.-YIGITLER	07.11.1974		64.0	165
526	ALAŞEHIR Creek.-BAKLACI	10.04.1969	10.11.1989	1613.6	145
527	GORDES Creek.-DARIBUKU	01.10.1978		1430.5	123

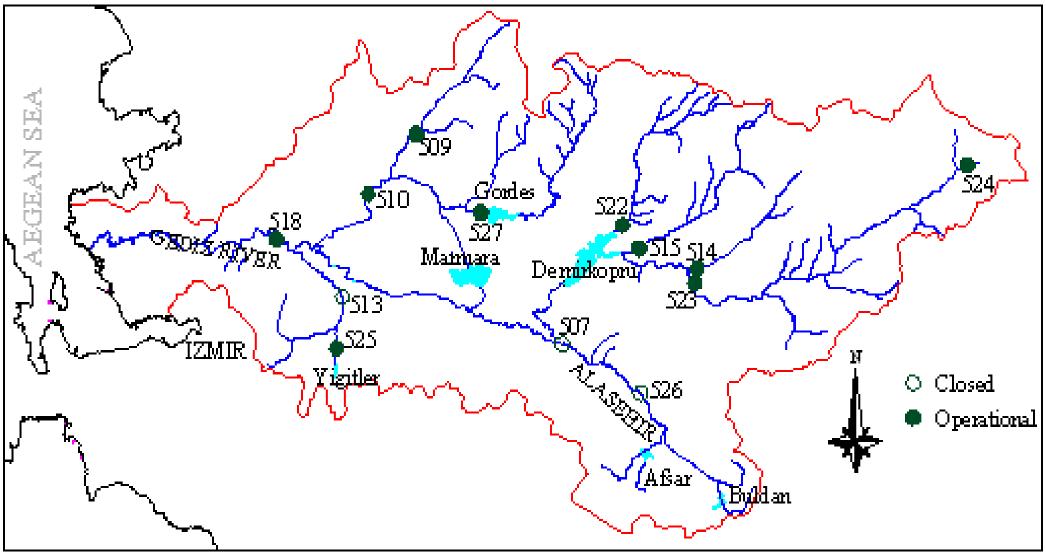


Figure 4.1 EIE monitoring stations evaluated in the optimization analyses.

4.3 Application of the Stream Orders Method (Sanders Method) to Gediz River Basin and Comparison with the Existing EIE SGS Network.

4.3.1 A Previous Study by Cosak (1999)

Application of the stream ordering procedure, i.e., identification of steam order numbers and the determination of hierarchical levels, was accomplished by Cosak (1999) in the Gediz River Basin. The study was carried out, using basin maps with a scale of 1/250 000. As a result, the stream order number of the reach near the Aegean Sea was obtained as 119. 4 hierarchical levels were determined, and 16 preliminary station locations were identified. Station locations and their hierarchical levels as specified by this study are presented in Figure 4.2.

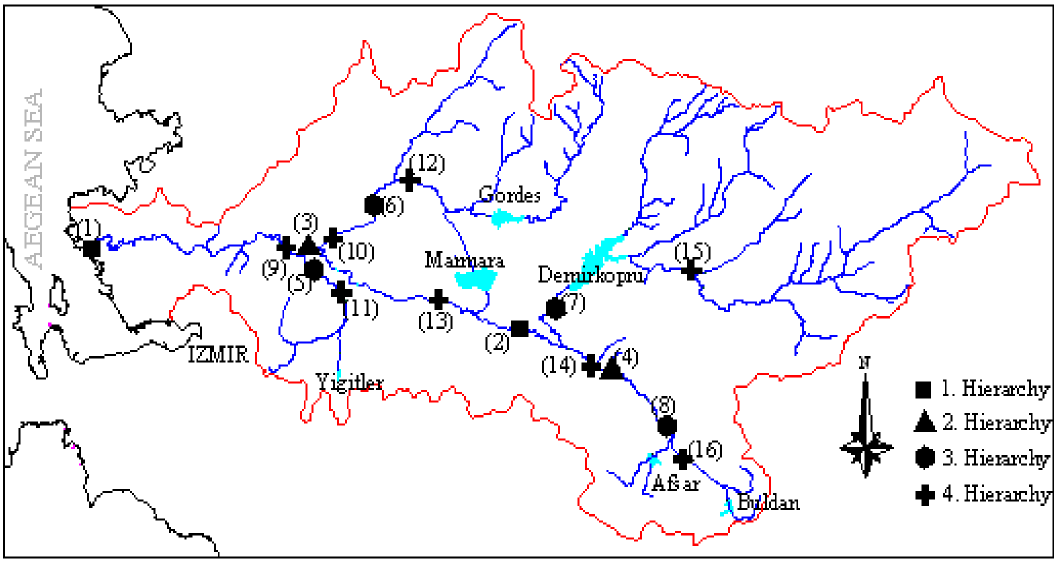


Figure 4.2 Preliminary station locations and their hierarchical levels identified by Coşak (1999)

4.3.2 Results Obtained by the Stream Ordering Approach

Hierarchical levels and station locations identified by Cosak (1999) have been used in this study for the preliminary analysis of EIE SGS network on Gediz River. To this end, 16 station locations derived through the stream ordering approach and the existing SGS network of EIE with 13 stations were compared as in Figure 4.3. This comparison has led to the following results:

- On the basis of the stream ordering approach, existing stations 510, 518 and 527 should be preserved in network.
- Stations 514 and 523 are located close to a 4th hierarchical level station; however, as these stations gage two main tributaries that feed Demirkopru Dam, both of them should be retained in network.
- Stations 513 and 526 are closed in the existing network; however, they are located close to the preliminary stations allocated by the stream ordering method and should restart operation.
- A SG station should be operated at the outlet of the basin.
- A station is needed at the junction of main Gediz River and the Alaşehir tributary.

- Station 524 on Murat Stream should be re-evaluated; it may be discontinued if there is no specific purpose in operating this station.
- The rest of the existing stations (509, 515, 522 and 525) should be re-evaluated for discontinuance on the basis of their operational purposes.

In summary, the stations close to the first, second and third hierarchical levels have the highest priorities; accordingly, the stations 518, 507 and 510 should be definitely kept in the network On the other hand, stations 509, 515, 522, 524 and 525 are situated at lower hierarchical levels so that a decision maker may have to assess the operational status of these stations in a network reduction attempt.

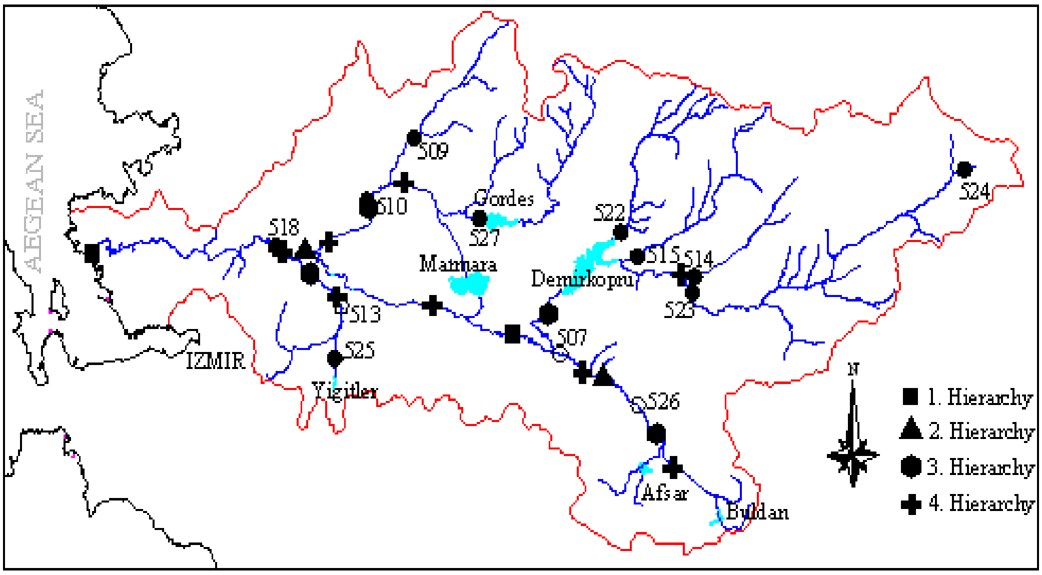


Figure 4.3 Existing and closed SG Stations of EIE (numbered) and preliminary allocated station locations by the Stream Ordering Method.

4.4 Application of the Dynamic Programming Approach of Lettenmaier et. al. (1984) to the Gediz River Basin

The dynamic programming approach explained in Chapter 3 is applied to the SGS network in the Gediz basin, which comprises 13 gauging stations operated by EIE. The application of the network optimization methodology comprises the basic steps described in the previous chapter. Initially, Gediz Basin is divided into hydrologic subbasins, each of which has at least one station in operation. Next, the hierarchical structure of the existing stations in the subbasins is identified, and the possible combinations of stations to be retained in the network are determined through the use of stream order numbers (Cosak, 1999). Data representing the attributes of stations are prepared, and uniformized total scores of station combinations are computed. Finally, dynamic programming is applied to optimize the reduced network, and the stations to be retained in the network are determined.

4.4.1 Determination of Primary Subbasins

The determination of primary subbasins in Gediz is realized by using GIS facilities. To this end, the 90 m x 90 m resolution SRTM digital elevation model (DEM) of the basin is obtained through the Internet, which is then resampled into 180 m x 180m resolution to achieve more rapid results. Through the use of this new DEM, the river network and subbasins in the basin are derived via the GIS software called Idrisi Klimanjaro, as shown in Figure 4.4. Here, some subbasins had to be merged to preserve at least 1 station in each subbasin so that, finally, 6 primary subbasins were specified for the optimization procedure (Figure 4.5). On the other hand, the very downstream regions of the basin close to the Aegean Sea were neglected due to errors encountered in the pit removal phase of DEM development. Yet, the optimization approach depends solely on the upstream specifications of stations so that this issue does not create a problem in application of the procedure.

The specified subbasins and their gauging stations are summarized Table 4.2. The first subbasin, which covers the downstream part of Gediz, has only one station labeled as 518. Kumcay, Medar and Gordes tributaries are merged into one subbasin with three stations, 509, 510 and 527. The middle part of Gediz River and Alasehir subbasin are also combined to arrive at two stations on the Alasehir tributary: 507 and 526. Nif is another subbasin with two stations 512 and 525, with the latter situated on Yigitler Creek. Demirci, Deliinis and Selendi tributaries are considered in another subbasin which has the stations 514, 515 and 522. The subbasin of Murat tributary is also considered as one of the 6 subbasins, with stations 523 and 524.

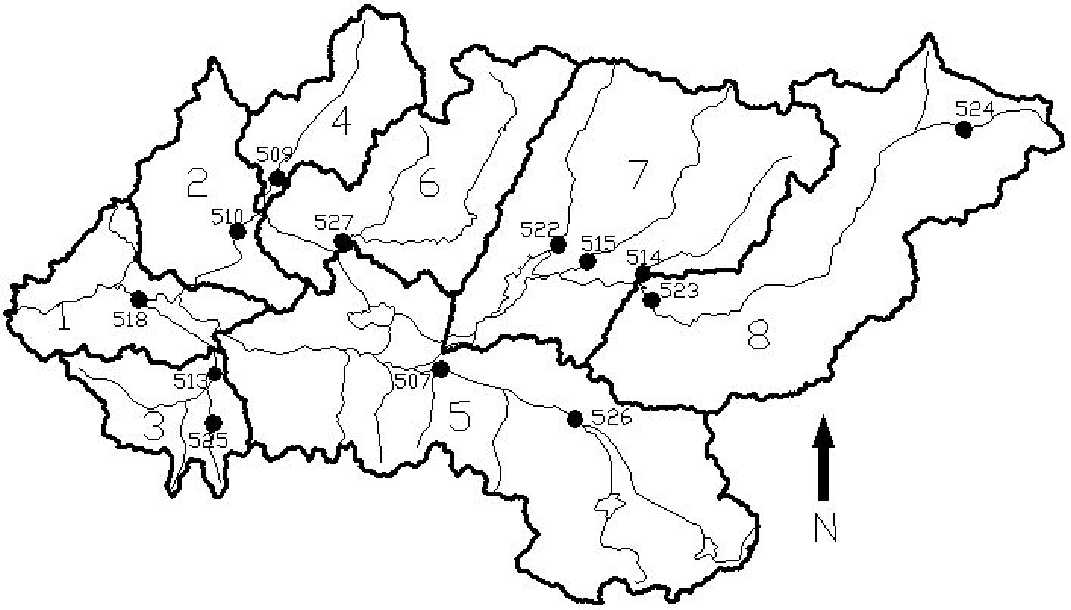


Figure 4.4 River network and subbasins derived from the 180mx180m DEM

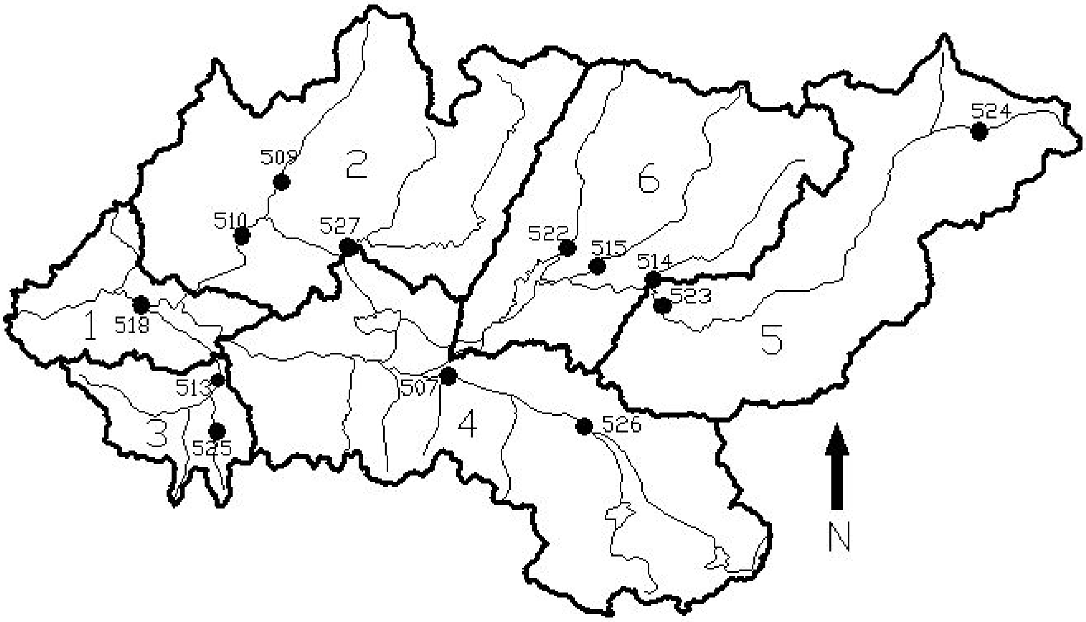


Figure 4.5 6 subbasins and their SGS in the Gediz Basin.

Table 4.2 Gediz subbasins and the SGS in each subbasin

Subbasin	**Stations**
1 (Manisa)	518
2 (Kumcay)	509-510-527
3 (Nif)	513-525
4 (Alasehir)	507-526
5 (Murat)	523-524
6 (Selendi, Deliinis, Demirci)	514-515-522

4.4.2 Alternative Station Combinations

In the next step of the study, the hierarchical structure and the station combinations for each subbasin are derived as shown in Table 4.3. The hierarchical structure mentioned in the left column of Table 4.3 indicates the upstream-downstream type of relationship between the stations in each subbasin. The station combinations are derived, regarding the highest sum of the stream order numbers identified for the stations. Lettenmaier et. al.'s (1984) approach described in the previous chapter is adopted in determining the combinations of stations for the 6 subbasins.

4.4.3 Definition of Station Attributes

Each station in a monitoring network must be identified with its attributes that comply with basin management objectives and the relevant operational goals of the network. These attributes may be selected as the drainage area, population, irrigation area etc., considering the physical conditions that affect the monitoring station. Number of observations, length of the observation period, and similar attributes may be selected to define station specific characteristics.

Regarding the goals of the existing SGS monitoring network of EIE (i.e., gathering data for determination of water potential and statistical analyses of hydrologic phenomena), two different sets of attributes are considered for purposes of the optimization procedure. The first set of these attributes are oriented on general data and physical features of the station, whereas the second set focuses on "metadata" of the station and gathered data. The purpose of this categorization is to assess the impacts of attribute selection. One may refer to section 3.4.6.1 of the study for a further discussion of the attribute selection phase. The first set of attributes is as follows:

Table 4.3 Subbasins and station combinations in the Gediz Basin

Subbasin	**Hierarchical relation and combinations**
1 P = 1	518
2 P = 3	527 → 510 509 → 510 Combinations: 510 (1) 510-509 (2a) 510-527 (2b) 510-509-527 (3)
3 P = 2	525 → 513 Combinations: 513 (1) 513-525 (2)
4 P = 2	507 → 526 Combinations: 507 (1) 507-526 (2)
5 P = 2	523 → 524 Combinations: 523 (1) 523-524 (2)
6 P = 3	514 515 522 Combinations: 522 (1) 522-514 (2a) 522-515 (2b) 522-514-515 (3)

Drainage Area: Drainage area is the area (km^2) that feeds the SGS. This attribute also indicates the area where other attributes are also effective as the latter depend on the drainage area.

Length of the observation period: This refers to the total observational period of a station in terms of years. Stations with longer periods of records are preferred.

Number of observations: Number of historic samples collected at a station is significant in terms of the information produced by that station, e.g. for statistical analyses; thus, stations with higher numbers of observations are preferred.

Long-term Mean Discharge: Mean discharge is important for the determination of water potential at a particular section of the river represented by the SGS; thus, it affects the preferable location of a station when possible sites are considered within a problem-oriented approach.

Instant peak flow: This attribute may be useful for purposes of statistical analyses.

The second set of attributes is as follows:

Length of the observation period (Oper): The same attribute is also considered for the first attribute set as explained above.

Continuity (Cont): The continuity of a station is defined as:

$$Cont = 1 - \frac{DWO}{TD} \tag{4.1}$$

where DWO is the "days without observation" and TD is the "total number of the days in observation period.

Technology (Tech): This attribute defines the monitoring technology used at the station such satellite remote sensing, limnigraph etc. The value is 0 for old-style conventional stations or 1 for stations with limnigraphs as in the Gediz case of the EIE network.

Project orientation (Pro): This attributes takes on the value 0 for stations which are not supposed to collect data for a specific project, and 1 for vice versa.

Coefficient of variation of observed floods (Cv): This is the Cv value of the observed floods at the station.

Coefficient of skewness of observed floods (Cs): This is the Cs value of the observed floods at the station.

Flood level exceedance (FEx): This attribute defines the number of floods in history exceeding a certain level to cause harm downstream of the SGS; however, despite its usefulness, no data are available on this attribute in the Gediz Basin. Therefore, it is neglected in application of the method.

4.4.4 Normalization and Uniformization of Station Attribute Values

As indicated previously, the methodology adopted by Lettenmaier et al. (1984) had the property that all the values computed for attributes should be approximately uniformly distributed in the interval (0, 100). To achieve this, a uniform distribution is attained by an inverse normal transformation of all attributes of the stations as explained in Section 3.4.6.3. Table 4.4 shows the numerical values of the first set of attributes for each station that are processed in the optimization procedure.

The normalization of the first set attribute values is realized through the standard Box-Cox transformation, and the normalized values of the attributes are further uniformized through the basic theorem of Probability-Integral Transformation. This theorem simply relates to the equality between the cumulative distribution function $F(x)$ of attribute data ($x = SR_{j(i)kl}$), which is normal, and the cumulative distribution function $F(y)$ of the line ($y = SU_{j(i)kl}$), which is uniformly distributed. The normalized and uniformized attribute "scores" ($SU_{j(i)kl}$) for Gediz SGS are given in Table 4.5. The network reduction procedure is based on the optimization of these scores.

Table 4.4 The first set of attributes of SGS in the Gediz Basin

Station ID No:	Drainage Area (km^2)	Number of Observations (days)	Operational Period (years)	Long-term Mean (m^3/s)	Instant Peak Flow (m^3/s)
507	2,512.8	3,241	10	12	480
509	901.6	13,095	42	3	433
510	3,184.8	12,266	42	6	1,494
513	690.4	2,098	5	4	512
514	689.6	10,950	37	3	860
515	739.6	10,953	36	3	1,025
518	15,616.4	11,928	39	42	812
522	818.8	7,655	30	3	890
523	3,272.4	9,059	31	10	1,290
524	176.0	8,034	28	2	100
525	64.0	6,998	25	1	153
526	1,613.0	4,745	19	1	404
527	1,430.0	4,316	21	5	1,555

Table 4.5 The first set attribute scores for Gediz SGS, obtained through normalization and uniformization within the interval 0 – 100.

Station ID No:	Drainage Area	Number of Observations	Operational Period	Long-term Mean	Instant Peak Flow
507	73.440	9.422	7.584	85.710	28.879
509	43.258	93.924	93.005	42.692	25.050
510	79.271	89.434	93.005	67.361	92.968
513	35.542	6.438	5.821	52.792	31.566
514	35.510	78.658	78.604	37.771	61.209
515	37.480	78.687	74.734	49.371	73.029
518	98.405	87.092	85.453	97.830	57.366
522	40.415	40.667	49.095	46.242	63.528
523	79.890	57.253	53.334	82.713	86.672
524	8.687	44.980	41.089	20.278	4.801
525	2.009	33.690	30.724	4.132	7.039
526	60.915	16.017	16.640	4.833	22.773
527	57.282	13.765	20.405	61.195	94.282

4.4.5 Network Reduction Based on the Optimization Procedure

Through the use of the optimization procedure, the number of stations in the Gediz SGS network has been reduced from 13 to 10 stations on the basis of the existing EIE network. The optimization procedure is carried out for four different scenarios based on possible basin management objectives. Each scenario comprises different weighting numbers assigned to attribute scores that are relevant to the objective to be met. The first scenario includes only the attributes of drainage area, operation period, and the total number of observations. Since flows in the Gediz are highly regulated by 3 reservoirs, this scenario may be helpful for minimizing the bias in determination of mean flows and flood discharges. The second scenario includes the long-term mean flows of stations, whereas the third scenario covers the attributes of the first scenario and the instant peak flood discharges observed during the operational period of the station. The last scenario covers all of the attributes defined above. In each scenario, the weighting numbers are varied between 0 and 1 as shown in Table 4.6.

Table 4.6 Weights assigned to station attributes for different basin management objectives (scenarios)

Attribute	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Drainage Area	1	1	1	1
Operation Period	1	1	1	1
Number of Obs.	1	1	1	1
Mean flow	0	1	0	1
Peak flood	0	0	1	1

Table 4.7 lists the 10 stations retained in the subbasins under each scenario. Stations 518, 509, 510, 507, 523, 514, 515 and 522 appear to be significant in all scenarios so that these stations should always be preserved in any probable network modification in the Gediz Basin. Station 513 is repeated in three of the scenarios; yet, stations 507 on Alasehir tributary and 513 on Nif Creek are not operational at present so that their status should be reconsidered by EIE in order to avoid spatial deficiency of the existing network. Figure 4.6 shows the stations preserved according to scenarios 1 and 2; Figures 4.7 and 4.8 represent the stations retained in the network for scenarios 3 and 4, respectively.

Table 4.7 Optimum combinations of stations to be retained in the Gediz SGS network for each basin management scenario, derived through the optimization procedure.

	Stations to be retained in the subbasin			
Subbas	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
1	**1/1** (518)	**1/1** (518)	**1/1** (518)	**1/1** (518)
2	**2/3** (509-510)	**2/3** (509-510)	**3/3** (509-510-527)	**3/3** (509-510-527)
3	**1/2** (513)	**1/2** (513)	**0/2**	**1/2** (513)
4	**1/2** (507)	**1/2** (507)	**1/2** (507)	**1/2** (507)
5	**2/2** (523-524)	**2/2** (523-524)	**2/2** (523-524)	**1/2** (523)
6	**3/3** (514-515-522)	**3/3** (514-515-522)	**3/3** (514-515-522)	**3/3** (514-515-522)

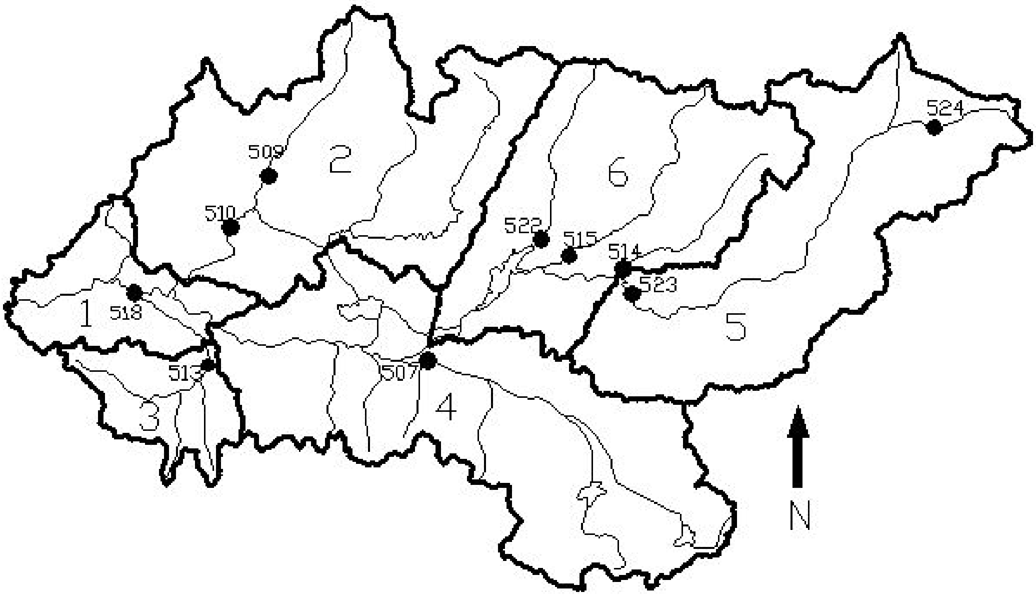


Figure 4.6 Stations to be retained in the Gediz Basin according to scenarios 1and 2

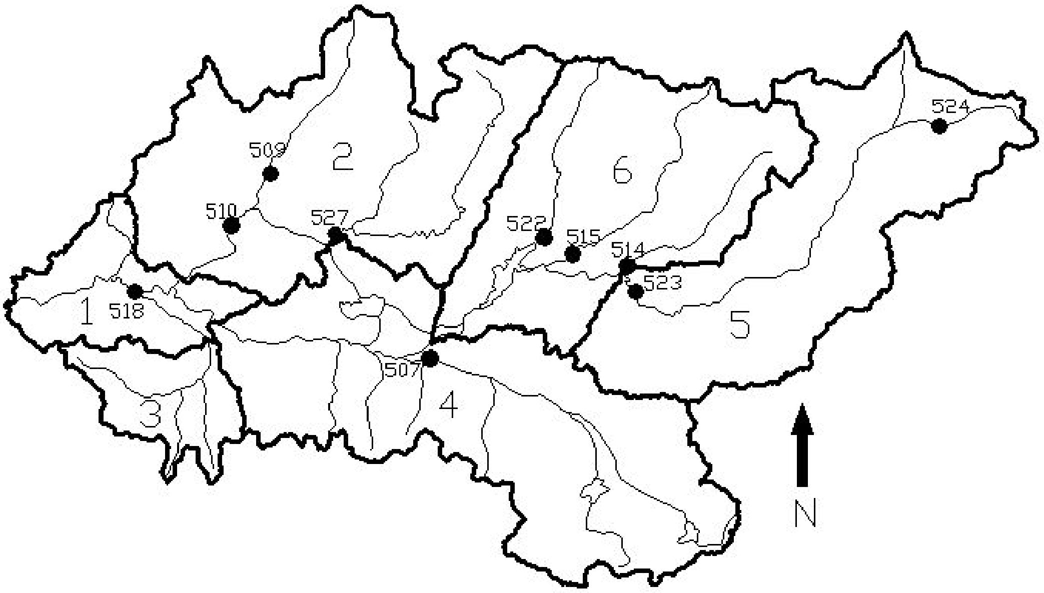


Figure 4.7 Stations to be retained in the Gediz Basin according to scenario 3

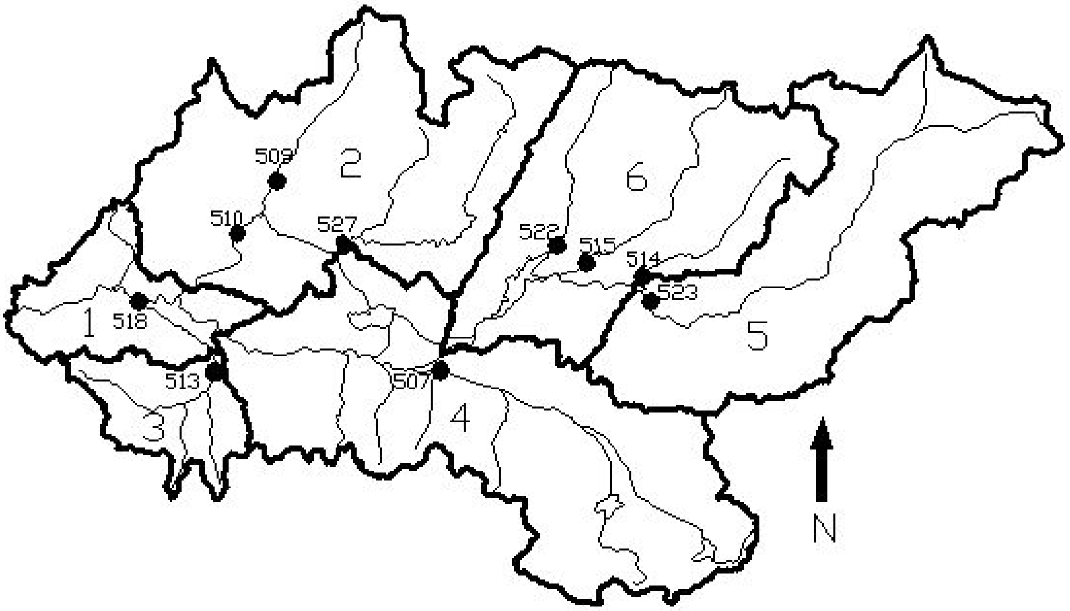


Figure 4.8 Stations to be retained in the Gediz Basin according to scenario 4

The results presented above show that some attributes such as the drainage area have dominated the selection of stations, and project-oriented SGS on small tributaries are overlooked in the network reduction attempt. Although this result reflects a preference for distributed information gathering and promotes the stations on unobserved tributaries, the reduction plan is not considered satisfactory since the above-mentioned project-oriented stations may have a higher priority than what is assigned by the methodology. Therefore, a new set of attributes has to be introduced for a better multi-criteria design to promote the above mentioned stations. On the other hand, attributes governed directly by the magnitude of the collected data are avoided in re-design efforts.

The second set of attributes (Table 4.8), which is generally based on metadata, has also been used in the optimization procedure. Table 4.9 indicates the uniformized values of the second set of attributes. For purposes of comparison with the fourth scenario considered above, the weights of the second set of attributes are defined as "1" for each attribute. The application steps of the method are repeated for the second set of attributes, and the results indicating the stations to be retained in the network are listed in Table 4.10 and presented in Figure 4.9.

Table 4.8 The values of the second set of attributes for the Gediz SGS network

Station ID No:	**Cv**	**Cs**	**OPer**	**Cont.**	**Tech**	**Pro**
507	0.78	2.09	10.00	0.53	0	0
509	0.73	1.35	42.00	0.84	0	0
510	0.87	1.67	42.00	0.79	1	0
513	0.51	0.36	5.00	1.00	1	0
514	0.79	1.23	37.00	0.97	1	0
515	0.66	0.77	36.00	0.97	0	0
518	0.55	0.68	39.00	1.00	1	0
522	0.72	1.64	30.00	0.87	1	0
523	0.74	2.19	31.00	0.99	1	0
524	0.89	3.11	28.00	1.00	1	1
525	1.08	3.61	25.00	0.97	1	1
526	0.90	1.88	19.00	0.69	0	0
527	1.01	3.37	21.00	0.75	1	1

Table 4.9 Scores of the second set of attributes for the Gediz SGS, obtained through normalization and uniformization within the interval 0 – 100.

Station ID No:	**Cv**	**Cs**	**OPer**	**Cont.**	**Tech**	**Pro**
507	48.78	63.85	7.60	52.51	0.00	0.00
509	35.44	34.45	93.02	83.60	0.00	0.00
510	69.74	47.58	93.02	78.93	100.00	0.00
513	3.71	3.74	5.84	100.00	100.00	0.00
514	51.71	29.64	78.60	96.71	100.00	0.00
515	22.20	13.08	74.72	96.74	0.00	0.00
518	6.52	10.61	85.46	100.00	100.00	0.00
522	34.39	46.36	49.06	86.99	100.00	0.00
523	38.31	67.15	53.30	99.22	100.00	0.00
524	73.79	89.06	41.05	100.00	100.00	100.00
525	96.70	94.76	30.69	97.34	100.00	100.00
526	76.79	56.03	16.63	68.61	0.00	0.00
527	48.78	63.85	7.60	52.51	0.00	0.00

Table 4.10 Optimum combinations of stations to be retained in the Gediz SGS network for the second set of attributes and their comparison with Scenario 4 stations.

	Stations to be retained in the subbasin	
Subbasin	**Scenario 4**	**Optimization of the second set of attributes**
1	**1/1** (518)	**1/1** (518)
2	**3/3** (509-510-527)	**1/3** (510)
3	**2/2** (513-525)	**2/2** (513-525)
4	**1/2** (507)	**1/2** (507)
5	**2/2** (523-524)	**2/2** (523-524)
6	**3/3** (514-515-522)	**3/3** (514-515-522)

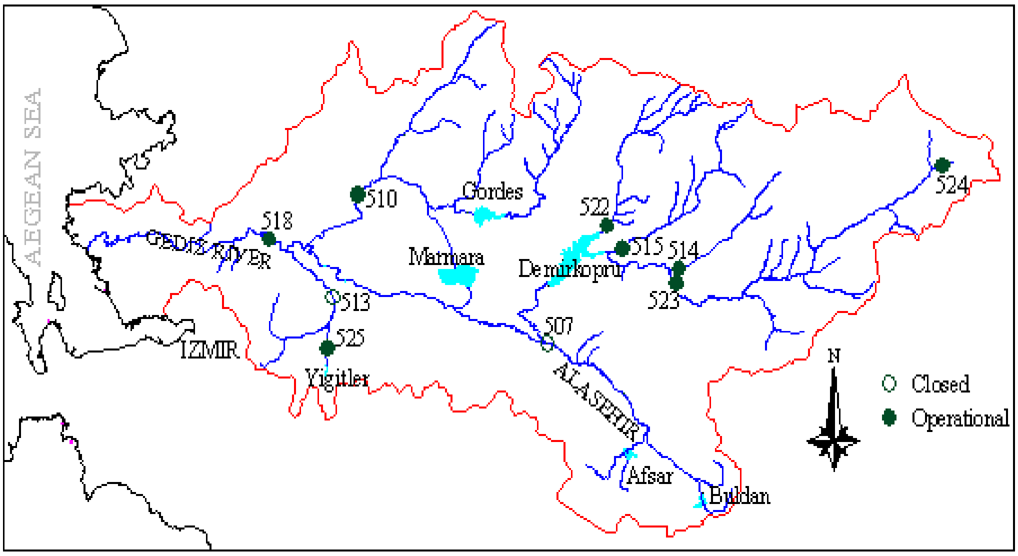


Figure 4.9 Stations to be retained in the Gediz Basin according to the second set of attributes.

The optimization results obtained through the second set of attributes differs from the previous results based on the first set of attributes. This indicates the vital importance of the selection of proper attributes in a dynamic programming approach. On the other hand, station 526 is neglected in both optimization attempts; hence, it can be concluded that the decision for closing this station is an accurate one.

In summary, the results of the dynamic programming approach for the Gediz Basin indicate that the existing monitoring stations do not sufficiently reflect the hydrological conditions over the basin. In that regard, it is important that station 507 on Alasehir tributary right before it confluences with the main Gediz becomes operational again so that flow characteristics of this tributary can be identified. For similar reasons, the monitoring agency should consider re-operating station 513 on Nif tributary. These issues essentially reflect a positive aspect of the methodology such that it permits evaluating the reliability of decisions on station discontinuance.

4.4.6 Change of Information Content With Respect to the Number of Stations Retained in the Network

One of the questions to be solved by the optimization procedures of this study is to determine the number of stations to be retained within the basin monitoring network. The establishment and operation costs of the network need to be considered with respect to the budgetary constraints of responsible agencies; hence the number of stations to be retained in the basin should be identified so as to avoid the collection of "repeated information" and thus a waste of time and money.

In the dynamic programming approach, the information produced by the retained stations in the network is defined by the cumulative sum of maximum total maximum total scores (MTMTS). This sum is derived as a result of the optimization procedure based on dynamic programming, which comprises the total scores obtained through the computation of attribute scores. According to the scenarios developed above, the MTMTS values vary with respect to the number of stations preserved in the network.

Figures 4.10 through 4.13 show the graphical representation of the results obtained for each of the four scenarios specified earlier. In the graphs, the X- axis represents the number of stations to be preserved in the network, and the Y – axis shows the MTMTS values obtained by the optimization procedure for the number of stations retained. On each graph, a parabola is fitted to the obtained curve and defined by the correlation coefficient and the regression equation to represent the relation between natural curve and fitted parabola.

Figures 4.14, 4.15, 4.16, and 4.17 denote the percentage change in information for every station added to the total network. The change in percentage is calculated by subtracting the next MTMTS value from the previous one and finding the ratio of this difference to the MTMTS value (Eq. 4.2.). Exponential curves are fitted to the natural curves presented in Figs.4.14 through 4.17. The correlation coefficients and regression equation results for the fitted exponential relations are also indicated on the figures.

$$[\mathrm{MTMTS}_{(i+1)} - \mathrm{MTMTS}_{(i)}] / \mathrm{MTMTS}_{(i+1)} \qquad (4.2)$$

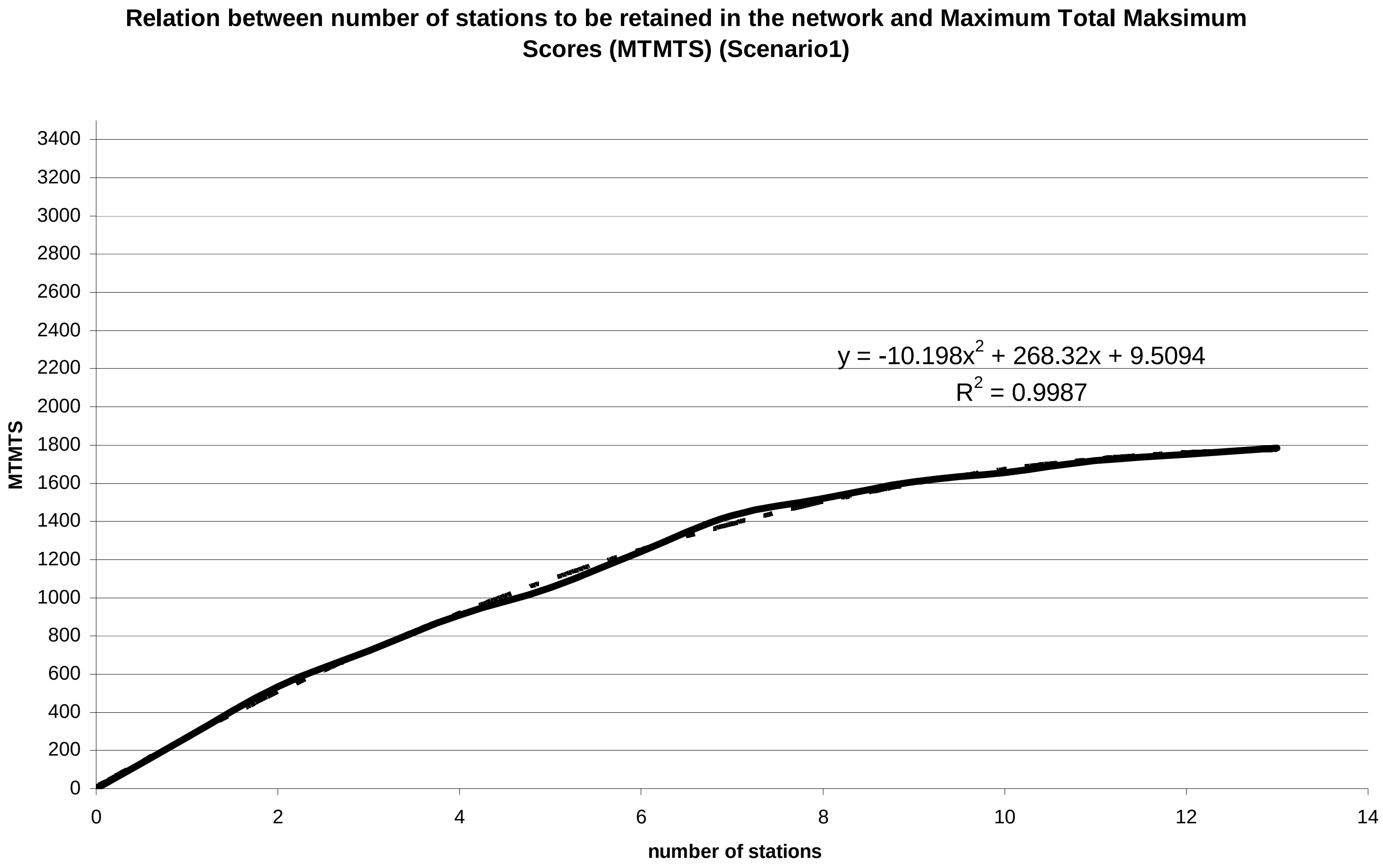


Figure 4.10 The changes in information scores with respect to the number of stations retained in the network for scenario 1 (drainage area, number of observations, operation period) Dashed line shows the fitted trend line.

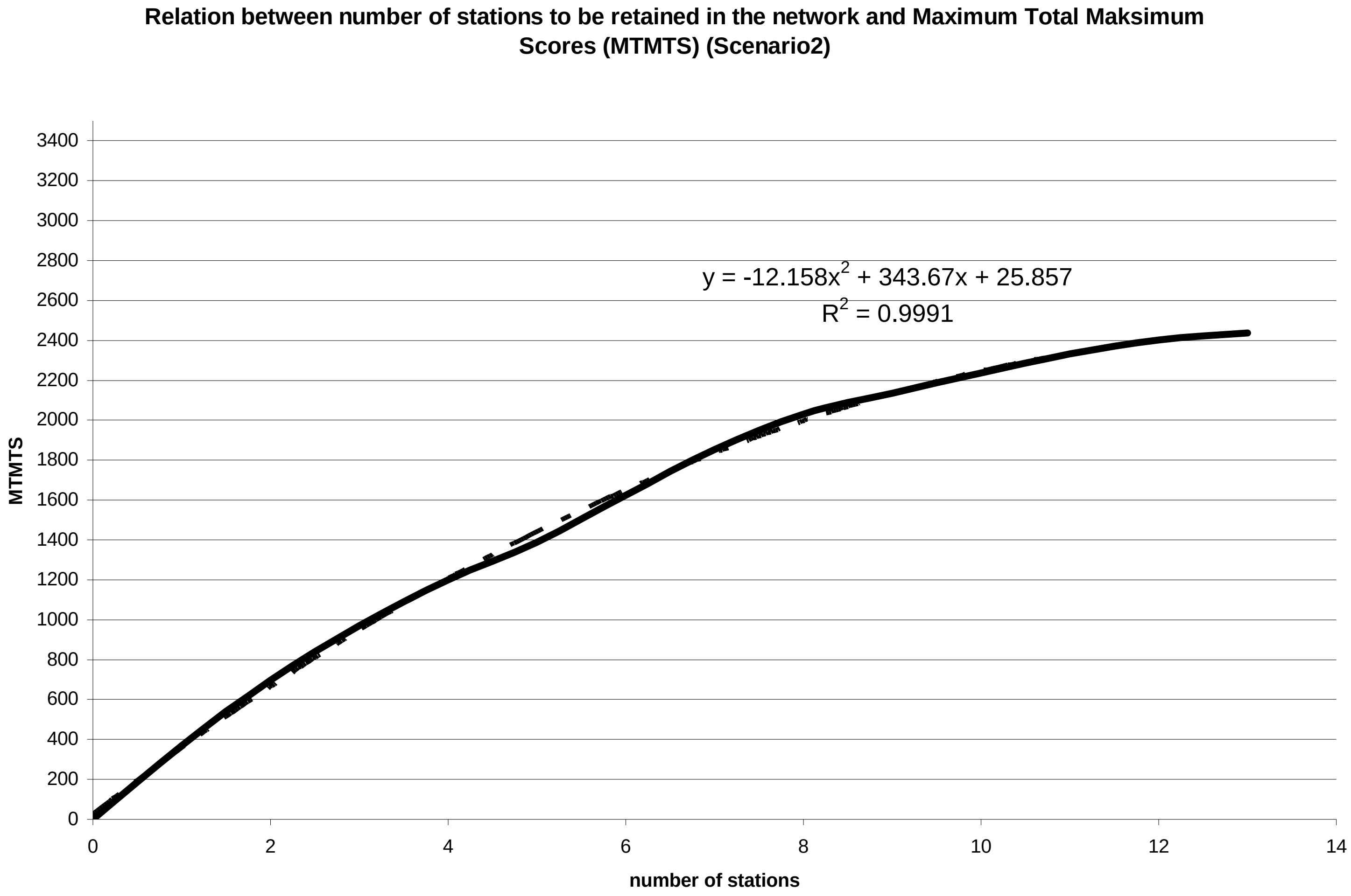


Figure 4.11 The changes in information scores with respect to the number of stations retained in the network for scenario 2 (drainage area, number of observations, operation period and mean flow) Dashed line shows the fitted trend line.

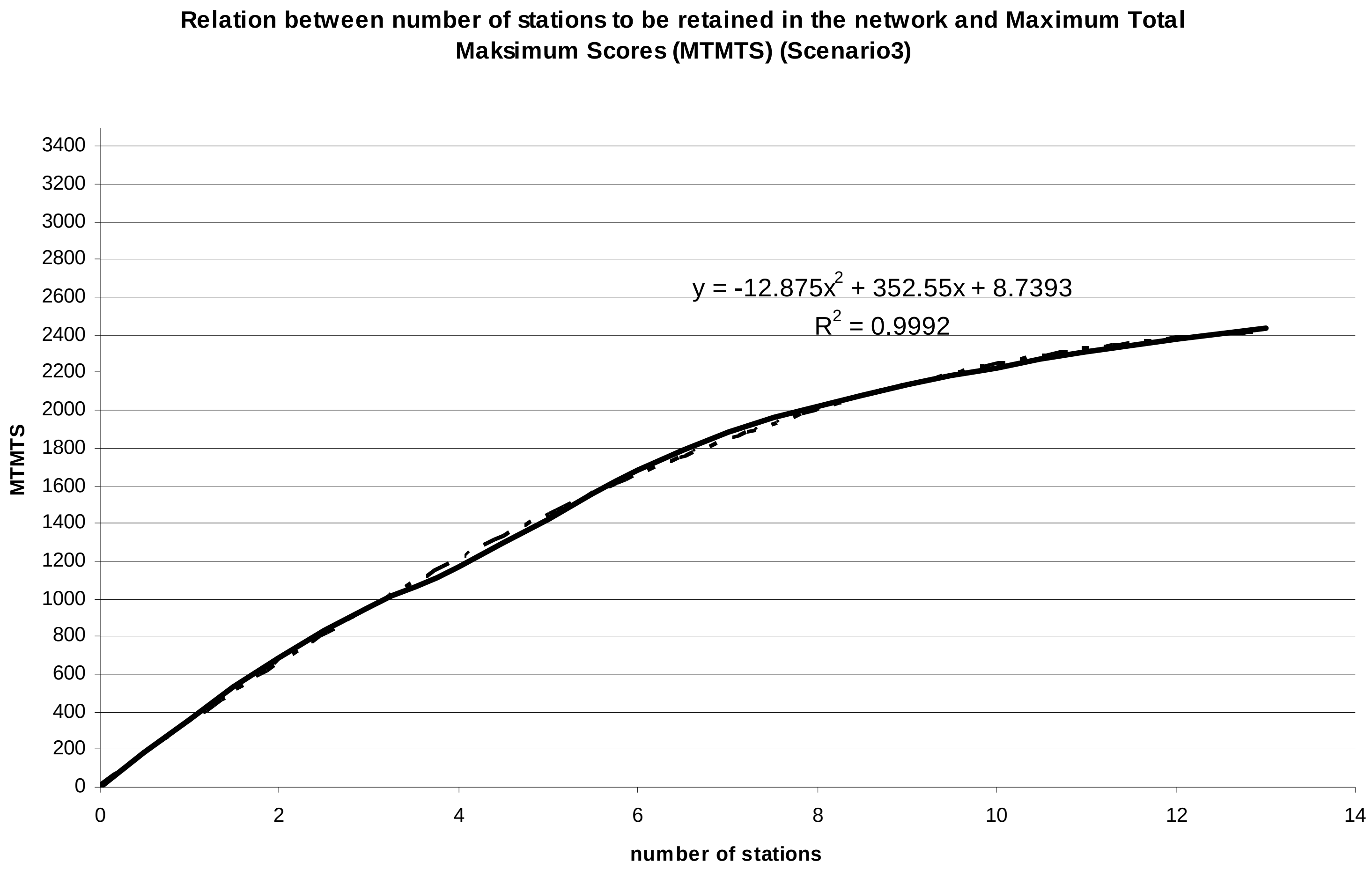


Figure 4.12 The changes in information scores with respect to the number of stations retained in the network for scenario 3 (drainage area, number of observations, operation period and instant peak flood discharge) Dashed line shows the fitted trend line.

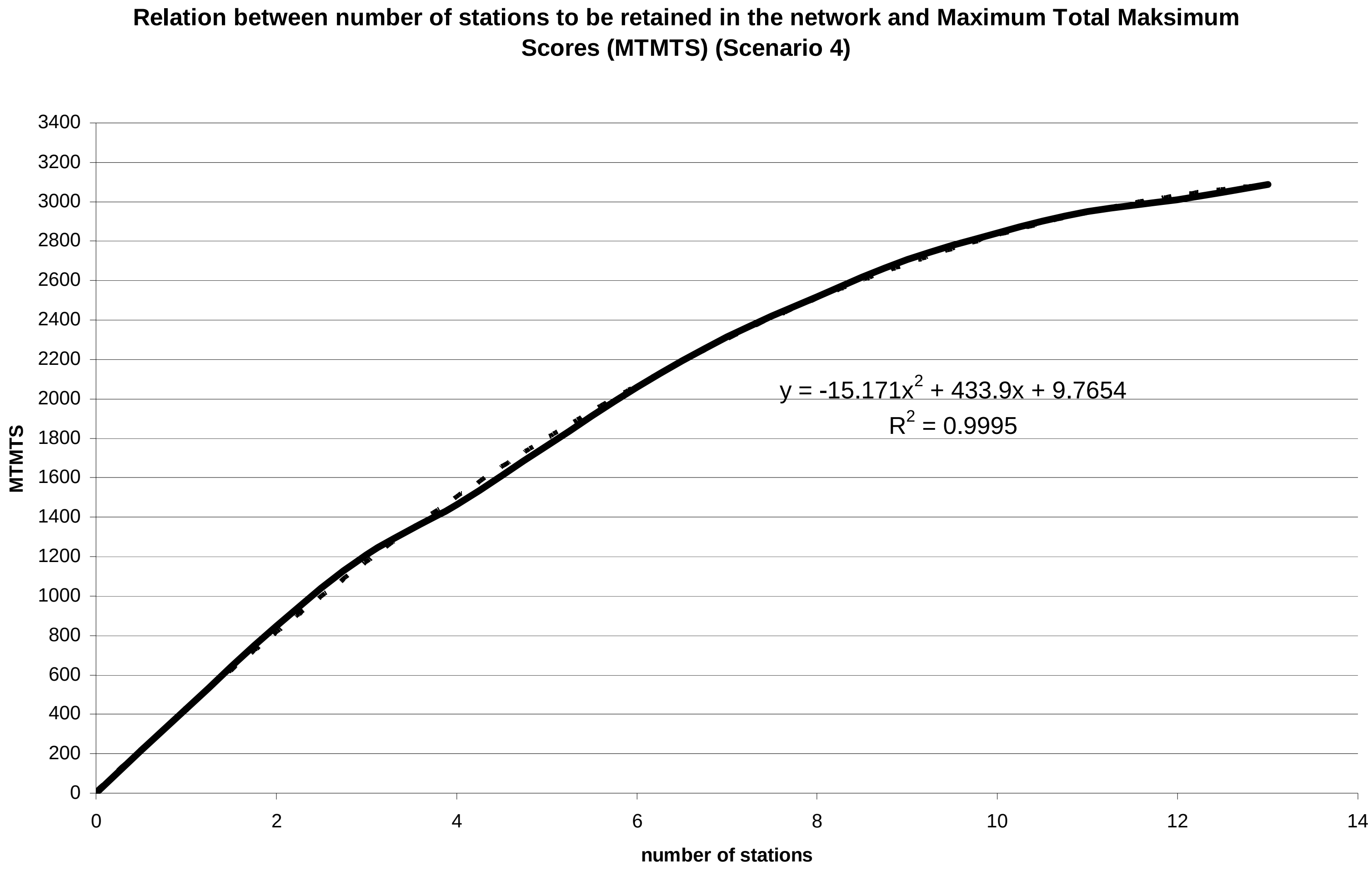


Figure 4.13 The changes in information scores with respect to the number of stations retained in the network for scenario 4 (drainage area, number of observations, operation period, mean flow and instant peak flood discharge). Dashed line shows the fitted trend line.

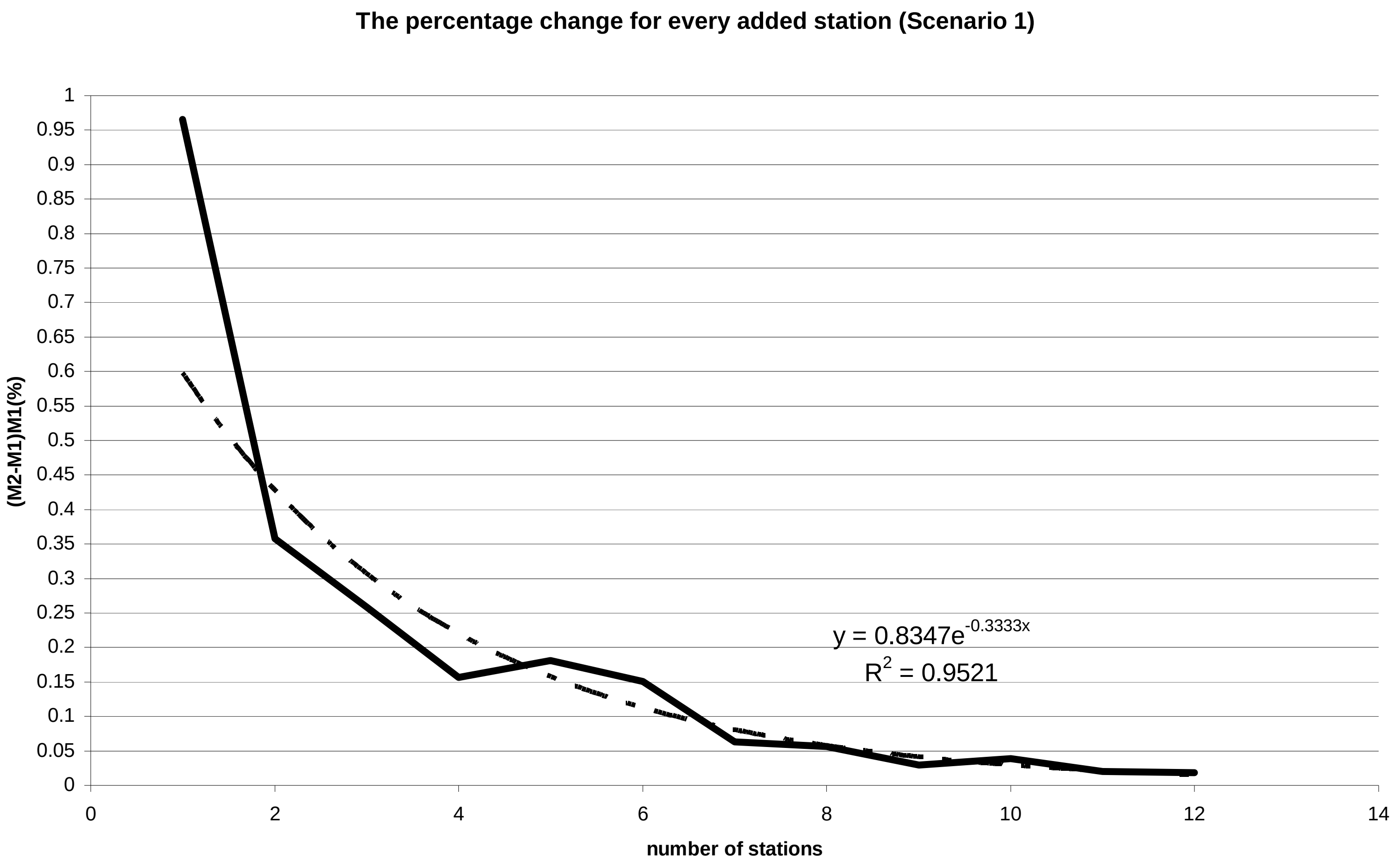


Figure 4.14 The percentage change of information with respect to the number stations retained in the network for scenario 1. Dashed line shows the fitted trend line.

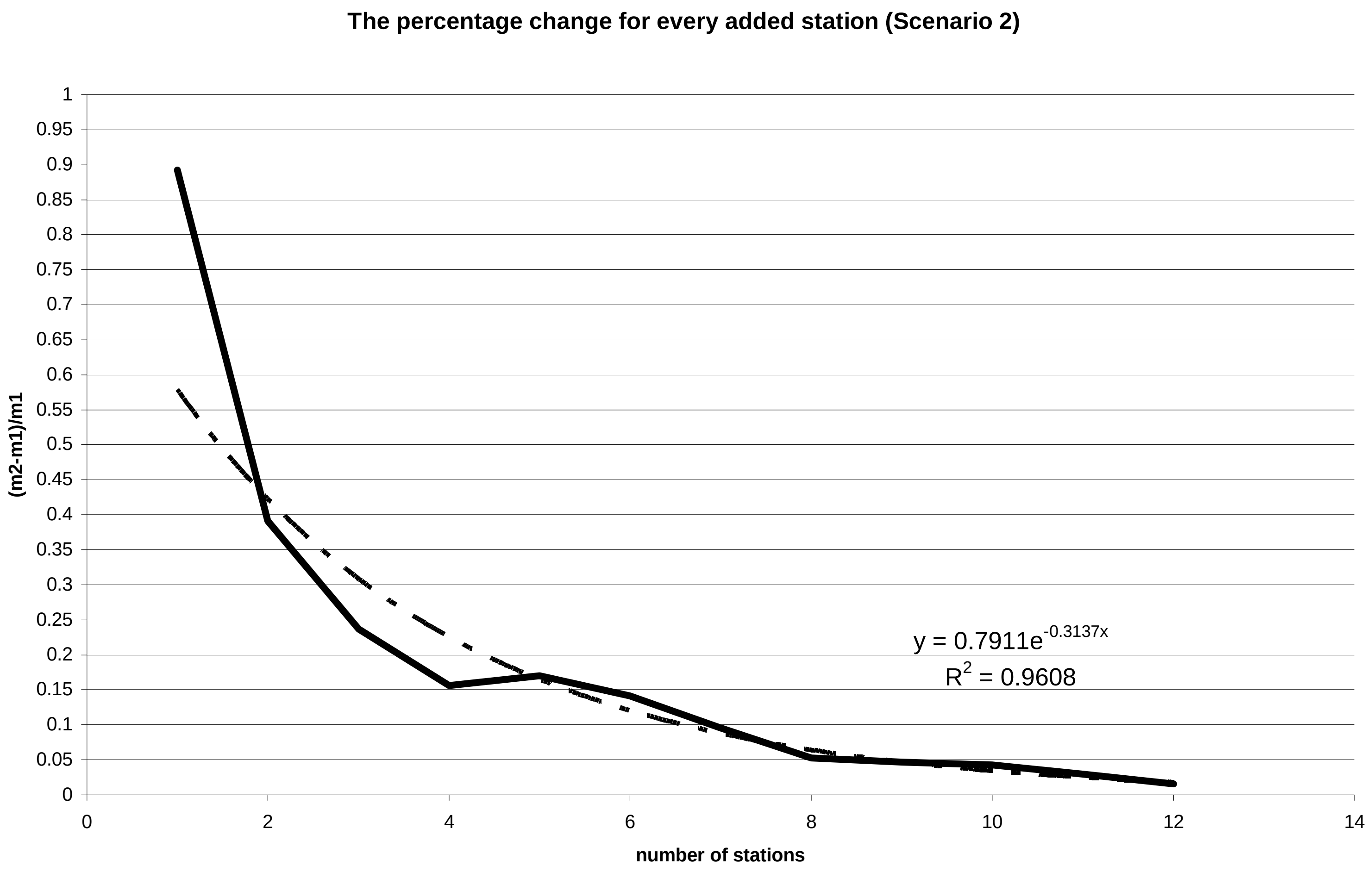


Figure 4.15 The percentage change of information with respect to the number stations retained in the network for scenario 2. Dashed line shows the fitted trend line.

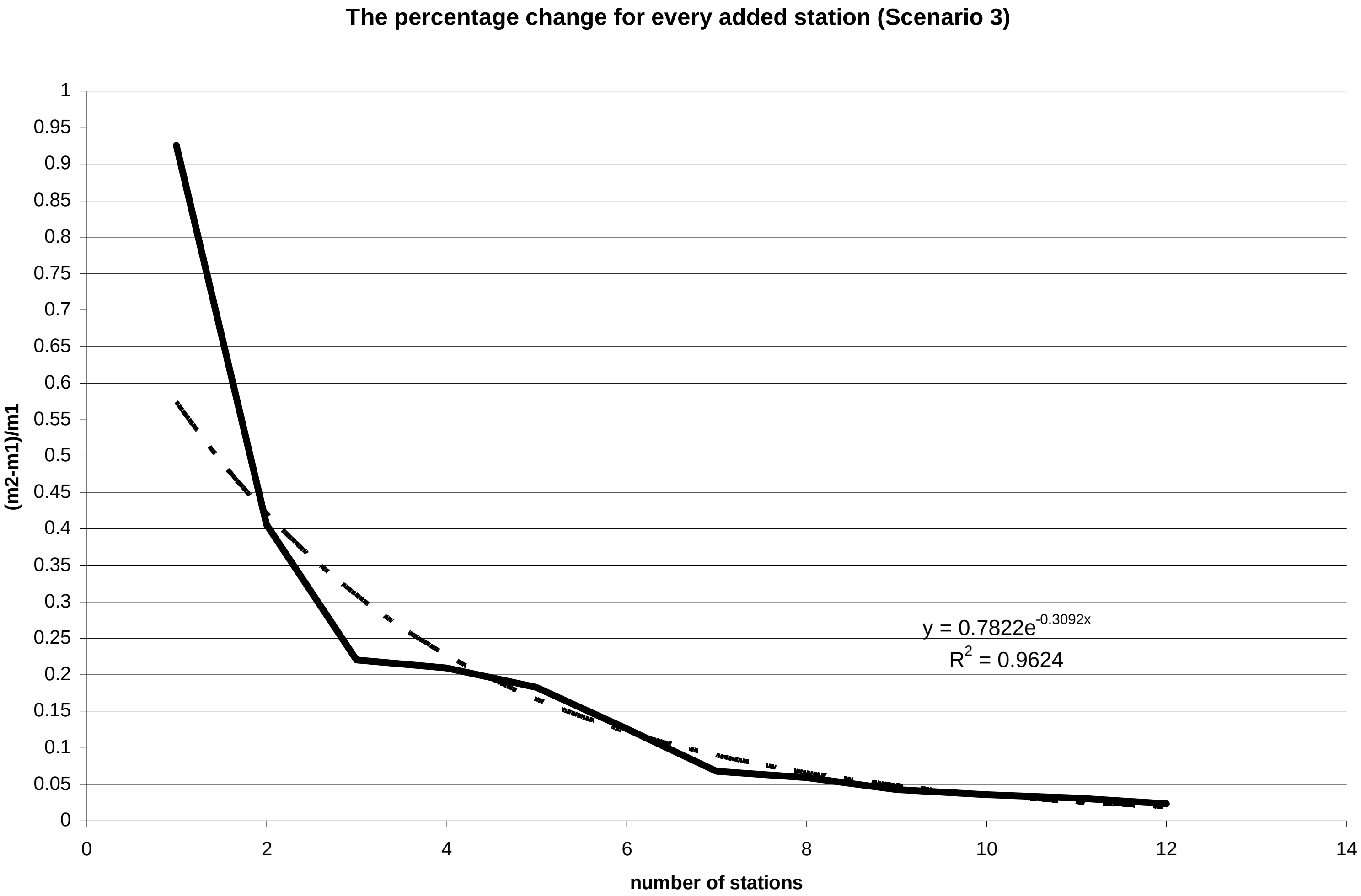


Figure 4.16 The percentage change of information with respect to the number stations retained in the network for scenario 3. Dashed line shows the fitted trend line.

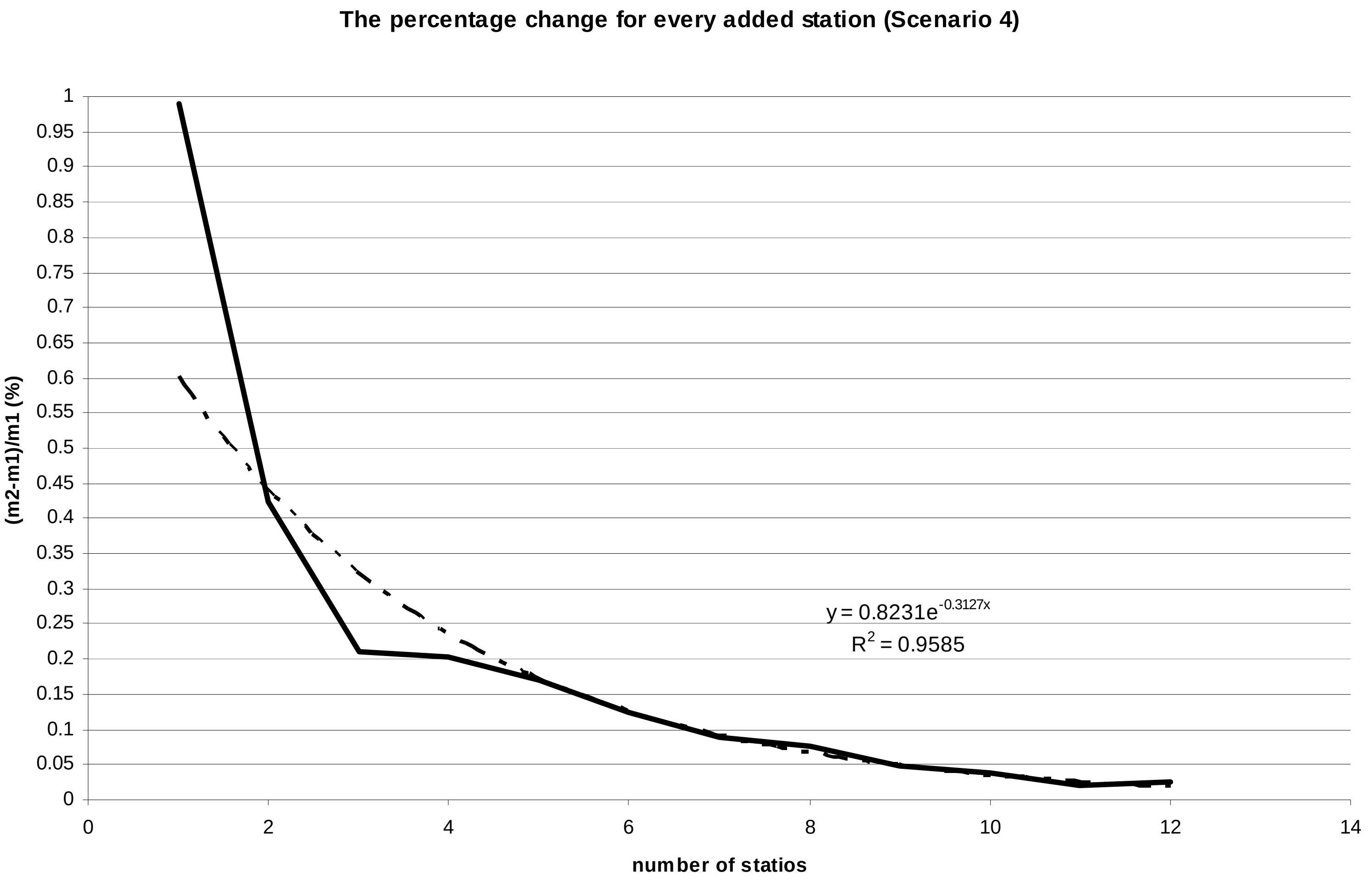


Figure 4.17 The percentage change of information with respect to the number stations retained in the network for scenario 4. Dashed line shows the fitted trend line.

In Figs. 4.10 to 4.13, the increases in total information content with respect to the number of stations retained fit second order equations with high correlation coefficients. This issue is interpreted as a reflection of the impact of cumulative drainage area characteristics of the stations. The information contents may increase due to the attributes directly or indirectly related to the drainage area, such as instant peak flow and the long-term average flow. Essentially this issue has to be investigated further through an iterative reduction of attributes to be explained more effectively.

As noted above, the graphical curves of percentage changes in information versus every station added to the network have exponential structures with high correlation coefficients. This feature may be used to determine the optimum number of stations in the network to obtain sufficient information about the river system. In each figure from 4.14 to 4.17, the slope of the tangents of the curves decrease at 7-8 number of stations; thus, the required number of stations in the network may be identified as being 8 for all management scenarios considered.

4.5 Network Reduction in Gediz River Basin by the Analytic Hierarchy Process (AHP)

As indicated in Section 3.4.6, the overall objective of the study is to solve the network reduction problem, and the AHP methodology may as well be applied to the Gediz basin by specifying a decision matrix and elicited weights for attributes defined for each station in the existing network. An issue to be considered here is that the available stream gauging network in Gediz is operated for different purposes. This is due to the fact that data needs vary along the basin; e.g., some particular stations such as 518 is operated to provide data for hydrologic budget assessments and flood modeling purposes, whereas some stations such as 525 at Yigitler Creek collect data the design and construction of specific water structures like the Yigitler Dam. Accordingly, a suitable approach to the network reduction problem can be developed by identifying a decision value tree with different hierarchical levels to cover different management objectives and criteria.

The second set of attributes mentioned in Section 4.4.3 are used in the decision making process by AHP on the basis of concerns previously mentioned, and their normalization is carried out by dividing their values by the total sum of the attribute values (Table 4.11)

Table 4.11 Normalized values (S_{ij}) of the second set of attributes for the Gediz SGS network

Station ID No:	Cv	Cs	OPer	Cont.	Tech	Pro
507	0.076	0.087	0.027	0.046	0.000	0.000
509	0.071	0.056	0.115	0.074	0.000	0.000
510	0.085	0.070	0.115	0.069	0.111	0.000
513	0.050	0.015	0.014	0.088	0.111	0.000
514	0.077	0.051	0.101	0.085	0.111	0.000
515	0.065	0.032	0.099	0.085	0.000	0.000
518	0.054	0.028	0.107	0.088	0.111	0.000
522	0.071	0.068	0.082	0.077	0.111	0.000
523	0.072	0.091	0.085	0.087	0.111	0.000
524	0.087	0.130	0.077	0.088	0.111	0.333
525	0.106	0.151	0.068	0.086	0.111	0.333
526	0.088	0.079	0.052	0.060	0.000	0.000
527	0.099	0.141	0.058	0.066	0.111	0.333
TOTAL	1	1	1	1	1	1

4.5.1 Network Reduction by a Decision Matrix

Although the decision matrix method is the simplest way of decision making for the network reduction problem, another challenge emerges during the elicitation of weights to relevant attributes. To preserve consistency in comparing the AHP results with those produced by the other methods, it is preferred herein to select the contribution of all attributes equal so that the weights are elicited as 1 / n, where n is the total number of attributes. Since 6 attributes from the second set are employed in the decision making problem, each of the six attributes has a weight value w_j of 0.16667. The priority rankings of the stations are obtained by multiplying the S_{ij} normalized attribute values by the w_j attribute weights (Figure 4.18).

$$\underset{S}{\begin{array}{c|cccccc} & \mathbf{Cv} & \mathbf{Cs} & \mathbf{OPer} & \mathbf{Cont.} & \mathbf{Tech} & \mathbf{Pro} \\ \hline \mathbf{507} & 0.076 & 0.087 & 0.027 & 0.046 & 0.000 & 0.000 \\ \mathbf{509} & 0.071 & 0.056 & 0.115 & 0.074 & 0.000 & 0.000 \\ \mathbf{510} & 0.085 & 0.070 & 0.115 & 0.069 & 0.111 & 0.000 \\ \mathbf{513} & 0.050 & 0.015 & 0.014 & 0.088 & 0.111 & 0.000 \\ \mathbf{514} & 0.077 & 0.051 & 0.101 & 0.085 & 0.111 & 0.000 \\ \mathbf{515} & 0.065 & 0.032 & 0.099 & 0.085 & 0.000 & 0.000 \\ \mathbf{518} & 0.054 & 0.028 & 0.107 & 0.088 & 0.111 & 0.000 \\ \mathbf{522} & 0.071 & 0.068 & 0.082 & 0.077 & 0.111 & 0.000 \\ \mathbf{523} & 0.072 & 0.091 & 0.085 & 0.087 & 0.111 & 0.000 \\ \mathbf{524} & 0.087 & 0.130 & 0.077 & 0.088 & 0.111 & 0.333 \\ \mathbf{525} & 0.106 & 0.151 & 0.068 & 0.086 & 0.111 & 0.333 \\ \mathbf{526} & 0.088 & 0.079 & 0.052 & 0.060 & 0.000 & 0.000 \\ \mathbf{527} & 0.099 & 0.141 & 0.058 & 0.066 & 0.111 & 0.333 \end{array}} \quad \underset{x}{\mathrm{X}} \quad \underset{W}{\begin{array}{l|l} & w_j \\ \mathrm{Cv} & 0.16667 \\ \mathrm{Cs} & 0.16667 \\ \mathrm{Oper} & 0.16667 \\ \mathrm{Cont} & 0.16667 \\ \mathrm{Tech} & 0.16667 \\ \mathrm{Pro} & 0.16667 \end{array}}$$

Figure 4.18 Multiplication of the decision matrix (stations versus the their normalized attribute values (S)) by attribute weight matrix (W).

Table 4.12 shows the results of the multiplication and the priority ranking of the stations with respect to the attribute scores. It should be noted here that such ranking is sensitive to weights elicited to the attributes, since any slight change in the decision makers' preferences may result in a different priority ranking for the stations.

Table 4.12 Priority ranking of stations by the decision matrix approach.

Station ID No:	**SxW**	**R_i**
525	0.143	1
524	0.138	2
527	0.135	3
510	0.075	4
523	0.074	5
514	0.071	6
522	0.068	7
518	0.065	8
509	0.053	9
515	0.047	10
526	0.047	11
513	0.046	12
507	0.039	13

The ranking of Gediz stations in Table 4.12 by the use of the decision matrix indicates that the three non-operational stations 507, 513 and 526 have the least priorities within the network. However, it should be noted that the above ranking may change if the decision maker such as EIE explicitly expresses his/her specific preferences for management of the network.

4.5.2 Network Reduction by a Decision Value Tree

The utilization of a decision tree allows a deeper understanding of the nature of the decision making problem. As mentioned above, the primary concern here is network reduction; however, it must also be considered that a network like that in the Gediz Basin serves different objectives in data collection. The stream gauging network in the basin includes different types of stations operated for varying purposes. Thus, there exists more than one management objective for the network, the most important ones being:

1.) Flood Management (FM): The purpose of some SGS in the network is to create an “early warning system” for areas downstream of the station. On the other hand, some stations are operated in order to obtain data for the statistical analysis of historical floods.

2.) Assessment of Water Potential (AWP): In Gediz Basin, some of the SGS on small tributaries are operated to collect data for the design and construction of dams like Gordes, Yigitler and Kelebek.

3.) Modeling and Allocation Management (MAM): In particular, stations located at the outlet of the basin or a subbasin are operated to produce data for basin modeling purposes, and collected data are used to validate the established hydrologic models, which may be utilized for water allocation strategies among different water user sectors such as irrigation, industry, etc., along the basin.

The above three objectives are regarded as "criteria" for the network reduction problem, and values of these criteria indicate the performance of stations in the network for each objective. Furthermore, such criteria may be represented by station attributes identified in earlier sections of the study.

For the Gediz case, the second set of attributes covering mainly metadata on the stations is used to determine the values of the criteria for each station. In order to define the contribution of the SGS to a specific monitoring objective, the attributes are classified in terms of the criteria as shown in Table 4.13 below.

Table 4.13 Classification of attributes with respect to criteria

Flood Management (FM)	**Assessment of the Water Potential (AWP)**	**Modeling and Allocation Management (MAM)**
Coefficient of variation of observed floods (Cv)	Project orientation (Pro)	Length of the observation period (Oper)
Coefficient of skewness of observed floods (Cs)	Length of the observation period (Oper)	Continuity (Cont)
Technology (Tech)	Continuity (Cont)	Technology (Tech)
Length of the observation period (Oper)		
Continuity (Cont)		

Some attributes such as "*technology", "length of observation period"* etc. contribute to more than one criterion, whereas some others such as *"project orientation"* and *"coefficient of skewness of observed floods"* are unique for particular criteria. Next, the stream gauging stations are interpreted as the "decision alternatives" and the decision value tree for the network reduction problem is constructed as in Fig. 4.19. The decision weights for each attribute and criteria are set equal to each other in order to obtain some comparable results with outcomes of the previously applied methods (Table 4.14).

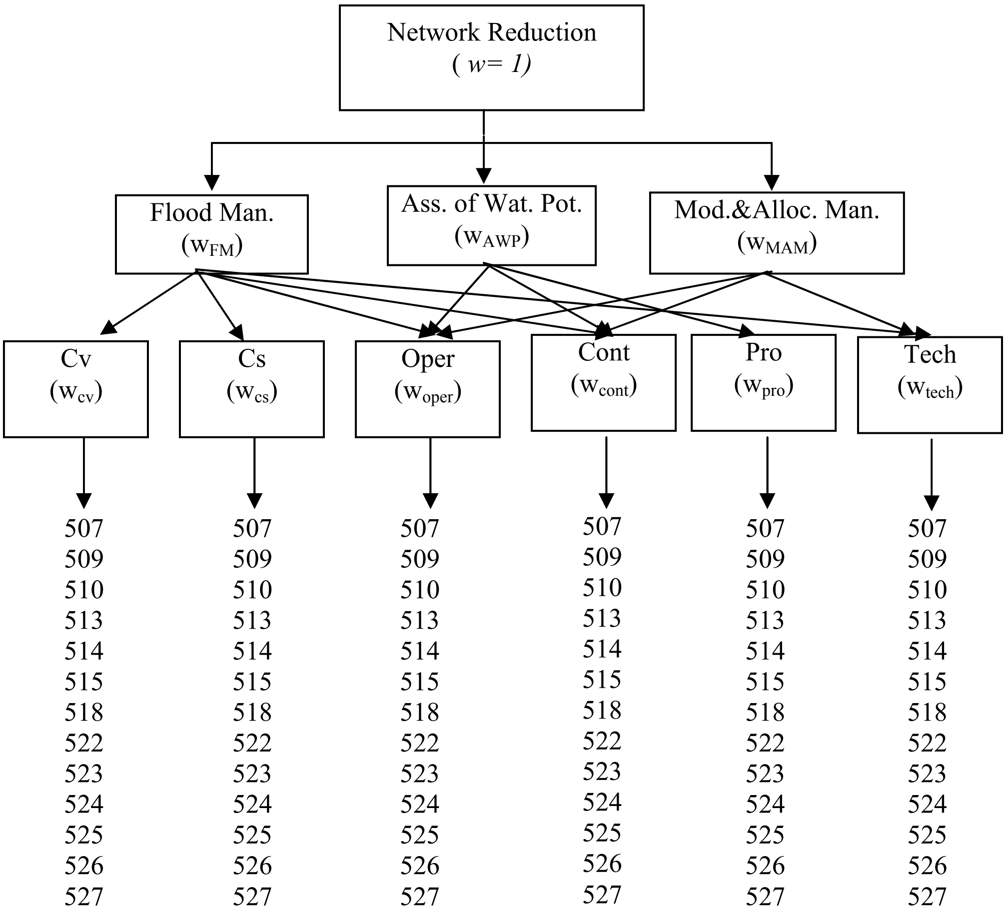


Figure 4.19 The decision value tree of the network reduction problem for Gediz Basin.

Table 4.14 Weights assigned to the criteria and selected attributes

Hierarchical Level	**Objective / Criteria / Attributes**								
1	Network Reduction ***w* =1**								
2	(FM) w_{FM} = ***0.3333***			(AWP) w_{AWP} = ***0.3333***			(MAM) w_{MAM} = ***0.3333***		
3	w_{Cv}	=	**0.2**	w_{Pro}	=	**0.3333**	w_{Oper}	=	**0.3333**
	w_{Cs}	=	**0.2**	w_{Oper}	=	**0.3333**	w_{Cont}	=	**0.3333**
	w_{Tech}	=	**0.2**	w_{Cont}	=	**0.3333**	w_{Tech}	=	**0.3333**
	w_{Oper}	=	**0.2**						
	w_{Cont}	=	**0.2**						

The computations for each hierarchical level in the decision value tree are carried out as shown in Fig. 4.20. The resulting matrix indicates the total performance of stations within the network with respect to the defined criteria, attributes and their assigned weights. Accordingly, the station with the highest value has the first rank and the station with the lowest value has the least priority in the network. The ranking order of the stations is given in Table 4.15. The results show that stations 507, 513 and 526 have the lowest priorities so that, if the network is to be reduced to 10 stations, these three stations are the ones to be closed.

$$\begin{array}{c|ccccc} \mathit{Station\ /\ Attr.} & Cv & Cs & Tech & Oper & Cont \\ \hline 507 & 0.076 & 0.087 & 0 & 0.027 & 0.046 \\ 509 & 0.071 & 0.056 & 0 & 0.115 & 0.074 \\ 510 & 0.085 & 0.070 & 0.111 & 0.115 & 0.069 \\ 513 & 0.050 & 0.015 & 0.111 & 0.014 & 0.088 \\ 514 & 0.077 & 0.051 & 0.111 & 0.101 & 0.085 \\ 515 & 0.065 & 0.032 & 0 & 0.099 & 0.085 \\ 518 & 0.054 & 0.028 & 0.111 & 0.107 & 0.088 \\ 522 & 0.071 & 0.068 & 0.111 & 0.082 & 0.077 \\ 523 & 0.072 & 0.091 & 0.111 & 0.085 & 0.087 \\ 524 & 0.087 & 0.130 & 0.111 & 0.077 & 0.088 \\ 525 & 0.106 & 0.151 & 0.111 & 0.068 & 0.086 \\ 526 & 0.088 & 0.079 & 0 & 0.052 & 0.060 \\ 527 & 0.099 & 0.141 & 0.111 & 0.058 & 0.066 \end{array} \times \begin{vmatrix} 0.20 \\ 0.20 \\ 0.20 \\ 0.20 \\ 0.20 \end{vmatrix} = \begin{array}{c|c} & FM \\ \hline 507 & 0.047 \\ 509 & 0.063 \\ 510 & 0.090 \\ 513 & 0.056 \\ 514 & 0.085 \\ 515 & 0.056 \\ 518 & 0.078 \\ 522 & 0.082 \\ 523 & 0.089 \\ 524 & 0.099 \\ 525 & 0.104 \\ 526 & 0.056 \\ 527 & 0.095 \end{array}$$

$$\begin{array}{c|ccc} \mathit{Station\ /\ Attr.} & Pro & Oper & Cont \\ \hline 507 & 0 & 0.027 & 0.046 \\ 509 & 0 & 0.115 & 0.074 \\ 510 & 0 & 0.115 & 0.069 \\ 513 & 0 & 0.014 & 0.088 \\ 514 & 0 & 0.101 & 0.085 \\ 515 & 0 & 0.099 & 0.085 \\ 518 & 0 & 0.107 & 0.088 \\ 522 & 0 & 0.082 & 0.077 \\ 523 & 0 & 0.085 & 0.087 \\ 524 & 0.333 & 0.077 & 0.088 \\ 525 & 0.333 & 0.068 & 0.086 \\ 526 & 0 & 0.052 & 0.060 \\ 527 & 0.333 & 0.058 & 0.066 \end{array} \times \begin{vmatrix} 0.3333 \\ 0.3333 \\ 0.3333 \end{vmatrix} = \begin{array}{c|c} & AWP \\ \hline 507 & 0.024 \\ 509 & 0.063 \\ 510 & 0.061 \\ 513 & 0.034 \\ 514 & 0.062 \\ 515 & 0.061 \\ 518 & 0.065 \\ 522 & 0.053 \\ 523 & 0.057 \\ 524 & 0.166 \\ 525 & 0.162 \\ 526 & 0.037 \\ 527 & 0.152 \end{array}$$

$$\begin{array}{c|ccc} \mathit{Station\ /\ Attr.} & Tech & Oper & Cont \\ \hline 507 & 0 & 0.027 & 0.046 \\ 509 & 0 & 0.115 & 0.074 \\ 510 & 0.111 & 0.115 & 0.069 \\ 513 & 0.111 & 0.014 & 0.088 \\ 514 & 0.111 & 0.101 & 0.085 \\ 515 & 0 & 0.099 & 0.085 \\ 518 & 0.111 & 0.107 & 0.088 \\ 522 & 0.111 & 0.082 & 0.077 \\ 523 & 0.111 & 0.085 & 0.087 \\ 524 & 0.111 & 0.077 & 0.088 \\ 525 & 0.111 & 0.068 & 0.086 \\ 526 & 0 & 0.052 & 0.060 \\ 527 & 0.111 & 0.058 & 0.066 \end{array} \times \begin{vmatrix} 0.3333 \\ 0.3333 \\ 0.3333 \end{vmatrix} = \begin{array}{c|c} & MAM \\ \hline 507 & 0.024 \\ 509 & 0.063 \\ 510 & 0.098 \\ 513 & 0.071 \\ 514 & 0.099 \\ 515 & 0.061 \\ 518 & 0.102 \\ 522 & 0.090 \\ 523 & 0.094 \\ 524 & 0.092 \\ 525 & 0.088 \\ 526 & 0.037 \\ 527 & 0.078 \end{array}$$

Figure 4.20 Computation of station ranks for the network reduction process by AHP.

$$\begin{array}{c|ccc|} \mathit{Station\ /\ Attr.} & \mathit{FM} & \mathit{AWP} & \mathit{MAM} \\ \hline 507 & 0.047 & 0.024 & 0.024 \\ 509 & 0.063 & 0.063 & 0.063 \\ 510 & 0.090 & 0.061 & 0.098 \\ 513 & 0.056 & 0.034 & 0.071 \\ 514 & 0.085 & 0.062 & 0.099 \\ 515 & 0.056 & 0.061 & 0.061 \\ 518 & 0.078 & 0.065 & 0.102 \\ 522 & 0.082 & 0.053 & 0.090 \\ 523 & 0.089 & 0.057 & 0.094 \\ 524 & 0.099 & 0.166 & 0.092 \\ 525 & 0.104 & 0.162 & 0.088 \\ 526 & 0.056 & 0.037 & 0.037 \\ 527 & 0.095 & 0.152 & 0.078 \end{array} \times \begin{vmatrix} 0.3333 \\ 0.3333 \\ 0.3333 \end{vmatrix} = \begin{array}{c|c} & \mathit{Network\ Reduction} \\ \hline 507 & 0.032 \\ 509 & 0.063 \\ 510 & 0.083 \\ 513 & 0.054 \\ 514 & 0.082 \\ 515 & 0.060 \\ 518 & 0.082 \\ 522 & 0.075 \\ 523 & 0.080 \\ 524 & 0.119 \\ 525 & 0.118 \\ 526 & 0.043 \\ 527 & 0.109 \end{array}$$

Figure 4.20 (cont.) Computation of station ranks for the network reduction process by AHP.

Table 4.15 Results of decision value tree approach by AHP.

Station No:	**Score**	**Ri**
524	0.119	1
525	0.118	2
527	0.109	3
510	0.083	4
514	0.082	5
518	0.082	6
523	0.080	7
522	0.075	8
509	0.063	9
515	0.060	10
513	0.054	11
526	0.043	12
507	0.033	13
Total =	1.000	

To demonstrate the use of ratio scales in preference judgements in AHP, three criteria, i.e.,“flood management”, “assessment of water potential” and “modeling & allocation management”, are evaluated within a preference matrix through the use of Saaty’s scale explained in Table 3.1 (Saaty, 1980). Since the other network operator in Gediz, i.e., DSI, has an “early flood warning system” called “TEFER” with some stations along the basin, “assessment of water potential” criterion is regarded with *“demonstrated importance”* over the “flood management” criterion that corresponds to “7”; “modeling & allocation management” has *“absolute importance”* over “flood management" which corresponds to "9"; and finally, "modeling & allocation management" has *"weak importance"* over "assessment of water potential" that corresponds to "2" in the scale given in Table 3.1. Figure 4.21 demonstrates the computation of weights in a preference matrix. The values are obtained by the eigenvalue approach as explained in Section 3.4.5.2.

$$\begin{array}{c|ccc|} & FM & AWP & MAM \\ \hline FM & 1 & \frac{1}{7} & \frac{1}{9} \\ AWP & 7 & 1 & \frac{1}{2} \\ MAM & 9 & 2 & 1 \end{array} \quad = \quad \begin{array}{c|ccc|} & FM & AWP & MAM \\ \hline FM & 1 & 0.1429 & 0.1111 \\ AWP & 7 & 1 & 0.5 \\ MAM & 9 & 2 & 1 \end{array} \quad \Rightarrow$$

$$\begin{array}{c|c} & w_{ij} \\ \hline FM & 0.057 \\ AWP & 0.346 \\ MAM & 0.597 \end{array} \quad \Rightarrow$$

$$\lambda_{max} = 3.0217 \qquad CI = 0.011 \qquad CR = 0.018 \le 0.10$$

Figure 4.21 Computation of weights derived from the preference matrix as defined by the AHP scale.

The preference matrix constituted has the maximum eigenvalue of 3.0127; the consistency index CI and the related consistency ratio index RCI are computed through Eqs. 3.38 - 3.39 with the help of Table 3.2. The RCI value obtained is lower than 0.10; therefore the preference matrix is considered as a "consistent" one.

The results obtained with respect to new weights for the criteria are given in Table 4.16. Although there are slight changes in ranking of the stations, the lowest values are again encountered for the same three stations; 507, 513 and 526..

Table 4.16 Results of decision value tree approach with the weights derived from a preference matrix of AHP.

Station No:	**Score**	**Ri**
524	0.118	1
525	0.115	2
527	0.105	3
518	0.088	4
514	0.085	5
510	0.085	6
523	0.081	7
522	0.077	8
509	0.063	9
515	0.061	10
513	0.057	11
526	0.038	12
507	0.026	13
Total =	0.999	

4.6 Network Reduction by the Reference Point Approach and Its Application to Gediz River Basin

The reference point approach is explained in detail in Sections 3.4.4.4 and 3.4.6.3. The application of the method is carried out with the second set of attributes defined in the previous sections of this chapter. To deal with the incommensurability issue for the sum model employed in the method, some of the defined attributes, such as Cv, Cs, Oper are to be normalized and uniformized between the interval 0 and 1 to determine their station-specific attribute scores. However, the attributes Tech, Cont. and Pro are left as they are since their scores are already uniform. The normalization and uniformization process of the attribute set for each station is realized in the same manner as it is done in the dynamic programming approach (Table 4. 17).

Similar to the application of the AHP method, the overall objective in the Reference Point Approach is set as “network reduction”; and three criteria, “flood management”, “assessment of water potential” and “modeling & allocation management” are defined for the stations. The classification of the attributes for the related criteria is considered as same way as in the AHP method (Table 4.13). Since the method does not require any specification for the weights, the performance values of the stations are computed through the sum model given in Eq. (3. 47). Once the scores of the attributes are defined, the total score created by a station for a specific criterion is computed as the sum of the scores of the attributes classified in the context of that criterion (Table 4.18).

Table 4.17 Uniformized attribute scores (au_{ij}) of the stations.

Station	Cv	Cs	OPer	Cont.	Tech	Pro
507	0.488	0.638	0.076	0.525	0	0
509	0.354	0.344	0.930	0.836	0	0
510	0.697	0.476	0.930	0.789	1	0
513	0.037	0.037	0.058	1.000	1	0
514	0.517	0.296	0.786	0.967	1	0
515	0.222	0.131	0.747	0.967	0	0
518	0.065	0.106	0.855	1.000	1	0
522	0.344	0.464	0.491	0.870	1	0
523	0.383	0.672	0.533	0.992	1	0
524	0.738	0.891	0.410	1.000	1	1
525	0.967	0.948	0.307	0.973	1	1
526	0.768	0.560	0.166	0.686	0	0
527	0.919	0.925	0.204	0.751	1	1

Table 4.18 Sum of attribute scores (SC_{im}) for the three criteria

Station	FM	AWP	MAM
507	1.727	0.601	0.601
509	2.465	1.766	1.766
510	3.893	1.719	2.719
513	2.133	1.058	2.058
514	3.567	1.753	2.753
515	2.068	1.715	1.715
518	3.026	1.855	2.855
522	3.168	1.360	2.360
523	3.580	1.525	2.525
524	4.039	2.410	2.410
525	4.195	2.280	2.280
526	2.181	0.852	0.852
527	3.799	1.955	1.955

Considering the monitoring criteria, a perfect station should have all of its attribute scores as “1”, and the result of the sum model is the number of attributes considered within the criterion. Accordingly, a perfect station for the “flood management” criterion should have a total score of “5”, and, for “assessment of water potential" and "modeling & allocation management" criteria, a total score of "3" for each. Any station with a sum score closer to these numbers has a higher priority in the context of the specified monitoring criteria. Therefore, a hierarchical order for the stations is to be developed to help the decision maker compare different stations according to the specified criteria and delineate his/her preferences.

For multi-criteria decisions where two or more objectives are involved, the reference point for a perfect station is defined in a two or more dimensional space, where the coordinates of the reference point are regarded as the highest possible sum of each objective. For instance, for a "flood management", "assessment of water potential" and "modeling & allocation management" multi-criteria case, the decision space is a cubic volume where the boundaries are 5 for "flood management" and 3 for each of the "assessment of water potential" and "modeling & allocation management" criteria. Thus, the reference point (RP) has the coordinates {5, 3, 3} as shown in Fig. 4. 22. Just like the reference point, the stations themselves are identified as points in the cubic decision space, and their coordinates are nothing else but the SC_{im} values obtained for each criterion.

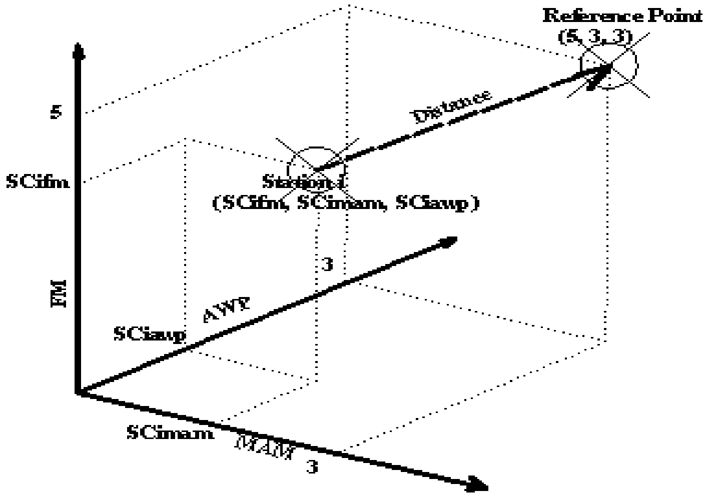


Figure 4.22 Representation of the reference point approach in a three dimensional decision space for the i-th station

The performance of any station is then measured by the distance between the reference point and the point corresponding to the i^{th} station in the decision space. The lowest distance indicates the best-performance station within the network in terms of defined criteria, and the longest distance defines the worst performing station. Table 4.19 summarizes the Euclidian distance to the reference point for each station and the ranking order (R) with respect to all the three criteria selected.

Table 4.19 Ranking of Gediz stations by the reference point approach with respect to all criteria specified.

Station	**Distance**	**R**
524	1.273	1
525	1.298	2
510	1.716	3
527	1.904	4
514	1.916	5
523	2.102	6
518	2.287	7
522	2.541	8
509	3.078	9
515	3.450	10
513	3.589	11
526	4.144	12
507	4.714	13

According to the results presented in Table 4.19, the three non-operational stations in Gediz, 513, 526 and 527, have the least priority within the network. This result was also obtained by application of the other methods in earlier sections; however, the priority ranking of the other stations is changed when the reference point approach is applied.

The same approach can be applied for a single criterion or their bi-combinations, but the analyst should take into account that the dimensions of the decision space depend on the number of criteria involved in decision making, and the coordinates of the reference points are related to the number of attributes introduced for each criterion. Tables 4.20 and 4.21 present the results of the application of the reference point approach for a single criterion and bi-combinations of criteria, respectively.

Table 4.20 Results of the reference point approach when a single criterion is defined

Order	FM		AWP		MAM	
	Station	**Distance**	**Station**	**Distance**	**Station**	**Distance**
1	525	0.805	524	0.590	518	0.145
2	524	0.961	525	0.720	514	0.247
3	510	1.107	527	1.045	510	0.281
4	527	1.201	518	1.145	523	0.475
5	523	1.420	509	1.234	524	0.590
6	514	1.433	514	1.247	522	0.640
7	522	1.832	510	1.281	525	0.720
8	518	1.974	515	1.285	513	0.942
9	509	2.535	523	1.475	527	1.045
10	526	2.819	522	1.640	509	1.234
11	**513**	2.867	**513**	1.942	**515**	1.285
12	**515**	2.932	**526**	2.148	**526**	2.148
13	**507**	3.273	**507**	2.399	**507**	2.399

Table 4.21 Results of the reference point approach for bi-combinations of criteria.

	FM-AWP		FM-MAM		AWP-MAM	
Order	**Station**	**Distance**	**Station**	**Distance**	**Station**	**Distance**
1	525	1.080	518	0.147	510	1.186
2	524	1.128	514	0.618	525	1.242
3	527	1.592	522	0.662	514	1.278
4	510	1.693	523	0.750	509	1.305
5	514	1.900	510	0.936	515	1.370
6	523	2.047	524	1.195	524	1.414
7	518	2.282	513	1.280	522	1.550
8	522	2.459	527	1.315	518	1.760
9	509	2.819	509	1.345	507	1.923
10	515	3.201	525	1.395	523	2.071
11	**513**	3.463	**515**	1.587	**513**	2.470
12	**526**	3.544	**526**	2.299	**527**	2.617
13	**507**	4.058	**507**	2.716	**526**	3.038

The results for the single criterion case presented in Table 4.20 indicate that station 507 always has the least ranking. For the “flood management” criterion, the top ranked stations are 525 and 524 with higher values of Cv and Cs of observed floods. Both stations also have the highest ranks for the “assessment of water potential” criterion due to their operational purpose. However, for the “modeling &

allocation management" criterion, station 518 attains the highest rank due to the fact that it is the closest station to the outlet of the basin. This feature also serves to validate the result obtained by the reference point method, since station 518 is the first station to be used for calibration of a water budget model for the whole basin.

The results presented in Table 4.21 indicate that station 526 has the least importance, but the other two stations to be abandoned vary due to the different needs emerging with the combination of the monitoring criteria. However, in the AWP and MAM combination, station 527 (Gordes Dam) is also abandoned although it is a high priority station for the "assessment of water potential" criterion. This is due to the fact that the operational period for this station is short, and missing data in its records decrease its continuity value. Both of these issues also underline the deficiencies in the operational policy of this station.

The design criteria used in application of all the methods above are considered as general constraints for the network reduction problem, and the assessment of the performances of stations is based on the assumption that the three criteria specified are overall measures in the decision making process. Although application of the methods above produced valid results, it does not cover all possible multi-objectives throughout the basin. If network reduction is the purpose of a re-design procedure, different objectives for each of the operated streamflow gauging stations (SGS) should be considered. The presented methods primarily tend to retain stations on the basis of weighted overall criteria for the network; yet, in many cases, decision makers do prefer keeping some specific SGS such as 515 and 527 to collect data for realization of a particular project such as the construction of a dam, weir, or power station, etc. The performances of such stations should be evaluated within the context of their operational purposes instead of rating them on the basis of all criteria.

Considering the issue above, the operational purpose of each station in the network is determined in terms of the associated criteria; and the performance of the station is evaluated in its decision space dimensioned by the related criteria. Similar to the reference point approach demonstrated above, the station that has the closest distance to its identified reference point has the first priority and vice versa. Through this approach again, a ranking order for the stations is obtained to aid the decision maker in making his/her choices for network reduction. Table 4.22 summarizes the operational purposes of Gediz stations with respect to the three defined criteria. The coordinates of the reference point for the ith station are again the numbers of the relevant attributes, which are associated with the criteria assigned to the ith station. For example, station 509 has two criteria ("flood management" and "assessment of water potential") to contribute to its operational purpose; hence, its decision space is two dimensional, and the coordinates of the reference point is defined as 5 and 3, which are the numbers of attributes involved for each criteria.

Table 4.22 Determination of the criteria associated with the operational purposes of the stations and the coordinates of the reference points.

Station	FM	AWP	MAM	Coordinates of RP
507	+	-	+	(5, 3)
509	+	+	-	(5, 3)
510	+	-	-	(5)
513	+	-	+	(5, 3)
514	-	+	+	(3, 3)
515	-	+	+	(3, 3)
518	-	-	+	(3)
522	-	+	+	(3, 3)
523	-	+	+	(3, 3)
524	+	+	-	(5, 3)
525	+	+	-	(5, 3)
526	+	-	-	(5)
527	-	+	-	(3)

The sum of attribute scores for the criteria defines the coordinates of the station in its decision space, and the distance to the reference point is computed. The results and the ranking orders of Gediz stations are presented in Table 4.23. The stations 509, 507 and 513 have the lowest ranks, and these three stations should primarily be considered in a network reduction attempt. Stations 518, 527 and 525 have the best rankings, and it can be concluded that these three stations fulfill their operational purposes better than the other stations.

The approach used above in the assessment of stations enables the decision maker to rate the performance of each station on the basis of its own operational purpose. Such an approach is especially beneficial for the study of networks which do not have a specific overall target but consist of stations with unique operational purposes.

Table 4.23 Ranking of Gediz stations with respect to station specific operational purposes

Order	Station	Distance
1	518	0.145
2	527	1.045
3	525	1.080
4	510	1.107
5	524	1.128
6	514	1.271
7	523	1.550
8	522	1.760
9	515	1.817
10	526	2.819
11	509	2.819
12	513	3.018
13	507	4.058

CHAPTER FIVE
DISCUSSION ON THE APPLIED METHODS

5.1 Method of Stream Orders

The stream ordering approach presented by Horton (1945) and employed by Sharp (1970, 1971) and Sanders *et. al* (1983) is a preliminary design method to establish a network on an ungauged stream; but it may also be used for the assessment of an existing one. The data required for application of the method is solely the river network itself, i.e, the main stream and its contributing tributaries. Such data are derived from an available map or a digital elevation model (DEM) so that stream orders and hierarchical levels are easily obtained. Sharp (1971) claims that the stream ordering methodology results in a spatially optimum distribution of stations within a network. Sanders *et. al* (1983) further indicate that the method is able to macro-locate a required number of stations in a network with respect to identified hierarchical levels, which, in turn, can be increased as much as needed and merged at where hierarchical levels coincide. On the other hand, the spatial optimality of the method as claimed by Sharp (1971) is criticized by Dixon *et. al.* (1996, 1999), who proposed a better method in their relevant publication.

Despite its advantages (e.g., minimum data requirements, ease of application, etc.), the stream ordering approach has some deficiencies to be noted. First of all, the approach does not account for any specific monitoring objective in the design and/or re-design phases. This is a major deficiency of the method since many hydrological monitoring networks are already installed in the majority of river basins in Turkey, and these networks require an assessment of their performances on the basis of their operational objectives.

Furthermore, when evaluated with respect to a network re-design process, it must be considered that the stream ordering method does not account for any station specific attributes such as station discontinuance, operational period or project orientation, etc. For example, some stations such as 525 in the Gediz Basin are operated to satisfy the data requirements for the design and construction of a water structure construction plan; yet, such stations are eliminated by the method if they are located on upstream branches of the river and thus attain low stream order numbers.

On the other hand, the stream order numbers derived for each river reach depend strictly on the scale and details of the map used. A map with a large scale may cover some minor intermittent tributaries which are then accounted for by the method; however, this results in a major change in macrolocation of the stations. The same problem occurs if a DEM is used, as in this case, the threshold value used for derivation of the river network becomes important. In both cases, the determination of the hierarchical levels and station locations depends on the availability of larger scale maps and the experience of the analyst; so that the final decision still depends on subjective judgment of the designer.

5.2 Dynamic Programming Approach

The dynamic programming approach presented in the study facilitates decision making on hydrometric network assessment and reduction. It is highly flexible in the sense that various basin management objectives can be accounted for by selecting appropriate attributes for stations and assigning weights to them in such a way as to reflect the objectives. This property is especially advantageous for network assessment purposes in view of changing basin management objectives.

On the other hand, some disadvantages of the methodology must also be mentioned. The identification of subbasins is basically based on subjective judgments and experiences on the designer’s side. Another property of the approach that is open to subjective judgments is that the stream ordering method and, thus, the identification of station hierarchies depend on the scale of the maps used or to the threshold values of digital maps. As the scale or the threshold value is decreased, the number of tributaries to be considered increases so that stream order numbers and the hierarchical ordering of the stations are changed. However, the effects of map scales may be minimized by ensuring a criterion such as the presence of a particular minimum flow in a tributary for it to be included in stream ordering.

Another feature of the dynamic programming approach which may be considered deficient is that it does not account for a hierarchical priority order of stations so that a station selected at one stage may not be preferred at another stage. That is, when the number of stations to be retained in a network is changed, one may arrive at a different combination of stations. In a way, this means that the method does not produce station-specific but combination-specific results. For example, the method operates in such a way that a station selected in a 9-station combination for the network may be excluded in a 10-station combination. This situation creates some difficulties for the decision maker and leads to confusion in evaluation of the obtained results. Furthermore, it also leads to a strict decision about the exact number of stations to be retained in the network

The weights assigned to the selected attributes on the basis of monitoring objectives (scenarios) are evaluated for the entire network along the basin. However, since some stations with local and specific operational purposes are also evaluated within the same framework, the method may as well eliminate such stations from the monitoring system. Furthermore, the method employs a complicated procedure for dynamic programming; hence, it is hard for the decision makers to understand especially when they lack sufficient scientific background on optimization methodologies.

5.3 The Analytic Hierarchy Process (AHP)

The common criticism on MCDM methods is that they focus on the adoption of a stance of a “given problem”. This criticism is also valid for the AHP methodology; yet, it provides some advantages to designers and decision makers. In particular, once the related attributes are defined and their weights are assigned, the assessment of the hierarchical priority order of the stations (alternatives) by the decision matrix approach simplifies the computations and enables rapid results. Similarly, despite its complex structure, the decision value tree approach enables a better understanding of the nature of the problem and the relevant criteria.

AHP obligates a close and interactive relation between the designer and the decision maker. This fact enables the acquisition of “desired” results rather than “forced” ones, which are perhaps the best solutions but do not reflect the tendencies and preferences of the decision makers. Moreover, the results obtained through the application of AHP are in order of priority; therefore, decision makers can be more confident in evaluating the results and can take the necessary steps to accomplish improvements towards their “desired” solution.

On the other hand, the AHP approach as applied for network assessment and reduction problem possesses the same disadvantages and deficiencies of the general methodology of AHP. The eigenvalue-eigenvector approach of the method is still controversial in literature, as indicated in Section 3.4.5.2; and there is a certain degree of opposition to the approach.

Another issue to be stressed here is related to the difficulties in weight elicitation in AHP applications. In some cases, the inconsistent nature of human rationality is reflected in the preference matrix derived through the identified relative importance scale (Table 3.5). In the case of an inconsistently elicited preference matrix, the designer should enforce the decision maker to re-examine his/her preferences with respect to the same relative importance scale. Although this situation enforces the decision maker for more realistic statements, it may also lead to a dead end for the preference matrix. Another difficulty in weight elicitation emerges with an increase in the number of criteria considered, as this increase complicates the derivation of the preference matrix. Furthermore, in case of an inconsistent matrix, the re-examination of preferences becomes more difficult for the decision maker.

Similar to the dynamic programming approach, the AHP method regards only the overall objectives and criteria which are valid for the entire network. This issue disables any performance assessment at station scale where a particular station may have been operated for local purposes instead of overall basin network objectives.

5.4 The Reference Point Approach

The reference point method provides a simple and clear decision aid to the designer and the decision maker. The method gives the designer the flexibility to use different performance assessment models such as the "sum of attribute values", as utilized in the Gediz case. The basic approach here resembles that of the decision value tree analysis; but, since the reference point methodology does not require any weight elicitation, the problems mentioned above for the AHP method are overcome. Moreover, similar to the decision value tree approach presented in the earlier section, one attribute may contribute to more than one criterion or objective, which leads to a parsimony in the number of attributes considered. This feature of the method also assists decision making in cases with limited data and metadata.

The simplicity of the method is an asset that enables a better and open relationship between the designer and the decision makers. Since the method does not require weights and preference statements by the decision makers, any increase in the number of objectives, criteria and related attributes does not complicate the decision making process. The only challenge herein is the identification of objectives, criteria and the related attributes, namely a comprehensive definition of the problem; yet, this challenge is also valid for the application of other methods used in the study.

Furthermore, through the use of the method, conflicting objectives of multiple stakeholders and decision makers may be reflected in the decision making process. The specified objectives constitute only one dimension of the decision space; hence, multiple preferences of multiple stakeholders may as well be presented at the same time, and trade-offs between the alternatives (i.e, stations) can be identified in a more transparent manner during the post decision analysis.

Similar to the AHP method, the results obtained through the application of the reference point approach are in order of priority. Furthermore, in contrast to the dynamic programming and stream ordering approaches, AHP and the reference point methods evaluate each station as a separate alternative that is not constrained by hydrological catchment or the entire river network. This feature enables the inclusion of a wider set of alternatives; therefore, the AHP and reference point methods may be used for the performance assessment of monitoring activities at larger scales such as a region or a country. This asset may assist the nation-wide monitoring network operators such as EIE and DSI in assessing their operational networks in terms of defined criteria and objectives. On the other hand, AHP considers solely the overall objectives and criteria set for the monitoring program, whereas the reference point approach is able to evaluate a single station with respect to its local operational purposes. Thus; the latter method is more suitable for network assessment purposes at regional or national scales.

On the other hand, the reference point approach has one general deficiency: If one or more coordinates of an alternative overcomes one or more coordinates of the reference point, the method still measures the distance between them; therefore, an alternative which even dominates the defined reference point may have a lesser priority than an alternative which is actually closer. In this case, one may consider two options: a) the reference point defined by the decision maker is underestimated and should be revised, b) a better performance is not expected from the alternative, and one may decide to reduce the monitoring effort, which, in general, indicates preference for cost reduction (economy) in the monitoring activity. With respect to option (a), the designer or the decision maker may set the coordinates of the reference point as the highest possible values (as in the Gediz case) or select the maximum scores for any criteria to overcome this issue and then assess the performances of the stations in this decision space.

CHAPTER SIX
CONCLUSION

In the study presented, three methodologies were investigated and assessed towards spatial optimization of hydrometric gauging networks. The third methodology based on multi-criteria decision making (MCDM) is an innovative feature of the study as this is essentially the first time MCDM is used for purposes of network reduction.

The first method based stream ordering has the advantages of minimum data requirements and ease of application. However, it also has some deficiencies to be noted. First of all, the approach does not account for any specific monitoring objective in the design and/or re-design phases. This is a major deficiency of the method since many hydrological monitoring networks are already installed in the majority of river basins in Turkey, and these networks require an assessment of their performances on the basis of their operational objectives. Furthermore, when evaluated with respect to a network re-design process, it must be considered that the stream ordering method does not account for any station specific attributes such as station discontinuance, operational period or project orientation, etc. On the other hand, the stream order numbers derived for each river reach depend strictly on the scale and details of the map used. A map with a large scale may cover some minor intermittent tributaries which are then accounted for by the method; however, this results in a major change in macrolocation of the stations. The same problem occurs if a DEM is used, as in this case, the threshold value used for derivation of the river network becomes important. In both cases, the determination of the hierarchical levels and station locations depends on the availability of larger scale maps and the experience of the analyst; so that the final decision still depends on subjective judgment of the designer.

The dynamic programming approach presented in the study facilitates decision making on hydrometric network assessment and reduction. It is highly flexible in the sense that various basin management objectives can be accounted for by selecting appropriate attributes for stations and assigning weights to them in such a way as to reflect the objectives. This property is especially advantageous for network assessment purposes in view of changing basin management objectives. On the other hand, some disadvantages of the methodology must also be mentioned. The identification of subbasins is basically based on subjective judgments and experiences on the designer’s side. Another property of the approach that is open to subjective judgments is that the stream ordering method and, thus, the identification of station hierarchies depend on the scale of the maps used or to the threshold values of digital maps. One other feature of the dynamic programming approach which may be considered deficient is that it does not account for a hierarchical priority order of stations so that a station selected at one stage may not be preferred at another stage. That is, when the number of stations to be retained in a network is changed, one may arrive at a different combination of stations. In a way, this means that the method does not produce station-specific but combination-specific results. Furthermore, the weights assigned to the selected attributes on the basis of monitoring objectives (scenarios) are evaluated for the entire network along the basin. However, since some stations with local and specific operational purposes are also evaluated within the same framework, the method may as well eliminate such stations from the monitoring system. Furthermore, the method employs a complicated procedure for dynamic programming; hence, it is hard for the decision makers to understand especially when they lack sufficient scientific background on optimization methodologies.

For the third methodology used, the common criticism on MCDM methods is that they focus on the adoption of a stance of a “given problem”. This criticism is also valid for the AHP methodology; yet, it provides some advantages to designers and decision makers. In particular, once the related attributes are defined and their weights are assigned, the assessment of the hierarchical priority order of the stations (alternatives) by the decision matrix approach simplifies the computations and enables rapid results. Similarly, despite its complex structure, the decision value tree approach enables a better understanding of the nature of the problem and the relevant criteria. Furthermore, AHP obligates a close and interactive relation between the designer and the decision maker. This fact enables the acquisition of “desired” results rather than “forced” ones, which are perhaps the best solutions but do not reflect the tendencies and preferences of the decision makers.

Another issue to be stressed here is related to the difficulties in weight elicitation in AHP applications. In some cases, the inconsistent nature of human rationality is reflected in the preference matrix derived through the identified relative importance scale (Table 3.5). Another criticism on AHP is that the eigenvalue-eigenvector approach of the method is still controversial in literature.

Similar to the dynamic programming approach, the AHP method regards only the overall objectives and criteria which are valid for the entire network. This issue disables any performance assessment at station scale where a particular station may have been operated for local purposes instead of overall basin network objectives.

In contrast to the above methodologies, the reference point method provides a simple and clear decision aid to the designer and the decision maker. The method gives the designer the flexibility to use different performance assessment models such as the “sum of attribute values”, as utilized in the Gediz case. The basic approach here resembles that of the decision value tree analysis; but, since the reference point methodology does not require any weight elicitation, the problems mentioned above for the AHP method are overcome. The simplicity of the method is an asset that enables a better and open relationship between the designer and the decision makers. Since the method does not require weights and preference statements by the decision makers, any increase in the number of objectives, criteria and related attributes does not complicate the decision making process.

Similar to the AHP method, the results obtained through the application of the reference point approach are in order of priority. Furthermore, in contrast to the dynamic programming and stream ordering approaches, AHP and the reference point methods evaluate each station as a separate alternative that is not constrained by hydrological catchment or the entire river network. This feature enables the inclusion of a wider set of alternatives; therefore, the AHP and reference point methods may be used for the performance assessment of monitoring activities at larger scales such as a region or a country. On the other hand, AHP considers solely the overall objectives and criteria set for the monitoring program, whereas the reference point approach is able to evaluate a single station with respect to its local operational purposes. Thus; the latter method is more suitable for network assessment purposes at regional or national scales.

The reference point approach has one general deficiency: If one or more coordinates of an alternative overcomes one or more coordinates of the reference point, the method still measures the distance between them; therefore, an alternative which even dominates the defined reference point may have a lesser priority than an alternative which is actually closer

Apart from the specific methodologies investigated, the presented study reveals some basic issues that must be taken into account by both the designers and the decision makers towards the solution of network design and redesign problems. First of all, monitoring agencies should decide upon what their action plan should be in revising a network, i.e., whether it should be network performance assessment, network reduction, network expansion, or the similar. Once the goal is specified, network specific and station specific objectives and criteria should be identified with due respect to basin water resources problems. At these initial stages, the designer should support the decision maker.

After the objectives and the criteria are specified for the network redesign problem, a mathematical model, such as the Weighted Sum Model-WSM, should be developed to numerically determine the current and expected performances of network stations The structure of the model should be selected so as to account for existing data at the sampling sites, characteristics of the stations and the metadata to be derived from the observed data series. Furthermore, such a model and the assessment methodology should be simple and easy to understand. for increased applicability. Complicated methods and models may not often be favored by the decision makers so that their chances of application become low.

When the methods used in this study are considered, it is evident that station attributes must be selected with care by designers and decision makers with respect to basin management objectives. When multiple objectives and criteria exist, priorities among them should be identified. It is important that the designer knows the priorities and preferences of the decision makers in operating their networks.

Performance of each station within a network should be assessed with the model selected, giving due consideration to objectives and criteria. In this case station performance relates to how well the station conforms to the objectives. Stations with low performances, i.e., those that do not fulfill the objectives, are the ones to be rehabilitated or eliminated from the network. However, it must be remembered that the results obtained by application of various assessment/redesign methods are not exact so that the decision makers should be involved in the post-decision making phase. Optimum solutions may not always be the most “desired” solutions.

The decisions made and implemented as a result of the above activities should be re-evaluated for effectiveness after the network is operated under the revised conditions. Network operation, like all natural phenomena, is a dynamic process to be assessed on an iterative basis. As objectives and priorities change in time, a perfectly designed network will remain perfect for a limited period of time and will lose its effectiveness as new demands arise. Thus, it is essential that a network assessment and redesign methodology is flexible enough to adapt to the new conditions.

It is also important to note and record the difficulties encountered in the redesign process. To be able to tackle with these difficulties in the next iterative phase, designers should note down the data and information required in the previous phase. An example would be the attribute of “flood exceedance level (Fex)” defined in Chapter 4 among the second set of station attributes. The significance of this attribute is that it reveals the volume of the hazardous flood or at least the number of hazardous floods downstream of a river section. This volume or the number floods is an indication of the sensitivity of the area served by a monitoring station. Thus, it also shows the effectiveness of that station in producing information for early warning purposes or for the design of flood control schemes. Recording of such rare data helps to discard or minimize problems in performance assessment of the station at the next iterative assessment phase.

Finally, the study is deemed to fulfill its objectives on investigating and assessing various network design and redesign methodologies towards network consolidation. In essence, the results obtained for the Gediz case study have validated the advantages and disadvantages of the methods studied.

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