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Mulugeta Bereded Zelelew

Improving Runoff Estimation at Ungauged Catchments

NTNU
Norwegian University of Science and Technology
Thesis for the degree of Philosophiae Doctor
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Improving Runoff Estimation at Ungauged Catchments

A dissertation
submitted to the
Faculty of Engineering Science and Technology,
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in fulfilment of the requirements for the degree of
Philosophiae Doctor (PhD)
By
Mulugeta Bereded Zelelew

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Professor Knut Alfredsen

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Professor Ånund Killingtveit, Norwegian University of Science and Technology, Trondheim, Norway – Administrator

In memory of my late father Bereded Zelelew and late brother Kasahun Bereded

Abstract

Water infrastructures have been implemented to support the vital activities of human society. The infrastructure developments at the same time have interrupted the natural catchment response characteristics, challenging society to implement effective water resources planning and management strategies. The Telemark area in southern Norway has seen a large number of water infrastructure developments, particularly hydropower, over more than a century. Recent developments in decision support tools for flood control and reservoir operation has raised the need to compute inflows from local catchments, most of which are regulated or have no observed data. This has contributed for the motivation of this PhD thesis work, with an aim of improving runoff estimation at ungauged catchments, and the research results are presented in four manuscript scientific papers.

The inverse distance weighting, inverse distance squared weighting, ordinary kriging, universal kriging and kriging with external drift were applied to analyse precipitation variability and estimate daily precipitation in the study area. The geostatistical based univariate and multivariate map-correlation concepts were applied to analyse and physically understand regional hydrological response patterns. The *Sobol* variance based sensitivity analysis (*VBSA)* method was used to investigate the *HBV* hydrological model parameterization significances on the model response variations and evaluate the model's reliability as a prediction tool. The *HBV* hydrological model space transferability into ungauged catchments was also studied.

The analyses results showed that the inverse distance weighting variants are the preferred spatial data interpolation methods in areas where relatively dense precipitation station network can be found. In mountainous areas and in areas where the precipitation station network is relatively sparse, the kriging variants are the preferred methods. The regional hydrological response correlation analyses suggested that geographic proximity alone cannot explain the entire hydrological response correlations in the study area. Besides, when the multivariate map-correlation analysis was applied, two distinct regional hydrological response patterns - the radial and elliptical-types were identified. The presence of these hydrological response patterns influenced the location of the best-correlated reference streamgauges to the ungauged catchments. As a result, the nearest streamgauge was found the best-correlated in areas where the radial-type hydrological response pattern is the dominant. In area where the elliptical-type hydrological response pattern is the dominant, the nearest reference streamgauge was not necessarily the best-correlated. The *VBSA* verified that varying up to a minimum of four to six influential *HBV* model parameters can sufficiently simulate the catchments' responses characteristics when emphasis is given to fit the high flows. Varying up to a minimum of six influential model parameters is necessary to sufficiently simulate the catchments' responses and maintain the model performance when emphasis is given to fit the low flows. However, varying more than nine out of the fifteen *HBV* model parameters will not make any significant change on the model performance.

The hydrological model space transfer study indicated that estimation of representative runoff at ungauged catchments cannot be guaranteed by transferring model parameter sets from a single donor catchment. On the other hand, applying the ensemble based model space transferring approach and utilizing model parameter sets from multiple donor catchments improved the model performance at the ungauged catchments. The result also suggested that high model performance can be achieved by integrating model parameter sets from two to six donor catchments. Objectively minimizing the *HBV* model parametric dimensionality and only sampling the sensitive model parameters, maintained the model performance and limited the model prediction uncertainty.

Acknowledgments

It would not have been possible to achieve this PhD study without the help and support of many people around me, to only some of whom it is possible to mention here.

This PhD study would not have been possible without the help and support of my supervisor Prof. Knut Alfredsen. His advice, support, encouragement and friendship have been invaluable to me on both an academic and a personal level, for which I am extremely grateful.

I would like to acknowledge the financial support by the Norwegian research council (Project number: ISP10300637) under the "Sustainable Infrastructure" strategic program. I would also like to acknowledge the Norwegian University of Science and Technology for the academic and technical support. The Norwegian Water and Energy Directorate (*NVE*) and Norwegian Meteorological Institute (*NMI*) provided the necessary data for the study. I am grateful to Stein Beldring at *NVE*, Torill Engen Skaugen at *NMI*, Kolbjørn Engeland and Sjur Kolberg at *SINTEF* for providing me with data and materials for my study. The lectures and the discussions with Prof. K. J. Beven at the summer course at Uppsala University, Sweden, were helpful for my PhD thesis work. I am grateful to Prof. K. J. Beven.

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The social environment initiated by Tesfaye, Girumsew, Yordanos, Teferi, Nunu, Meselu, Asmamaw, Zerihuun, Bedilu, Samson, Alemu and their families was refreshing. I am grateful to them. I would also like to thank my friends Genet, Biniam, Tewodros Haile and Yisak who made my second introduction to Norway easier.

My brother Nigussie, who took the responsibility from our late father to take care of our family, is always the greatest and inspiring person in my life. I am very grateful for him. My mother Sindenesh

(Sinde); Misrak; my sister Fantu; Abeba, Tiruye, Kalkidan, Sintayehu, Fetle, Yeshi; my brothers Getachew, Eshetu, Tsegaw and Biniam; Tewodros, Amanuel, Natinael and Girum; my friends Daniel and Hailemelekot, have given me their full support throughout, as always, for which my expression of thanks will not be sufficient for them. The support of my father-in-law Col. Girma, mother-in-law Asrat (Sindu) and their family was great for me and my family. I am grateful to them. I would also like to thank Tenagne and her family for supporting my family during my PhD study period.

Finally, I would like to thank my wife Samrawit Girma (Lina) for her personal support and great patience at all times. My words of thanks will not be sufficient to express my feelings to her, but I say thank you and I love you!

List of papers

The present thesis is based on the following papers, which will be referred in the text by their Roman numerals.

I. Daily precipitation estimation using spatial data analyses methods
Zelelew, Mulugeta B., Alfredsen, K. and Rød, J. K.
Submitted manuscript

II. The use of co-kriging and map-correlation to study hydrological response patterns and select reference streamgauges for ungauged catchments
Zelelew, Mulugeta B. and Alfredsen, K.
In review: Journal of Hydrologic Engineering

III. Sensitivity-guided evaluation of the *HBV* hydrological model parameterization
Zelelew, Mulugeta B. and Alfredsen, K.
Accepted for publication: Journal of Hydroinformatics

IV. Hydrological model space transferability studies to estimate runoff at ungauged catchments
Zelelew, Mulugeta B. and Alfredsen, K.
Submitted manuscript

In all the papers, I was responsible for the analyses and writing of the papers. The co-authors have contributed ideas, advice and feedbacks during the paper work. The use of Paper **III** in this thesis is accepted by the Journal of Hydroinformatics.

The papers are not included in this summary version of the thesis but can be obtained from NTNU Library. Information can be obtained from Universitetsbiblioteket i Trondheim, Biblioteket Valgrinda, S.P. Andersens v.5, 7491 Trondheim or through email address valpur@ub.ntnu.no.

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1
Introduction

1.1 Background and motivation

For centuries, human civilization flourished in close proximity to river banks, shores, estuaries and inland water bodies (Rodda and Ubertini, 1992; Yevjevich, 1992). In the industrial and post-industrial periods of the 20th and 21st centuries, the understanding of the basic principles of hydraulics helped to create many hydraulic structures to control water distribution in water resources systems (Yevjevich, 1992). The infrastructures have been implemented to support the vital activities of human society. One region where the water resources system has been significantly influenced by human civilization is southern Norway. This region has, over the last 100 years, seen a large number of hydropower developments, dam constructions for water storage and flood control purposes, diversion works, and inter-basin flow transfer tunnel and canal constructions (source: national digital database of Norway: *http://www.statkart.no/Norge_digitalt/*; Norwegian Water and Energy Directorate: http://atlas.nve.no/).

While the harnessing of the water resources system led to the advancements in living standards of human society, occurrence of floods has also damaged the infrastructures and the environment and adversely affected human welfare. Jonkman (2005) estimated that floods killed 100,000 people and affected 1.4 billion in the last decade of the 20th century. Though precise estimation of economic losses from floods are difficult, the annual average loss from floods in Europe was estimated as USD 3.8 billion over the period 1970–2006 (normalized in 2006 values) (Barredo, 2009). The study by *UNESCO* (2009) also indicated that losses from extreme flood events increased ten-fold between the 1950s and 1990s. Floods are an integral part of the natural functioning of a river system. To understand flood responses and mitigate flood damages however, it is imperative to have a good knowledge of the natural catchment response characteristics.

Hydrological processes take place in the entire extent of catchments and hydrological phenomena are spatially and temporally continuous (Gottschalk and Askew, 1987; Uhlenbrook, 2006). The spatial location and temporal resolution of observed hydrological and climatic data in a catchment are therefore critical to understand the runoff generation mechanisms and estimate its magnitude for water resources system planning and management. However, the location of observed data are often influenced by operational purposes rather than scientific ones aimed at understanding the hydrological processes in the entire catchments systems (Kirchner, 2006). There is also a noticeable global trend in hydrometric station density reduction, due to, *inter alia*, insufficient funding, inadequate institutional frameworks and lack of appreciation for the value of long-term hydrological data (Mishra and Coulibaly, 2009). The Global Runoff Data Centre (*GRDC*) database shows that the number of the daily runoff observation stations has reduced from about 4000 in the 1980s to approximately 2000 in the 2000s (*GRDC*, 2012). The ongoing development of infrastructures within the water resources system has also contributed to the reduction of the existing runoff observation stations, in which case, the observations become obsolete in terms of recording representative and unregulated data.

There are more climate observation stations, in comparison to runoff observation stations. However, the stations are often located at easily accessible sites (close to cities, towns, villages, roads and valley bottoms) and data from mountainous areas are scarce compared to data from lowland areas (Viviroli et al., 2011; Vuille and Bradley, 2000). The representativeness of the input data used in hydrological models at the same time, is the determining factor in the computed volume and distribution of catchment runoff.

Alternative methods such as making good use of the link between historical catchment response observations and catchment hydro-climatic and physiographic characteristics, and applying hydrological models, provide important decision support information for managing ungauged and regulated river systems. A catchment that is the basic landscape unit of a river drainage system is a complexly self-organizing system and the variation among the spatial characteristics of different catchments can be immense (Sivapalan, 2006). Despite the complexities and differences among catchments, characteristic patterns and connections might also be evident. These connections can advance the hydrologic science through the formulation of hypotheses and establishing relationships between catchment variables (Wagener et al., 2007). Studies demonstrated that spatial patterns of catchment characteristics provide useful information to link runoff generation and its controlling factors among different catchments and within catchments. For instance, spatial soil moisture variability can be explained by the spatial variability of terrain attributes and soil properties in catchments (e.g., Ali et al., 2010; Buttle et al., 2004; Keim et al., 2005; Meyles et al., 2003; Western et al., 1998; Western et al., 2004; Zhao et al., 2011). Hydrological models have also been applied to understand catchment response controlling factors (e.g., Abdulla and Lettenmaier, 1997; Beldring et al. 2003; Berger and Entekhabi, 2001; Engeland and Hisdal, 2009; Fernandez et al., 2000; McIntyre et al., 2005; Merz and Blöschl, 2004; Parajka et al., 2005; Wagener and Wheater, 2006). Hydrological regionalisation studies showed that the physiographic catchment characteristics - mean catchment elevation, mean catchment slope, drainage area, drainage density, vegetation cover and soil depth; and the hydro-climatic catchment characteristics - long-term average annual precipitation, wetness (or aridity) index, base flow index and dynamic catchment response characteristics have dominant roles in controlling catchment responses (e.g., McIntyre et al., 2005; Oudin et al., 2008; Oudin et al., 2010; Reichl et al., 2009; Yadav et al., 2007).

Hydrological models of varying complexity have been developed in the last four decades (e.g., Singh and Woolhiser, 2002; Singh and Frevert, 2006). The models have been used to solve different hydrological problems, for example, to model catchment responses, evaluate impacts of land uses and climate changes on catchment responses and extrapolate hydrological system knowledge into extremes (Andréasson et al., 2004; Bergström, 1991; Elfert and Bormann, 2010; McIntyre et al., 2005; Steele-Dunne et al., 2008). The models have also been used as management tools for water resources systems (e.g., Bergström, 2006). It is argued that applying model structures with increased parameterization increases model flexibility during model calibration (Snowling and Kramer, 2001; Tripp and Niemann, 2008). However, for a given model parameter identification, the information extracted from the input data during model calibration is critical to discriminate between model parameter sets (Vrugt et al., 2002; Wagener et al., 2003). In addition, over-parameterization increases parameter interaction and model sensitivity to inputs. This is a challenge in making consistent inferences about model predictions uncertainty and model parameter distributions (Beven et al., 2000). Assessing the model parametric complexity and its performance with respect to the data information content used to constrain the model residuals is a useful approach to develop and configure a hydrological model that is suitable for water resources planning and management applications. Sensitivity analysis can be applied to parameterized and complex models in order to identify influential model parameters for model response variations, simplify model parametric dimensionality and limit model prediction uncertainty (Reusser et al., 2011; Saltelli et al., 2008; Sobol, 2001; Spear and Hornberger, 1980).

The challenge to develop an effective water resources planning and management strategy is increasing with the development of infrastructures within the water resources systems. The traditional approach of calibrating and applying hydrological models cannot directly be applied at ungauged and regulated river systems (Blöschl and Sivapalan, 1995). On the other hand, making use of the relationship between catchment response observations and catchment characteristics, analysing the correlation patterns in catchment responses and linking the hydrological processes with factors that control catchment response, both within and between catchments, can be useful to estimate the un-observed responses at ungauged and regulated catchments. Recent development of a decision support tool for flood control and reservoir operations in the Telemark area of southern Norway (Skien river basin in *Figure 2*) has raised the need to compute inflows from local catchments, most of which are regulated or have no observed data (Killingtveit et al., 2008). This has contributed to the motivation for this PhD research.

1.2 Aim of the thesis

The aim of this PhD thesis work is to improve runoff estimation at ungauged catchments (*i.e.*, where the runoff records are inadequate in terms of both data quantity and quality (Sivapalan et al., 2003)) to achieve reliable inflow estimation for planning and management of water resources systems. The general objective of the thesis has been guided by the aim of improving catchment runoff estimation based on an understanding of catchment responses through statistical analyses of observed data, regional analyses of hydrological response correlation patterns and enhancing the prediction reliability of a hydrological model. The general objective can be listed down into five specific objectives.

- Analyse spatial variability of precipitation data and investigate methods to estimate representative precipitation input data at catchment scale
- Analyse regional hydrological response patterns based on observed catchment responses
- Extend regional hydrological response patterns to select reference streamgauges for ungauged catchments
- Assess hydrological model parameterization, model parameter influences on model response variations and model parametric dimensionality to enhance model prediction reliability and limit model prediction uncertainty

- Assess methods for transferring hydrological model spaces into ungauged catchments for estimating representative ungauged catchment runoff

1.3 Outline of the thesis

The thesis introduction presents a general overview of the results which were the outcomes of this research; and which have been comprehensively presented in four manuscript journal papers. At the time of writing, Paper **III** was accepted and the three manuscripts have been submitted to scientific journals for publication. The thesis introduction also provides additional information and detailed description of the study area. The remaining part of the thesis introduction is structured as follows.

- Part-2 introduces and describes the study area, data applied for the research and the study setup
- Part-3 briefly describes the methodologies, data and tools applied in each paper and the research work.
- Part-4 presents the summary of the results of the analyses from the papers
- Part-5 briefly discusses the results from the papers, presents the main conclusions of the research work and provides recommendations for future research work

2
Study area, data and study setup

2.1 Study area

The study area is located in southern Norway and consists of five river basins: Skien, Numedalslaagen-Silijan, Kragerø, Arendal and Vegaar-Gjerstad (*Figure 2*). The total size of the study area is about 24,000 km^2, the largest and smallest river basins being Skien and Vegaar-Gjertaad with an area size of about 11,300 and 1,300 km^2 respectively. The elevation in the study area varies from 5 metres above sea level (m.a.s.l) to over 1850 m.a.s.l (*Figure 4*).

The study area receives a mean annual precipitation varying between 430 mm/year and 3050 mm/year and generates mean annual runoff between 160 mm/year and 2985 mm/year. The mean annual daily mean temperature varies between −3.81 °C and 6.93 °C.

In terms of the density of the water resources infrastructures, the study area is one of the regions in Norway which has undergone extensive development in the past 100 years. The number of hydropower plants (*HP*) with installed capacity of 1MW and above is about 88. The number of dams and weirs with at least 100 m wide crest length is about 87. Currently, a minimum of 220 diversion works, inter-river transfer canals and tunnels are operational in the study area (*Figure 2*).

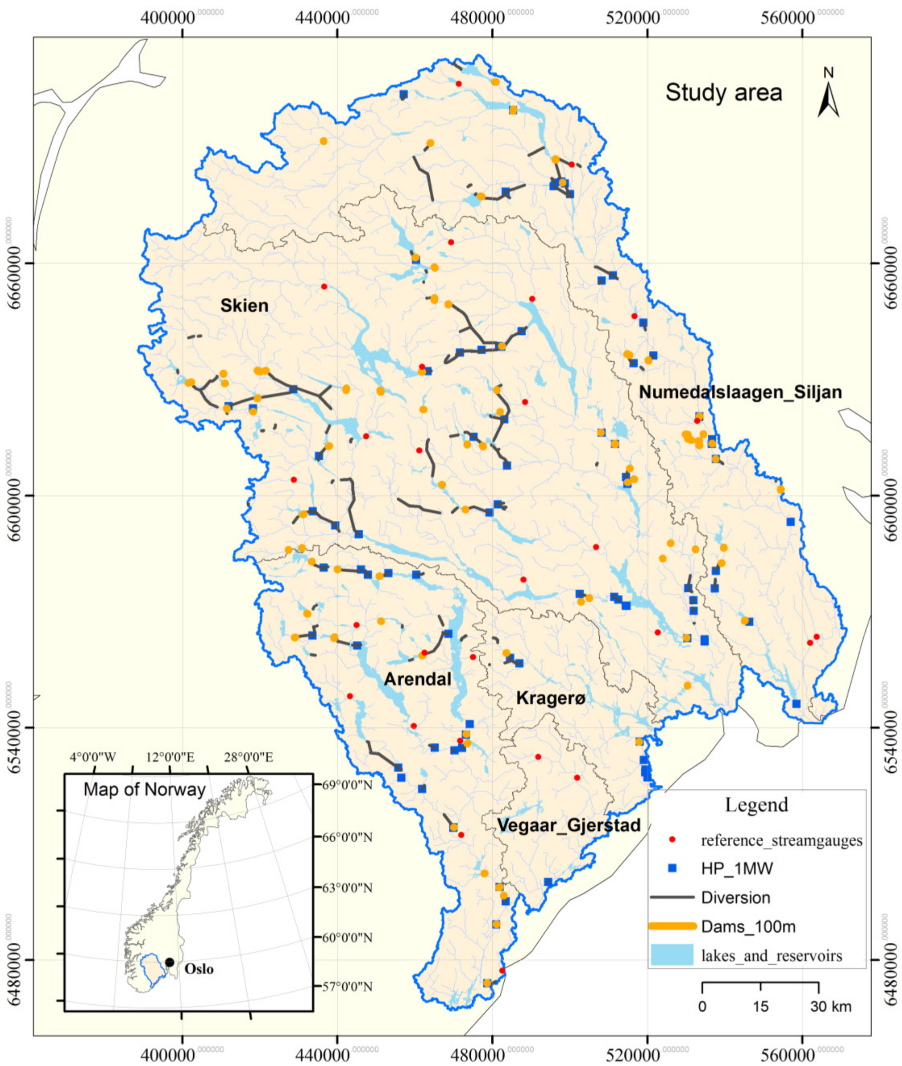

Figure 2. Location of the study area, river basins and water resources infrastructures in the study region. Note that the map is displayed in UTM32 projected geographic coordinates system (Source: *http://www.statkart.no/Norge_digitalt/*; http://atlas.nve.no/).

The land cover types are summarized based on the classification found in Bjørndal et al. (2004) and data available from 54 catchments (27 gauged and 27 ungauged) considered for the study (Paper **II**). Coniferous, deciduous and mixed forests (land cover classes 24-26) dominate the study area (*Table 1, Figure 3*), and account for more than 50% of the catchment areas on about 64% of the catchments. The area covered by hard and shallow soil depth (land cover classes 27-28) is the next dominant land cover type accounting for about 24.4% of the study catchment areas. The areal coverage of water bodies and developed areas is about 6.1% and 4.5% respectively. Bog (marshy lands) (land cover classes 11-14) accounts for about 4.2% of the area of the catchments. Land that is suitable for agriculture and pasture (land cover classes 21-23) covers about 2.8%. Mountainous areas (land cover class 29) and areas covered with rocks and gravels (land cover classes 31-32) account for about 2.2% and 0.5% of the catchment areas respectively.

Table 1. Summary of land cover classifications and descriptions.

Land cover class	Land cover description
[11, 12, 13, 14]	Bog type (marshy) areas with coniferous, deciduous, mixed forest and firm grounds
[21, 22, 23]	Land suitable for small scale and mechanized agricultural practices and pasture
[24, 25, 26]	Area covered with coniferous, deciduous and mixed forests
[27, 28]	Area covered with hard soil, shallow soil depths, not used for agricultural practices and not covered with forest
[29]	Mountainous and with more than 50% mountainous areas
[31, 32]	Rock/gravel area and area mainly covered with boulders and gravels

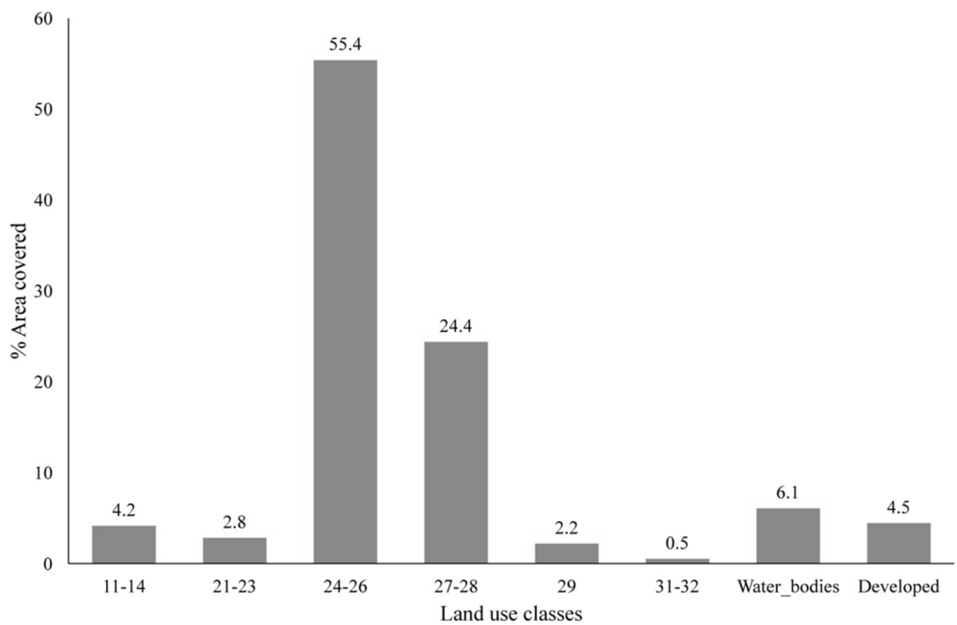

Figure 3. Land cover based on data from 54 catchments in the study region.

The timberline *i.e.*, the elevation beyond which vegetation cannot grow, lies between 800 and 1100 m.a.s.l for catchments located at high altitudes (for instance in catchments Austbygdaai and Gjuvaa (*Figure 4*)). The limiting elevation varies between 680 and 800 m.a.s.l for catchments located at lower altitudes (for instance in catchments Horte and Jondalselv (*Figure 4*)). Catchment Austbygdaai (*Figure 4*) has the highest proportion of area above the timberline accounting for about 59% of the total catchment area.

2.2 Data available for the study

Unregulated daily streamflow records from 27 hydrometric stations (with variable records from the period 1970–2009) were provided by the Norwegian Water and Energy Directorate (*NVE*). Daily precipitation and temperature observations from 57 and 15 climate stations respectively (*Figure 4*); and a 1 km x 1 km gridded normal precipitation, runoff and actual evaporation data from the standard period 1961-1990, were made available by the Norwegian Meteorological Institute and *NVE*.

At least 22 streamgauges are operational at the time of writing. The density of operational climate stations recording precipitation is more than 2.5 times that of the operational streamgauges in the study area. On the contrary, temperature data are generally scarce in the study area in which case only 15 climate stations have continuous temperature records with few missing data.

For the avaialble unregulated streamflow observations, base flow indices (*BFI*) were computed following the automated method described in Arnold and Allen (1999). Reference monthly potential evapo-transpiration was computed using the Thornthwaite monthly water balance model (McCabe and Markstrom, 2007).

Physiographic catchment characteristics for the study were obtained from the national digital database of Norway (*http://www.statkart.no/Norge_digitalt/*). The catchment areas, drainage density, topographic wetness index (*TWI*) and elevations of the case study catchments were based on a digital elevation model (*DEM*) of resolution 25 m x 25 m. The land cover characteristics used for the study were based on the national *N50* maps (Scale 1:50,000).

2.3 Study setup

A total of 55 catchments, of which 27 and 28 are unregulated and ungauged respectively, were considered for the study (the details can be found in Paper **II**). The catchments were selected based on the availability of data for unregulated streamflow, climate and catchment characteristics. Further, 12 out of the 27 unregulated catchments were considered for hydrological model application assessment in the study region (*Figure 4*). The 12 case study catchments for the hydrological model assessment were selected based on the availability of catchment characteristics data and continuous streamflow observation from the recent years (up to the year 2009). Detailed drainage and flow characteristics of the 12 case study catchments are provided in sub-sections 2.3.1 and 2.3.2.

2.3.1 Drainage characteristics

The drainage characteristics of a catchment can be explained by the shape and integral area of a hypsometric curve which relates the horizontal cross-sectional area of a catchment to the relative elevation above the catchment outlet (Strahler, 1964). Its shape and the hypsometric integral (*HI*), *i.e.,* the area under the curve, are indicators of the catchment geomorphologic and land forms, slope and development stages (Cohen et al., 2008; Strahler, 1964; Willgoose and Hancock, 1998). The *HI* provides a quantitative value for comparing catchments. Strahler (1964) suggested that the *HI* for rivers which are at equilibrium development stages ranges between 0.40 and 0.60. For young catchments, most of the catchment area lie at high plateau areas with high catchment relief (*i.e.*, the elevation difference between the plateau and the catchment outlet) resulting in concave downward shaped hypsometric curves. On the other hand, when the upland plateau areas are eroded, the catchment valleys get wider, decreasing the upland plateau catchment areas and resulting in concave upward hypsometric curves.

The hypsometric curves for the case study catchments were computed from the *DEM* of the catchments in *ArcGIS 9.3*. A dimensionless hypsometric curve was prepared to compare the catchment characteristics (*Figure 5*). Most of the case study catchments have *HI* values between 0.35 and 0.60 suggesting that the catchments are at an equilibrium catchment development stage. With respect to the *HI* values, the system of channels and valley walls are well developed within the catchments. The *HI* value at one catchment (*i.e.*, catchment Austbygdaai) (*refer to Figure 4 for catchment names*) is slightly higher (*HI*=0.66), mainly due to the fact that most of the catchment area is located at high altitudes. The similarity between most of the dimensionless hypsometric curves indicates that the distribution of the land mass in the elevation zones of the catchments follows a similar pattern despite the differences in relief, drainage density, micro-climate system, vegetation and soil characteristics among the catchments.

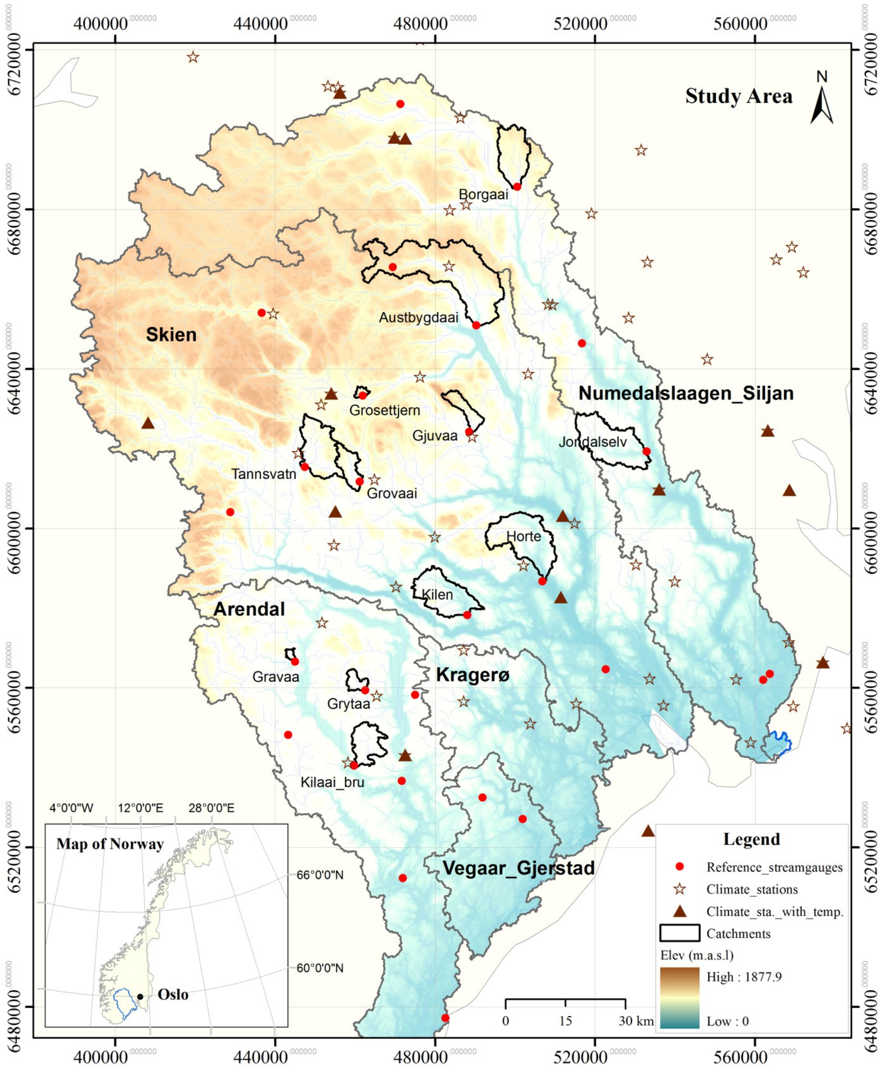

Figure 4. Hydrometric and climate station distributions and location of case study catchments applied for hydrological model assessment in the study region.

The hypsometric curves based on the absolute altitude and area values showed that the catchments are clustered into two groups. The hypsometric curves of catchments Jondalselv (*JON* [1]), Kilen (*KIL*), Horte (*HOR*), Kilaai-Bru (*KLB*), Grytaa (*GRY*) and

[1] *The three letters abbreviations are used for later presentations.*

Gravaa (*GRA*) (one group) vary between altitudes 30 and 1300 m.a.s.l and that of catchments Borgaai (*BOR*), Grovaai (*GRV*), Austbygdaai (*AUS*), Gjuvaa (*GJU*), Grosettjern (*GRS*) and Tannsvatn (*TAN*) (second group) vary between altitudes 200 and 1620 m.a.s.l. About 5% of the catchment areas lie in mountainous areas with altitudes varying between 800 and 1620 m.a.s.l and about 95% of the catchment areas lie at altitudes above 200 m.a.s.l in all catchments.

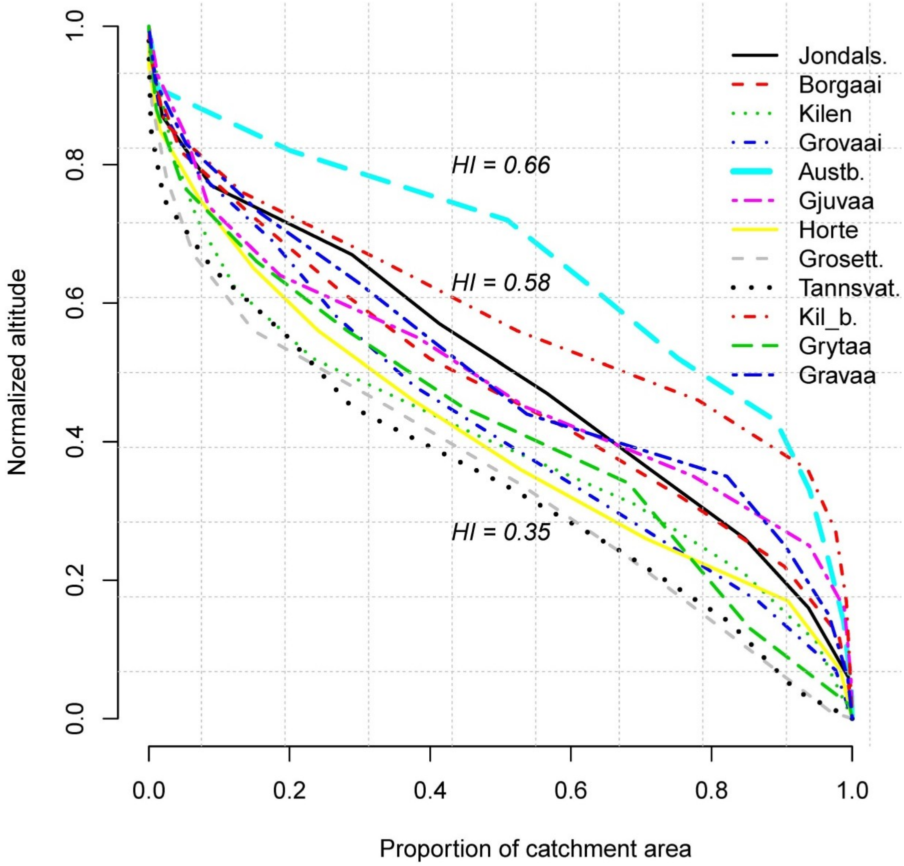

Figure 5. Dimensionless hypsometric curves of the case study catchments applied for hydrological model assessment in the study region.

2.3.2 Flow characteristics

The runoff at the outlet of a catchment integrates the effects of land use, climate, topography and the underlying geology. The distribution of the flow both in time and magnitude is thus influenced by the catchments' physical and climatic characteristics. The flow duration curve (*FDC*) relating the flow to the percentage of time that a given flow equalled or exceeded was used to summarize the flow characteristics at the case study catchments (*Figure 6*). The *FDC* was prepared from the mean daily catchment outflows of length varying from eight to thirty years from the recent flow records (up to the year 2009).

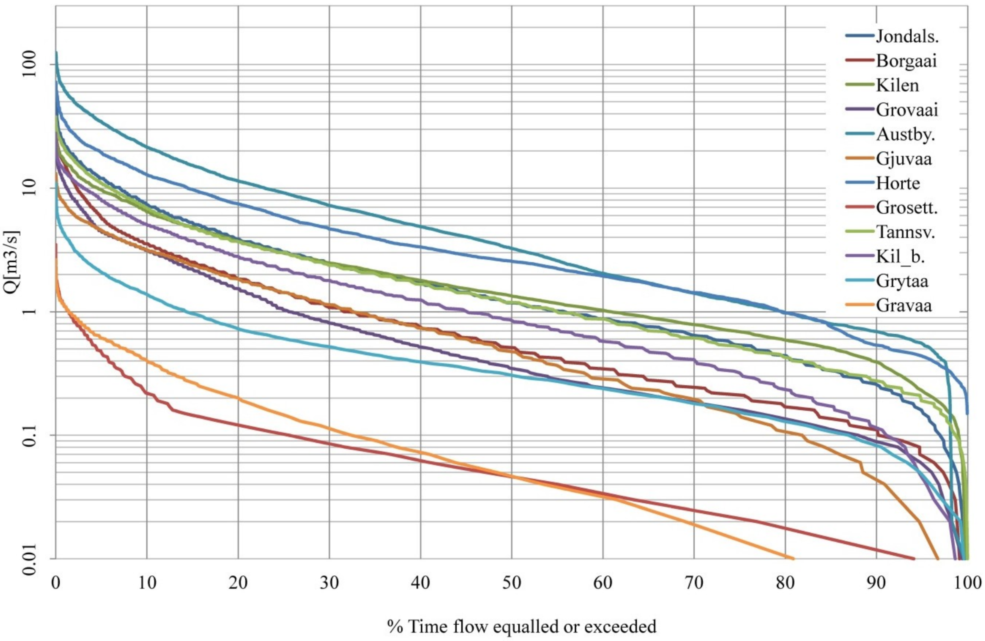

Figure 6. *FDCs* of the case study catchments applied for hydrological model assessment in the study region.

The *FDC*s are typically dominated by gentle slopes for the majority of the time that a flow has occurred (*Figure 6*). The shape of the *FDC*s is an indicator that the flows from the catchments are less variable during the flow record periods. The presence of the gentle slopes in the *FDC* plots is also an indicator of the combined balancing effects of snow and ground water storages and catchment topography on the flow distribution both in time and magnitude. The steep slopes at the beginning and end of the *FDC* envelopes are common characteristics to all catchments representing the floods, and low flows during the snowmelt and winter seasons, respectively

3
Methods

3.1 General

In the PhD thesis work, a number of methods were applied to assess precipitation variability; integrate observed catchment responses, physiographic and hydro-climatic catchment characteristics; and assess hydrological model prediction reliability in order to improve catchment runoff estimations. In Paper **I**, deterministic and geostatistical based (Goovaerts, 1997; Goovaerts, 2000) spatial data analyses methods were used to study precipitation variability in the study area. Univariate and multivariate geostatistical based methods were applied in Paper **II** to analyse regional hydrological response patterns. The *HBV* hydrological model (Bergström and Forsman, 1973) was applied to simulate catchment responses in the research area. To limit the model prediction uncertainty and improve the *HBV* hydrological model reliability as a prediction tool, the model parametric dimensionality was evaluated in Paper **III** using the global sensitivity analyses techniques (Sobol, 2001; Spear and Hornberger, 1980). Alternative approaches to transfer the *HBV* hydrological model space into ungauged catchments and estimate ungauged catchments runoff were investigated in Paper **IV**. The methodologies applied to address the specific research objectives set in the PhD thesis work have been comprehensively described in each paper. In this section, only the brief descriptions of the methodologies, data and tools applied for the studies are presented.

3.2 Precipitation data variability analysis

The inverse distance weighting (*IDW-1*) and inverse distance squared weighting (*IDW-2*) deterministic based; and the ordinary kriging (*OK*), universal kriging (*UK*) and kriging with external drift (*KED*) geostatistical based spatial data interpolation techniques were considered in Paper **I** to analyse the precipitation variability and estimate representative precipitation input for a site within the study region.

Data used for the analyses include precipitation inputs from 57 climate stations (*Figure 4*), *DEM* (to extract elevations), distance to coast and spatial coordinates. Cross-validation was carried out at 30 reference climate stations where the precipitation records were found continuous during the period 2004-2006. A multi-criteria evaluation (*MCE*) approach was followed to compare and evaluate the performances of each spatial data interpolation method. To evaluate the precipitation interpolation methods overall performances, the linear correlation coefficient, mean absolute error and error standard deviation (*i.e.,* the error distribution about the mean error) were applied (Willmott, 1982). *ArcGIS 9.3* and *R*-statistical programme and the related *geoR* software package were the tools applied for the spatial precipitation variability analyses (Diggle and Ribeiro, 2007; R Development Core Team, 2011)).

3.3 Regional hydrological response pattern analysis

In Paper **II**, regional hydrological response patterns were analysed using the univariate map-correlation method (Archfield and Vogel, 2010). Further, the univariate map-correlation method was developed into multivariate map-correlation in order to physically understand and enhance the regional hydrological response correlation at ungauged catchments. Best-correlated reference streamgauges to ungauged catchments were then selected based on the multivariate map-correlation analysis.

Data applied in the regional hydrological response pattern analysis include daily unregulated catchment streamflows from 27 reference streamgauges (with variable records from 1970-2009), topographic variables (*i.e.,* catchment compactness ratio (*Cr*), relief ratio (*Rr*), drainage density (*Dd*) and *TWI*); and hydro-climatic variables (*i.e.,* normal precipitation to normal actual evaporation ratio (*P/Ea*) and normal runoff to precipitation ratio (*R/P*)) from 55 catchments (*i.e*., 27 gauged and 28 ungauged).

ArcGIS 9.3 and *R*-statistical programme and the related *geoR* and *gstat* software packages were used for the regional hydrological response pattern analysis (Diggle and Ribeiro, 2007; Pebesma, 2004; R Development Core Team, 2011). The relation between the reference streamgauges and their separation distances were investigated with the rank-based *Kendall's tau* correlation coefficient (Helsel and Hirsch, 2002). The Nash-Sutcliffe model efficiency measure (Nash and Sutcliffe, 1970) computed based on the untransformed and square-root transformed daily streamflows (*NSE* and *TNSE* correspondingly) were used to evaluate the estimated daily streamflows from the nearest and best-correlated streamgauges (Oudin et al., 2006; Pushpalatha et al., 2012).

3.4 Sensitivity analysis

The siginificance of the *HBV* hydrological model parametrization to the model's response variations was evaluated in Paper **III** using the *Sobol's* variance based sensitivity analysis (*VBSA*) method (Saltelli et al., 2008; Sobol, 2001). The analyis was also supplemented by the generalized sensitivity analysis (*GSA*) method in cases of negative *Sobol* sensitivity indices that can be a result of insufficient sample size in connection with complex model response surfaces (Spear and Hornberger, 1980). The model was applied to simulate runoff responses at twelve case study catchments (*Figure 4*).

Three to ten hydrological years (in the period 1999-2009) of streamflows, precipitation and temperature data were used for the study. The model response was evaluated when all model parameters, influential model parameters for high and low flow variations were sampled. The *NSE* and *TNSE* were applied to evaluate the model responses at high and low flow variations respectively.

3.5 Hydrological model space transferability investigation

Three alternative approaches to transfer the *HBV* hydrological model space into ungauged catchments and estimate the un-observed runoff were investigated in Paper **IV**. The methods include:

(1) Directly transferring model parameter sets from a single donor catchment (*direct*)
(2) Transferring model parameter sets from neighbouring donor catchments (*neighbouring*) and,
(3) Transferring model parameter sets from all potential donor catchments (*ensemble based modelling*).

The applicability of the hydrological model space transferring alternatives were evaluated by a Jack-knife procedure (Miller, 1964), where one catchment was treated as if ungauged at a time and behavioural model parameter sets from potential donor catchments (*i.e.*, from a single physiographically nearest, five neighbouring and all potential donor catchments) were used to estimate the un-observed catchment runoff. Model prediction uncertainty with respect to the model parametric dimension configurations was also investigated. The model was applied to simulate runoff responses at eleven case study catchments (*Figure 4*).

Three hydrological years (2006-2009) of streamflows, precipitation and temperature data were used for the study. Six catchment attributes - area (*A*), *Rr*, *BFI*, mean annual precipitation (*MAP*), forest (*FOR*) and bog (*BOG*) covers were considered to evaluate catchment physiographic similarities and compute posterior likelihoods of model parameter sets. Geographic distances between donor and target catchments within adjacent re-sampled mean elevation classes were used to select neighbouring donor catchments. The *NSE, TNSE,* root mean square error (*RMSE*) and long-term volumetric water balance error (*VE*) model efficiency measures were applied to evaluate the model performances at the ungauged catchments. The full range of the model performance was assessed when all model parameters and influential model parameters for high and low flow variations were sampled.

4
Results

4.1 General

This section presents the summary of results that have been comprehensively presented in the four papers. Paper **I** deals with precipitation variability assessment and investigation of methods to estimate daily precipitation. Infrastructures and development activities within water resources systems influence the availability of observed catchment responses. Paper **II** contributes to the understanding of regional hydrological response correlation in order to select suitable reference streamgauges for ungauged catchments. Hydrological models are widely applied in water resources planning and management. Despite the wide applications of hydrological models, over-parameterization and complexity has also become an issue in their development and applications. Paper **III** contributes to the identification of influential model parameters for the *HBV* hydrological model response variations. The model parametric dimension complexity and simplicity with respect to improving its performance was also investigated in Paper **III**. Hydrological models have been applied to estimate un-observed catchment responses. Paper **IV** explores options for transferring the *HBV* hydrological model spaces from donor catchments into ungauged catchments to estimate the un-observed catchment responses. The following sub-sections present summaries from each paper.

4.2 Precipitation data variability analysis

Paper I: Daily precipitation estimation using spatial data analyses methods

The *MCE* based cross-validation results of the spatial precipitation analyses indicated that the kriging variants (*i.e., OK, UK and KED*) introduced minimum error compared to the *IDW* variants (*i.e., IDW-1 and IWD-2*) in areas where the precipitation station network density is relatively sparse (**Zone II** and **III** in *Figure 7*). Besides, specifying a precipitation dependency trend on the covariates has a marginal advantage to achieve better precipitation estimations in the upper mountainous and western parts of the study area (**Zone III** in *Figure 7*). The influence of the covariates (*i.e.* elevation, distance to coast and spatial coordinates) on the precipitation variability was minimal in the middle parts of the study area. The constant local mean based model, *OK* and distance based weighting, *IDW* spatial data interpolation methods are alternatives to achieve better precipitation estimations in the middle parts of the study area (**Zone II** in *Figure 7*). In the lower parts of the study area where a relatively denser precipitation climate station network is found, the *IDW* variants provided better precipitation estimations (**Zone I** in *Figure 7*).

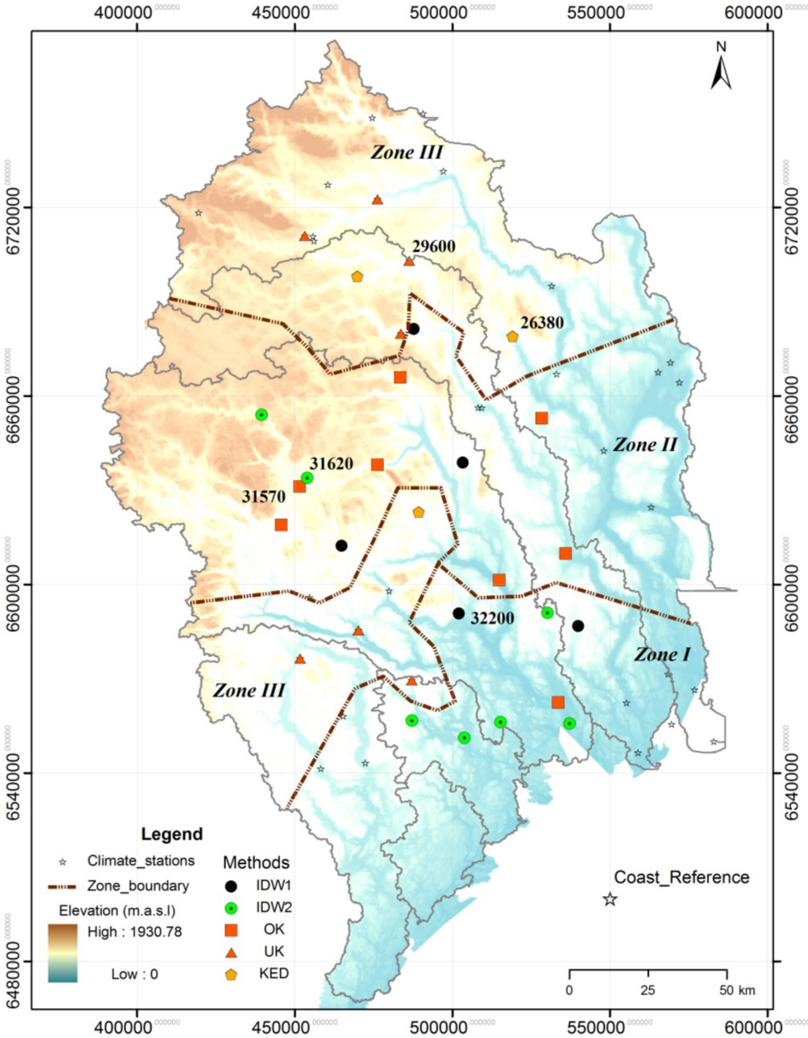

Figure 7. Distribution of the most appropriate spatial precipitation interpolation methods in the study area, in southern Norway (Note that the zone boundaries are approximately drawn at midpoints between the methods).

4.3 Regional hydrological response pattern analysis

Paper II: The use of co-kriging and map-correlation to study hydrological response patterns and select reference streamgauges for ungauged catchments

The regional hydrological responses correlation analysis showed that there exists a decreasing hydrological response correlation trend with increasing streamgauges separation distances among the 27 reference streamgauge observations applied for the study. However, the strength of the reference streamgauge observation correlations was not necessarily dependent on the geographic proximity between the reference streamgauges. As a result, only about 33% of the observed hydrological responses were best-correlated with the geographically nearest streamgauge observations.

The drainage-area based daily streamflow estimation evaluation indicated that the relationship between the reference streamgauge separation distances and *NSE (or TNSE)* does not show a clear trend despite the *NSE (or TNSE)* values being high for streamgauge separation distances less than about 30 km (*Figure 8(a)*). This confirmed that geographic proximity cannot guarantee the selection of appropriate reference streamgauge to estimate daily streamflows at ungauged catchments in the study area. On the other hand, the relation between the *Kendall's tau* (*i.e.*, correlation coefficient) and *NSE (or TNSE)* showed a general increasing *NSE (or TNSE)* trend with increasing *Kendall's tau* value with few exceptions (*Figure 8(b)*). The result indicated that the *Kendall's tau* is a suitable variable to model the regional hydrological response correlations and select appropriate reference streamgauges for ungauged catchments in the study region.

While applying the univariate map-correlation analyses, two distinct regional hydrological response patterns - the radial and elliptical types were revealed. The radial type hydrological response pattern expands from the coast to the inland and in the upper parts of the study area. The elliptical type hydrological response pattern expands in the south-to-west and north-to-east directions. Further, the multivariate map-correlation analyses confirmed that the identified distinct regional hydrological responses patterns were clearly visible in the study region (Examples in *Figure* 9(a-b)). The presence of the distinct regional hydrological response patterns consequently influenced the location of the best-correlated reference streamgauges for the ungauged catchments in the study area. The nearest streamgauge does not seem to be the best-correlated reference streamgauge for the elliptical type of hydrological response pattern (Example in *Figure* 9(a)). In the case of the radial type hydrological response pattern, the nearest reference streamgauge appears to be the best-correlated reference streamgauge (Example in *Figure* 9(a)). The overall results suggested that geographic proximity alone cannot explain the entire hydrological response correlations in the study area.

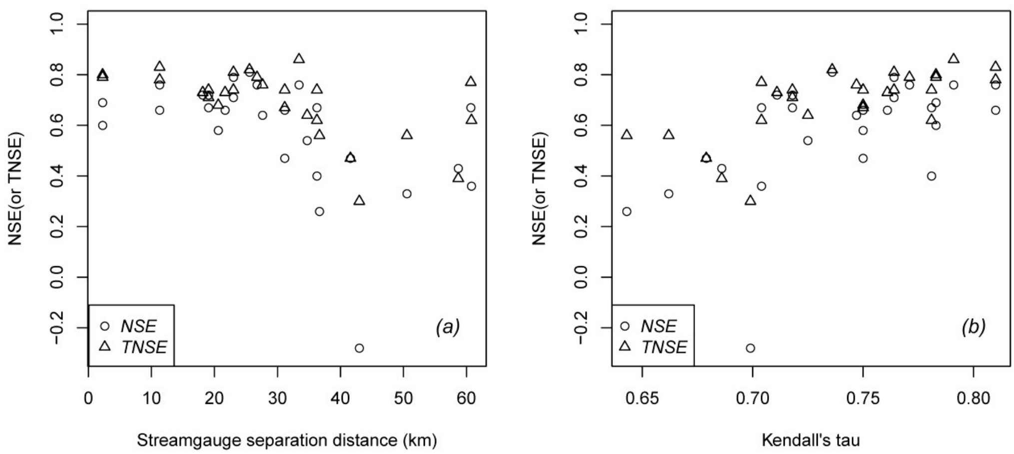

Figure 8. Relation between (a) streamgauge separation distance and *NSE (or TNSE)*, and (b) *Kendall's tau* and *NSE (or TNSE)* for the 27 reference streamgauges in southern Norway considered in the study. The comparison was based on the reference and best-correlated streamgauges

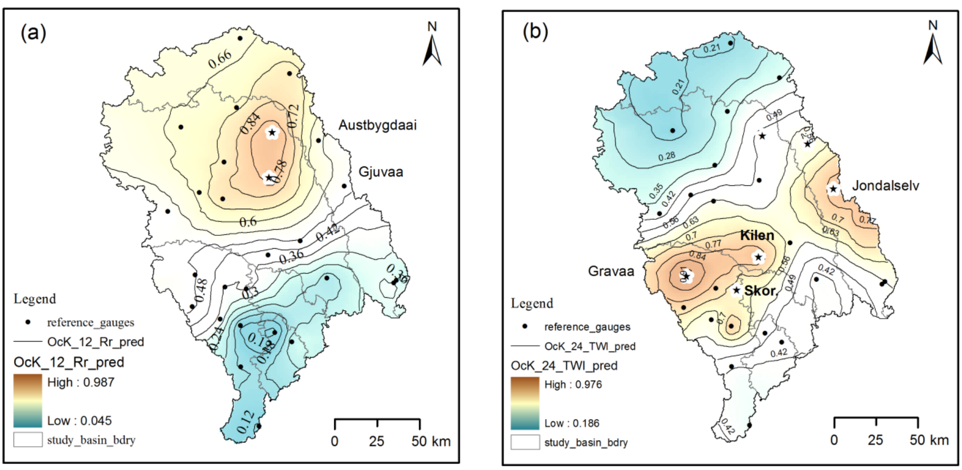

Figure 9. Example of regional hydrological response patterns where the nearest streamgauge is (a) the best-correlated and (b) not the best-correlated, with the reference streamgauges.

From the mapping of the best-correlated reference streamgauges for the ungauged catchments considered in the study, it became apparent that the identified regional hydrological response patterns were dominant in the study area. The elliptical and radial type catchment response correlations extended into the entire extent of the study region. This trend suggested that correlated catchments can be found at faraway locations while following a certain hydrological response pattern.

4.4 Sensitivity analysis

Paper III: Sensitivity-guided evaluation of the *HBV* hydrological model parameterization

The model parameter sensitivity ranking by the first and total-order *Sobol* sensitivity indices indicated that some of the snow, soil and upper runoff response zone routines parameters are among the influential parameters for the *HBV* model response variations. The model parameters *Tr, CX, CXN*, *FC* and *β* have the highest first-order *Sobol* sensitivity indices when emphasis was made to fit the high flow hydrograph (*Figure 10*). Model parameters *Ts, Tsn, uz2* and *uz1* mainly influenced the model response variation by interaction effects. The runoff response parameters (*k2, k1, ko, klz, perc*) and the soil routine potential evapotranspiration threshold (*lp*) were identified as the least sensitive model parameters.

The *Sobol* sensitivity indices computed based on the square root transformed streamflows indicated that model parameters *Tr, CX, CXN*, and *β* have the highest first-order *Sobol* sensitivity indices when emphasis was made to fit the low flow hydrograph (*Figures 11*). In addition, the individual contribution of *uz2* increased and that of *FC* decreased at several catchments when the low flow fitting criterion was considered. The interaction role of model parameters *uz2* and *uz1* also became significant at least at seven catchments compared to the high flow fitting conditions (*Figure 10*, *Figure 11*). However, the characteristics of the least sensitive model parameters remained unchanged (*i.e. k2, k1, ko, klz, perc* and *lp*).

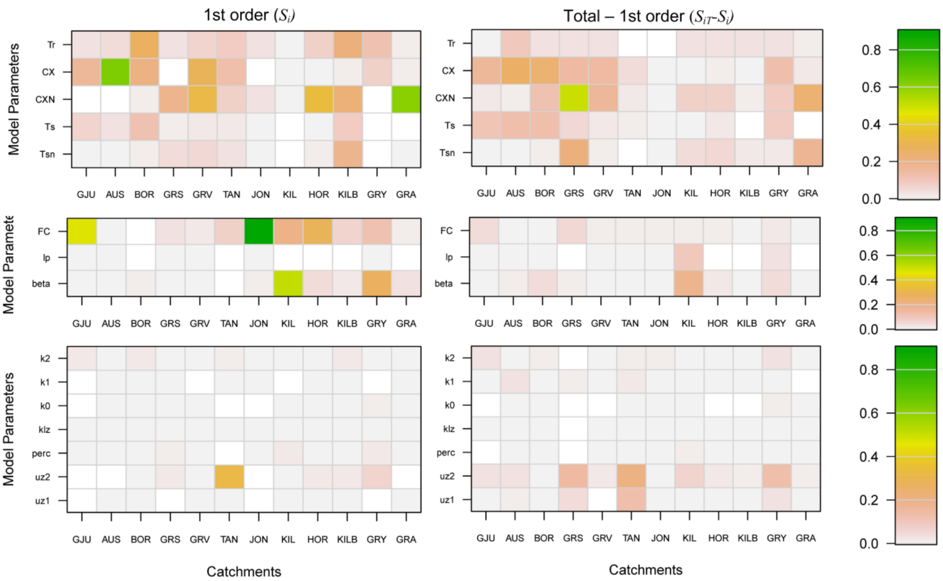

Figure 10. Summary of *Sobol* sensitivity indices for snow (*top*), soil (*middle*) and runoff response (*bottom*) routines parameters at high flow conditions. The first and second columns show the first-order (S_i) and differences between the total and first-order (S_{iT}-S_i) *Sobol* sensitivity indices respectively. High (S_i) and (S_{iT}-S_i) indicates the parameters' significant individual contribution and important interaction role of the parameters' with other parameters for the model response variations respectively.

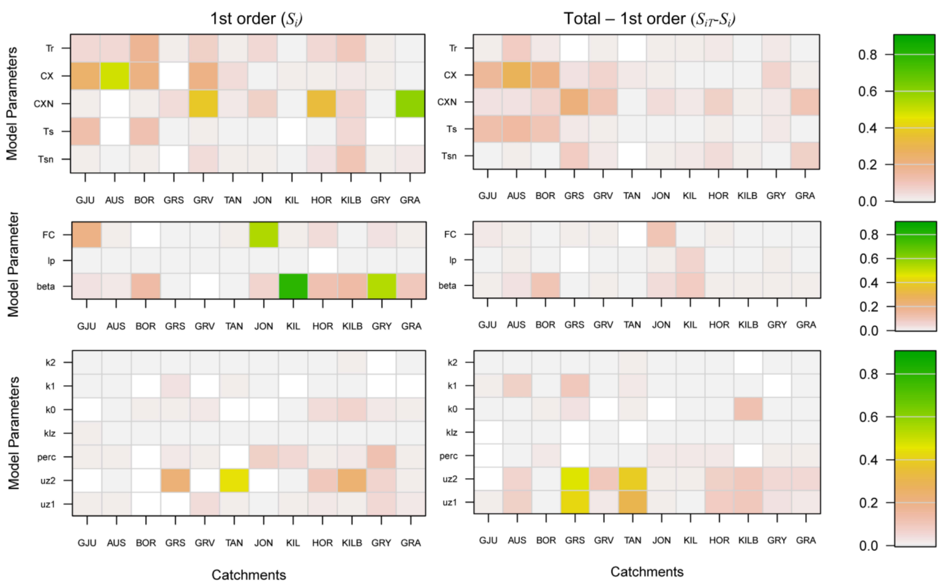

Figure 11. Summary of *Sobol* sensitivity indices for snow (*top*), soil (*middle*) and runoff response (*bottom*) routines parameters at low flow conditions.

Sampling model parameters based on the total-effect *Sobol* indices and following a step-wise model simulation procedure showed that sampling more than four to six influential model parameters does not necessarily add significant improvement on the model performance for high flow conditions. On the other hand, it was necessary to sample more than six influential model parameters to sufficiently capture the catchment responses at most of the case study catchments, when emphasis was given to fit the low flow. However, varying more than nine model parameters does not make any significant change to the model performance, both for the high and low flow variation conditions. On the contrary, varying the least sensitive model parameters and setting the influential model parameters at nominal values has insignificant influence on the model performance improvement.

4.5 Hydrological model space transferability investigation

Paper IV: Hydrological model space transferability studies to estimate streamflow at ungauged catchments

Following the Jack-knife model performance evaluation procedure, the model parameter set information transferred was maximized towards the direct, neighbouring and ensemble based model space transferring methods. The results showed that transferring model parameter sets from a single physiographically nearest donor catchment resulted in a relatively poor model performance at the majority of the ungauged catchments (*Figure 12 (top and middle plots)*). On the other hand, better model performance was achieved when model parameter sets from the neighbouring and all potential donor catchments were used (*Figure 12 (middle and middle plots)*). Further model performance evaluation indicated that the ensemble based model space transferring method provided an overall better model performance at the majority of the ungauged catchments (*Figure 12*).

By applying the ensemble based model space transferring method and starting from any donor catchment's model parameter sets, the model performance was bracketed between the highest possible and lowest model performances (*Figure 13*). In general, integrating model parameter sets from two to six donor catchments supplemented the lack of effective model parameter sets at one or a combination of several donor catchments, and significantly improved the model performances. Moreover, integrating further model parameter sets stabilized the model performance by minimizing the *RMSE* and *VE* (*Figure 13 (columns two and three)*). The analyses results also revealed that despite the influence of the starting donor catchments' model parameter sets, the model performance converged to an average model performance when the model parameter sets of all potential donor catchments were integrated (*Figure 13*).

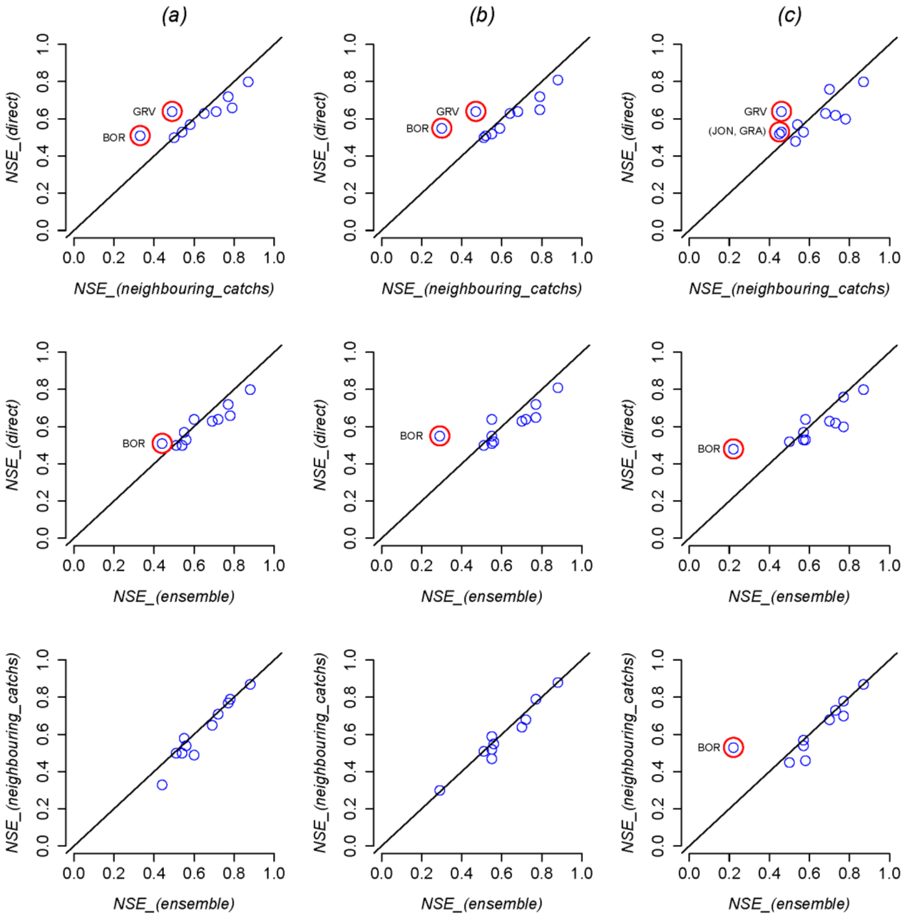

Figure 12. Model performance inter-comparisons by transferring model parameter sets from a single physiographically nearest (*direct*), five neighbouring (*neighbouring_catchs*) and all donor (*ensemble*) catchments into the ungauged catchments. The model parameter sets were sampled when (a) all parameters and (b, c) influential parameters for high and low flows variations respectively were considered. The red circles indicate better model performances at the ungauged catchments by transferring model parameter sets from a single physiographically nearest donor catchment.

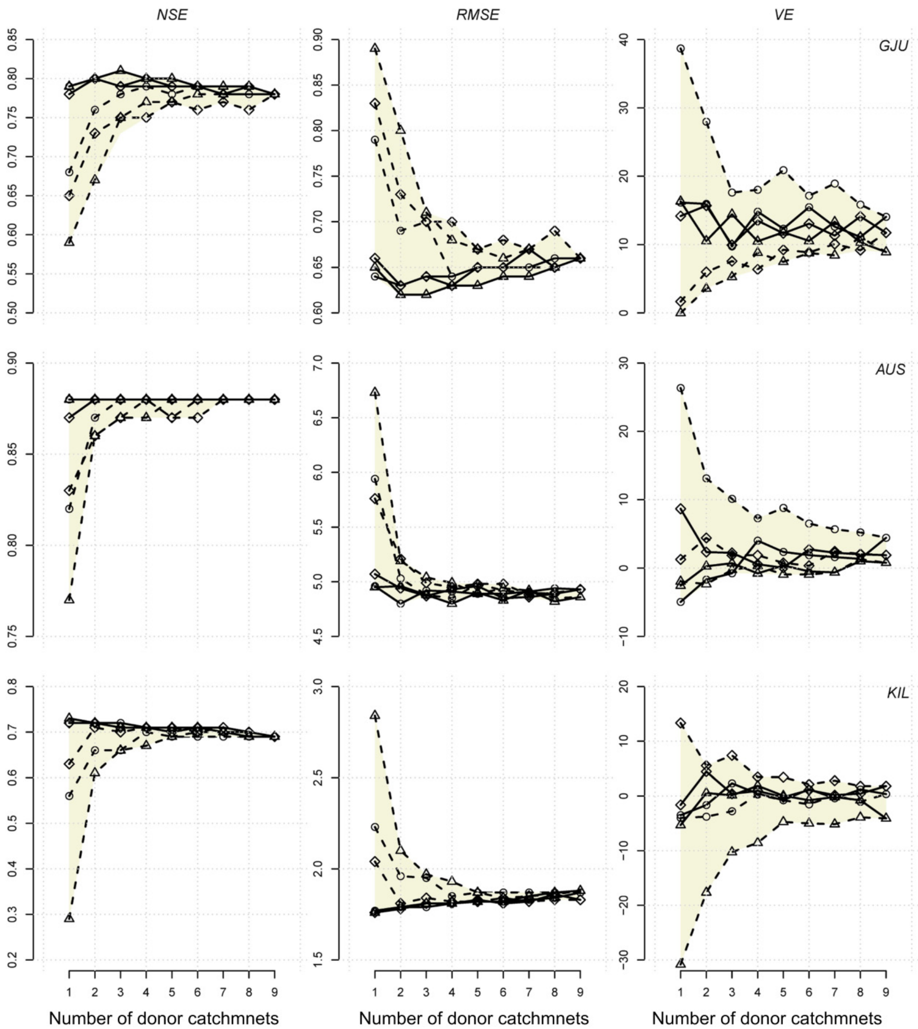

Figure 13. Examples of model performances at the ungauged catchments based on the ensemble based model space transferring method. The circle symbol refers to the model performance when all model parameters were sampled; and triangle and rectangle symbols refer to the model performances when influential model parameters for high and low flow variations were sampled respectively. The solid and dashed lines represent the most and least-effective initial donor catchments respectively.

Reducing the model parametric dimensionality by identifying model parameters that significantly influence the model response to high and low flow variations sufficiently captured the key hydrological response behaviours and maintained the model performance at the highest possible level (*Figure 13 (triangle and rectangle symbols)*).

Besides, limiting the model parametric dimensionality by identifying influential model parameters for the model response variations constrained the model prediction uncertainty.

5
Discussion and conclusions

5.1 Discussion

The availability of unregulated catchment runoff is among the most important sources of decision support information for effective planning and management of water resources systems. Owing to infrastructure developments taking place within the water resources systems, insufficient funding and lack of incentive for measurement, access to such information is becoming increasingly difficult. Alternatively, valuable information on catchment response functions can be obtained from the knowledge of the interactions between physical, climatic and topographic catchment characteristics (Sivapalan, 2003). The methods applied in this thesis have potential applications for improving runoff estimation at ungauged and regulated catchments. The analyses results demonstrated that the methods can contribute to the reliable estimation of ungauged catchment runoff to support decision making for planning and management of water resources systems.

The use of representative precipitation inputs in a hydrological model is critical to estimate reliable catchment runoff. The spatial data analyses methods and evaluation procedures followed in Paper **I** are useful to generate representative precipitation inputs at catchment scales, which will lead to the eventual improvement of catchment runoff estimation.

Spatial proximity between catchments has been widely applied as a measure to transfer hydrologic information into ungauged catchments (Merz and Blöschl, 2004; Oudin et al., 2008; Zhang and Chiew, 2009). The application of the multivariate geostatistical based method; and analyses of the co-variation of catchment responses and its controlling factors are presented in Paper **II**. The study demonstrated that limited observed hydrological response correlations can be extended into regions where the hydrological response correlations are deficient. Hence, the selection of reference streamgauges based on geographic proximity to estimate streamflow at ungauged catchments can be evaluated. In general, the analyses results from this study showed that reference streamgauge selection based on geographic proximity to ungauged catchments is not fully supported in the study area. It is rather the existence of distinct regional hydrological responses patterns that justifies the selection of a suitable reference streamgauge to the ungauged catchments (Paper **II**). Studies outside of the current study region also reported findings which are comparable to the current one (e.g., Archfield and Vogel, 2010; Patil and Stieglitz, 2012). Similarity in physiographic features and hydro-climatic characteristics between catchments plays an important role for catchment responses variations, and also in the selection of suitable reference streamgauges to estimate runoff at ungauged catchments.

Apart from revealing the complete feature of the regional hydrological responses correlations, the geostatistical based multivariate map-correlation analyses approach followed in Paper **II** can be applied to optimally design and locate future hydrometric station networks reflecting the regional hydrological response. The approach can be useful to cope with the water resources planning and management challenges that can potentially be posed by future infrastructure developments within the water resources system in the study area. Studies suggested that limited streamflow measurements can contain much information content to estimate the un-observed continuous catchment runoff (e.g., Konz and Seibert, 2010; Perrin et al., 2007; Seibert and Beven, 2009). Optimally locating a hydrometric station network in a river basin can also have equivalent significances in estimating the ungauged catchment runoff.

Hydrological models are built for general purpose applications. It is essential that the model parameterization matches the information content of the input data used to constrain the model residuals. The model parametric complexity and simplicity should also be evaluated at regional and catchment scale levels. From the *Sobol's VBSA* analyses applied in this thesis work, it was verified that varying and sampling all the fifteen *HBV* model parameters do not necessarily improve the model performance at most of the case study catchments (Paper **III**). Other similar investigations on hydrological model parametrizations also showed that only the variation of few model parameters play significant role for model performances and response variations (e.g., Griensven et al., 2006; Nossent et al., 2011; Rosero et al., 2010; Werkhoven et al., 2008; Werkhoven et al., 2009).

Uncertainty in model prediction is linked to errors in the model structure, input data and estimated model parameter values (Beven et al., 2000). In addition to the influence of these errors, model prediction uncertainty estimation is also highly dependent on how the uncertainty is apportioned and linked to the model parameters (e.g., Saltelli et al., 2004). Over-parameterization is also another cause of model prediction uncertainty (Beven et al., 2000; Sivapalan, 2003). The *Sobol's VBSA* and step-wise parameter sampling and model simulation investigated in Paper **III** indicated that only the variations of a handful of influential *HBV* hydrological model parameters are critical for the model response variations. Model parameters with high first-order *Sobol* sensitivity indices significantly influence the model responses by main effects and the corresponding parameter values should be carefully determined during the model calibrations (Ratto et al., 2007; Reusser et al., 2011). Conversely, model parameters with low total-effect *Sobol* sensitivity indices are non-influential for the model response variations, and the parameter values can be set to nominal values within the parameters' uncertainty ranges. The non-influential model parameters can then be excluded during the model calibrations. These approaches are essential to rationally minimize the hydrological model parametric dimensionality and limit the model prediction uncertainty. It is also useful for selecting influential model parameters and estimate representative ungauged catchments runoff responding to the information content of the input data.

Estimating catchment runoff by applying the traditional hydrological model calibration-verification framework (Blöschl and Sivapalan, 1995) at ungauged and regulated catchments is not achievable due to the lack and modification of the conditioning data respectively. From the *HBV* hydrological model space transferability assessment investigated in Paper **IV**, it was revealed that ungauged catchment runoff estimation cannot be guaranteed by transferring model parameter sets from a single donor catchment. On the other hand, the model performances at the ungauged catchments were improved when model parameter sets from two to six donor catchments were integrated with the ensemble based model space transferring approach (Paper **IV**). Related studies also suggested that the number of donor catchments to increase hydrological model prediction performances at ungauged catchments varies from five to ten (e.g. McIntyre et al., 2005; Oudin et al., 2008; Patil and Stieglitz, 2012; Shu and Ouarda, 2012; Zhang and Chiew, 2009).

Much of the uncertainty in ungauged catchment prediction is due to the lack of knowledge about the catchment behaviour and conditioning data. As a result, it will be a challenge to quantify all the model prediction uncertainty that will occur. In such circumstances, the ensemble based modelling framework followed in Paper **IV** is one way of quantifying uncertainty – thus accepting the existence of these problems, and learning about the catchment's hydrological characteristics in order to consider alternative approaches for ungauged catchment runoff estimation.

5.2 Conclusions

This thesis presented methods for improving runoff estimation at ungauged catchments. Decision making for water resources planning and management needs to be supported by recommendations logically derived from the analyses of components of water resources system. This involves the understanding of the hydrological processes of the basic landscape unit of a river system, *i.e.,* the catchment response characteristics; and the generated runoff amount and its distribution. Based on the specific objectives of this thesis work, the main outcomes of the research are summarized in the following paragraphs.

1. Ground gauge based observed precipitation data will continue as an important source of precipitation input for hydrological modelling. However, sufficient representation of precipitation data at catchment scale is a constraint. The spatial data analyses techniques applied in this study are useful to estimate precipitation inputs at catchment scale.

2. Geographic proximity based reference streamgauge selection to estimate daily streamflow at ungauged catchments is not fully supported in southern Norway where this research has focused.

3. Existence of distinct regional hydrological response patterns fundamentally justifies the selection of a suitable reference streamgauge for estimating un-observed runoff at ungauged catchments. Where distinct regional hydrological response patterns can be identified, the reliability of the geographical proximity based reference streamgauge selection can also be explicit.

4. The geostatistical based multivariate map-correlation method assists to reveal detailed hydrological response patterns, adding a physical understanding to the hydrological response correlations between ungauged catchments and existing reference streamgauges.

5. The multivariate map-correlation approach can be used to optimally design hydrometric station networks so that the locations of the stations reflect the regional hydrological response patterns. Hence, limited catchment response observations can be informative and effectively applied for water resources planning and management.

6. The *Sobol's VBSA* technique is a powerful tool to objectively minimize model parametric dimensionality, improve model prediction reliability and limit model prediction uncertainty.

7. Varying up to a minimum of four to six influential *HBV* hydrological model parameters can sufficiently capture catchments' responses characteristics when emphasis is given to fit the high flows. Varying up to a minimum of six influential model parameters is necessary to sufficiently capture catchment responses and maintain the model performance when emphasis is given to fit the low flows. On the contrary, varying more than nine out of the fifteen *HBV* model parameters will not make any substantial model performance changes both for high and low flows fitting conditions.

8. Estimation of representative streamflows at ungauged catchments cannot be guaranteed by transferring model parameter sets from a single donor catchment. However, transferring model parameters sets from available donor catchments with the ensemble based model space transferring approach improves model performances at ungauged catchments.

9. Applying the ensemble modelling approach and transferring *HBV* model spaces from two to six donor catchments was found sufficient to achieve the maximum possible model performances at the ungauged catchments in the current study area in southern Norway.

10. The ensemble based modelling approach is a useful way of quantifying uncertainty and a way to expect the problem that arises from lack of knowledge of the catchment hydrological characteristics and lack of data. This will in the long run assist to understand and learn about the catchment runoff generation behaviours and consider alternative ungauged catchment runoff estimation strategies.

5.2.1 Future research

A natural catchment is quite complex. Continued research is indispensable to gain incremental understanding of the hydrologic functioning of catchments. The following recommendations are suggested for further research work.

1. The potential applications of the geostatistical based multivariate map-correlation method for analysing regional hydrological response patterns has been successfully demonstrated for the research area. The method should further be applied and evaluated in other areas.

2. The length of data of the 27 unregulated catchments used for the multivariate map-correlation method in this study is variable. Effort has been made to use overlapping data sets when comparing the hydrological responses correlations between catchments. However, the restriction was relaxed over the extent of the study area. This may have influence on the outcome of the multivariate map-correlation method. Any future applications of the multivariate map-correlation method should consider potential influences of data lengths.

3. The model performance exploration by the *Sobol's VBSA* technique in this study accounts for the low and high flow variations of the streamflow hydrograph. The influence of temporal hydrological changes may affect the sensitivity of the model parameters and model performance. *Sobol's VBSA* analyses in a temporal framework to account for the dynamic variations of the hydrological processes should be considered in further research.

4. The methods followed to transfer the *HBV* model parameters into ungauged catchments in the current study should be compared with alternative model parameter space approaches.

5. The methods applied to select appropriate reference streamgauges for ungauged catchments; and methods applied to transfer the *HBV* model parameters into ungauged catchments should be considered and implemented for operational models in the Telemark area.

6. As the development of water resource systems continues, it is likely that human activity and potential climate changes will influence the land use and hydrological response characteristics of catchments. This may limit the applicability of historical data to predict the future hydrologic characteristics of water resources system components. Continued effort of measuring representative data should be encouraged.

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Appendix: Papers

The papers are not included in this summary version of the thesis but can be obtained from NTNU Library. Information can be obtained from Universitetsbiblioteket i Trondheim, Biblioteket Valgrinda, S.P. Andersens v.5, 7491 Trondheim or through email address valpur@ub.ntnu.no.