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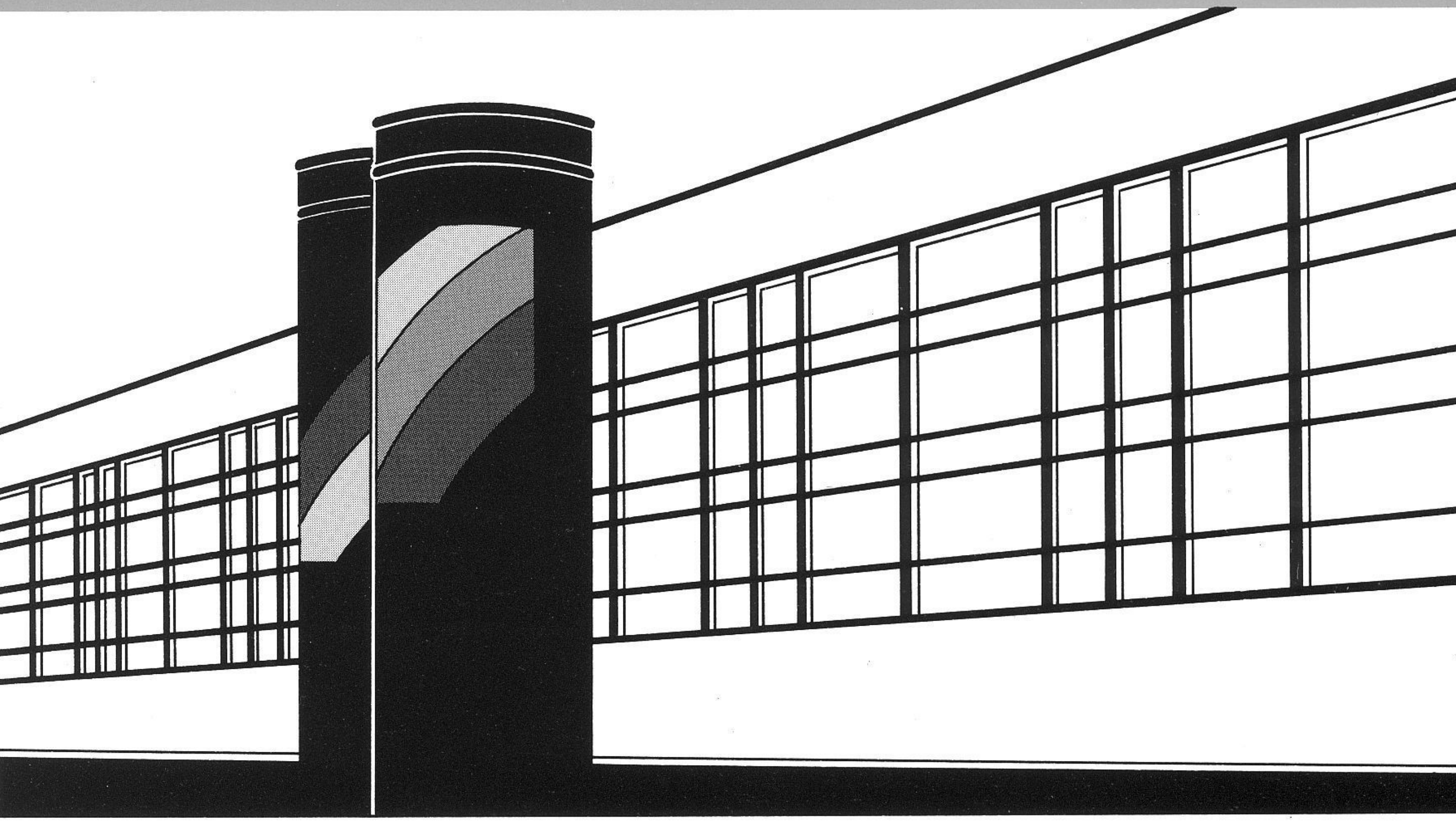

Heft 175 Sachin Ramesh Patil

Regionalization of an Event Based Nash Cascade Model for Flood Predictions in Ungauged Basins

Regionalization of an Event Based Nash Cascade Model for Flood Predictions in Ungauged Basins

Von der Fakultät Bau- und Umweltingenieurwissenschaften der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von

Sachin Ramesh Patil

aus Jalgaon, Indien

Hauptberichter:	Prof. Dr. rer.nat. Dr.-Ing. habil. András Bárdossy
Mitberichter:	Prof. Dr.-Ing. Uwe Haberlandt

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von
Dr.-Ing.
Sachin Ramesh Patil

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Abstract

This study was aimed at developing a practical, robust and physically reasonable methodology for estimation of design flood and its key characteristics under data scarce conditions. The key inputs for the planning and design of flood protection schemes are the design flood characteristics, such as flood runoff volume, peak runoff and time to peak runoff. The design flood characteristics are usually obtained through discharge-frequency analysis or a hydrological model calibrated for the location under consideration. These approaches are based on two implicit assumptions: that a sufficient length of discharge time series is available, and the past of the catchment represents its future. However, due to lack of sufficient discharge data and inconstant hydrological conditions, application of discharge-frequency analysis or calibration of a hydrological model is not always viable. In such case, instead of calibration, model parameters are obtained through regionalization procedure. The regionalization procedures usually associate model parameters with hydrological characteristics through regional transfer functions. A regional transfer function for a model parameter, derived using gauged catchments in a region, can be then used to estimate the parameter for a "similar" ungauged catchment in the region, using its hydrological characteristics.

Most of the existing regionalization procedures derive a transfer function using two step regionalization procedure: calibration of a model parameter for each of the gauged catchments separately, then establish the relationship between the calibrated parameter and hydrological characteristics through regression procedure. However, due to inter-parameter interaction, calibration often leads to more than one equally good parameters (equifinality), thus not each of them may fit into a unique transfer function. The derivation of a transfer function through the two step regionalization procedure, is subjected to parameter identification problem. The parameter identification problem often leads to weak regional transfer functions. Besides, parameter sets calibrated at catchment scale often do not correspond to an optimum parameter set at regional scales. To obtain an efficient and robust regionalization methodology, it must be developed for optimum regional performance instead of catchment specific performance.

Furthermore, transfer functions are usually derived through purely-data-driven regression approaches. In doing so, the physical implications of the derived relationships, with respect to underlying rainfall-runoff processes, are usually disregarded. The purely-data-driven approach may lead to excellent goodness fit performance during regression, however the derived transfer function may not represent the physical relationships. Such transfer functions, due to their lack of a physical basis, can lead to erroneous and implausible predictions.

The main objective of this study was to derive a regionalization methodology for flood predictions in ungauged catchments, which is strictly based on physically reasonable transfer functions, corresponding to the optimum regional performance and adequately addressing the problem of parameter equifinality. Not only catchment specific, but event specific hydrological characteristics were also considered during the study. Furthermore, a part of the study was intended to outline the significance of physically reasonable approach for hydrological predictions. A possibility of assessment of impact of land use changes on flood characteristics was also investigated during the study.

An event based hourly Nash cascade model was developed to derive the direct runoff hydrograph from rainfall time series. The model was implemented on a semi-distributed scale, i.e. the direct runoff hydrograph is estimated at sub-catchment scale (50 km^2 to 75 km^2), then it is routed to the outlet of the catchment using the Muskingum routing procedure. The model uses three model parameters, the runoff coefficient (RC), the number of reservoirs (N) and a reservoir constant (K). For ungauged catchments, the model parameters RC, N and K must be estimated through a regionalization procedure. The routing procedure uses two parameters: Muskingum retention constant (k_m) and weighting factor (x_m), which were estimated through a readily available empirical method. The study was focused on derivation of transfer functions to facilitate estimations of the model parameters RC, N and K in ungauged catchments.

The study was conducted using 209 rainfall-runoff events from 41 mesoscale catchments in the south-west region of Germany, which includes the Black Forest and the Swabian Alps. The study area drains into the three major rivers: Rhein, Neckar and Danube. Among the 41 catchments, 22 were used for optimization of the regionalization methodology and 19 were used for its validation. Areal rainfall time series for the events were estimated through external drift kriging of ground based rainfall measurements. Various event and catchment specific hydrological characteristics, describing event specific conditions, topography, morphology, soil and land use were estimated for each of the events.

If total rainfall (P_t) and rainfall loss (P_l) occurred during a rainfall-runoff event are known, RC for the event can be estimated. Therefore, the transfer function for P_l, instead of for RC, was derived during this study. "Observed" P_l for the events was estimated using the observed runoff hydrograph and applying the straight line hydrograph separation method. Four different approaches were employed to derive four different transfer functions for P_l: a multiple linear transfer function (MLTF), an artificial neural network transfer function (ANNTF), a fuzzy logic transfer function (FLTF) and a logistic transfer function (LoTF).

MLTF, ANNTF and FLTF represent purely-data-driven approaches, i.e. the transfer functions were derived simply by optimizing the goodness fit between observed and calculated P_l without taking account of physical processes of rainfall loss. ANNTF and FLTF, due to their flexibility to replicate non-linear relationships, yielded a very high goodness fit of 0.95 for the correlation coefficient ($Corr$). MLTF, however, yielded moderate goodness fit of $Corr = 0.90$, because of the limitation of linearity. On the other hand, LoTF represents data-plus-knowledge driven approach, i.e. the transfer function was derived by incorporating the *a priori* knowledge of the physical processes of rainfall loss into the function while optimizing the goodness fit. The optimized LoTF, which yielded goodness fit of $Corr = 0.95$, relates P_l with total rainfall, antecedent precipitation index, river density, month of event, land use, field capacity and the hydraulic conductivity of soil. During the validation, ANNTF, FLTF and LoTF exhibited a high goodness fit with $Corr = 0.94$ over the catchments which were not used for optimization.

In order to investigate whether the transfer functions are physically reasonable, validation for physical relationships was carried out by comparing the signs of derivatives of the functional relationships between the predictors and P_l, as featured in the transfer functions, with the signs of derivatives of the physical relationships derived from the *a priori* knowledge of rainfall loss processes. The validation revealed that the response of ANNTF and FLTF to hydrological changes often conflicts with the response of the physical relationships. Thus, ANNTF and FLTF do not seem to be robust and physically reasonable. Due to the lack of a physical basis, application of the purely-data-driven approaches for extrapolation (or regionalization) to predict a response beyond the range of the dataset used their derivation is highly questionable. On the other hand, the validation of LoTF for the physical relationships showed that the signs of derivatives of the functional relationships featured in LoTF are consistent with that of the physical relationships, thus, it is robust and physically reasonable. For being physically reasonable as well as efficient in terms of goodness fit, the data-plus-knowledge driven approach proved to be most suitable for regionalization of P_l and, subsequently, RC.

The Nash cascade parameters N and K are strongly correlated with each other, and can be associated with each other through an inter-parameter function. The inter-parameter function can be represented by a power function with an exponent ($\alpha = -1.0$) and a coefficient β which exhibits strong correlations with the hydrological characteristics. Therefore, regionalization of K and the coefficient β was carried out, where N can be estimated by using K and the inter-parameter function. Thus, the problem of equifinality was handled by regionalizing the inter-parameter relationship itself. In order to obtain regionally optimum transfer functions, they were optimized using the mean Nash-Sutcliffe coefficient ($\overline{NS}$) as a aggregated goodness fit measure (of runoff hydrograph) for a set of gauged catchments. The optimization was carried out using a simulated annealing algorithm. The optimized non-linear transfer functions relate the parameters K and β with duration of rainfall, total rainfall, time of concentration, slope, perimeter and land use. During the optimization of the transfer functions, aggregated goodness fit of $\overline{NS} = 0.72$ was achieved. For 70 % of the events, event specific Nash-Sutcliffe coefficient (NS) was higher than 0.7. The goodness fit obtained for peak runoff ($NS_{Qpeak} = 0.93$) and time to peak runoff ($NS_{Tpeak} = 0.89$) also suggests highly acceptable performance of the transfer functions.

The validation of the transfer functions yielded $\overline{NS} = 0.75$, for 69 % of the events

$NS > 0.7$ was achieved. The goodness fit obtained for peak runoff and for time to peak runoff were respectively $NS_{Qpeak} = 0.93$ and $NS_{Tpeak} = 0.87$. The performance for validation was equally good as that of optimization, which indicates that the transfer functions are both reliable and efficient at transferring the model parameters to ungauged catchments. The Nash casade paramters are conceptaul, their physical relationship with the hydrological characteristics cannot be explained. However, physical relationship between unit hydroraph shape and the hydrological characteristics can derived from *a priori* knowledge of runoff propagation processes. Therefore, validation of the transfer functions was carried out by comparing the change in the shape of modeled unit hydrograph, due to change in the hydrological characterisics, with the change anticipated from the *a priori* knowledge of runoff propagation processes. The validation ensured that the transfer functions are physically reasonable with respect to the catchment characteristic used in the tranfer funtions.

The optimization and validation performance of the derived regionalization methodology suggest that it is highly efficient at estimation of flood runoff volume, peak runoff and time to peak runoff for sufficiently large rainfall events in ungauged catchments. The regionalization methodology is built on physically reasonable relationships with event as well as catchment specific hydrological characteristics. Therefore, it is robust and suitable for both the temporal as well as the spatial transfer of the model parameters. Since the methodology uses readily available hydrological characteristics and parsimonious modeling as well as transfer function approach, it can be regarded as simple and practical.

In order to evaluate the usefulness of the derived regionalization methodology for practical application, its performance was compared with the existing common practices, such as SCS curve number method and the Lutz procedure, which is derived and commonly used for the study area. The comparisons revealed that for the study area under consideration, the regionalization methodology performs better than the existing practices. Thus, the regionalization methodology seems to be useful for practice oriented applications. The approach employed for this study is general and may be transferable to other "similar" regions, however the transfer functions derived during the study are specific for the study area under consideration and may not be directly transfered to other regions.

Although the overall performance of the derived regionalization methodology is highly acceptable, the analysis of the performance for individual events revealed that the derived regionalization methodology fails to produce acceptable estimates of rainfall loss and runoff hydrograph for small rainfall events. The derived transfer functions may not be valid for the rainfall events which are below certain threshold of amount ($< 20\ mm$) and duration ($< 10\ hr$) of rainfall. The performance for the catchments in the karstic region at foothills of Swabian Alps is also poor, which was expected due to the fact that the drainage in the region is dominated by subsurface flow.

Practical application of the derived regionalization methodology to estimate design flood hydrograph and its characteristics is demonstrated using a case study of the catchment Tübingen. The relative areas of urban and forest land use are used in the transfer functions to estimate the model parameters, therefore, there is a possibility to use the regionalization methodology for assessment of impact of land use changes on flood runoff characteristics. The assessment of impact of land use changes on flood characteristics was carried out for three different land use scenarios in the catchment Tübingen. The attempt led to the conclusion that there is a reasonable chance of using such methodology for assessment of impact of land use changes.

Kurzfassung

Diese Untersuchung beschäftigte sich mit der Entwicklung einer praktischen, robusten und physisch begründeten Methodologie zur Schätzung der Bemessungshochwasser und ihrer Eigenschaften in Regionen mit mangelhafter Datengrundlage. Die Haupteingaben für die Planung und den Entwurf von Hochwasserschutzsystemen sind die Eigenschaften der Bemessungshochwasser, wie zum Beispiel das Hochwasservolumen, der Hochwasserscheitel und der Zeitpunkt des Hochwasserscheitels. Üblicherweise wird zur Abschätzung der Eigenschaften der Bemessungshochwasser die Abfluss-Frequenz Analyse oder ein hydrologisches Modell, das für das jeweilige Einzugsgebiet Fall kalibriert ist, benutzt. Solche Abschätzungen basieren auf zwei impliziten Annahmen: Erstens, dass eine ausreichend lange Abflussganglinie zur Verfügung steht, und dass zweitens die Vergangenheit des Einzugsgebiets die Zukunft richtig repräsentiert. Allerdings ist, aus Mangel an ausreichenden Abflussdaten und nichtstationären hydrologischen Verhältnissen, die Anwendung der die Abfluss-Frequenz Analyse oder Kalibrierung eines hydrologischen Modells nicht immer geeignet. In diesem Fall müssen, anstelle der Kalibrierung, die Modell-Parameter mit einem Regionalisierungsverfahren berechnen werden. Das Regionalisierungsverfahren verbindet die Modell-Parameter durch regionale Transfer-Funktionen mit hydrologischen Merkmalen. Eine regionale Transfer-Funktion für einen Modellparameter, welche von den beobachtete Einzugsgebieten in einer Region abgeleitet wurde, kann für die Schätzung der Parameter für ein "ähnliches" unbeobachtete Einzugsgebiet in der Region verwendet werden.

Die meisten der bestehenden Regionalisierungsverfahren leiten die Transfer-Funktion durch ein Zweischrittverfahren ab: Erst die Kalibrierung eines Modell-Parameter für die einzelnen beobachteten Einzugsgebieten, dann die Ableitung der Beziehung zwischen den Parametern und der hydrologischen Merkmale durch Regressionsverfahren. Aber wegen der Abhängigkeiten der Parameter untereinander, führt die Kalibrierung oft zu mehr als einem guten Parameterset (Äquifinalität), und darum kann nicht für jeden Parameter eine eindeutige Transferfunktion angepasst werden. Die Ableitung einen Transfer-Funktion durch das Zweischrittverfahren unterliegt dem Parameter-Identifizierung Problem. Das Parameter-Identifizierung Problem führt oft zu schwachen regionalen Transfer-Funktionen. Außerdem entsprechen Parametersätze, die für die einzelnen Einzugsgebiete kalibriert sind, oft nicht dem optimalen Parameterset im regionalem Maßstab. Um eine leistungsfähige und robuste Regionalisierungsmethodologie zu erzielen, muss diese für eine optimale Modellleistung in regionalem Maßstab entwickelt werden.

Desweiteren werden die Transfer-Funktionen durch datengestützte Regressionsansätze abgeleitet. Dabei wird die physikalische Bedeutung der abgeleiteten Beziehung, hinsichtlich des Niederschlag-Abfluss Prozesses, in der Regel nicht berücksichtigt. Dieser

rein statistische Ansatz kann bei der Regression zu einer sehr hohen Anpassungsgüte führen und trotzdem vertreten die abgeleiteten Transfer-Funktionen nicht die physikalischen Beziehungen. Solche Transfer-Funktionen können, aufgrund des Fehlens der physischen Grundlagen, zu fehlerhaften und unplausiblen Vorhersagen führen.

Das Hauptziel dieser Untersuchung war es, eine Regionalisierungsmethodologie zu entwickeln, die auf physisch begründeten Transfer-Funktionen basiert, der optimalen Modellgüte im regionalen Maßstab entspricht und das Parameter-Identifizierungs-Problem adäquat berücksichtigt. Außer den Einzugsgebietsmerkmalen, wurden von der Untersuchung auch ereignisspezifische Merkmale in Betracht gezogen. Darüber hinaus sollte die Untersuchung dazu dienen, die Relevanz physikalisch sinnvoller Ansätze für die Güte hydrologischer Vorhersagen herauszustellen. Zusätzlich wurde untersucht, ob es möglich ist, die Auswirkungen von Landnutzänderungen auf die Hochwasser-eigenschaften zu bewerten.

Es wurde ein ereignisbasiertes Nash-Kaskade-Modell mit einstündiger Auflösung entwickelt, um den Hydrographen des Direktabflusses aus der Niederschlagszeitreihe abzuleiten. Das Modell wurde auf ein semi-flächendifferneziertes Modellgebiet angewendet, d.h. die Abflussganglinie wird für Untereinzugsgebiet (50 km^2 bis 75 km^2) geschätzt, dann die Abflussganglinie an der Mündung des Einzugsgebiet mit Muskingum Routing-Verfahren weiterleitet. Das Modell verwendet drei Modellparameter, den Abfluss Koeffizienten (RC), die Zahl der Reservoire (N) und die Reservoir Konstante (K). Für unbeobachteten Einzugsgebieten, müssen die Modellparameter RC, N und K durch ein Regionalisierungsverfahren geschätzt werden. Die Routing-Verfahren verwendet zwei Parameter, die Muskingum-Retentionskonstante (k_m) und den Gewichtungsfaktor (x_m), die mit einem empirischen Verfahren geschätzt werden. Die Untersuchung konzentrierte sich nur auf die Ableitung von Transfer-Funktionen die die Schätzungen der Modellparameter RC, N und K in unbeobachteten Einzugsgebieten ermöglichen.

Die Untersuchung wurde mit 209 Niederschlag-Abfluss Ereignissen aus 41 Einzugsgebieten im Süd-Westen von Deutschland durchgeführt; die Region erfasst den Schwarzwald und die Schwäbische Alb. Das Untersuchungsgebiet entwässert in die drei Flüsse Rhein, Neckar und Donau. Von den 41 Einzugsgebieten, wurden 22 zur Ableitung der Regionalisierungsmethodologie und 19 zur Validierung der Methodologie verwendet. Der Gebietsniederschlag für die Ereignisse wurde durch Externe-Drift-Kriging von beobachteten Niederschlagesdaten abgeschätzt. Für jedes Regenereignis wurden verschiedene sowohl ereignis-, als auch einzugsgebietsspezifische hydrologische Merkmale bestimmt, die Topographie, Morphologie, Böden und Landnutznutzung beschreiben.

Wenn der Gesamtniederschlag (P_t) und Niederschlagsverlust (P_l) während eines Niederschlag-Abfluss Ereignis bekannt sind, kann RC für das Ereignis geschätzt werden. Deshalb wurde in dieser Untersuchung die Transfer-Funktion für P_l, anstatt für RC, abgeleitet. "Beobachtete" P_l für die Ereignisse wurde aus der beobachteten Abflussganglinien mittels Straight-Line-Hydrograph-Seperation Methode abgeschätzt. Vier verschiedene Ansätze zur Ableitung vier verschiedener Transfer-Funktionen für P_l wurden verwendet: eine multiple lineare Transfer-Funktion (MLTF), eine neuronales Netzwerk Transfer-Funktion (ANNTF), eine Fuzzy-Logik Transfer-Funktion (FLTF) und eine logistische Transfer-Funktion (LoTF).

MLTF, ANNTF und FLTF repräsentieren den rein datengestützten Ansatz, d.h. dass die Transfer-Funktionen durch Optimierung der Anpassung zwischen beobachteten und berechneten P_l, ohne Berücksichtigung der physikalischen Prozessen, abgeleitet wurden. ANNTF und FLTF, aufgrund ihrer Fähigkeit nicht-lineare Beziehungen explizit abzubilden, erzielten einen sehr hohen Korrelationskoeffizienten der Anpassung von $Corr = 0,95$. MLTF, jedoch, wegen der Begrenzung auf Linearität, ergab eine moderate Anpassung mit $Corr = 0,90$. LoTF hingegen repräsentiert einen Ansatz, der sich sowohl auf Daten als auch auf physikalisches Wissen stützt. Das bedeutet, dass. während der Optimierung der Anpassung, *a priori* Erkenntnisse über die physikalischen Prozesse des Niederschlagverlusts in die Transfer-Funktion eingehen. Die optimierte LoTF, die eine Anpassung mit $Corr = 0,95$ ergab, setze P_l in Beziehung zum Ereignisniederschlag, zum Vorregenindex, zur Flussdichte, zum Ereignismonat, zur Landnutzung, zur Feldkapazität und zum Bodendurchlässigkeitsbeiwert. Bei der Validierung zeigten ANNTF, FLTF und LoTF hohe Anpassungsgüten mit $Corr = 0,94$ für die Einzugsgebiete, die nicht für die Kalibrierung verwendet wurden.

Um zu untersuchen, ob die Transfer-Funktionen physikalisch sinnvoll sind, wurde eine Validierung des physikalischen Zusammenhangs durchgeführt. Die Vorzeichen der Ableitungen des funktionalen Zusammenhangs zwischen Predigtoren und P_l in der jeweiligen Transfer-Funktion wurden mit den Vorzeichen verglichen, die sich aus dem *a priori* Wissen über den physikalischen Zusammenhang ergeben. Die Validierung zeigte auf, dass die Reaktion der ANNTF und FLTF auf hydrologische Veränderungen oft den physikalischen Beziehungen widerspricht. ANNTF und FLTF scheinen weder robust genug und noch physikalisch sinnvoll zu sein. Wegen dem Fehlen physikalischer Grundlagen, ist eine Anwendung der rein datengestützten Ansätze für die Extrapolation (oder Regionalisierung) zur Vorhersage von Ereignissen außerhalb des Kalibrierungsbereichs sehr fragwürdig. Auf der anderen Seite hat die Validierung von LoTF für die physikalischen Beziehungen gezeigt, dass die Vorzeichen der Ableitungen der funktionalen Beziehungen den physikalischen Beziehungen, übereinstimmen. Somit ist LoTF robust und physisch sinnvoll. Weil er physikalisch sinnvolle Ergebnisse lieferte und gleichzeitig eine sehr hohe Anpassungsgüte, stellte sich in dieser Analyse der Ansatz, die Datenanpassung mit physikalischem a priori Nutzen zu verbinden, als am besten heraus für die Regionalisierung von P_l.

Die Nash-Kaskade Parameter N und K sind untereinander stark korreliert. und können mit einer interparametrischen Funktion miteinander assoziiert werden. Die inter-parametrische Funktion kann durch eine Potenzfunktion mit einem Exponent ($\alpha = -1,0$) und einem Koeffizient (β) repräsentiert werden. β zeigt eine starke Korrelation mit den hydrologischen Merkmalen. Daher wurde eine Regionalisierung von K und β durchgeführt, wobei N mittels K und der interparametrischen Funktion geschätzt werden kann. Somit, wurde das Problem der Äquifinalität durch Regionalisierung der interparametrischen-Beziehung selbst abgehandelt. Um eine in der Region optimale Transfer-Funktionen zu erlangen, wurden diese über den gebietsgemittelten Nash-Sutcliffe Koeffizient (NS) optimiert, als ein aggregiertes Maß der Anpassungsgüte für ein Set an beobachteten Einzugsgebieten. Die Optimierung wurde mit einem Simulated-Annealing Algorithmus ausgeführt. Die optimierten nicht-linearen Transfer-Funktionen setzen die Parameter K und β in Beziehung zur Ereignisdauer, Ereignisniederschlag, Konzentrationszeit, Gefälle, Perimeter und Landnutznutzung. Während der Optimierung der Transfer-Funktionen, wurde eine aggregierte Anpassungsgüte von $\overline{NS} = 0,72$ erreicht. Für 70 % der Ereignisse wurde eine Ereignisspezifische Anpassungsgüte von $NS > 0,7$ überschritten. Die Anpassung den Hochwasserscheitel ($NS_{Qpeak} = 0,93$) und die Anpassung der Zeit der Hochwasserscheitel ($NS_{Tpeak} = 0,89$) implizieren ebenfalls, dass die Transfer-Funktionen ein akzeptables Anpassungsverfahren sind.

Die Validierung der Transfer-Funktionen ergab $\overline{NS} = 0,75$. Für 69 % der Ereignisse wurde $NS > 0,7$ erreicht. Die Anpassung von der Hochwasserscheitel und die Zeit der Hochwasserscheitel waren $NS_{Qpeak} = 0,93$ und $NS_{Tpeak} = 0,87$. Die Anpassungsgüte bei der Validierung war ebenso gut wie bei der Optimierung, was darauf hinweist, dass die Transfer-Funktionen sehr zuverlässig und effizient sind, um die Modellparameter in unbeobachteten Einzugsgebieten zu abschätzen. Die Nash-Kaskade Parameter sind konzeptionell, ihre physikalischen Beziehungen zu den hydrologischen Merkmalen können nicht erklärt werden. Allerdings kann die physikalische Beziehung zwischen der Form der Einheitsganglinie und den hydrologischen Merkmalen aus *a priori* Wissen über die Niederschlag Prozesse hergeleitet werden. Daher wurde die Validierung der Transfer-Funktionen durchgeführt, indem die Veränderung der modellierten Einheitsganglinie aufgrund der Veränderung der hydrologischen Merkmale verglichen wurde mit den Veränderungen, die man mit dem a priori Wissen über die Abflussbeschleunigung Prozessen erwarten würde. Die Validierung bekräftigt, dass die Transfer-Funktionen physikalisch begründet sind.

Die Anpassungsgüte Leistung der abgeleitete Regionalisierungsmethodologie bei der Optimierung und der Validierung deutet darauf hin, dass die Methodologie hoch effizient ist zur Abschätzung des Hochwasservolumen, der Hochwasserscheitel und dem Zeitpunkt des Hochwasserscheitels für ausreichend große Niederschlag-Abfluss Ereignisse in den unbeobachteten Einzugsgebieten. Die Regionalisierungsmethodologie basiert auf physikalisch begründeten Beziehungen zu Ereignis- und Einzugsgebietspezifischen hydrologischen Merkmalen. Daher ist sie robust und geeignet für die zeitliche sowie räumliche Extrapolation der Modellparameter. Da die Methodologie leicht zugängliche hydrologische Merkmale verwendet, sowie einen effizienten Modellierungs- und Regionalisierungsansatz ist sie einfach und praktisch.

Zur Beurteilung der Nützlichkeit der abgeleiteten Regionalisierungsmethodologie für die praktische Anwendung, wurde sie mit den existierenden, üblicherweise verwendeten Anwendungen verglichen, wie zum Beispiel der SCS-Curve-Number Methode und dem Lutz Verfahren, die für das Untersuchungsgebiet abgeleitet und verwendet wurden. Der Vergleich ergab, dass die Regionalisierungsmethodologie für das Untersuchungsgebiet zu besseren Ergebnissen führt als die üblichen Anwendungen. Somit scheint die Regionalisierungsmethodologie nützlich für praxisorientierte Anwendungen zu sein. Der Ansatz, der für diese Untersuchung eingesetzt wurde, ist allgemein und kann für andere “ähnliche” Regionen verwendet werden, aber die

Transfer-Funktionen sind spezifisch für das Untersuchungsgebiet und können nicht direkt in anderen Regionen angewendet werden.

Obwohl die Modellgüte der Regionalisierungsmethodologie sehr hoch ist, ergab die Analyse der Leistung für einzelne Ereignisse, dass die Methodologie bei Schätzungen des Niederschlagsverlust und der Abflussganglinie für die kleine Ereignisse versagt. Die abgeleiteten Transfer-Funktionen sind möglicherweise nicht gültig für Ereignisse mit einer Gesamtniederschlagshöhe unter 20 mm und einer Ereignisdauer kleiner als 10 *Stunden*. Die Modellgüte für Einzugsgebiete im Karst der Schwäbischen Alb ist erwartungsgemäß ebenfalls schlecht aufgrund der Tatsache, dass die Entwässerung in der Region vom Untergrundabfluss dominiert wird.

Die praktische Anwendung der Regionalisierungsmethodologie zur Abschätzung des Bemessungshochwassers und dessen Eigenschaften wird mit einem Fallbeispiel vom Einzugsgebiet Tübingen demonstriert. Da der Anteil der Wald- und Siedlungsflasche in den Transfer-Funktionen zur Parameterabschätzung benutzt werden, besteht die Möglichkeit, die Regionalisierungsmethodologie zu nützen, um den Einfluss von Landnutzänderungen auf den Hochwassereigenschaften zu bewerten. Diese Bewertung von Landnutzungsänderungen wurde für drei verschiedene Landnutzungsszenarien im Einzugsgebiet Tübingen durchgeführt. Der Versuch führte zu der Aussage, dass es möglich ist, die Methodologie zur Bewertung der Beeinflussung von Landnutzänderungen anzuwenden.

1 Introduction

1.1 Dealing with floods

Rivers are as vital for human settlements as they are for the ecosystem. Civilizations have flourished on the banks of the ancient rivers of the World. Ironically, these rivers have also caused the destruction of some of the well-developed ancient civilizations such as Harappan (Indus River) and Sanxingdui (Yangtze River). Rivers have provided the mankind with inexhaustible water resources for irrigation, drinking and even for industrial use during the current industrial era. But at the same time the rivers, owing to their powerful surge during floods, have led to immense destruction of life and wealth over the centuries.

River flooding is defined as overflow of river water onto the land which is otherwise dry, it is a natural phenomenon of periodical occurrence caused typically due to excessive rainfall or snowmelt which cannot be retained by soil and vegetation. Floods are the most frequent natural disasters, destructions caused by floods often include damage to infrastructure, buildings and crops, drinking water contamination, and in severe cases human and live stock deaths. World flood statistics since 1985 indicates that on an average 150 flood instances, causing about 7500 human deaths and wealth loss of about $ 15 Billion, occur per year (Dartmouth, 2004). Furthermore, the recent investigations conclude that flood severity is climbing high due to climate and land use changes (Reynard et al., 2001; Bronstert et al., 2002; Pfister et al., 2004).

Under the shadow of the ever increasing severity of extreme rainfall events and human settlement areas, "dealing with floods" has become a very important issue on the international and national agendas. The World Bank and various national and private institutions are increasingly spending billions of dollars on flood prevention and protection schemes. The most commonly implemented flood protection measures can be classified into two categories:

1. Non-structural measures
   - Flood plain planing
   - Early flood warning and evacuation system
2. Structural measures
   - Flood retention reservoirs
   - Dikes and levees
   - By pass channels

1.2 Design floods and their prediction

To ensure adequate protection, the flood protection measures are designed and constructed to stand with extreme flood events. However, the design and construction for safety against "most extreme flood likely to occur" is not always economically and practically feasible. Hence, the design of any flood protection measure is essentially based on a design flood. The design flood is expressed in terms of its return period or frequency of occurrence. It is an engineering aspect of planning and design of a flood protection measure, adopted in order to ensure optimum balance between required safety against possible floods and cost-effective implementation of a flood protection measure. A design flood of higher return period means higher magnitude of the design flood and, consequently, higher safety. The return period of design flood may vary from 10 years to 10,000 years depending upon population density in a region under consideration, economic value of the region, estimated life span and cost of the flood protection structures. Planning, design and operation of a flood protection measure and its components are essentially based of following key characteristics of design flood (Maidment, 1992; Chow, 1988):

- Total flood runoff volume
- Magnitude of peak flood runoff at the location to be protected
- Time to occurrence of peak flood runoff at the location

Selection of appropriate method for estimation of design flood depends upon availability of hydrological information. Several statistical and deterministic methods to estimate design floods and their characteristics are prevalent in applied hydrology. These methods can be classified into three categories:

1. Historical flood records based methods
2. Runoff based methods (discharge -frequency analysis)
3. Rainfall based methods

1.2.1 Historical flood records based methods

These methods consider records of catastrophic floods occurred in history of a region, these records may be physical signs of water levels on old buildings, memories of old citizens, or historical documents, news reports etc. Once the water level during a historical flood event at a location is known then the corresponding flood runoff may be estimated according to hydraulic capacity of the location. Using such runoff estimations for a set of historical floods, design flood can be obtained through statistical approximations. Few statistical methods can be found in literature to interpret historical flood records to estimate design flood (Kottegoda et al., 1997). These methods are useful for rough estimations of design flood if no rainfall-runoff data is available. But they are limited by availability of historical records and applicable only to the regions where hydraulic conditions have remain unchanged.

1.2.2 Runoff based methods

Runoff based methods, widely known as discharge-frequency analysis, are based on an assumption that a discharge time series for a stream flow can be represented by a definite discharge-frequency relationship. If a significantly long observed discharge time series is available, then obtaining discharge-frequency curve becomes the relatively straightforward statistical task of reorganizing the discharge time series into a frequency distribution curve. Thus, a flood of a desired frequency can be simply selected from the discharge-frequency curve (Hazen, 1914). Such discharge-frequency analysis solely depends upon statistical properties of the observed discharge time series and seldom considers its hydrological context.

Since first proposed by Fuller (1914), there has been plethora of studies carried out to develop different statistical approaches for discharge-frequency analysis (Rao, 2000). Often, the length of available discharge time series does not coincide with the desired return period. In such cases extreme value statistic is employed to extrapolate discharge-frequency curves (Hipel, 1994; Kumar et al., 2005). But even the application of extreme statistic procedures is subjected to minimum required length of time series. If the observed discharge time series for a stream under consideration is not available then regional discharge-frequency analysis is performed by transferring discharge-frequency statistics from neighboring "hydrologically similar" catchment where observed discharge time series is available (Fiorentino et al., 1985; Bhaskar et al., 1989).

However, the common discharge-frequency analysis techniques are based on hydrologically invalid hypotheses (Klemes, 2000). The theory behind discharge-frequency analysis is supported by following two hypotheses:

- A hydrological variable, such as discharge, is an "independent identically distributed random variable" having a continuous distribution of a fairly simple mathematical form.
- The long observed discharge time series required for the analysis, is a "random sample" from this continuous distribution.

To the contrary, it is evident that sequential hydrological phenomenon are not completely independent. In the fact climate as well as hydrological changes in most catchments are continuously influencing their hydrological response, which suggests that hydrological distributions are neither stationary nor identical. Moreover, frequency distribution models are derived from general shape of discharge-frequency curve which is usually dominated by low and medium discharge observations. Consequently, the models attempts to extrapolate extreme floods based on the observations which are hydrologically least relevant to extreme floods (Klemes, 2000).

Furthermore, discharge-frequency analysis concerns itself only with extracting probability statistics of a discharge time series. Being purely data based, its reliability is highly correlated with length and quality of available data (Hashemi et al., 2000; Michele et al., 2001). Lacking consideration for underlying hydrological circumstances, discharge-frequency analysis does not respond to regional changes in land use and climate. Therefore, its application is restricted only to the regions where flow regime has not gone under major changes (Hann, et al., 1994). Moreover, it provides estimation of peak flood runoff only, the other key characteristics of flood hydrograph which are important for design purposes remains unknown.

1.2.3 Rainfall based methods

The application of rainfall based methods is an indirect approach to estimate design flood characteristics, and becomes inevitable if insufficient or no discharge data is available. These methods make use of rainfall data along with additional hydrological information such as area, land use, topography, antecedent moisture conditions etc. Rainfall based methods typically employ empirical, conceptual or physically based rainfall-runoff models to transform rainfall histogram into discharge time series.

The earlier and simple rainfall based methods are empirical formulas, which link flood characteristics in a catchment to one or more important hydrological characteristics of catchment. The parameters of the empirical formulas are generally derived through regression procedures. Such formulas, once derived for a region, can only be used for the region. Number of empirical formulas for different regions of the world have been proposed and used frequently due to their simplicity (NERC, 1975). The drawback of these methods is that by using these formulas the occurrence frequency of estimated discharge can hardly be specified. Moreover, the associated estimation error can be as high as 100 % (Chow, 1964).

The later rainfall based methods include application of an event based or continuous rainfall-runoff models. The application of event based model is evolved into two different approaches, the design storm event approach and the derived distribution approach. In the design storm event approach, design flood characteristics are estimated from design storm event using an event based rainfall-runoff model. If past rainfall records are available, the design storm event can be estimated through intensity-duration-frequency analysis. Otherwise, it can be constructed using regional rainfall characteristics such as probable maximum rainfall and probable maximum storm (Chow et al., 1988). It is relatively simple and deterministic approach. However, the predictions are subjected to the uncertainty of estimation of design storm duration and intensity (Hill et al., 1996; Perera, 1999).

In the derived distribution approach, several storm events are stochastically generated and corresponding flood characteristics are estimated with their probability distribution. The approach requires stochastic rainfall model in addition to an event based rainfall-runoff model. Although the approach is more complex and computationally demanding as it combines the stochastic and deterministic methods, it considerably reduces the subjectivity of prediction to uncertainty of design storm event by having considered several storm events and combinations of several flood producing factors (Raines et al., 1993; Rahman et al., 2002).

Application of continuous rainfall-runoff models also use a combination of deterministic and probabilistic methods. The approach involves estimation of continuous discharge time series using rainfall time series observed continuously over several years, followed by discharge-frequency analysis of the discharge time series. The approach requires a full-fledged continuous simulation model with a soil moisture routine, long term rainfall time series, and a large amount of hydrological data (Boughton et al. 1999; Eberle et al, 2002).

Literature review (Bocchiola et al. 2003; Charalambous, 2004) on the methods for design flood prediction points out that, although discharge frequency analysis has been exploited vigorously in the past, they are becoming less popular for practical applications due to their various limitations. On the other hand, the rainfall based methods are gaining wide acceptance mainly due to the following advantages:

- Rainfall based methods provide not only the peak runoff but also the additional information such as time to occurrence of peak runoff, flood volume etc.
- They are not restricted by the requirement of very long discharge time series
- They demonstrate ability to tackle regional hydrological changes
- They also exhibit potential to handle climate change scenarios through adaptation of rainfall predictions to climate change.

1.3 Rainfall-runoff modeling

A rainfall-runoff model is a set of stochastic or deterministic equations, or combination thereof, designed to estimate runoff hydrograph from one or more hydrological characteristics such as rainfall, land use, soil, topography etc. Rainfall-runoff models are regularly used for scientific investigations as well as engineering applications (Singh, 1995). Since the introduction of one of the earliest single parameter models in the $19th$ century (Mulvany, 1851), and consequent developments such as the concept of isochrones (Clark, 1945) and the unit hydrograph (Sherman, 1932) which could simulate only surface runoff hydrograph. Modern rainfall-runoff models have come a long way to the generation of complex, non-linear, computer based models which facilitate the construction of the time series of different runoff components.

1.3.1 Classification of rainfall-runoff models

The vast number of rainfall-runoff models, developed since the first attempts, can be classified into three distinct classes: empirical models, conceptual models and physically based models, depending on the nature and degree of the process description used to derive the models (Wagener et al., 2004).

Empirical models

Empirical models use observed discharge data to establish model structure and corresponding model parameters by fitting a function of hydrological characteristics with observed discharge using regression procedures. Empirical models completely ignore the underlying physical processes, hence they solely depend upon the information carried by observed data. Early modeling approaches until 1930s were linear or non-linear empirical equations derived to address the basic hydrological problem of design flood prediction for specific cases. They were further developed to estimate the runoff hydrograph. Empirical models are still in use mainly due to their simplicity, but their consistency and transferability between catchments is questionable. The presently used empirical models include multiple regression models (Holder 1985), artificial neural network models (Lange, 1999; Dawson et al., 2001; Kumar et al., 2002) and fuzzy rules based models (Stueber et al., 2000; Hundecha et al., 2001; Bárdossy et al., 2006) etc.

Conceptual models

Conceptual models are built on simplified concepts derived from physical processes of rainfall-runoff phenomena. In conceptual models the relationships between hydrological characteristics and responses are loosely based on the physical processes and do not use their strict representation. Parameters of conceptual models are derived by fitting the modeled discharge with observed discharge. Due to the incorporation of process knowledge, while keeping a simple structure, these models are relatively robust and reliable. A vast number of conceptual models, beginning from reservoir cascade model (Nash, 1957) and geomorphologic unit hydrograph (Rodriguez-Iturbe et al., 1979) to the recent once like IHACRES model (Jakemann et al., 1990) and HBV (Bergstrom, 1995), have been devised and extensively used so far for practical as well as scientific purposes.

Physically based models

The third category of rainfall-runoff models is physically based models which venture to pursue precise representation of the physical processes. These models are usually based on principles of physics such as mass balance or momentum equation. Parameters of physically based models have physical meanings and they can be derived from hydrological characteristics. However, these models are complex, data intensive and computationally demanding. The physically based models include SHE (Abbott et al., 1986), IHDM (Beven et al., 1987), LARSIM (Bremicker, 2000) etc.

1.3.2 Temporal scale of rainfall-runoff models

Rainfall-runoff models are applied over different temporal scales, ranging from a few hours to several years, depending upon the required and available hydrological information. Based on temporal scale, rainfall-runoff models can be classified into two categories: event based models and continuous models.

Event based models

Event based models represent only a single rainfall-runoff event. The temporal scale of event based models, which typically ranges from a few hours to several days, is restricted by the beginning and end of a rainfall-runoff event under consideration. The hydrological conditions prior to an event, such as base flow and antecedent soil moisture, are presumed or derived empirically.

Event based models usually take into account only surface runoff process. The negligence of groundwater and intermediate flow as well as the other complex hydrological processes is attributed to their longer temporal scales. Due to this, event based models are simple and parsimonious. However the reliability of event based models is highly influenced by the input of prior hydrological conditions and representation of short term dynamics of rainfall-runoff processes (Hydrocomp, 2002; Bárdossy, 2000).

Event based models are commonly used for predictions of extreme flood events and consequent erosion. Examples of event based models include EPIC (Williams et. al., 1983) and KINEROS (Smith et. al., 1995).

Continuous models

Continuous models represent time series of rainfall-runoff events and subsequent recessions, the temporal scale of these models typically ranges over few years. Continuous model simulate hydrological conditions during rainfall periods as well as dry periods without an interruption. Thus the models keep a continuous account of the hydrological conditions prior to an event. At the beginning of model run, the initial conditions must be known or assumed. However, as the simulation advances, the models adjust to more “realistic” hydrological conditions.

To keep a continuous account of hydrological conditions, continuous models utilize broad descriptions of rainfall-runoff processes including groundwater flow, evapotranspiration, soil water storage etc. This often makes continuous models more complex, data intensive and over parameterized as compared to event based models (Hydrocomp, 2002; Bárdossy, 2000).

Continuous models are used for predictions of long term water balance, drought or wet periods, ecological aspects etc., which are usually necessary to determine water management policies. Examples of continuous models include HBV (Bergstrom, 1995) and TOPMODEL (Beven et al., 1987).

The rainfall-runoff models can be also classified based on the spatial scale of implantation of hydrological characteristics and processes. Models which assume that the entire catchment is “hydrologically homogeneous” and implements spatially uniform hydrological characteristics and processes are referred as lumped models. The models which divides a catchment into smaller ’homogeneous’ sub-catchments to implement uniform hydrological characteristics and processes over each sub-catchment are referred as semi-distributed models. There are models with even finer spatial disintegration, namely distributed models, which divide a catchment further into number of small ’homogeneous’ grid cells of few square meters in size (Hundecha, 2004).

1.3.3 Limitations of rainfall-runoff models

Any rainfall-runoff model, whether it is empirical, conceptual or physically based, cannot capture the precise nature of rainfall-runoff processes. This is principally due to the lack of thorough understanding of the physics behind rainfall-runoff processes and inadequate representation of the available process knowledge. The present knowledge on complex interactions among various hydrological variables and the presently employed formulations to characterize them in model structure are hardly enough to mimic their vastly complex nature (Sivapalan et al., 2003).

Furthermore, the immense spatial heterogeneity of hydrological characteristics is beyond the reach of present modeling practices. The known physical descriptions such as Darcy's law are derived at laboratory scales, their application at catchment scale necessitates hydrological input at each point in the catchment which is practically impossible. In the best cases hydrological characteristics are measured at few points scattered in a given catchment. For modeling purpose the point values are up-scaled or down-scaled to model scale (sub-catchment or grid cell etc.) under the assumption that the point values are homogeneously distributed in the catchment. The inevitable averaging effect of the scaling procedure confines the ability of the models to capture the heterogeneity. Secondly, the numerical approximations implemented to simplify the model calculations pose their own limitations on the modeled processes and response (Hundecha, 2004).

1.3.4 Model parameters and calibration

In order to account for the "unidentified and unrepresented" rainfall-runoff processes and the "immeasurable" heterogeneity of hydrological variables, rainfall-runoff models use certain coefficients, namely model parameters. Model parameters are inherent in all models. Some parameters (e.g., gas constant, gravitational acceleration) are accepted as universal constants, but parameters of rainfall-runoff models, very often, are not constant and may vary in time and space (Duan et al., 2006).

In ideal sense, if a model precisely represents the physical processes, the model parameters can actually be obtained through field measurements or calculations based on the principles of physics. However, since the presently existing models are limited due to complexity of rainfall-runoff processes and heterogeneity of hydrological characteristics, measurements or direct estimations of parameters are not viable. Instead, calibration procedures which estimate model parameters indirectly using observed discharge data are commonly employed to estimate the parameters. In the calibration procedure model parameters are indeed treated as tuning knobs to match the modeled response with observed response. The calibration procedure (figure 1.1) for rainfall-runoff models essentially involves:

1. Modeling of discharge time series using the model under consideration, hydrological inputs and initial values model parameters.

2. Estimation of objective function (OF) which is a statistical measure (e.g. root

mean squared error, correlation etc.) of goodness fit between observed discharge time series (Q_{ob}) and the modeled discharge time series (Q_{ca}).

3. Searching for the best model parameters by optimizing the objective function in a systematic way.

4. Validation, where the performance of the calibrated model parameters is cross-checked for the part of the data which is not used for the calibration.

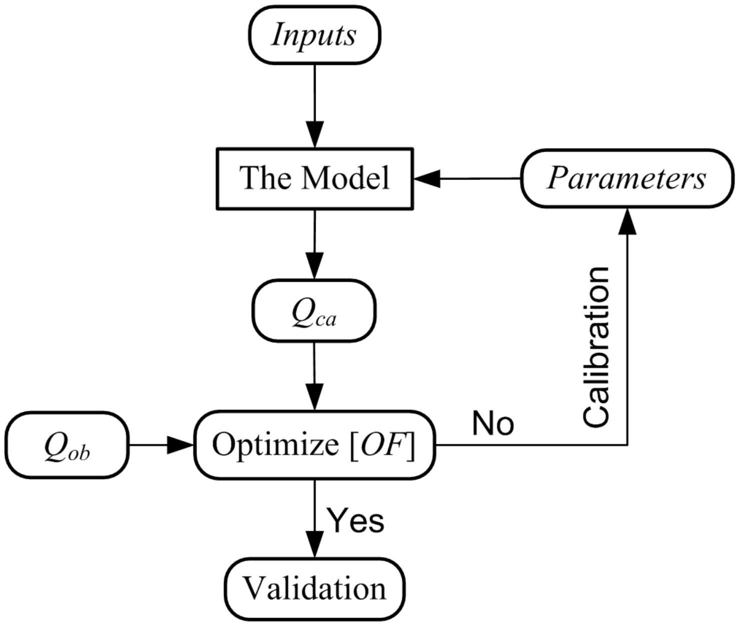

Figure 1.1: Calibration procedure for rainfall-runoff models

Calibration of rainfall-runoff models for a catchment is carried out under the implicit assumption that the hydrological conditions in the catchment are unchanged and the past of the catchment can be adequately used for estimations of the catchment's present and future. Availability of adequate discharge time series is the most important issue for calibration of rainfall-runoff models. The necessary length of a discharge time series for a "good" calibration depends upon the temporal hydrological variability captured by the time series (Gupta et al., 1983) and the number of parameters to be calibrated (Franchini et al., 1991). In general, discharge time series for at least one complete year, if it is of a sufficiently high quality and covers a high degree of temporal variability, is essential for a "good" calibration of a continuous model (Wagener et al., 2004).

1.4 Problem of predictions in ungauged catchments

Ungauged catchments are those catchments in which the river discharges have not been measured in the past, hence, no observed discharge time series is available for rainfall-runoff model calibration. Catchments for which available observed discharge time series is inadequate for the calibration are also considered ungauged. Since all rainfall-runoff models chiefly depend upon observed discharge time series to derive at least a few selected model parameters, in principle, rainfall-runoff models can be applied only to those catchments where observed discharge time series are available.

However, very few catchments in the world are actually monitored. Most of the catchments, especially in the developing world, lack the adequate discharge measurements necessary for model calibration. Even in case of a gauged catchment, predictions are sometimes necessary at interior points for which discharge measurements are inexistent. These facts lead hydrologists to the challenge of predictions in ungauged catchments. Further, due to the nature and human induced changes in the spatial and temporal distribution of hydrological characteristics (e.g. mean annual rainfall, land use), hydrological conditions in many catchments are subjected to changes. Consequently, past discharge time series do not represent the present and future hydrological conditions. Hence, even for those catchments where discharge data is available, the conventional calibration procedures may not be sufficient.

1.5 Objective of the study

This study was intended to address the problem of predictions of flood characteristics: flood runoff volume, peak runoff and time to occurrence of peak runoff, in ungauged catchments. One possible approach to deal with the problem of predictions in ungauged catchments is to establish transfer functions which associate model parameters with relevant hydrological characteristics using a set of gauged catchments. Thus, the parameters for an ungauged catchment, which is "identical" to the gauged catchments, can be estimated through the transfer functions using its hydrological characteristics. If the event specific hydrological characteristics (e.g. soil moisture, duration) are used in the transfer functions, temporal extrapolation of the parameters is also possible for the catchments where the hydrological conditions have undergone changes. The approach is commonly known as regionalization and has been widely recognized as a potential technique to tackle the problem of predictions in ungauged catchments.

The main objective of the study was to derive physically reasonable, robust and spatially transferable regionalization methodology which is specifically aimed at predictions of flood characteristics in ungauged catchments. The specific research goals of the study were identified as:

- To set up a parsimonious, event based, semi-distributed unit hydrograph model for predictions of flood runoff volume, peak runoff and time to occurrence of peak runoff.

- To derive transfer functions associating the model parameters with readily available hydrological characteristics. The transfer functions are intended for associating the model parameters not only with catchment characteristics, but also with event specific characteristics. Thus, spatial regionalization as well as temporal extrapolation of the model parameters can be achieved.

- To demonstrate the importance of physically reasonable modeling approaches to hydrological predictions.
- To demonstrate a possibility of using regionalization approach for assessment of impact of land use changes on flood characteristics.

2 Regionalization of Hydrological Models and the Proposed Methodology

2.1 Regionalization: a state of art

As discussed in chapter 1, parameters of conceptual and physically based rainfall-runoff models must be calibrated using observed discharge time series, which is not possible in the case of ungauged catchments. Hence, the application of rainfall-runoff models in ungauged catchments is a long-standing issue in hydrology. Since the early notable studies by Nash (1960) and Manley (1978), plethora of methodologies have been introduced for estimation of model parameters in ungauged catchments. Most of these methodologies have proposed spatial transfer of model parameters from gauged catchments to "similar" ungauged catchments. The spatial transfer of model parameters, commonly referred as regionalization, is based on the assumption that if hydrological characteristics of two catchments are identical, their hydrological responses will be identical too (Bloeschl, 2005). The regionalization approaches proposed so far can be classified into two categories:

- Direct parameter transfer approach
- Regional transfer function approach

2.1.1 Direct parameter transfer approach

The regionalization approach of direct parameter transfer from gauged catchments to unagaued catchments is derived from the assumption that the similar catchments can be represented by identical parameter sets. The simplest approach for direct parameter transfer is to use geographical proximity as the similarity measure. The approach is based on the rationality that the spatial variability of rainfall-runoff relationships is smooth, hence, neighboring catchments exhibit relatively similar rainfall-runoff relationships. Thus, for an ungauged catchment, model parameters can be simply borrowed from the closest gauged catchment in the neighborhood. However, Vandewiele et. al (1995) have demonstrated that using model parameters from only one closest catchment may not be enough. They proposed kriging of the model parameters calibrated for number of gauged catchments in the neighborhood. Further, Haberlandt et. al. (2001) applied external drift kriging to regionalize base flow index using hydrological characteristics as drift variable. Some other studies have proposed averaging of model parameters over nested catchments (Merz and Bloeschl, 2004; Schreider et. al., 2002), zonal clustering of model parameters (Heuvelmans et. al., 2004), etc.

Post et. al. (1998) and Beven (2000) determined that the model parameter transfer from neighboring catchments does not always lead to good parameters for an ungauged catchment. Sometimes, even the neighboring catchments may have entirely different hydrological characteristics. Andrade (1999) and Kokkonen et. al. (2003) proposed that clustering of homogeneous catchments based on hydrological characteristics is possible regardless of the spatial location of the catchments and yields better results than geographical proximity approach. Earlier, Burn and Boorman (1993) had also reached similar conclusions. These studies hypothesized that if the hydrological characteristics of two catchments are similar, then the rainfall-runoff relationships for the two catchments, regardless of their spatial location, might be similar too. Further, these studies proposed clustering of catchments based on similarity of response relevant hydrological characteristics. In this approach, matrix of characteristic distances between several pairs of catchments is established, then homogeneous clusters of the catchments are formed using statistical methods such as cluster analysis, principle component analysis, classification trees, etc. Shu and Burn (2003) utilized a fuzzy expert system to delineate such homogeneous clusters of catchments. Some recent studies (Rao and Srinivas, 2006; Wagener et. al., 2006) have also presented uncertainty analysis for such direct parameter transfer approaches.

Uhlenbrook et. al. (2007) and Leavesley and Stannard (1995) used the clustering approach for identifying homogeneous response units (HRU) of catchments. They divided catchments into several sub-units by overlaying spatially distributed hydrological characteristics. Then the sub-units with identical characteristics were clustered into homogeneous response units (HRUs). Thus, all the sub-units which may be from gauged or ungauged catchments but belong to a same HRU, hypothetically, exhibit similar rainfall-runoff relationships. Hence model parameters calibrated for a sub-unit, which belong to a certain HRU and located in a gauged catchment, can be directly transfered to a sub-unit that also belong to the same HRU but located in an ungauged catchment. The advantage of using HRUs is that, due to higher spatial resolution, relatively higher homogeneity and, subsequently, better parameter allocation can be achieved. But this approach is effective only in the case of physical based models. Moreover, it is extremely difficult to calibrate independent model parameters sets for different HRUs in a catchment using only one observed discharge time series at outlet of the catchment.

Catchments can be considered similar if the dimensionless similarity indices derived from topographic, landscape or stream flow characteristics are similar (Bloeschl, 2005). Moore et. al. (1991) used topographic wetness index (Beven and Kirkby, 1979) to assess similarity between catchments. Cunderlik and Burn (2001) demonstrated application of the flood regime similarity index which considers seasonal pattern and regularity of floods for regional discharge-frequency analysis. More examples of similarity indices include geomorphological characteristics such as stream orders and bifurcation ratio (Horton, 1945), drainage density, hillslope peclet number (Berne et al., 2005) etc. Sivapalan et. al. (1987) derived five dimensionless similarity indices to account for runoff generation processes and combined effect of topographic, soil and rainfall characteristics of a catchment. However, similarity indices are not widely used in practice because their applicability depends on real time catchment and climatic conditions (Bloeschl, 2005).

2.1.2 Regional transfer function approach

The regionalization approach of transferring model parameters from gauged catchments to ungauged catchments through regional transfer functions is established on the assumptions that consistent relationships between model parameters and hydrological characteristics exist and for "similar" catchments their relationships are similar (Jakeman et. al. 1992; Sefton et. al., 1995; Abdulla and Lettenmaier, 1997; Post and Jakeman, 1999; Croke and Norton, 2004). Thus a regional transfer function associates a model parameter with the relevant hydrological characteristics through a unique relationship for a "homogeneous" region or a set of "similar" catchments. Wagener et. al. (2004) obtained strong correlations between the model parameters and the hydrological characteristics for 9 catchments in the United Kingdom, which further promotes the possibility of estimating model parameters through regional transfer functions. A regional transfer function (f_t), as shown in equation 2.1 (Wagener et. al., 2006) defines statistical relationship between a model parameter (MP) and hydrological characteristics (HCs).

$$MP = f_t(HCs_j|\Theta_j) + E \tag{2.1}$$

where,

Θ coefficients of regional transfer function

E regression error

Derivation of regional transfer function

Derivation of regional transfer function is based on the hypothesis that an optimum parameter of a conceptual model, assuming that it represents the inherent heterogeneity and complexity of hydrological processes in a catchment, can be statistically estimated through a unique combination of the hydrological characteristics.

The derivation and application of transfer function (figure 2.1) to predict desired response (R_p) in an ungauged catchment, typically involves the following steps:

1. Selection of the gauged catchments which are "similar" to the ungauged catchment under consideration. The gauged catchments may be selected using geographical proximity approach, hydrological characteristics or similarity indices. It is preferable to have more than one gauged catchment in order to obtain a reliable transfer function.

2. Calibration of model parameters for the gauged catchments using the respective observed responses (R_{ob}).

3. Selection of appropriate hydrological characteristics considered to be relevant to the model parameters. The selection may be based on *a priori* knowledge of hydrological processes or statistical analysis such as correlation or principle component analysis.

4. Derivation of a regional transfer function for each model parameter through regression.

5. Validation of the transfer functions over the gauged catchments which are not used for the regression by assessing the goodness fit of the response modeled using the parameters estimated through the transfer functions.

6. Estimation of the model parameters for the ungauged catchment by inserting the hydrological characteristics of the catchment into the validated transfer functions, and prediction of the response using the estimated model parameters.

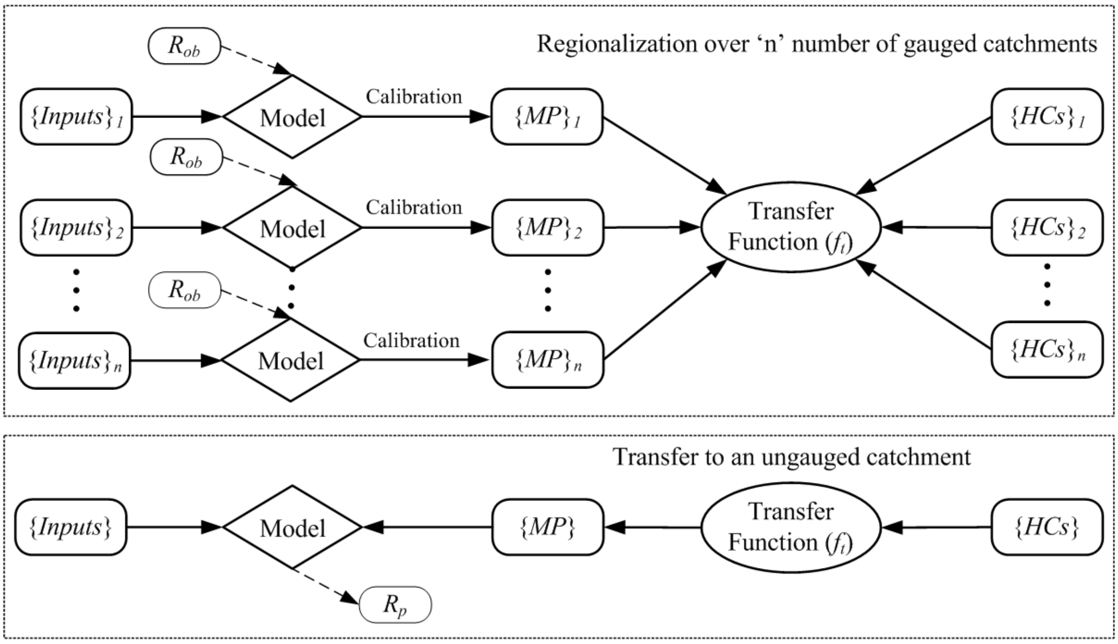

Figure 2.1: Derivation and application of regional transfer function

In the conventional procedure to derive regional transfer function, as outlined above, the calibration of model parameters for gauged catchments is carried out separately for each of the catchments. Thus, the model parameters are calibrated to the optimum for each gauged catchment without any reference to the regional hydrological characteristics. This procedure is based on underlying assumptions that the errors in the calibration of model parameters are normally distributed and that the model parameters are independent of each other (McIntyre et. al., 2005). However, due to the weakness of the assumptions, such regionalization procedures often face the following two problems:

- The problem of equifinality, "optimum parameter set may not be unique" (Beven and Freer, 2001). Due to inter parameter interaction, more than one parameter set may lead to an equally acceptable model performances. Thus, the strength of a transfer function directly depends upon the parameter set selected for its regression from the several optimum parameter sets. Correlations of the model parameters with the hydrological characteristics can be inconsistent for different optimum parameter sets (Merz and Bloeschl, 2004; Lee et. al., 2005).

- Furthermore, even a unique optimum parameter set may not yield good regional transfer function due to the fact that the optimum model performance at catchment scale does not always correspond to the optimum performance at regional scale (Wagener et. al., 2006). Optimum local performance may lead to deteriorated regional performance and *vice versa* (Funke et. al., 1999).

Several modifications over the conventional procedure of calibration and regression have been proposed in order to overcome these problems. Fernandez et. al. (2000) used an overall objective function which aggregates calibration performances for a whole set of gauged catchments as well as regional performances of transfer functions for all the parameters of a monthly water balance model. Thus the local and the regional performances were optimized simultaneously. In the similar attempt, Hundecha and Bárdossy (2004) achieved efficient parameter regionalization of a daily continuous rainfall-runoff model by optimizing only regional performance using aggregated objective function to calibrate coefficients of a predetermined transfer function.

Young (2000) addressed the problem of inter parameter interaction by assuming linear relationship among the model parameters as a function of linear relationship among the hydrological characteristics. Lamb and Kay (2004) used a stepwise procedure to derive transfer functions for each individual model parameter. In the first step of the procedure, a transfer function was derived only for the regionally most sensitive parameter, then the parameter was fixed to the derived transfer function while the rest of the parameters were recalibrated. In the next step, the procedure was repeated for the next most sensitive model parameter. In this way the remaining parameters become more identifiable and the problem of selecting optimum local parameter for regression can be reduced (Wagener et. al., 2006). Kokkonen et. al. (2003) regionalized only one of the two parameters of their model and related the other parameter to the regionalized one through a function. Thus, they tried to the exploit the strong relationship between the two parameters.

Koren et. al. (2000) and Duan et. al. (2001) proposed an approach to estimate model parameters directly from catchment characteristics. They assumed that the parameters of a lumped conceptual model are more or less equivalent to a combined effect of catchment characteristics such as hydraulic conductivity or field capacity. Therefore, they can be estimated by using physically reasonable empirical function of the relevant catchment characteristics. However, the approach is based on the weak assumption that lumped model parameters can be related to point observations of catchment characteristics.

2.2 Existing methods for flood predictions in ungauged catchments

Several different methods, based on the above discussed regionalization approaches, have been proposed for flood predictions in ungauged catchments. Among them, Soil Conservation Service (SCS) method (SCS, 1972) is being commonly applied in the various parts of the world. Lutz's procedure (Lutz, 1984), however, was specifically derived for the study area under consideration. The SCS method and the Lutz procedure were used as references to assess the performance of the regionalization methodology derived during this study.

2.2.1 SCS method

The SCS method, originally developed by U.S. Soil Conservation Service (SCS, 1972), is widely accepted as a standard practice in many parts of the word with few modifications. Initially, the method was used for estimating volume and peak of flood runoff for storm events, and for evaluating the impact of land use changes. Later, it was modified with slope correction for the purpose of erosion modeling (Sharpley and Williams, 1990). The method comprises of: SCS curve number method to estimate runoff volume and SCS dimensionless unit hydrograph to estimate peak runoff and the time to peak runoff.

SCS curve number method

Equation 2.2 shows the empirical formula developed by Soil Conservation Service to estimate specific direct runoff volume (V_{Qd}). The equation uses only one parameter, the curve number (CN), which depends upon land use and soil characteristics of catchment. Based on extensive field surveys and data analysis, NRCS (2004) has recommended the curve numbers for various combinations of land use and soil types.

$$V_{Qd} = \frac{\left[P_t - \frac{5080}{CN} + 50.8\right]^2}{\left[P_t + \frac{20320}{CN} - 203.2\right]} \tag{2.2}$$

where,

V_{Qd} specific direct runoff volume $[mm]$

P_t total rainfall during an events $[mm]$

Before using in the equation 2.2, the curve number must be modified for season of occurrence of event and antecedent soil moisture conditions, as shown in table 2.1 (SCS, 1972). Assessment of antecedent soil moisture conditions is usually based on 5 days antecedent rainfall. The originally recommended curve numbers belong to class II (CN_{II}), curve number for class I (CN_I) and class III (CN_{III}) can be estimated using equation 2.3 and 2.4.

$$CN_I = \frac{CN_{II}}{2.281 - 0.01281 CN_{II}} \tag{2.3}$$

Table 2.1: Curve number classification based on antecedent rainfall and seasons (SCS, 1972)

CN **class**	5-day antecedent precipitation $[mm]$		
	Dormant season	**Growing season**	**Average**
I	< 13	< 36	< 23
II	13 - 28	36 - 53	23 - 40
III	> 28	> 53	> 40

$$CN_{III} = \frac{CN_{II}}{0.427 + 0.00573 CN_{II}} \tag{2.4}$$

Modified SCS curve number method

Sharpley and Williams (1990) incorporated slope correction into SCS curve number method by adjusting the originally recommended curve number (CN_{II}) to mean slope (SL) of catchment. A curve number can be adjusted to slope (CN_{IIs}) using equation 2.5, which can be then used in equation 2.3 and 2.4 to estimate CN_{Is} and CN_{IIIs}.

$$CN_{IIs} = \frac{1}{3}\left(CN_{II} e^{0.00673(100 - CN_{II})} - CN_{II}\right)\left(1 - 2e^{-13.86 SL}\right) + CN_{II} \tag{2.5}$$

SCS dimensionless unit hydrograph

SCS dimensionless unit hydrograph is based on the analysis carried out by Mockus (1957) using large number of observed runoff hydrographs from the catchments of largely varying sizes and geographical locations. SCS (1972) proposed a standard dimensionless unit hydrograph (DUH) which was obtained by averaging the unit hydrographs derived from the observed runoff hydrographs. The ordinates of the DUH (figure 2.2) are expressed as ratio of discharge to peak discharge (Q/Q_{peak}) and the abscissas are expressed as ratio of time to time to peak (t/t_{peak}). The ordinates and corresponding abscissas of the standard DUH are listed in SCS (1972).

However, to derive direct runoff hydrograph from DUH Q_{peak} and t_{peak} must be known. To reduce the unknowns, DUH was further approximated by a triangular unit hydrograph (TUH; figure 2.2) by keeping the same percent of runoff volume on the rising side of TUH as that on the rising side of DUH. Thus, the only unknown remained is t_{peak} which can be determined from time of concentration (TC; see: section 3.4.2) using various empirical formulas, such as equation 2.6. Direct runoff hydrograph for a storm event, the corresponding peak runoff and the time to the peak runoff can be then approximated using TUH through the principles of unit hydrograph theory (see: section 2.3.1).

$$t_{peak} = 0.6\ TC \tag{2.6}$$

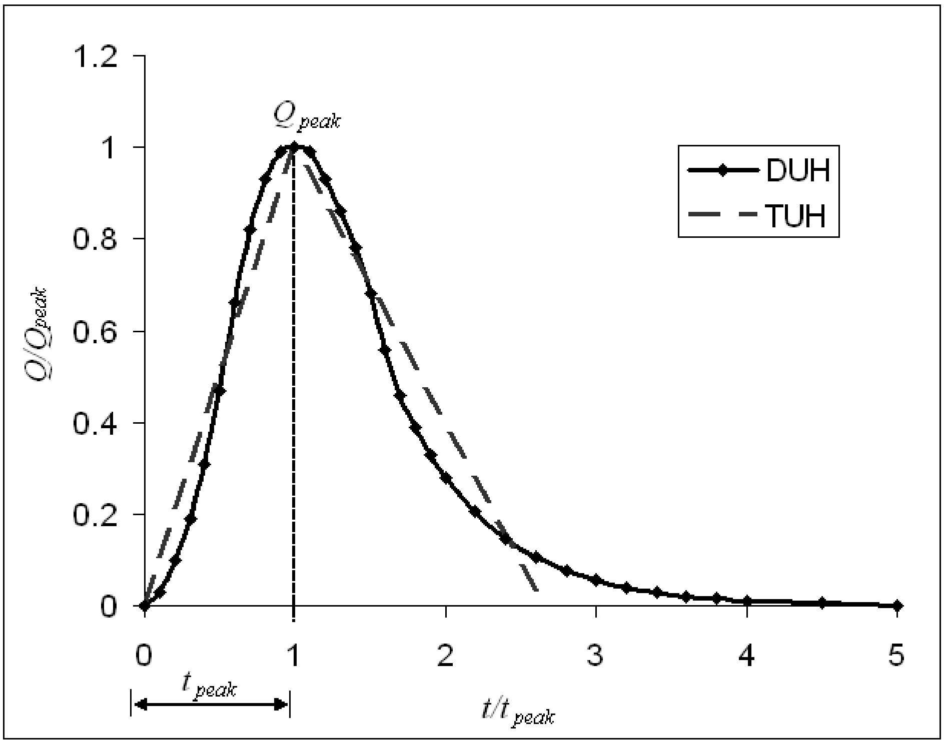

Figure 2.2: SCS dimensionless and triangular unit hydrograph

Limitations of the SCS method

The SCS curve number method can be applied only in the case of big storm events. If the total rainfall depth is below 50 mm, the method often underestimates the direct runoff volume (Bárdossy, 2000). Furthermore, the method does not explicitly account for antecedent moisture condition which, although, has a great impact on runoff generation (Beven, 2001). Morel-Seytoux and Verdin (1981) demonstrated that SCS curve number method may not be physically reasonable because it estimates increasing rate of water retention in a catchment with increase in rainfall intensity. SCS DUH or TUH provides only empirical approximation of flood runoff characteristics, its reliability is limited to the type and the size of the catchments which were used for its derivation.

2.2.2 Lutz procedure

Lutz (1984) developed the regionalization procedure to predict direct runoff volume and hydrograph for storm events in ungauged catchments in the western part of Germany. The procedure was developed through rigorous analysis of rainfall-runoff relationship for 961 storm events from 75 catchments which also include the catchments in the study area under consideration (see: chapter 3). The procedure has been used as a standard practice to estimate design flood and the impact of land use changes in the south-west part of Germany. The Lutz procedure comprises of two parts: the Lutz direct runoff volume and the Lutz direct runoff hydrograph.

Lutz direct runoff volume

In the Lutz procedure, runoff generation for sealed area and unsealed area is calculated separately. Runoff generation over sealed area is considered to be function of empirical parameters which represent initial loss, and a runoff factor for the sealed area. Runoff generation over the unsealed area is considered to be function of land use, soil type, antecedent base flow, week of occurrence of event, duration of event and related empirical parameters. Equations 2.7 to 2.10 describe estimation of rainfall loss using Lutz procedure. The recommendations for values of various empirical parameters used in the procedure can be found in Lutz (1984).

$$a = C_1 \; e^{-C_2/WZ} \; e^{-C_3/q_B} \; e^{-C_4 T_D} \tag{2.7}$$

$$V_{Qd,s} = \left[P_t - A'_v\right] \Psi_s \frac{A_{E,s}}{A_E} \tag{2.8}$$

$$V_{Qd,us} = \left[(P_t - A_v)c - \frac{c}{a}(1 - e^{-a(P_t - A_v)})\right] \frac{A_E - A_{E,s}}{A_E} \tag{2.9}$$

$$V_{Qd} = V_{Qd,s} + V_{Qd,us} \tag{2.10}$$

$V_{Qd,s}$ direct runoff generation over sealed areas $[mm]$

$V_{Qd,us}$ direct runoff generation over unsealed areas $[mm]$

A'_v initial rainfall loss for sealed areas $[mm]$

A_v initial rainfall loss for unsealed areas $[mm]$

A_E area of catchment $[km^2]$

$A_{E,s}$ area of sealed areas $[km^2]$

Ψ_s runoff factor for sealed areas [-]

C maximum runoff factor weighted over unsealed areas of different land use and soil types [-]

a event dependent factor $[1/mm]$

C_1, C_2, C_3, C_4 catchment and land use dependent empirical parameters [-]

WZ week factor [-]

q_B antecedent base flow $[l/s/km^2]$

T_D duration of rainfall event $[hr]$

Lutz direct runoff hydrograph

The Lutz procedure to derive direct runoff hydrograph is based on the concept of the linear reservoir cascade (Nash, 1957; see: section 2.3.1). The Nash cascade parameters N and K are considered to be function of length of main river channel, length of main river channel up to centroid of catchment, slope of main river channel, proportion of area of urban and forest land use, and an empirical catchment factor. Additional correction factors for event specific conditions are implemented as functions of rainfall intensity, month of occurrence of event and runoff coefficient. The recommendations for catchment factor for various regions in Germany can be found in Lutz (1984). Equations 2.11 to 2.15 demonstrate Lutz procedure to estimate the Nash cascade parameters, where N is derived through iterative procedure using equation 2.14. After deriving the Nash cascade parameters, a direct runoff hydrograph can be estimated using equation 2.19.

$$t_A = P1 \left(\frac{L\ L_c}{I_g^{1.5}}\right)^{0.26} e^{-0.016\ U}\ e^{0.004\ W} \tag{2.11}$$

$$t'_A = a_1\ a_2\ a_3\ t_A \tag{2.12}$$

$$u_{max} = 0.464\ (t'_A)^{-0.824}\ \ (for\ hourly\ interval) \tag{2.13}$$

$$u_{max}\ t'_A = \frac{(N-1)^N}{\Gamma(N)}\ e^{-(N-1)} \tag{2.14}$$

$$t'_A = (N-1)\ K \tag{2.15}$$

t_A rising time of unit hydrograph $[hr]$

t'_A corrected rising time of unit hydrograph $[hr]$

$P1$ empirical catchment factor [-]

L length of main river channel $[km]$

L_c length of main river channel up to centroid of catchment$[km]$

I_g weighted slope of main river channel [-]

U percentage of urban area [%]

W percentage of forested area [%]

$a_1,\ a_2,\ a_3$ event specific correction factors depending on rainfall intensity, month and runoff coefficient [-]

u_{max} value of peak ordinate of unit hydrograph $[1/hr]$

Limitations of Lutz procedure

The Lutz procedure uses several catchment and region specific empirical coefficients which were approximated by Lutz. Due to this fact, it is virtually impossible to employ the procedure in a catchment for which the coefficients are not available. Although the procedure is still being commonly applied, it was developed in 1984 under the limiting data and computational conditions. It would be worthwhile to develop a revised regionalization methodology using more extensive and better quality data as well as advanced computational facilities.

2.3 The proposed methodology

Regional transfer functions, if derived through purely data driven regression, may lead to the functional relationships which are contradicting with the physical relationships of rainfall-runoff phenomena. Such physically unreasonable transfer functions, although they often perform efficiently within the range of the dataset used for the regression, are unsubstantial and may lead to erroneous predictions for the circumstances beyond the range of the dataset. Therefore, to obtain a physically reasonable and robust regionalization methodology, it is important that the relationships between the end response of the model and the hydrological characteristics used in the regional transfer functions truly represent the physical relationships.

The regionalization methodology proposed during this study is based on the regional transfer function approach. In addition to addressing the problem of parameter interaction and discrepancies between the local and regional optimum parameters, the methodology is aimed at deriving the transfer functions which are physically reasonable and adheres to the physical processes of runoff generation and propagation.

2.3.1 The rainfall-runoff model

Complex and over parameterized models suffer high parameter interaction, subsequently leading to weak regional parameter transfer functions. Therefore in the context of regionalization, it is crucial to use simplistic models which describe only essential components of rainfall-runoff processes with minimum number of parameters (Post et. al., 1998; Wagener et. al., 2002). Such models are often referred as parsimonious models. While selecting a model concept for the purpose of predictions of design flood characteristics in ungauged catchments, following criterion were considered.

- Since only flood events are to be predicted, event based modeling is sufficient.
- In order to minimize parameter interaction, the selection of a parsimonious model concept is crucial.
- To facilitate predictions under data scarce conditions, the intended model should be operable with readily available data.

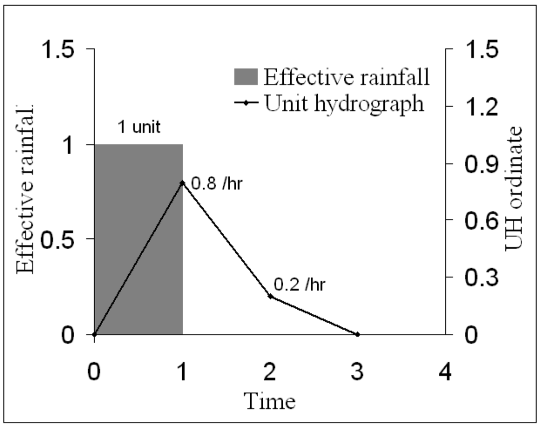

Figure 2.3: Unit hydrograph of 1 hour duration

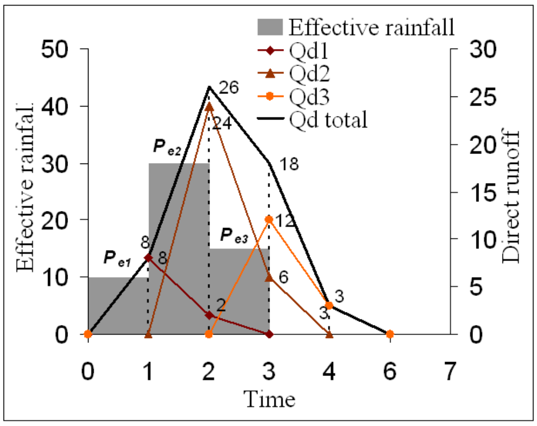

Figure 2.4: Superposition of direct runoff hydrographs

The model concept

The unit hydrograph is the most commonly used approach to model rainfall-runoff events. A unit hydrograph for a given catchment is defined as the direct runoff hydrograph produced by 1 unit depth of effective rainfall generated uniformly over the catchment area at a uniform rate during a specified duration (figure 2.3). The unit hydrograph theory proposed by Sherman (1932) is based on following assumptions (Chow, 1988):

- The base length, i.e. time length, of direct runoff hydrograph produced by an effective rainfall of specified duration is essentially constant, regardless of total depth of effective rainfall.
- The ordinates of the direct runoff hydrographs of a common base length are directly proportional to the corresponding total depth of effective rainfall.
- For a catchment, the shape of direct runoff hydrograph produced by a given effective rainfall of specified duration reflects combined effect of the catchment characteristics, and it is independent of time or the concurrent runoff produced by antecedent effective rainfall.

The first two assumptions are known as principles of proportionality and superposition, the third assumption is known as principle of time invariance. Using the principles of proportionality, direct runoff hydrograph can be calculated for any depth of effective rainfall of specified unit-hydrograph-duration. Further, using the principle of superposition, direct runoff hydrograph produced by high-intensity rainfall event of any pattern can be reconstructed by superposing the direct runoff hydrographs corresponding to the depths of the effective rainfalls occurred during successive time intervals of the event duration (figure 2.4). The principle of time invariance underlines that unit hydrograph is unique for a catchment and invariable with respect to time (Chow et. al., 1988).

Due to its simplicity and flexibility, the unit hydrograph theory is widely adapted in practice for deriving flood runoff hydrograph from design storm event and, for flood forecasting based on prediction of extreme storm event. However, the unit hydrograph theory is valid only under the condition that effective rainfall is uniformly distributed, which limits its application to relatively small scale ($< 100\ km^2$) catchments. Furthermore, it can be used only for relatively short duration ($< 12\ hr$) events with nearly constant effective rainfall intensity (Chow et. al., 1988).

The unit hydrograph produced by 1 unit depth of hypothetical effective rainfall of infinitesimally small duration is termed as instantaneous unit hydrograph (IUH). IUH represents impulse response function of catchment characteristics. The main advantage of IUH is that it characterizes the catchment response to rainfall without any reference to rainfall duration. Thus, it can be used to derive direct runoff hydrograph for an event of any duration (Chow et. al., 1988). Since IUH represents combined effect of hydrological characteristics, if parameterized, it can be also used for regionalization. IUH can be determined through: mathematical approaches such as harmonic analysis (ODonnell, 1960), Laplace transform (Chow et. al., 1988) etc. or, conceptual approaches such as geomorphological analysis (Rodriguez-Iturbe and Valdes, 1979), time-area diagram (Clark, 1945), linear reservoir cascade (Nash, 1957) etc.

Based on the previously mentioned selection criterion, the concept of linear reservoir cascade was selected to develop an event based Nash cascade model. The concept of linear reservoir cascade is derived from the assumption that the operation performed by a catchment on effective rainfall is analogous to that performed by routing through a series of linear reservoirs (figure 2.5). Thus the unit hydrograph can be estimated using equation 2.16. Despite of being simple and parsimonious, the concept is flexible enough to approximate the complex shape of any flood runoff hydrograph (Dooge, 1977).

The proposed event based Nash cascade model uses two Nash cascade parameters: number of reservoirs (N) [-] and reservoir constant (K) [hr], and one runoff generation parameter: runoff coefficient (RC) [-] which is defined as a fraction of total rainfall that contributes to effective rainfall or direct runoff volume at outlet of a catchment during a rainfall-runoff event.

$$g_i = \frac{1}{K\ \Gamma(N)}\ e^{-(\frac{t_i}{K})}\ \left(\frac{t_i}{K}\right)^{(N-1)} \tag{2.16}$$

$$RC = \frac{V_{Qd}}{P_t} = 1 - \frac{P_l}{P_t} \tag{2.17}$$

where,

g_i ordinate of unit hydrograph at time step i [$1/hr$]

t_i time elapsed at time step i [hr]

N number of reservoirs in cascade (series) [-]

K retention time of reservoirs $[hr]$

RC runoff coefficient [-]

V_{Qd} specific direct runoff volume $[mm]$

P_t total rainfall during an event $[mm]$

P_l rainfall loss occurred during an event $[mm]$

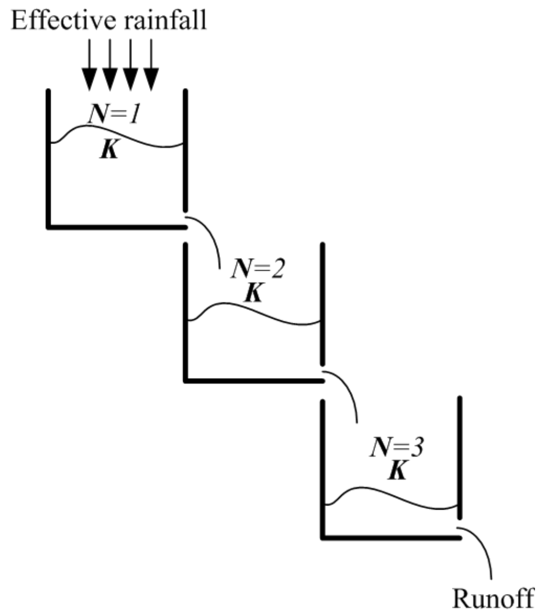

Figure 2.5: Concept of Nash cascade linear reservoirs

The model setup

To capture heterogeneity of hydrological characteristics to a better extent by avoiding averaging over larger areas, the model setup (figure 2.6) is implemented at the subcatchment scale of 50 km^2 to 75 km^2. Various methods, such as runoff coefficient method, constant or variable loss rate method etc., are commonly applied to estimate effective rainfall at each time interval of a rainfall-runoff event. In the proposed model setup effective rainfall at hourly time intervals is estimated using constant loss rate method (equation 2.18). Then, as shown in equation 2.19, the effective rainfall time series for each subcatchment is transformed into hourly direct runoff hydrograph using the Nash cascade parameters for the respective subcatchment. Finally, the direct runoff hydrographs for the subcatchments are routed to outlet of the catchment using flood routing procedure.

The model setup and the flood routing procedure was encoded into computer program using the FORTRAN programming language.

$$P_{e(i,j)} = P_{(i,j)} - \phi_j \tag{2.18}$$

$$Q_{d(i,j)} = \sum_{l=1}^{i} \frac{P_{e(i-l+1,j)}\ A_j}{3.6\ K_j\ \Gamma(N_j)}\ e^{-\left(\frac{t_l}{K_j}\right)}\ \left(\frac{t_l}{K_j}\right)^{(N_j-1)} \tag{2.19}$$

where,

$P_{(i,j)}$ rainfall at time step i at outlet of subcatchment j $[mm/hr]$

$P_{e(i,j)}$ effective rainfall intensity at time step i at outlet of subcatchment j $[mm/hr]$

ϕ rainfall loss rate $[mm/hr]$

N_j number of reservoirs in cascade for subcatchment j [-]

K_j reservoir constant for subcatchment j $[hr]$

$Q_{d(i,j)}$ direct runoff at time step i at outlet of subcatchment j $[m^3/s]$

A_j area of subcatchment j $[km^2]$

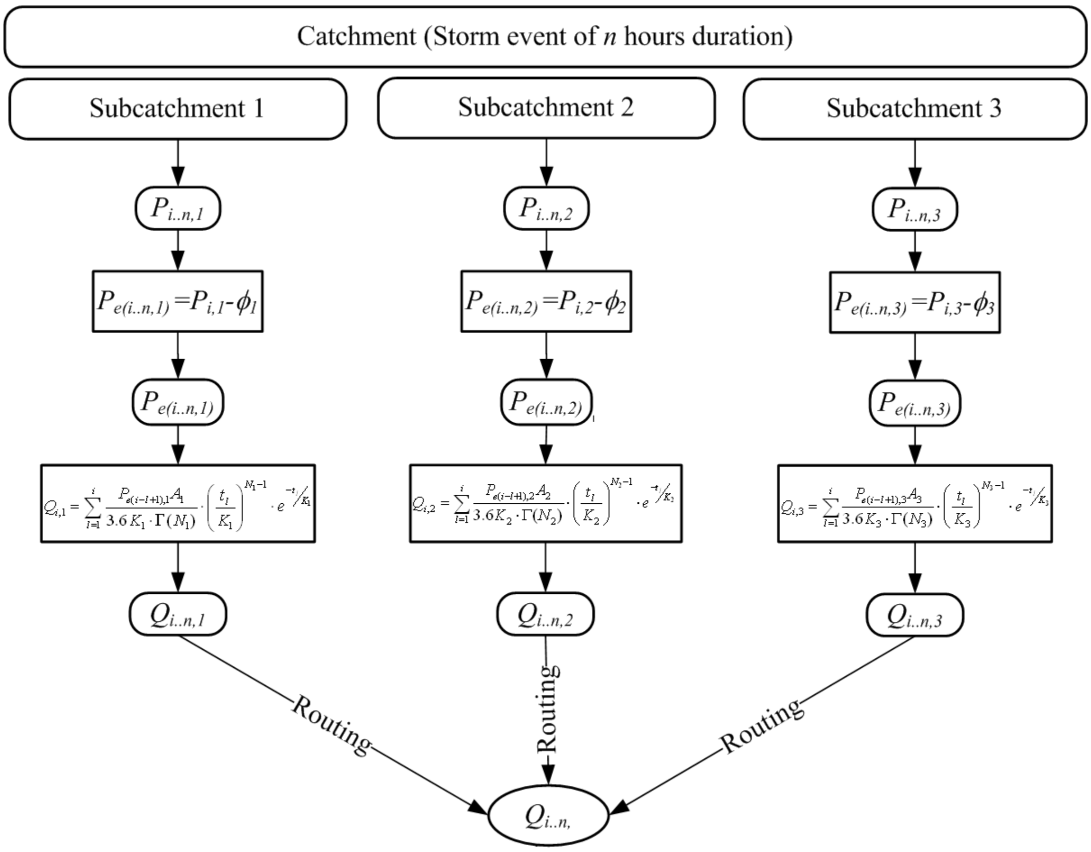

Figure 2.6: Semi-distributed, event based Nash cascade model

2.3.2 Flood routing

Flood routing is necessary in order to account for change in the shape of runoff hydrograph during its propagation from outlet of a subcatchment to outlet of a catchment. The Muskingum flood routing procedure was adopted for the proposed model setup because of its simplicity and less data requirement (Tung, 1985; Gill, 1978). Muskingum routing procedure estimates the outflow at the end of a river stretch using equations 2.20 to 2.24 and the two routing parameters: retention constant (k_m) [s] and weighting factor (x_m) [-].

$$Qout_i = C_1 Qin_i + C_2 Qin_i + C_3 Qout_{i-1} \tag{2.20}$$

$$C_1 = -\frac{k_m x_m - 0.5\Delta t}{k_m(1 - x_m) + 0.5\Delta t} \tag{2.21}$$

$$C_2 = \frac{k_m x_m + 0.5\Delta t}{k_m(1 - x_m) + 0.5\Delta t} \tag{2.22}$$

$$C_3 = \frac{k_m - k_m x_m - 0.5\Delta t}{k_m(1 - x_m) + 0.5\Delta t} \tag{2.23}$$

$$C_1 + C_2 + C_3 = 1 \tag{2.24}$$

where,

$Qout_i$ outflow of at the end of river channel at time step i $[m^3/s]$

Qin_i inflow of at the beginning of river channel at time step i $[m^3/s]$

k_m Muskingum retention constant of river channel $[s]$

x_m Muskingum weighting factor [-]

In the case of gauged catchments, the Muskingum routing parameters k_m and x_m can be estimated through calibration. But for ungauged catchments, the parameters must be estimated using the Muskingum-Cunge (Chow, 1988) method, as shown in equations 2.25 and 2.26. Muskingum-Cunge method uses flow and river channel characteristics to estimate the parameters, these characteristics are usually derived from morphological data. However in the case of this study, due to lack of the morphological data, direct application of Muskingum-Cunge method was not possible. Tewolde and Smithers (2006) demonstrated an empirical approach (equations 2.27 to 2.32) to estimate the flow and river channel characteristics where no morphological data is available. The empirical approach was used to estimate the flow and river channel characteristics, which can be then inserted into Muskingum-Cunge equations to obtain the routing parameters k_m and x_m.

$$k_m = \frac{L}{V_w} \tag{2.25}$$

$$x_m = \frac{1}{2} - \frac{Q_r}{2sP_w V_w L} \tag{2.26}$$

$$Q_r = Q_b + 0.5(Q_p - Q_b) \tag{2.27}$$

$$P_w = 3.82\sqrt{Q_r} \ (for\ cohesive\ river\ bed) \tag{2.28}$$

$$y = \left(\frac{Q_r}{0.508 P_w \sqrt{s}}\right)^{\left(\frac{3}{5}\right)} \tag{2.29}$$

$$R = \frac{2y}{3} \ (for\ wide\ parabolic\ channels) \tag{2.30}$$

$$V_{av} = \frac{R^{\left(\frac{2}{3}\right)}\sqrt{s}}{n} \tag{2.31}$$

$$V_w = \frac{11V_a v}{9} \ (for\ wide\ parabolic\ channels) \tag{2.32}$$

where,

Q_r reference discharge $[m^3/s]$

Q_b base flow $[m^3/s]$

Q_p peak flow $[m^3/s]$

P_w weighted perimeter $[m]$

y flow depth $[m]$

R hydraulic mean depth $[m]$

V_{av} average velocity $[m/s]$

s slope of river channel [-]

L length of river channel [-]

n Manning's roughness coefficient [-] (here, n=0.035)

V_w celerity $[m/s]$

2.3.3 Regionalization of the model parameters

Among the three model parameters of the proposed event based Nash cascade model, runoff coefficient RC deals with runoff generation, on the other hand Nash cascade parameters N and K represent runoff propagation. The two processes are independent of each other, hence, RC can be treated independent of N and K. This facilitates to break up the regionalization procedure of the model parameters into into two steps.

Since the parameter RC is independent of the other two parameters, the parameter identification (equifinality) problem does not exist for RC. In the case of gauged catchments, RC for an event can be calculated from "observed" direct runoff volume for the event. However, in the case of ungauged catchments where the observed runoff hydrograph is not available, the direct runoff volume must be determined indirectly by deducting rainfall loss from the total rainfall occurred during the event. Rainfall loss occurred during an event represents infiltration and interception of rainfall, which directly depends upon catchment and event specific hydrological characteristics. Thus, there is a possibility to estimate rainfall loss through the regional transfer function approach. Therefore, it is intended to derive a transfer function for rainfall loss which can be then used to calculate RC as shown in equation 2.17. Four different possibilities, using purely data driven as well as data-plus-knowledge driven approaches, were investigated to obtain a robust and physically reasonable transfer function for rainfall loss.

On the other hand, in the case of Nash cascade parameters N and K, it has been observed that calibrating parameters for a rainfall-runoff event in a catchment may result in large number (> 100) of parameter sets yielding equally high model performance (Bárdossy, 2007), which underlines the strong interaction between the two parameters. Therefore, to derive transfer functions for the Nash cascade parameters, a different approach was employed. The approach is aimed at exploiting the inter-parameter relationship to reduce the uncertainty due to parameter identification problems. Furthermore, it is intended to derive regionally optimum solution by optimizing the regional performance of the transfer functions.

The regionalization procedures for the three parameters of the event based Nash cascade model and the respective results are discussed in details in chapter 4 and chapter 5.

3 Overview of the Study Area and the Hydrological Characteristics

3.1 General description of the study area

The study under discussion was carried out over the south-west region of Germany (figure 3.1). The region is governed under the state authorities of Baden-Wuerttemberg. Stuttgart, Karlsruhe and Tuebingen are the major urban settlements in the region. The main rivers in the region are Rhein, Danube and Neckar. The Rhein river forms western boundary of the region and the Neckar flows through central part of the region to meet the Rhein at Manheim. The 367 km long stretch of the Neckar divides the region into western and eastern parts. The western part is covered with the Black Forest and the eastern part stretches over the Swabian Alps. The selected catchments form major part of the Rhein basin; 13,000 (km^2) of which is drained through the Neckar and the remaining through various small tributaries. A small part of the study area drains into the Danube which flows along the south-east foothill of the Swabian Alps.

The region extends over wide range of landscape features. Although in the South it exhibits highly varying altitudes, the cities on the North are situated in the relatively flat valley of the Neckar river. Topographic elevation in the region ranges from 124 m.a.s.l to 1487 m.a.s.l. with a mean elevation of about 600 m.a.s.l. Although maximum slopes in parts of Black Forest and the Swabian Alps are as high as 150 %, the mean slope in the region is only 15 %, with 90 % of the slopes are within range of 0 % to 32 %.

The oldest geologic formations in the region are the variegated sandstone formations. The variegated sandstone formations are covered with variety of sediment formations from the Jurassic and the Triassic periods which are predominantly composed of malm, doggerlime, keuper, shelly limestone and sandstone. Some parts at the foothill of the Swabian Alp are composed of karstic rock formations. The karstic rock formations act as interconnected subsurface reservoirs causing considerably large amount of subsurface water transfer from one catchment to another catchment on relatively short time scale. The subsurface flow directions are not yet fully understood which often leads to discrepancies in water balance calculations for the region.

Variations in the soil cover of the region is a direct consequence of the geological variability. Soil cover in the area of the Black Forest, which is made of shallow podsols and grey brown podsols, is formed by weathered variegated sandstones. The eastern areas are covered with layers of loess, sandy soils as well as heavy clay originated from shelly limestone and keuper formations.

The dominating vegetation in the region is forest of spruce, fir and beech. The fertile areas on the either banks of the Neckar and foothills of the Swabian Alps are mostly used for agriculture, pasture and meadows. The slopes of the Swabian Alps are partly used for cultivation of wine yards, fruits etc. and partly covered with ash, beech and elm trees. The barren soil on the top of the Swabian Alps is covered with heath and juniper.

The climate of the region is influenced by both continental as well as oceanic weather systems. But due to western wind flowing through the region, the impact of the Atlantic Ocean is relatively higher. The weather is characterized by warm-to-hot summers and mild winters. The minimum average temperature in the region is estimated to be -0.5^oC in January and the maximum average temperature to be 17.3^oC in July. The annual mean potential evapotranspiration is estimated to be 560 mm, with the minimum monthly potential evapotranspiration of about 10 mm in January and the maximum monthly potential evapotranspiration of about 90 mm in July.

Mean annual rainfall in the region ranges from 740 mm near Stuttgart to 1790 mm in the Black Forest with spatial mean of 1160 mm. Mean summer rainfall and the mean winter rainfall are respectively estimated to be 645 mm and 520 mm. From December to April precipitation usually occurs as snow fall, most of the runoff events occurring during this period can be attributed to snow melt. The runoff events in the months of July, August and September can be attributed to east bound advective storm coming from the Atlantic Ocean.

The above mentioned description of the study area is based on the descriptions provided by Bárdossy et. al. (1999), Patil (2004) and Das (2006).

3.2 Data situation of the study area

The meteorological, hydrological and landscape data for the region was provided by German Weather Service (DWD) and State Agency for Environmental Protection, Baden-Wuerttemberg (LFU-BW). Detailed description of the available data is presented in table 3.1.

3.3 Selection of catchments and events

The crucial criteria behind the selection of the catchments was the availability of the hydrological data at required spatial and temporal resolution. During the selection, only the mesoscale catchments with area ranging for 50 km^2 to 1000 km^2 were considered. The catchments influenced by hydraulic control structures and hydro-power plants were deliberately neglected.

With the intention to cover the wide extent of the regional characteristics, 41 catchments were selected across the region. Twenty one of the selected catchments drain into the Neckar, 17 catchments drain into the Rhein through various small tributaries

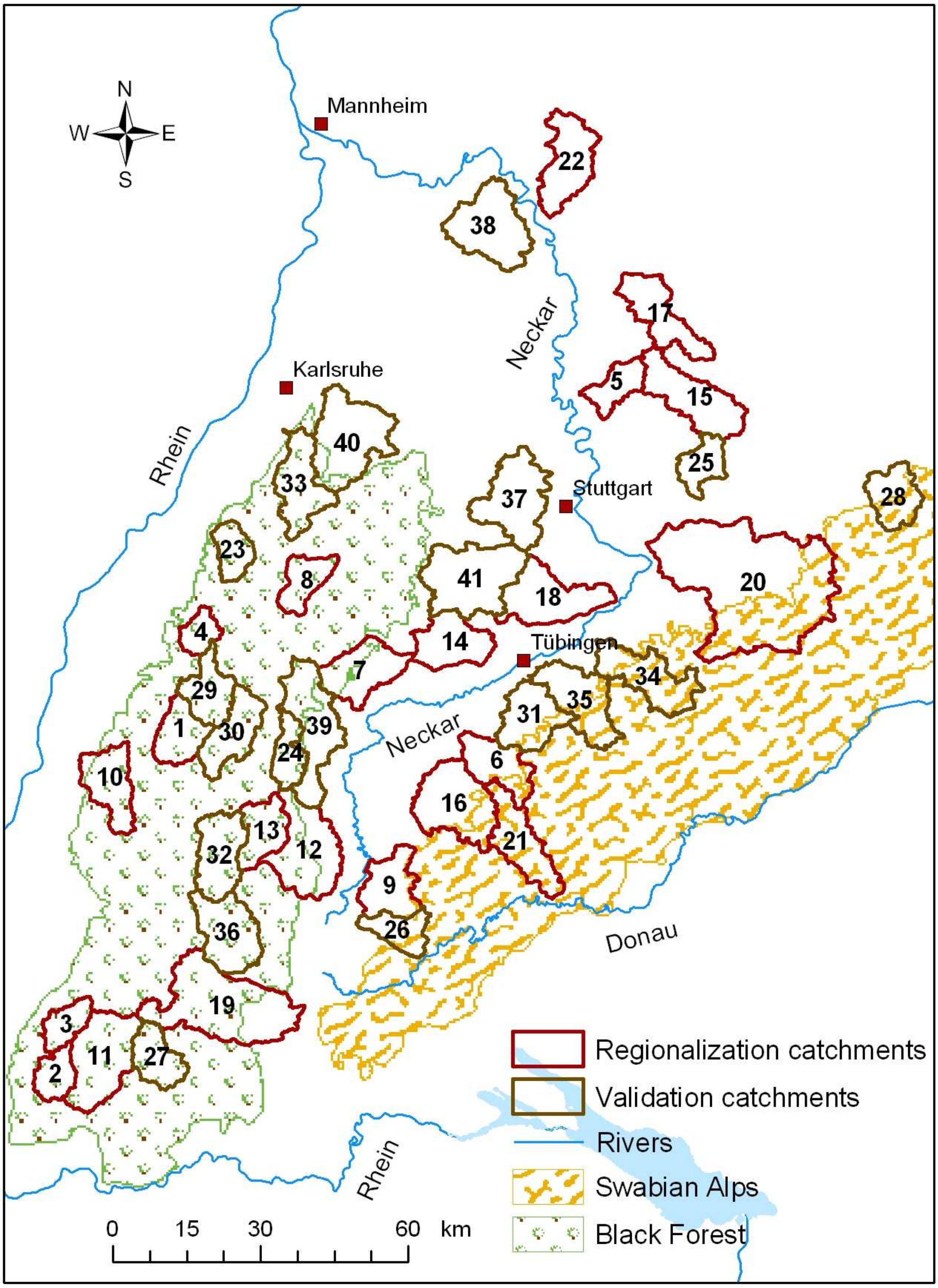

Figure 3.1: Overview of the study area and selected catchments

Table 3.1: Description of the available data

Data	Time /period	Number of stations	Temporal scale	Spatial Scale
Discharge time series	1974-2003	41	hourly	-
Rainfall time series	1980-2003	212	hourly	1 station/180 km^2
Rainfall time series	1958-2003	475	daily	1 station/80 km^2
Digital elevation map	-	-	-	30 m x 30 m
Land use (10 classes)	1975	-	-	50 m x 50 m
Land use (16 classes)	1993	-	-	30 m x 30 m
Land use (16 classes)	2000	-	-	30 m x 30 m
Soil classification map	-	-	-	1:600,000
Stream flow network	-	-	-	1:500,000

and the rest 3 directly drain into the Danube.

Standard split sampling method was used for the optimization and validation of the regionalization methodology. It was assumed that the region is relatively homogeneous and the selected catchments are relatively similar. Hence regionalization and validation sets were formed by randomly distributing the catchments into the either sets. Out of the 41 catchments, 22 catchments (regionalization set: catchments 1-22 in table 3.2) were used to set up and to optimize the proposed regionalization methodology and rest 19 catchments (validation set: catchments 23-41 in table 3.2) were used for validation of the regionalization methodology.

More than 200 large rainfall-runoff events, which occurred during the period from 1989 to 2003, were selected from the catchments. Out of them, 104 events belong to the regionalization set and 105 events belong to the validation set. In order to avoid snow melt events, the events occurred during the period from beginning of December to end of April were not considered for the selection. The table 3.4 shows the statistics of hydrological characteristics for the regionalization and validation sets. Figure 3.2 and 3.3 show overview of the spatial distribution of highest and mean specific peak runoff (q_{peak}) $[mm/hr]$ for the events selected from each catchments.

3.3.1 Estimation of rainfall

The event based Nash cascade model needs input of hourly rainfall time series lumped at subcatchment scale. In order to estimate the rainfall input for the subcatchments, it was essential to interpolate the point measurements of rainfall to grid cells. The interpolation was carried out by using a external drift kriging procedure (Ahmed and Marsily, 1987). To account for the orographic effect on the rainfall fields, square of topographic elevation was used as the external drift variable.

Initially, only hourly rainfall data was used for the estimations. However, it was

Table 3.2: Summary of the selected Catchments

Catchment number	Catchment name	Area (km^2)	Number of subcatchments	Number of events
1	Zell am Harmersbach	103	2	1
2	Tegernau	70	2	9
3	Untermünstertal	66	2	8
4	Kappelrodeck	53	2	6
5	Steinheim	76	2	6
6	Rangendingen	123	2	6
7	Iselshausen	147	3	6
8	Lautenhof	85	2	5
9	Göllsdorf	124	3	5
10	Lahr	130	3	5
11	Zell	206	4	5
12	Horgen-Kläranlage	208	3	5
13	Hinterlehengericht	106	2	4
14	Pfäffingen	134	3	4
15	Oppenweiler	181	3	4
16	Owingen	206	4	4
17	Neuenstadt	141	3	3
18	Oberensingen	178	4	3
19	Ewattingen	341	7	2
20	Plochingen	704	12	2
21	Unterschmeien	151	3	1
22	Mosbach	156	3	1
23	Baden-Baden	71	2	7
24	Schenkenzell	76	2	9
25	Haubersbronn	77	2	1
26	Tuttlingen	81	2	4
27	St. Blasien	97	2	9
28	Hüttlingen	107	2	3
29	Ramsbach	108	2	8
30	Oberwolfach	126	2	7
31	Tübingen	141	3	4
32	Gutach	145	3	8
33	Ettlingen	149	4	3
34	Riederich	160	3	3
35	Wannweil	161	3	8
36	Hammereisenbach	164	3	6
37	Talhausen	192	3	7
38	Eschelbronn	198	4	4
39	Hopfau	202	4	9
40	Berghausen	232	5	1
41	Schafhausen	238	5	4

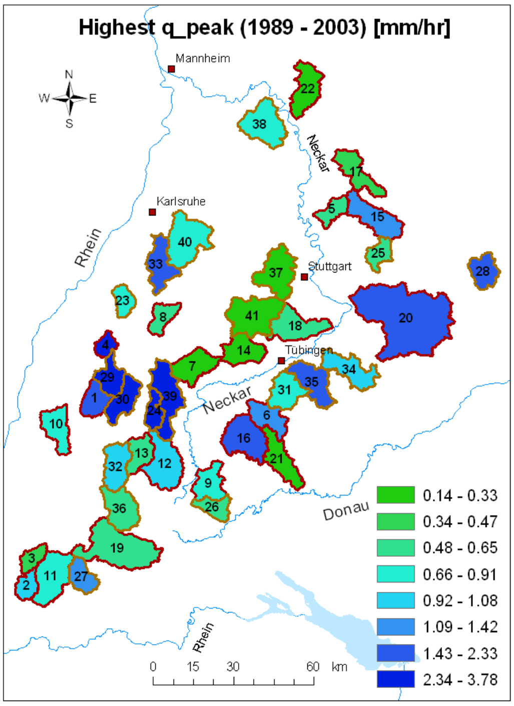

Figure 3.2: Maximum spec. peak runoff

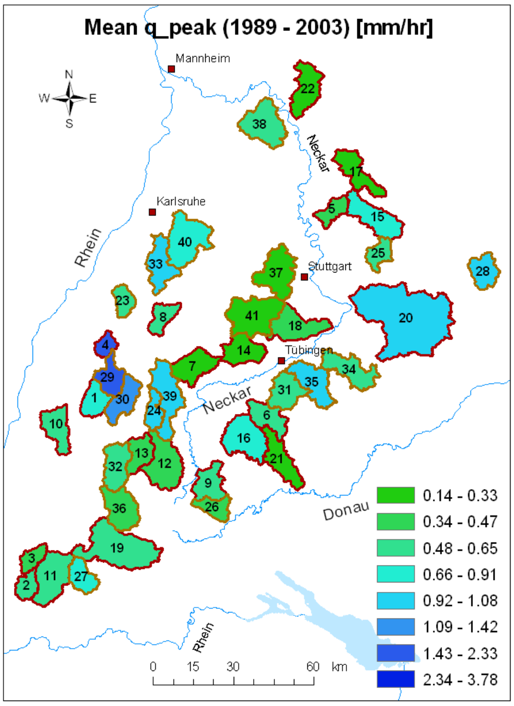

Figure 3.3: Mean spec. peak runoff

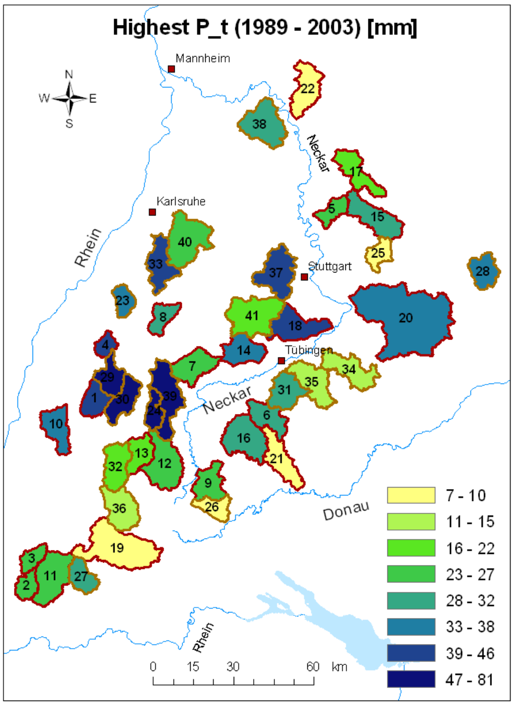

Figure 3.4: Maximum total rainfall

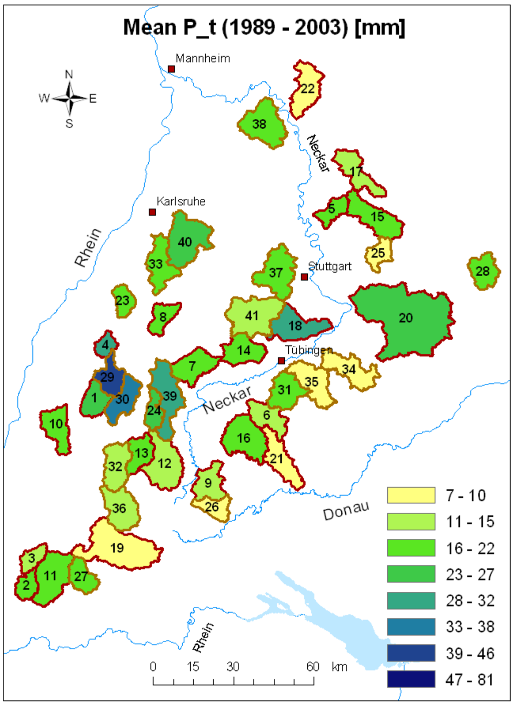

Figure 3.5: Mean total rainfall

observed that the hourly rainfall data, although representing temporal distribution of the rainfall quite well, leads to frequent underestimations of amount of rainfall. Figure 3.6 shows the interpolated rainfall and the direct runoff hydrograph for one of the selected rainfall-runoff events. It can be observed that, although the temporal distribution of the interpolated rainfall is correlated with the direct runoff, the specific volume of the interpolated rainfall (4.4 mm) is actually less than the specific direct runoff volume (5.1 mm) for the event. This is due to the fact that the network of the hourly rainfall measurement stations is not dense enough to capture the spatial distribution of the rainfall fields. On the other hand, density of the daily rainfall measurement stations is high, and allows for the capture of spatial distribution of the daily rainfall fairly well. Hence, the daily rainfall (P_{dly}) [mm] at each grid cell, was weighted by the hourly rainfall (P_{hr}) [mm] at the grid cell, as shown in equation 3.1, to disintegrate the daily rainfall into hourly time step. Thus, modified rainfall estimations, although do not solve the problem completely, lead to improvement over the previous estimations. The corrected lumped hourly rainfall time series ($P_{hr,corr}$) [mm] was then used as the main input for the event based model.

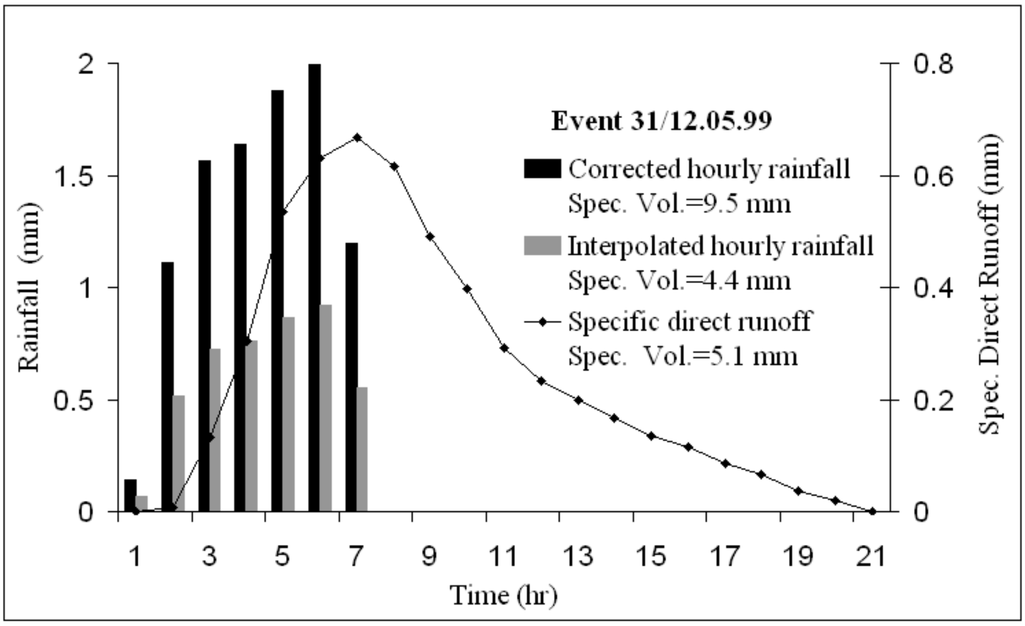

Figure 3.6: Interpolated hourly rainfall and corrected hourly rainfall

$$P_{i,hr,corr} = \frac{P_{i,hr}}{\sum_{j=1}^{24} P_{j,hr}} \cdot P_{dly} \qquad (3.1)$$

3.4 Estimations of hydrological characteristics

To capture the heterogeneity of the hydrological characteristics to a better extent by avoiding averaging over larger areas, the selected catchments were divided into subcatchments of size 50 km^2 to 75 km^2. Estimation of the hydrological characteristics was carried out at the subcatchment scale using the data set mentioned in the table 3.1. Delineation of the subcatchments and drainage network as well as estimation of the spatial hydrological characteristics was carried out using GIS tools. The various hydrological characteristics are classified into two groups: event specific characteristics and catchment specific characteristics. The relevance of the hydrological characteristics to rainfall-runoff processes and their estimations are discussed in the following sections. Statistics of the hydrological characteristics for the regionalization and validation sets are given in table 3.4, at the end of this chapter.

3.4.1 Event specific characteristics

Event specific characteristics are those which are dependent on the rainfall-runoff event and the conditions prior to the event. The event specific characteristics include total rainfall, event duration, season, antecedent moisture conditions etc. Due to the fact that hydrological conditions in a catchment are continuously alternating, response of a catchment to two identical but temporally separate rainfall events can be very different from each other (Beven, 2001). Therefore, while modeling rainfall-runoff processes, it is crucial to account for the event specific conditions of a catchment. Inclusion of the event specific characteristics in the regional transfer functions may also facilitate temporal extrapolation of the model parameters.

Total rainfall and duration

Total rainfall and the duration of a rainfall event may have a significant influence on the runoff generation process during the event. Higher total rainfall may lead to a larger runoff coefficient (RC) [-]. On the other hand, longer event duration may lead to smaller runoff coefficients. The influence of total rainfall and duration on the runoff propagation is, however, not yet fully understood. Total rainfall (P_t) $[mm]$ and duration (T_p) $[hr]$ were estimated for the selected rainfall-runoff events using the respective rainfall time series. Figure 3.4 and 3.5 show the spatial distribution of maximum and mean total event rainfall for the events selected from each catchment.

Season

The season of a rainfall-runoff event can be represented by the month (M) of occurrence of the event. Seasonal variations in the catchment conditions such as soil moisture, temperature, vegetation etc. greatly influence the runoff generation process. The summer months lead to smaller runoff coefficient due to presence of vegetation and rapid evaporation. On the other hand, saturated soil conditions and the lack of vegetation in the winter, often lead to a larger runoff coefficient.

Antecedent precipitation index

The soil moisture condition prior to a rainfall event has great influence on runoff generation process, higher moisture content, generally, leads to a higher runoff generation (Chow, 1988) and *vice versa*. Exact soil moisture condition prior to a rainfall-runoff event, practically, cannot be determined. Hence, antecedent precipitation index (API) $[mm]$ is often used as a measure of the soil moisture condition. Antecedent precipitation index is based on the assumption that soil moisture after a rainfall event decreases exponentially. The more time elapsed after rainfall is ceased the less moisture remained in soil due to evaporation and infiltration losses. The antecedent precipitation index can be calculated using equation 3.2. The decay factor λ normally ranges between 0.85 and 0.98, depending on the catchment or the region. However, most of the empirical investigations suggest $\lambda = 0.90$ which was commonly used for all the catchments under consideration. The impact of rainfall preceding an event by more than 7 days was not considered ($n = 7$ days).

$$API(t_0) = \sum_{i=1}^{n} P_{dly}(t_{0-i}) \cdot \lambda^i \tag{3.2}$$

3.4.2 Catchment specific characteristics

Catchment specific characteristics are those which do not change significantly with time or event, however, may vary with respect to spatial location. The catchment specific characteristics include catchment shape, morphology, topography, soil properties etc. Rainfall-runoff processes in a catchment are chiefly governed by the catchment specific characteristics, most of the existing regionalization methods associate the model parameters only with catchment characteristics. Thus, the relationship between model parameters and catchment specific characteristics facilitates spatial extrapolation or regionalization of the model parameters.

Area and perimeter

Form of a catchment, which can be expressed in terms of its area (A) [km^2] and perimeter (Per) [km], may considerably influence runoff generation as well as propagation process in the catchment. The larger area and perimeter of a catchment, the longer traveling distances and the subsequent retention time which leads to higher rainfall loss and delayed arrival of runoff at outlet of the catchment.

Shape factor

The shape factor (SF) [-] is an approximate representation of shape of a catchment in the form of ratio of area of the catchment and square of length of the longest path in the catchment. For two catchments with equal areas, a smaller value of the shape factor means an elongated catchment and larger values are representative of fan-shaped catchments. Elongated catchments usually exhibit longer time to occurrence of peak runoff due to longer flow paths, on the other hand a compact fan-shaped catchment may cause quick runoff concentration at its outlet.

$$SF = \frac{A}{L_l^2} \tag{3.3}$$

Mean slope

Runoff generation process, surface and groundwater flow patterns are greatly influenced by the topographic patterns in a catchment (Beven, 2001). Surface slope is the most prominent variable through which catchment topography can be expressed.

Steep slopes in a catchment cause faster runoff propagation, thus may lead to large runoff volume and high peak runoff. Local slopes for each grid cell were calculated from the digital elevation map by means of GIS tools, then the mean slope (SL) [-] of each subcatchment was estimated by taking spatial average of the grid based slope. The spatial distribution of SL for the catchments is shown in figure 3.7.

Mean topographic wetness index

Topographic wetness index is the variable that describes topographical patterns, it represents the propensity of any point in a catchment to develop saturated conditions (Beven, 2001). Topographic wetness index for a point is expressed as a ratio of the drainage area (a) to upstream of a point to the local topographic slope ($\tan\beta$), as shown in equation 3.4. Topographic wetness index was used in TOPMODEL (Beven and Kirkby, 1979) to predict saturated areas contributing to runoff generation at each time step. In equation 3.5, a negative value of D_i indicates that the area is saturated and saturation overland flow is generated. A positive value of D_i indicates that there is a storage deficit. Thus, each point with the same topographic wetness index behaves functionally in an identical manner (Beven, 2001). Therefore, topographic wetness index may represent the hydrological similarity. High values of the topographic wetness index means either large drainage area or flat slope angles leading to a large storage potential. Thus, a high topographic wetness index may result in a small runoff coefficient and slower runoff propagation. Mean topographic wetness index (TWI) [-] for each subcatchment was calculated by averaging grid based topographic wetness index. Figure 3.8 shows the spatial distribution of TWI for the catchments.

$$twi = ln(\frac{a}{\tan\beta}) \tag{3.4}$$

$$D_i = \overline{D} + m[TWI - ln(\frac{a}{\tan\beta})] \tag{3.5}$$

twi topographic wetness index [-]

TWI mean topographic wetness index [-]

a drainage area to upstream of a point in a catchment [m^2]

$\tan\beta$ local topographic slope at the point [-]

D_i local storage deficit at the point and time step i [m]

$\overline{D}$ mean storage deficit over a catchment [m]

m change in transmissivity with depth [m]

Terrain ruggedness index

Terrain ruggedness index represents the terrain roughness. Terrain ruggedness index for a grid cell is expressed as root mean of the sum of squared elevation differences between the grid cell and its 8 adjacent cells in digital elevation map (Riley et. al., 1999). Higher terrain ruggedness may cause longer retention time, which consequently may lead to smaller runoff coefficient and longer travel time. Terrain ruggedness index for each grid cell was calculated using equation 3.6, then the grid based index was averaged over respective subcatchments to obtain mean terrain ruggedness index (TRI) [m]. The spatial distribution of TRI is shown in figure 3.9.

$$TRI_i = \sqrt{\frac{\sum_{j=1}^{8}(Elv_i - Elv_j)^2}{8}} \tag{3.6}$$

TRI_i terrain ruggedness index for grid cell i

Elv_i elevation of grid cell i

Elv_j elevation of j$^{\text{th}}$ adjacent cell

River density

River density represents network of river streams in a catchment. It is expressed as ratio of sum of lengths of all river streams ($L_{i..n}$) in a catchment and area of the catchment (A). River density is highly correlated with runoff generation process, a dense river network results in higher runoff generation and faster runoff propagation (Patil, 2004). The line density method illustrated by Silvermann (1986) was used to estimate the river density (DR) [$1/km$] for the subcatchments. Figure 3.10 shows the spatial distribution of DR.

$$DR = \frac{\sum_{i=1}^{n} L_i}{A} \tag{3.7}$$

Time of concentration

Time of concentration is the time after which runoff produced at the farthest point from the outlet of a catchment, reaches the outlet. Theoretically, it represents the time at which runoff from complete area of the catchment under constant rainfall begins to concentrate at the outlet and the runoff curve reach at its peak. For small catchments time of concentration is very close to time to occurrence of peak runoff at outlet, but for large catchments it is often greater than the time to occurrence of peak runoff. However, time of concentration usually exhibits high correlations with time to occurrence of peak runoff at outlet and the peak runoff itself. Time of concentration (TC) [hr] can be estimated by means of the Kirpich formula (equation 3.8; Kirpich, 1940) using the longest flow path in the catchment (L_l) [m] and slope of the longest flow path (S).

$$TC = 0.0003245 \cdot \frac{L_l^{0.77}}{S^{0.385}} \tag{3.8}$$

Soil classes based on hydraulic conductivity

Infiltration of rainfall into the soil surface directly depends upon vertical hydraulic conductivity [mm/hr] of the soil (Chow, 1988), hence, vertical hydraulic conductivity of soil plays significant role in runoff generation process. Higher vertical hydraulic

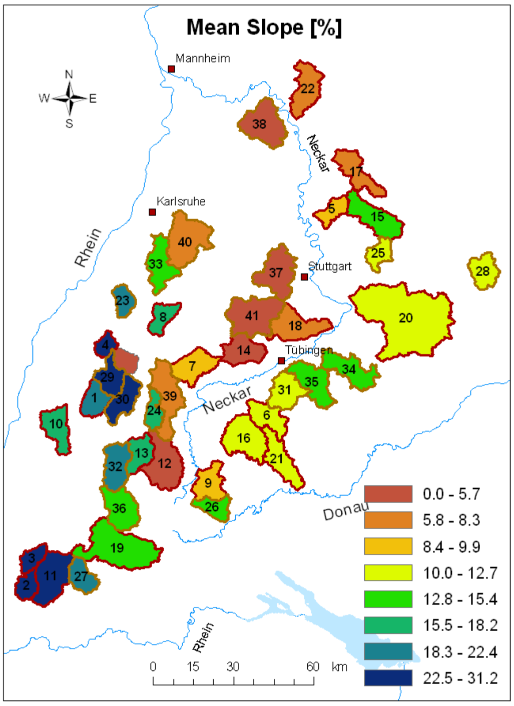

Figure 3.7: Mean slope

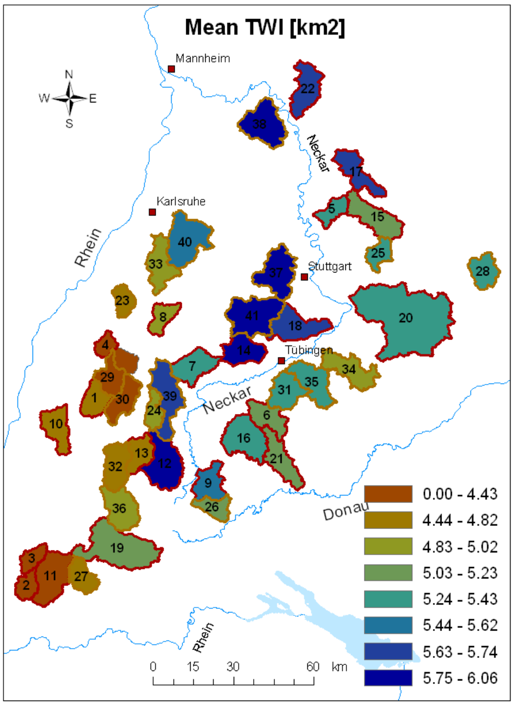

Figure 3.8: Mean top. wetness index

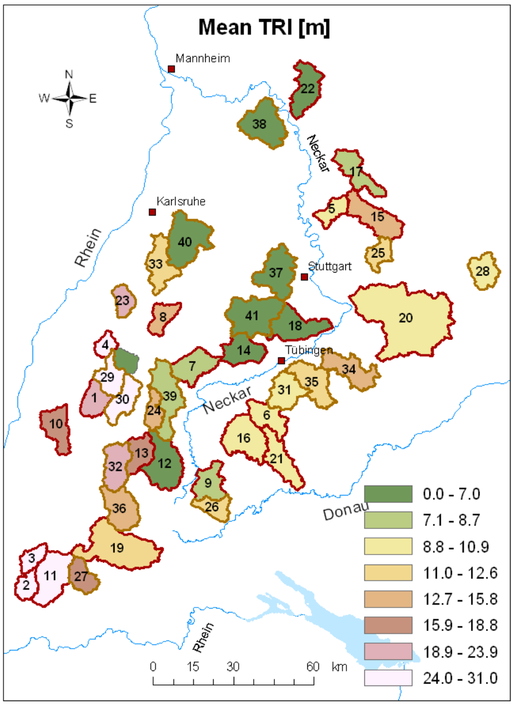

Figure 3.9: Mean top. ruggedness index

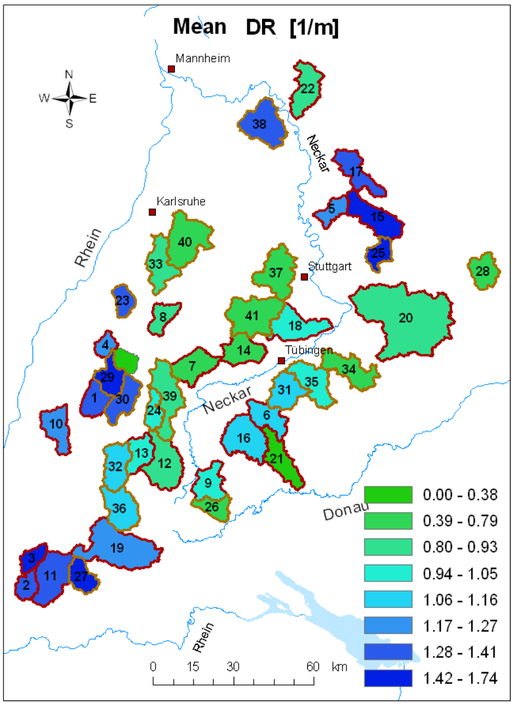

Figure 3.10: Mean river density

conductivity may lead to higher infiltration losses, consequently, smaller runoff volume. The available soil map is provided with 10 soil classes based on the field measurement of vertical hydraulic conductivity, the soil classes were reclassified into three classes, ranging from low to high hydraulic conductivity as shown in table 3.3. Relative areas of the soil classes (Kv) were used as the hydrological variables to describe the hydraulic conductivity. The spatial distribution of the soil classes is shown in figure 3.11.

Table 3.3: Soil classes based on hydraulic conductivity

Notation	Hydraulic conductivity (mm/hr)	Class
Kv_1	< 42	low
Kv_2	42-292	medium
Kv_3	> 292	high

Field capacity

Field capacity of soil is the maximum amount of water per unit area that can be retained by the soil against the force of gravity. The infiltration rate of soil is also related to its field capacity, higher field capacity may lead to lower runoff generation due to large volume of water retained in the soil. Approximate estimations of mean field capacity (FC_m) $[m]$ for the subcatchments were obtained from the available soil map. The spatial distribution of FC_m is shown in figure 3.12.

Land use classes

Recent studies conclude that there are clear indications of effects of land use changes on rainfall-runoff processes (Hundecha and Bárdossy, 2004). Increases in the amount of urban area or decreases in forest area leads to higher runoff generation and faster runoff propagation. Thus, deforestation and urbanization have led to increase in flood severity to disastrous levels. Hence, it was inevitable to incorporate land use characteristics in the proposed regionalization methodology. For simplification the 16 land use classes of the original data sets were reorganized into four classes: Forest (LU_f), Urban (LU_u), Agriculture (LU_a) and water bodies (LU_w). Unlike the other catchment specific characteristics, land use is likely to change not only with space but also with time. Therefore, the relative area of each land use class for each event was estimated through linear interpolation or extrapolation between the land use for year 1993 (figure 3.13) and year 2000 (figure 3.14).

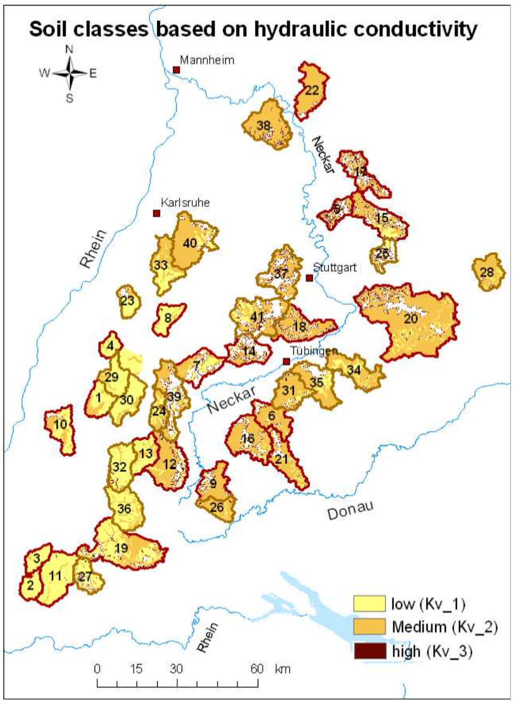

Figure 3.11: Soil classes

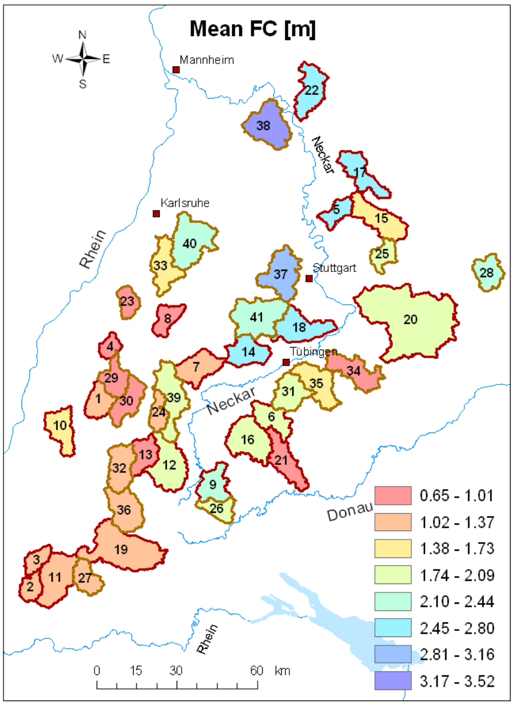

Figure 3.12: Mean field capacity

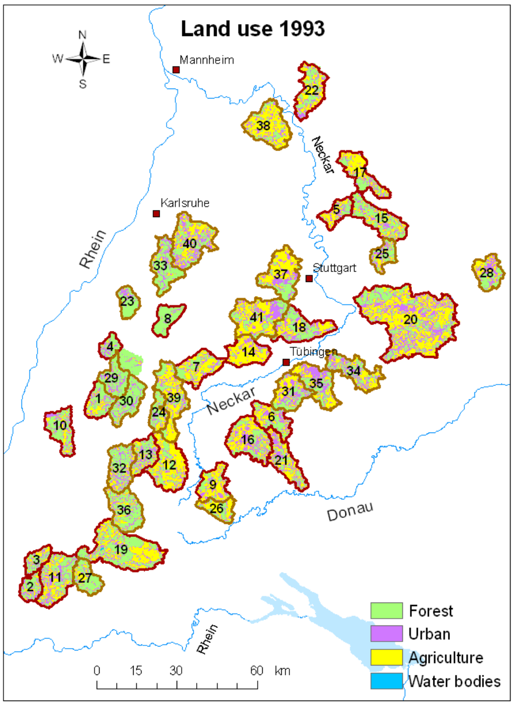

Figure 3.13: Land use in year 1993

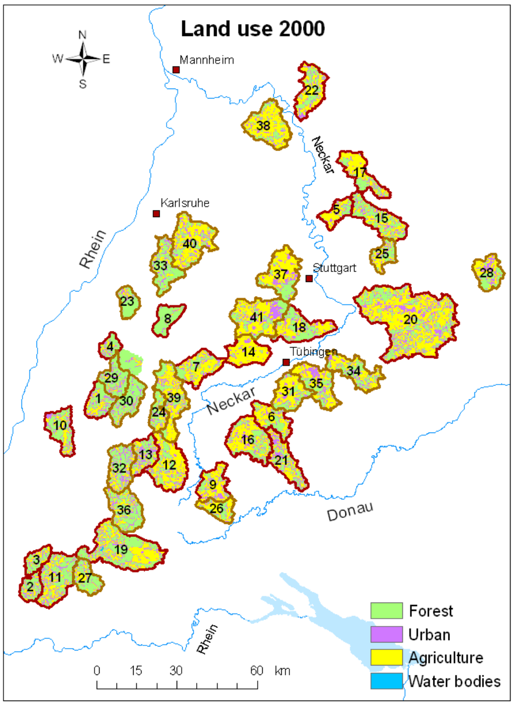

Figure 3.14: Land use in year 2000

Table 3.4: Statistics of the hydrological characteristics (HCs)

	Regionalization set (22 catchments, 104 events)				Validation set (19 catchments, 105 events)			
HCs	**Max**	**Min**	**Mean**	**Std dev**	**Max**	**Min**	**Mean**	**Std dev**
event specific characteristics								
q_{peak}	3.78	0.12	0.58	0.49	3.51	0.12	0.79	0.71
P_t	45.6	4.4	17.6	9.2	80.8	4.2	22.0	14.9
T_p	26.0	2.0	8.9	4.9	38.0	2.0	11.6	6.5
API	26.7	0.00	11.2	6.9	84.2	0.73	15.4	13.6
catchment specific characteristics								
A	53	693	158	125	71	337	154	68
Per	43	229	90	36	50	163	92	29
SL	0.05	0.31	0.15	0.08	0.06	0.27	0.14	0.06
TWI	4.28	6.06	5.16	0.52	4.43	6.00	5.18	0.48
TRI	4.95	31.04	14.20	7.60	5.37	26.41	13.58	6.27
DR	0.38	1.74	1.08	0.30	0.68	1.68	1.07	0.30
TC	1.03	6.01	2.77	1.05	1.53	4.00	2.72	0.72
SF	0.10	0.37	0.23	0.08	0.11	0.39	0.22	0.07
Kv_1	0.00	0.93	0.20	0.34	0.00	0.96	0.39	0.35
Kv_2	0.00	0.91	0.31	0.33	0.00	0.91	0.30	0.28
Kv_3	0.00	0.07	0.01	0.02	0.00	0.01	0.00	0.00
FC_m	0.00	3.10	1.24	1.14	0.00	3.52	1.11	0.83
LU_f	0.17	0.94	0.55	0.18	0.30	0.88	0.58	0.19
LU_u	0.00	0.11	0.02	0.03	0.00	0.05	0.02	0.01
LU_a	0.00	0.23	0.01	0.05	0.00	0.67	0.26	0.19

4 Regionalization of Rainfall Loss

4.1 Runoff coefficient

A runoff hydrograph can be separated into two types of runoff sources: base flow and direct runoff. Base flow is the part of rainfall that infiltrates into the soil. The infiltrated rainfall water flows horizontally either through soil layer as subsurface water or along the confining geological formation as groundwater. If the flow comes across a river channel, a portion of it joins the river as base flow. Direct runoff is the portion which flows over the land surface, it can be attributed to either Hortonian overland flow or saturated overland flow (Chow et. al., 1988). Hortonian overland flow occurs when rainfall intensity exceeds infiltration rate and saturated overland flow occurs when soil is completely saturated.

Since subsurface flow and groundwater flow move much slower as compared to overland flow, the effects of base flow produced during a rainfall-runoff event may occur in rivers several hours, days, or even weeks after the event. Therefore the contribution of base flow to flood runoff is often very small as compare to that of direct runoff. The flood runoff hydrograph for a rainfall-runoff event is usually dominated by direct runoff. Hence, for estimations of flood runoff volume only direct runoff is considered and the amount of rainfall infiltrated into the soil is treated as rainfall loss. The amount of rainfall which forms the overland flow and contributes to the direct runoff at each time step of a rainfall-runoff event is referred as effective rainfall intensity (P_e). To derive a direct runoff hydrograph for a given rainfall-runoff event, the total direct runoff volume and the effective rainfall intensity at each time step of the event must be known.

The runoff coefficient (RC) for a rainfall-runoff event represents the fraction of total rainfall that contributes to the direct runoff at the outlet of a catchment. It is expressed as the ratio between the total direct runoff and the total rainfall occurred during the event (equation 4.1). If the runoff coefficient is known, the direct runoff volume and the corresponding effective rainfall intensity at each time step of a rainfall-runoff event can be estimated using either runoff coefficient method (figure 4.1) or constant loss rate (ϕ-index) method (figure 4.2).

$$RC = \frac{V_{Qd}}{P_t} = 1 - \frac{P_l}{P_t} \tag{4.1}$$

RC runoff coefficient for an event [-]

V_{Qd} specific direct runoff volume [mm]

P_t total rainfall during the event [mm]

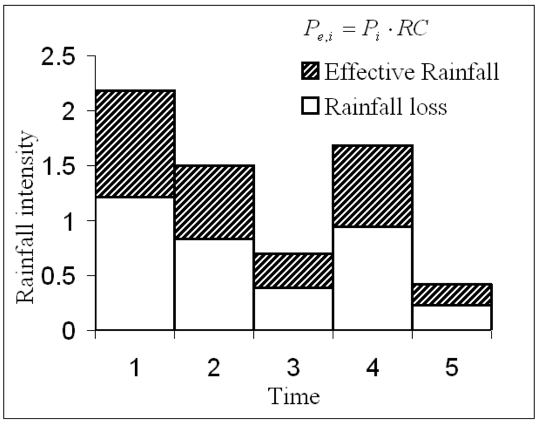

Figure 4.1: Runoff coefficient method

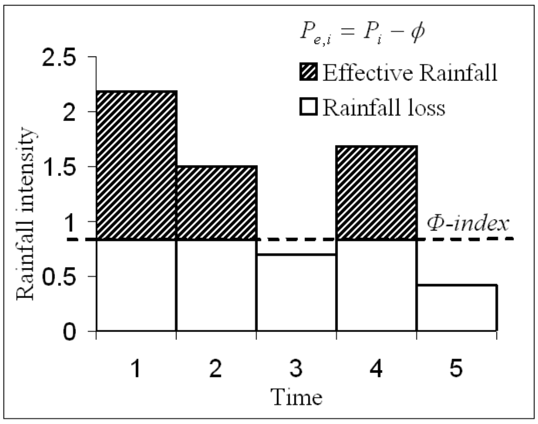

Figure 4.2: Constant loss rate method

P_l rainfall loss during the event $[mm]$

P rainfall intensity during the event $[mm/hr]$

P_e effective rainfall intensity $[mm/hr]$

ϕ constant rainfall loss $[mm/hr]$

In the case of gauged catchments, the runoff coefficient can be estimated by using the observed direct runoff volume. "Observed" direct runoff volume can be obtained from observed runoff hydrograph by means of a simple straight line hydrograph separation method as shown in figure 4.3.

However, in the case of ungauged catchments, where observed runoff hydrograph is not available, direct runoff volume must be determined indirectly by deducting rainfall loss from total rainfall occurred during an event. Rainfall losses represent infiltration of rainfall into soil, and to some extent the interception of rainfall due to the presence of vegetation. Rainfall loss occurred during an event directly depends upon the catchment as well as event specific hydrological characteristics. Therefore, there is a possibility to estimate rainfall loss through the regional transfer function approach based on catchment as well as event specific hydrological characteristics. Then, estimated rainfall loss can be used to calculate direct runoff volume and runoff coefficient.

4.2 Transfer function for rainfall loss

Several different approaches can possibly be adopted to derive the transfer function that associates rainfall loss with the hydrological characteristics. The approaches can be classified into two categories: purely data driven approaches and data-plus-knowledge driven approaches.

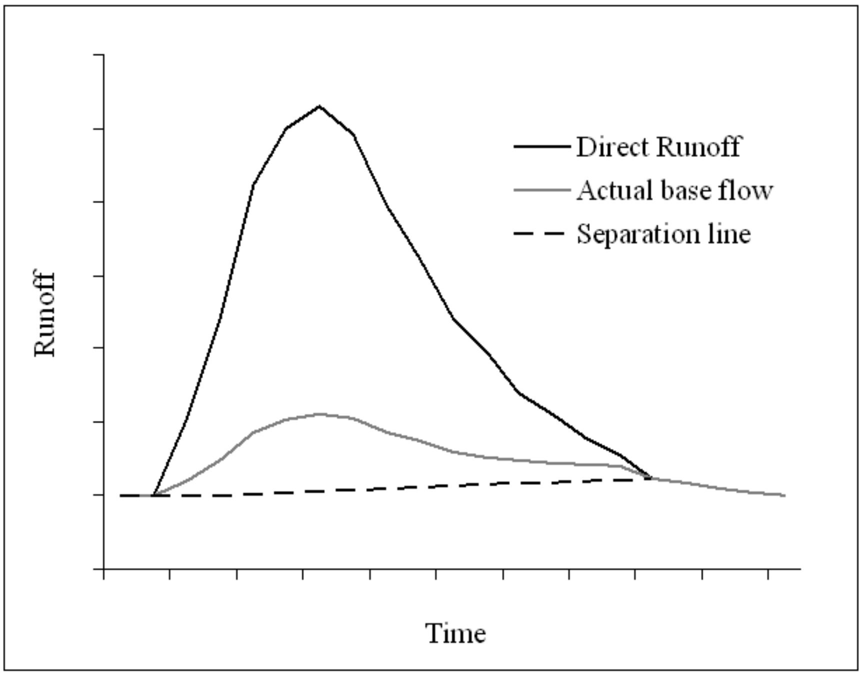

Figure 4.3: Straight line hydrograph separation method

Purely data driven approaches derive the functional relationship between predictors and a response variable solely from an observed dataset, by calibrating (or regressing) the coefficients of a convenient functional form to achieve desired degree of goodness fit between calculated and observed response. The purely data driven approaches do not take account of the physical relationships between predictors and a response variable. One other hand, data-plus-knowledge driven approaches exploit *a priori* knowledge of the physical relationships to guide the derivation of the functional relationships between predictors and a response variable. The coefficients of such, physically reasonable, functional relationships are derived through calibration (or regression) against observed response. Thus, the data-plus-knowledge driven approaches are partially deterministic.

The purely data driven approaches, such as artificial neural networks, are excellent at fitting the observed response with calculated response. Mainly, because of their extreme flexibility which is able to replicate non-linear relationships. However, due to the lack of physical basis purely data driven approaches may lead to erroneous and potentially counterfactual predictions, especially for extrapolation beyond the range of the data which was used for its derivation. To obtain efficient and plausible regionalization, it is important that the transfer function, not only replicates non-linear relationships but also appropriately represents physical relationships between predictors and the response variable.

During this study, four different approaches were employed to derive four different transfer functions for rainfall loss. Three of them are purely data driven approaches based on multiple linear regression, the artificial neural network (ANN) and fuzzy logic. The fourth approach is a data-plus-knowledge driven approach based on logistic regression. The rainfall-runoff events in the regionalization set (see: section 3.3) were used to derive and optimize the transfer functions. Validation of spatial transferability of the transfer functions was carried out using the validation set of the events. The "observed" direct runoff volume and the corresponding rainfall loss for the events was estimated using the straight line hydrograph separation method (figure 4.3).

The derivation procedure for the transfer functions using the four approaches, their goodness fit performance and aptness with respect to the physical relationships underlying rainfall loss processes are discussed in the following part of the chapter.

4.2.1 Multiple Linear Regression

Multiple linear regression (MLR) is a classic approach to fit a multivariate linear function between a response variable and a set of more than one predictors. A multivariate linear function (equation 4.2) between response variable Y and predictors $X_1,\ X_2, ...,\ X_n$ comprises of an intercept β_0 and coefficients $\beta_1,\ \beta_2, ...,\ \beta_n$ corresponding to each of the predictors. The intercept and the coefficients must be estimated through a regression procedure.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n \tag{4.2}$$

The simulated annealing optimization algorithm (Kirkpatrick et. al., 1983) was adopted to carry out the multiple linear regression procedure. The optimization algorithm was aimed at minimizing the root-mean-squared error ($RMSE$; equation 4.3) and maximizing the correlation coefficient ($Corr$) between the observed rainfall loss ($P_{l,ob}$) and the calculated rainfall loss ($P_{l,ca}$) for $n = 104$ number of events in the regionalization set.

$$Minimize \left[RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(P_{l,ob} - P_{l,ca}\right)^2}{n}} \right] \tag{4.3}$$

Initially, 14 probable predictors, describing various event and catchment specific hydrological characteristics (see: section 3.4), were associated with rainfall loss through a multiple linear transfer function (MLTF). The insignificant predictors were then eliminated using backward stepwise procedure. The backward stepwise procedure begins with all the probable predictors, some of the predictors are then eliminated from the function in an iterative process. The intercept and the coefficients are optimized after elimination of each potentially "insignificant" predictor. After elimination of a predictor, if the goodness fit performance of the function reduces, then the eliminated predictor is considered as significant and retained, and if the performance increases or does not change then the predictor is considered as insignificant and eliminated permanently. Finally, If further elimination of any predictor leads to significant reduction in the goodness fit, the analysis is stopped.

The multiple linear regression, through a backward stepwise procedure, leads to MLTF for rainfall loss as shown in equation 4.4. MLTF relates six predictors: total rainfall (P_t), antecedent precipitation index (API), river density (DR), month (M), field capacity (FC) and soil class (Kv_2) with rainfall loss. The performance of MLTF for the regionalization set ($RMSE = 3.15$, $Corr = 0.90$) and the validation set ($RMSE = 3.29$, $Corr = 0.90$) are shown in figure 4.4 and 4.5 respectively, which indicates fairly acceptable goodness fit. However, the correlation plots in the figures show that MLTF failed to produce good estimations in case of high rainfall events with high rainfall loss.

$$P_l = 0.982 + 0.004P_t + 0.002API + 0.161DR + 0.178Kv_2 - 0.056FC - 0.006M \quad (4.4)$$

4.2.2 Artificial Neural Network

The artificial neural network (ANN), conceptually borrowed from the biological context of the nervous system, is an information processing tool based more on mathematical principles than on biological ones (Dreyfus, 2005). An artificial neuron (figure 4.6) is a nonlinear, parameterized, bounded function, also known as an activation function. Commonly used forms of the activation functions are sigmoid functions (e.g. tan-sigmoid, log-sigmoid etc.), Gaussian bar functions and radial basis functions. The inputs of the neurons are the products of the predictors ($i_1,\ i_2, ...,\ i_n$) and their respective weights ($w_1,\ w_2, ...,\ w_n$), and an additive constant term 'bias' (b). The value of the function is the output (O) of the neuron . Mathematically, the activation function may be described as:

$$O = f\left(b + \sum_{k=1}^{n} w_k i_k\right)$$

An ANN is composed of two or more neurons (figure 4.7). The end neuron (i.e. output of which is the final output of the whole network) is termed as the output neuron and all other intermediate neurons are known as hidden neurons. A network may consist of several hidden layers of hidden neurons. Each of the neurons in hidden layers processes input and passes its output to the next connected hidden or output neurons as an input. The training of an ANN means adjusting the weights and biases of the neurons so that the output of the whole network fulfills the desired objectives. Once the weights are adjusted to the optimum, then the network structure with optimized weights and biases can be validated and implemented for predictions (Dreyfus, 2005).

ANNs are classified depending on the connections among the neurons, the number of layers and the type of the activation functions. The ANN in which information flows only in the forward direction (from the input to the output layer) is known as the feedforward neural network. The feedforward neural networks with sigmoid nonlinearities are known as multilayer perceptrons (MLP), they are the most com-

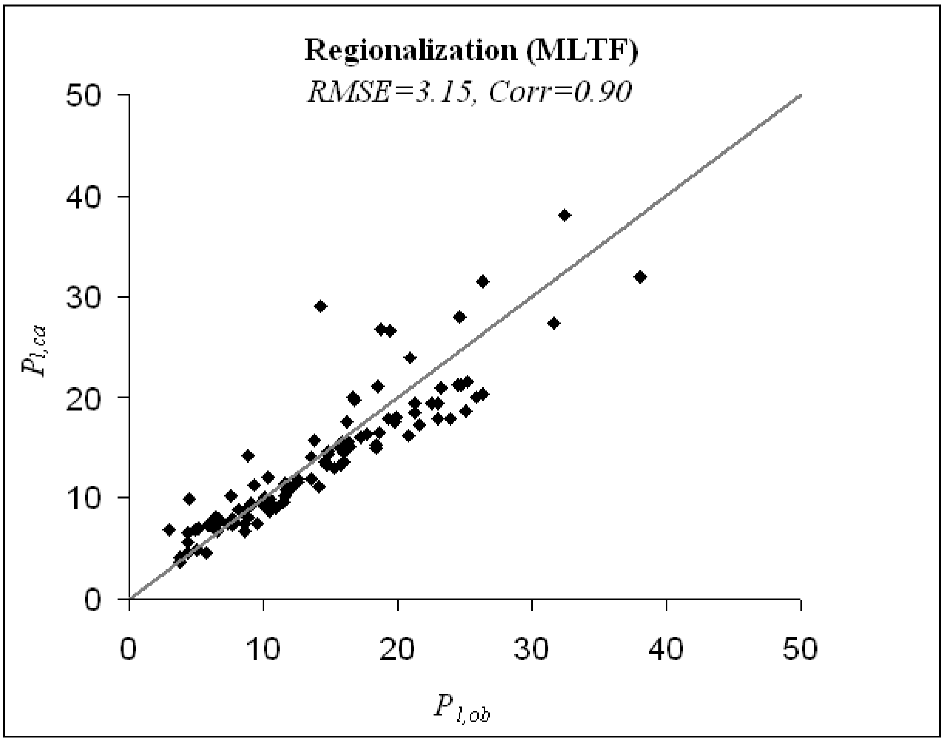

Figure 4.4: Performance of MLTF over regionalization set

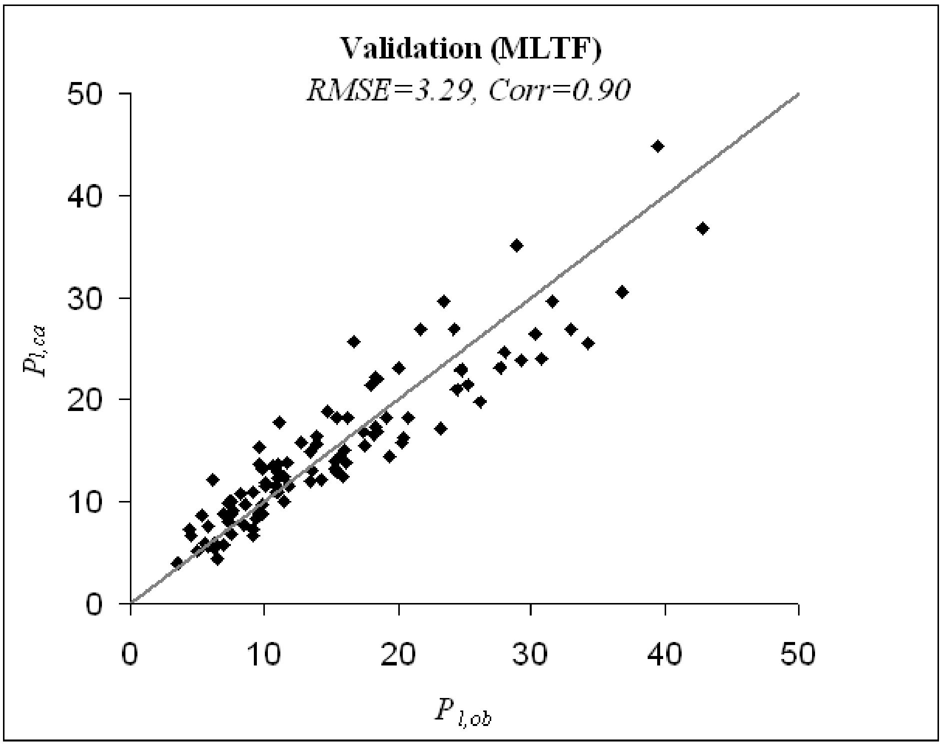

Figure 4.5: Performance of MLTF over validation set

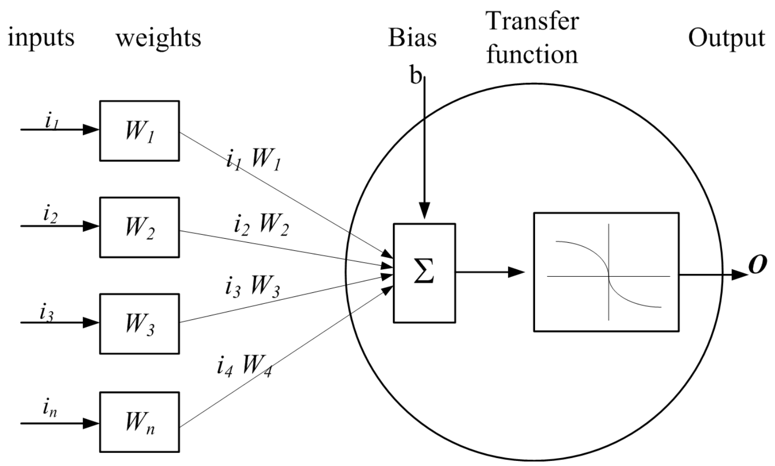

Figure 4.6: An artificial neuron

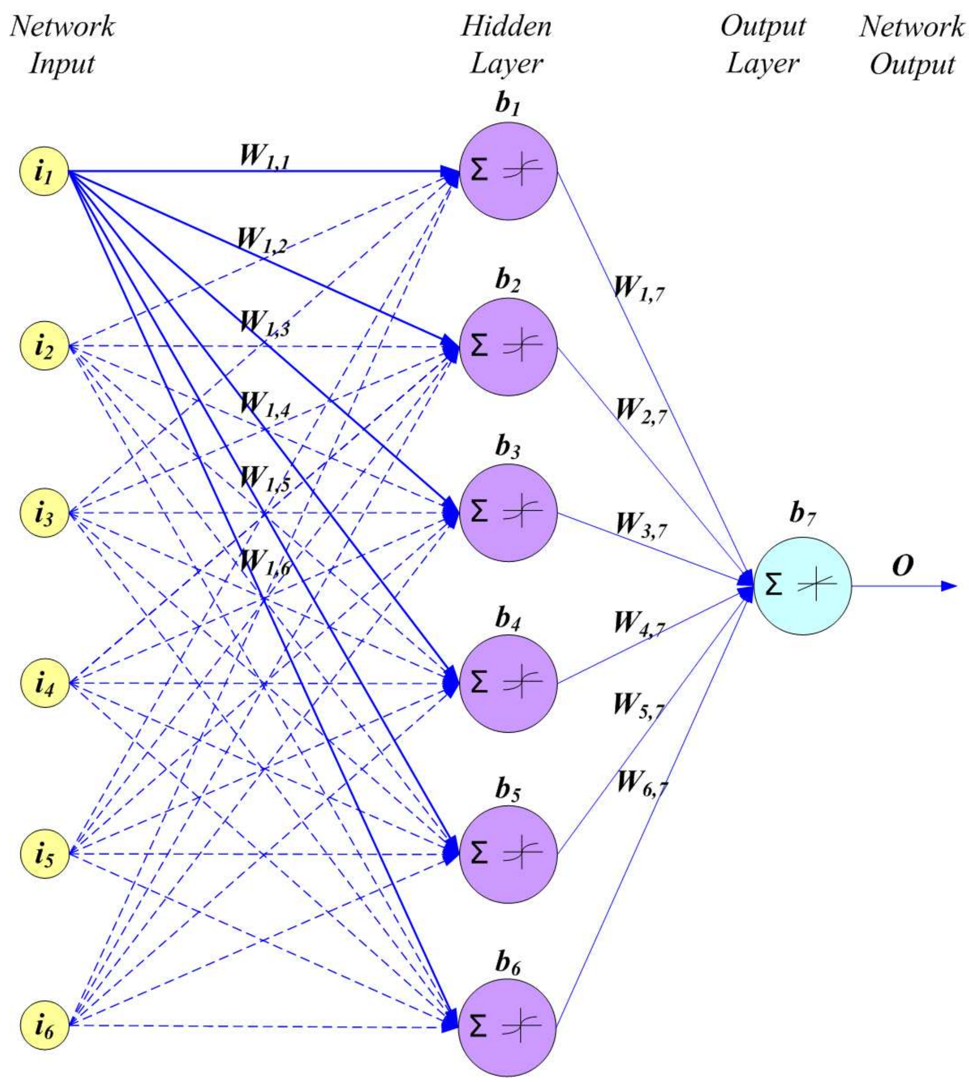

Figure 4.7: Artificial Neural Network

monly used form of ANNs (Dawson Wilby, 2001). Mathematically, an MLP can be described as shown in equation 4.5.

$$O(i, w) = \sum_{j=1}^{m} \left[w_{(m+1,j)} \cdot tanh \left(b_j + \sum_{k=1}^{n} w_{k,j} i_k \right) \right] + b_{(m+1)} \tag{4.5}$$

i input variable or predictor

O outputs or response variable

w weight of each variable for each hidden neuron [-]

b bias for each hidden neuron

n number of input variables

m number of neurons in hidden layer

An MLP with a hidden layer of nonlinear neurons and an output layer of a linear neuron was adopted for this case study due to its simplicity and widespread applications. The training of the MLP began with a hidden layer of one nonlinear neuron and an output layer of one linear neuron. The number of neurons in the hidden layer was then increased step by step. For each step the weights and biases were optimized using the Levenberg-Marquardt back propagation algorithm (Hagan and Menhaj, 1994) and the objective function $RMSE$. Various activation functions, which are available in the neural network toolbox of the software package MATLAB 7.0, were considered during the training. To avoid over-fitting of the MLP, optimization of weights and biases was followed by simultaneous cross-validation. The training of the MLP and the optimization of the weights and biases was continued until no further improvement was able to be achieved.

The obtained ANN transfer function for rainfall loss (ANNTF; figure 4.7) begins with an input layer of six neurons for the six predictors: P_t, API, DR, M, FC and Kv_2. The only hidden layer of the ANNTF consists of six neurons with tan-sigmoid activation functions and the output layer consists of one linear neuron. ANNTF leads to high degree of goodness fit between observed and calculated rainfall loss for the regionalization set ($RMSE$ = 2.43, $Corr$ = 0.94; figure 4.8), as well as for the validation set ($RMSE$ = 2.47, $Corr$ = 0.96; figure 4.9).

4.2.3 Fuzzy Logic

The fuzzy logic approach is based on the theory of fuzzy sets. Fuzzy sets (Zadeh, 1965) define relationships between predictors and a response variable as a vague linguistic expressions rather than as a mathematical function. In contrast to ordinary sets where the class boundaries are clearly defined, a fuzzy set is a set of objects without clear boundaries or without well defined characteristics (Bárdossy and Duckstein, 1994). Suppose X is the domain and A is a fuzzy set, then A is expressed as:

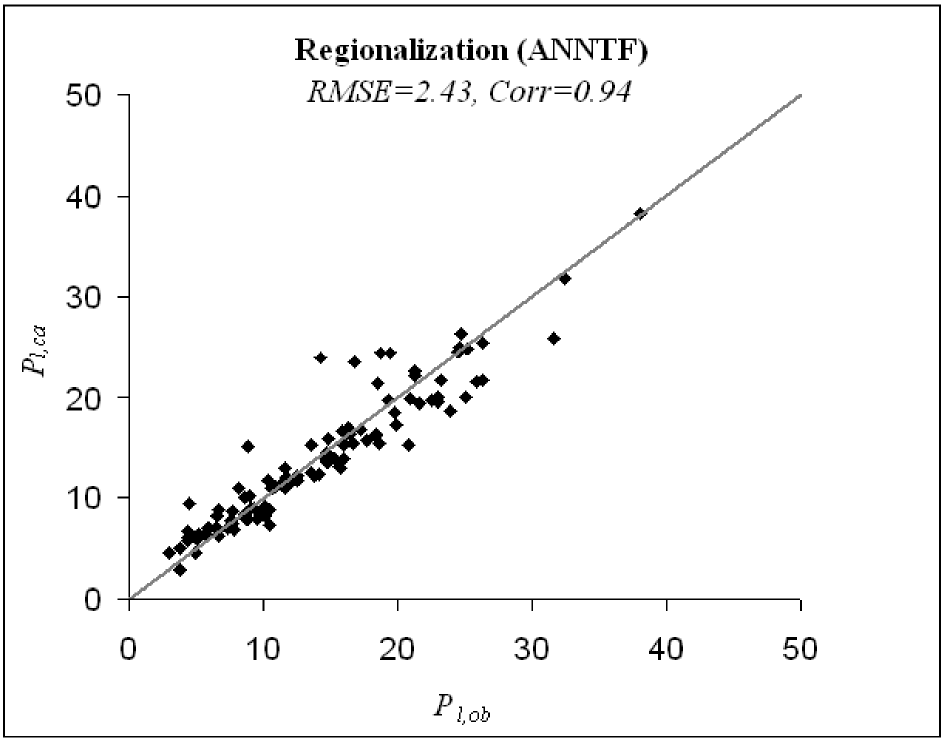

Figure 4.8: Performance of ANNTF over regionalization set

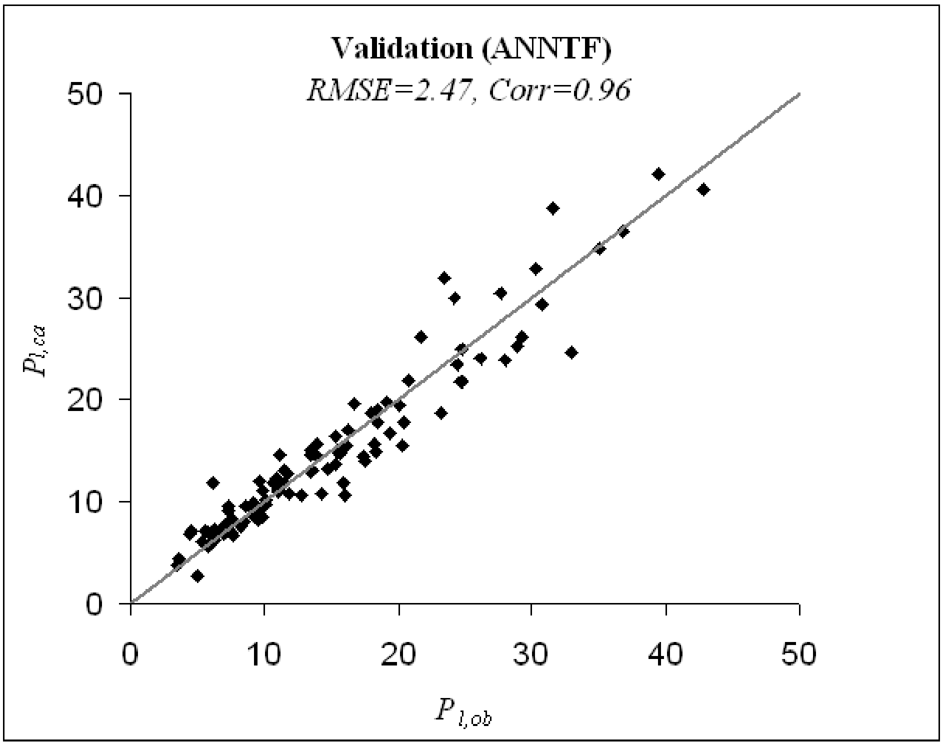

Figure 4.9: Performance of ANNTF over validation set

$A = \{(x, \mu_A(x));\ x \in X \mu_A(x) \in [0, 1]\}$

Where, $\mu_A(x)$ is a membership function of x in A and defines "how much" x belongs to the fuzzy set A, its value is said to be the membership value of x. The closer $\mu_A(x)$ is to 1, the more x is considered to belong to A; and the closer it is to 0, the lesser it is considered to belong to A. If the elements of domain X are expressed as discrete values, then the fuzzy set A can also be described by a definite membership value of its elements in X. If X is given as an interval instead of as a discrete value, then fuzzy set A is essentially described by a membership function of its element in X. Commonly used memberships functions are triangular, trapezoidal and Gaussian functions.

In a fuzzy logic based approach, predictors and response variables are classified into different fuzzy classes. A specific combination of fuzzy classes derives response of a fuzzy system to particular circumstances. Thus, fuzzy classes are arranged into various combinations to produce responses representing various circumstances. A specific combination of fuzzy sets is defined using fuzzy rules. There are few approaches to formulate the fuzzy rules, the most common approach is Mamdani's in which fuzzy rules are composed of 'IF-THEN' statements (Bárdossy et. al., 2003). Suppose for a given dataset T, the goal is to describe the relationship between the predictors $x_1,\ x_2, ...,\ x_J$ and the response variable y using fuzzy rules:

$T = (x_1(t), ...x_j(t), y(t)\ t = 1, ...T)$

The fuzzy rules are formulated using predefined fuzzy sets $j\{A_{j,1}, ..., A_{j,K_j}\}$ for each predictor. A fuzzy rule i can be therefore described as:

$if\ x_1\ is\ A_{1,k_{i,1}},\ and\ x_2\ is\ A_{2,k_{i,2}},\ and...,\ and\ x_j\ is\ A_{j,k_{i,j}}\ then\ y\ is\ B_{li,1}$

The most important task for the application of a fuzzy system is the assessment of the suitable rules. A fuzzy system consisting of I number of rules should be trained such that, after a combination and defuzzification, the rule response R for each t should be close to the observed value.

$R\{x_1(t), ..., x_j(t)\} \approx y(t)$

The membership functions and the fuzzy rules were generated and optimized to develop a fuzzy system to estimate rainfall loss using the hydrological characteristics. The optimization of the membership functions and the fuzzy rules was carried out using the simulated annealing algorithm to minimize $RMSE$. The derived fuzzy system, i.e. fuzzy logic transfer function (FLTF), uses the six predictors: P_t, API, DR, M, FC and Kv_2. FLTF consists of nine triangular membership functions and 12 fuzzy rules. Figure 4.10 and 4.11 show the correlation plots between the observed and the calculated rainfall loss. The correlation plots indicate high degree of goodness fit for the regionalization set ($RMSE = 2.41$, $Corr = 0.95$) as well as the validation set ($RMSE = 2.85$, $Corr = 0.95$).

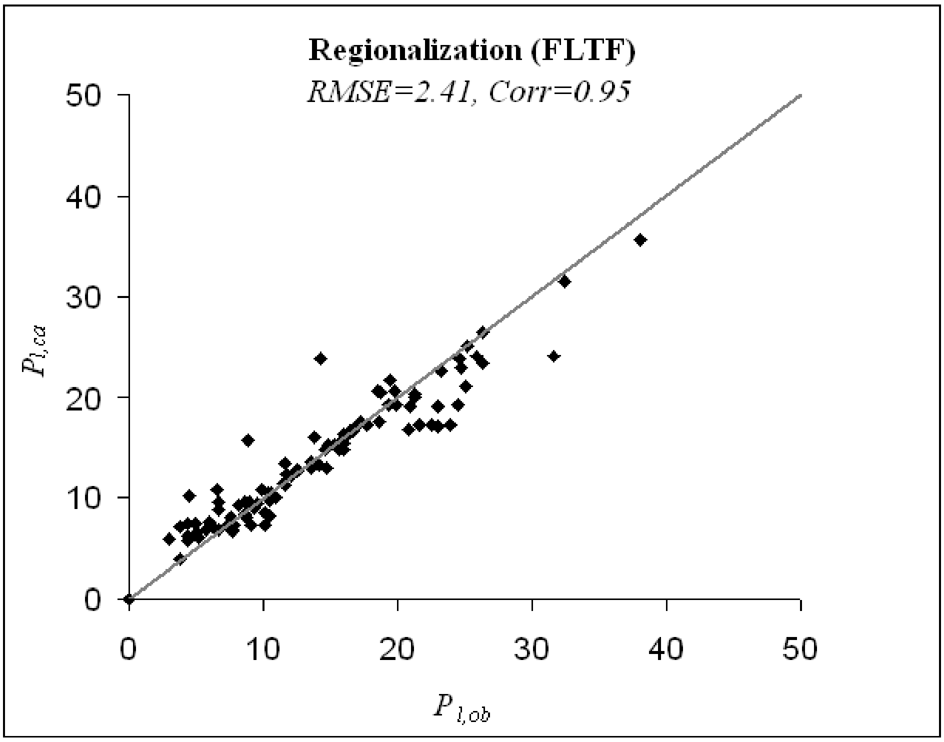

Figure 4.10: Performance of FLTF over regionalization set

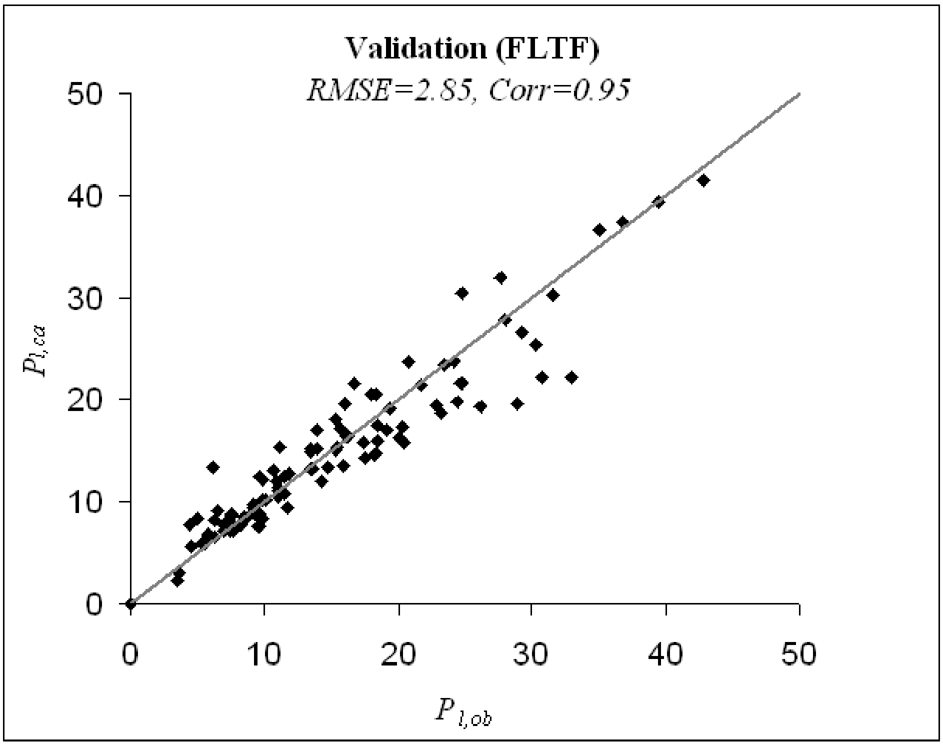

Figure 4.11: Performance of FLTF over validation set

4.2.4 Logistic Regression

A logistic function is a generalized linear model which allows one to predict a response variable from a set of non-normally distributed variables that may be continuous, discrete, or dichotomous. The logistic function, as shown in equation 4.6, is a logit transformation of the response variable Y that essentially varies between 0 and 1 (Hosmer and Lemeshow, 2000). The logistic relationship (figure 4.12) is linear in the mid range and becomes nonlinear as it approaches to the extremes.

$$Y = \frac{1}{1+e^{(X)}} \qquad Where, X = \beta_0 + \beta_1 \cdot X_1 + \beta_2 \cdot X_2 + ... + \beta_n \cdot X_n \tag{4.6}$$

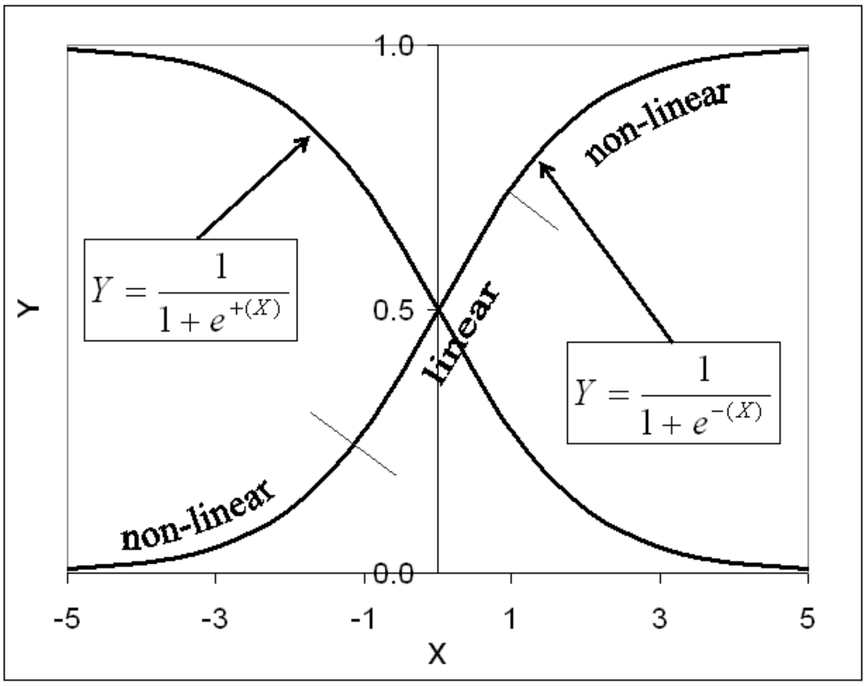

Figure 4.12: Logistic Relationship

Logistic functions although seldom employed to solve hydrological problems, exhibit potential to handle asymmetrically distributed hydrological responses of extreme occurrence (Augustin et. al., 2001). The advantage of using a logistic function over simple linear function is that it is flexible enough to capture linear as well as nonlinear relationships, and it is also capable of dealing with skewed distributed variables (Ashkar and Mahdi, 2003). Moreover, it is transparent such that relationships between predictors and a response variable can be easily analyzed and controlled. Thus, physically unreasonable relationships between a response variable and predictors can be avoided (Press and Wilson, 1978).

For the simple logistic functions shown in figure 4.12, if the exponent term has positive arithmetic sign (+), the response variable Y decreases monotonically with increase in the value of predictor X. However, if the exponent term has negative arithmetic sign (−), Y increases monotonically with increase in the value of predictor X. This inherent property of logistic functions can be used to depict the physical relationships between rainfall loss and the hydrological characteristics in a form of function. Furthermore, since a logistic function varies between lower limit of '0' and the upper limit equal to the numerator, rainfall loss can be restricted within its physically feasible limits, i.e. $0 \leq P_l \leq P_t$.

Logistic regression procedure was employed as a data-plus-knowledge driven approach to derive transfer function for rainfall loss. During the logistic regression, the *a priori* knowledge of the physical relationships underlying rainfall loss processes was incorporated into the logistic function using its property of monotonic behavior.

A priori knowledge of rainfall loss processes

The *a priori* knowledge of rainfall loss processes can be established through conventional theories, experiences and general understanding of hydrology. Rainfall loss during a rainfall-runoff event is a result of two distinct processes: infiltration and interception. Infiltration of rainfall during an event is likely to be influenced by amount of rainfall, rainfall intensity, antecedent moisture conditions, land use, slope of terrain, hydraulic conductivity and field capacity of soil, river density, catchment size and the season. The interception of rainfall depends upon land use and the season.

Rainfall loss occurred during an event can be expressed in terms of a dimensionless number: rainfall loss coefficient (PlC; equation 4.7). Rainfall loss coefficient is the fraction of the total rainfall which does not contribute to the direct runoff at the outlet of a catchment.

$$PlC = \frac{P_l}{P_t} \tag{4.7}$$

Following inferences about the physical relationships between rainfall loss coefficient and the relevant hydrological characteristics can be outlined on the basis of the *a priori* knowledge of rainfall loss processes:

1. Rainfall loss coefficients are smaller for the events with higher total rainfall and rainfall intensity. For the longer duration events, the rainfall loss coefficient is larger.

2. Due to soil saturation, rainfall loss coefficient tends to be smaller if the antecedent soil moisture content is higher.

3. Due to sealed surfaces, the rainfall loss coefficient is minimum for urban areas. On the other hand, forests lead to bigger rainfall loss coefficient due to high infiltration and interception of rainfall.

4. Steep slopes in a catchment cause decrease in rainfall loss coefficient due to accelerated drainage rates.

5. Rainfall loss coefficient tends to be smaller for a catchment with higher river density, as it allows faster drainage and lesser surface area for infiltration.

6. Soils with higher field capacities hold more water, and may lead to increases in the rainfall loss coefficient.

7. Higher hydraulic conductivity of soil implies higher infiltration rate, and consequently a larger rainfall loss coefficient.

8. Large catchment areas may lead to larger rainfall loss coefficients due to longer retention times.

9. The season which can be expressed in terms of the month, has a great influence on rainfall losses. In summer, the rainfall loss coefficient is larger as compared to that in winter due to the presence of vegetation and soil water evaporation.

Regression procedure

The logistic regression began with 11 predictors representing the above mentioned catchment and event specific hydrological characteristics. The "insignificant" predictors were then eliminated from the function through the backward stepwise procedure. Again the optimization of the coefficients of the transfer function was carried out using the simulated annealing algorithm and $RMSE$.

During the optimization the arithmetic signs of the predictors were arranged in the intended logistic transfer function in such a way that the functional relationships between the rainfall loss coefficient (PlC) and the hydrological characteristics were fixed to the physical relationships between them. For example, according to the physical relationship, the PlC decreases with increase in the soil moisture (API). Therefore, the arithmetic sign of API in the logistic transfer function was set as positive (+). Thus, due to the monotonic behavior of logistic function, if API increases, then the corresponding calculated PlC decreases and *vice versa*. PlC is larger in the summer months and smaller in the winter months, therefore, the relationship was represented by sinusoidal function of month.

The predictors which significantly improve the goodness fit, but do not comply with the physical relationships, were also eliminated from the function. For example, the logistic function shown in equation 4.8 and 4.9. The function exhibits a high degree of goodness fit ($RMSE = 2.29$, $Corr = 0.96$). However, the functional relationship between rainfall duration (T_p) and PlC contradicts with the physical relationships between them. According the *a priori* knowledge, PlC increases with the increase in T_p, contrastingly, the positive (+) arithmetic sign of T_p in the function indicates that PlC decreases with the increase in T_p. The physically unreasonable functional relationship between the two is further demonstrated in the figure 4.13, which shows how calculated PlC changes with the (hypothetical) change in T_p for an event. Thus, the inclusion of T_p in the logistic function, although improves the goodness fit, leads to physically unreasonable transfer function. On the other hand, setting the arithmetic sign of T_p as negative (−) does not lead to any improvement in the goodness fit. Therefore, T_p was eliminated from the logistic transfer function.

$$P_l = P_t \left[\frac{64.58 + sin\left(\frac{\pi}{6}(M-4)\right)}{1 + 64.58\ e^{(X)}} \right] \tag{4.8}$$

$$X = 0.02T_p + \frac{P_t}{1 + 668.2\ e^{(0.66FCm - Dr)}} + \frac{API}{1 + 5018.8\ e^{(-5.96Kv_2)}} \tag{4.9}$$

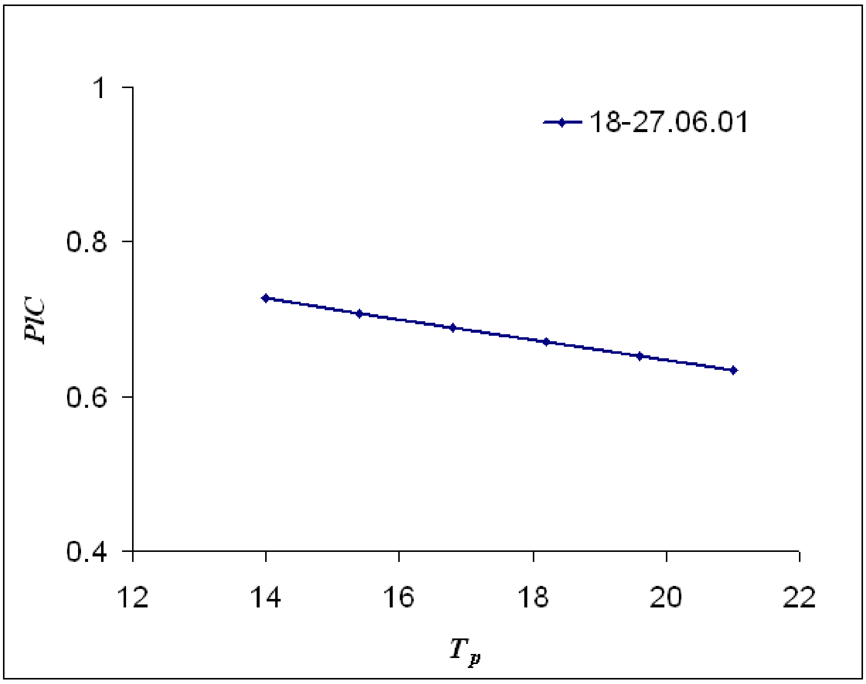

Figure 4.13: Physically unreasonable functional relationship between PlC and T_p

The regression results

The optimized logistic transfer function (LoTF) for rainfall loss, as shown in equation 4.10 and 4.11, consists of eight predictors and six coefficients. It may be observed that the logistic relationship of each predictor with rainfall loss represents the physical relationship. Among the hydrological characteristics used in the derived LoTF, P_t, API and M are the event specific characteristics that may provide basis for temporal extrapolation of rainfall loss. The others, FC, DR, Kv_2 and land use (LU_f and LU_u) are the catchment specific characteristics which may facilitate spatial extrapolation of rainfall loss. The correlation plot between the calculated and the observed rainfall loss (figure 4.14), implies that the goodness fit performance ($RMSE = 2.32$, $Corr = 0.95$) of LoTF, achieved during the regression, is highly efficient.

$$P_l = P_t \left[\frac{39.73 + sin\left(\frac{\pi}{6}(M-4)\right)}{1 + 39.73\ e^{(X)}} \right] \tag{4.10}$$

$$X = \frac{P_t}{1 + 42.08\ e^{\left(1.07FCm - Dr + 0.045\left(\frac{LU_f}{LU_u}\right)\right)}} + \frac{API}{1 + 5267.8\ e^{(-5.57Kv_2)}} \tag{4.11}$$

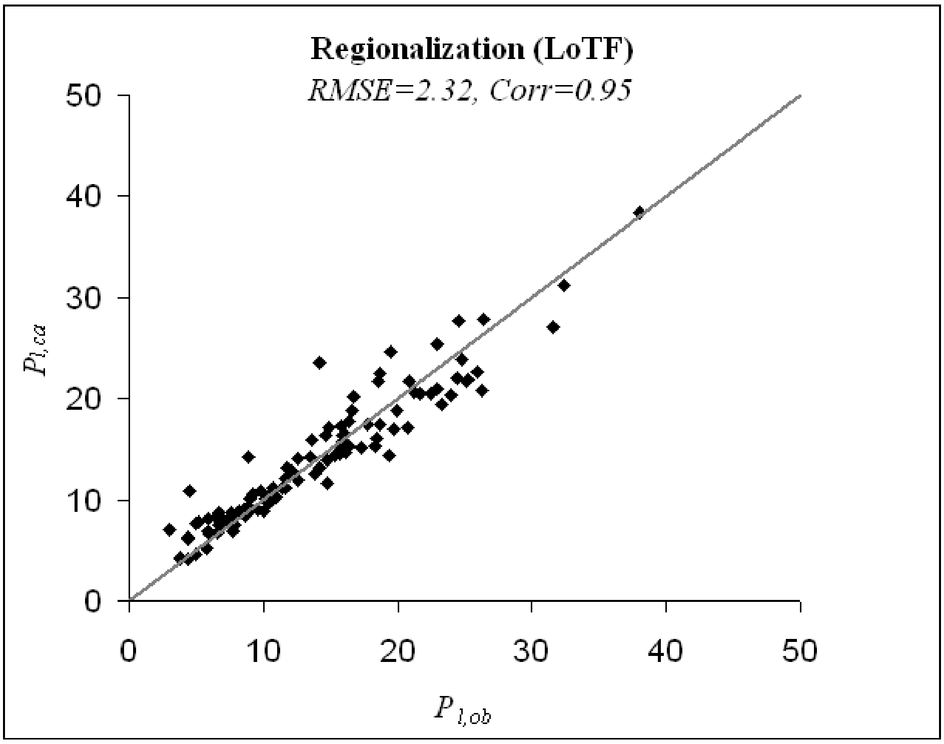

Figure 4.14: Performance of LoTF over regionalization set

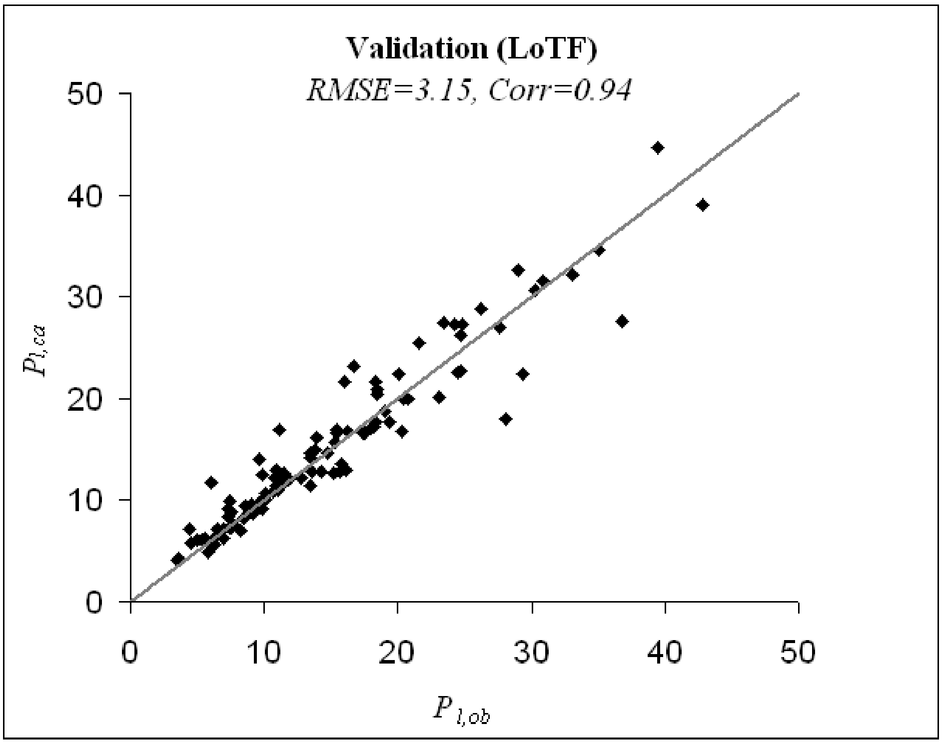

Figure 4.15: Performance of LoTF over validation set

The validation results

The validation of spatial transferability of LoTF, as shown in figure 4.15, indicates the acceptable degree of goodness fit ($RMSE = 3.15$; $Corr = 0.94$) between the calculated and the observed rainfall loss for the events in the validation set. Hence, it may be concluded that LoTF is efficient and consistent at estimating rainfall loss in the catchments which are not used during the regression. Thus, it is transferable to the ungaguged catchments in the study area.

4.3 Validation for physical relationships

After looking at the goodness fit performance of the four transfer functions: MLTF, ANNTF, FLTF and LoTF, one may straightforwardly conclude that all of the transfer functions are capable of estimating rainfall loss with acceptable efficiency. But the goodness fit achieved by the transfer functions provides very little information regarding their ability to capture the underlying physical relationships.

For a hydrological problem such as flood prediction, reliable estimation of effective rainfall for an individual storm event is essential. Thus, it is also important that a transfer function behaves in physically reasonable and consistent manner for each individual event. Therefore in order to investigate the appropriateness of the transfer functions with respect to the physical relationships, their performance for each individual event was analyzed against the known physical relationships between the predictors and PlC.

The validation of the transfer functions for the physical relationships was carried out for each event by comparing the arithmetic signs of the derivatives of the functional relationships between the predictors and PlC *vis-à-vis* the signs of the derivatives of the physical relationships. Derivative of a relationship between PlC and a predictor can be described as change induced in PlC, due to change in the predictor. The derivative is positive, if PlC increases with an increase in the predictor and *vice versa*. It is negative, if PlC decreases with the increase in the predictor and *vice versa*.

4.3.1 Derivatives of physical relationships

The positive and negative signs of the derivatives of the physical relationships between PlC and the predictors, which can be derived from the *a priori* knowledge of the physical relationships, are shown in table 4.1.

The *a priori* knowledge suggests that PlC may decrease with increasing amount of rainfall (P_t) due to increasing soil saturation. Similarly, PlC is small if soil saturation (API) prior to an event is high. Higher density of drainage network leads to faster drainage and lesser time for infiltration of rainfall, thus, PlC tends to be smaller for the catchments with higher drainage density (DR). Hence, the signs of the derivatives of the physical relationships of PlC with P_t, API and DR are negative($-$).

On the other hand, if field capacity (FC_m) of soil in a catchment is high, due to higher water retention, the corresponding PlC is also high. Therefore, the sign of the derivative of the physical relationship between PlC and FC_m is positive (+). PlC may decrease with increase in deforestation and urbanization. Hence, the sign of the derivative of the physical relationship between PlC and ratio between relative areas of forest and urban land use (LU_f/LU_u) is also positive. PlC is larger in the summer months due to presence of vegetation and evaporation, and is smaller in the winter months due soil saturation and lack of vegetation. Therefore, it may vary in a sinusoidal cycle with respect to month (M) of occurrence of an event .

Table 4.1: Signs of derivatives of the physical relationships PlC and the predictors

Hydrological characteristics		Rainfall loss coeff. coefficients		Sign of derivative derivative
P_t	$\Uparrow$	PlC	$\Downarrow$	negative
API	$\Uparrow$	PlC	$\Downarrow$	negative
DR	$\Uparrow$	PlC	$\Downarrow$	negative
FC_m	$\Uparrow$	PlC	$\Uparrow$	positive
LU_f/LU_u	$\Uparrow$	PlC	$\Uparrow$	positive
M	$\Uparrow$	PlC	S	-
$\Uparrow$: Increase;		$\Downarrow$: Decrease;		S: Sinusoidal

4.3.2 Derivatives of functional relationships

To derive the sign of the derivative of a functional relationship between PlC and a predictor for a transfer function, the value of the predictor was modified by a certain modification factor (MF) while keeping all other predictors unchanged. New PlC for the modified dataset was then estimated using the transfer function. The increase in the PlC due to increase in the predictor signifies the positive (+) sign of the derivative of the functional relationship between PlC and the predictor, and the decrease in the PlC due to increase in the predictor signifies the negative (−) sign of the derivative. The procedure was repeated for each of the predictors and the four transfer functions, using $MF = [0.7,\ 0.8,\ 0.9,\ 1.1,\ 1.2,\ 1.3]$. The season of occurrence of an event was varied by modifying the month of occurrence of the event. Figure 4.16 shows the response of the four transfer functions to the modifications in the predictors for one of the events. The response of each transfer function represents the corresponding functional relationship between PlC and the predictor.

4.3.3 Comparison of the derivatives

Subsequently, the obtained signs of derivatives of the functional relationships for the four transfer functions were then compared with the signs of derivatives of the physical relationships between PlC and the predictors. If the derivative of a functional relationship possesses the same sign as that of the physical relationship, the func-

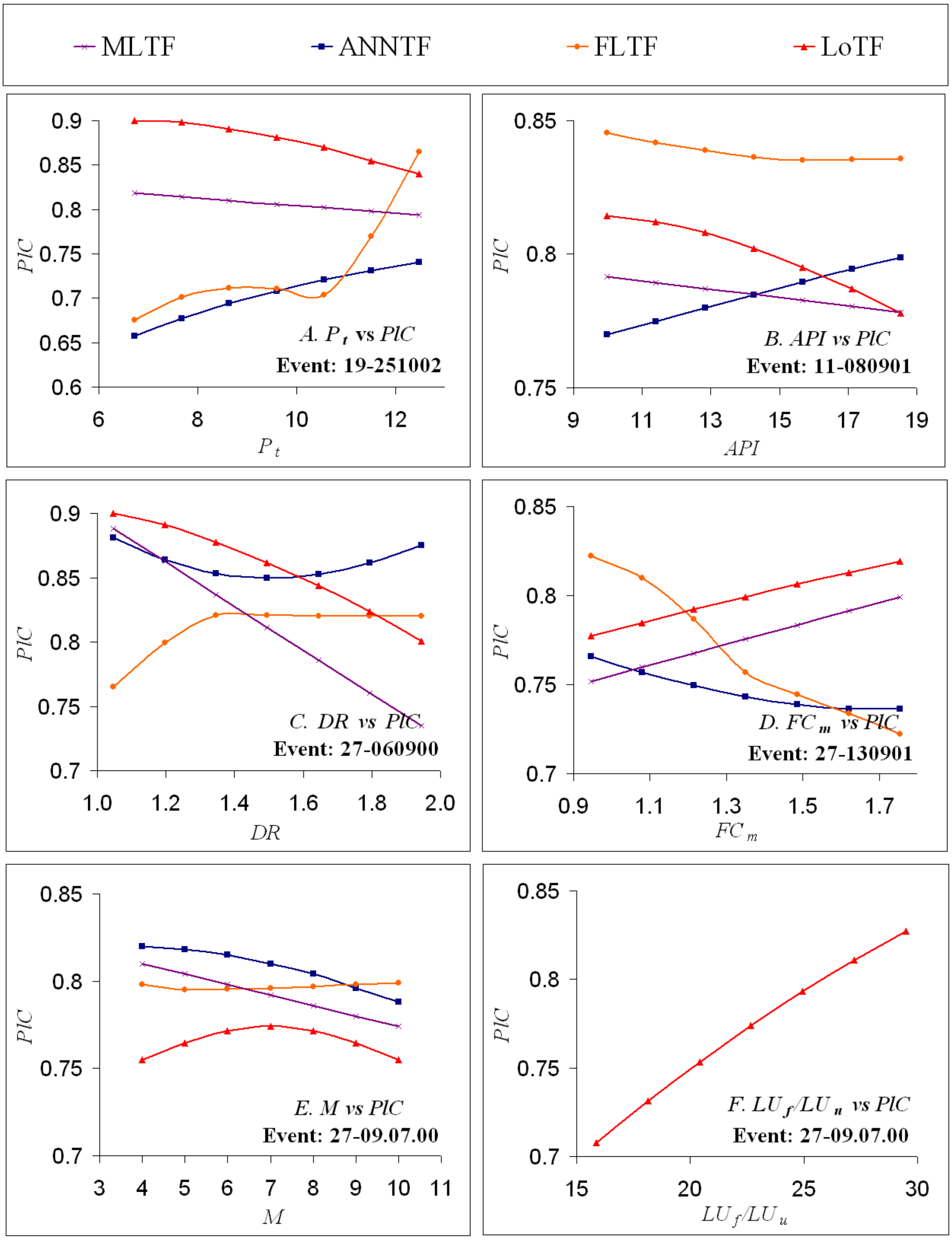

Figure 4.16: Functional relationships between PIC and the predictors; ***A***. P_t, ***B***. API, ***C***. DR, ***D***. FC_m, ***E***. M, ***F***. LU_f/LU_u.

tional relationship is physically reasonable; and if it does not, then it fails to capture the physical relationship.

In the figure 4.16, plot 4.16.A shows that, in the case of LoTF PlC decreases with increase in P_t. Thus, the sign of derivative of LoTF with respect to P_t is negative $(-)$, which is same as that of the physical relationship between PlC and P_t (table 4.1). Similarly, in the case of MLTF the sign of the derivative with respect to P_t is same as that of the physical relationship. However, in the case of ANNTF PlC increases with increase in P_t, i.e. the sign of the derivative of the functional relationship is positive which contradicts with that of the physical relationship. In the case of FLTF no definite relationship between PlC and P_t can be recognized.

In the plots 4.16.B and 4.16.C, again in the case of LoTF and MLTF, PlC decreases with increase in API and DR, which is in agreement with the physical relationship between them. In the case of ANNTF, PlC increases with increase in API and changes parabolically with DR, again, contradicting with the physical relationship. For FLTF, the functional relationships of PlC with API and DR are ambiguous.

Plot 4.16.D indicates that, in the case of LoTF and MLTF, PlC increases with increase in FC_m. Thus, the signs of derivatives of LoTF and MLTF with respect to FC_m are positive $(+)$, which are same as that of the physical relationship between PlC and FC_m. In the case of ANNTF and FLTF, "decrease in PlC with increase in FC_m" implies the negative $(-)$ sign of the derivatives of the functional relationships, which does not comply with the physical relationship.

Plot 4.16.E shows that, for LoTF, PlC is higher in the summer months as compare to that in the winter months, which is correct in the context of the physical relationship between PlC and M. However, MLTF, ANNTF and FLTF fail to reproduce the physical relationship. Plot 4.16.F implies that the sign of derivative of the functional relationship between LU_f/LU_u for LoTF is positive $(+)$, which is same as that of the physical relationship.

The statistics of the signs of the derivatives of the functional relationships for the four transfer functions, over 211 selected events, are shown in table 4.2. The left most column in the table indicates the modification factors for the predictors. The other columns indicate the number of events for which change in PlC, corresponding to change in a predictor, was positive (+ve) or negative (-ve). From the statistics, it can be seen that the signs of the derivatives of the functional relationships for LoTF and MLTF conform with the signs of the derivatives of the physical relationships for each of the 211 events and for all the predictors. However, in the case of the ANNTF and FLTF, the statistics reveal that there is no definite relationship between PlC and the predictors. For a large number of events, the signs of the derivatives of the functional relationships for ANNTF and FLTF do not comply with that of the physical relationships.

ANNTF and FLTF, owing to their extreme flexibility that can replicate any nonlinearity, achieves much better goodness fit as compared to that of MLTF. However,

Table 4.2: Number of positive (+ve) and negative (-ve) changes in *PlC* corresponding to the changes in the predictors for 211 events; ***A***. LoTF, ***B***. MLTF, ***C***. ANNTF, ***D***. FLTF

A	P_t		API		DR		FC_m	
MF	***-ve***	***+ve***	***-ve***	***+ve***	***-ve***	***+ve***	***-ve***	***+ve***
0.7	211	0	211	0	211	0	0	211
0.8	211	0	211	0	211	0	0	211
0.9	211	0	211	0	211	0	0	211
1.0	0	0	0	0	0	0	0	0
1.1	0	211	0	211	0	211	211	0
1.2	0	211	0	211	0	211	211	0
1.3	0	211	0	211	0	211	211	0
B	P_t		API		DR		FC_m	
MF	***-ve***	***+ve***	***-ve***	***+ve***	***-ve***	***+ve***	***-ve***	***+ve***
0.7	211	0	211	0	211	0	0	211
0.8	211	0	211	0	211	0	0	211
0.9	211	0	211	0	211	0	0	211
1.0	0	0	0	0	0	0	0	0
1.1	0	211	0	211	0	211	211	0
1.2	0	211	0	211	0	211	211	0
1.3	0	211	0	211	0	211	211	0
C	P_t		API		DR		FC_m	
MF	***-ve***	***+ve***	***-ve***	***+ve***	***-ve***	***+ve***	***-ve***	***+ve***
0.7	157	54	133	78	168	43	140	71
0.8	157	54	135	76	167	44	137	74
0.9	157	54	134	77	167	44	134	77
1.0	0	0	0	0	0	0	0	0
1.1	53	158	79	132	44	167	87	124
1.2	54	157	76	135	45	166	93	118
1.3	53	158	76	135	45	166	99	112
D	P_t		API		DR		FC_m	
MF	***-ve***	***+ve***	***-ve***	***+ve***	***-ve***	***+ve***	***-ve***	***+ve***
0.7	166	45	112	99	106	106	112	99
0.8	145	66	108	103	108	103	114	97
0.9	108	103	105	106	112	99	112	99
1.0	0	0	0	0	0	0	0	0
1.1	153	58	105	106	105	106	104	107
1.2	178	33	106	106	108	103	95	116
1.3	186	25	106	106	109	102	94	117

the comparison of the signs of derivatives of the functional relationships with that of the physical relationships reveals that, for an individual event, the response of ANNTF and FLTF to hydrological changes does not always comply with the physical relationships derived from the *a priori* knowledge of the rainfall loss precesses. Thus, the functional relationships represented by ANNTF and FLTF lack the physical basis, which may lead to fallacious, if not unrealistic, predictions. Due to the lack of the physical basis ANNTF and FLTF, although exhibits excellent goodness fit performance within the range of the dataset used for optimization, are not suitable for extrapolation or regionalization.

MLTF exhibits physically reasonable functional relationships of PlC with P_t, API, DR and FC_m. However, due to its limitation of linearity, MLTF fails to capture the seasonal variability of PlC. The limitation of linearity also restricts the goodness fit performance of MLTF.

In the case of LoTF, for each and every event under consideration, the sign of derivative of the functional relationship of PlC with each the predictors matches with that of the physical relationships, which implies that LoTF is absolutely consistent with the physical relationships. Thus, LoTF for rainfall loss is physically reasonable and, consequently, more robust. LoTF is also flexible enough to replicate the non-linear relationships, therefore, achieves reasonably high goodness fit performance. For being based on physically reasonable relationships and efficient in terms of goodness fit performance, LoTF makes the most suitable transfer function to estimate rainfall loss in the ungauged catchments in the study area under consideration.

4.4 Comparison of LoTF with existing practices

In order to assess the practical applicability of LoTF to estimate rainfall loss, its goodness fit performance was compared *vis-à-vis* the existing practices namely, modified SCS curve number method (see: section 2.2.1) and Lutz procedure (see: section 2.2.2).

4.4.1 Modified SCS curve number method

Specific direct runoff volume for the events in the validation set was estimated using modified SCS curve number method with slope correction. The estimated specific direct runoff volume was then used in equation 4.12 to obtain rainfall loss. Figure 4.17 shows the correlation plot between the calculated and the observed rainfall loss for the events. The estimation error for modified SCS curve number method was $RMSE = 7.29$, which is much higher as compared to that for LoTF. In terms of correlation coefficient also ($Corr = 0.60$), SCS curve number method performs poorly.

$$P_l = P_t - V_{Qd} \tag{4.12}$$

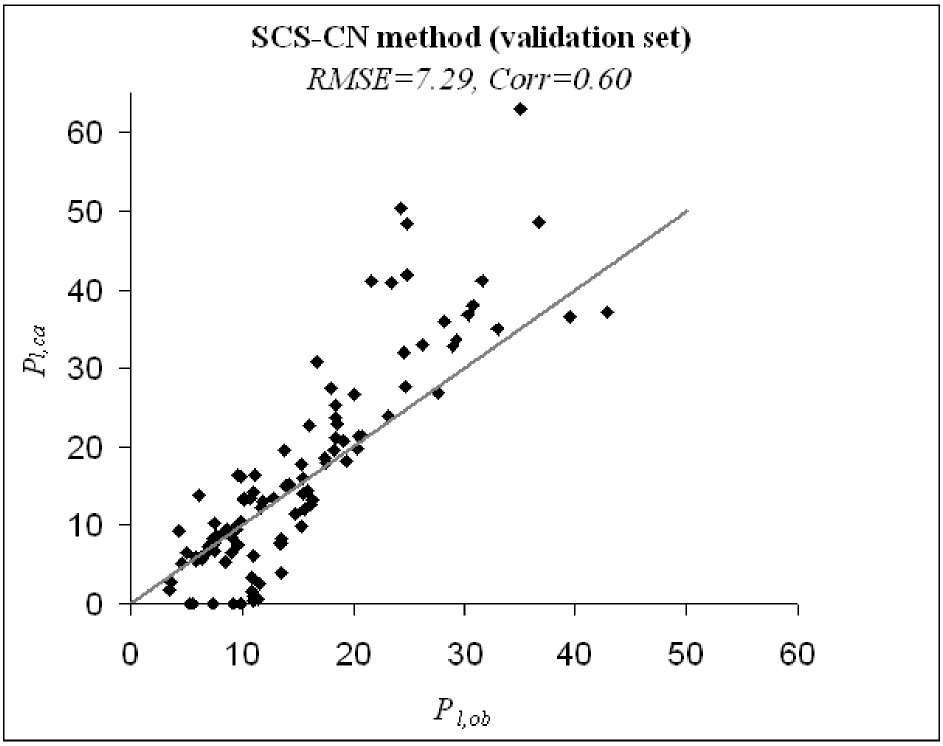

Figure 4.17: Performance of SCS curve number method over validation set

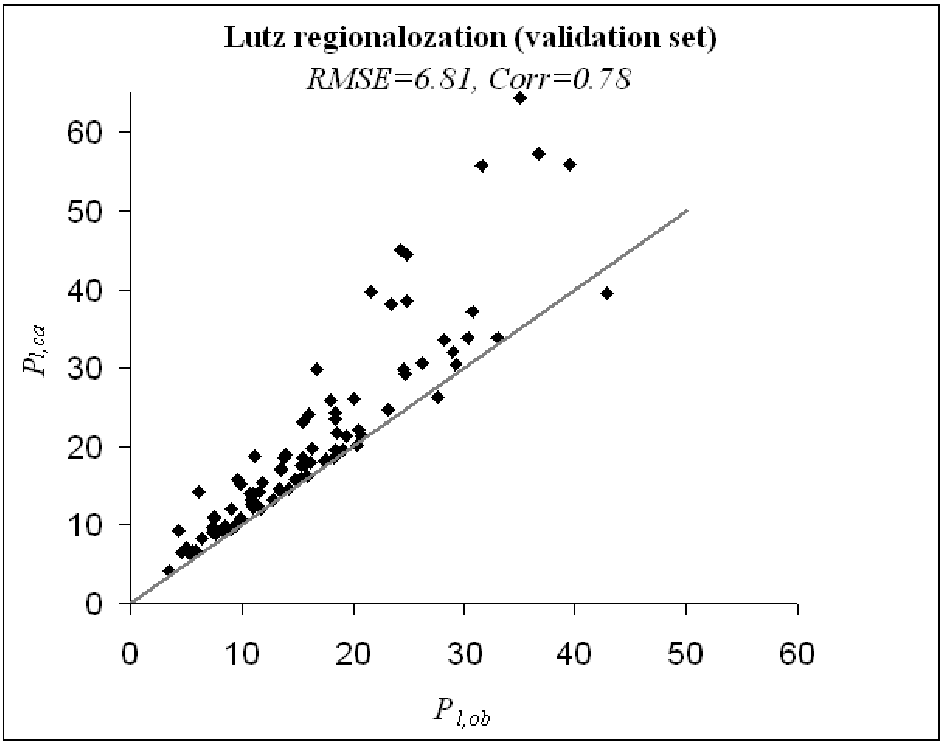

Figure 4.18: Validation performance of Lutz procedure

4.4.2 Lutz procedure

Specific direct runoff volume for the events in the validation set was again estimated using Lutz procedure and the corresponding rainfall loss was estimated using equation 4.12. Figure 4.18 shows the correlation plot between the observed rainfall loss and the rainfall loss calculated using Lutz procedure. The Lutz procedure performs better in terms of $RMSE$ ($RMSE = 6.81$) and correlation coefficient ($Corr = 0.78$) as compared to modified SCS curve number method, because it is adapted to the regional hydrological characteristics. However, the performance of Lutz procedure is not as high as that of LoTF. The correlation plot also reveals that Lutz procedure tends to overestimate the rainfall loss.

The comparisons of LoTF with global and regional standard practices indicate that LoTF performs better than the standard practices for the catchments which were not used for its derivation. Thus, in the context of the study area under consideration, LoTF seems to be practically more suitable and efficient for estimation of rainfall loss as compared to the other methods.

4.5 Discussion on the estimation error of LoTF

Table 4.3 presents the statistics of the absolute relative error of LoTF in estimating rainfall loss for the events in the regionalization and the validation set. The mean absolute relative error is 16.3 % and 13.5 % respectively for the regionalization and the validation set, which is within the acceptable limits.

Table 4.3: Statistics of absolute relative estimation error (%)

Statistic	Relative error (%)	
	Regionalization	**Validation**
Mean	16.3	13.5
90-percentile	26.9	26.4
Minimum	0.3	0.0
Maximum	141.6	94.3

However, for almost 10 % of the events from the regionalization set as well as the validation set, the absolute relative esimation error is higher than 27 %. The main source of the error could be the estimation of rainfall. Figure 4.19 shows that the positive relative error is very high for some of the events for which the "observed" PlC is very small. On the other hand, figure 4.20 reveals that the positive relative error is also very high for the events for which total rainfall is relatively small ($P_t < 20\ mm$). Thus, rainfall loss seems to be highly overestimated for the events for which total rainfall and "observed" rainfall loss are relatively smaller. This fact can be associated with the underestimation of total rainfall for the events. Most of the events under consideration are short duration events originated from relatively smaller advective storm fields. Adquate estimations of rainfall distribution for such events, using the available spatial density of rainfall data, are difficult to achieve. This often leads to the underestimation of total rainfall for the events (see: section 3.3.1). The underestimation of total rainfall leads to underestimation of "observed" rainfall loss, subsequently, leading to high relative error. However, one may also conclude that LoTF may not be efficient in the case of small rainfall events and tends to overesimate rainfall loss if total rainfall is below certain threshold.

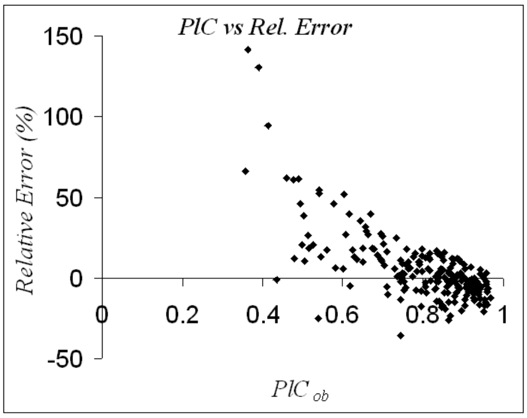

Figure 4.19: *PlC* vs. relative error

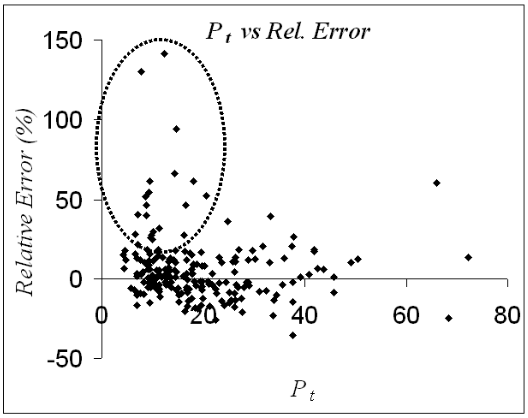

Figure 4.20: P_t vs. relative error

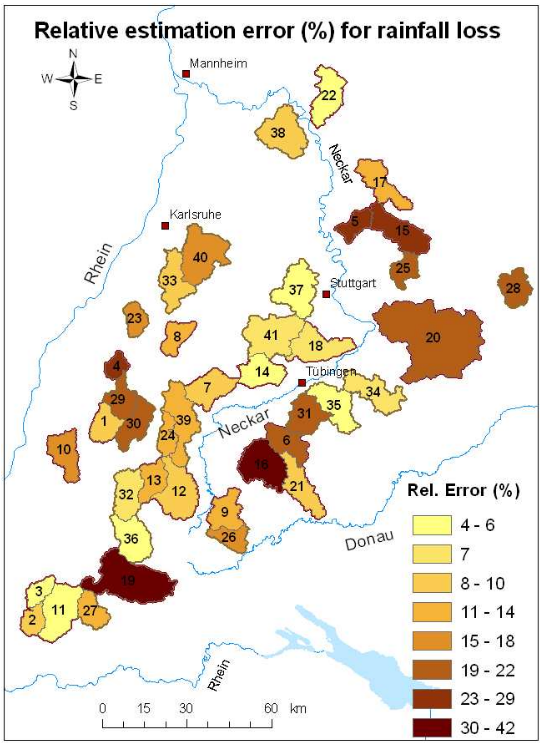

Figure 4.21: Spatial distribution of mean relative error for catchments

Mean absolute relative error for each catchment was estimated by averaging the relative error over the number of events selected from the respective catchment. Spatial distribution of mean relative error, as shown in figure 4.21, does not indicate any specific pattern. However, it can be observed that the catchments along the south-east border of the study area, specifically, at the foothill of Swabian Alps show relatively high error, which is due the presence of karstic rock formations.

5 Regionalization of Nash Cascade Parameters

5.1 Nash cascade parameters

Nash (1957) had proposed the concept of hypothetical linear reservoir cascade, which is based on the assumption that operations performed by catchment on effective rainfall are analogous to those performed by routing through a cascade of linear reservoirs. According to Nash cascade concept, instantaneous unit hydrograph (IUH) can be estimated using equation 5.1 which consists of two parameters: N [-] and K [hr]. The parameter N represents the number of identical reservoirs and the parameter K represents the storage constant of the reservoirs.

$$g_i = \frac{1}{K\ \Gamma(N)}\ e^{-\left(\frac{t_i}{K}\right)}\ \left(\frac{t_i}{K}\right)^{(N-1)} \tag{5.1}$$

g_i ordinate of unit hydrograph at time step i [1/hr]

t time elapsed at time step i [hr]

N number of reservoirs in cascade (series) [-]

K retention time of reservoirs [hr]

In the case of gauged catchments, Nash cascade parameters can be determined through the method of moments or calibration using observed runoff hydrograph. However, for ungauged catchments the parameters must be derived indirectly through a regionalization procedure. The regional transfer function approach, which associates model parameters with hydrological characteristics (see: chapter 2), was adopted to derive regionalization methodology for Nash cascade parameters.

5.2 Transfer functions for Nash cascade parameters

The existing approaches to derive transfer functions for Nash cascade parameters (Onyando et. al., 2005; Schumann, 1993; Lutz, 1984) use the conventional two step regionalization procedure, in which model parameters are first calibrated separately for each catchment in a set of gauged catchments, then the transfer functions for the parameters are derived through regression procedures.

However, the conventional regionalization procedure often faces the problems of equifinality, i.e. unique optimum parameter identification. Figure 5.1 shows scatter plots of Nash cascade parameters corresponding to high goodness fit performance of the event based Nash cascade model for two separate events. The parameters were obtained through conventional calibration procedure using Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) as a measure of goodness fit between modeled and observed direct runoff hydrograph (NS; equation 5.5). The scatter plots reveal that the parameters spaces for the respective events yield hundreds of different sets of N and K which lead to high goodness fit of $NS > 0.90$. The examples demonstrate that the parameters N and K varies within their a fixed parameters space while producing equally high goodness fit performance. Thus, due to large number of equally good parameter sets, it is difficult to identify the one that adequately fits adequately into regional transfer functions.

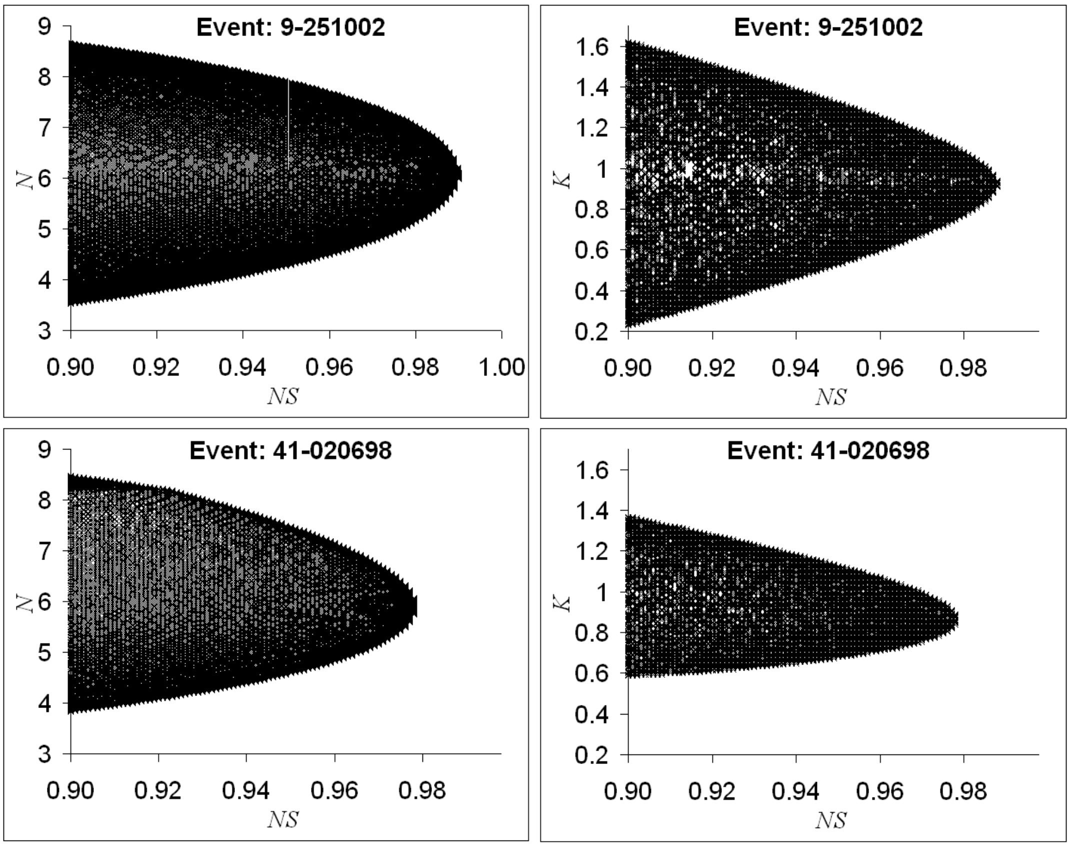

Figure 5.1: Distribution of Nash cascade parameters corresponding to high goodness fit performance

Another problem with the conventional regionalization procedure is the discrepancy between optimum local and regional parameter sets. Even if one manage to distinguish a unique optimum parameter set for a catchment, it is very likely that it may not correspond to the optimum performance of regional transfer functions and *vice versa*.

Last but not least, the conventional regionalization procedures are often based on purely data driven regression which does not consider the physical relationships between predictors and response. Hence, the transfer functions derived through such approaches are often physically unreasonable and lack the robustness which is necessary for extrapolation or regionalization.

The methodology, followed to derive transfer function for Nash cascade parameters, attempts to reduce uncertainty of parameter identification due to problem of equifinality by exploiting inter-parameter relationships. The methodology was specifically aimed at obtaining regionally optimum transfer functions through regional optimization. Since Nash cascade parameters are conceptual, their physical relationships with hydrological characteristics can not be identified and embedded into the transfer functions. However, the derived transfer functions were validated for the physical relationships between the relevant hydrological characteristics and the end response of the model.

5.2.1 Inter-parameter relationship

The problem of equifinality originates from the inter parameter interaction between N and K. Figure 5.2 shows scatter plots of N versus K for more than 100 parameter sets for four separate events, all of which lead to high goodness fit of $NS > 0.90$. The high negative correlation coefficients ($Corr$) for all the four events demonstrate the existence of strong relationship between the parameters N and K. Furthermore, the shape of the scatter plots and trend line analysis reveal the possibility of hyperbolic relationship (power function) between the parameters.

Tung et. al. (1997), in an attempt to regionalize Nash cascade parameters through multivariate regression, demonstrated that the inter-parameter relationship between N and K can be used to achieve better regional parameter estimations. Thus, instead of deriving separate transfer functions for N and K, it is more appropriate to derive transfer function only for the parameter K as shown in equation 5.2 and then estimate the parameter N using the inter-parameter relationship between N and K.

$$K = f_t(HCs_j|\theta_j) \tag{5.2}$$

f_t transfer function

HCs hydrological characteristics

θ coefficient of the transfer function [-]

j $= 1, .., n$ where, n is number of hydrological characteristics used in the function

As a preliminary attempt to establish the inter-parameter relationship, following procedure was carried out:

- For each event, more than 100 sets of parameters N and K, which lead to high goodness fit performance of $NS > 0.85$ were selected using Monte-Carlo simulations (Rubinstein and Kroese, 2007). In the Monte-Carlo simulation, a potential parameter is selected from a predefined parameter space. If the parameter leads to acceptable goodness fit, it is accepted else it is rejected.

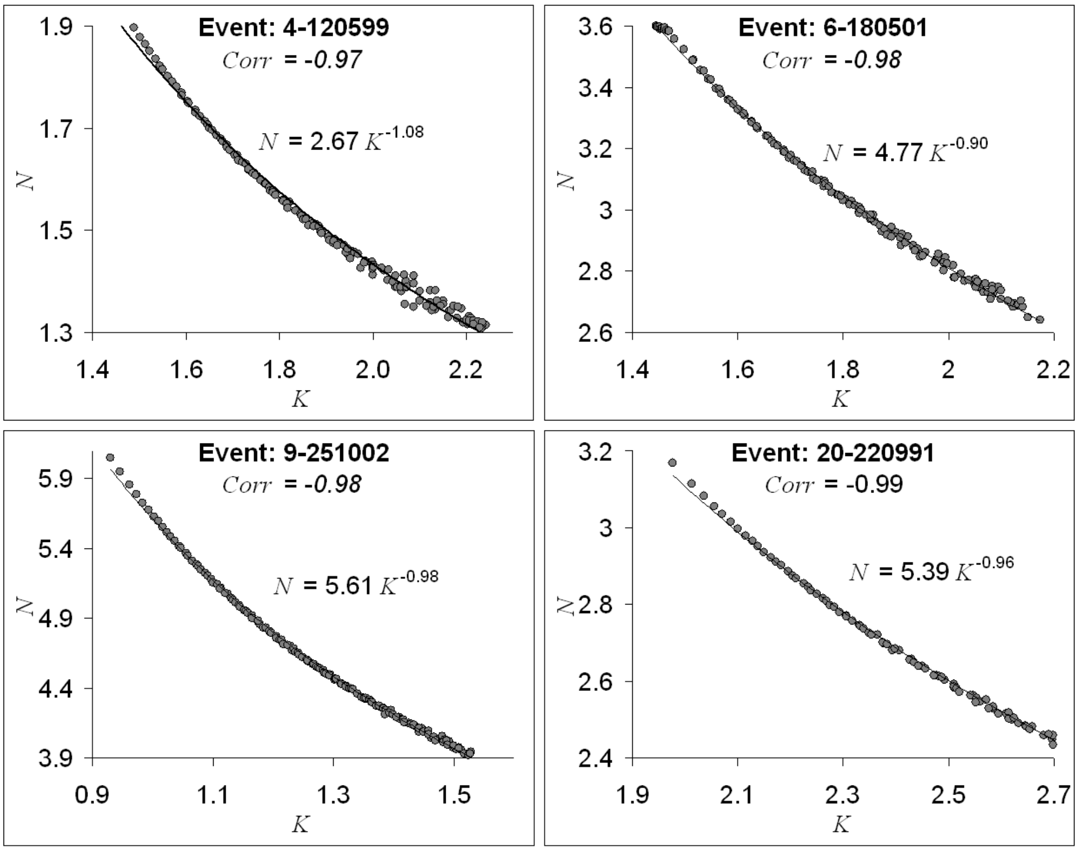

Figure 5.2: Inter-parameter relationship between N and K

- The inter-parameter function between N and K was derived for each event through non-linear regression using the selected parameter sets.

The procedure was repeated for the events in the regionalization and the validation set (see: section 3.3), table 5.3 shows summary of the optimum performance achieved during the Monte-Carlo simulations for the respective sets. The optimum performance was regarded as a preliminary performance and, later, was compared with the performance of the derived regionalization methodology.

The non-linear regression to establish inter-parameter relationship for each event leads to a power function that associates N with K as shown in equation 5.3, this was also supported by the earlier trend line analysis (figure 5.2). The regression also reveals that, for most of the events, the value of exponent α is close to -1.0. Correlation analysis of α against catchment and event specific hydrological characteristics (see: section 3.4) does not indicate significant correlations with the hydrological characteristics (table 5.1). Therefore, for the sake of simplification of the inter-parameter function, $\alpha = -1.0$ was assumed to be true for all the events. Thus, the inter-parameter function was reduced to only one unknown, i.e. coefficient β.

$$N = \beta\ K^{\alpha} \quad where,\ \alpha = -1.0 \tag{5.3}$$

β coefficient of the inter-parameter function [-]

α exponent of the inter-parameter function [-]

Although the form of the inter-parameter function remains same and α remains fairly constant, the coefficient β differs widely from event to event. Furthermore, the correlation analysis of β against the hydrological characteristics suggests that β might be well associated with some of the hydrological characteristics (table 5.1). Thus, there is a possibility to establish a transfer function between β and the hydrological characteristics and, subsequently, regionalize the inter parameter relationship. Therefore, a second transfer function to estimate the coefficient β, as shown in equation 5.4, was introduced into the proposed regionalization methodology.

$$\beta = f_t(HCs_j|\psi_j) \tag{5.4}$$

ψ coefficient of the transfer function [-]

j $= 1, .., n$ where, n is number of hydrological characteristics used in the function

5.2.2 Selection of the predictors

Correlation analysis is a commonly used procedure for selection of potential predictors to predict a response variable under consideration. Table 5.1 shows correlations of the relevant catchment and event specific hydrological characteristics with parameter K and coefficient β, which are obtained through the Monte-Carlo simulations and the subsequent regression. K and β are highly correlated with most of the hydrological characteristics specified in the table. The correlation analysis also points out that K and β are associated more with the event specific characteristics than the catchment specific characteristics.

However, correlation analysis may not provide sufficient basis to select the potential predictors. Correlation analysis may identify only those predictors which are linearly related to response variable, the relationship which are non-linear in nature may not show significant correlations. Moreover, existence of multicollinearity among predictors may also affect correlation analysis (Johnson and Wichern, 1992).

Therefore, in addition to the correlation analysis, literature and *a priori* knowledge of runoff propagation processes were also considered for selection of the potential predictors. Previous regionalization studies (Tung et. al., 1997; Schumann, 1993) and the *a priori* knowledge suggest that Nash cascade parameters can be associated with topographic and morphological characteristics, such as area, perimeter, time of concentration, slope, shape factor etc. Onyando et. al. (2005) and Lutz (1984) suggest that the parameters can be also associated with land use.

The previous studies associate Nash cascade parameters only with catchment characteristics. However, Serrano et. al. (1985) have attributed the distinctness of the parameters for the several rainfall-runoff events, occurred in the Middle Thames River over a period of 30 years, to event specific characteristics. Lutz's (1984) attempt

Table 5.1: Correlations of the hydrological characteristics with K, β and α

	Regionalization set			Validation set		
	K	β	α	K	β	α
P_t	0.56	0.46	0.16	0.49	0.47	0.14
T_p	0.50	0.49	0.08	0.36	0.57	-0.14
A	0.23	0.40	-0.04	0.02	0.37	-0.17
Per	0.25	0.53	-0.05	0.10	0.36	-0.18
TC	0.24	0.60	-0.11	0.01	0.31	-0.20
SF	0.12	-0.04	0.02	0.13	0.30	-0.17
SL	0.00	-0.33	0.18	0.17	-0.07	0.26
DR	0.06	0.00	0.20	0.25	0.20	0.07
TRI	-0.02	-0.35	0.17	0.18	-0.04	0.23
TWI	0.30	0.60	-0.19	0.10	0.39	-0.23
LU_f	0.10	-0.06	0.09	0.21	0.03	0.14
LU_u	0.16	0.47	-0.12	-0.14	-0.08	0.28
LU_a	0.15	0.42	-0.07	-0.08	0.24	-0.26

to regionalize the parameters also includes indirect consideration of event specific characteristics such as rainfall intensity, season and runoff coefficient. Therefore, in addition to the catchment characteristics, event specific characteristics are also thought to be the potential predictors to estimate K and β.

Based on the above discussion, 11 relevant hydrological characteristics: total rainfall, event duration, area, perimeter, time of concentration, shape factor, slope, terrain ruggedness index, topographic wetness index, river density and land use were selected as the potential predictors to derive the transfer functions for the parameter K and the coefficient β.

5.2.3 Form of the transfer functions

Nash cascade parameters and the coefficient β are rather conceptual representations. Due to the absence of their physical explanations, the physical relationships of K and β with the selected predictors cannot be established through the *a priory* knowledge of runoff propagation processes. Trend line analysis of the relationships of K and β with the highly correlated predictors is presented in Figure 5.3 and 5.4. However, due to multicollinearity, the trend line analysis does not provide more than a slightest hint of non-linearity of the relationships. Hence, the functional form of the transfer functions can not be presumed.

Therefore, the form of the transfer functions was derived through trial-and-error procedure. Initially, the transfer functions were assumed to be linear, during the trial-and-error procedure, various non-linear multivariate forms, such as power, exponential and logistic functions as well as their combinations, were tried out to achieve physically reasonable and efficient regional transfer functions.

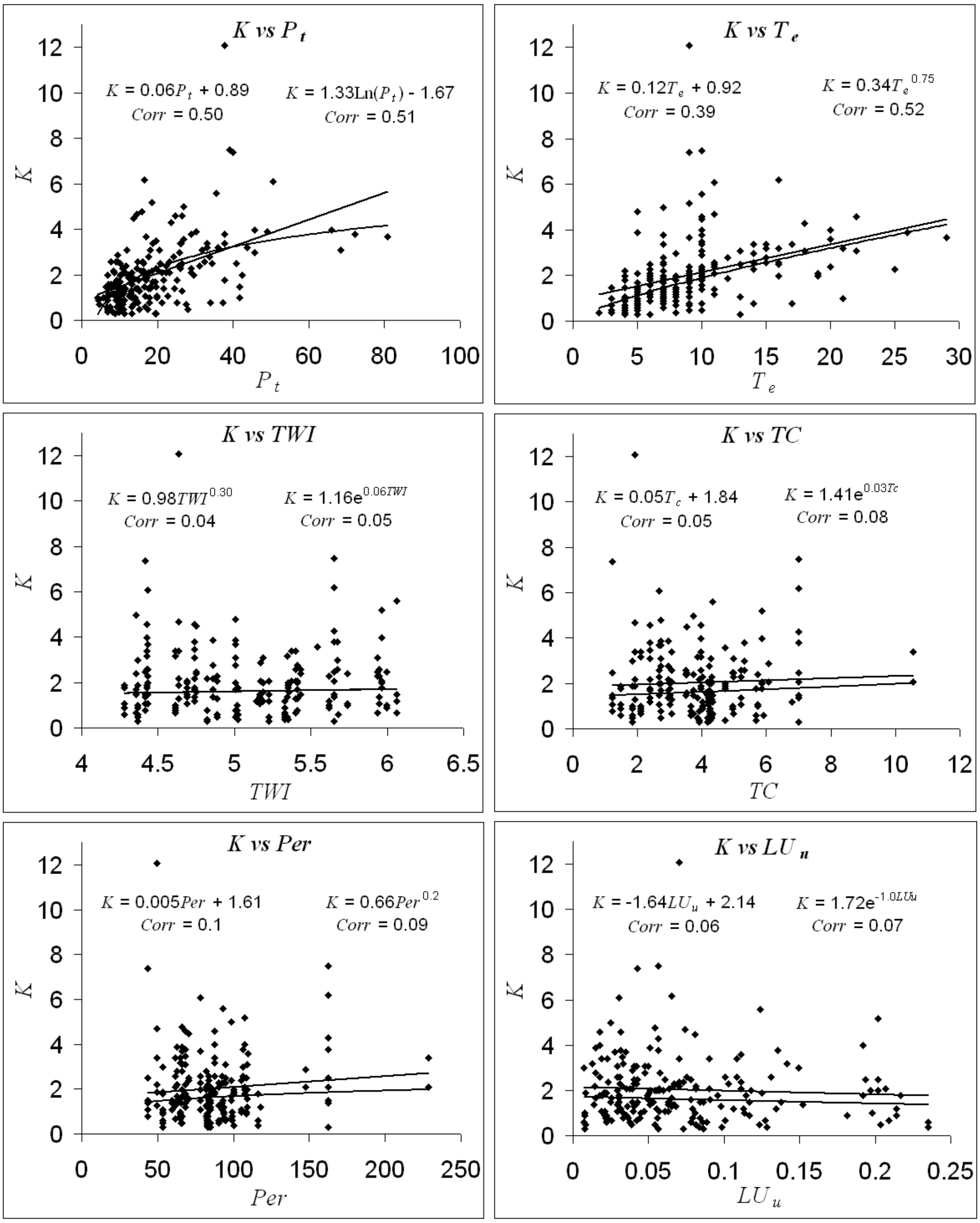

Figure 5.3: Trend line analysis of relationship between K and the potential predictors

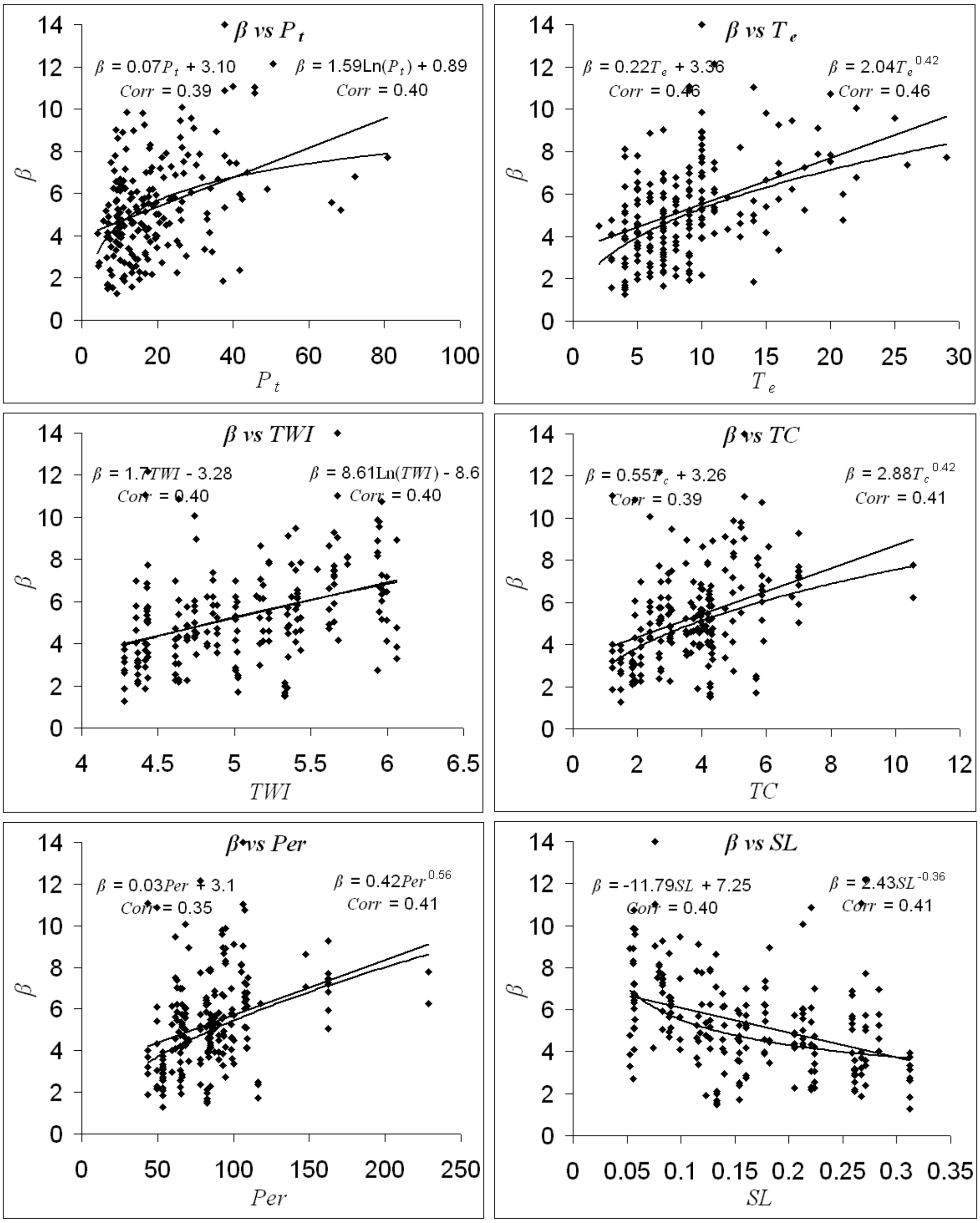

Figure 5.4: Trend line analysis of relationship between β and the potential predictors

5.2.4 Regional optimization procedure

The parameter sets calibrated for optimum performance at catchment scale may not correspond to optimum performance at regional scale, thus, may lead to weak regional transfer functions. Instead, if the coefficients of predefined transfer functions are calibrated to optimize regional performance, there is a better chance to obtain robust regional transfer functions (Hundecha and Bárdossy, 2004). Hence, the coefficients of predefined forms of the transfer functions for K and β were calibrated by optimizing regional performance of the event based Nash cascade model.

The regional optimization was carried out by using an aggregated objective function which ensures fairly good performance for individual rainfall-runoff events at catchment scale and optimum performance at regional scale. Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) was used as the objective function for the optimization. Nash-Sutcliffe coefficient was weighted by observed discharge in order to emphasize goodness fit of peak runoff. The performance for an individual rainfall-runoff event was assessed through discharge weighted Nash-Sutcliffe coefficient for the respective events, as shown in equation 5.5. The aggregated regional performance was assessed by taking the mean of the performance obtained for the events in the regionalization set, as shown in equation 5.6.

$$NS = 1 - \frac{\sum_{i=1}^{n} Q_{ob,i}(Q_{ca,i} - Q_{ob,i})}{\sum_{i=1}^{n} Q_{ob,i}(Q_{ob,i} - \overline{Q_{ob}})} \tag{5.5}$$

$$Maximize \left[\overline{NS} = \frac{\sum_{j=1}^{m} NS_j}{m} \right] \tag{5.6}$$

NS discharge weighted Nash-Sutcliffe coefficient [-]

$\overline{NS}$ mean discharge weighted Nash-Sutcliffe coefficient for a set of events [-]

Q_{ob} observed direct runoff $[m^3/s]$

Q_{ca} modeled direct runoff $[m^3/s]$

$\overline{Q_{ob}}$ mean observed discharge for a event $[m^3/s]$

n number of time steps [-]

m number of events in a set [-]

During the trial-and-error procedure, optimization of every presumed linear or non-linear form of the transfer functions was begun with associating K and β with all the potential predictors. During the backward stepwise procedure the predictors which do not show significant sensitivity toward model performance, and those which do not form physically reasonable relationships, were eliminated. The regional optimization procedure (figure 5.5) was carried out as following:

1. Randomly selected values of the coefficients (θ and ψ) of transfer functions for K and *beta* were inserted into the predefined form of the transfer functions.

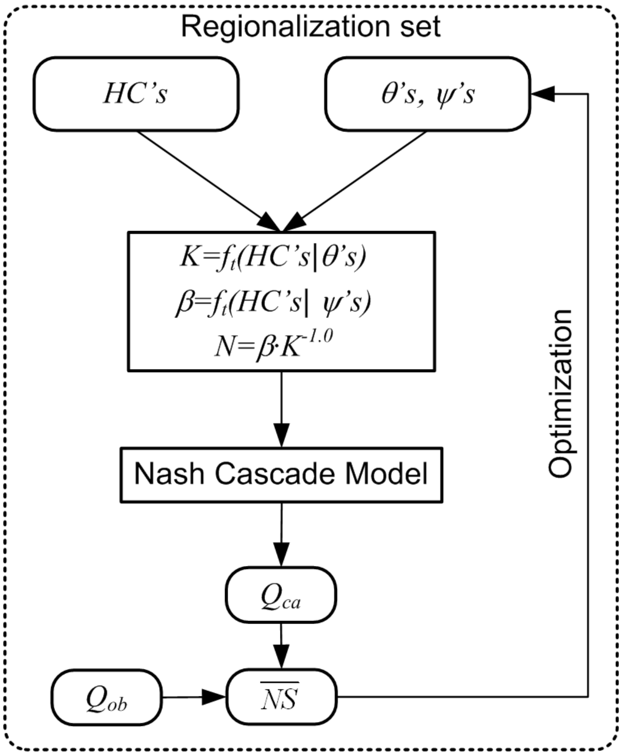

Figure 5.5: Regional optimization procedure

K, β and N were estimated for each event by using the normalized predictors (hydrological characteristics) in the respective transfer functions. The predictors for an event were normalized by dividing the original values of predictors by maximum values the respective predictors in the regionalization set.

2. Then, for each event, the estimated parameters were used in the event based Nash cascade model (figure 2.6) to derive direct runoff hydrograph. NS corresponding to individual events was calculated using equation 5.5. Finally $\overline{NS}$ was obtained by averaging NS over all the events in the regionalization set.

3. Steps 1 to 3 were repeated to optimize $\overline{NS}$ by calibrating the coefficients of the transfer functions through simulated annealing algorithm.

5.2.5 Simulated annealing algorithm

Simulated annealing optimization algorithm is a Monte-Carlo simulation technique, conceptually borrowed from annealing procedure for heat treatment of metals (Kirkpatrick et. al., 1983). Simulated annealing optimization begins at a high hypothetical temperature, the temperature is reduced by a certain factor in the subsequent steps. At each temperature reduction step several Monte-Carlo simulations, using randomly selected parameters, are carried out. At the beginning, the high temperature prompts higher acceptance of Monte-Carlo simulations, event if they do not lead to better performance. Hence, at the beginning, the algorithm has more freedom to select parameters from broad (global) parameter space. As the temperature is reduced, more and more of those Monte-Carlo simulations, which do not lead to better performance, are rejected. Thus, the acceptance ratio, and consequently, the available parameter space also reduces. When the temperature is reduced to a desired degree at which the available parameter space is very limited, the algorithm is stopped.

Due to extensive global parameter search simulated annealing optimization may take longer computational time, however, the optimization process does not get confined at local optima and may lead to globally optimum parameters. Simulated annealing algorithm was chosen during this study, mainly, due to its ability to search for global optimum parameters.

5.2.6 The optimization results

The optimization results suggest that K and β can be optimally represented by combination of power and exponential functions of the hydrological characteristics. The transfer function for K associates the parameter with time of concentration (TC), duration of rainfall (T_e) and relative area of urban land use (LU_u). The transfer function for coefficient of inter-parameter function β associates the coefficient with duration of rainfall (T_e), total rainfall (P_t), slope (SL) and perimeter (Per). The optimum regional transfer functions for K and β, which lead to regional performance of $\overline{NS} = 0.72$, are shown in equation 5.7 and equation 5.8. Further, N can be estimated using equation 5.9 respectively.

$$K = 7.14\ T_p^{0.7}\ TC^{0.22}\ e^{0.53 LU_u} \tag{5.7}$$

$$\beta = 5.62\ T_p^{0.37}\ SL^{-0.42}\ Per^{0.083}\ e^{0.18 P_t} \tag{5.8}$$

$$N = \beta\ K^{-1.0} \tag{5.9}$$

Conventionally, it is believed that Nash cascade parameters are functions of catchment specific hydrological characteristics. However, the correlation analysis for K and β (table 5.1) suggested that they may be well associated with event specific hydrological characteristics. The derived transfer functions further confirm that Nash cascade parameters are, indeed, highly dependent of event specific hydrological characteristics. Both, K and β, exhibit strong relationship with T_e. β is also associated with P_t. However, despite of the strong correlation in table 5.1, K did not indicate sensitivity toward P_t.

On the other hand, although the correlation analysis suggested that K may not be related with TC and LU_u, the transfer function for K reveals that it is associated with the two catchment specific characteristics. The transfer function for β indicates that it is reasonably dependent on SL and Per, instead of TWI as shown by the correlation analysis. The physical significance of the relationships featured in the transfer functions is discussed in the later part of this chapter.

Table 5.2 presents the summary of the aggregated performance the derived transfer functions. The median NS ($\widetilde{NS}$) over the regionalization set was as high as 0.78

and, for almost 70 % of the total number of events high goodness fit of $NS > 0.7$ was achieved. Only for 14 % of events the performance was below $NS < 0.5$.

Table 5.2: Aggregated performance of the derived transfer functions

Data set			**% events**	**% events**		
	$\overline{NS}$	$\widetilde{NS}$	$NS > 0.7$	$NS < 0.5$	NS_{Qpeak}	NS_{Tpeak}
Regionalization	0.72	0.78	70	14	0.93	0.89
Validation	0.75	0.82	69	16	0.93	0.87

Overview of the performance of the derived transfer functions for individual events in the regionalization set suggests that the typical high performance ranges between $NS = 0.85$ and $NS = 0.99$. The highest performance was achieved for event 3-120997 which occurred in the catchment Untermünstertal. Although the lowest performance was $NS = -0.33$ for event: 12-120799 in the catchment Horgen-Kläranlage, the typical low performance ranges between $NS = 0.1$ and $NS = 0.5$. Figure 5.6 and 5.7 show the modeled (Q_{ca}) and observed (Q_{ob}) runoff hydrographs along with effective rainfall (Pe) for typical high performance and typical low performance respectively. The overview of the performance for the individual events points out that the regionalization methodology may not be efficient at modeling relatively small rainfall events. Detailed discussion regarding the low performance and possible sources of errors is given at the end of this chapter.

In the context of design and operation of flood protection measures and their components, peak runoff and time to peak runoff are the most critical characteristics of design flood hydrograph (see: section 1.2). Therefore, goodness fit between observed and modeled peak runoff as well as time to peak runoff were estimated as shown in equation 5.10 and 5.11 respectively. Figure 5.8 and 5.9 present the goodness fit of peak runoff and time to peak runoff respectively. The goodness fit of peak runoff ($NS_{Qpeak} = 0.93$) and time to peak runoff ($NS_{Tpeak} = 0.89$) achieved during the optimization are high enough to conclude that the derived transfer functions lead to reasonably acceptable performance for the regionalization set.

$$NS_{Qpeak} = 1 - \frac{\sum_{i=1}^{m}(Qpeak_{ca,i} - Qpeak_{ob,i})}{\sum_{i=1}^{n}(Qpeak_{ob,i} - \overline{Qpeak_{ob}})} \tag{5.10}$$

$$NS_{Tpeak} = 1 - \frac{\sum_{i=1}^{m}(Tpeak_{ca,i} - Tpeak_{ob,i})}{\sum_{i=1}^{n}(Tpeak_{ob,i} - \overline{Tpeak_{ob}})} \tag{5.11}$$

NS_{Qpeak} Nash-Sutcliffe coefficient for peak runoff [-]

NS_{Tpeak} Nash-Sutcliffe coefficient for time to peak runoff [-]

$Qpeak_{ob}$ observed peak runoff $[m^3/s]$

$Qpeak_{ca}$ modeled peak runoff $[m^3/s]$

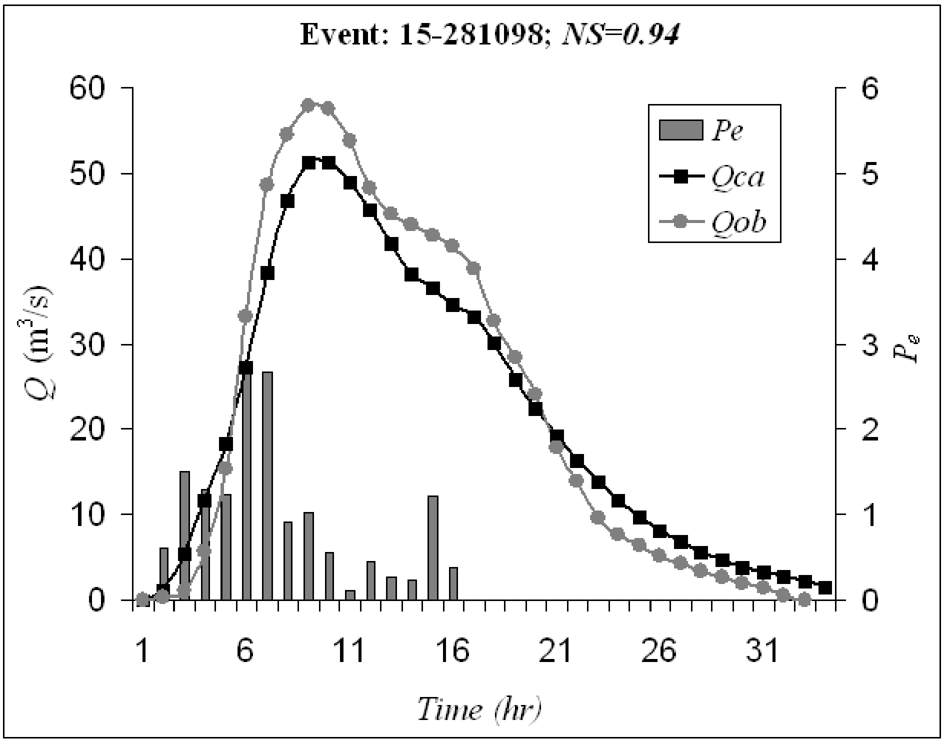

Figure 5.6: Modeled runoff hydrograph for event: 15-281098 in catchment Oppenweiler

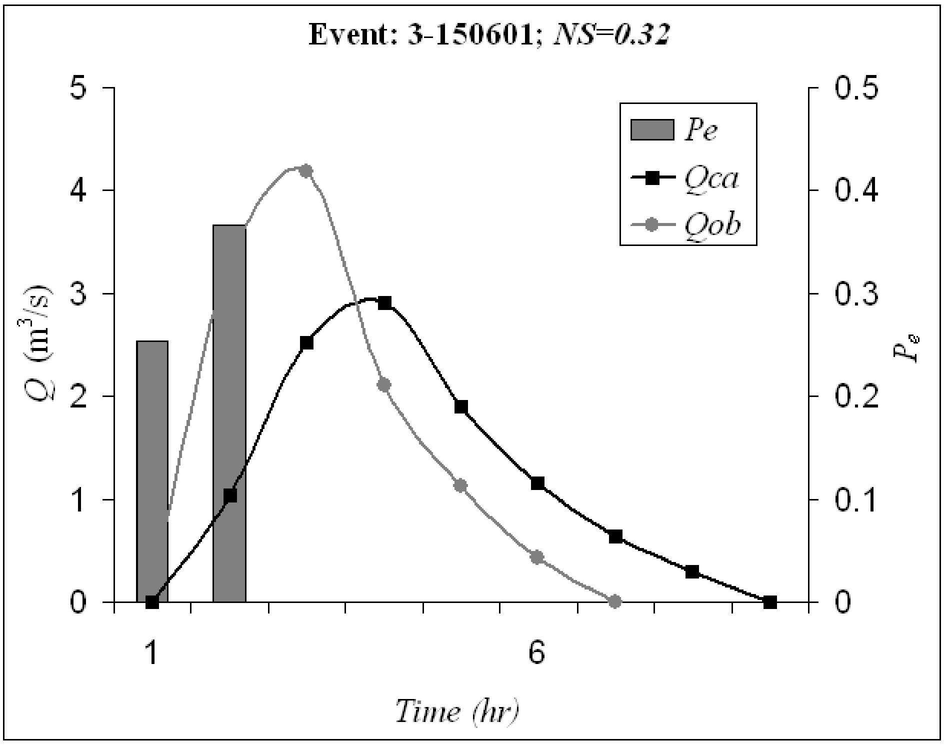

Figure 5.7: Modeled runoff hydrograph for event: 3-150601 in catchment Untermünstertal

$Tpeak_{ob}$ observed time to peak runoff [hr]

$Tpeak_{ca}$ modeled time to peak runoff [hr]

m number of events in a set [-]

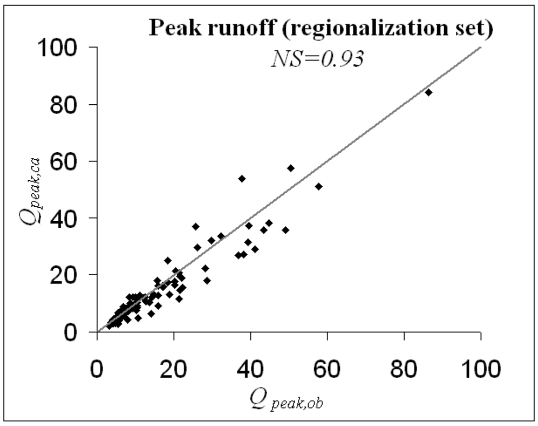

Figure 5.8: Goodness fit: peak runoff

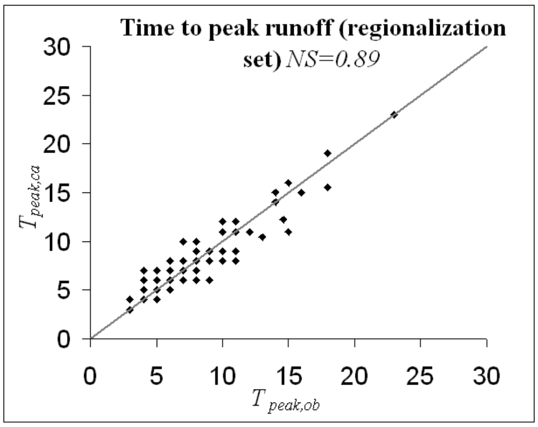

Figure 5.9: Goodness fit: time to peak runoff

5.2.7 The validation results

In order to examine the ability of the derived transfer functions to transfer Nash cascade parameters to ungauged catchments, the transfer functions were employed in the validation catchments (table 5.2) which were not used for its derivation. The summary of the aggregated performance of the transfer functions for the validation set is presented in table 5.2. Aggregated performance for the validation set was estimated to be $\overline{NS} = 0.75$ and $\widetilde{NS} = 0.82$. For more than 69 % of the total number of events $NS > 0.7$ was achived. For 16 % of the events the performance was $NS < 0.5$. The aggregated performance implies that the derived transfer functions perform equally good for the validation set as for the regionalization set.

The overview of the performance for individual events in the validation set also shows the similar distribution as that for the regionalization set. Typical high performance ranges between $NS = 0.85$ and $NS = 0.98$, and the typical low performance ranges between $NS = 0.1$ and $NS = 0.5$. The highest performance ($NS = 0.98$) was achieved for event: 27-090700 occurred in the catchment St. Blasien and the lowest performance $NS = -0.14$ was obtained for event: 37-050799 in the catchment Talhausen. The runoff hydrographs representing typical high performance (figure 5.10) and typical low performance (figure 5.11), again, suggest that the transfer functions fail to model small rainfall events.

Correlation plots between observed and modeled peak runoff as well as time to peak runoff are shown in figure 5.12 and 5.13 respectively. The correlation plots indicate high goodness fit of peak runoff ($NS_{Qpeak} = 0.93$) and time to peak runoff

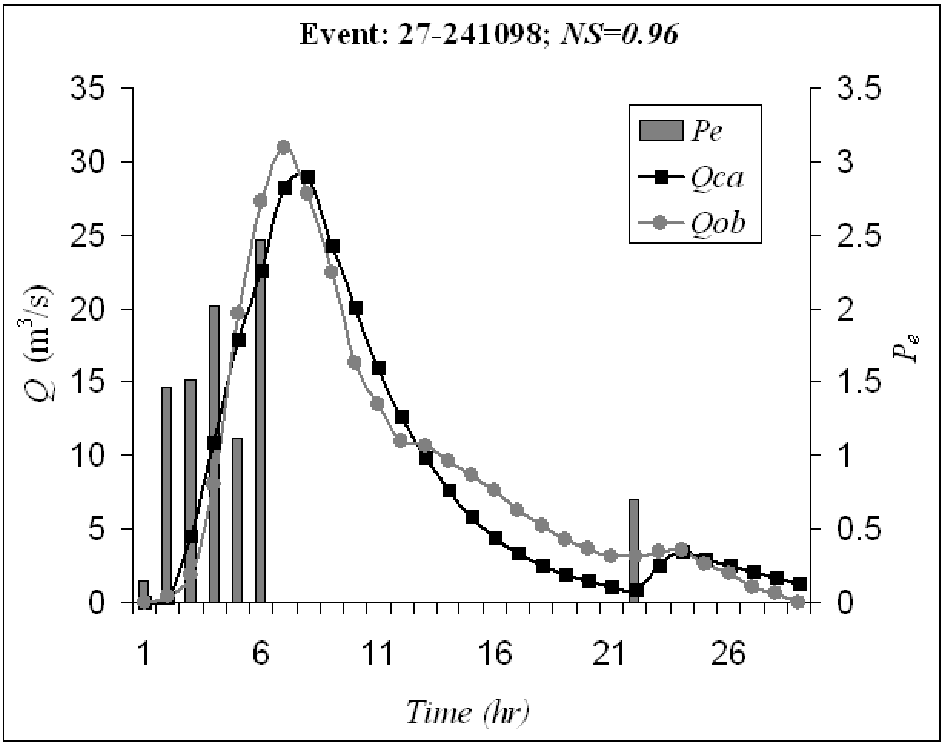

Figure 5.10: Modeled runoff hydrograph for event: 27-241098 in catchment St. Blasien

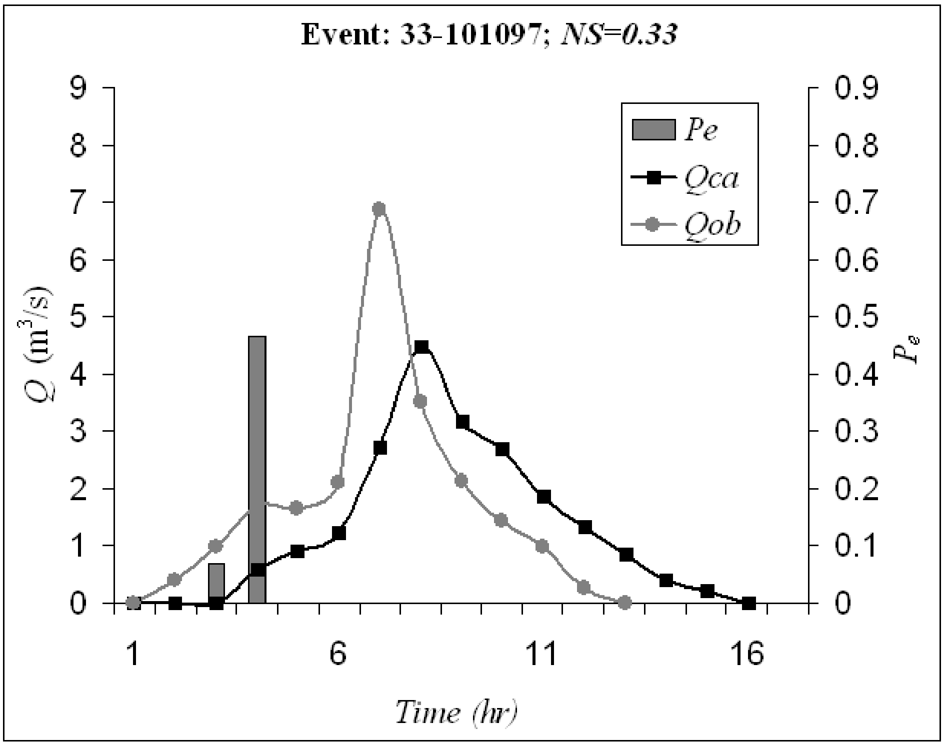

Figure 5.11: Modeled runoff hydrograph for event: 33-101097 in catchment Ettlingen

($NS_{Tpeak} = 0.87$). The transfer functions, as in the case of the regionalization set, exhibit excellent goodness fit of the two critical characteristics of flood hydrograph for the events in the validation set.

The assessment of the overall performance of the transfer functions for the validation set suggests that the transfer functions are consistent and efficient to transfer Nash cascade parameters to ungauged catchments.

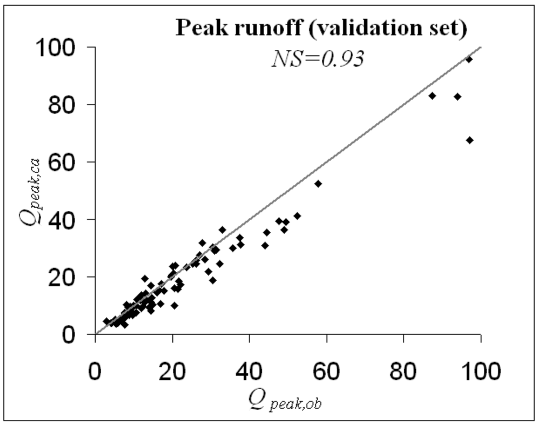

Figure 5.12: Goodness fit peak runoff

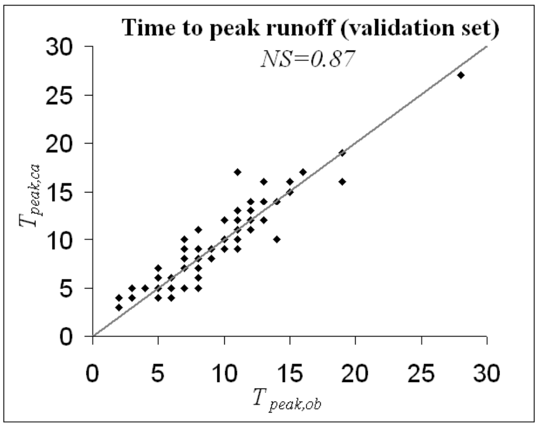

Figure 5.13: Goodness fit time to peak runoff

5.2.8 Comparison with the preliminary performance

Table 5.3 shows the preliminary performance obtained during the Monte-Carlo simulations (see: section 5.2.1). The performance suggests that for most of the events a very high goodness fit performance can be achieved through conventional calibration. The table also indicates the excellent goodness fit of peak runoff and time to peak runoff.

Table 5.3: Aggregated preliminary performance (Monte-Carlo simulations)

Data set			**% events**	**% events**		
	$\overline{NS}$	$\widetilde{NS}$	$NS > 0.7$	$NS < 0.5$	NS_{Qpeak}	NS_{Tpeak}
Regionalization	0.96	0.97	100	0	0.99	0.97
Validation	0.96	0.97	100	0	0.99	0.93

The comparison of the performance of the derived transfer functions with the preliminary performance reveals that the Monte-Carlo simulations clearly outperform the transfer functions. The aggregated performance of the Monte-Carlo simulations for the regionalization and the validation sets ($\overline{NS} = 0.96$ *and* 0.96 respectively) is much higher as compare to that of the transfer functions ($\overline{NS} = 0.72$ *and* 0.75 respectively). The highest performance achieved for the both is $NS = 0.99$. However, the lowest performance for the transfer functions ($NS = -0.33$), obtained for Event:

1-010591 in the catchment Zell am Harmersbach, was far worst than the lowest performance for the Monte-Carlo simulations ($NS = 0.82$) obtained for the same event. Although the goodness fit of runoff hydrograph for the Monte-Carlo simulations is far better than that for the transfer functions, the goodness fit of peak runoff and time to peak runoff achieved for the both are comparable.

The better performance of the Monte-Carlo simulations than that of the transfer functions is not unexpected. During the Monte-Carlo simulations the parameters are selected from relatively wide parameter space without any constraints. Therefore, it unrestrictedly leads to any, physically reasonable or unreasonable, parameter value that yields best goodness fit. However, in the case of the transfer functions the parameter space is constrained through the forced relationship between the parameters and the hydrological characteristics. Therefore, the transfer functions are restricted only to those parameters which satisfy the physically reasonable relationships which, consequently, limits the performance.

5.3 Validation for physical relationships

The derived transfer functions were also scrutinized to ensure that they represent physically reasonable relationships. Based on the *a priori* knowledge of runoff propagation processes, gained through conventional theories, experience and general understanding of hydrology, following inferences can be drawn regarding the physical relationships between shape of unit hydrograph and the catchment characteristics used in the transfer functions. However, the influence of the event specific characteristics could not be interpreted due to lack of sufficient understanding of runoff propagation.

1. Longer time of concentration implies longer travel time, which leads to relatively lower peak and wider loop of unit hydrograph.
2. Similarly, longer perimeter means bigger catchment, which also leads to relatively lower peak and wider loop of unit hydrograph due to longer travel time.
3. Steep slope in a catchment implies faster runoff propagation, thus, leading to relatively higher peak and narrower loop of unit hydrograph.
4. Due to sealed areas and artificial drainage system, runoff propagation in urban area is much faster as compared to that in non-urban areas, hence an increase in urban area may cause higher peak and narrower loop of unit hydrograph.

In order to validate the transfer functions for the above mentioned physical relationships, an assessment of the effects of change in the predictors which represent the catchment characteristics, on the response of the transfer functions in terms of shape of unit hydrograph was carried out. To carry out the assessment for a predictor the predictor was modified by a certain modification factor (MF) while keeping all the other predictors constant. Nash cascade parameters and the unit hydrograph corresponding to the modified predictor were derived using the transfer functions and the model. The procedure was repeated, one by one, for TC, Per, SL and LU_u use by using $MF = [0.5,\ 0.75,\ 1.25\ 1.5]$. The shape of the unit hydrographs corresponding to the modified predictors were then compared with the shape of the unit hydrograph corresponding to the original predictors.

Figure 5.14, 5.15, 5.16 and 5.17 present the unit hydrographs, corresponding to the original predictors (M.F=1.0) and to the modified predictors, for Event: 32-080901 ($NS = 0.97$) in the catchment Gutach. Figure 5.14 shows that the peak of the unit hydrograph reduces and the loop of the unit hydrograph tends to be wider with increase in TC, which is in accordance with the physical relationship. Similarly figure 5.15 signifies reduction in the peak and widening of the loop of the unit hydrograph due to increase in Per, which also conforms with the physical relationship. Figure 5.16 indicates the strong influence of SL on shape of unit hydrograph. Withstanding the physical relationship, increase in SL induces significant increase in the peak and narrowing of the loop of the unit hydrograph. Figure 5.17 reveals that influence of urban area, although only marginally captured by the transfer functions, also matches with the physical relationship.

The validation of the transfer functions for physical relationships suggests that the derived transfer functions appropriately represent the physical processes of runoff propagation. Thus, the transfer functions may facilitate robust and physically reasonable regionalization methodology to estimate Nash cascade parameters in ungauged catchments.

5.4 Comparison with Lutz procedure

To assess the usefulness of the derived transfer functions for practical application, their performance was further compared with that of Lutz procedure. Lutz procedure (Lutz, 1984), as described in chapter 2 (section 2.2.2), has been used as a standard practice for estimation of design flood hydrograph in the south-west part of Germany.

Direct runoff hydrographs for the events in the validation set were estimated using Lutz procedure, table 5.4 shows the summary of the aggregated performance. The aggregated performance was estimated to be $\overline{NS}$=0.33 and $\widetilde{NS}$=0.46, which is much lower as compared to that of the transfer functions. Only for 35 % of the events $NS > 0.7$ was achieved, where for more than 50 % of the events the performance was $NS < 0.5$.

Table 5.4: Aggregated performance of Lutz procedure

Data set			**% events**	**% events**		
	$\overline{NS}$	$\widetilde{NS}$	$NS > 0.7$	$NS < 0.5$	NS_{Qpeak}	NS_{Tpeak}
Validation	0.33	0.46	35	51	0.81	0.42

In terms of goodness fit between observed and calculated peak runoff ($NS_{Qpeak} = 0.81$) as well as the time to peak runoff ($NS_{Tpeak} = 0.42$) the Lutz procedure also

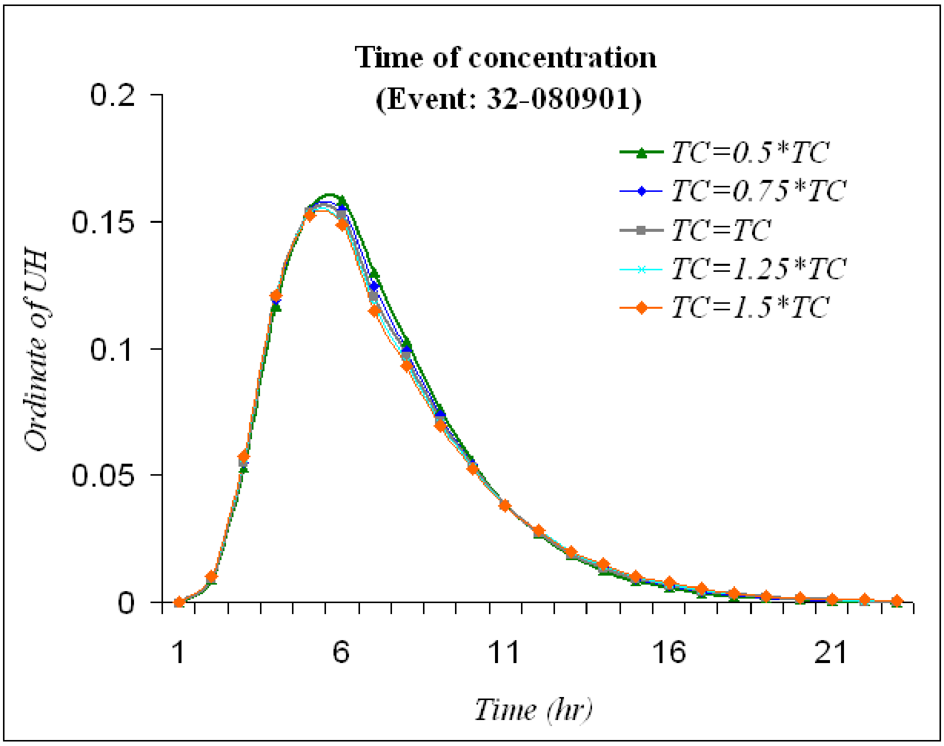

Figure 5.14: Time of concentration (TC) versus unit hydrograph

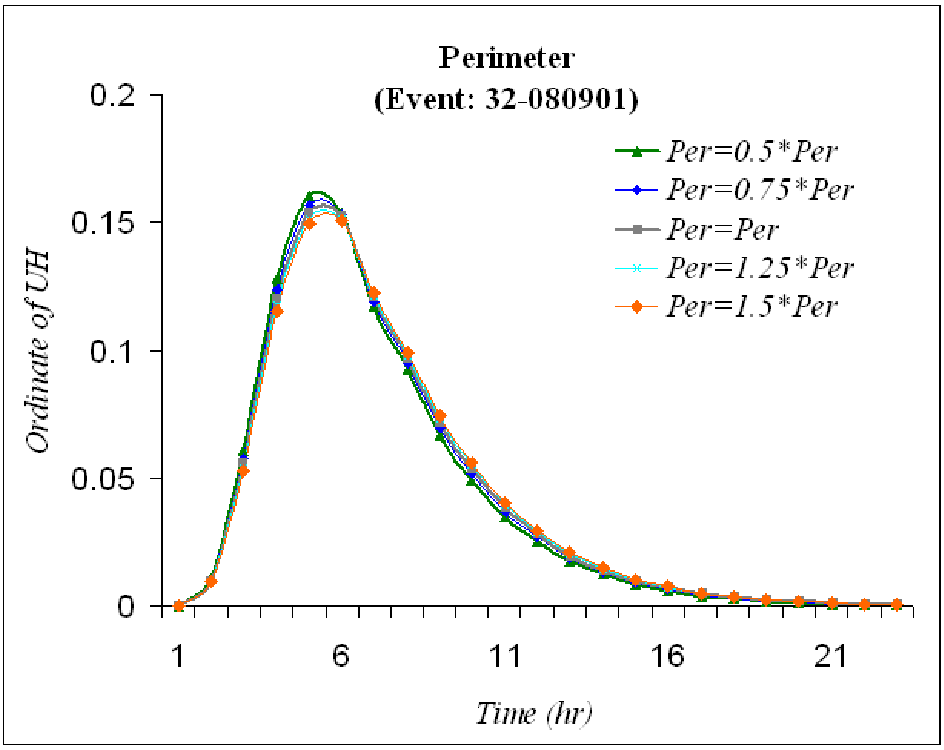

Figure 5.15: Perimeter (Per) versus unit hydrograph

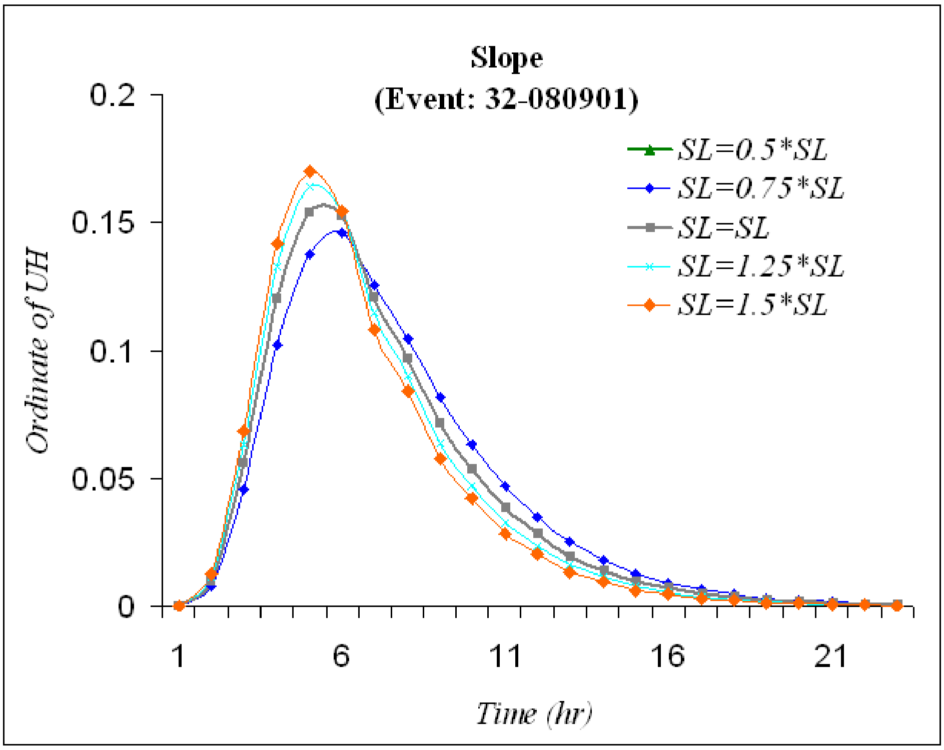

Figure 5.16: Slope (SL) versus unit hydrograph

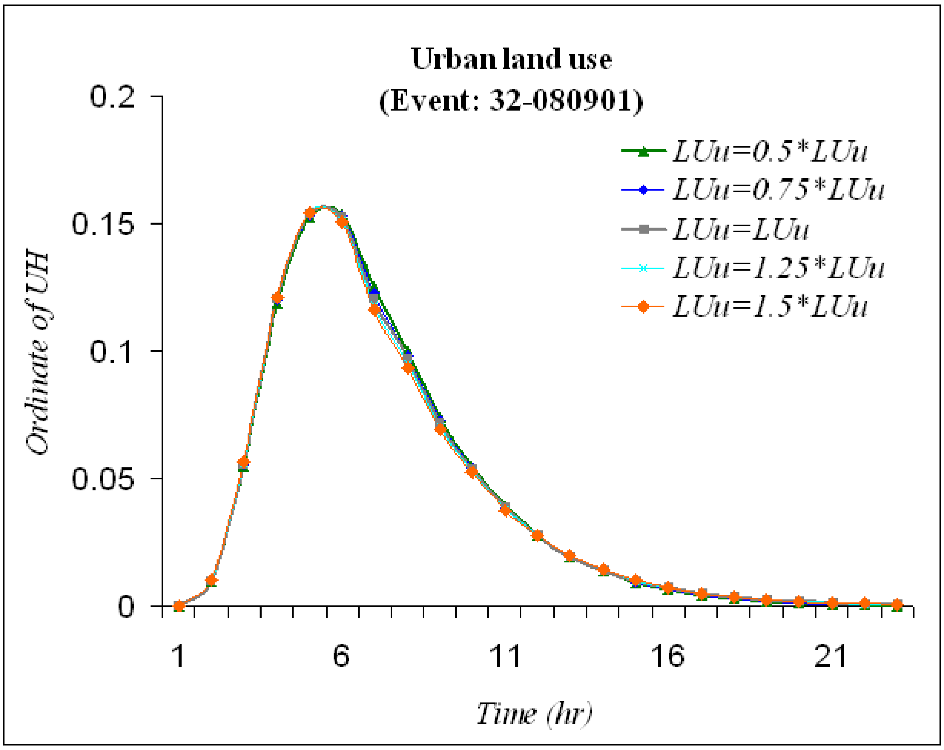

Figure 5.17: Urban land use (LU_u) versus unit hydrograph

fails to achieve the performance comparable to that of the derived transfer functions. Figure 5.18 reveals that Lutz procedure frequently underestimates the peak runoff for large events. On the other hand, figure 5.19 indicates that it overestimates the time to peak runoff. The comparison between the performance of Lutz procedure and the transfer functions derived during this study, indicates that the transfer functions are more efficient and reliable than Lutz procedure. Thus, the derived transfer functions can be regarded as applicable for practice oriented purpose of estimation of design flood hydrograph in ungauged catchments in the study area under consideration.

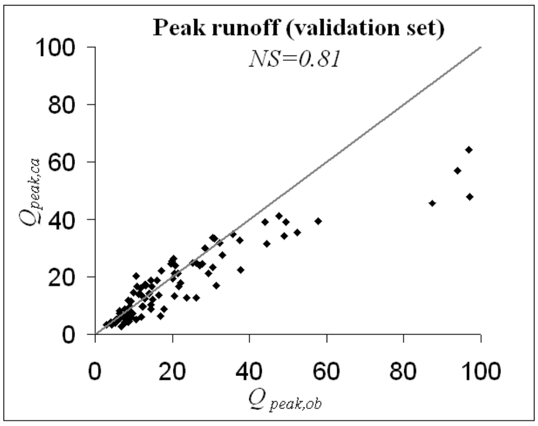

Figure 5.18: Goodness fit: peak runoff (Lutz procedure)

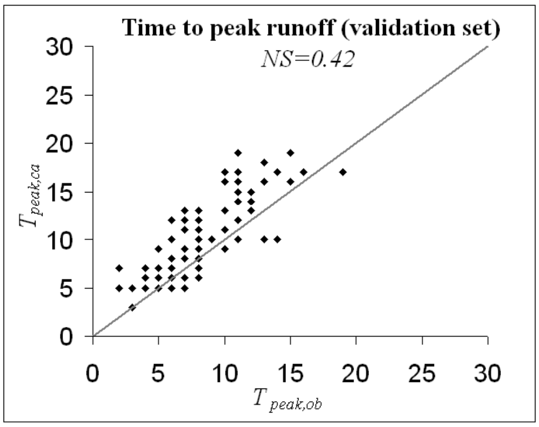

Figure 5.19: Goodness fit: time to peak runoff (Lutz procedure)

5.5 Discussion on the estimation error

Although the overall goodness fit performance of the transfer functions derived during this study is highly acceptable, for about 15 % of the total number of events the individual goodness fit performance was below the acceptable limit. The performance does not show any specific pattern with respect to the catchments, however, it was observed that goodness fit was typically high for the big events with long duration and it was typically low for small rainfall events with shorter duration. Thorough analysis of the performance for individual events suggusts that for very small rainfall events with $P_t < 20\ mm$, the performance is quite poor (figure 5.20). Figure 5.21 reveals that the performance is also poor for the events with short rainfall duration ($T_e < 10\ hr$). This leads to the conclusion that the performance of the derived transfer functions is limited due to size of the event in terms of amount and duration of rainfall. The transfer functions fail to achieve satisfactory estimation of Nash cascade parameters for the rainfall-runoff events produced by small amount of rainfall occured over short duration.

Mean NS for each catchment was estimated by averaging NS for the individual events selected from the respective catchment. The spatial distribution of mean NS, shown in figure 5.22, reveals that the catchment specific performance is worse in catchment Schafhausen (34) and Berghausen (35) which fall in the region of karstic

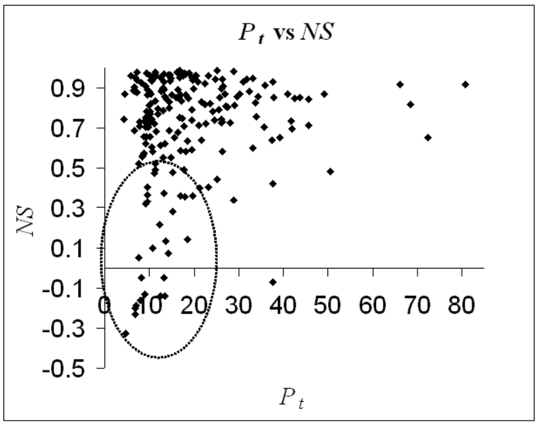

Figure 5.20: Total rainfall vs. NS

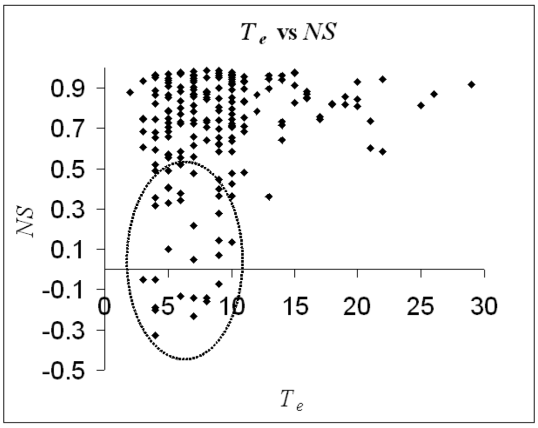

Figure 5.21: Duration vs. NS

rock formations. This is due to the fact that the drainage in this region is dominated by subsurface flow through highly previous karstic rock formations.

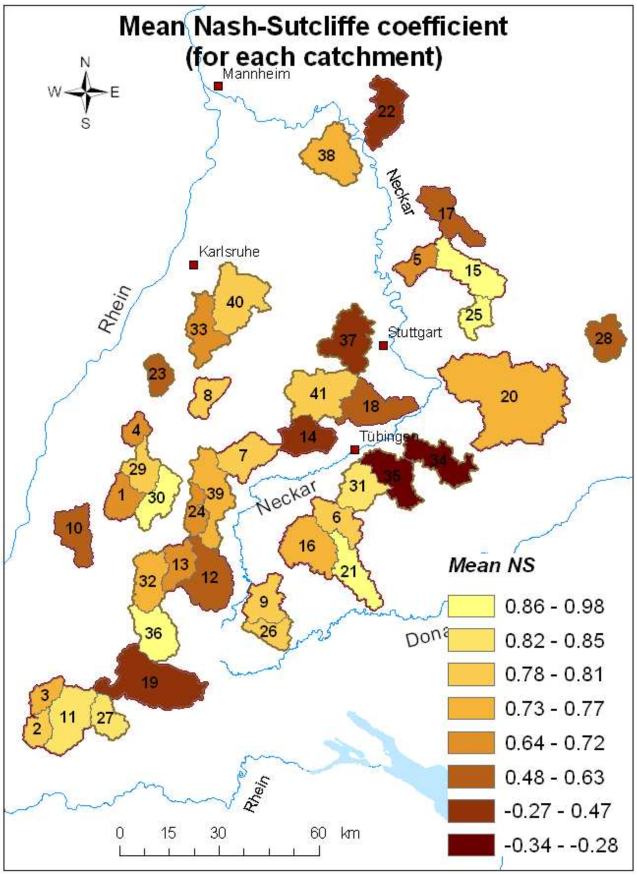

Figure 5.22: Mean NS for the catchments

6 Case Study: Catchment Tübingen

This chapter is aimed at illustrating the application of the regionalization methodology developed during this study, by means of a case study. Estimation of design flood hydrograph from design storm rainfall, in an ungauged catchment, is explained using the case study of catchment Tübingen. Further the impact of land use changes on flood characteristics is also demonstrated with the help of the case study.

6.1 Application of the regionalization methodology

6.1.1 Description of the case study

The catchment Tübingen (no. 31 in table 3.2) drains into the creek Steinlach which is a tributary of Neckar. The catchment Tübingen, which is a mesoscale catchment with area of 141 km^2, is divided into three subcatchments. The summary of hydrological characteristics of the subcatchments is presented in table 6.1.

Hydrograph for design flood of 100 years return period is to be estimated for the catchment, assuming that the event would occur in the month of May under the antecedent conditions given in the table 6.1. The table also gives normalizing factor for each hydrological characteristic, which represents the maximum value of the respective characteristic in the regionalization set. The amount and duration of design storm rainfall of 100 years return period is recommended as 120 mm and 12 hours (DWD, 1997). The recommended temporal distribution of the design storm rainfall is shown in figure 6.1 (DVWK, 1999).

Assuming that the rainfall is uniformly distributed over the catchment, identical rainfall time series for the subcatchments can be estimated as shown in figure 6.2 using the recommendations for design storm rainfall.

6.1.2 Estimation of runoff coefficient

The rainfall loss for the design storm event can be estimated by using the logistic transfer function shown in equation 6.1 and 6.2:

$$P_l = P_t \left[\frac{39.73 + sin\left(\frac{\pi}{6}(M-4)\right)}{1 + 39.73\ e^{(X)}} \right] \tag{6.1}$$

$$X = \left(\frac{P_t}{1 + 42.08\ e^{\left(1.07FCm - Dr + 0.045\left(\frac{LU_f}{LU_u}\right)\right)}} + \frac{API}{1 + 5267.8\ e^{(-5.57Kv_2)}} \right) \tag{6.2}$$

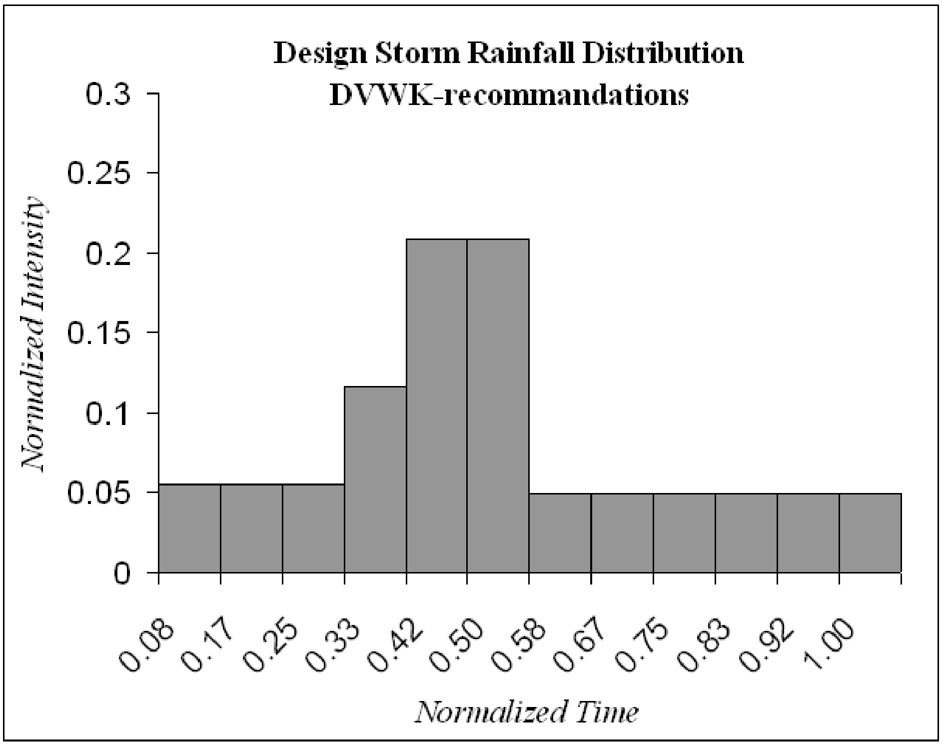

Figure 6.1: Normalized temporal distribution of design storm rainfall (DVWK, 1999)

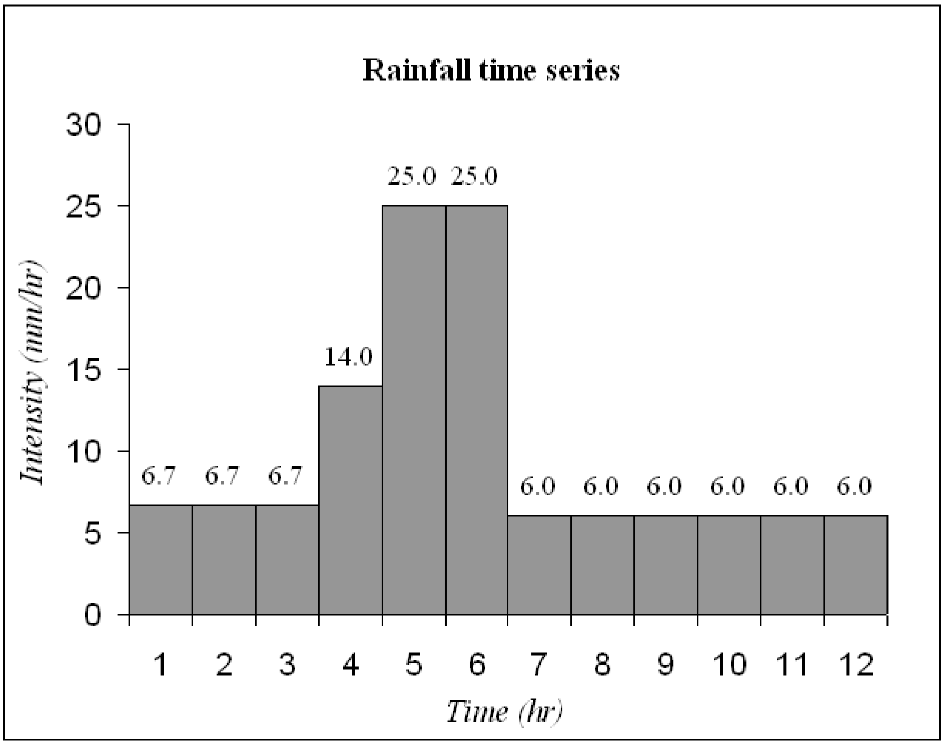

Figure 6.2: Rainfall time series

Table 6.1: Hydrological characteristics of the subcatchments (Tübingen)

HCs	Subcatchments			**Normalizing factor**
	A	**B**	**C**	
M	5	5	5	11
API	14.39	16.35	18.34	88.28
P_t	120	120	120	82.31
T_p	12	12	12	38.00
A	40.38	36.08	64.56	73.88
Per	58.38	48.24	55.26	73.08
TC	1.92	2.02	1.67	3.20
SL	0.06	0.11	0.15	0.35
DR	1.24	1.06	1.04	1.77
Kv_2	0.61	0.49	0.71	0.98
LU_f	0.18	0.38	0.48	0.96
LU_u	0.13	0.12	0.09	0.21
FC	2.76	1.52	1.59	3.92
Q_b	3.33	3.33	3.33	-

Using the equation 6.1 and 6.2 the hydrological characteristics, rainfall loss for subcatchment A can be calculated as following:

$$\begin{aligned} X &= \left(\frac{120}{1 + 42.08\ e^{\left(1.07 \cdot 2.76 - 1.24 + 0.045\left(\frac{0.18}{0.13}\right)\right)}} + \frac{14.39}{1 + 5267.8\ e^{(-5.57 \cdot 0.61)}} \right) \\ &= 0.56 \end{aligned}$$

hence,

$$\begin{aligned} P_{l,A} &= 120 \left[\frac{39.73 + sin\left(\frac{\pi}{6}(5-4)\right)}{1 + 39.73\ e^{(0.56)}} \right] \\ &= 67.2\ mm \end{aligned}$$

Runoff coefficient (RC) for subcatchment A can be estimated as,

$$\begin{aligned} RC_A &= 1 - \frac{P_l}{P_t} \\ &= 1 - \frac{67.2}{120} \\ &= 0.44 \end{aligned}$$

Using iteration procedure to determine ϕ:
$\phi_A \ = \ 5.6$

Similarly,
for subcatchment B:
$RC_B = 0.76$
$\phi_B = 2.4\ mm$

for subcatchment C:
$RC_C = 0.74$
$\phi_C = 2.6\ mm$

Table 6.2 shows the effective rainfall time series for the subcatchments, calculated using the respective ϕ.

6.1.3 Estimation of Nash cascade parameters

The transfer functions derived to estimate Nash cascade parameters N and K in ungauged catchment, using its hydrological characteristics, are as follows:

$$K = 7.14\ T_p^{0.7}\ TC^{0.22}\ e^{0.53LU_u} \tag{6.3}$$

$$\beta = 5.62\ T_p^{0.37}\ SL^{-0.42}\ Per^{0.083}\ e^{0.18P_t} \tag{6.4}$$

$$N = \beta\ K^{-1.0} \tag{6.5}$$

Before using in the transfer functions, the hydrological characteristics were normalized by the respective normalizing factors. Using the normalized hydrological characteristics in the equations 6.3 to 6.5, the Nash cascade parameters for subcatchment A can be calculated as follows:

$$\begin{aligned} K_A &= 7.14 \cdot 0.316^{0.7} \cdot 0.6^{0.22} \cdot e^{0.53 \cdot 0.606} \\ &= 3.95\ hr \end{aligned}$$

$$\begin{aligned} \beta_A &= 5.62 \cdot 0.316^{0.37} \cdot 0.171^{-0.42} \cdot 0.8^{0.083} \cdot e^{0.18 \cdot 1.45} \\ &= 9.68 \end{aligned}$$

$$\begin{aligned} N_A &= 9.68 \cdot 3.95^{-1.0} \\ &= 2.45 \end{aligned}$$

Similarly,
for subcatchment B:
$K_B = 3.9\ hr$
$N_B = 1.88$

for subcatchment C:
$K_C = 3.5\ hr$
$N_C = 1.88$

6.1.4 Estimation of flood hydrograph

Once the parameters N and K are estimated, the Nash cascade unit hydrograph and the corresponding direct runoff hydrograph for a subcatchment 'j' can be derived using equation 6.6 and 6.7. Table 6.5 shows the ordinates of unit hydrographs and the direct runoff hydrographs estimated for the subcatchments.

$$g_i = \frac{1}{K\ \Gamma(N)}\ e^{-(\frac{t_i}{K})}\ \left(\frac{t_i}{K}\right)^{(N-1)} \tag{6.6}$$

$$Q_{d(i,j)} = \sum_{l=1}^{i} \frac{P_{e(i-l+1,j)}\ A_j}{3.6\ K_j\ \Gamma(N_j)}\ e^{-\left(\frac{t_l}{K_j}\right)}\ \left(\frac{t_l}{K_j}\right)^{(N_j-1)} \tag{6.7}$$

The direct runoff hydrograph for a subcatchment can be routed to outlet of the catchment using Muskingum routing procedure as explained in the subsection 2.3.2 of chapter 2. Figure 6.3 shows the design flood runoff hydrograph at the outlet of catchment Tübingen, obtained after routing the direct runoff and adding the base flow. The specific flood runoff volume (V_{Qd}), peak discharge (Q_{peak}) and time to its arrival at outlet of the catchment (T_{peak}), which are the essential characteristics for design and planning of flood protection schemes, are estimated from the design flood runoff hydrograph as follows:

$V_{Qd} = 79\ mm$
$Q_{peak} = 257\ m^3/s$
$T_{peak} = 9\ hours$

Table 6.2: Effective rainfall time series for the subcatchments (Tübingen)

Time	Subcatchments **A**	**B**	**C**
1.0	1.1	4.3	4.0
2.0	1.1	4.3	4.0
3.0	1.1	4.3	4.0
4.0	8.4	11.6	11.4
5.0	19.4	22.6	22.4
6.0	19.4	22.6	22.4
7.0	0.4	3.6	3.4
8.0	0.4	3.6	3.4
9.0	0.4	3.6	3.4
10.0	0.4	3.6	3.4
11.0	0.4	3.6	3.4
12.0	0.4	3.6	3.4

The figure 6.3 also shows the flood hydrograph corresponding to rainfall durations of 8 *hours* and 16 *hours*, for the same amount of rainfall. One may observe that the

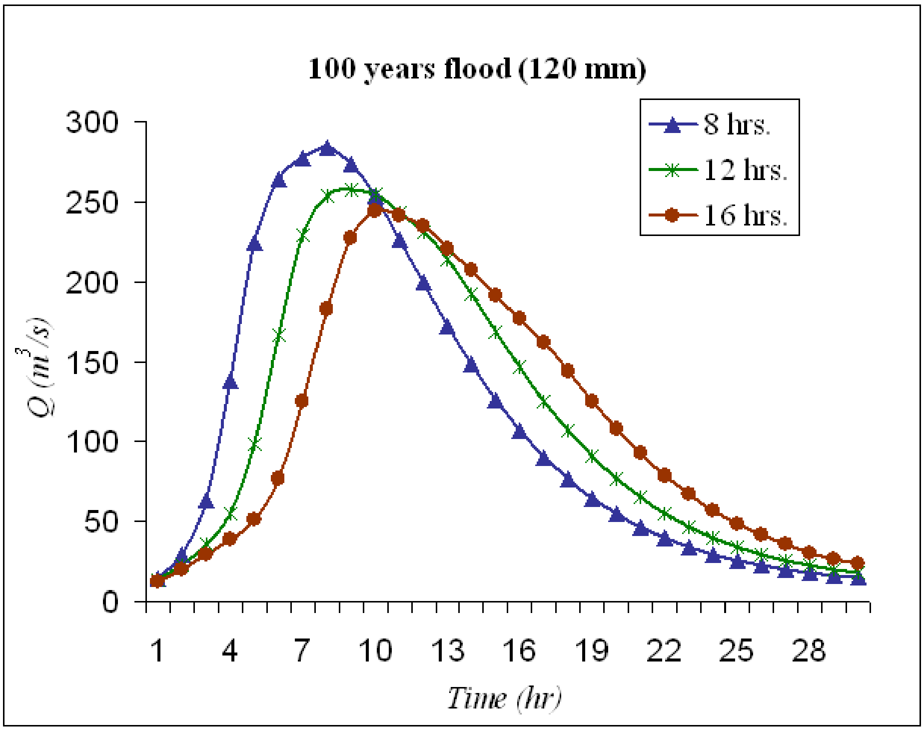

Figure 6.3: Design flood hydrographs for different rainfall durations (Tübingen)

same amount rainfall over shorter duration may produce steeper hydrograph with much higher and quicker peak, on the other hand the longer duration of the rainfall leads to reduced and delayed peak. However the derived regionalization methodology does not indicate the effect of rainfall duration on the flood runoff volume.

6.2 Assessment of impact of land use changes

Rapid land use changes, particularly deforestation due to ever increasing anthropogenic activities in the past few centuries, have reflected in severe impact on catchment and regional hydrology in various parts of the world. Of the most critical factors influenced by land use changes are the processes of runoff generation and runoff propagation. Quantification of the impact of land use changes on the hydrological processes has been keenly pursued by hydrologist during the last decades. Harbor (1994) employed SCS curve number based distributed model for assessment of long-term hydrological impact of land use changes. Wooldridge et. al. (2001) as well as Hundecha and Bárdossy (2004) associated the parameters of semi-distributed conceptual models with relative area of land use classes, thus, conveyed the impact of land use changes on the runoff response via model parameters. Samaniego (2003) carried out the assessment of hydrological consequences of different land use scenarios in meso-scale catchments by associating the critical runoff characteristics with physiographical factors, which represent topography, morphology, climate and land use of a catchment, through empirical models. The land use scenarios were predicted using spatially distributed stochastic model. Several other region specific studies are published on the issue in recent years.

The regionalization methodology derived during this study associates the model parameters, runoff coefficient (RC) and retention time of reservoirs (K), with relative area of urban and forest land use through the regional transfer functions. Thus, there is a possibility to quantify the impact of land use changes on the direct runoff volume (V_{Qd}), peak runoff (Q_{peak}) and time to peak runoff (T_{peak}) through the land use dependent estimation of the model parameters. The case study of catchment Tübingen was adopted to demonstrate the application of the regionalization methodology to assess the impact of land use changes on the design flood characteristics.

In order to assess impact of land use changes, three different cases of land use scenarios were considered. Table 6.3 summarizes the three scenarios for the catchment Tübingen. In the first case deforestation scenario, i.e. increase in urban area against decrease in forested area by 15 % of the respective subcatchment area, is considered. The second case considers the original scenarios, i.e. no change. In the third case afforestation scenario, i.e. increase in forested area against decrease in urban area by 8 % of the respective subcatchment area, is considered.

Table 6.3: Land use scenarios for the subcatchments (Tübingen)

Case	**land use**	Subcatchments		
		A	**B**	**C**
Case 1	LU_f	0.03	0.23	0.33
	LU_u	0.28	0.27	0.24
Case 2	LU_f	0.18	0.38	0.48
	LU_u	0.13	0.12	0.09
Case 3	LU_f	0.26	0.46	0.56
	LU_u	0.05	0.04	0.01

Design flood runoff hydrographs corresponding to the three cases were estimated using the regionalization methodology. The runoff hydrographs and the flood characteristics are respectively presented in figure 6.4 and table 6.4. In the first case, the peak of the hydrograph is higher and time to its occurrence is shorter as compared that in the other cases. This is due to the fact that the larger sealed surfaces in urban area prompt higher runoff generation and faster drainage. The third case indicates significant reduction in the flood runoff volume as well as the peak, due to the larger forested area which acts as a retention reservoir. The occurrence of the peak is also delayed due the increased retention time of the catchment. In the third case the flood runoff volume is decreased by almost 37 % with respect to 8 % change in the land use area. On the other hand, in the first case the flood runoff volume is increased by only 6 % with respect to 15 % change in the land use area.

The case study demonstrates that there is reasonable possibility to employ such regionalization methodology for the assessment of the impact of land use changes on

Table 6.4: Design flood characteristics corresponding to the land use scenarios

	V_{Qd}	Q_{peak}	T_{peak}
Case 1	83.9	262	7
Case 2	79.0	257	9
Case 3	50.3	191	10

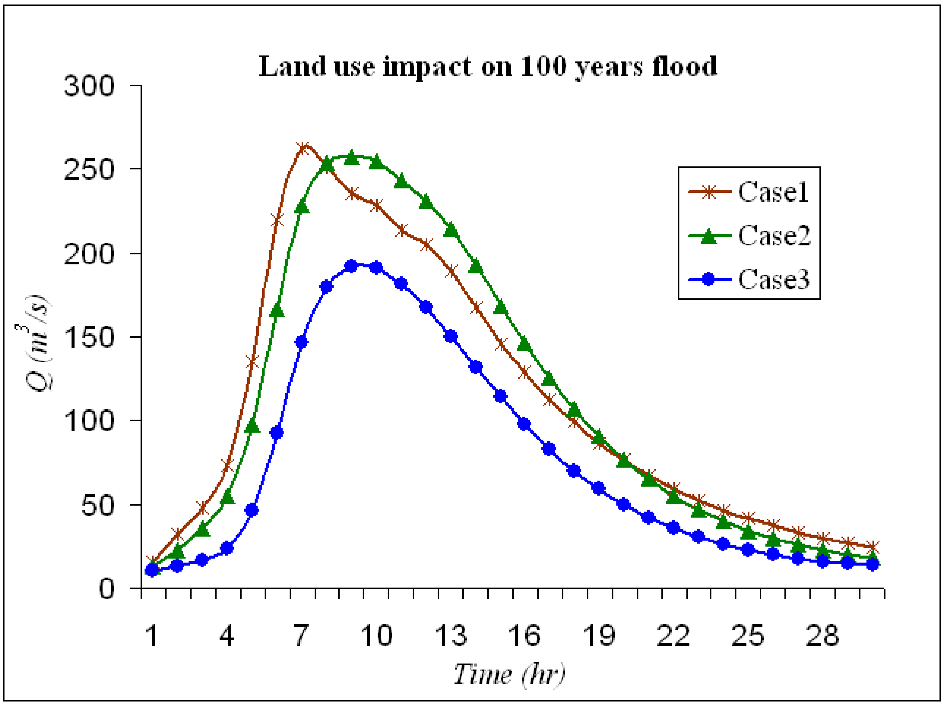

Figure 6.4: Flood runoff hydrographs corresponding to the land use scenarios

the flood characteristics. However, the case study also reveals that the assessment for the three land use scenarios, when compared to each other, seems to be inconsistent. The reason behind the inconsistency, can be explained as the lower sensitivity of the logistic transfer function for rainfall loss to the smaller ratio between areas of forest and urban land use ($\frac{LU_f}{LU_u}$).

Table 6.5: Ordinates of unit hydrograph and direct runoff hydrograph for the subcatchments (Tübingen)

Time	Subcatchments					
	A		B		C	
	UH	Q	UH	Q	UH	Q
1	0.021	0.2	0.063	2.7	0.074	5.4
2	0.044	0.8	0.090	6.6	0.103	12.8
3	0.062	1.5	0.099	10.8	0.110	20.8
4	0.073	4.1	0.099	19.7	0.107	38.3
5	0.078	11.2	0.093	37.2	0.098	73.5
6	0.079	22.7	0.084	58.0	0.087	114.6
7	0.077	32.8	0.075	67.4	0.075	130.6
8	0.072	39.7	0.065	70.8	0.063	134.2
9	0.067	43.5	0.056	70.8	0.053	131.1
10	0.060	44.7	0.047	68.9	0.044	124.7
11	0.054	44.1	0.040	65.9	0.036	116.9
12	0.047	42.2	0.033	62.6	0.029	108.8
13	0.041	39.5	0.028	56.9	0.023	96.7
14	0.036	36.1	0.023	50.4	0.019	83.6
15	0.031	32.5	0.019	43.8	0.015	70.9
16	0.026	28.9	0.015	37.5	0.012	59.2
17	0.022	25.4	0.013	31.8	0.010	48.9
18	0.019	22.1	0.010	26.8	0.008	40.1
19	0.016	19.1	0.008	22.3	0.006	32.6
20	0.013	16.4	0.007	18.5	0.005	26.3
21	0.011	13.9	0.005	15.3	0.004	21.1
22	0.009	11.8	0.004	12.6	0.003	16.9
23	0.008	9.9	0.004	10.3	0.002	13.4
24	0.006	8.3	0.003	8.4	0.002	10.7
25	0.005	7.0	0.002	6.8	0.001	8.4
26	0.004	5.8	0.002	5.5	0.001	6.7
27	0.003	4.8	0.001	4.5	0.001	5.2
28	0.003	4.0	0.001	3.6	0.001	4.1
29	0.002	3.3	0.001	2.9	0.001	3.2
30	0.002	2.7	0.001	2.3	0.000	2.5

7 Summary and Outlook

7.1 Summary

Although several regionalization methodologies have been proposed for hydrological predictions in ungauged catchments, only few of them are based on physically reasonable approaches. Most of the existing methodologies employ a purely data driven regression approach to derive regional transfer functions which associate model parameters with hydrological characteristics. While doing so, the physical implications of the derived relationships, with respect to underlying rainfall-runoff processes, are usually disregarded. The purely data driven approach may lead to an excellent goodness fit performance during regression, however, the derived transfer functions may not represent physically reasonable relationships. A transfer function with no physical basis may exhibit excellent goodness fit during regression, however, can lead to wholly fallacious, if not unrealistic, predictions for an event beyond the data set used for the regression. Such transfer functions often lack the robustness and transferability to produce reliable predictions in ungauged catchments.

The conventional approaches employ a two step procedure to establish transfer functions: separate calibration of model parameters for each of the gauged catchments, then derivation of the transfer function which associates a parameter with hydrological characteristics through a regression procedure. However, due to inter-parameter interaction, calibration often leads to several equally good parameters, not each of them may fit into a unique transfer function. Thus, the derivation of transfer functions through the two step regionalization procedure is subjected to the parameter identification problem. This often leads to weak regional transfer functions. Finally, parameter sets calibrated at catchment scale often do not correspond to optimum parameter set at regional scale. To obtain an efficient and robust regionalization methodology, it must be developed for optimum regional performance instead of catchment specific performance.

The main goal of this study was to develop a robust, physically reasonable and practically simple regionalization methodology for predictions of flood runoff volume, peak runoff and time to peak runoff, in ungauged catchments. Instead of developing catchment specific solutions, the study was aimed at a general methodology for regional solutions. To keep the methodology practically simple, a parsimonious event based Nash cascade conceptual model was adopted. The model uses three parameters: runoff coefficient (RC), number of reservoirs (N) and reservoir constant (K). Transfer functions to estimate the model parameters in ungauged catchments, using readily available hydrological characteristics, were derived for the study area under consideration. The study was essentially focused on deriving the transfer functions which are based on physically reasonable relationships. To ensure the optimum regional solution, the transfer functions were optimized for aggregated regional model performance.

If total rainfall (P_t) and rainfall loss (P_l) occurred during a rainfall-runoff event are known, RC for the event can be estimated. Therefore, a transfer function for P_l, instead of for RC, was derived during this study. Four different approaches were employed to derive four different transfer functions for P_l. Three of them were purely data driven approaches, based on multiple linear regression (MLTF), artificial neural network (ANNTF) and fuzzy logic (FLTF). The fourth approach was a data-plus-knowledge driven approach based on logistic regression (LoTF). All the approaches lead to highly acceptable goodness fit between observed and calculated P_l, especially, ANNTF, FLTF and LoTF yield excellent goodness fit primarily due to their high flexibility.

However, the validation for physical processes reveals that the purely data driven approaches fail to capture the physical relationships pertaining to rainfall loss processes. The comparison of the signs of derivatives of the functional relationships with that of the physical relationships between P_l and the predictors reveals that, for an individual event, the response of ANNTF and FLTF to hydrological changes often conflicts with the response anticipated from the *a priori* knowledge of rainfall loss precesses.

Conceptual and empirical functions are extensively implemented for predicting various hydrological responses mainly, to address the lack of sufficient hydrological data and understanding of the physical processes. Usually, they are not based on detailed descriptions of the physical processes. However, it is crucial that the conceptual and empirical functions provide not only good “curve fitting” tools but also “correct” representations of the known rainfall-runoff processes. Due to their excessive freedom, ANNTF and FLTF lead to extremely flexible, non linear transfer functions which perform excellent in terms of goodness fit. However, they fail to capture any physical relationship pertaining to rainfall loss processes, and thus do not lead to physically reasonable transfer functions. Hence, application of these approaches for extrapolation (or regionalization), to predict a response beyond the range of the dataset used their derivation, is highly questionable. MLTF exhibits physically reasonable relationships except for the predictor “month”, however, it cannot capture the non-linearities of the relationships.

A highly flexible transfer function without an appropriate physical basis may lead to a disastrous anomaly between predicted response and the response of rainfall-runoff processes in nature, and consequently, to highly uncertain predictions. The fuzzy logic approach is transparent and easy to incorporate *a priori* knowledge of rainfall-runoff processes in the form of fuzzy rules. But, in the case of artificial neural network (ANN), due to its opaque structure, it is extremely difficult to analyze the functional relationships and to incorporate *a priori* knowledge. Thus, the purely data driven approaches, such as ANN, limit themselves merely to black box approaches whose predictive uncertainty is difficult, if not impossible to analyze.

In the case of LoTF, the *a priori* knowledge of the physical relationships between P_l and the predictors was embedded into the transfer function. The validation of LoTF for the physical relationships confirms that LoTF represents physically reasonable relationships. The validation of LoTF for spatial transferability, for the catchments which were not used for its derivation, suggests that the transfer function is efficient at estimating P_l and, subsequently, RC in ungauged catchments. Being based on physically reasonable relationships and flexible enough to replicate non-linear relationships, LoTF makes the most suitable transfer function to estimate P_l in the ungauged catchments in the study area under consideration.

Due to strong inter-parameter interaction between Nash cascade parameters N and K, separate regionalization of the parameters was not viable. The initial attempt to derive the inter-parameter function led to the revelation that the parameters can be related to each through a power function, and further, the coefficient (β) of the power function can be attributed to hydrological characteristics. Therefore, the transfer functions were derived for the parameter K and the coefficient β. Thus, K and β can be estimated from hydrological characteristics and N can be estimated using the inter-parameter function. The approach addresses the problem of parameter identification by regionalizing the inter-parameter relationship itself. To obtain optimum regional transfer functions, the transfer functions were optimized at once for the whole set of gauged catchments, using mean Nash-Sutcliffe coefficient as an aggregated regional objective function. The optimization leads to fairly high regional performance as well as goodness fit of peak runoff and time to peak runoff. The optimized transfer function for K associates the parameter with time of concentration, duration of rainfall and relative area of urban land use. The transfer function for β associates the coefficient with duration of rainfall, total rainfall, slope and perimeter. Both transfer functions were formed using a combination of power and exponential functions.

Since Nash cascade parameters are conceptual, their physical relationship with hydrological characteristics can not be identified and embedded into the transfer functions. However, the physical relationships between the catchment characteristics, used in the transfer functions, and shape of unit hydrograph can be derived from the *a priori* knowledge of runoff propagation processes. Therefore, the transfer functions were validated for their response, in terms of shape of modeled unit hydrograph, to changes in the catchment characteristics. The validation led to the conclusion that the derived transfer functions captures the physical relationships between the catchment characteristics and shape of unit hydrograph, thus, can be regarded as physically reasonable. The validation for spatial transferability indicates that the transfer functions leads to robust and highly efficient performance, in terms of goodness fit of runoff hydrograph, peak runoff, and time to peak runoff in the catchments which are not used for the optimization.

Analysis of performance of the derived regionalization methodology, for individual events, reveals that the methodology performs poorly for small rainfall events. This leads to the conclusion that the methodology may not be valid for the small rainfall events which are below certain threshold of amount ($< 20\ mm$) and duration ($10\ hr$)

of rainfall. The performance of the methodology might also be hindered due to inadequate estimation of rainfall input. The performance in the catchments at foothills of Swabian Alps is also poor. This was expected due to the presence of the karstic aquifers which lead to the dominance of subsurface drainage.

The derived regionalization methodology uses readily available hydrological characteristics and parsimonious modeling as well as transfer function approach. It is based on physically reasonable relationships, thus, "appropriately" represents rainfall-runoff processes. The methodology reasonably handles the problem of parameter identification by regionalizing the inter-parameter relationship, additionally, it is optimized for the regional performance. Therefore, the derived regionalization methodology, although it may not offer the best catchment specific solution, is a practical, robust and efficient regional approach to reliable predictions of design flood characteristics in ungauged catchments in the region.

To examine its utility, the derived regionalization methodology was compared with SCS curve number method and the Lutz procedure, which are the widely used standard practices for flood predictions in ungauged catchments. The comparisons reveal that the derived regionalization methodology performs better than those standard practices, at least for the region under consideration. This also implies that the derived methodology is practically useful and can be adopted into practice beyond its academic purpose. The case study of catchment Tübingen demonstrates the application of the methodology to estimate design flood characteristics in an ungauged catchment.

In case of continuous simulations, in order to adapt to event specific conditions, a continuous model must be run for at least a complete hydrological cycle prior to an event. But the derived regionalization methodology estimates the model parameters using, not only the catchment characteristics, but also the event specific characteristics. Thus, the regionalization methodology adapts the event based model to event specific hydrological conditions without having it to run for long duration. Since the regionalization methodology also utilizes relative area of urban and forest land use, it may be used for predictions under changing land use conditions. The possibility of using the regionalization methodology for assessment of impact of land use changes on flood runoff characteristics was investigated through the case study of catchment Tübingen. Although the case study demonstrates a reasonable possibility of using the methodology for such assessment, the conclusion can be made that the derived transfer functions are inconsistent in reproducing impact of land use changes due to the lack of "enough sensitivity" to the changes.

Finally, it must be mentioned that the approach employed during this study is general and may be transferable to other "similar" regions. However the transfer functions derived during the study are specifically for the study area under consideration and may not be directly transfered to other regions.

7.2 Outlook

Based on the observations and the experiences gained during the course of this study, following suggestions may be pointed out for the further possible studies in the similar direction:

- Due to inadequate quality of hourly rainfall data, daily rainfall data was disintegrated into hourly scale using the available hourly data. This led to satisfactory rainfall estimations, however, not essentially reliable. Further improvement in the rainfall estimations, e.g. using radar measurements, may lead to significant increase in the performance of the methodology.

- Due to lack of necessary data, soil classes based on hydraulic conductivity were used during the study. However, the soil classes may not properly represent the effect of the soil property on runoff generation. For the future study, if possible, use of mean hydraulic conductivity of subcatchment is recommended.

- During this study, investigation for the homogeneity of the region was not conducted, it was assumed to be fairly homogeneous. However, it may be worthwhile to carry out catchment classification based on hydrological homogeneity, such classification may further improve the performance. The derived regionalization methodology itself can be used for the catchment classification. The coefficients of the transfer functions can be calibrated separately for each catchment in the region using a same synthetic rainfall-runoff event. The catchments which yield similar coefficients of the transfer functions can be regarded as relatively homogeneous catchments.

- There is a possibility to use the derived regionalization methodology for assessment of impact of land use changes on flood characteristics. However the role of land use in the transfer functions must be reinvestigated. The potential improvement in the assessment of the impact of land use changes lays in consideration of seasonal land use management and using distributed modeling approach designed to estimate the impact at smaller scales of 5 km^2 to 10 km^2.

- During the optimization of the transfer functions for Nash cascade parameters, the uncertainty due to equifinality was reduced by restricting the parameter space through simplified inter-parameter relationship and the hydrological characteristics. However, it will be worthwhile to investigate the uncertainty related to the simplification of the inter-parameter relationship. Furthermore, since runoff response of a catchment is highly influenced by spatial rainfall distribution, the assessment of the uncertainty related to the estimation of spatial rainfall distribution is also recommended.

- The examples of purely data driven and data-plus-knowledge driven approaches underline the significance of incorporating *a priori* knowledge of physical processes into a model. ANN and fuzzy logic approaches have shown signs of great potential as futuristic tools for hydrological predictions, but their excessive flexibility must be restricted by using the available knowledge of underlying physical processes.

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Zadeh, 1965: Zadeh, L. A., 1965. *Fuzzy Sets*, Information and Control, Vol. 12(2), 338-353.

Curriculum Vitae

Sachin Ramesh Patil
Sachin612@yahoo.com

06.12.1978	Born in Jalgaon, India
1984 – 1987	Primary school am Ravsaheb Rupchand Vidyalay, Jalgaon, India
1987 – 1994	Secondary school am Ravsaheb Rupchand Vidyalay, Jalgaon, India
1994 – 1997	Diploma – civil engineering, Govt. Polytechnic, Jalgaon, Board of Technical Education, Mumbai, India
1997 – 2001	Bachelor - civil engineering, Veermata Jijabai Technological Institute, University of Mumbai, India
2001 – 2004	Master of Science - WAREM "Water Resources Engineering and Management" Universität Stuttgart
2004 – 2008	Doctoral research candidate, Institute of Hydraulic Engineering, Universität Stuttgart

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Institut für Wasserbau
Universität Stuttgart

Pfaffenwaldring 61
70569 Stuttgart (Vaihingen)
Telefon (0711) 685 - 64717/64749/64752/64679
Telefax (0711) 685 - 67020 o. 64746 o. 64681
E-Mail: iws@iws.uni-stuttgart.de
http://www.iws.uni-stuttgart.de

Direktoren
Prof. Dr. rer. nat. Dr.-Ing. András Bárdossy
Prof. Dr.-Ing. Rainer Helmig
Prof. Dr.-Ing. Silke Wieprecht

Vorstand *(Stand 1.2.2008)*
Prof. Dr. rer. nat. Dr.-Ing. A. Bárdossy
Prof. Dr.-Ing. R. Helmig
Prof. Dr.-Ing. S. Wieprecht
Prof. Dr.-Ing. habil. B. Westrich
Jürgen Braun, PhD
Dr.-Ing. H. Class
Dr.-Ing. S. Hartmann
Dr.-Ing. H.-P. Koschitzky
PD Dr.-Ing. W. Marx
Dr. rer. nat. J. Seidel

Emeriti
Prof. Dr.-Ing. habil. Dr.-Ing. E.h. Jürgen Giesecke
Prof. Dr.h.c. Dr.-Ing. E.h. Helmut Kobus, PhD

Lehrstuhl für Wasserbau und Wassermengenwirtschaft
Leiter: Prof. Dr.-Ing. Silke Wieprecht
Stellv.: PD Dr.-Ing. Walter Marx, AOR

Lehrstuhl für Hydromechanik und Hydrosystemmodellierung
Leiter: Prof. Dr.-Ing. Rainer Helmig
Stellv.: Dr.-Ing. Holger Class, AOR

Lehrstuhl für Hydrologie und Geohydrologie
Leiter: Prof. Dr. rer. nat. Dr.-Ing. András Bárdossy
Stellv.: Dr. rer. nat. Jochen Seidel

***VEGAS,* Versuchseinrichtung zur Grundwasser- und Altlastensanierung**
Leitung: Jürgen Braun, PhD
Dr.-Ing. Hans-Peter Koschitzky, AD

Versuchsanstalt für Wasserbau
Leiter: apl. Prof. Dr.-Ing. habil. Bernhard Westrich

Verzeichnis der Mitteilungshefte

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