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Hydrologie des bassins versants Libanais dans le contexte Méditerranéen

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Résumé

Le Liban est un petit pays montagneux à climat typiquement méditerranéen avec une grande variabilité spatiale des précipitations dont une quantité substantielle est sous forme de neige. La majorité des terrains libanais sont karstiques. En plus, le pays est fortement urbanisé avec une grande pression anthropique sur les ressources en eau. En outre, les bassins versants libanais manquent de longues séries de données à cause de l'arrêt des mesures durant la guerre civile (1975-1990) et l'après guerre (1990-2000).

Ce travail vise à comprendre les caractéristiques de la réponse hydrologique des bassins versants libanais dans le contexte méditerranéen et à classer ces bassins en fonction de leurs propriétés physiques et hydrologiques. La thèse est structurée en trois parties : une revue bibliographique de l'hydrologie méditerranéenne, une analyse des données hydrologiques du Liban et la comparaison au contexte méditerranéen, et finalement un essai de classification et de modélisation des bassins versants Libanais.

La première partie concerne une synthèse bibliographique basée sur 152 articles portant sur l'hydrologie méditerranéenne (article accepté dans Hydrological Sciences Journal). Les études ont été classées selon trois catégories d'objectifs : étude du bilan hydrologique, les crues et la sécheresse. La méthodologie adoptée porte aussi bien sur l'étude des processus hydrologiques à l'échelle d'un bassin versant particulier que des études de régionalisation sur plusieurs bassins versants. La zone d'étude est divisée en trois parties : nord-ouest (NWM), est (EM) et sud (SM) Méditerranée. L'analyse montre les disparités régionales : fortes intensités des pluies et des crues dans la région NWM, faibles écoulements et longues périodes de sécheresse en SM, et une situation intermédiaire pour EM. Une tendance à la réduction des ressources en eau entraînées par les pressions anthropiques et climatiques et un régime de précipitations plus extrêmes sont également perceptibles. Les bassins versants montrent des réponses hydrologiques très hétérogènes dans le temps et l'espace. La modalisation du fonctionnement hydrologique de ces bassins est souvent difficile accompagnée de grandes incertitudes dans les prévisions. Cependant, peu de modèles ont été développés pour répondre aux spécificités des bassins méditerranéens. Les études de régionalisation sont rares et les résultats des différentes études difficilement transposables d'une zone à une autre. Des études supplémentaires sont nécessaires pour améliorer la compréhension des processus hydrologiques en milieu méditerranéen et pour tenir compte des spécificités régionales.

La deuxième partie porte sur l'analyse des données cartographiques et pluie/débit des bassins libanais et la comparaison de ces bassins aux bassins méditerranéens étudiés précédemment. Vingt huit bassins versants libanais sont étudiés sur la période 2001-2011. Une base de données cartographique et hydrologique a été constituée. Les données cartographiques concernent le relief, les cours d'eau, le sol, la géologie, la présence du karst, et l'occupation du sol. Les données pluie/débit concernent l'analyse des données pluviométriques (32 stations à pas de temps mensuel et journalier quand disponible), les données du couvert neigeux, l'évapotranspiration (à partir des images satellites MODIS à pas de temps mensuel) et les débits (vingt quatre stations à pas de temps journalier et quatre stations à pas de temps mensuel). Ces données pluie/débit sont comparées à une base de données de la période précédant la guerre civile. L'acquisition de données pluie/débit était un véritable défi. Ces données ne sont pas toujours disponibles pour la même période et une partie étant payante (données pluviométriques). A partir de ces données, nous avons établis des indicateurs pour décrire les caractéristiques physiques des bassins versants et les caractéristiques de la réponse hydrologique. Ensuite, les réponses hydrologiques des bassins versants libanais sont comparées à celles des autres bassins versants méditerranéens. A l'échelle du bilan annuel, les valeurs du coefficient de ruissellement sont élevées à travers tout le pays. À l'échelle de l'événement de crue, comme pour les autres régions méditerranéennes, les précipitations pendant un seul événement peut représenter jusqu'à 40 % du total annuel des précipitations. Le débit de pointe spécifique diminue avec la surface du bassin versant. Le coefficient de ruissellement à l'échelle de l'événement de crue est beaucoup plus élevé que les valeurs observées enregistrées dans l'EM et est dans la gamme des bassins versants NWM.

La troisième partie présente un essai de classification et de modélisation des bassins versants libanais en fonction de leurs caractéristiques physiographiques et hydrologiques. Les variables définies à partir de l'analyse des données ont été utilisées pour la classification. Trois classifications ont été menées sur la base des indicateurs physiques, hydrologiques et physiques et hydrologiques. Cinq classes de bassins physiquement et hydrologiquement similaires ont été identifiées. Enfin, un essai de modélisation au pas de temps mensuel en utilisant le modèle GR2M a été entrepris. Plusieurs approches de régionalisation ont été comparées. La discussion porte sur l'analyse du fonctionnement hydrologique de chaque bassin versant et de chaque classe de bassins.

Mots-clefs hydrologie; Liban ; basin versant Méditerranéen ; bilan annuel; pluie-débit; sécheresse; modélisation; régionalisation ; classification

Résumé substantiel

Introduction

L'hydrologie libanaise

Situé sur la rive orientale de la mer Méditerranée. Le Liban est un petit pays montagneux à climat typiquement méditerranéen avec d'importantes variations locales en raison de son relief important. Le pays est fortement urbanisé avec une grande pression anthropique sur les ressources en eau. En outre, les bassins versants libanais sont pauvrement-jaugés due principalement à une grande perte de données causée par les 15 années de guerre civile.

Bien qu'un réseau météorologique et hydrométrique avait été progressivement construit depuis les années 1930 et a atteint son apogée dans les années 1970 (Sene et al. 1999), l'éclatement de la guerre civile libanaise en 1975 a créé une lacune dans les données de plus de 20 ans. De nouveaux réseaux sont en construction depuis la fin des années 1990, cependant, la qualité des ces données est discutable.

Ainsi, les bassins versants libanais sont mal jaugés et dans un contexte d'augmentation de la pression anthropique sur les ressources en eau. En outre, le Liban a beaucoup de particularités. D'un point de vue géomorphologique, le pays est formé de deux chaînes de montagnes parallèles à la mer. La chaine du Mont Liban délimite une étroite plaine côtière et la chaîne orientale (Anti-Liban). Les deux chaines sont séparées par une plaine élevée, la vallée de la Bekaa. Ce complexe relief cause une grande variabilité spatiale des précipitations. D'où la moyenne des précipitations annuelles peut dépasser 1500 mm dans certaines régions du Mont-Liban et tomber en dessous de 200 mm dans la partie nord-est semi-aride du pays. En outre, une quantité substantielle de précipitations est sous forme de neige. De plus, en ajoutant à la complexité du relief et la variabilité spatiale des précipitations, le substrat de la plupart des terrains libanais est formé de roches carbonatées. Il en résulte la formation de paysages karstiques dans tout le pays. Par conséquent, la majorité des rivières libanaises trouvent leurs origines dans les sources karstiques. Cela rend l'étude de la réponse hydrologique des bassins versants libanais un véritable défi.

En termes des caractéristiques de la réponse hydrologique des bassins versants libanais, la majorité des études dans le pays se concentrent davantage sur les aspects hydrogéologiques. Pour les études hydrologiques classiques (hydrologie de surface) moins d'études existent. On peut citer les travaux de Sene et al. (1999, 2000). Les auteurs ont étudié les variations spatiales et temporelles des débits mensuelles de rivières pour cinq bassins versants et la répartition régionale des débits de pointes au Liban. Hreiche (2003) a présenté un modèle conceptuel développé pour le climat méditerranéen (MEDOR), calibré et validé sur différents bassins versants libanais et français. Hreiche et al. (2007) a couplé un module de neige à MEDOR pour mieux simuler l’impact de la neige. Des études de modélisation pour la gestion des ressources hydriques et la détection des tendances existent également (Massoud et al. 2006, Ramadan et al. 2012). Les études de régionalisation dans le pays sont très préliminaires. En plus des études mentionnées précédemment (Sene et al. 1999, 2000), Abou Daher (2006) a établi des modèles globaux de régression linéaire pour l'estimation du coefficient de ruissellement annuel. Ces études préliminaires ont suggéré que les paramètres hydrologiques montrent un remarquable degré de cohérence spatiale.

Compte tenu de la qualité des données pluie/débit des bassins versants libanais (mal jaugés), et puisqu’il n’y a pas d’études de classification de ces bassins, il serait d'un grand intérêt d’analyser la réponse hydrologique des bassins versants libanais et de les comparer à une référence de la littérature (autres bassins versants méditerranéens) et enfin de tenter une classification des bassins versants libanais.

La région méditerranéenne

Le climat méditerranéen est caractérisé par une forte variabilité interannuelle et intra-annuelle des précipitations, une sécheresse estivale, et la forte intensité des épisodes pluvieux. En raison des caractéristiques climatiques, les régions méditerranéennes sont confrontées à des problèmes de disponibilité en eau (Morán-Tejeda et al. 2010). En effet, dans les vingt dernières années, de nombreux pays du bassin méditerranéen ont connu des périodes de sécheresse pendant plusieurs années (FAO, 2006). De nombreuses études (par exemple Milly et al. 2005, IPCC 2014) prédisent que les ressources en eau vont même se raréfier en raison du changement climatique et de la demande croissante en eau par les différents secteurs économiques. En outre, les événements de précipitations se produisent habituellement sous forme de tempêtes de courte durée à forte intensité pluvieuse ce qui provoquent des inondations intenses (par exemple Anquetin et al. 2010, Vincendon et al. 2010, Moussa et Chahinian 2009 [France], Koutroulis et Tsanis 2010 [la Grèce], Brath et al. 2004 [Italie], Rozalis et al. 2010 [Israël]). Les bassins versants méditerranéens sont donc caractérisés par trois caractéristiques principales: des ressources en eau limitées, des étés secs et des événements pluvieux de forte intensité qui génèrent des fortes inondations.

De nombreuses études existent sur différents aspects des réponses hydrologiques des bassins versants méditerranéens. Cependant, les études sur des bassins individuels ou les études de régionalisation, sont tous limitées à des bassins spécifiques ou à une région géographique. Toutefois, aucune étude n'a encore tenté de regrouper les différents aspects de l'hydrologie méditerranéenne et de synthétiser des travaux antérieurs réalisés partout dans la Méditerranée. Par conséquent, dans ce travail, nous présentons une revue de la réponse hydrologique des bassins versants méditerranéens à l'échelle annuelle des ressources en eau, à l'échelle de l'événement de crue et à l’échelle de la période sèche.

Les informations recueillies seront également utilisées comme référence pour comparer la réponse hydrologique d'un environnement à données limitées comme les bassins libanais.

Classification des bassins versants

La classification des bassins versants a pour objectif de regrouper des bassins qui partagent des caractéristiques physiques et / ou hydrologiques « similaires ». Elle permet de comparer un large échantillon de bassins versants situés dans différents contextes hydro-climatiques. Andréassian et al. (2006) souligne l'importance de travailler avec un grand nombre de bassins; l'objectif est de comparer et d'apprendre des différences et des similitudes entre les sites (Parajka et al. 2013, Salinas et al. 2013). Cette démarche contribue aux travaux en cours pour le développement d'un système mondial de classification qui fait encore défaut en hydrologie (Sivapalan 2005, Wagener 2007). En outre, la classification des bassins est utilisée dans les études de régionalisation pour le transfert de l'information hydrologique des bassins versants jaugés à ceux non jaugés (Oudin et al. 2010), ce qui est d'un grand intérêt dans un monde où la majorité des bassins sont non jaugé (Hrachowitz et al. 2013).

Ce travail vise à comprendre les caractéristiques de la réponse hydrologique des bassins versants libanais dans le contexte méditerranéen et à classer ces bassins en fonction de leurs propriétés physiques et hydrologiques. La thèse est structurée en trois parties. Nous commençons par une revue bibliographique sur les caractéristiques de la réponse hydrologique des bassins versants méditerranéens à différents échelles de temps. Ensuite, une analyse détaillée des données des bassins versants libanais en termes de caractéristiques physiographiques, climatiques et hydrologiques est présentée. La réponse hydrologique des bassins versants libanais est alors comparée avec d'autres bassins versants méditerranéens. Enfin des descripteurs physiographiques et des signatures hydrologiques sont définis pour chaque bassin et sont utilisés pour classer les bassins libanais en groupes de bassins physiquement et/ou hydrologiquement similaires. Enfin, un essai de modélisation au pas de temps mensuel en utilisant le modèle GR2M a été entrepris. Plusieurs approches de régionalization ont été comparées. La discussion porte sur l'analyse du fonctionnement hydrologique de chaque bassin versant et de chaque classe de bassins.

Partie I : Hydrologie du bassin méditerranéen

C'est la première partie de la thèse constituée d'un seul chapitre (chapitre 1 ; article accepté avec révision dans Hydrological Sciences Journal).

Un total de 152 études sur la région méditerranéenne publiées principalement au cours des deux dernières décennies ont été analysées.

Pour étudier les tendances régionales dans la zone méditerranéenne, la région d'étude a été divisée en trois zones : Méditerranée nord-ouest (NWM, englobant l'Albanie, la Croatie, la France, l'Italie, le Monténégro, le Portugal, la Slovénie et l'Espagne; 102 études), Méditerranée orientale (EM, englobant Chypre, la Grèce, Israël, Liban, territoires palestiniens, la Syrie et la Turquie; 35 études) et sud de la Méditerranée (SM, englobant le Maroc, l'Algérie et la Tunisie; 15 études).

Les études ont été divisées en trois groupes : des études de bilan annuel (68 études), événements pluie-débit (48 études) et des études sur les périodes de sécheresses (36 études). Dans chaque groupe, les études sur les bassins versants individuels (120 études) et les études de régionalisation pour les prévisions dans les bassins non jaugés (32 études) ont été analysées séparément.

Pour chaque étude, des informations clés comprenant (i) la référence et les coordonnées de l'emplacement du bassin; (Ii) les objectifs de l'étude; (Iii) les caractéristiques du bassin, comme la surface, l'élévation, la pente, l'occupation du sol, les classes de sols, la géologie et la présence possible de karst; (Iv) les caractéristiques de données hydrométéorologiques, comme la période de mesure pluie-débit, le pas de temps des mesures, la moyenne annuelle des précipitations, l'évapotranspiration de référence, l'écoulement annuel moyen, le coefficient de ruissellement et de la contribution de la neige; pour les études basées sur des événements, des informations détaillées sur les réponses des bassins (profondeur des précipitations, la lame d'eau écoulée, le débit de pointe) ont également été extraites lorsqu'ils sont disponibles; (V) les caractéristiques des modèles, tels que le nom du modèle et la référence d'origine, les processus hydrologiques simulés, la résolution spatiale (modèles globaux, semi-distribués ou distribués), le pas de temps et les critères d'évaluation du modèle; pour les études de régionalisation, des informations sur les méthodes de régionalisation et leurs performances relatives ont également été identifiées.

La revue sur l'hydrologie des bassins versants méditerranéens montrent des disparités régionales (entre les différentes sous-régions NWM, EM et SM) dans la distribution des caractéristiques de réponse climatiques et hydrologiques à l'échelle du bilan annuel et à l'échelle de l'événement. La sous-région NWM présente le régime pluviométrique le plus extrême dans la région méditerranéenne, en particulier dans un arc qui s'étend du nord-est de l'Espagne au nord-est de l'Italie. Une tendance à la baisse des ressources en eau entraînées par la pression anthropique (principalement le changement d'occupation du sol) et la pression climatique (diminution des précipitations, augmentation de la température) et vers un régime de précipitations plus extrêmes avec une fréquence plus élevée d'événements pluvieux extrêmes en dépit de la réduction de la quantité annuelle totale de pluie. En outre, les réponses des bassins versants à l'échelle de l'événement pluvieux sont très hétérogènes dans le temps et l'espace. Par conséquent, des limites importantes confrontent les approches de modélisation classique qui visent à simuler la réponse du bassin versant méditerranéen en particulier lors des crues en raison des caractéristiques spécifiques des événements pluvieux méditerranéennes.

D'autre part, les études de régionalisation dans la région ne sont pas assez nombreuses, même en termes de débits d'étiages et des courbes de débit classées ce qui est surprenant dans une région sous contraintes hydriques. En termes de performances, les prédictions de l'hydrogramme donnent de mauvais résultats dans le contexte hydro-climatique méditerranéen. Pour la prévision des courbes de débits classés et les débits d'étiages, les méthodes statistiques et les méthodes géostatistiques performent mieux que les approches paramétriques et les modèles de régression, respectivement. Des résultats mixtes ont été trouvés pour l'analyse des crues régionales.

Partie II : Analyse des données des bassins versants libanais

C'est la deuxième partie de la thèse avec 4 chapitres (chapitres 2, 3, 4, et 5).

Caractéristiques géographiques (chapitre 2)

Une liste complète des descripteurs qui représentent différents aspects des caractéristiques physiques de bassins versants a été extraite pour les vingt huit bassins étudiés à partir des données spatiales disponibles tels : la morphométrie du bassin comme la surface, le drain le plus long, la pente, la densité de drainage, l'élévation ; les formations géologiques et karst ; les sols ; l'occupation des sols.

Le substrat géologique des bassins a été décrit en termes de la perméabilité de la roche. Donc, en fonction de leurs caractéristiques, ces formations rocheuses ont été classées en trois catégories selon leur perméabilité (Abdallah et al. 2006). Les principales propriétés qui influent sur la perméabilité sont la présence de porosité secondaire (fractures et des fissures), le degré de karstification et la teneur en argile.

De même, les caractéristiques du sol ont également été prises en compte. En fonction de leurs propriétés de texture et de leur contenu en matière organique, les sols sont classés en fonction de leur capacité d'infiltration (basées sur Abdallah et al. 2006).

Enfin, l'occupation du sol est divisée en six grandes catégories: zones urbaines, agriculture, forêt, garrigues, prairie et terres nues.

Une liste complète des variables décrivant les caractéristiques physiques (géographiques et climatiques) des bassins versants libanais a été extraite des données disponibles. La grande majorité des bassins versants étudiés sont des petits et moyens bassins versants d'une superficie ne dépassant jamais 500 km^2. Seuls deux bassins versants (Litani et Oronte) ont une superficie supérieure à 1000 km^2. La pente médiane est de 8,3 % tandis que le quart a une pente supérieure à 14 %. En raison de leurs petites surfaces et leurs pentes importantes, les plus longs drains sont généralement courts; ne dépassant jamais 60 km et la densité de drainage est élevée avec une valeur médiane d'environ 3,38 km/km^2. Tous les bassins versants sont de montagne avec la grande majorité ayant une élévation moyenne de plus de 1000 m, et plus de la moitié d'entre eux avec au moins 20% de la superficie totale du bassin au dessus de 1800 m. La géologie du pays est principalement composée de roches carbonatées très karstifiées. Le substrat est fait principalement de roches très perméables et tous les bassins versants étudiés ont au moins 50% de leur surface karstifiée. En plus, étant donné la nature montagneuse du Liban, les sols sont généralement peu profonds avec une moyenne à haute capacité d'infiltration. Des sols bien développés et profonds sont surtout présents dans les bassins versants avec des terrains agricoles. La répartition des classes d'utilisation des terres varie largement.

Caractéristiques climatiques (chapitre 3)

A partir des données climatiques disponibles (32 stations pluviomètriques sur la période 2001-2011 au pas de temps mensuel et parfois journalier), des caractéristiques climatiques telles que la moyenne interannuelle des précipitations et d'évapotranspiration de référence ont été calculées pour les bassins étudiés. En outre, vue l'état des données libanaises (deux bases de données, une avant la guerre et une autre après la guerre avec une grande réduction de nombre de stations), une évaluation de l'impact de réduction de nombre de station pluviométriques sur la spatialisation de la pluie a été entamée.

Les précipitations moyennes annuelles varient largement dans le temps et l'espace. Elles sont de l'ordre de 500 mm dans l'Oronte, dans la partie nord-est du pays et à plus de 1200 mm dans la partie centrale du Mont-Liban. L'indice d'aridité (défini comme le rapport de la moyenne annuelle des précipitations et de l'évapotranspiration de référence) suit la même distribution spatiale des précipitations. L'évaluation de l'impact de la réduction de nombres de stations pluviométriques sur la spatialisation de la pluie prouve qu'un petit nombre de stations réparties intelligement peut être suffisant.

Caractéristiques hydrologiques (chapitre 4)

De l'information hydrologique disponible une liste de variables qui reflètent les différents aspects de la réponse hydrologique des bassins (signatures de ruissellement) a été produite. Ces variables sont largement utilisés dans la littérature pour la classification des bassins versants (Olden and Poff 2003, Alcazar et Palau 2010, Sawicz et al. 2011, 2014, Archfield et al. 2013, Viglione et al. 2013). Elles représentent tous les aspects du régime hydrologique : l'ampleur, la fréquence, la durée, et le taux de changement (voir

Poff et Zimmerman 2010). Cela permet la classification des bassins versants en fonction de leurs caractéristiques hydrologiques.

Le jeu de données hydrologiques disponibles (pour la période 2001 - 2011) a été utilisé pour extraire des signatures hydrologiques qui représentent les caractéristiques hydrologiques des bassins versants libanais. Ces principaux caractéristiques montrent une sorte de tendances régionales à travers le pays avec des bassins versants dans la partie centrale du Mont-Liban (la région la plus humide) présentant les valeurs les plus élevées en termes de débits moyens annuels, coefficients de ruissellement annuels et de débits journaliers. En outre, en termes de distribution journalière de débits (courbe de débits classés) ces mêmes bassins versants ont les pourcentages les plus élevés avec des valeurs élevées de débits moyens journaliers. À l'autre extrême, les bassins dans la partie intérieure du pays semblent présenter les valeurs les plus basses en termes de moyennes annuelles, coefficients de ruissellement et débit moyen journalier. Ceci est due à la fois à la grande superficie des bassins et à des plus faibles précipitations. Les bassins versants dans le nord du Liban semblent former une classe intermédiaire.

Comparaison de la réponse hydrologique entre bassins libanais et bassins méditerranéens (chapitre 5)

La réponse hydrologique des bassins versants libanais à l’échelle du bilan annuel et à l’échelle de l’événement de crue est comparée à celle des bassins méditerranéens (chapitre 1).

Comparé à d'autres bassins versants méditerranéens, les valeurs annuelles du coefficient de ruissellement sont élevées à travers le Liban. Ces valeurs élevées ne pourraient être attribuées uniquement à une sous-estimation de la moyenne annuelle des précipitations (il ya sûrement une sous-estimation des précipitations annuelles moyennes par manque de stations pluviométriques en haute montagne) mais aussi à des valeurs élevées d’écoulement annuel qui pourrait être expliqué par une combinaison de l'accumulation de neige et de sources karstiques qui affectent fortement le bilan d'eau au Liban.

Pour les événements pluvieux, la quantité de précipitations dans un événement donné peut présenter jusqu'à 40% du total annuel des précipitations. Cela ne surprend pas compte tenu de la nature du climat dominant. Les débits de pointes instantanés ne sont pas disponibles et nous nous sommes limités à l’étude des débits journaliers maximaux. Le débit spécifique maximal diminue avec la surface du bassin versant ; il n’y a pas de corrélation avec la quantité des précipitations. Cependant, certain regroupement géographique est apparu pour les valeurs les plus élevées de débits de pointes spécifiques enregistrées dans la partie centrale plus humide du Mont-Liban. Le coefficient de ruissellement de l'événement est élevé, même comparé à d'autres bassins versants méditerranéens; en fait, il est beaucoup plus élevé que les valeurs enregistrées dans le EM et est dans la gamme des bassins versants NWM. Encore une fois cela pourrait être en partie attribuable à une sous-estimation des précipitations mais aussi à la nature karstique des bassins versants étudiés et les conditions antécédentes d'humidité du sol.

Partie III : Classification et modélisation

C’est la troisième partie de la thèse, elle comporte deux chapitres (chapitre 6 et 7)

Classification des bassins versants (chapitre 6)

Les descripteurs physiques et les signatures hydrologiques sont utilisés pour classer les bassins versants libanais en fonction de leurs caractéristiques physiques et hydrologiques.

La méthode utilisée ici pour le classement des bassins versants est une classification hiérarchique ascendante. C’est une approche de classification par similarité où les individus les plus similaires sont regroupés dans une même classe.

Une analyse en composantes principales (ACP) a été appliquée à chaque ensemble de variables (descripteurs physiques et signatures hydrologiques) indépendamment en utilisant la matrice de corrélation comme entrée à l'ACP. L'objectif est de réduire la dimension de l'espace de variables et de retenir les caractéristiques qui contribuent le plus à la variance. L’ACP permet aussi de minimiser la redondance et la multi-colinéarité entre les variables choisies (Olden and Poff, 2003). Cela réduit la dimension des ensembles de données par transformation de l'espace à n dimensions (n = nombre de variables initiales) en un nouveau espace à m dimensions, où m ($1 <= m <= n$) est le nombre de nouvelles variables qui sont les composantes principales. Ces composantes principales ne sont pas corrélées et orthogonales entre elles et classée tel que la première composante représente la plus grande quantité de la variance dans l'ensemble de données d'origine.

Une classification hiérarchique ascendante en utilisant une matrice de dissimilarité basée sur la distance euclidienne a ensuite été effectuée pour regrouper les stations de jaugeage en grappes de bassins relativement homogènes avec des caractéristiques physiques ou hydrologiques similaires (Olden et al. 2011). Les classes ont été générées en minimisant les sommes de carré de la distance à la moyenne de centre (Ward, 1963).

Enfin, les bassins versants qui sont simultanément dans un groupe de bassins versants physiquement similaires et un groupe de bassins hydrologiquement similaires sont mis ensemble dans un même groupe de bassins physiquement et hydrologiquement similaires.

Cinq groupes de bassins versants qui sont simultanément physiquement et hydrologiquement similaires ont été alors identifiés: le groupe PH1 composées de cinq bassins versants avec des régimes de ruissellement dominé par la contribution nivale. Ce sont principalement des bassins versants dans le nord du Liban. Ce sont des bassins de taille moyenne avec une fraction considérable de la surface touchée par la neige. La réponse hydrologique est induite à la fois par les précipitations et la fonte des neiges tandis que les contributions des eaux souterraines maintiennent une bonne quantité de volume de ruissellement pendant la saison sèche; le groupe PH2 est similaire au précédent, mais ici l'impact des pluies en aval est plus important que dans le groupe précédent, en raison à la fois des pentes plus raides et des conditions plus humides; les groupes PH3 et PH4 sont composées de bassins versants où la pluie est le principal contributeur aux débits fluviaux cependant la contribution de la neige n'est pas absente en particulier dans la partie supérieure des bassins versants qui constitue le groupe PH4; le groupe PH5 est composé de deux sources karstiques où la rivière Ibrahim émerge. Leur entrée principale est la fonte des neiges. Enfin, cinq bassins versants ne rentrent pas dans un groupe et constitue un groupe de bassins versants non similaires.

Modélisation de la réponse hydrologique des bassins libanais (chapitre 7)

GR2M (modèle de Génie Rurale à 2 paramètres Mensuel) est un modèle global mensuel à 2 paramètres, développé dans les années 1980 par le Cemagref. La version utilisée ici est celle de Mouelhi et al. (2003). Le modèle associe deux réservoirs: un pour la production et l'autre pour le transfert. La fonction de production du modèle est basée sur le réservoir de production qui simule les conditions d'humidité du sol. La capacité du réservoir est représentée par un paramètre X1. Un autre paramètre X2 associé au réservoir de transfert ouvre un échange avec l'extérieur du bassin.

Les entrées du modèle sont les précipitations et l'évapotranspiration de référence en mm. Les deux paramètres du modèle sont calibrés en utilisant les lames écoulées observées en mm. La fonction critère utilisée est le critère d'efficacité de Nash et Sutcliffe.

Dans notre étude, nous avons appliqué GR2M sur les bassins versants libanais pour la période 2001-2011. Nous avons divisé l'échantillon en deux: nous avons calibré le modèle sur la période 2001-2006 et validé sur la période 2006-2011 et vice versa.

Finalement, la modélisation par GR2M donne des résultats acceptables avec une valeur médiane du coefficient de Nash autour de 0,55. Cinq bassins donnent des bons résultats avec des valeurs de Nash supérieur à 0.7. Neuf autres donnent des résultats assez acceptables avec des Nash entre 0.5 et 0.65. Pour le reste, la simulation donne des résultats médiocres. La comparaison des différentes approches de régionalisation donnent des résultats mixtes pour les méthodes basées sur la similarité hydrologique et/ou physique, tandis que la méthode basée sur proximité spatiale donne les plus mauvais résultats. L'examen détaillé de la simulation montre l'impact important de la neige qui peut couvrir plus que la moitié de la surface de certains bassins et qui n'est pas pris en compte par le GR. En plus une forte récession qui n'est pas bien capturée par le GR est observée durant la période sèche. Elle peut être due à une surexploitation des eaux de surfaces. Tout futur essai de modélisation des bassins libanais doit prendre en compte ces particularités.

Hydrology of Lebanese catchments in the Mediterranean context

Abstract

Lebanon is a small mountainous country with a typical Mediterranean climate and a high spatial variability of precipitation with a substantial amount occurring as snow. Moreover, the majority of Lebanese terrains are karstic. It is a heavily urbanized country with increasing anthropogenic pressure on water resources. Furthermore, the Lebanese catchments are poorly-gauged due mainly to a large gap of data (1975 - 2000) caused by the civil war (1975 - 1990).

However, previous studies on regionalization suggested that across Lebanon when physical characteristics are not changing, hydrologic parameters shows a remarkable degree of spatial coherence. Thus, with an integration of more physical and functional characteristics, a regionalization procedure could be considered as a framework for defining the physical and hydrological characteristics of the Lebanese catchments.

Consequently, this work aims to understand the hydrological response characteristics of Lebanese catchments in the Mediterranean context and to classify these catchments according to their physical and hydrological properties. It is structured into three parts: (i) a review on Mediterranean catchments hydrology, (ii) a datal analysis of the Lebanese catchments and comparison to the Mediterranean context, and finally (iii) a classification and modeling of the Lebanese catchments.

The first part reviews 152 hydrological studies conducted in the Mediterranean region at various time scales (paper accepted in Hydrological Sciences Journal). This study also compares methods and modeling approaches used for individual-catchment or regionalization studies. The study area is divided into the northwestern (NWM), eastern (EM) and southern (SM) Mediterranean. The analysis indicates regional discrepancies in which the NWM shows the most extreme rainfall regime. A tendency for reduced water resources driven by both anthropogenic and climatic pressures and a more extreme rainfall regime are also noticeable. Catchments show very heterogeneous responses over time and space, resulting in limitations in hydrological modelling and large uncertainties in predictions. However, few models have been developed to address these issues. Regionalization studies are scarce and inconsistent in the Mediterranean. Additional studies are necessary to improve the knowledge of Mediterranean hydrological features and to account for regional specificities.

In the second part, an inventory of the available spatial and temporal data was carried out and followed by a detailed data analysis of twenty eight Lebanese catchments through extracting the physical and hydrological response characteristics for the period 2001 – 2011. The spatial data concerns the morphometry, drainage system, geology, karst, soils and land cover. The temporal data concerns the precipitation (32 stations at a daily –when available- and monthly time step), evapotranspiration (remote sensing data at a monthly time step) and discharge data (24 gauging stations at a daily time step and 4 at a monthly time step). Gathering the available temporal data was a real challenge since these data are not always available for the same period and precipitation data is expensive. The 2001 - 2011 temporal data was analyzed and compared with a database from the pre-war period. Afterwards, the hydrological responses of the Lebanese catchments are compared with other Mediterranean catchments at different time scales. At the annual water balance level, runoff ratio values are found to be high across the country. At the event scale, the amount of rainfall in a given event represents a substantial amount of the total annual rainfall. Moreover, unit peak flow [maximum daily discharge] decreases with the catchment area and is not correlated with the rainfall depth of an event. Event runoff ratio is high; in fact it is much higher than values recorded in the EM and is the range of the NWM catchments.

The third part concludes with a new clustering of the Lebanese catchments according to their physical and hydrological characteristics. The variables defined from the data analysis were used for the classification. Three classifications were carried out using catchments physical descriptors and runoff signatures separately. Catchments holding simultaneously the same physical and hydrological similarities were grouped together forming five “physically and hydrologically similar” catchments’ classes. Finally, a simple modeling approach at a monthly time step was tested using GR2M model. Different regionalization approaches were also compared. The discussion focuses on the analysis of the hydrological functioning of each basin and each class of basins.

Keywords hydrology; Lebanon, Mediterranean catchment; annual water balance; rainfall-runoff events; droughts; modeling, regionalization; classification

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Part I: State of the art

Part II: Lebanese catchments characteristics and data analysis

Part III: Classification and Modeling

GENERAL INTRODUCTION

The Mediterranean catchments hydrology

The Mediterranean climate is characterized by high inter-annual variability of precipitation, seasonal rainfall pattern, summer drought, and intense rainfall intensities. Due to the characteristics of their climate, Mediterranean areas face water availability problems (Morán-Tejeda et al. 2010). Indeed, with 8 % of the world population, renewable water resources represent only 3 % of the entire renewable water resources on Earth. In the last 20 years, many countries of the Mediterranean basin have witnessed drought periods over several years (FAO 2006). Many studies (e.g. Milly et al. 2005, IPCC 2014) predict that water resources will even become scarcer due to climate change and the increasing demand on water by various economical sectors. Moreover, rainfall events that usually occur as high intensity short duration storms cause intense flood events (e.g. Anquetin et al. 2010, Vincendon et al. 2010, Moussa and Chahinian 2009 [France], Koutroulis and Tsanis 2010 [Greece], Brath et al. 2004 [Italy], Rozalis et al. 2010 [Israel]). Mediterranean catchments are therefore characterized by three main features: limited water resources, dry summers and high intensity rainfall events that generate flashy and strong flood events.

Many attempts have been made to provide an overview on the hydrology of the Mediterranean region. Reviews have already detailed specific aspects of the hydrology of Mediterranean catchments, such as rainfall interception (Llorens and Domingo 2007), the impact of the Mediterranean forest on catchment responses (Cosandey et al. 2005), the dryland hydrology (Cudennec et al. 2007), the impact of human activities on fluvial systems (Hooke 2006), erosion processes (Shakesby 2011, Garcia-Ruiz et al. 2013) and the hydrology of mountainous catchments (Latron et al. 2009). Other studies synthesized the results of climate change impact studies in the region, such as in Alpert et al. (2008) and Philandras et al. (2011). The Mediterranean region has been studied as part of a larger geographical area, for example, the Euro-Mediterranean zone in the study on the daily precipitation concentration index in Europe (Cortesi et al. 2012), Europe in studies on extreme flash floods (Marchi et al. 2010), and Europe in studies on the regional flood frequency (Salinas et al. 2014a, b).

Various studies exist on different aspect of the hydrological responses of the Mediterranean catchments. However, individual catchments studies or regionalization studies, all are limited to specific catchment and a geographical region. So far no study had yet attempted to regroup different aspect of the Mediterranean hydrology and to synthesize previous work from all over the Mediterranean region. Accordingly, this work will identify the objectives and the modelling approaches, and will present a review on the Mediterranean catchments' hydrological response at the annual water balance, at event scale and during dry periods.

The information gathered herein will be also used as a reference to compare the hydrological response of a data limited environment: the Lebanese catchments.

The Lebanese catchments hydrology

Lebanon is a small mountainous country located on the eastern shores of the Mediterranean Sea. It has a typical Mediterranean climate with important local variations because of its complex relief. It is a heavily urbanized country with more than 88 % of the population living on a narrow coastal plain (World Bank 2010). Moreover, with widespread pollution and a large temporal variability of rainfall within the rainfall season and between consecutive years, along with the absence of management strategies, Lebanon will be unable to meet his water demand in the near future.

In Lebanon, a meteorological and hydrometric network had been gradually constructed since the 1930's and reached its peak in the 1970's (Sene et al. 1999). The unset of the Lebanese civil war in the 1975 created a data gap of more than 20 years. New networks are in construction since the late 1990's, however, the quality of the data –especially for the hydrometric network- is questionable. Thus the Lebanese catchments generally lack reliable data that permits a long term monitoring of both climatic and hydrological characteristics with an increase of anthropogenic pressure on water resources.

So, the Lebanese catchments are poorly gauged catchments in a context of increasing anthropogenic pressure on water resources. Moreover, Lebanon has many particularities. From a physiographic point of view, the country is formed by two mountain ranges that run parallel to the sea. The Mount Lebanon range delineates a narrow coastal plain and the Eastern chain. The two ranges are separated by an elevated plain, the Bekaa valley. This complex relief results in a high spatial variability of precipitation. Hence mean annual precipitation can exceeds 1500 mm in some parts of Mount Lebanon and fall below 200 mm in the semi-arid northeastern part of the country. Moreover, a substantial amount of precipitation occurs as snow. Furthermore, adding to the complex relief and the high spatial variability of precipitation, the substratum of most of the Lebanese terrains is made of carbonates rocks. This results in the formation of karstic features all over the country. Hence, the majority of Lebanese rivers find their sources in karstic springs. This makes the study of the hydrological response of the Lebanese catchments a real challenge.

Previous studies on different aspects of the hydrological cycle in Lebanon exist. So, for the precipitation inputs, various attempts were made to assess the spatial distribution of mean annual precipitation all over the country. Rey (1954) established the first rainfall distribution map for Lebanon. Another map was produced in 1972 by Plassard; this map is still used as a reference for rainfall distribution over Lebanon. Other more recent maps were also produced (Traboulsi 2010; Abdallah et al. 2013). A detailed study of the climatic characteristics of Lebanon was presented as a PhD thesis by Blanchet in 1976. The estimation of snow melt contribution to the water balance of Lebanon was also a main concern. The first study in this regard was by Abd El-Al in 1947. More recent studies exist, one can mention: Touma 2002, Shaban et al. 2004, Aouad-Rizk et al. 2005, Corbane et al. 2005, Mhawej et al. 2014, etc.

In term of the hydrological response characteristics, the majority of studies in Lebanon focused more on the hydrogeological aspects. In 1970 the UNDP presented the first assessment of Lebanon groundwater resources, this assessment is currently being updated by the UNDP and the Lebanese Ministry of Energy and Water. Other studies dealing with the functioning of karstic aquifers are quite abundant, one can mention among others: Ukayli et al. 1971, Mroueh et al. 1996, Bakalowicz et al. 2002, 2008, 2015, El-Hakim 2005, El-Hakim and Bakalowicz 2007, El-Hajj 2008, and many others. Now, as for classical hydrological studies (surface hydrology) fewer studies exist. One can mention the work of Sene et al (1999, 2000). The author studied the spatial and temporal variations in flows for five catchments and the regional distribution of maximum instantaneous flows in Lebanon; they found a certain regional pattern. Moreover, Hreiche (2003) presented a conceptual model created for the Mediterranean climate (MEDOR), calibrated and validated on various Lebanese and French catchments. Hreiche et al. (2007) coupled a snow module to MEDOR to better simulate snow melt contribution on Mount Lebanon. Bernier et al. (2003) used remote sensing to improve hydrological modelling of catchments in Mont Lebanon. Modelling studies for trend detection and water resources management also exist (Massoud et al. 2006, Ramadan et al. 2012). Regionalization studies in the country are very preliminary. Other then the previously mentioned studies by Sene et al. (1999, 2000), moreover, Abou Daher (2006) established global linear regression models for the estimation of annual runoff ratio. These preliminary studies suggested that all across Lebanon when structural characteristics are not varying, hydrologic parameters shows a remarkable degree of spatial coherence. Therefore, with an integration of more structural and functional characteristics of basins, a regionalization procedure could be undertaken for the Lebanese watersheds. Highlighting the status of the Lebanese catchments -poorly gauged with undeveloped classification scheme- it would be intersting to analyze the hydrological response and compare it with referenced Mediterranean catchments to present a complete classification scheme of the Lebanese catchments.

Catchment classification

Catchment classification is used to group catchments that share physical and/or hydrological characteristics. It permits to compare between large samples of catchments across different hydro-climatic conditions. Andréassian et al. (2006) emphasizes the importance of working with a large number of basin datasets; the aim is to compare and learn from catchments differences and similarities in different locations (Parajka et al. 2013, Salinas et al. 2013) which contributes enormously to the ongoing work towards the development of a global classification scheme which is still lacking in hydrology (Sivapalan 2005, Wagener 2007). Moreover, catchment classification is used in regionalization studies - the transfer of hydrological information from gauged catchments to ungauged ones (Oudin et al. 2010) - which is of great interest in a world where the majority of basins worldwide are ungauged and so "*in the presence of data scarcity it would be compelling to infer hydrologic function from the metric of catchment form*" (Hrachowitz et al. 2013).

Generally, in order to classify catchments a set of variables representing the physical and functional characteristics of the catchments are needed. These variables are widely available in the literature (Yadav et al. 2007, Olden and Poff 2003, etc.). One of the most commonly used classification method is cluster analysis (Alcazar and Palau 2010, Sawicz et al. 2011, 2014, Archfield et al. 2013 among others). Here, the initial set of individuals (catchments) is re-arranged into groups in such a way that each group (cluster) contains individuals that are the most similar. There are multiple algorithms to perform clustering. One can mention the distance-based method, such as hierarchical clustering, where groups are built according to distance connectivity (Archfield et al., 2013). Another algorithm is K-means clustering where individuals are grouped in clusters in which every individual belong to the cluster with the nearest mean (Mehaiguene et al., 2012). Many other clustering algorithms exist and are in use by hydrologists, such as hybrid cluster analysis and fuzzy cluster analysis (Ramachandra Rao and Srinivas 2006).

This work articulates on three main axes. First a review on the Mediterranean catchments' hydrology is conducted, than the physical and hydrological descriptors of the Lebanese catchments are extracted, analyzed and compared with other Mediterranean catchments. Last and not least, a classification scheme of the Lebanese catchments is performed following the hydrological knowledge accumulation framework promoted by Blöschl et al. (2013) (Fig. I).

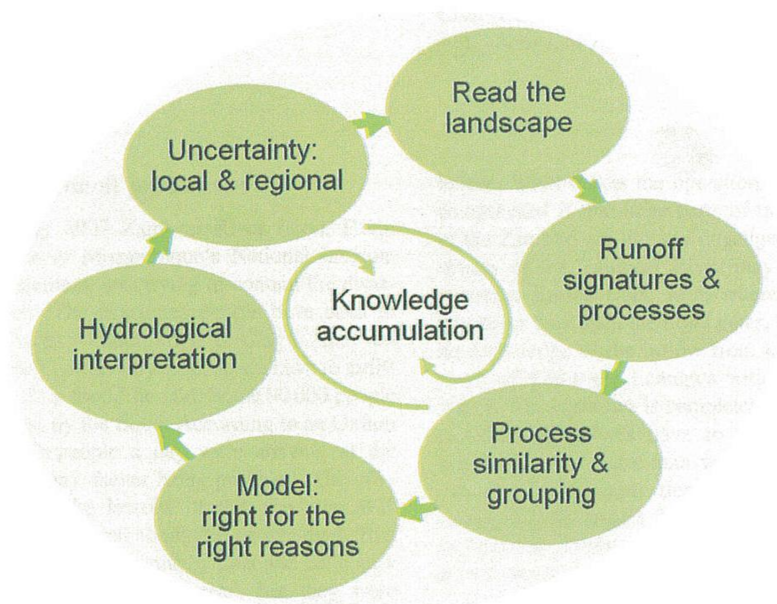


Fig. I Knowledge accumulation through Prediction in Ungauged Basins (Blöschl et al. 2013).

Thesis objectives

This work aims to understand the hydrological response of the Lebanese catchments in a Mediterranean context and classify these catchments according to their physical and hydrological characteristics. It begins by a review of the hydrological response of

Mediterranean catchments at different time scale. Afterwards, a detailed data analysis for the Lebanese catchments in term of physical, climatic and hydrological characteristics is presented, than we compare the hydrological response of Lebanese catchments with other Mediterranean catchments. Finally catchments descriptors and runoff signatures are used to define classes of physically and/or hydrologically similar catchments. Conceptual model are than proposed for each of the defined physically and hydrological similar catchments group.

The objective of this thesis is threefold:

Review the hydrological response characteristics of Mediterranean catchments in term of annual water balance, rainfall-runoff events and droughts for individual catchments studies and regionalization studies.

Analyze the physical, climatic and hydrological characteristics of Lebanese catchments and compare them to the wider Mediterranean context.

Classify the Lebanese catchments in groups of catchments with physical and hydrological similarities and propose conceptual models that best represent catchments functioning in each group.

Thesis structure

This thesis is structured in three parts and seven chapters

Part I "state of the art" is made of one chapter. It forms a review article accepted with revisions to Hydrological Sciences Journal. It presents a review on hydrological response characteristics of Mediterranean catchments. The review begins by defining the limits of Mediterranean region**.** Then follows a review on hydrological studies for continuous stream flow simulation, event based studies and drought studies. This part ends with a discussion that tries to identify patterns of hydrological response in different Mediterranean subregions, assess and compare hydrological modelling and regionalization techniques used in the Mediterranean context.

Part II "Lebanese catchments characteristics and data analysis" is made of four chapters. It presents a detailed data analysis of the Lebanese catchments characteristics. Two lists of variables that represent the catchments physical characteristics and hydrological response characteristics respectively are extracted from this part. The part ends with a comparison between Lebanese catchments and other Mediterranean catchments.

Chapter 2 presents a detailed description and analysis of geographical characteristics of the Lebanese catchments. The available data were presented and a list of catchment descriptors was extracted.

Chapter 3 presents a detailed description and analysis of the climatic characteristics of the Lebanese catchments. The available climatic data were presented and the methodology used for rainfall spatial interpolation is also discussed.

Chapter 4: presents a detailed description and analysis of the hydrological response characteristics of the Lebanese catchments. The available hydrological data are presented and analyzed, and a list of runoff signatures was extracted from the data.

Chapter 5 compares the Lebanese catchments to their Mediterranean counterparts in term of hydrological response at the annual water balance scale and the event scale.

Part III “classification and modelling” comprises two chapters. This part presents a classification of the Lebanese catchments according to their physical and hydrological characteristics. The variables defined in the previous part were used here for the classification. Moreover, a simple modelling approach were undertaken to test the robustness of the classification. The part ends by a proposition of conceptual models that represents the different groups.

Chapter 6 presents the classification of the Lebanese catchments by their physical and hydrological characteristics. Here, the physical and hydrological variables extracted in chapters 2 to 4 were used for the classification using an agglomerative hierarchical clustering analysis.

Chapter 7 presents a simple modeling approach at a monthly time scale for the Lebanese catchments. A simple but robust monthly time step model, GR2M, was used to assess the modeling quality of the Lebanese catchments and to compare different regionalization approaches.

The thesis ends with a general conclusion that summarizes the main findings and limitations of this work and identifies key questions that need to be addressed in order to better understand the hydrology of Mediterranean catchments and more particularity the Lebanese catchments.

Annexes

Annex A: a list of acronyms for the used variables

Annex B, C and D: a review of modeling approaches, regionalisation approaches and regionalisation studies in the Mediterraean respectively.

Annex E: Lebanese data collection and availability detailing the data collection methodology and treatement and the meta-data of the used temporal data.

Annex F: physical characteristics of the studied Lebanese catchments.

Annex G: descriptions of the used variables and their calculation method.

Annex H: hydrogeology of Lebanon.

PART I.

STATE OF THE ART

This part consists of one chapter. It is a review of hydrological characteristics of Mediterranean catchments at the annual water balance scale, rainfall-runoff event scale and the dry period. It also compares methods and modeling approaches used for individual-catchment studies. More details about global modeling techniques and regionalization methods are available in annexes B and C, and detailed review of regionalization studies in the Mediterraean region areis presented in annex D.

This part forms an article accepted in Hydrological Sciences Journal:

Mohammad Merheb, Roger Moussa, Chadi Abdallah, François Colin, Charles Perrin and Nicolas Baghdadi, 2016. Hydrological response characteristics of Mediterranean catchments at different time scales: a meta-analysis. Hydrological Sciences Journal, in press. http://dx.doi.org/10.1080/02626667.2016.1140174.

1 HYDROLOGY OF MEDITERRANEAN CATCHMENTS: A REVIEW

1.1 Introduction

1.1.1 The Mediterranean as a focus of research

The Mediterranean climate is characterized by high inter-annual variability in precipitation, seasonal rainfall patterns, summer drought, and intense rainfall. Because of the characteristics of the climate, Mediterranean areas face water availability problems (Morán-Tejeda et al. 2010). In the last 20 years, many countries of the Mediterranean Basin have witnessed multi-year drought periods (FAO 2006). Many studies (e.g., Parry et al. 1999, Milly et al. 2005, IPCC 2014) predict that water resources will even become scarcer due to climate change and the increasing demands on water by various economic sectors. Moreover, the irregular spatial distribution of precipitation leads to large differences in water availability across territories (Morán-Tejeda et al. 2010). Furthermore, high-intensity but short rainfall events cause intense flooding (e.g., Vincendon et al. 2010, Moussa and Chahinian 2009 [France], Koutroulis and Tsanis 2010 [Greece], Brath et al. 2004 [Italy], Rozalis et al. 2010 [Israel]). Mediterranean catchments are therefore characterized by three main features: limited water resources, dry summers and high-intensity rainfall events that generate flash floods.

Many attempts have been made to provide an overview on the hydrology of the Mediterranean region. Reviews have already detailed specific aspects of the hydrology of Mediterranean catchments, such as rainfall interception (Llorens and Domingo 2007), the impact of the Mediterranean forest on catchment responses (Cosandey et al. 2005), the dryland hydrology (Cudennec et al. 2007), the impact of human activities on fluvial systems (Hooke, 2006), erosion processes (Shakesby 2011; Garcia-Ruiz et al. 2013) and the hydrology of mountainous catchments (Latron et al. 2009). Other studies synthesized the results of climate change impact studies in the region, such as in Alpert et al. (2008) and Philandras et al. (2011) and the impact of global changes on Mediterranean water resources (Garcia-Ruiz et al. 2011). The Mediterranean region has been also studied as part of larger geographical areas (Gaume et al. 2003a, Marchi et al. 2010, Cortesi et al. 2012, Salinas et al. 2014a, b).

Moreover, many international projects were conducted on the Mediterranean region to study the hydrological cycle generally. Among others, the FRIEND Alpine and Mediterranean Hydrology (AMHY) project was launched in 1991 as part of the UNESCO International Hydrological Program (Servat and Demuth 2006, Gustard and Cole 2002). The project involves 19 countries from southern Europe and the Mediterranean Basin. Since 2007, the HyMeX project (www.hymex.org) has been promoting a multidisciplinary approach to analyse all components of the Mediterranean water cycle (see Llasat et al. 2013 for more details). This project focuses on physical aspects, the socio-economic impacts of extreme events, and the adaptation capacity to changes. Another example of current initiatives in the Mediterranean is the MEDEX project (http://medex.aemet.uib.es), which focuses on meteorological scenarios with high hydrological impacts.

1.1.2 Objectives of the review

This paper aims to present an overview of the hydrological response characteristics of Mediterranean catchments and to identify the main objectives and modelling approaches of studies conducted in the region. It focuses on studies related to annual water balance, flood events and droughts.

The methodology consists of analysing recent individual catchments studies that have been published over the last two decades. It starts by defining the study area, followed by the collected database representation. The hydrological response characteristics and the methods used for a general discussion of the main outcome of this review is provided answering the following questions:

- Can we identify regional hydrological tendencies in the Mediterranean region?
- What is required to model Mediterranean catchments?
- What are the main challenges for future research in the Mediterranean?

Note that this analysis does not specifically review the studies on ungauged catchments for sake of brevity. The reader may refer to the recent general reviews on prediction on ungauged basins proposed by Blöschl et al. (2013) or Hrachowitz et al. (2013), which include studies on the Mediterranean basin.

1.2 The Mediterranean region

1.2.1 Boundary of the Mediterranean region

The Mediterranean climate is not confined to the Mediterranean Sea region. In fact, much of California, parts of Western and South Australia, southwestern South Africa, and parts of central coastal Chile have Mediterranean climates. According to the Köppen (1936) classification, Mediterranean climates are characterized as subtropical climates with dry summers. Nevertheless, this paper was intentionally limited to the Mediterranean basin because this region shares more than climatic features. The basin has homogenous geological and physiographic settings (Wainwright and Thornes 2004), and it forms a geographical unit that faces the challenges of large socio-economic exchanges and enormous anthropogenic pressure.

There is no worldwide consensus on the definition or boundaries of the Mediterranean region (Hooke 2006, Shakesby 2011). Several characteristics are commonly used to define the Mediterranean region (Fig. 1.1a):

- The boundaries of the basins that drain into the Mediterranean Sea (e.g., Milano et al. 2012): such a definition omits regions that share similar climatic and physiographic characteristics, such as Portugal, and adds regions that might not be considered Mediterranean from a climatic and hydrological point of view, such as parts of Libya and Egypt.
- The climate regime: several definitions and classifications denote boundaries that are not completely consistent (e.g., Köppen 1936, Thornthwaite 1948). For example, the Köppen (1936) classification, which is commonly used, classifies regions that are usually considered Mediterranean, such as southeastern and central Spain, as cold semi-arid regions; it also uncharacteristically extends the Mediterranean to areas in the Middle East.
- The vegetation types (e.g., Quezel 1985): such definitions are usually called bio-climatic because vegetation reflects the climatic conditions. Nevertheless, such definitions inherit some of the problems of the climatic definition. The distribution of many species considered as indicators of the Mediterranean (e.g., olive trees) are highly related to human activities.
- The administrative divisions of the countries surrounding the Mediterranean Sea: these definitions are also problematic because they often have no natural basis (Wainwright and Thornes 2004).

In this work, the “Mediterranean” is considered as any catchment falling within one of the above-mentioned boundaries and defined by authors as Mediterranean but excluding the administrative boundaries from this assumption (Fig. 1.1 (a, b, and c)).

1.2.2 Physical characteristics of the Mediterranean region

The Mediterranean region has a total area of approximately 1,100,000 km² (Grove and Rackham 2001). Mountain ranges surround the Mediterranean Sea (Fig. 1.1a): the Pyrenees in south-western Europe, the Alps in southern France and north-western Italy, the Apennines along the Italian coast, the Dinaric Alps along the coast of the Adriatic Sea, the mountains of Greece, the Taurus Mountains in Turkey, Mount Lebanon in the eastern Mediterranean and the Atlas Mountains in northern Africa. The proximity of the mountain ranges to the sea explains why a majority of the Mediterranean catchments are medium-sized and sloping. Lower hills, such as the Cevennes region in France, and plains also exist along the coasts and in some interior regions; thus, the landscape is quite heterogeneous.

Most of the underlying geology comprises limestone with sandstone, sedimentary deposits and metamorphic granites (Di Castri 1981). The prevalence of limestone rocks means that karstic catchments are very common in the region.

Vegetation is mainly dominated by evergreen trees and shrubs (the famous Mediterranean “Maquia” or “Garrigue”). In mountainous areas with wetter conditions, several deciduous tree species prevail. Conversely, the driest areas are dominated by steppe (Bonada and Resh 2013). However, Mediterranean catchments exhibit a particular relief-driven organization in the distribution of land types. Hence, forests grow directly under the rocky summits of Mediterranean mountains; agricultural terraces exist downslope. Further down, the Mediterranean Garrigue is present. Finally, agriculture dominates the coastal plains. This pattern is partly attributed to past human activities, but it is now disturbed by the intense urbanization in Mediterranean coastal plains and the abandonment of the agricultural terraces for Mediterranean forests, particularly in Europe (e.g., Gallart and Llorens 2004, Lana-Renault et al. 2007, Ceballos-Barbancho et al. 2008, Morán-Tejeda et al. 2010). These changes certainly have an impact on the hydrological responses of Mediterranean catchments.

1.3 Review extent and database

1.3.1 Review information

A total of 140 studies on the Mediterranean region published over the last two decades were analysed.

To study regional tendencies in the Mediterranean zone, the study region was divided into:

- the North-Western Mediterranean (NWM), encompassing Mediterranean Albania, Croatia, France, Italy, Montenegro, Portugal, Slovenia and Spain, with 84 analysed studies
- the Eastern Mediterranean (EM), encompassing Cyprus, Egypt, Greece, Israel, Lebanon, Palestinian territories, Syria and Turkey, (42 studies) ;
- and the Southern Mediterranean (SM), encompassing Algeria, Egypt, Libya, Morocco and Tunisia, (14 studies).

These studies were divided into three groups focusing on the annual water balance (58 studies), flood events (49 studies) and droughts (33 studies).

For each study, the key information that was systematically collected and analysed includes:

(i) Basin location (reference and coordinates)

(ii) Study objectives

(iii) Basin characteristics, such as the area, mean elevation, mean slope, land use, soil classes, geology and the possible presence of karst;

(iv) Hydro-meteorological data characteristics, such as the rainfall-runoff measurement period, the time step of the measurements, the mean annual precipitation, the reference evapotranspiration, the mean annual runoff, the runoff coefficient and the snow contribution; for event-based studies, detailed information on catchment responses (rainfall, runoff, peak discharge) for each event was also extracted when available;

(v) Mode characteristics, such as the model name and original reference, the simulated hydrological processes, the spatial resolution (lumped, semi-distributed or distributed), the time step and the model evaluation criteria.

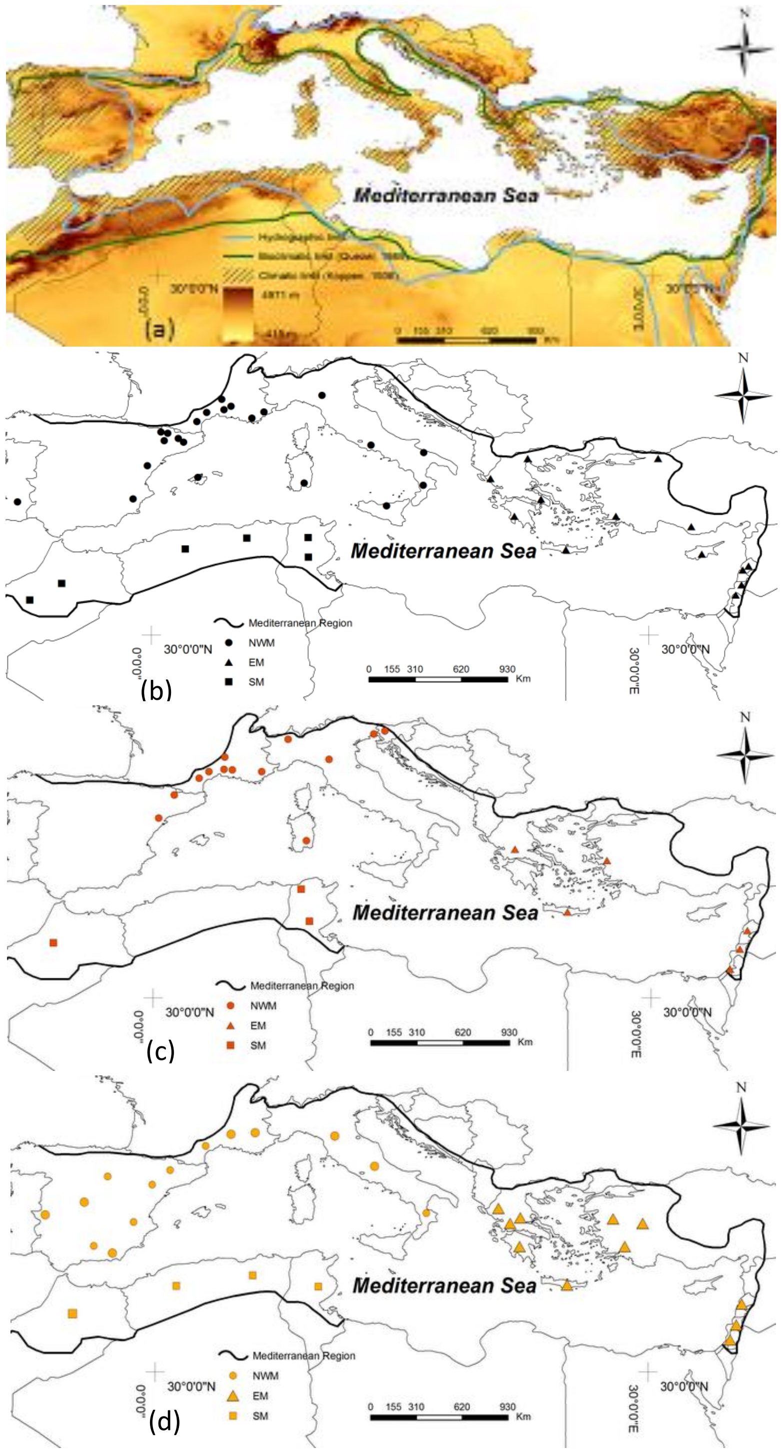


Fig. 1.1 The Mediterranean region: (a) Relief and different limits; (b) Annual water balance studies; (c) Event-based studies and (d) Drought studies.

1.3.2 Annual water balance studies

The reviewed studies (Fig. 1.1b) with information about the components of the water balance equation (40 out of 58) include approximately 139 Mediterranean catchments:

70 catchments in the NWM, 43 in the EM and 26 in the SM (Table 1.1). The majority (27 out of 40) are studies on individual catchments, while only 13 compare 2 or more catchments. The catchment areas range from 0.35 km² to 16,000 km², with a median of 286 km²; 75% of the catchment areas are below 640 km². Eighteen catchments are karstic, having hydrogeological boundaries that do not necessarily match the topographic boundaries. Snow represents a significant portion of the precipitation for 21 catchments. Thus, it is an essential component in those water balances.

1.3.3 Rainfall-Runoff event-based studies

Among the forty nine flood studies, twenty one includes useful information for quantative on 136 catchments and 191 events (Fig. 1.1c and Table 1.2).

The analysis was only conducted on hydrological studies at the catchment scale. Hence, studies focusing on the hydraulic aspects of the catchment response at the reach scale were excluded. These studies are not limited to extreme flood events (such as Marchi et al. 2010 and Tarolli et al. 2012) but comprise any runoff-generating rainfall event study that contains substantial event-related information. However, this information is not equally available to all. Details on each study and event-related data are presented in Table 1.2. Here, one must clarify that a single event can affect more than one catchment and that more than one event could be reported for the same catchment. Among these studies, 13 were conducted in NWM, 5 in EM, and 3 in SM. One study (Tarolli et al. 2012) was an analysis of flash flood regimes in the northwestern Mediterranean (France, Spain, Italy) and the southeastern Mediterranean region (Israel). Moreover, 69 catchments out of a total of 136 are located in the NWM. The rest of the catchments are divided between the EM (22) and SM (45). The catchments areas range from 3.83 km² for the Valsecure catchment (a headwater catchment of the Gardon d'Anduze, Southern France; Tramblay et al. 2010) to 16,330 km² for the Negada catchment at Lassoud in Tunisia (Abida and Ellouze 2008).

Table 1.1 Characteristics of the annual water balance studies in Mediterranean catchments. Nc: number of catchments; Ac: catchment area; Zc: catchment mean elevation; Period: period or number of years used to calculate the water balance components.

Region	Country	Study	Nc	Ac range (km²)	Zc range (m)	Period/Number of years
NWM	France	Adamovic et al. 2015	4	16.7 - 103	892 - 1142	2000 - 2008
		Lespinas et al. 2014	6	130 - 4957	367 - 1076	1960 - 2004
		Tramblay et al. 2013	1	1808	-	1984 - 2010
		Coustau et al. 2012	1	114	-	1994 - 2008
		Fox et al. 2012	1	234	0 - 144	1950 - 2003
		Goswami et al. 2007	3	150-291	79 - 850	1995 - 2003
		Moussa et al. 2007	1	545	123 - 1567	1975 - 1984
	Italy	Tayfur et al. 2014	1	137	250 - 887	1989 - 2010
		Pumo et al. 2013	1	9.5	792	1957 - 2004
		De Giroloma and La Porto 2011	1	488	70 - 960	1996 – 2007
		Longobardi and Vallini 2008	28	18 – 5586	240 – 1397	6 – 65
		Fiorentino et al.2007	2	462 – 511	-	1951 - 1961
		Burlando and Russo 2002	1	4000	1000	1953 – 1992
		Brath and Montanari 2000	1	1294	20 – 2121	1923 – 1970
	Portugal	Nunes et al. 2011	1	290	-	1961 - 1990
	Spain	Bernal et al. 2013	1	2.05	650-1343	1983 - 2010
		Candela et al. 2012	1	615	20-1200	1984 - 2008
		Gallart et al. 2011	2	504-1386	-	1940 - 2000
		Delgado et al. 2010	1	256	-	1940 - 2001
		Estrany et al. 2010	1	1.03	0-144	1974 - 2006
		Lana-Renault et al. 2007	1	2.84	910-1340	1999 - 2005
		Ceballos and Schnabel 1998	1	0.35	378	1991 - 1997
		Pinol et al. 1997	2	0.38-0.51	680-1084	1981 - 1988
EM	Cyprus	Hessling 1999	5	23 - 234	115 - 1400	1989 - 1994
	Greece	Koutroulis et al. 2013	15	22-1294	-	1970 - 1999
		Nikolaidis et al. 2013	1	132	0 - 2120	1973 - 2010
		Vasiliades and Loukas 2007	7	133 - 6591	415 - 1400	1960 - 2002
		Tzoraki and Nikolaidis 2007	1	149	0 - 2356	-
		Niadas 2005	12	154 -1118	565-1509	5 - 10
	Israel	Rimmer and Salingar 2006	1	783	-	1969 - 2004
	Lebanon	Sene et al. 2001	16	77 - 1815	-	1967 - 1974
	Turkey	Kukul et al. 2007	1	17200	220	-
		Fujihara et al. 2008	1	21700	-	1990 - 2004
SM	Algeria	Bakreti et al. 2013	5	236 - 1819	205 - 760	1975 - 2006
		Mehaiguene et al. 2012	24	95 - 2526	153 - 1139	30
		Benkaci Ali and Dechemi 2004	1	575	-	1979 - 1989
	Morocco	Bouabid and Chafai Elalaoui 2010	4	-	-	1959 - 2009
		De Jong et al. 2008	1	1239	1500 - 4071	1963 - 1998
	Tunisia	Raclot and Albergel 2006	1	2.45	-	1995 - 2002
		Bouraoui et al. 2005	1	16000	132 - 1373	1988 - 1999

Table 1.2 Summary information of the flood studies on Fig. 1.1c. Nc: number of catchments; Ne: number of events; Ac: catchment area; X: available data; and (-) not available.

Region	Country	Study	Nc	Ne	Ac (km²)	Available data			
						Peak Discharge	Rainfall Depth	Runoff Depth	Event duration
NWM	France	Nguyen et al. 2014	18	13	6 - 2240	X	-	-	-
		Garambois et al. 2013	6	9	144 - 619	X	X	-	-
		Artigue et al. 2012	1	4	222	X	X	-	-
		Coustau et al. 2012	1	21	114	X	X	X	-
		Tramblay et al. 2010	1	20	3.83	X	X	X	X
		Vincendon et al. 2010	4	4	1090 - 1910	X	X	-	X
	Italy	De Waele et al. 2010	1	1	105	X	X	-	-
		Sangati et al. 2009	6	3	75 - 2586	X	X	X	X
		Borga et al. 2007	10	1	23.9 - 1843	X	X	X	X
		Brath et al. 2004	1	15	1050	X	X	X	X
	Slovenia	Zanon et al. 2010	4	1	31.8 - 211.9	X	X	X	X
	Spain	Lana-Renault et al. 2014	2	5	3340 - 4915	X	X	X	-
		Amengual et al. 2006	5	1	0.12 – 2.84	X	X	-	X
EM	Greece	Massari et al. 2014	1	16	109	X	X	X	X
		Koutroulis and Tsanis 2010	1	9	158	X	X	X	X
	Israel	Rozalis et al. 2010	1	20	27	X	X	X	X
	Lebanon	Sene et al. 2001	16	16	102 - 1345	X	-	-	-
NWM and EM	NWM and Israel	Tarolli et al. 2012	12	12	12 - 699	X	X	X	X
SM	Morocco	Tramblay et al. 2012	1	16	665	X	X	X	X
	Tunisia	Abida and Ellouze 2008	42	-	3.2 - 16330	X	-	-	-
		Nasri et al. 2004	2	4	3.16 – 18.1	X	X	X	-

1.3.4 Drought studies

Drought definitions vary according to the variables used to describe the drought (Mishra and Singh 2010, 2011). One can define three major types of droughts: meteorological or climatic drought; agro-meteorological or agricultural drought; and hydrological drought (Gumbel 1963, Palmer 1965).

Socioeconomic impacts of drought are defined in terms of losses from an average or expected return and are measured by both social and economic indicators (Mishra and Singh 2010). All these droughts aspects are interrelated and are measured in terms of their intensities, durations and frequencies. In this work, we cite recent studies in the Mediterranean region that characterize droughts, and we discuss the main objectives and methods used (Fig. 1.1d and Table 1.3).

Table 1.3 Summary information of the chosen droughts studies on Fig. 1.1d. Nc: number of catchments.

Region	Country	Study	Nc	Period
NWM	France	Ruffault et al. 2013	-	1971 - 2006
		Vidal et al. 2012	-	1957 - 2007
		Chaouche et al. 2010	13	1970 - 2006
	Italy	Capra et al. 2013	-	1921 - 2007
		Diodato and Bellocchi 2008	-	1961 - 2006
		Mendicino et al. 2008	16	1957 - 2007
	Spain	Terrado et al. 2014	1	1951 - 2000
		Vicente-Serrano et al. 2014	-	1961 - 2011
		López-Bustins et al. 2013	3	1984 - 2008
		Marquèz et al. 2013	1	1971 - 2100
		Bangash et al. 2012	1	2002 - 2006
		Gomez and Blanco 2012	1	1941 - 2009
		Ruiz-Sinoga et al. 2012	-	1964 - 2008
		Lorenzo-Lacruz et al. 2010	3	1961 - 2006
		Vicente-Serrano and López-Moreno 2005	1	1950 - 2000
	Spain and Portugal	Vicente-Serrano 2006	-	1910 - 2000
EM	Greece	Vrochidou et al. 2013	1	1974 - 1999
		Tigkas et al. 2012	6	1970 - 1997
		Mavromatis and Stathis 2011	-	1961 - 2006
		Vangelis et al. 2010	-	1955 - 2002
		Nalbentis and Tsakiris 2009	-	1970 - 2000
		Vasiliades and Loukas 2009	7	1960 - 2002
		Tsakiris et al. 2007	2	1962 - 2001
	Israel	Aviad et al. 2009	-	1960 - 1990
		Kafle and Bruins 2009	-	1970 - 2002
	Lebanon	Shaban 2009	-	1963 - 2007
	Turkey	Dogan et al. 2012	1	1972 - 2009
		Yilmaz and Harmancioglu, 2010	1	1995 - 2003
		Turkes and Tatli 2009	-	1929 - 1993
SM	Algeria	Hamlaoui-Moulai et al. 2013	4	1914 - 2004
		Hamlat et al. 2012	4	2006 - 2030
	Morocco	Esper et al. 2007	-	1050 -2000
	Tunisia	Abouabdillah et al. 2010	1	1992 - 1996

Droughts are usually studied in a regional context due to their large-scale characteristics (Mishra and Singh 2010). Here, thirty three drought-related studies published in the last decade in the Mediterranean region are presented (Fig. 1.1d and Table 1.3). Eighteen studies are conducted at the catchment scale, while the others have a greater spatial extension, generally an entire country or geographical region. Approximately half of the studies are conducted in the NWM, with a majority (10 articles) in the Iberian Peninsula (mostly Spain), 13 studies were conducted in the EM and only 4 were conducted in the SM region. Drought studies are usually conducted at long time scales (several decades).

1.4 hydrological response characteristics

In this section we analyse the hydrological response characteristics of the studied Mediterranean catchments based on the collected data described above, in terms of annual water balance, rainfall-runoff events and drought.

1.4.1 Annual water balance studies

The mean annual precipitation (MAP), reference evapotranspiration (ET0), and mean annual runoff (MAQ) are highly variable across the three Mediterranean sub-regions. The median values show decreasing MAP, MAQ, MAQ/MAP and an increasing ET0 from NWM to EM and SM (Table 1.4).

The relationship between MAQ and MAP is plotted whereeach point represents a studied catchment (Figure 1.2). The results show a significant correlation (R^2=0.745) between MAQ and MAP reported in all studies. Most low-yielding catchments with MAP values lower than 400 mm are located in the SM. For a larger MAP, the graph shows important scattering. The graph also shows that even for large MAP values (800 - 900 mm), the runoff yield can be very low (approximately 30 mm); this is true for catchments in Crete (Koutroulis et al. 2013). Thus, the catchment yield is highly variable. The trend for the EM and the NWM catchments is quite similar, with an intercept close to 500-550 mm and comparable slopes. The trend is different for the SM catchments with an intercept close to 250-300 mm and a lower slope. For a few catchments (especially in NWM and EM), the MAQ is larger than the MAP. Here, two factors may explain this phenomenon: the contribution of snow amounts in mountainous catchments that is underestimated and the presence of karsts that may greatly increase the effective catchment area.

A similar analysis (not shown) that accounted for catchment area and elevation was undertaken. Catchment area does not appear to influence catchment response, expressed as the water depth (mm per time step). The impact of the elevation, however, could not be neglected because both the MAP and catchment runoff increased with elevation.

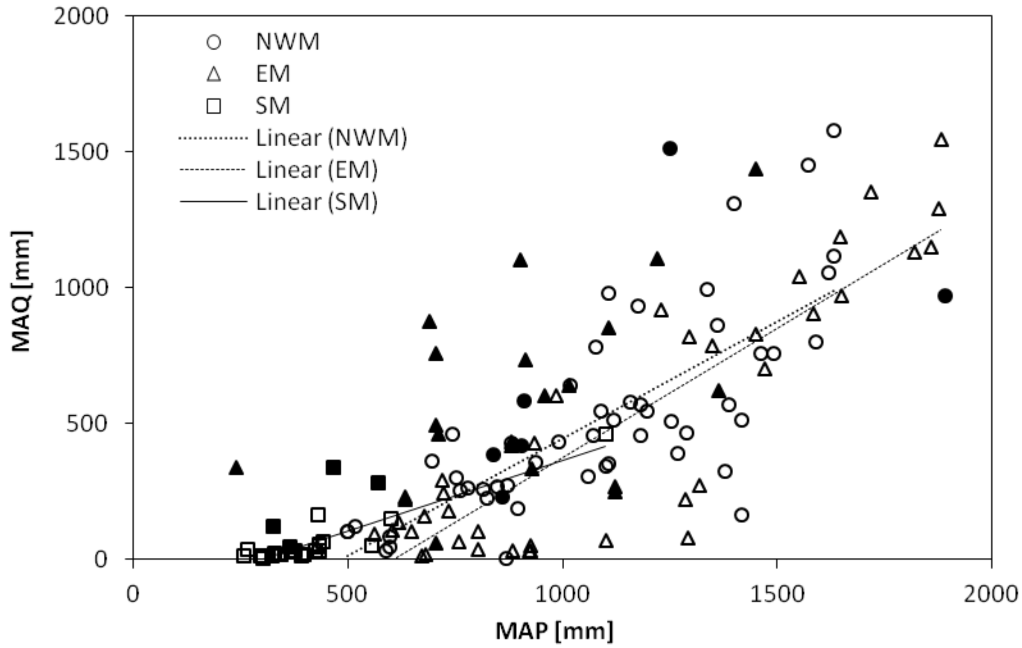


Fig. 1.2 Relationship between the Mean Annual Runoff (MAQ) and the Mean Annual Precipitation (MAP) for the three studied sub-regions (NWM, EM and SM). Plain symbols indicate karstic catchments in each sub-region.

Table 1.4 Summary statistics of climatic and hydrological variables for the studied catchments (Table 1.1 and Fig. 1.1b) for the three Mediterranean sub-regions (NWM, EM and SM). MAP: Mean Annual Precipitation; ET0: reference evapotranspiration; MAQ: Mean Annual Runoff.

		MAP (mm)	ET0 (mm)	MAQ (mm)	ET0/MAP (-)	MAQ/MAP (-)
NWM	Min-Max	589 -1892	775 -1617	33 -1579	0.45 - 2.21	0.06 - 1.21
	Median	1113	933	485	0.84	0.46
	Interquartile range	891 -1366	868 - 990	319 - 763	0.67 -1.04	0.32 - 0.62
EM	Min-Max	428 -1718	957 - 1517	12 - 1437	0.62 - 2.91	0.02 - 0.99
	Median	924	1391	105	1.56	0.17
	Interquartile range	713 -1294	1120 -1444	105 - 649	1.02 - 1.99	0.06 - 0.57
SM	Min-Max	257 -1100	519 - 2382	4 - 460	1.07 - 4.29	0.01 - 0.73
	Median	376	1157	33	2.88	0.08
	Interquartile range	327 - 433	811 - 1272	15 - 56	2.39 - 3.19	0.05 - 0.14

To investigate the climatic features of Mediterranean catchments, a Budyko-type plot (Budyko 1974, Andréassian and Perrin 2012) (Fig. 1.3) shows the mean annual runoff coefficient MAQ/MAP as a function of the aridity index AI = ET0/MAP. When ET0/MAP<1, wet conditions prevail. When ET0/MAP>1, dry climatic conditions prevail. The lines MAQ/MAP=1 and MAP=MAQ+ET0 represent the water and energy limits. Catchments are expected to fall within these limits for a closed water balance. Otherwise, the catchment is either gaining (catchment with MAQ/MAP>1) or losing (catchment with MAP<MAQ+ET0) water, or there might be errors in the data. Four catchments fall outside the water or energy limits. These catchments are karstic (e.g., Nikolaidis et al. 2013 [Greece], Longobardi and Vallini 2008 [Italy]), which may explain the presence of underground water gain or loss processes. Most catchments (60%) can be considered water-stressed, with an aridity index greater than 1.

Figure 1.3 shows a geographical cluster of catchments: (i) NWM catchments with the lowest aridity index and a large variation in catchment water yields (MAQ/MAP); (ii) SM catchments with the lowest runoff yields; (iii) EM catchments with a large variation in both the aridity index and catchment water yields. This large heterogeneity in the climatic features and hydrological response of EM catchments can be explained by the complex geomorphologic features of this region and the prevalence of karstic and mountainous catchments.

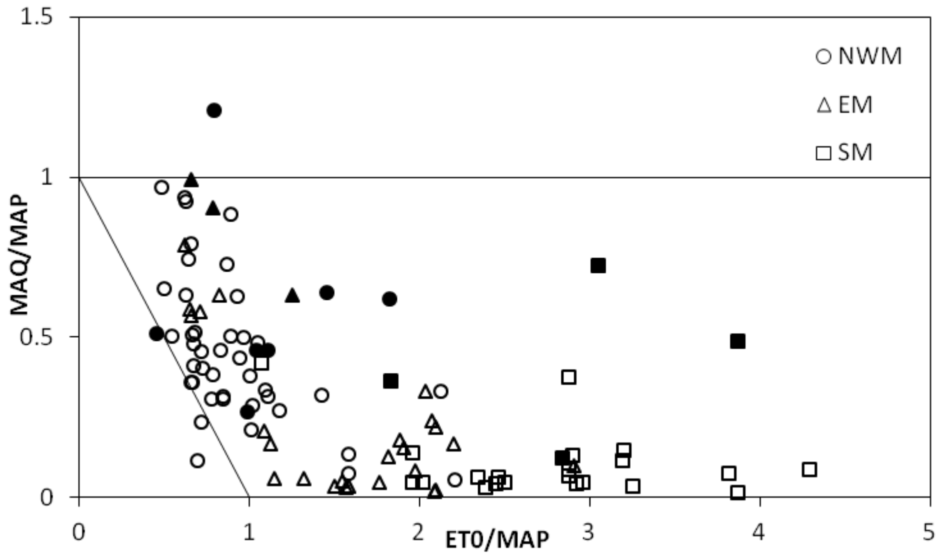


Fig. 1.3 Plot of mass balance data from the study catchments on the Budyko diagram: the mean annual runoff coefficient MAQ/MAP function of the aridity index ET0/MAP/ MAP: Mean Annual Precipitation; MAQ: Mean Annual Runoff; ET0: Mean Annual Reference Evapotranspiration for the 3 sub-regions NWM, EM and SM; Plain symbols indicate karstic catchments in each sub-region.

To summarize, Mediterranean catchments exhibit a high variability in terms of both climatic characteristics and catchment hydrological responses at the annual scale. The latter can highly vary, even for the same amount of rainfall input, which may seriously challenge any modelling approach. Nevertheless, some regional patterns exist, and catchments in each of the above-mentioned sub-regions appear to have somewhat similar characteristics.

1.4.2 Rainfall-runoff event-based studies

1.4.2.1 *Rainfall events: amount and duration*

The monthly distribution of the number of events per geographic zone is presented in Fig. 1.4. Events in the NWM mostly occur in autumn (September to December), whilst in the EM region, events mostly occur in winter (January and February). For the SM, most of the studied events occur between September and February, with the highest frequency in January.

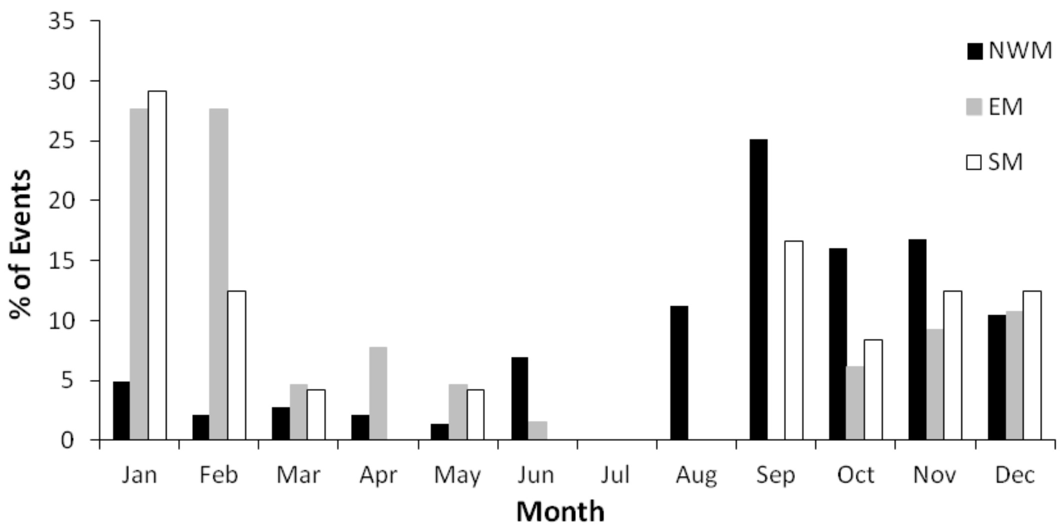


Fig. 1.4 Monthly distribution of events per geographic region.

For the 191 events presented here, the duration of the runoff generated by a rainfall event greatly varies between 2 h and 8 days. Similarly, event rainfall amounts show great variability, from 10.4 mm in the Giofyros Basin, Greece (Koutroulis and Tsanis 2010), to 540 mm in the Gard River Basin, France (Vincendon et al. 2010) over various durations. More extreme events were also reported in the literature, particularly in southern France. On 12-13 November 1999, the Aude River [Southern France] witnessed an extreme flood event generated by 700 mm of rainfall in 24 hrs (Gaume et al. 2004). The famous 8-9 September 2002 flood in the Gard region (southern France) was generated by approximately 600 mm of rainfall in 48 hrs.

Figure 1.5 represents the cumulative event rainfall as a function of the event duration, with large scattering in the relationship. For the same event duration, the total amount of cumulative rainfall can greatly vary over a location. Moreover, the rainfall amounts during a single event vary according to the geographical location, with the highest event rainfall (> 100 mm) located in the NWM.

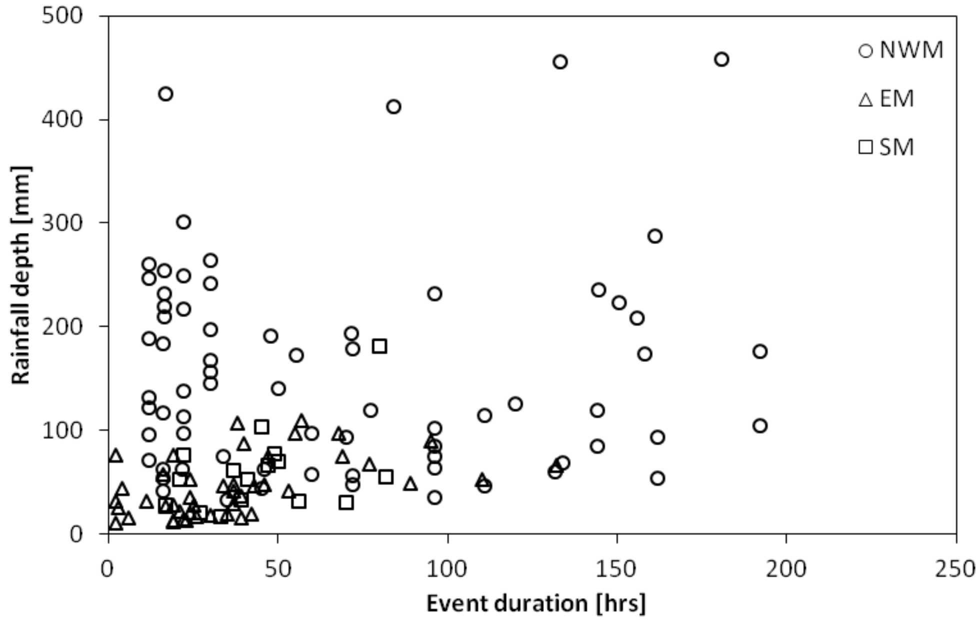


Fig. 1.5 Relationship between rainfall depth and event duration for the studied events on the three studied sub-regions (NWM, EM and SM).

1.4.2.2 Peak discharge

Event peak discharge is widely used as an indicator of the hydrological response of catchments. Here, we represent the catchment unit peak discharge (the peak discharge per km²) as a function of a catchment's area (Fig. 1.6a) and cumulative event rainfall (Fig. 1.6b). Numerous studies found a dependence of peak discharge on catchment area (e.g., Herschy and Fairbridge 1998, Herschy 2002, Furey and Gupta 2005, Marchi et al. 2010). Figure 1.6a represents a log-log diagram of the unit peak discharges of our catchment database (for each catchment, the highest peak flow was plotted) with two envelope curves developed by Tarolli et al. (2012) for the NWM (France, Italy and Spain) and for EM (Israel) flash floods.

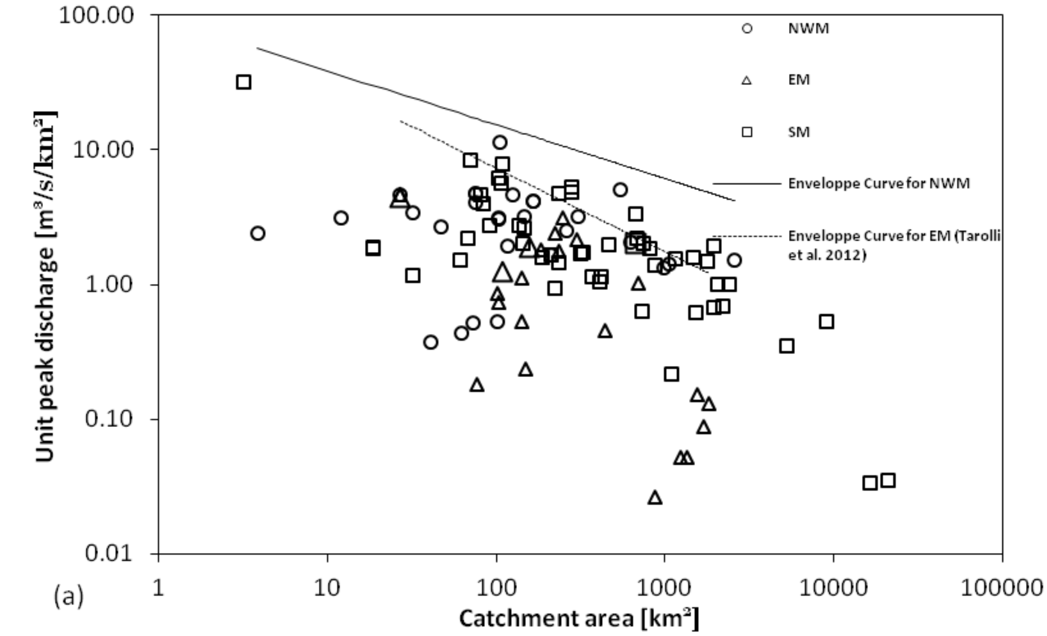
In Mediterranean catchments, unit peak discharges are extremely high. Indeed, values estimated from post-flooding investigations (Gaume et al. 2003b, Gaume et al. 2004, Gaume and Bouvier 2004) reached 30 m³/s/km² for the 8-9 September 2002 event for a 15 km² basin, exceeded 15 m³/s/km² in four basins, and exceeded 10 m³/s/km² in six other basins. This finding can be linked to the characterization of extreme flash floods in 60 catchments of five European climate zones (Mediterranean, Alpine-Mediterranean, Alpine, Continental and Oceanic) presented by Marchi et al. (2010). The authors found the highest unit peak flows in the Mediterranean region followed by the Alpine-Mediterranean.

In our dataset, the highest unit peak flow was recorded on the Alzon River at the Saint Jean de Pin, southern France (Nguyen et al. 2014), with a value of 33 m³/s/km² (catchment area = 30 km²). However, the unit peak discharges decrease rapidly with the increasing catchment area. This rapid decrease in the unit peak discharge with the increase in the catchment area may reflect the high spatial variability in the rainfall events that occurs in the Mediterranean and the high heterogeneity in the hydrological responses of different locations within a catchment (Latron and Gallart 2007, 2008). Thus, for a given catchment and a given rainfall event, the event does not necessarily affect the entire catchment, and the runoff-generating processes are not the same in all parts of the catchment.

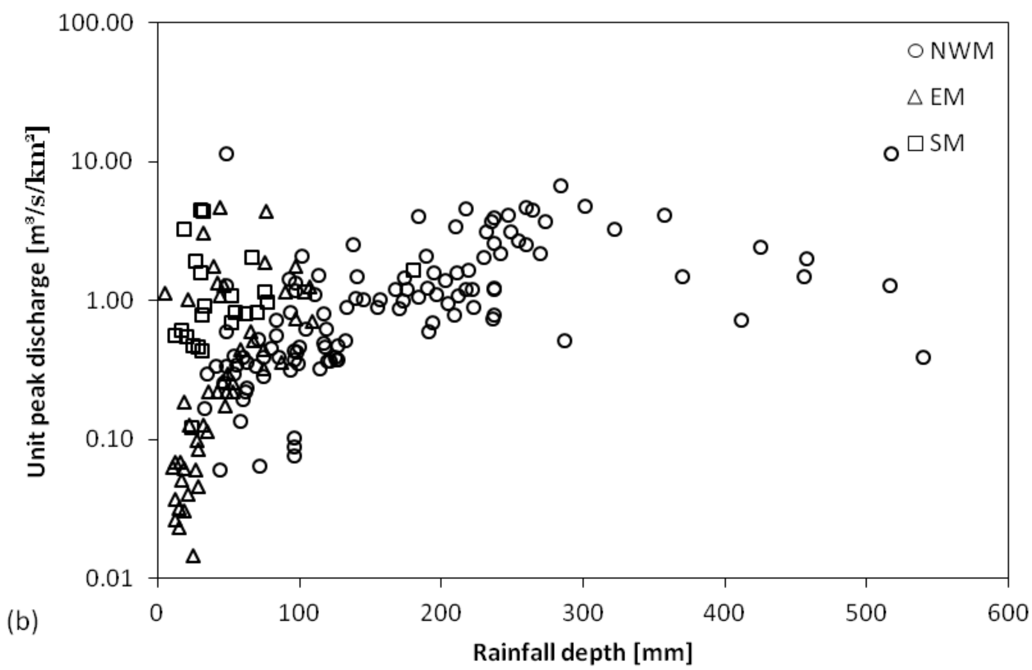
The differences in catchment responses in terms of unit peak discharges by geographical location are illustrated in Figure 1.6a. It clearly shows that the highest peak discharges are recorded in the NWM, followed by the SM. The lowest unit peak flows were recorded in the EM. The highest unit peak flows were recorded for the smallest catchments. For large catchments, values from the NWM and SM catchments are within the same range, whereas the EM records the lowest values. Nevertheless, although the NWM region is known for severe rainfall events and catastrophic floods, the highest peak flows may be partly attributed to the relatively denser gauging networks and larger number of research teams investigating post-flood conditions in that region. Hence, information on peak flows in small catchments (on the order of 10 km^2) is available. This information is rarely available for other areas of the Mediterranean.

Catchment unit peak discharges as a function of event rainfall depth (Fig. 1.6b) are highly scattered for a given amount of cumulative rainfall. Therefore, no correlation could be found between event rainfall depth and event peak flow, particularly for rainfall depths below 100 mm. However, above a 100 mm rainfall threshold, the unit peak discharge seems to increase continuously with the amount of event rainfall.

Another factor that may influence peak flow is the duration of the rainfall event. It is tempting to associate a longer event with a higher unit peak discharge. While this might be the case in humid environments, no obvious relationship exists in Mediterranean catchments. For a given event duration, the unit peak discharges greatly vary (Fig. 1.6c). However, this relationship is true for relatively short events (event durations of less than 50 hrs), whilst it seems from the analysis of Fig. 1.6(c) that for longer event durations, a particular pattern exists: the unit peak discharge appears to increase with the increasing event duration. Perhaps for really long events, catchment moisture conditions and runoff generation processes begin to resemble those of humid conditions. In fact, during the wet season, Mediterranean catchments may function similarly to catchments in humid climates (Latron et al. 2009, Gallart et al. 2011).



NWM
EM
SM
Envelope Curve for NWM
Enveloppe Curve for EM (Tarolli et al. 2012)
Unit peak discharge [m³/s/km²]
Catchment area [km²]
(a)



NWM
EM
SM
Unit peak discharge [m³/s/km²]
Rainfall depth [mm]
(b)

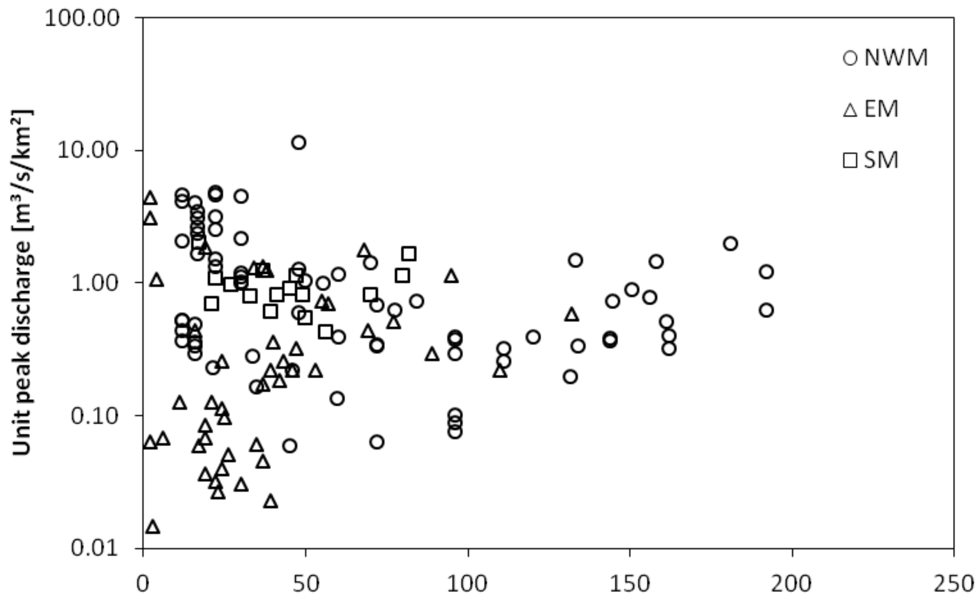
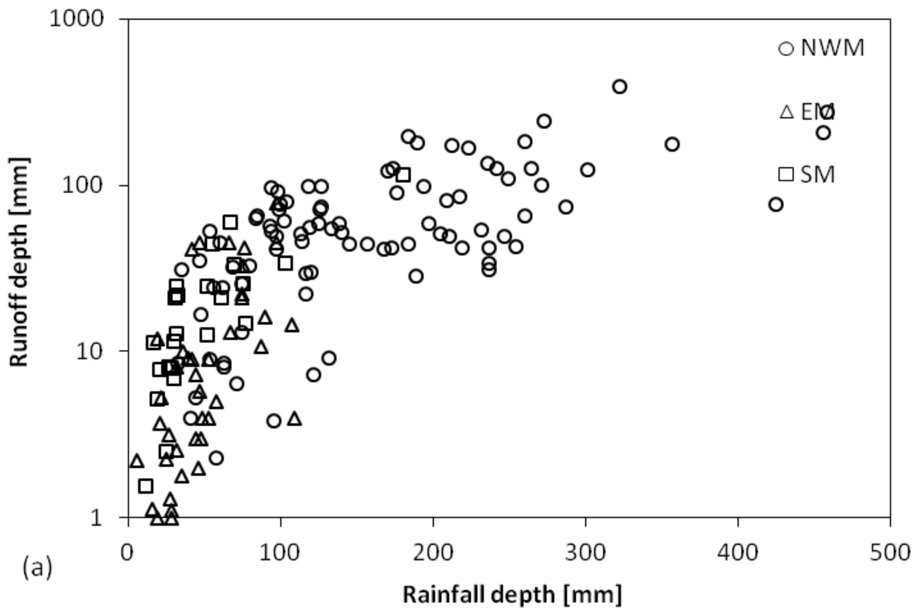


Fig. 1.6 Relationship between unit peak discharge and (a) catchment area, (b) rainfall depth and (c) event duration.

1.4.2.3 Runoff ratio

A very important concept for assessing the catchment hydrological response is the event runoff ratio, which is defined as the ratio of the event runoff volume to the event rainfall volume. Figure 1.7 presents the runoff depth (Fig. 1.7a) and the runoff ratio (Fig. 1.7b) as a function of the cumulative event rainfall. There is clear scattering in the response. Thus, for a given rainfall depth, both the runoff and runoff ratio may greatly vary.

In Mediterranean catchments, event runoff ratios vary over a large range (Fig. 1.7b). For instance, the ratio varies from 0.01 in the Rafina catchment (Greece; Massari et al. 2014) to 1.2 in the Lez catchment (France; Coustau et al. 2012). The mean value of the sample we studied was 0.37, with a standard deviation of 0.27. The median was 0.30, and the interquartile range was 0.14 - 0.51. There are geographical discrepancies in the catchment responses to rainfall events. Figure 1.7 shows that the highest runoff depth and runoff ratios appear in the NWM catchments. In fact, the median runoff ratios vary between regions, e.g., from 0.40 in the NWM (similar to the values found by Marchi et al. 2010) to 0.36 in the SM and only 0.12 for EM catchments. It is also obvious that for low rainfall depths (particularly below 50 mm), all events are from the EM and SM regions, which may exhibit very high runoff ratios despite low rainfall depths.



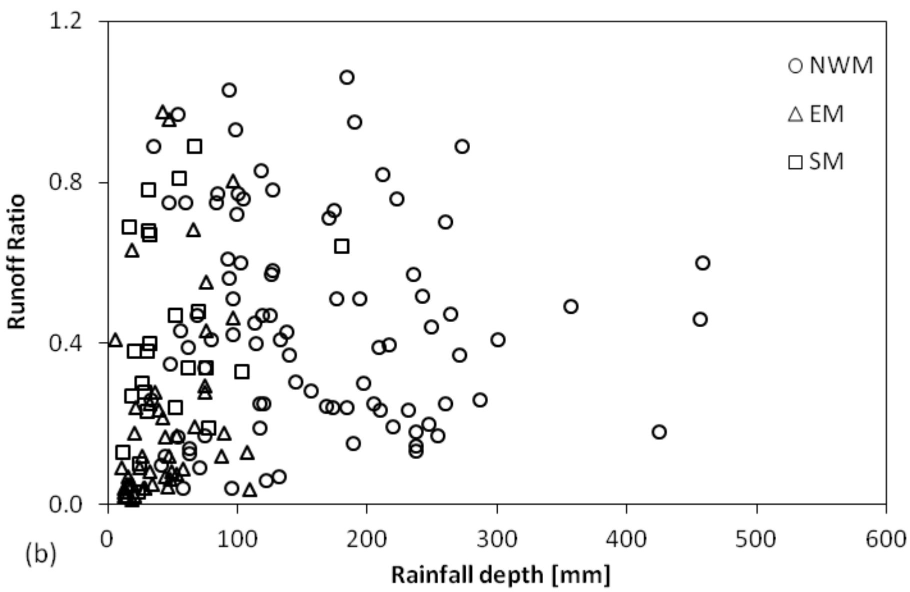


Fig. 1.7 Relationship between runoff depth and rainfall depth (a), and between runoff ratio and rainfall depth (b).

Extremely high runoff ratios recorded for some events may exceed 1. This finding can be explained by the karstic nature of the catchment, with a runoff-generating area that is much larger than the topographic basin. One example is the Lez catchment in France (Coustau et al. 2012). Other high runoff ratios were also estimated for other catchments, such as Merhavia in Israel (Rozalis et al. 2010), Reno River in Italy (Brath et al. 2004) and Mdouar in Morocco (Tramblay et al. 2012). Here, the events triggering such high runoff ratios usually occur after other large events. Thus, the initial moisture conditions influence the generation of important runoff amounts. These physical characteristics of the Mediterranean and the high seasonality of the climatic features may explain the large scattering in the catchment responses both in terms of event runoff ratios and peak discharges.

The relatively low dependency of the runoff ratio on the cumulative rainfall depth could be explained by many factors. First, under Mediterranean climatic conditions, Hortonian flows are expected to be dominant. Thus, the catchment hydrological response is rather controlled by rainfall intensity than depth. Moreover, for different events (even with the same amount of rainfall), the initial moisture conditions are different and trigger different hydrological responses. Furthermore, the temporal and spatial distributions of a rainfall event certainly play a role in shaping the catchment hydrological response. In Mediterranean catchments, the temporal and spatial distributions of rainfall events are highly variable. In addition, the runoff-generating processes along catchments are heterogeneous, and the percentage of the catchment area that actually contributes to runoff can vary by event.

1.4.3 Drought studies

In contrast to studies on the annual water balance and rainfall-runoff events, quantities comparison is difficult because the authors do not use the same variables to quantify droughts. Therefore, our analysis is more qualitative, and our conclusions could appear more subjective.

Climatic trends in the region show an overall decrease in the available water resources due a reduction in the annual rainfall and an increase in the annual temperature and reference evapotranspiration (ET_0) (Vicente-Serrano et al. 2014, Mavromatis and Stathis 2011, Chaouche et al. 2010, Kafle and Bruins 2009). However, important seasonal discrepancies exist in the evolution of different components of the water balance equation across areas of the Mediterranean. Studies show a high spatial and temporal variability of drought events across the Mediterranean, in the EM, the SM, parts of the Iberian Peninsula, the main islands and southeastern Italy.

Climatic change impact projections for the 21st century in the Mediterranean converge towards a drier climate by the end of the century (e.g., Capra et al. 2013, Marquéz et al., 2013, Vrochidou et al. 2013, Abuabdillah et al. 2010). The water management scenarios in different catchments show a large decrease in water availability, particularly during dry periods due to the large population increase in these catchments. However, important disparities can exist within the same catchment.

1.5 Objectives and methods of hydrological studies

In this section the main objectives that drove existing hydrological studies in the Mediterranean region and the most used modelling approaches for annual water balance, rainfall-runoff events and drought studies are discussed. In each case, the available studies are classified by their relative objectives or models used, and two main objectives, “simulation” and “scenario testing”, are then identified. The main objective behind this analysis is to evaluate whether the Mediterranean context requires further specific approaches.

1.5.1 Annual water balance studies

Table 1.5 gives the list of existing studies. The two main objectives include:

(1) “simulation”: characterization of hydrological processes, model performance assessment, model uncertainty reduction, development of new models, streamflow simulation with limited data and karstic zone modelling;
(2) “scenario testing”: assessment of the impacts of different scenarios of land use change (LUC) and climate change (CC) on water resources and erosion.

Apart from classical modelling objectives, such as assessing model performances, improving model predictability or developing and testing new models, continuous streamflow simulation studies in the Mediterranean regions focus on the impact of global change on hydrological responses. Mediterranean environments are water-stressed, and demands on water are increasing because of the increasing population and tourist industry. Moreover, the Mediterranean region is prone to climate change (IPCC 2014), and many studies have projected an increase in temperature and a decrease in precipitation over the Mediterranean Basin (Philandras et al. 2011, IPCC 2014, Alpert et al. 2002). Other studies address crucial features of Mediterranean environments, such as erosion (e.g., Garcia-Ruiz et al. 2013, Shakesby 2011, Lesschen et al. 2009, Raclot and Albergel 2006) and karstic influences (e.g., Touhami et al. 2013, Doglioni et al. 2012, Coustau et al. 2012).

Table 1.5 also illustrates that the same hydrological model was used for different objectives (e.g., SWAT or GR). However, some models were developed for a specific purpose: the HYdrological Land Use Change model (HYLUC) (Delgado et al. 2010) was used to evaluate the impact of land use change on catchment hydrological responses; the HYdrological Modelling for Karst Environment (HYMKE) (Rimmer and Salingar 2006) and 3D Karstic Flow Model (3dkflow) (Rozos and Koutsoyiannis 2006) were built and used for hydrological simulations in karstic catchments; and HYDROGEIOS which is a semi-distributed model for streamflow simulation in modified basins (Efstratiadis et al. 2008).

The model choice seems dependent on the data availability, the experience of the researcher (especially in terms of computing experience), and the available funding (some models are expensive). Except for some specific cases (e.g., Delgado et al. 2010 [Spain], Rozos and Koutsoyiannis (2006), Kourgialas et al. 2010 [Greece], Rimmer and salingar 2006 [Israel]), the objective of the study does not necessarily influence the model choice. These claims are more obvious when we evaluate the geographical distribution of the models in use. Indeed, complex and data-demanding models appear to be primarily in use in the Euro-Mediterranean part of the region and in Israel. Most models were applied in other climatic contexts.

1.5.2 Rainfall-runoff event-based studies

Like in the case of water balance studies, the two main objectives of rainfall-runoff event-based studies include (see detailed list in Table 1.6):

(1) “simulation”: similar objectives, with greater emphasis on runoff generation processes, wetness impacts on catchment responses and flash flood estimations, and sensitivity of model performance to data and parameters;
(2) “scenario testing”: similar objectives on LUC and CC impact assessment, as well as wildfire impact or flood risk mitigation.

Regarding event-based studies, the same model can be used for different objectives. These are classical models that are applied worldwide. There have only been a few attempts to develop models specifically for the Mediterranean environment (e.g., Manus et al. 2009, Nunes et al. 2011, Roux et al. 2011, Massari et al. 2015). Some authors slightly modified available models to account for specific features of the Mediterranean (e.g., Rozalis et al. 2010).

Modelling the hydrological response of Mediterranean catchments, particularly at the event level, using classical modelling techniques is somewhat controversial. In fact, the results from various studies characterizing hydrological responses of these catchments and runoff-generation mechanisms show that under Mediterranean conditions, runoff-generation mechanisms and catchment responses are heterogeneous. Hence, the most important rainfall events in terms of precipitation volume are not necessarily those with the highest runoff ratio or peak flow (Moussa and Chahinian 2009, Marchi et al. 2010, Tarolli et al. 2012), and different mechanisms can co-exist (Manus et al. 2009). Furthermore, different parts of the catchments can exhibit different runoff-generation processes, while some parts of the basin may not contribute at all (Latron and Gallart 2007). Catchment responses also depend on the initial wetness conditions, and they greatly fluctuate between seasons (Lana-Renault et al. 2007, Maneta et al. 2007, Huza et al. 2014). However, because of the high intensity of rainfall under Mediterranean conditions, infiltration excess is often dominant (Manus et al. 2009). The impact of high-intensity rainfall is particularly important for extreme events, where it becomes the sole factor that influences runoff generation (Brath and Montanari 2000, Lana-Renault et al. 2011).

Some of the most commonly used models (SCS CN) are threshold models, in which a portion of the precipitation is used to fill soil water content before generating runoff. Other models, e.g., based on TOPMODEL, were developed for more humid climates.

They use saturation excess mechanisms to generate runoff. The limitation of TOPMODEL for Mediterranean catchments was demonstrated by Gallart et al. (2007) in the Vallecebre catchment in Spain. TOPMODEL well simulates the hydrological response in the wet season. However, under dry conditions, the model performance decreases. Moreover, Mediterranean catchment responses at the event scale are very sensitive to the spatial and temporal (within-storm) variation in rainfall (Rozalis et al. 2010). High spatio-temporal resolution rainfall data, which are not available in many parts of the Mediterranean, particularly in North Africa and the Near East, are needed.

1.5.3 Drought studies

For the existing drought studies (see detailed list in Table 1.7), the two main objectives include:

(1) "simulation": characterization of the temporal and spatial variations of droughts and the methods for drought assessment;
(2) "scenario testing": assessment of the impact of different scenarios (climatic, anthropogenic, etc.) on drought characteristics in a catchment or region.

The methods used are also presented in Table 1.7. A description of the different indices used in these studies and their meanings are available in drought reviews (e.g., Mishra and Singh 2010, 2011).

Precipitation-based indices, such as the standardized precipitation index (SPI) and modified versions of such indices are most popular among meteorological-based indices. These indices are globally relevant and are applicable at different time scales to characterize short- and long-term droughts and their impacts on different components of the water balance. Hence, one must emphasize the importance of the choice of the index time scale. For instance, in the Mediterranean region, time steps that are too long (> 12 months) must not be used due to the high rainfall seasonality (Vicente-Serrano and López-Merano 2005). The objective of the index (impact on surface water, reservoirs, etc.) should constrain the choice of the time step.

Hydrological indices, such as the Palmer index (e.g., Vasiliades and Loukas 2009) and other hydrological indicators (e.g., Shaban 2009), indices related to soil moisture (Vidal et al. 2012) and groundwater indices (Mendicino et al. 2008) have been used. Agricultural drought indices are also prevalent in the Mediterranean literature (Diodato and Bellochi 2008).

The models used in drought studies are mainly water management models, such as the Water Evaluation and Planning system (WEAP) (Hamlat et al. 2012, Yilmaz and Hrmancioglu 2010) and inVEST model (Terrado et al. 2014, Marquéz et al. 2013), or simple water balance models, e.g., the SIERRA model (Ruffault et al. 2013).

Moreover, climatic trend analyses are also commonly used to assess the impact of temporal and spatial drought variations.

In summary, various methods are used for drought characterization in the Mediterranean. However, climate-based indices (such as the SPI) remain most popular. Moreover, the main concerns that drive drought studies appear to be global change impacts (climatic and anthropogenic pressure).

Table 1.5 The main objectives and the models used for continuous streamflow simulation studies in the Mediterranean.

Theme	Objectives	Region	Study	Model
Simulation	Assessment of model performance	NWM	Delgado et al. 2010	HYLUC
			Franchini and Pacciani 1991	STANFORD IV;TANK; APIC; SACRAMENTO; SSARR; XINANJIANG ; ARNO
		EM	Pisinaras et al. 2010	SWAT
			Hessling 1999	PHASE
		SM	Raclot and Albergel 2006	WEPP
			Bouraoui et al. 2005	SWAT
			Benkaci Ali and Dechemi 2004	GR3J, CREC, ARMAX
	Improve model performance and reduce uncertainty	NWM	Tayfur et al. 2014	GRNM
			Milella et al. 2012	DREAM
			Loiaza Uzuga and Pauwels 2008	TOPLATS
			Gallart et al. 2007	TOPMODEL
	New model development	NWM	Silvestro et al. 2013	Continuum model
			Moussa et al. 2007	ModSpa
		EM	Efstratiadis et al. 2008	HYDROGEIOS
			Rozos et al. 2004	Modified Thornwaite model coupled to a Darcian multi-cell groundwater flow module
			Hreiche 2003	MEDOR
	Limited data	EM	Ramadan et al. 2012	HRR
	Karstic catchment	NWM	Makropoulos et al. 2008	3 models: A quasi-physically based model; a black box/transfer function model and a conceptual model
		EM	Hartmann et al. 2012	Conceptual reservoirs models
			Nikolaidis et al. 2013	Modified SWAT
			Kourgialas et al. 2010	HSPF coupled to a snowmelt model and a conceptual Karstic reservoir and a karstic channel model
			Tzoraki and Nikolaidis 2007	HSPF coupled to a 2-reservoirs kartic model
			Rozos and Koutsoyiannis 2006	3dkflow
			Rimmer and Salingar 2006	HYMKE
Scenario testing	LUC impact	NWM	De Girolama and Lo Porto 2011	SWAT
			Estrany et al. 2010	Thornwaite-Mather model
	CC impact	NWM	Candela et al. 2012	HEC-HMS coupled to VisualBALAN
			Nunes et al. 2008, 2011	SWAT
			Senatore et al. 2011	In-STRHym
			Burlando and Russo 2002	PRMS
		EM	Hreiche et al. 2007	MEDOR
		SM	Bakreti et al. 2013	Hydrological indices
			Bouabid and Chafai ELalaoui 2010	IHACRES, HEC-HMS
	LUC and CC impact	NWM	Collet et al. 2013	GR4J
			D'Agostino et al. 2012	DiCaSM
			Gallart et al. 2011	SACRAMENTO ; Zhang Eq.
			Ceballos-Barbancho et al. 2008	Statistical Analysis
			Gallart and Llorens 2004	Annual Water balance (Dooge et al. 1999)
		EM	Albek et al. 2004	HSPF
	Erosion	NWM	Lesschen et al. 2009	LAPSUS
		SM	Raclot and Albergel 2006	WEPP

Table 1.6 The main objectives and the models used for event-based studies in the Mediterranean.

Theme	Objectives	Region	Study	Model
Simulation	Catchment characteristics and wetness conditions impact on catchment response	NWM	Massari et al. 2015	SCRRM coupled to H-SAF soil moisture product
			Huza et al. 2014	Field data analysis
			Molina et al. 2014	Field data analysis
			Manus et al. 2009	Tailor model in LIQUID
			Tramblay et al. 2010	SCS CN
			Brocca et al. 2008	A water balance
			Fiorentino et al. 2007	DREAM
			Brath and Montanari 2000	SCS CN
		EM	Massari et al. 2014	MISD and SCRRM
		SM	Tramblay et al. 2012	SCS CN
	Runoff generation processes and catchment hydrological response	NWM	Gallart et al. 2007, 2008, 2011	Rainfall-Runoff relationships, Water table dynamics; TOPMODEL
			Lana-Renault et al. 2007	Rainfall-Runoff relationships, Water table dynamics
	Peak flood estimation and flash floods characterization	NWM	Petroselli et al. 2013	SCS CN/Green Ampt
			Roux et al. 2011	MARINE
			Gaume and Bouvier 2004	SCS CN
			Gaume et al. 2003b, 2004	SCS CN ;
		EM	Koutroulis and Tsanis 2010	Empirical Eq.
			Rozalis et al. 2010	Modified SCS
		SM	Nasri et al. 2004	A Geomorphological model
	Impact of data and parameters input on model performance	NWM	Maneta et al. 2005	5-parameters overland flow model
			Brath et al. 2004	SCS CN
Scenario Testing	Land cover impact of floods	NWM	Cosandey et al. 2005	HRR
			Lana-Renault et al. 2011	Paired catchments
	Climate Change impact	NWM	Mediero et al. 2014	Trend analysis
			Nunes et al. 2013	MEFIDIS
	Fire impact on floods	NWM	Mayor et al. 2007	Paired catchments
		EM	Vafeidis et al. 2007	Paired catchments
	Flood risk mitigation	NWM	Ballesteros-Cánovas et al. 2013	HEC-HMS
		EM	Komuscu and Celik 2013	Hydro-meteorological analysis
			Gul et al. 2010	HEC-HMS

Table 1.7 The main objectives and methods used for the chosen drought studies in the Mediterranean.

Theme	Objectives	Region	Country	Study	Methods
Simulation	Drought Analysis	NWM	France	Vidal et al. 2012	ISBA model; SPI and SWI
			Italy	Diodato and Bellocchi 2008	Cy; HPR; MCDI
			Spain	Ruiz-Sinoga et al. 2012	DDSLR index
			Spain, Portugal	Vicento-Serrano 2006	SPI
		EM	Greece	Tsakiris et al. 2007	RDI; SPI
				Tigkas et al. 2012	RDI and SDI and Medbasin model
				Vangelis et al. 2010	Bivariate Analysis for RDI
				Nalbantis and Tsakiris 2009	SDI
			Lebanon	Shaban 2009	Hydrological Drought indices
			Israel	Aviad et al. 2009	DDSLR
		SM	Algeria	Hamlaoui-Moulai et al. 2013	Trend analysis, PCA
			Morocco	Esper et al. 2007	PDSI and Cedar Trees ring width
	Efficacy of Drought indices	NWM	Italy	Mendicino et al. 2008	GRI
			Spain	Vicento-Serrano and López-Moreno 2005	SPI
		EM	Greece	Vasiliades and Loukas 2009	PDI and UTHBAL model
			Turkey	Dogan et al. 2012	PN-Mean; RDDI; Z-score; CZI; SPI; EDI
				Turkes and Tatli 2009	SPI and modified SPI
Scenarios testing	Water resources management	NWM	Spain	Terrado et al. 2014	InVEST model
				Bangash et al. 2012	MIKE BASIN model
				Gomez and Blanco 2012	Risk Assessment model
		EM	Turkey	Yilmaz and Harmancioglu 2010	WEAP model
		SM	Algeria	Hamlat et al. 2012	WEAP model
	Climatic trends	NWM	France	Chaouche et al. 2010	Climatic trends
			Spain	Vicente-Serrano et al. 2014	12 methods for ET0 estimation
		EM	Greece	Mavromatis and Stathis 2011	Trends in Hydrological parameters
			Israel	Kafle and Bruins 2009	Climatic trends
	CC Impact	NWM	France	Ruffault et al. 2013	SIERRA model
			Italy	Capra et al. 2013	SPI
			Spain	López-Bustins et al. 2013	SWAT model; SPI and SPEI
				Marquèz et al. 2013	InVEST model
				Lorenzo-Lacruz et al. 2010	SPI and SPEI
		EM	Greece	Vrochidou et al. 2013	IHMS-HBV model
		SM	Tunisia	Abouabdillah et al. 2010	SWAT model

1.6 Discussion and perspectives

Sections 4 and 5 presented an overview of the recent studies in the Mediterranean in terms of hydrological response characteristics and modelling approaches at different time scales and for various objectives: annual runoff, floods and drought periods. This section discusses the main results and provides complementary responses to the three questions posed in the introduction.

1.6.1 Can we identify regional patterns in the Mediterranean?

The comparison of catchments in different Mediterranean areas shows that some regional tendencies exist. In terms of the annual water balance, catchments from the NWM have a higher humidity, a relatively low dryness index and higher annual runoff yields. This finding could be due to the influence of the humidity from the Atlantic Ocean, which modifies the seasonal pattern of rainfall, i.e., less precipitation in winter and a rainfall peak in autumn and/or spring (McNeill 1992). SM catchments are the driest, with the highest aridity index and lowest annual runoff yields. The EM proves to be more heterogeneous, with a relatively wide range of values in terms of both the aridity index and runoff yields (e.g., Rimmer and Salingar 2006, Tzoraki and Nikolaidis 2007, Kourgialas et al. 2010).

Regional tendencies also exist in the seasonal distribution and severity of extreme rainfall events. In fact, rainfall events in the NWM mostly occur in autumn, with a peak in September. Rainfall in the EM region mostly occurs in winter, with a peak in January and February. In the SM, the sample is too small to generalize. Moreover, in terms of the event rainfall depth, peak discharges and runoff ratios, the highest values occur in the NWM. These findings were reported by other authors who studied floods in the Mediterranean (Marchi et al. 2010, Tarolli et al. 2012, and Llasat et al. 2013). In fact, the NWM region exhibits extreme rainfall regimes, with rainfall commonly exceeding 200 mm in 24 hrs. Cortesi et al. (2012) studied the distribution of the daily precipitation concentration index across Europe. The highest values were computed for the coastal arc that extends from southeastern Spain to Sicily (Italy). Moreover, Reiser and Kutiel (2011) compared the rainfall regimes in Valencia (Spain) and Larnaca (Cyprus). The authors found that in Valencia, the rainfall regimes are more extreme than in Larnaca. Hence, in the NWM, daily rainfall values that exceed 600 mm have been recorded.

However, there is also overlap between morphometric and hydrological characteristics of particular catchments located in different regions, particularly between the NWM and EM. These similarities between catchments can highlight twin basins (e.g., basins with similar physiographic features and/or hydrological responses), for which hydrological responses can be transferred from gauged to ungauged basins.

1.6.2 What is required to model Mediterranean catchments?

A difference can be made between continuous streamflow simulations and event-based simulations. The former is usually applied to quantify water resources in the catchment of interest, assess land cover and/or climate change impacts, or test new modelling approaches. In event-based studies, the objectives may vary from flood risk mitigation to understanding flood-triggering characteristics. For continuous streamflow simulations, daily climatic and hydrological data are mostly used (sometimes monthly data). The applied models are often lumped as conceptual models with relatively good results. Nevertheless, modelling the catchment response at the event scale is a dilemma. The high rainfall intensity and spatial variability within a storm, along with a catchment's initial wetness conditions, complicate this task. Classical hydrological models are not well suited to the Mediterranean area. In fact, many of these models assume precipitation abstraction (such as the widely used SCS CN) or saturated excess mechanisms (such as the TOPMODEL family), which is not necessarily the case in the Mediterranean. Moreover, any suitable modelling approach for these catchments is highly demanding in terms of data. Hence, to account for the variability in the rainfall intensity in a short time, the model should be applied at the hourly (or shorter) scale for flood studies. Furthermore, this model should be able to account for any rainfall spatial variability and catchment wetness conditions. Therefore, information on soil properties and soil moisture conditions is needed.

The specificities of the Mediterranean catchment responses explain the large response heterogeneity in the region and outline the fact that modelling the hydrological behaviour of Mediterranean catchments is difficult (Oudin et al., 2008). In regional studies that involve catchments from Mediterranean and non-Mediterranean (humid) regions, such as in Goswami et al. (2007) and Oudin et al. (2008, 2010), the performance of the model-dependent regional approaches is worse in a Mediterranean climate. High-resolution spatial and temporal rainfall and soil properties and moisture data may be necessary to accurately simulate the hydrological behaviour of Mediterranean catchments. However, such data are rarely available. Consequently, detailed flood studies are usually performed in small, research catchments, with results often difficult to generalize in space and time (Gallart et al. 2007, Latron and Gallart 2007, Lana-Renault et al. 2007; Manus et al. 2009, Rozalis et al. 2010, Molina et al. 2014). This finding also explains why studies in large catchments are usually limited to flood risk mitigation or peak flow estimation, sometimes using lumped methods only.

To overcome the difficulties in modelling hydrological responses of Mediterranean catchments, particularly in terms of accounting for the high spatial variability in model parameters, radar rainfall, spatial soil moisture information and remote sensing data are considered (Massari et al. 2015; Tramblay et al. 2010, 2012, Rozalis et al. 2010). New approaches that couple observations (that are usually obtained on small catchments) and modelling are used to improve our understanding of flood-triggering processes. For example, recent work was undertaken within the HyMeX project on two French catchments (Braud et al. 2014). This is a multi-scale approach that assesses the runoff-generation processes from observations at a small hillslope scale; the rainfall variability and soil moisture, along with the network organization, were studied for medium-sized catchments (1 - 100 km²) and for river rooting and flooding at a large scale (100 - 1000 km²). Data analyses were coupled to modelling techniques, and the results are promising. However, these approaches are very demanding in terms of instrumentation, data, and computational efforts; thus, they may be very expensive. Thus, the majority of flood simulation studies in the Mediterranean are concentrated in the developed countries of the Euro-Mediterranean region and Israel.

1.6.3 What are the main challenges for future research in the Mediterranean?

In recent decades, we observed an important change in the scope of hydrological studies in the Mediterranean zone and consequently in the expected performance of hydrological modelling. Currently, there remains an important need for research on classical rainfall/runoff hydrological modelling for engineering applications in water resources management, water supply infrastructure design, flood and drought prediction, pollution projections and erosion processes. However, hydrological modelling has become an indispensable tool for many interdisciplinary projects in the Mediterranean. For example, anthropogenic and climatic change impacts on environmental variables, such as water, soil, biology, ecology and the socio-economy, can be assessed. Modelling is data intensive, and improving model performances involves the acquisition of new data at various spatiotemporal scales. Future research challenges in Mediterranean hydrology include:

- *Strengthening the hydrological knowledge in EM and SM*: The majority of studies focuses on the NWM. There is an urge to conduct more hydrological studies in the EM and SM, from the plot to the large catchment scales and from short time scales (a few minutes for flash flood genesis on hillslopes) to decades (impact of land use and climate change);
- *Improving measurements and data availability*: There is a need to improve measurements during extreme flash flood events, drought periods (absence of flow) and long-term land use and climate change. These data can be obtained through the installation of long-term environmental stations, dense precipitation and streamflow gauging networks. Radar data and remote sensing approaches are promising.
- *Conducting large-scale studies under Mediterranean conditions*: There is a need to lead studies at the scale of the entire Mediterranean region (e.g. Milano et al. 2012, Chenoweth et al. 2011, Garcia-Ruiz et al. 2011, Iglesias et al. 2007 among others). This would require setting up large datasets through scanning and digitizing old records, historical data, and previous studies. Thus, the current established database initiated in this work could be extended to all Mediterranean basins (e.g., the Mediterranean zones in Australia, California, Chile and South Africa) for a Mediterranean comparative hydrology. This comparison would provide a common basis for understanding the hydrological behaviour of catchments and improving regionalization approaches; In terms of hydrological modelling, models already applied at continental scales (e.g. EFAS, E-hype)

would be good candidates to conduct modelling studies at the Mediterranean scale;

- *Studying the Mediterranean under change*: Transferring the results between “similar” Mediterranean catchments can also be useful for predicting the effects of climate change or land use change on the hydrological response, following the objectives of the decadal “Pantha Rei” (2013-2022) of the International Association of Hydrological Sciences (IAHS) (Hrachowitz et al. 2013).
- *Improving hydrological modelling on small catchments:* Theoretical developments are needed, and classical models must be adapted by taking into account the representation of the main hydrological processes. In large catchments (> 500 km²), spatial rainfall and hydrographs are smoothed at the daily scale. Consequently, conventional hydrological models perform well and therefore remain well suited for understanding hydrological processes, testing hypotheses or simulating missing discharge data series. However, when moving to small catchments (< 100 km²), many hydrological processes remain poorly represented or neglected in classical models, e.g., threshold functioning for runoff genesis and the transfer on hillslopes and through the channel network (e.g., case of ephemeral and intermittent flows), the importance of flow in non-saturated zone, and the difficulties in modelling surface-subsurface interactions in dryland regions.
- *Accounting for variabilities:* New “tailor-made” models need to be developed to consider specific spatiotemporal heterogeneities of catchment responses in areas with specific hydrological functions, such as in karstic, urban s and peri-urban zones.

We believe that reviews at large regional scales, such as the one presented here, are essential for advancing our understanding of hydrological behaviour of highly complex areas, such as the Mediterranean region, in terms of comparative hydrology. Thereof, this review is an attempt to strengthen the research initiatives at this scale.

PART II.

LEBANESE CATCHMENTS CHARACTERISTICS AND DATA ANALYSIS

One of the objectives of this work is to classify the Lebanese catchments according to their physical and hydrological characteristics. More details on the data collection methodology, the available data and the meta-data of the used meteorological and hydrometric stations. In this part we have chosen to present 3 categories of data separately. Details about the used data are available in Annex E. Moreover, details about the formuals used to calculate the variables used in this part are available in Annex G.

Chapter 2 presents the study area (the Lebanese catchments) and the geographical data; these are data available from DEM and thematic maps (geology, soils, land use). From these data we will define physical descriptors that describe the physical characteristics of the catchments. The methodology used to do so is presented alongside the results in term of the distribution of descriptors by catchments. Details of physical characteristics for each catchment are presented in Annex F.

Chapter 3 presents the meteorological dataset used in our study. The chapter presents the dataset and a brief analysis of the different climatic characteristics of the study area. Finally the methodology applied in order to spatially interpolate precipitation across Lebanon and the results of the used approach are presented. More details about the river discharge data are available in Annex E.

Chapter 4 presents the hydrological dataset (discharge data) used in our study. In this chapter we define runoff signatures that are used to describe the hydrological function of the studied catchments. The hydrological characteristics of the studied catchments are then discussed. More details on the meteorological data are available in Annex E.

Chapter 5 analyzes the hydrological response of Lebanese catchments at the annual water balance and the event scale and compares their response to other Mediterranean catchments. The chapter begins by analyzing the annual water balance characteristics and comparing them to other Mediterranean catchments. Then we detail the catchment response characteristics at the event scale in term of maximum recorded flow and event runoff and runoff ratio taking into account the storm rainfall duration and amount.

2 GEOGRAPHICAL CHARECTERISTICS AND DATA ANALYSIS

2.1 Introduction

Lebanon (Fig. 2.1a) lies on the eastern shore of the Mediterranean Sea. The country has an area of about 10452 km². However, and despite its small surface it presents a complex physiography with many well-defined geomorphological units divided by many authors (Du Vaumas 1954, Abu Al Anin 1973, El-Fadel et al. 2000) into four major ones (Fig. 2.1.b):

- The narrow coastal plain: less than 5 km in width and less than 100 m altitude. It constitutes only 2 % of the Lebanese territory.

- The Mont Lebanon Mountain range that runs over the entire length of the area with a SSW-NNE trend with elevation ranging from 100 m to 3083 m (Qornet Es-Saouda). It occupies 59.6 % of the country area.

- The Bekaa valley is a graben-syncline filled with Quaternary and Neogene deposits. It represents 14 % of the area of Lebanon

- The Eastern mountain range occupies the eastern part of the country and runs parallel to Mount Lebanon and holds the highest peak at Mount Hermon (2814 m). It covers an area of 24.4 %.

Hence, Lebanon could be dissected into two main parts along the Mount Lebanon Range. The occidental slopes of Mount Lebanon, and the inland region: the Bekaa valley and Eastern chain (Fig. 2.1).

The objective of this chapter is to describe the study area in term of morphometry (landforms, topography), geology, soils and land use and to extract from these information descriptors that represent the catchments physical characteristics.

The chapter begins by presenting the study area with the available data maps, than we define the descriptors to be extracted and the methodology used to achieve so. Finally we present the results in term of the distribution of different descriptors in the studied catchments.

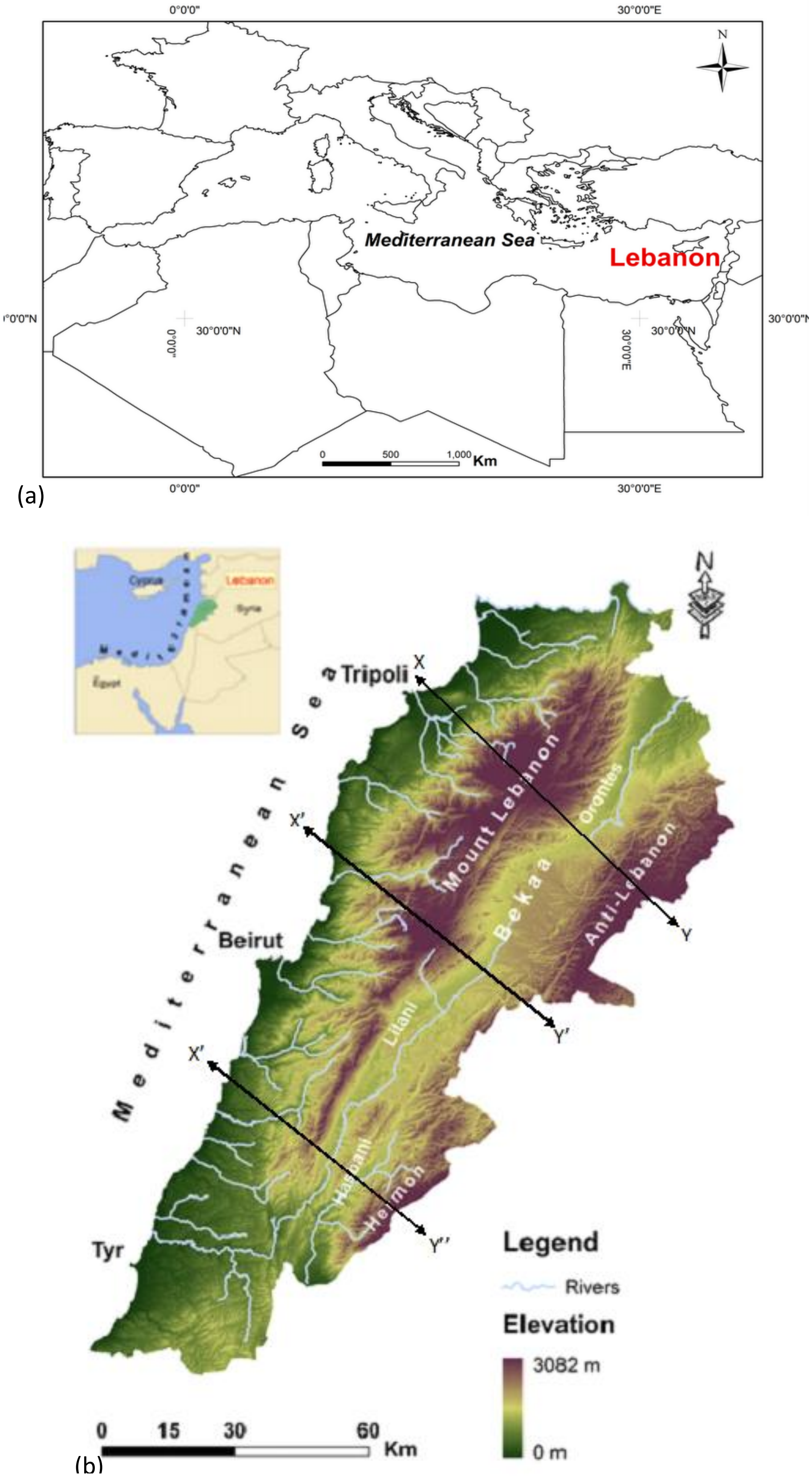


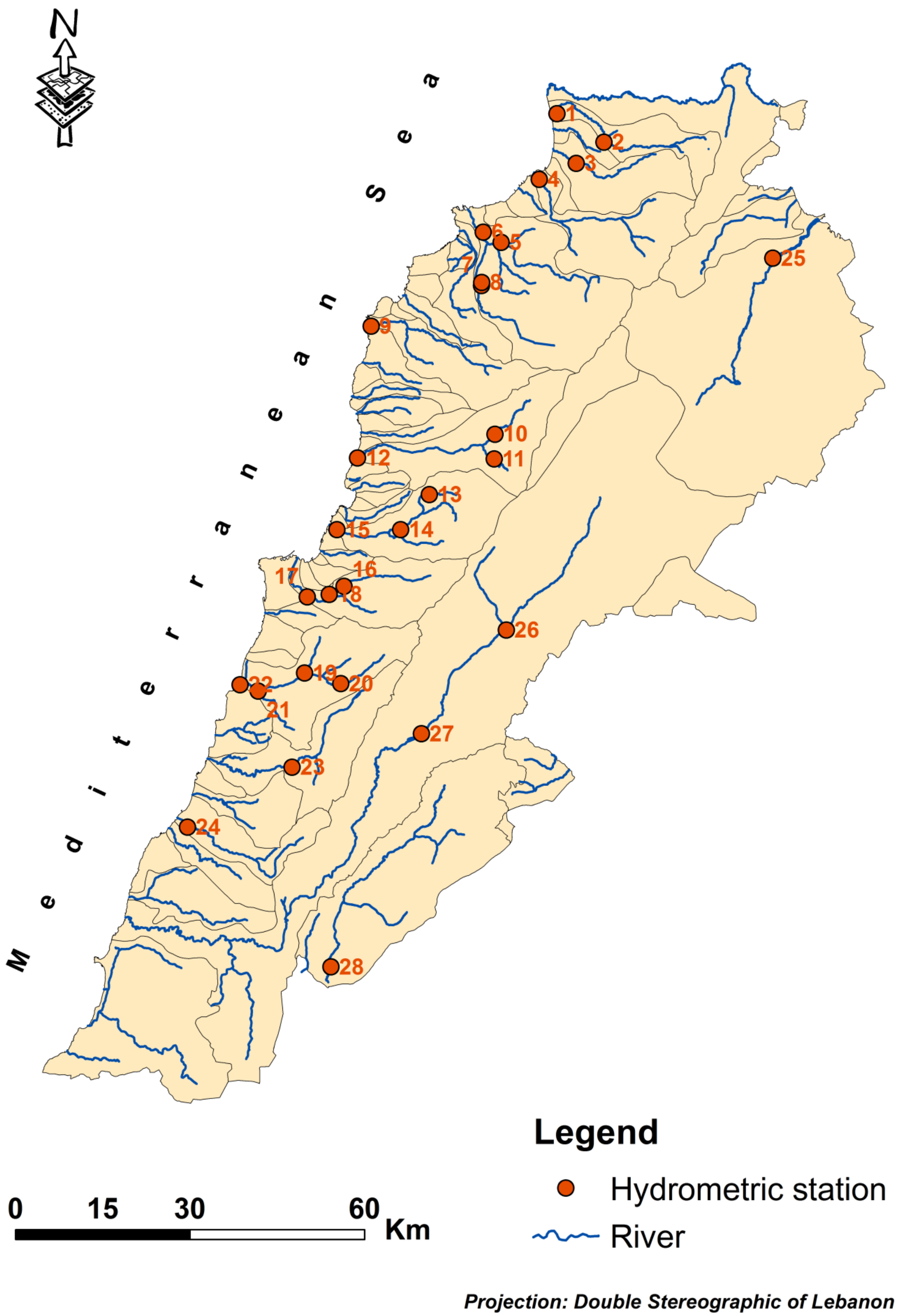
Fig. 2.1 (a) Geographical location of Lebanon and (b) its topography (source: CNRS 2010; resolution: 10 m) and main rivers.

2.2 Study area and data

From a hydrographic point of view, Lebanon could be dissected into two main parts. The occidental slopes of Mount Lebanon delineating a big number (more than 40) of small to medium sized basins (< 500 km^2), with only 14 basins drained by a permanent water course or river, all these rivers are short (< 60 km) and discharges into the Mediterranean sea. And the inland region with 3 major basins: the Orontes River which enters the Syrian territories; the Litani River which is the longest (170 km) and draining the largest basin in Lebanon (2200 km^2); and the Hasbani-wazani which forms one of the three main tributaries of the upper Jordan River. However, except for the 3 inland rivers, there is disagreement between authors on the number of permanent rivers on the western slopes of Mount Lebanon, this number could go from 10 to 14 (e.g., 10: Edgell 1997; 14: Plan Bleu 2001). Twenty eight gauging stations located on 14 rivers were discharge records are available are used to delineate 28 catchments (Fig. 2.2) that will be studied here. The location of these catchments, their names (rivers at gauging station) and main characteristics are presented in Fig. 2.2 and Table 2.1 respectively.

Figure 2.2 represents longitudinal profiles along 3 cross-sections (see Fig. 2.1). Here one can see the important altitudinal variability along one cross section and between them. This extreme variability will be reflected in a high spatial variability of rainfall inputs and evapotranspiration along different parts of the country, and will surely impact the hydrological response of the Lebanese catchments. Therefore, it is mandatory to define indices that characterize the morphometry of the studied catchments.

The underlining geology of the country is made mainly of carbonate rocks. The outcrops stratigraphic sequence exposes rocks from the lower Jurassic to the quaternary. The geology of the country is well documented in Dubertret (1955), El-Qareh (1967), Tuglaman (1975), Beydoun (1972, 1977, 1988), Walley (1998), and Abdallah et al. (2005). Almost all rock formations in Lebanon are carbonate in nature: limestone, dolomite limestone and dolomite, mostly from the Jurassic and the Cretaceous, Large areas of Eocene limestone also crops out in southern Lebanon. Middle Miocene strata occur occasionally in patches along the coast. Pliocene basalt fills the old valley of the upper Jordan River and a part of Akkar in the northernmost part of the country, Alluvium deposits from the quaternary fills the Bekaa valley, and part of the narrow coastal plain. The dominant formation in Lebanon is the Cenomanian (C4) (35 % of the total area of the country). It is formed by a chert-bearing massive thinly bedded, highly fractured and jointed, well karstified limestone and dolimitic limestone. Another important formation is the Middle to upper Jurassic (J4-7), that covers about 13 % of the country, and characterized by massive, thick bedded. Highly fissured, jointed and well karstified dolomite, limestone, and dolimitic limestone (Fig. 2.4).



Fig, 2.2 The location of the studied Lebanese catchments (source: Litani River Authority). Information about these catchments is presented in Table 2.1.

Table 2.1 Code, catchment name, gauging station name, area and elevation range of the studied Lebanese catchments (see location in Fig. 2.2).

Code	Catchment	Gauging Station	Area (km²)	Elevation range (m)
1	Ostouene	Sea mouth (sm)	151	10 - 1923
2	Ostouene	Halba	101	89 - 1923
3	Arka	Hakour	102	77 - 1951
4	Bared	Sea mouth	281	29 - 2878
5	Abu Ali	Racheine	202	80 - 3081
6	Abu Ali	Abu samra	466	46 - 3081
7	Abu Ali	Kousba	142	240 - 3081
8	Abu Ali	Daraya	144	174 - 3081
9	Jouz	Sea mouth	189	9 - 1360
10	Ibrahim	Roueiss	100	1073 - 2660
11	Ibrahim	Afqa	29	1113 - 2130
12	Ibrahim	Sea mouth	327	3 - 2660
13	Kelb	Hrajel	75	1178 - 2620
14	Kelb	Daraya	143	557 - 2620
15	Kelb	Sea mouth	257	12 - 2620
16	Beirut	Jaamani	127	270 - 2062
17	Beirut	Daychounyeh	209	73 - 2086
18	Beirut	Jisr El Basha	217	22 - 2086
19	Damour	Jisr Qadi	185	254 - 1941
20	Damour	Wadi Sett	40	536 - 1771
21	Damour	Connection	77	19 - 1941
22	Damour	Sea mouth	293	9 - 1941
23	Awali	Marj Bisri	78	398 - 1949
24	Zahrani	Sea mouth	152	3 - 1670
25	Orontes	Ain Zarqa	1241	590 - 3081
26	Berdawni	Damascus Road (D.R.)	77	880 – 2501
27	Litani	Joub Jannine	1433	859 - 2551
28	Hasbani	Wazzani	566	281 - 2810

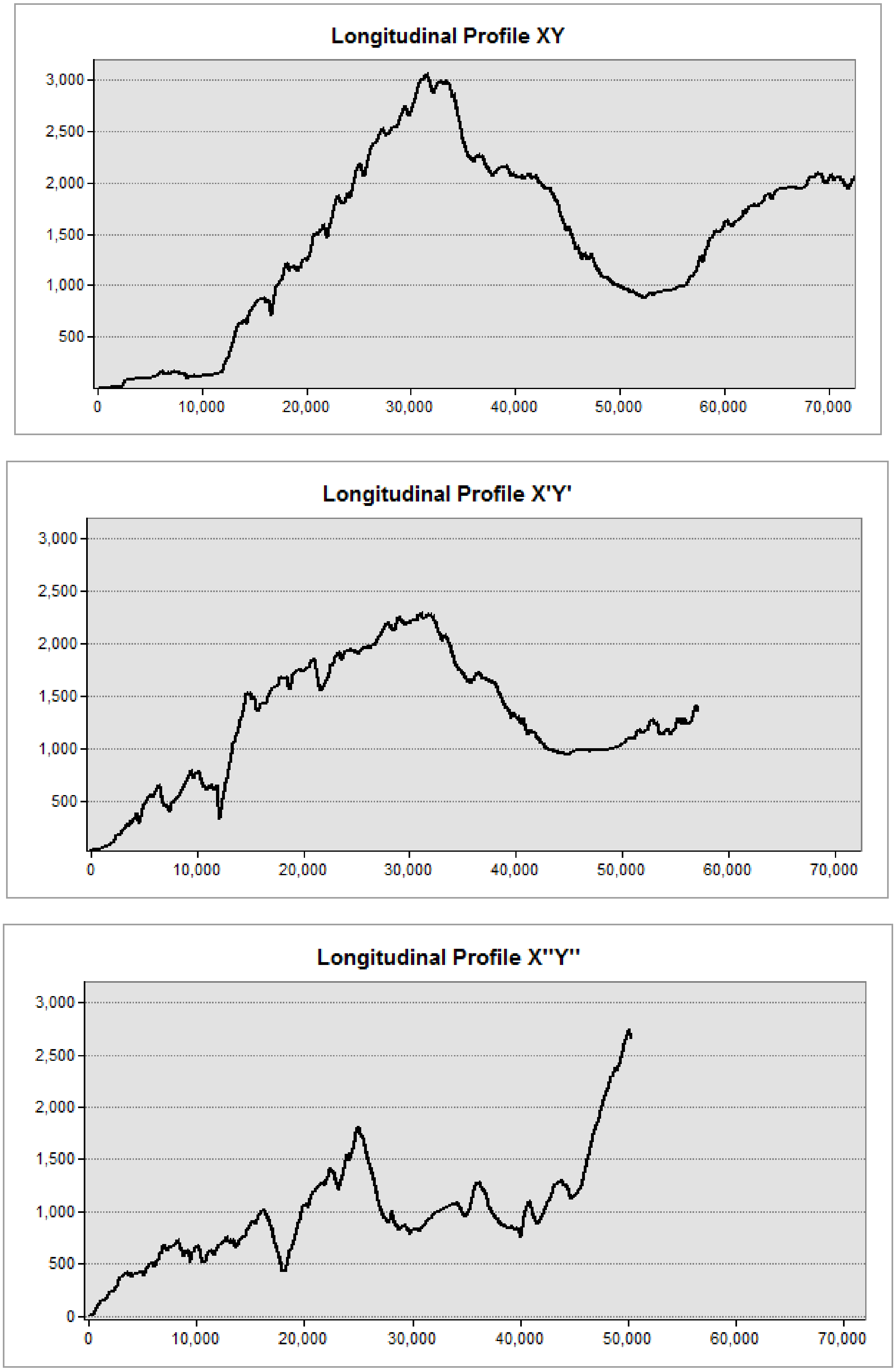


Fig. 2.3 Longitudinal profiles at 3 cross sections in Fig. 2.1. The x axis shows the distance in km while the y axis shows the elevation in m.

Since the majority of geological outcrops in Lebanon are made of exposed, stratified and fractured carbonate rocks, under conditions of relatively high precipitation, surface karst features of all kind have developed (Edgell 1997). According to Hakim (1985), 65 % of the Lebanese terrain is Karstified at different scales resulting in different local landforms that dominate the carbonate rocks. According to Bou Kheir et al (2003), four major karst morphologies can be recognized: sinkholes and depressions (3 %), lapies (10 %), areas with developed karst (34 %), such as karren and other surface dissolution features, and areas of non apparent karst (18 %), which are covered by thick soil accumulation. Figure 2.5 represents the distribution of apparent karst, non apparent karst and non-karstic areas across the country.

Karstic systems in Lebanon are deep and well developed. This is clear from cave systems such as Jeita which exists at almost sea level, indicating the surface karstification has cut deep through the thick Jurassic carbonate sequence. Some large springs even exist below sea level such as offshore from Ras Chekka (Edgell 1997). The high areal extent of the well fractured and highly karstified carbonate rocks, favorites infiltration. In fact, in a study for determining recharge potential zone in Occidental Lebanon (an area of about 5000 km^2, about 50 % of the total surface of the country), Shaban et al. (2006) classified 56% of the total studied are as having high to very high infiltration capacity, while only 28 % of this area have low infiltration capacity. Therefore, according to FAO (1967), in areas with high to very high infiltration capacity, about 30 to 50 % of total rainfall is estimated to infiltrates. For more details on the hydrogeology of Lebanon see Annex 3.

Based on the 1:200000 soil map of Lebanon, one can identify different soil type, the predominant are: Red soils, Brown soils, Yellowish mountainous soils, Black soils, Grayey soils, Chestnuts soils, Sandy soils, Alluvial soil, Sub-desertic yellowish soils, Rendzine and Mixed soils (Fig. 2.6).

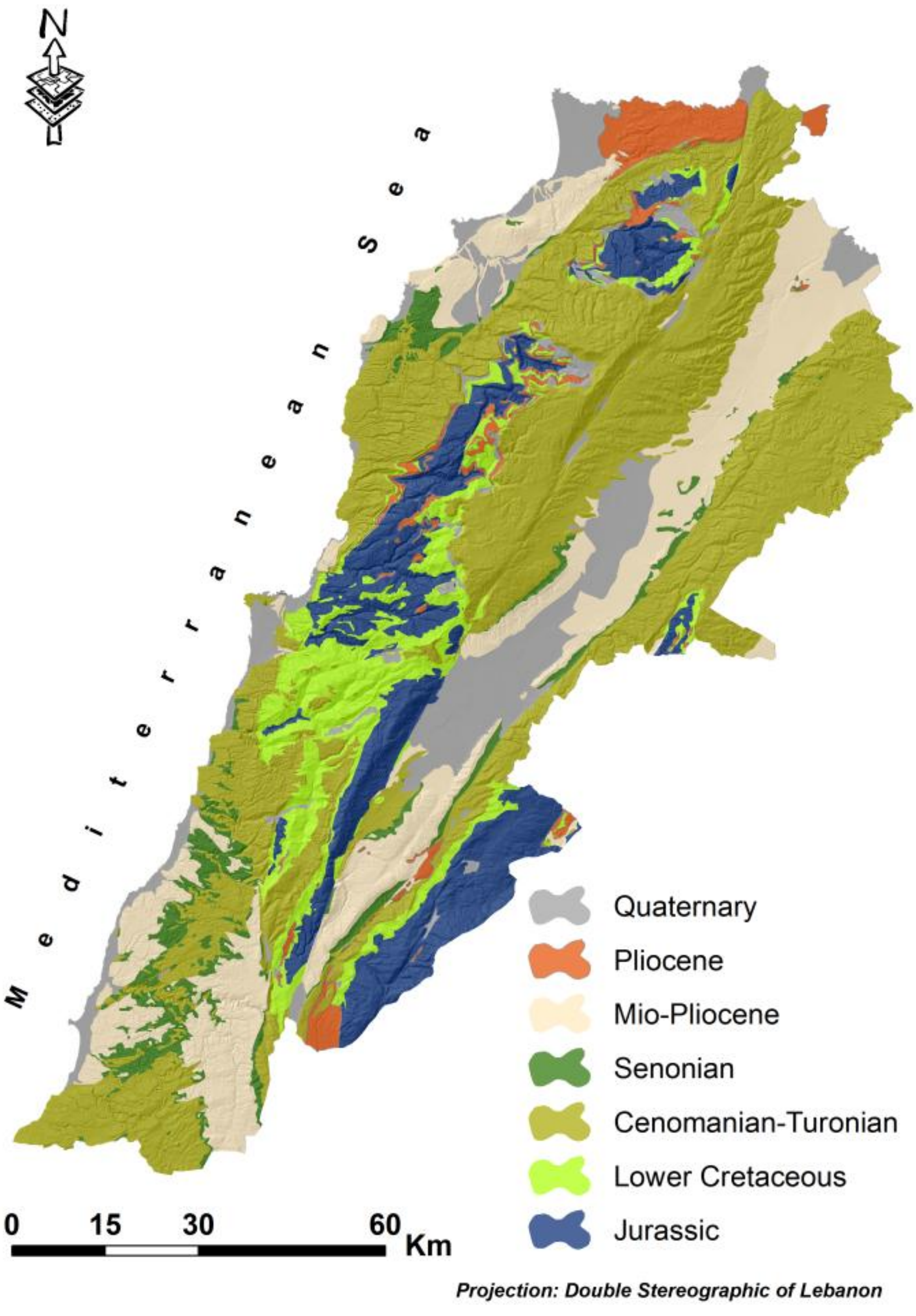


Fig. 2.4 Distribution of geological formations (source: Dubertret 1955; scale 1:200000).

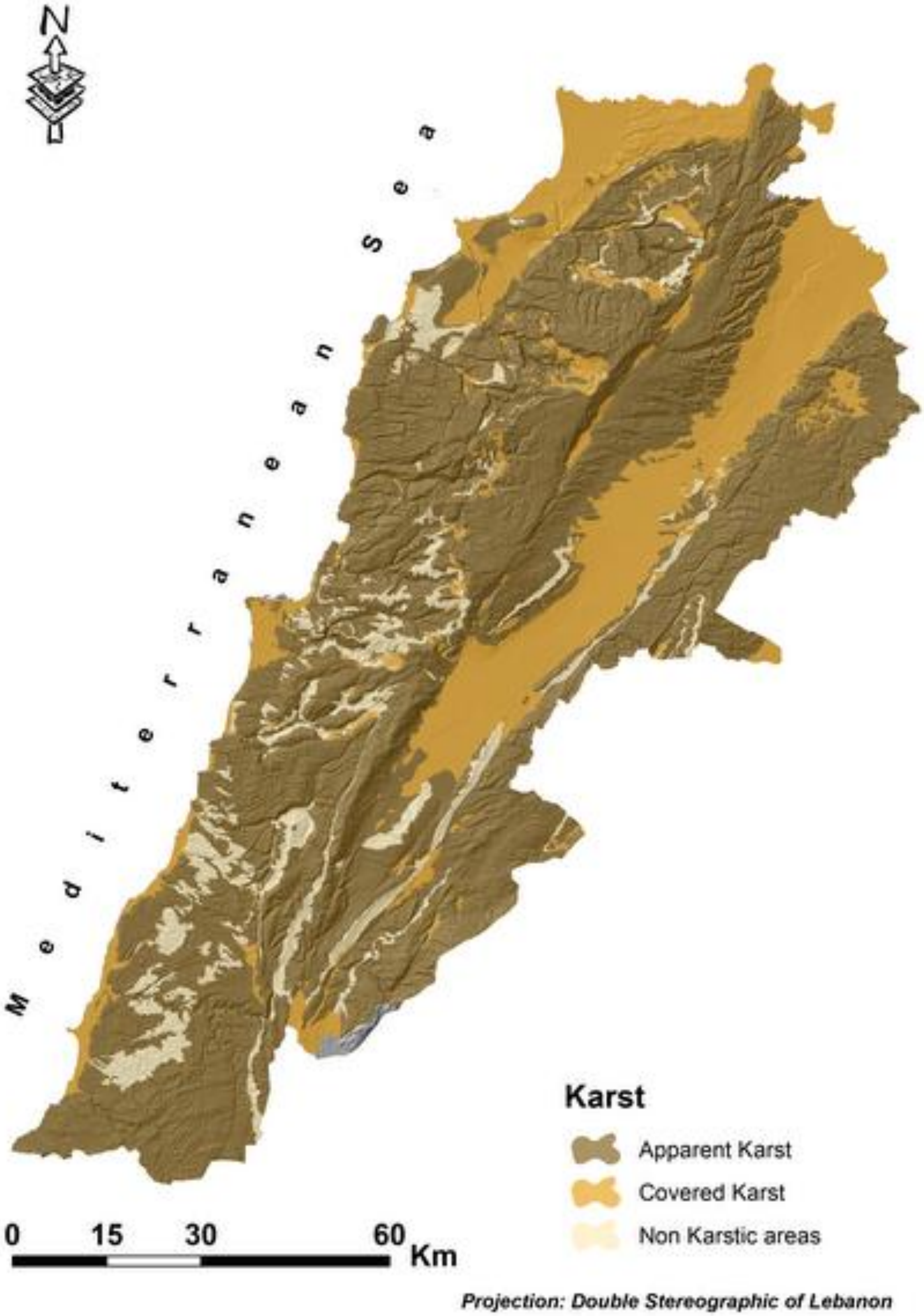


Fig. 2.5 Distribution of karstic areas (source: Abdallah and Bou Kheir 2006; scale: 1:50000).

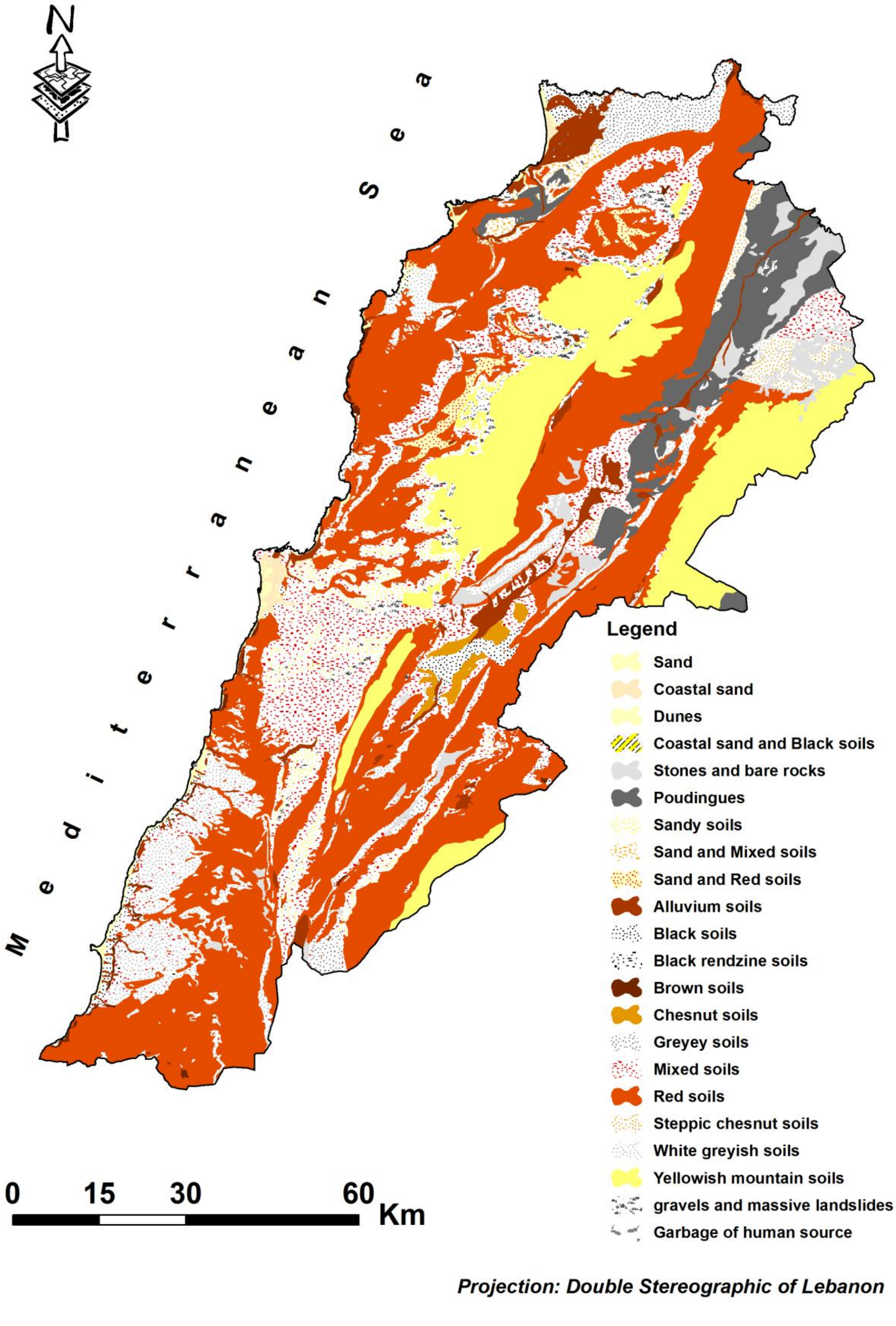


Fig. 2.6 Distribution of soils types (source: Gèze 1956; scale: 1:200000)

2.2.1 Land cover/use

Even though detailed land cover/use maps for Lebanon exists for different date (1965, 1986, 1998), however the classification scheme used in each map is different making it difficult to compare land cover/use classes and on different scales (1/200000), 1/50000), and 1/ 20000). Figure 2.7 represents the major land use classes across the country in 2010.

Lebanon is a highly urbanized country with 88 % of the population living in urban areas (World Bank, 2010). In the last few decades, urban expansion in the country is tremendous. Figure 2.8 shows the urban expansion between 1967 and 2010. One can notice the important increase in urban expansion. However, this expansion is mainly concentrated in the narrow coastal plain and the southern part of the country. In fact, in Lebanon, 45 % of the Lebanese population lives in agglomeration of 1 million people or more –the capital city of Beirut- (World Bank 2010). It is also estimated that the urban area of Lebanon will grow by 10 square Kilometers per year over the next 30 years (CDR-NLUMP 2004).

According to FAO Forest Resources Assessment (2005), forests cover 13.2 % of the Lebanese territory. Other wooded land adds an additional 11.3 % of the territory, yielding a total of 24.5 %. Jomaa et al. (2008) studied the evolution of the forest cover over a study area in northern Lebanon in the period between 1965 and 2003. According to the authors, forests cover decrease from 27 % of the study area in the 1965 to 20 % in 2003. However, the rate of deforestation has decreased during this period. Forest loss is mainly attributed to urban expansion. Moreover, another major risk for forest in Lebanon is forest fire where forest fires affect annually an area of 1500 to 2000 ha (El-Hajj and Mitri 2009).

Even though there are no accurate estimation for agricultural land in Lebanon, the increase in water demand for irrigation purposes in the last few years (870 Mm^3 for the year 2000 (El-Fadel et al. 2000) and 900 Mm^3 for 2010 (UNDP 2011), indicated that agricultural areas in Lebanon are expanding which means an increasing pressure on water resources.

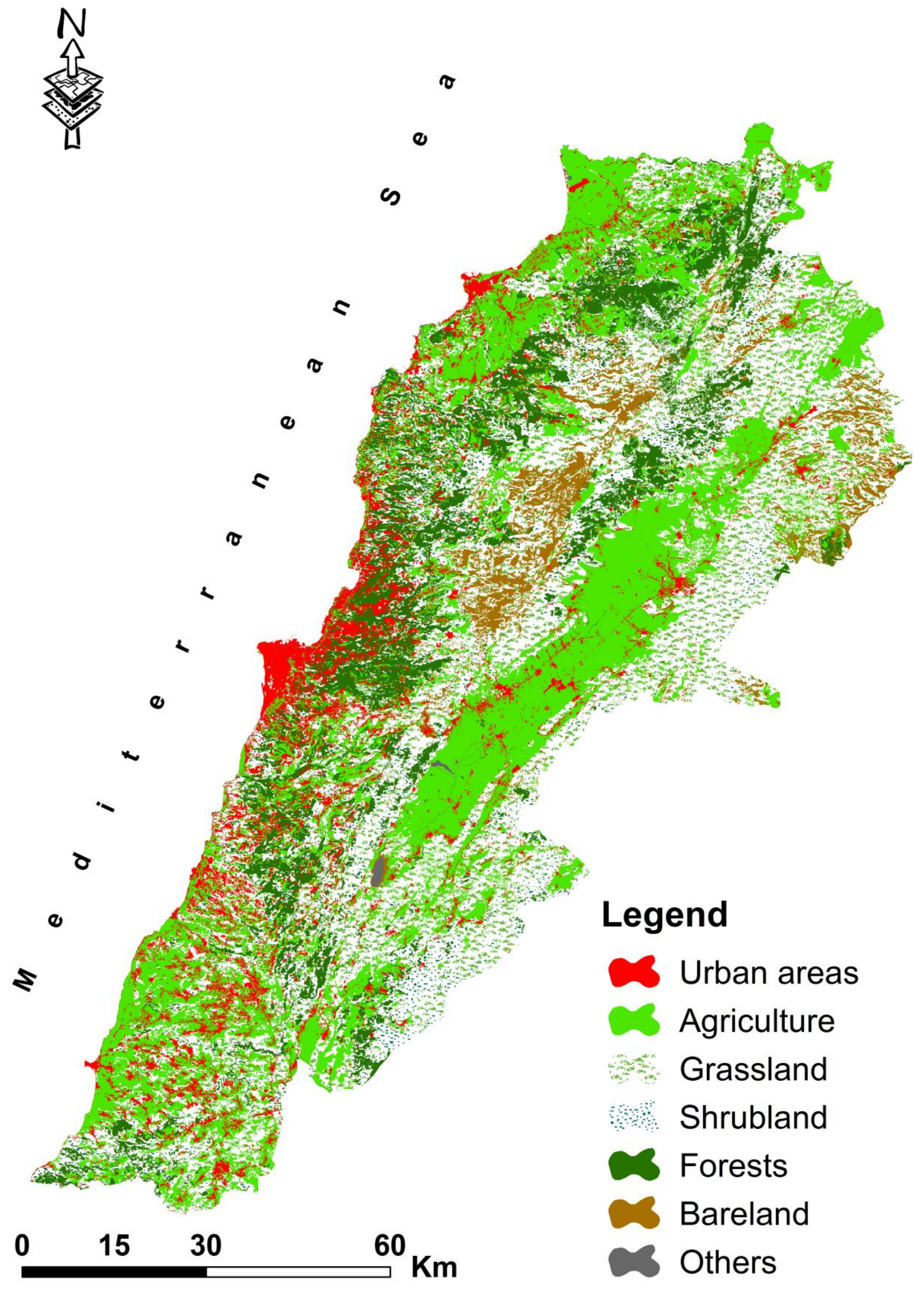


Fig. 2.7 Distribution of land use classes (source: CNRS 2010; scale: 1:10000).

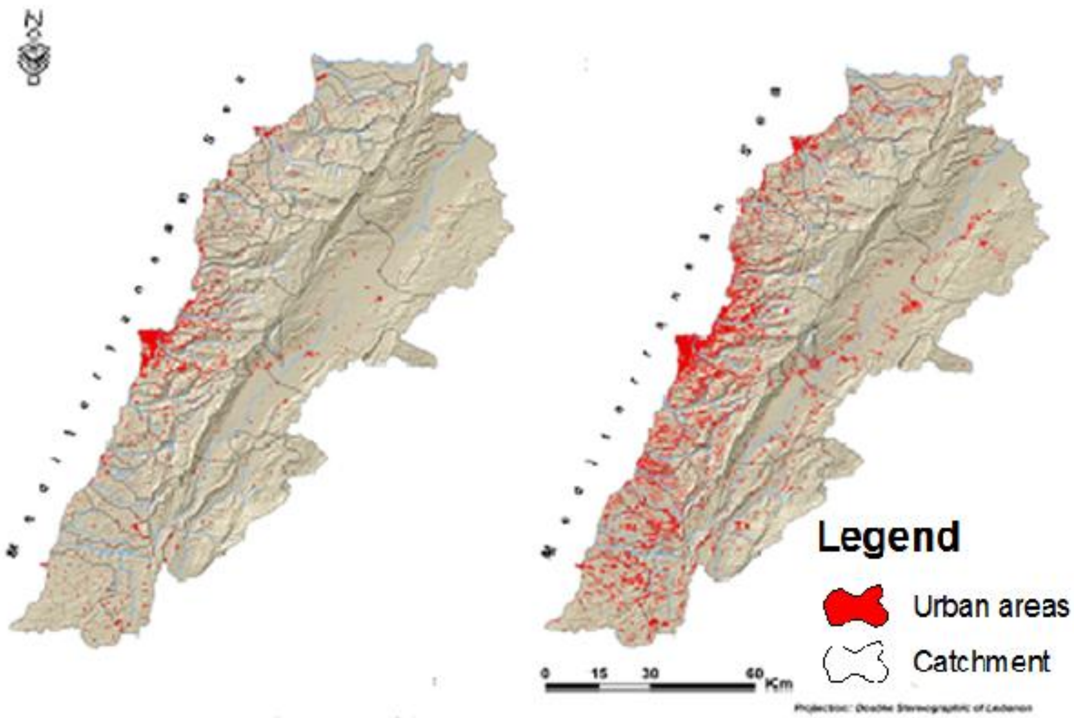


Fig. 2.8 Urban expansion between 1963 (left) and 2010 (right) (CNRS).

2.3 Methodology

A Comprehensive list of catchment descriptors that represent different aspects of catchments physical characteristics was extracted for the studied catchments from the available spatial data.

Hence, information about catchment morphometry such as catchment area, longest flow path, slope, drainage density, elevation; geological formations, soils and land cover use. Table 2.2 summarizes the different descriptors used. These indices are extracted from digital elevation model (DEM) with a 10 m spatial resolution developed by the CNRS (2010).

Moreover, catchments geological substratum was described in term of rock permeability. So, based on their characteristics, these rocks formations were classified into 3 classes according to their permeability (Abdallah et al. 2006). The main properties that influence the permeability are the presence of secondary porosity (fractures and fissures), the degree of karstification and the clay content.

Furthermore, soil characteristics were also taken into account. So, based on their textural properties and their organic matter contents, soils types are classified according to their infiltration capacity (based on Abdallah et al. 2006). Three classes were identified: soils with high infiltration capacity (HIS), soils with medium infiltration capacity (MIS) and soils with low infiltration capacity (LIS).

Finally, the land covers in the country is divided into 6 major classes: urban, agriculture, forest, shrubland, grassland, and bareland.

Table 2.2 The chosen physical catchments descriptors with their notations and units.

	Catchment Descriptors	Notation and units
Morphometry	Catchment area	Ac (km^2)
	Longest flow path	Lflow (km)
	Drainage Density	Dd (km/km^2)
	Slope along Lflow	Sc (%)
	Minimum Elevation	Min Zc (m)
	Mean Elevation	Zc (m)
	Maximum Elevation	Max Zc (m)
	Area above Zc=1800 m	Zc>1800
Geology and Karst	Apparent Karst	AK (%)
	High Permeability Rocks	HPR (%)
	Moderate Permeability Rocks	MPR (%)
	Low Permeability Rocks	LPR (%)
Soils	High Infiltration Capacity Soil	HIS (%)
	Moderate Infiltration capacity Soil	MIS (%)
	Low Infiltration Capacity Soil	LIS (%)
Land use	Forests	Fc (%)
	Urban areas	Uc (%)
	Bareland	Bare (%)
	Shrubland	Shrub (%)
	Grassland	Grass (%)
	Agriculture	Agr (%)

2.4 Results and Discussions

2.4.1 Morphometry

The cumulative frequencies of indices used to describe the morphometry of the studied catchments are presented in Fig. 2.9. Here one can see that the majority of these catchments are small to medium sized catchments with a median area of 152 km^2. These are mainly the catchments of the western slopes of Mount Lebanon with area never exceeding 500 km^2. Nevertheless, catchments in the inner parts of the country (the Bekaa valley) have larger areas sometimes exceeding 1000 km^2 (station 25 on the Orontes River, station 27 on the Litani River).

Median slope of the studied catchments is 8.3 %. Quarter of these catchments have a slope exceeding 14 % with 2 mountainous catchments (Ibrahim at Afqa –station 11- and Kelb at Hrajel –station 13-) having slopes greater than 20 %. All of the studied catchments have mean elevation greater than 500 m. And more than 80 % of these catchments have a mean Zc greater than 1000 m. As for the maximum elevation, it is more than 1000 m for all studied catchments and exceeding 2000 m for more than 75 %.

Due to their small area and relative steepness, the longest flow paths in the majority (more than 90 %) of these catchments are short, hence never exceeding 60 km. Moreover, the steepness of the catchments make that drainage density is relatively high with a median drainage density for all catchments of about 3.38 km/km^2.

The relatively small areas of the Lebanese catchments and their steepness are responsible for the short response time of these catchments. Hence, they are prone to flood events, which are common features of Mediterranean catchments (Barredo 2007; Marchi et al. 2010). Moreover, the high mean and maximum elevations of almost all studied catchments make that precipitation as snowfall contributes to an important part of their water balance (Abd El Al 1947; Shaban et al. 2004).

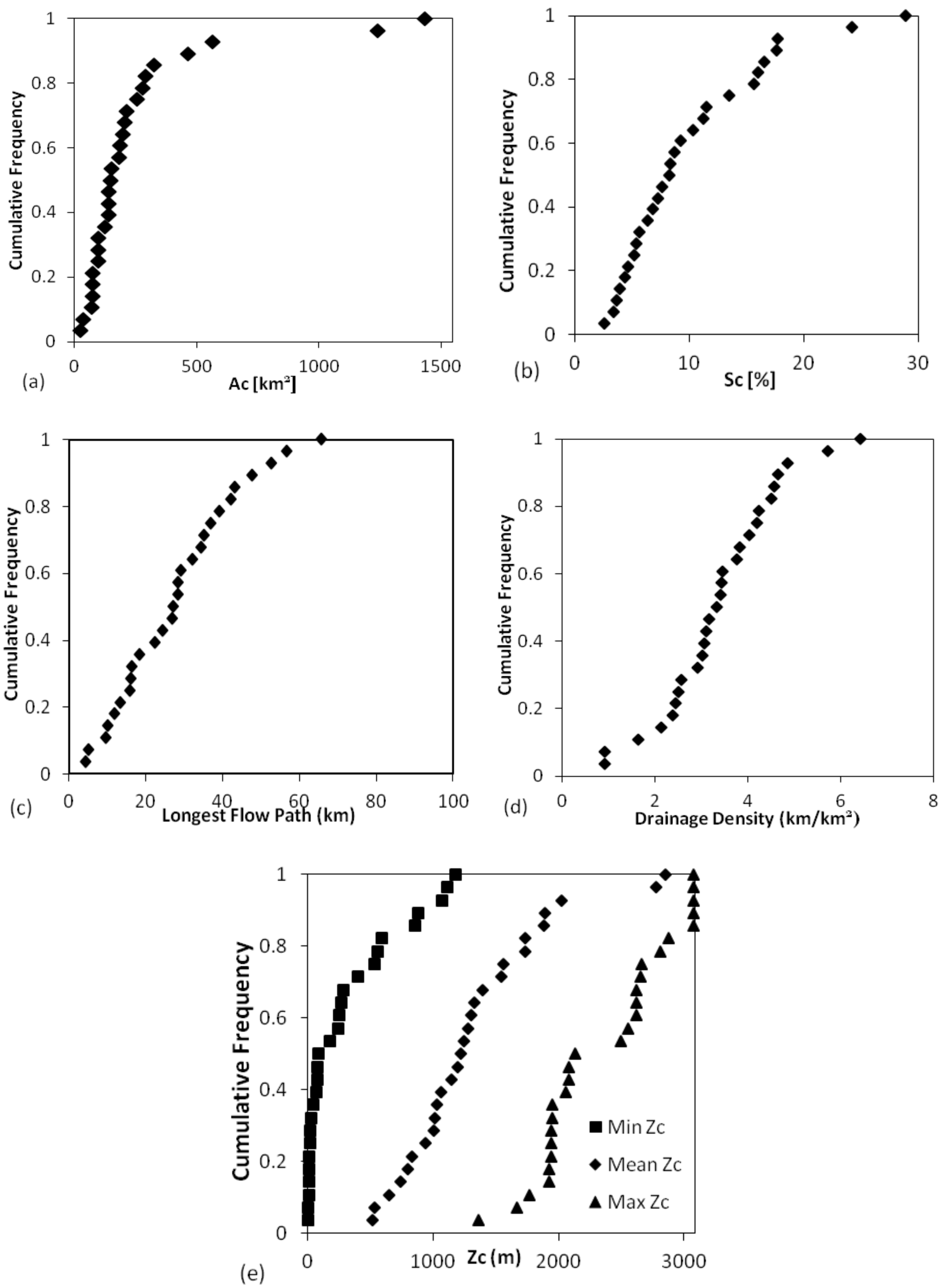


Fig. 2.9 Cumulative frequency of different indices used to describe the geomorphology of the studied Lebanese catchments; (a) catchment area (Ac in km^2), (b) slope along the longest flow path (Sc in %), (c) longest flow path (Lflow in km), (d) drainage density (Dd in km/km^2), and (e) minimum, mean and maximum elevation (Zc in m).

2.4.2 Geology and Karst

The outcome of the classification of major rocks type according to their permeability (Abdallah et al. 2006) is summarized in Table 2.3. Three main classes are identified: high permeability rocks, medium permeability and low permeability rocks (Fig. 2.10a).

Table 2.3 Different geological formations and their relative permeability.

Permeability classes	Permeability	Geological Formations	Effective infiltration elements
High [HPR]	Very High	Mid to Upper Jurassic J4-7	Secondary porosity (cracks and joints) of carbonate rocks + high karstification
	High	Lower Jurassic (J2-3), Aptien (C2), Cenomanian (C4), Eocene (E), Mio-pliocene (Mp)	Secondary porosity, different forms of Karstification, and presence of some marl intercalations
Moderate [MPR]	Moderate	Neocomian (C1), Turonian (C5)	Clay content and jointing system
	Slightly Moderate	Miocene (M), Pliocene (P), Quaternary (Q), and Basalts (B)	Considerable clayey content
Low [LPR]	Low	Albien (C3), Senonian (C6)	High clayey content

Figure 2.10 presents the cumulative distribution of the 3 identified permeability classes in the studied catchments. Here one can see that the substratum of these catchments is made primarily of highly permeable rocks. In fact, highly permeable rocks formations represent more than 56 % of almost 75 % of the studied catchments. In some cases, such as Ibrahim Basin (10, 11, and 12), HPR may reach more than 90 % of the catchment surface.

One can notice that all catchments have at least 40 % of their surface karstified. The percentage of karstified areas reaches more than 75 % for about half of the studied catchments.

The prevalence of highly permeable rocks and karst emphasizes the importance of infiltration in the hydrological processes that govern Lebanese catchments. Water from infiltration contributes to the recharge of many aquifers spread in the different geological formations of the country. These aquifers discharge in hundreds of springs that fed surface water. In fact, all of Lebanon permanent rivers are spring fed rivers. However, the fact that the extents of these aquifers are not limited to the surface catchment boundaries, and their very own nature (karstic aquifers), make that inter-connections between catchments is almost certain.

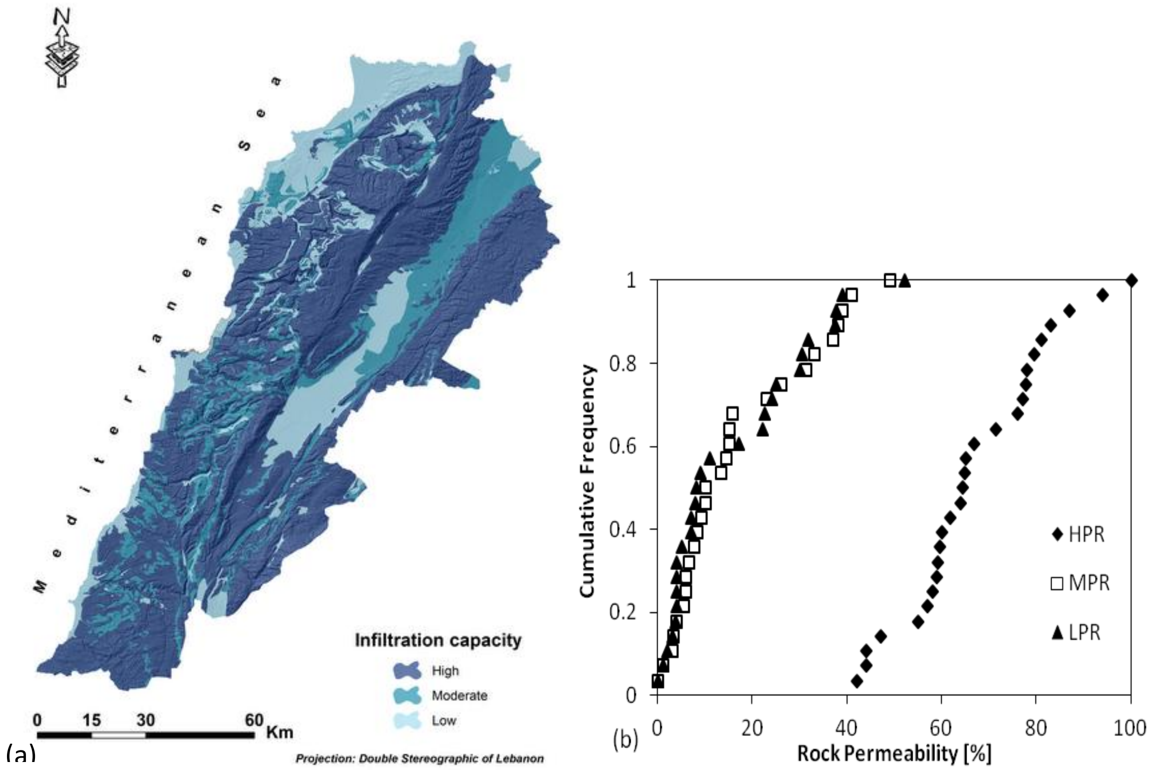


Fig. 2.10 (a) Distribution of infiltration capacity according to rock permeability (source: Abdallah et al. 2006) and (b) the cumulative frequency of different permeability classes across the studied catchments (c); HPR: High Permeability Rocks, MPR: Medium Permeability Rocks, and LPR: Low Permeability Rocks.

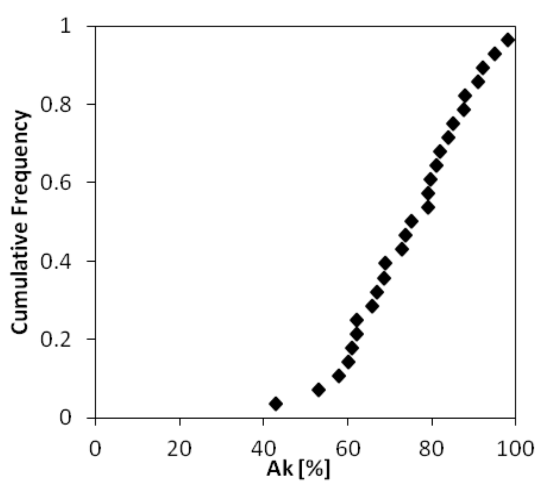


Fig. 2.11 Cumulative frequency of apparent karst (AK in %) across the studied catchments

2.4.3 Soils

The soil classification (Abdallah et al. 2006) results are presented in table 2.4. While Fig. 2.12a represents the distribution of different soil infiltration capacity classes across Lebanon. Moreover, Fig. 2.12b represents the cumulative frequency distribution of different soil classes across the studied Lebanese catchments. Soils in Lebanon are generally shallows with medium to high infiltration capacity. This is understandable given the mountainous nature of the majority of Lebanese terrains. Low infiltration capacity soils (LIS) are mostly common in agricultural terrains, where soils with high clay content, such as Red and Brown soils, are dominant. Hence, catchments with highest percentage of agricultural areas in the northern (especially the Akkar plain) and southern parts of Mount Lebanon (where the coastal plain is relatively larger, these are catchments at stations 1, 2, 3, 4, 5, 6, 9, 22 and 24) and in the inner catchments of Litani and Hasbani (stations 27 and 28) where agricultural areas are prevalent, show the highest percentage of Low infiltration capacity soils.

Table 2.4 Major soil types and their infiltration capacities.

Infiltration capacity	Properties	Soil types
High (HIS)	High sand and/or organic matter content	Sandy soil, Alluvial soils, Rendzine
Medium (MIS)	High silt and fine sand content	Yellowish mountainous soils, Black soils, Grayey soils, Chestnuts soils, Mixed soils, Subdesertic yellowish soils
Low (LIS)	High clay content	Red soils, Brown soils

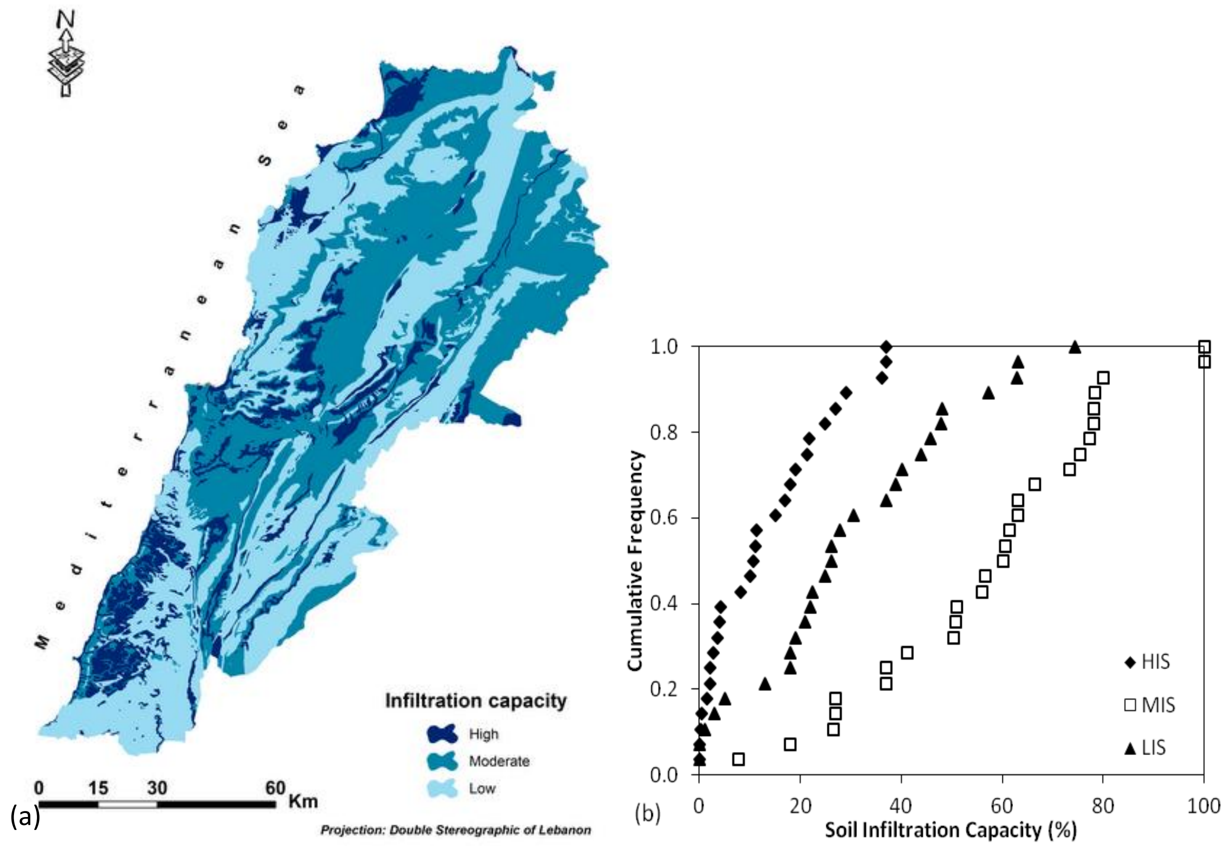


Fig. 2.12 (a) Distribution of infiltration capacities classes according to soil types and (b) the cumulative frequency of different infiltration capacity classes across the studied catchments; HIS: High Infiltration capacity Soils, MIS: Medium Infiltration capacity Soils, and LIS: Low Infiltration capacity Soils.

2.4.4 Land cover/use

The land covers in the country is divided into 6 major classes: urban, agriculture, forest, shrubland, grassland, and bareland.

The distribution of these classes varies largely across catchments (Fig. 2.13). Hence, catchments in the northern part of the countries show relatively high percentage of agricultural areas -more than 20 % of the total basin are- (catchments 1, 2, 3, 4, 5, 6, 7, 8 and 9). The same could be said about catchments in the southern part of the country (catchments 19, 20, 21, 22 and 24). The inner catchments (Litani at stations 26, 27 and 28) also show high percentage of agriculture. While other more mountainous catchments such as Ibrahim (10, 11 and 12) and the upper part of Nahr el Kelb (13 and 14) are mostly dominated by grasslands, shrubs and barelands. Catchments in the central part of Mount Lebanon, Beirut (16, 17 an 18), Damour (19, 20, 21 and 22) and Awali (23) are characterized by relatively high percentage of urban areas (10 to 17 % of the total catchment area). Forest cover represents around 20 % of catchments areas for the majority of catchments on the western slopes of Mount Lebanon, while in the interior catchments it only represents between 5 to 10 % of catchments areas.

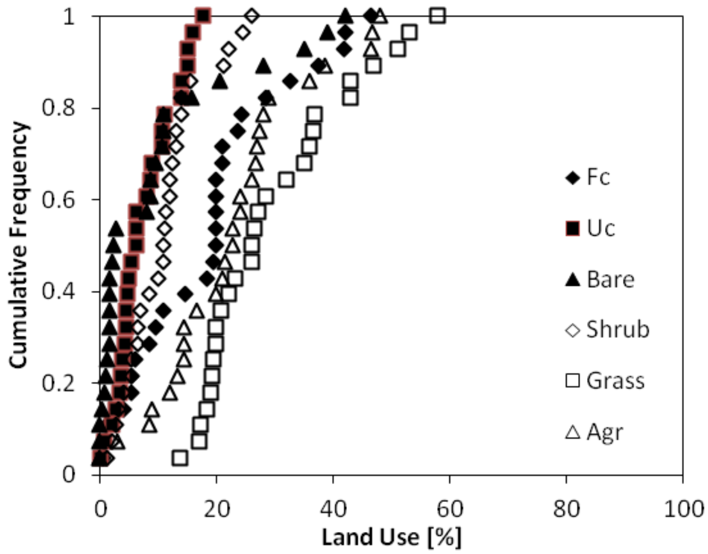


Fig. 2.13 The cumulative frequency of different land use classes across the studied catchments (see Table 2.2 for notations).

2.5 Conclusion

The great majority of the studied catchment is small to medium sized catchments with area never exceeding 500 km^2. Only 2 catchments (Litani and Orontes) have an area exceeding 1000 km^2. Median slope is 8.3 % while a quarter have a slope exceeding 14 %. Furthermore, due to their small area and relative steepness, longest flow paths are usually short never exceeding 60 km and drainage density is high with a median value of about 3.38 km/km^2. In addition, all are mountainous catchments with the great majority having a mean elevation over 1000 m, and more than half of them with at least 20 % of total basin area above 1800 m. Moreover, the geology of the country is mainly composed of highly karstified carbonate rocks. The substratum is made primarily of highly permeable rocks and all studied catchments have at least 50 % of their surface karstified. Furthermore, given the mountainous nature of Lebanon, soils are generally shallows with medium to high infiltration capacity. Deep well developed soils are mostly common in catchments with agricultural terrains. The distribution of land use classes varies largely. Finally, mean annual precipitation ranges from around 500 mm in the Orontes in the northeastern part of the country to more than 1200 mm in the central part of Mount Lebanon. Aridity index (defined as the ratio of mean annual precipitation to mean reference evapotranspiration) follows the same spatial distribution of rainfall.

3 CLIMATIC CHARACTERISTICS AND DATA ANALYSIS

3.1 Introduction

The important relief of the country and its specific physiographic characteristics result in a high spatial variability of climatic features across Lebanon. Moreover, the prevalent Mediterranean climate results in a high temporal evolution of precipitation. In this chapter we aim to analyze the climatic characteristics of Lebanon and present the methodology used for the spatial interpolation of precipitation.

The chapter begins with a short review of climatic change impact over the country, than we present the dataset used in this study; afterwards we discuss the climatic characteristics of Lebanon in term of temporal and spatial distribution of precipitation, temperature and evapotranspiration. Finally, we present the methodology used to interpolate the precipitation over Lebanon and the result of this approach.

3.2 Climatic change impact over Lebanon

For the Middle East region, studies dealing with climate change impact indicate a trend towards decreasing precipitation and a more extreme rainfall regime (Philandras et al. 2011). Hence, Global Climatic Model projections for the region at the end of 21th century, predict a decrease in precipitation, an increase in temperature (Ragab 2002; Hemming et al. 2010, IPCC, 2007, 2011, 2014) and a tendency towards a more extreme climate. Nonetheless, Bou-Zeid and El-Fadel (2002), and Hemming et al. (2010) pointed to the large uncertainties and discrepancies between different GCM projections. Moreover, as an example of the uncertainty related to the GCM projections, Ragab (2005) used a GCM with 2.5 x 3.75 ˚ grid squares for precipitation prediction, and 0.5 x 0.5 ˚ grid squares for temperature prediction. Such a resolution is way too coarse to account for the very highly spatial variability in rainfall and temperature in mountainous countries such as Lebanon.

Nevertheless, Regional Climate Models (RCM) -with a more finite resolution- were also used for climatic predictions in the region (Alpert et al. 2008; Black 2009; Hemming et al. 2010) and the results were constituent with the above-mentioned GCM predictions.

In Lebanon many authors point towards signs of increased hydrological droughts that could be partly –anthropogenic induced droughts such as changes in the land cover/use, the over-exploitation of groundwater resources, and the excessive use of surface water for irrigation, etc. were not taken into account- attributed to climate change. Shaban (2009, 2011) suggests that over the last few decades (1967 - 2006), Lebanon has witnessed a decrease in the annual discharges of river a drop down in groundwater piezometric level, and a decrease in the extent of the snow covered area. In addition, Ramadan et al. (2012), studied changes in runoff of the Litani River in the upper and lower Litani basins over the last century (1900 - 2008); they found that the Litani exhibits a drying trend with a reduction rate of 0.1-0.8 m^3/s per decade.

Even though, there is no decisive evidence on the influence of climate change on water availability in Lebanon (UNDP 2011). Signs of hydrological droughts are discernable in the country (Shaban 2009, 2011). Moreover, with increasing anthropogenic pressure from urbanization, land cover/use changes and extensive irrigation, water resources in Lebanon becomes more and more vulnerable quantitatively and qualitatively, and the available resources become unable to fulfill the water demand for the population. However, while many studies tried to quantify the impact of climate change on water resources in the country, the impact of land cover/use changes need profound studies.

3.3 Dataset

The American University of Beirut (AUB) meteorological station was the first to operate in Lebanon in 1891 and is still in use. By the year 1928, six meteorological stations were operating in Lebanon: AUB and Beirut Nazareth in Beirut, El-Qraye and Jezzine in the Central part of Mount Lebanon, and Rayak and Ksara in the Bekaa valley. During the 1930s the number of meteorological stations in the country increases, and in the year 1940, 31 stations were operating. However, due to the Second World War, no meteorological data exists for the period between September 1941 and August 1944. In the years following the war, the number of stations increased enormously and by 1950, 55 stations were operating throughout Lebanon. This network of meteorological stations expands more and more during the 1950s and 1960, and by 1970, a dense network of about 130 meteorological stations covered the whole country. For climatic and orographic considerations, the Lebanese territory was divided into 3 major parts. The coastal region: from sea level to 800m; the mountainous region, from 800m to the crest line of Mount Lebanon; and the internal region, from the crest line of Mount Lebanon downward to the Bekaa valley, this region also includes the Lebanese part of the Anti-Lebanon and Mount Hermon ranges. So this established meteorological network of the pre-war period provided a large set of climatic data such as precipitation, temperature, humidity, wind, etc. However, only daily precipitation records are available in an editable format, all other parameters are only available on hard copies and need to be digitized. Moreover, one should also notice, regarding the spatial and temporal extent of the pre-1970 meteorological network, that the spatial density and the length of the available data series vary from one region to another.

In 1975, the Lebanese Civil War started causing a big gap in the data for more than 15 years. Only very few Meteorological stations remain operating (Tripoli-IPC, Beirut International Airport, Al-Arz and Rayak) with large gaps in the records. After the war the Meteorological network was re-established but not to the same spatial extent. In our dataset only 32 stations with daily precipitation data (with missing data in the record) and monthly precipitation and temperature data are available for the period 2001 – 2011.The spatial extent of the pre-war and post-war Meteorological networks is represented in Fig. 3.1.

Finally, it must be noted that the pre and post-war Meteorological stations are controlled by the National Meteorological Service of The General Directory of Civil Aviation of the Ministry of Public works and Transport.

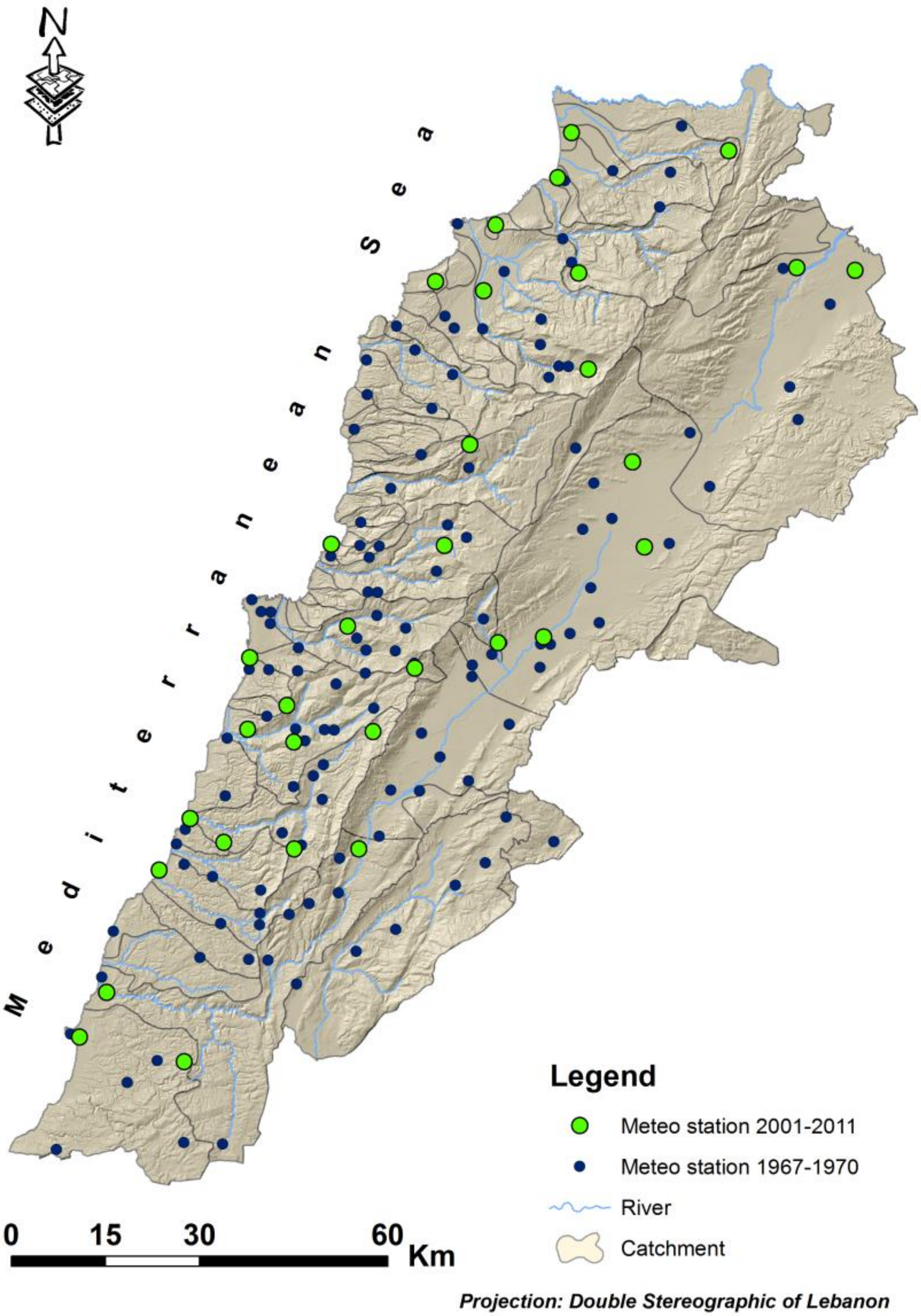


Fig. 3.1 Distribution of Meteorological stations for the 1967-1970 and 2001-2011 periods.

3.4 Climatic characteristics of Lebanon

3.4.1 Precipitations

a. Temporal variation of mean annual precipitation

Mediterranean climate is characterized in a high inter-annual variation of rainfall (Pagney 1994). In Lebanon, inter-annual variability of rainfall is high throughout the country, and slightly increases in the inland region (Sene et al. 1999), especially in the semi-arid northeastern part of the country. The coefficients of variation (CV) of mean annual precipitation values are consistent throughout the country ranging from 0.2 to 0.3 except for some stations in the northeast where it can reach more than 0.4. For some stations in the central part of Lebanon, CVs are high, but this is due mostly to measurement issues (snow contribution). These values of CVs are common in catchments with Mediterranean climate.

For Instance the mean annual precipitation for the period of 1921-2011 at Beirut station (Fig. 3.2) is 820 mm with a standard deviation of 214 mm. The lowest value was recorded in the hydrological year 1932/1933 with 413 mm, while the highest is 1600 mm recorded in 1968/1969. The median, first and third quartiles of annual rainfall are 807, 663, and 969 mm respectively. This gives an idea on how high the inter-annual variability of rainfall is in Lebanon. Mean annual precipitation values ranges from less than 50 % of the mean to about 200 % of the mean.

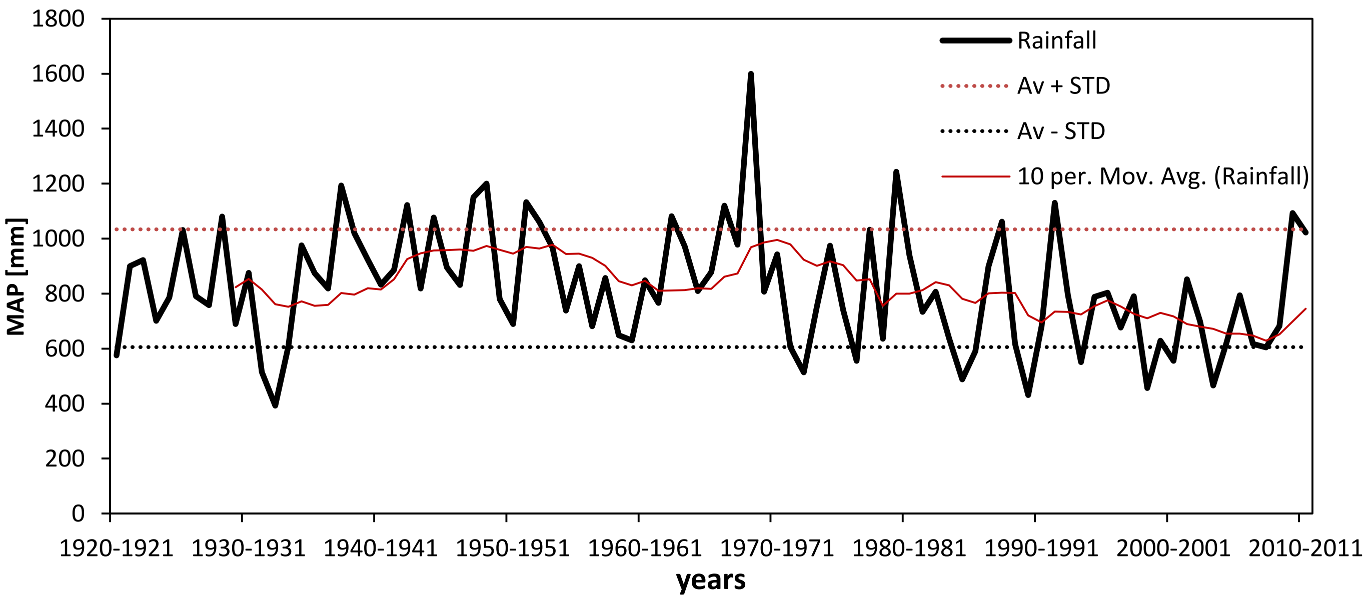


Fig. 3.2 Temporal variation of annual MAP and 10 years moving average, the lines represents average MAP +- standard deviation (Av +- STD)(American University of Beirut station).

b. Spatial distribution of mean annual precipitation

Despite the relatively small surface of Lebanon, rainfall is highly variable across the country due to its geo-morphological characteristics. Thus, according to rainfall distribution, Lebanon can be divided to five regions (Blanchet, 1976):

- The coastal region: the mean annual precipitation ranges from 700 to 900 mm, with a little increase (1000 mm) to the north of Beirut. However, precipitation decreases further to the north, Akkar plain, (750-800 mm), and the south (700 mm). This decrease is due to the less important relief in the extreme north and the southern part of the country.

- The Mount Lebanon: precipitations in this region are abundant but very variable, as a function of the altitude and the topography. It is the part of Lebanon which receives the maximum of precipitation. At the exception of the southern part of Lebanon, where the combined effect of the decreased altitude and the southern latitudinal position reduce precipitation to less than 800 mm per year, all of Mount Lebanon receives more than 1000 mm of precipitation per year. The maximum precipitation is witnessed in the mountainous mass, just to the north of Beirut (Sannine and Laklouk), with 1600 to 1700 mm of precipitation per annum. Here, one should point out to the fact that Mount Mekmel (the highest in Lebanon with a maximum elevation of 3088 m) receives less precipitation than Mount Sannine and the Laklouk (around 2600m). This could be attributed, on one hand, to the distance from the sea, Mount Sannine and Laklouk being very close to the sea. And on the other hand, to the foehn effect, Mount Mekmel being partially shaded from the humid SW-NE winds by Sannine and Laklouk mountains masses (Traboulsi, 2010). Due to the topography of the Mount Lebanon range, narrow steep slopes, the oriental slopes of Mount Lebanon receives good amount of precipitation (around 1000 mm).

- The Bekaa: the Bekaa plain is under the foehn effect. Air Masses lose their humidity while traversing the Mount Lebanon range. Precipitation decreases not also from west to east, but also, from south to north. Precipitation in the southern Bekaa valley may reach up to 700 mm, and decrease gradually towards the north of the Bekaa, where it reaches around 200 – 300 mm. The further decrease in precipitation to the north is due mainly to the excessive rain shadow effect caused by the Mount Mekmel, the largest and highest mountain in the Mount Lebanon range.

- Eastern chain: as for the Bekaa valley and the Eastern chain, they are shaded by Mount Lebanon. Precipitation decreases from about 700 mm in the south to 300 – 400 mm to the north. Here, one should note that the aforementioned values for precipitations in the Anti-Lebanon are estimations. Unfortunately, there are few gauging stations available for this part of the country (Traboulsi 2010).

- The Hermon: isolated in the southeastern part of the country Mount Hermon (peaks at 2814m) is well watered with precipitation ranging from 1000 to 1200 mm, and decreasing from south to north. This is due to the low altitude of the Mount Lebanon in the southern part of Lebanon.

This high spatial variability of rainfall across the country make it difficult to estimate rainfall amount over the Lebanese territories and have a great impact on the hydrological responses of the Lebanese catchments as we will see in the next chapters.

c. Snow

Snow in Lebanon is a major water resource where it is very common over altitude above 1200 m. Snow i cover, at its maximum extent, an area of more than 2000 km^2 (Mhawej et al. 2014) the number of days with snowfall increase with altitude, from 30 days at 1500 m to 60 days at 2000 m (Blanchet 1976). The snow covers the ground for a period ranging from 40 to 120 days between 1500 and 2000 m as a function of altitude while on the highest crests snow may persists for 9 months. The evolution of the areal coverage of snow over Lebanon Mountains is presented in Fig. 3.3 as10 year's average monthly snow coverage for the period 2002 - 2011. This was adapted from MODIS imageries at a 500m spatial resolution and 8-days temporal resolution.

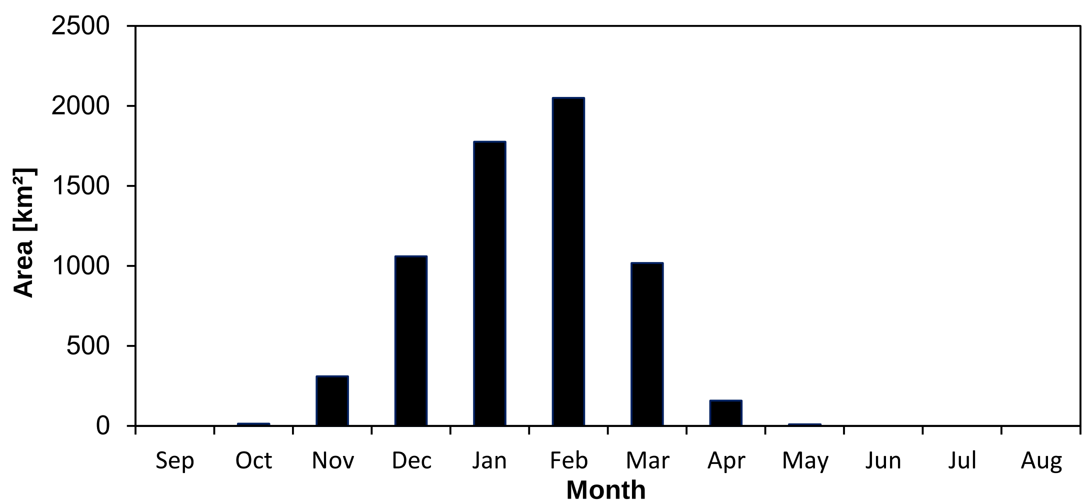


Fig. 3.3 Monthly average snows cover extent over Mount Lebanon (2001-2011).

In fact, snow melt contributes progressively to the alimentation of karstic springs (Aouad et al. 2004). Abd-El-Al (1947) estimates that snow melt contribute to about 40 % of the total discharge of the coastal rivers. However, Lebanon does not yet have the capacity to measure the volume of snow cover in any degree of confidence (UNDP, 2011), due to technical limitations, mainly the very limited number of snow measure stations (Shaban et al. 2004). Nevertheless, during the last decade, a number of studies were carried out to estimate the Snow Water Equivalent (SWE) over Mount Lebanon, using the enormous advancement in remote sensing techniques, coupled with some localized field measurements (Touma, 2002; Bernier et al. 2003; Shaban et al. 2004; Aouad-Rizk et al. 2005; Corbane et al. 2005; Mhawej et al. 2014). SWE is reported to be about 1100 Mm^3 (Million Cubic Meter) of water for the year 2001. Finally, one most mentions that these studies are only limited to Mount Lebanon, while there are no such studies relating to the snow cover of the Anti-Lebanon. As for Mount Hermon, a study conducted in Israel in 1990 (Gil'ad and Bonne 1990) found that snow melt over Mount Hermon contribute to only 10 % of the total annual yield of the upper Jordan River sources.

To calculate the catchment surface covered by snow, we divided the country into ranges of altitude (Fig. 3.4a) and calculated the cumulated area by range of altitudes (b). Afterwards, we crossed the area above each altitude with the available information on the monthly snow extent derived from MODIS imageries (Fig. 3.3) in order to estimate the percentage of catchment area covered by snow at a monthly timescale.

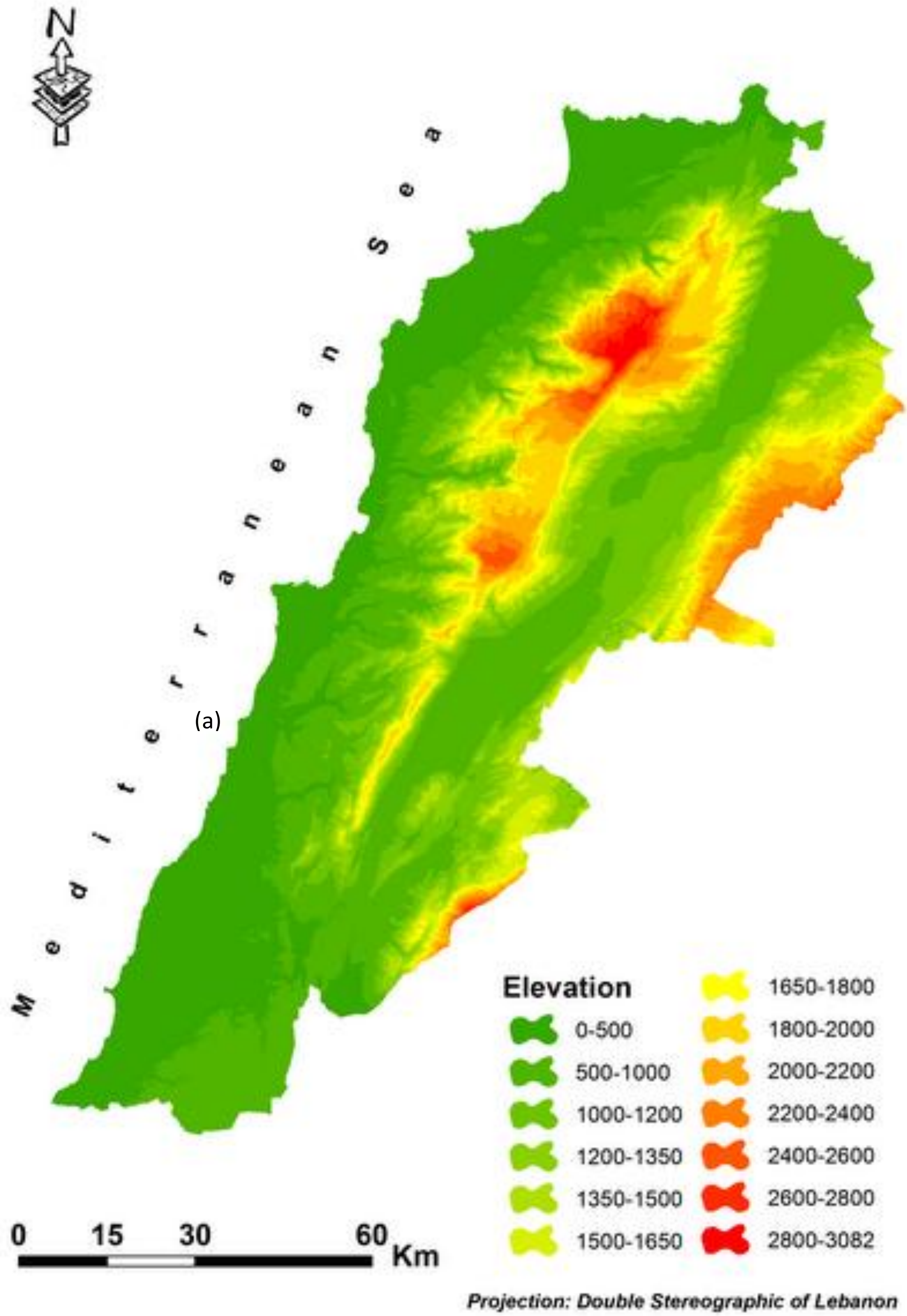


Fig. 3.4 (a) Elevation ranges over Lebanon.

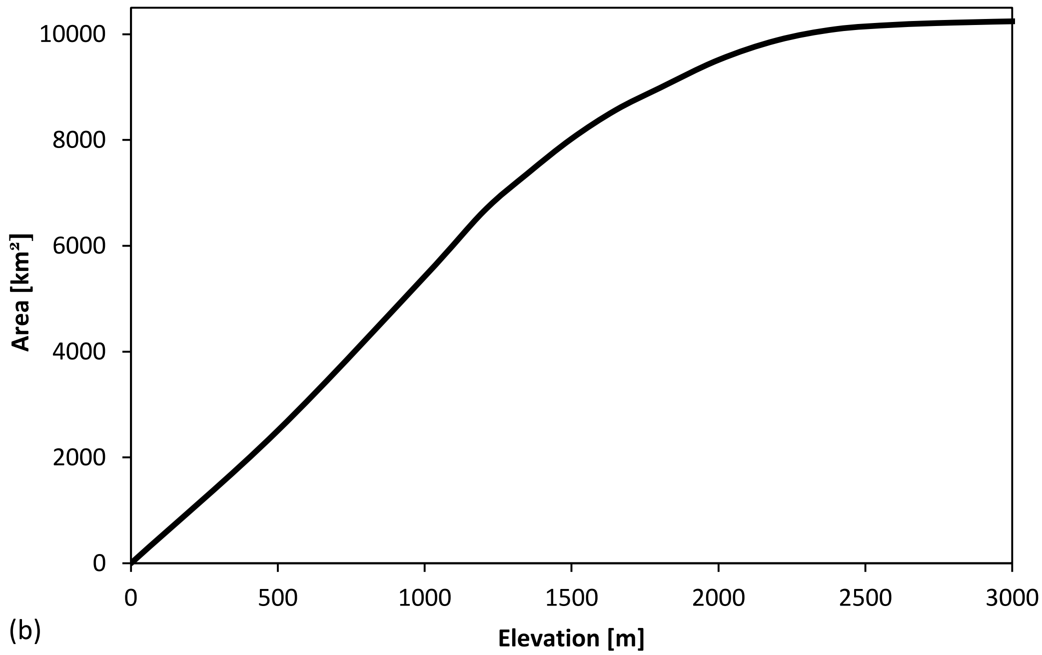


Fig. 3.4 (b) cumulative distribution of area by elevation range.

3.4.2 Temperatures and reference evapotranspiration

Temperature is highly variable as a function of altitude and distance to the sea. In the coastal region, temperatures are high, with mean annual temperatures between 18 and 20˚C. Mean monthly temperatures never drop under 10˚C, while many months have their mean annual temperatures above 20˚C. Annual amplitudes are less than 15˚C, while daily amplitudes are low and vary between seasons. In the Mount Lebanon region, temperature decrease with altitude, the rate of decrease is higher during the winter (0.7˚C/100 m in the winter, 0.4-0.5˚C in summer) (Blanchet 1976). Annual amplitudes are higher than the coast (15-19˚C). Winters are cold and get colder with elevation; the mean annual temperature is 0˚C at 1800 m. Freezing is very common with 100 frozen days per year at 1800 m. Warming is fast, temperature increase about 10.4˚C from February to May, which is very important for the dynamics of snowmelt. Summers, hot and humid on the low elevated slopes, become cooler with altitude (the mean of august is 20˚C at 1300 m). In the Bekaa valley, thermal amplitudes are high (in summer, daily thermal amplitude is about 16 to 20˚C). Winters are severe, monthly average for January is about 5 to 6˚C. In the central part of the Bekaa, 40 to 50 days of freezing are recorded. Warming is fast, temperature rise about 10˚C from February to May. During summers, the days are hot, especially in afternoon, while the nights are relatively cold. The Anti-Lebanon have even more continental characteristics than the Bekaa, annual and daily thermal amplitudes are very high (18 to 19˚C, and more than 15˚C, respectively). In comparison to Mount Lebanon, and for the same altitude, temperatures are lower/higher of about 2˚C during winter/summer. As for Mount Hermon, the dynamics of Temperature is very similar to Mount Lebanon (Blanchet 1976).

Mean annual ET0 values vary across the country. Its spatial distribution –as for temperature- is mainly controlled by the relief of the Lebanese terrains. Figure 3.5a represents the spatial distributions of long term mean annual ET0 over Lebanon. Mean annual ET0 varies between 703 and 1395 mm per annum with the lowest values at the elevated areas of Mount Lebanon, Anti-Lebanon and Mount Hermon. The highest values of ET0 are found in the inland part of the country (the Bekaa valley) (Fig. 3.5a).

Due to seasonality of the intra-annual distribution of rainfall under Mediterranean climate (precipitation occurs mainly in the mild to cold winter, whereas warm to hot summers are dry), and since reference evapotranspiration follows the dynamic of temperature, precipitation and reference evapotranspiration are in opposite phases (Fig. 3.5b). Hence, the maximum amounts of precipitation fall in the cold winter season where reference evapotranspiration is low, whilst the highest reference evapotranspiration values occur in the dry summer season. Thus, when reference evapotranspiration is at its peak, there are little or no water to evaporate. Therefore, under Mediterranean climate Actual evapotranspiration (ET) values are indeed less than the estimated reference evapotranspiration (Latron et al. 2009).

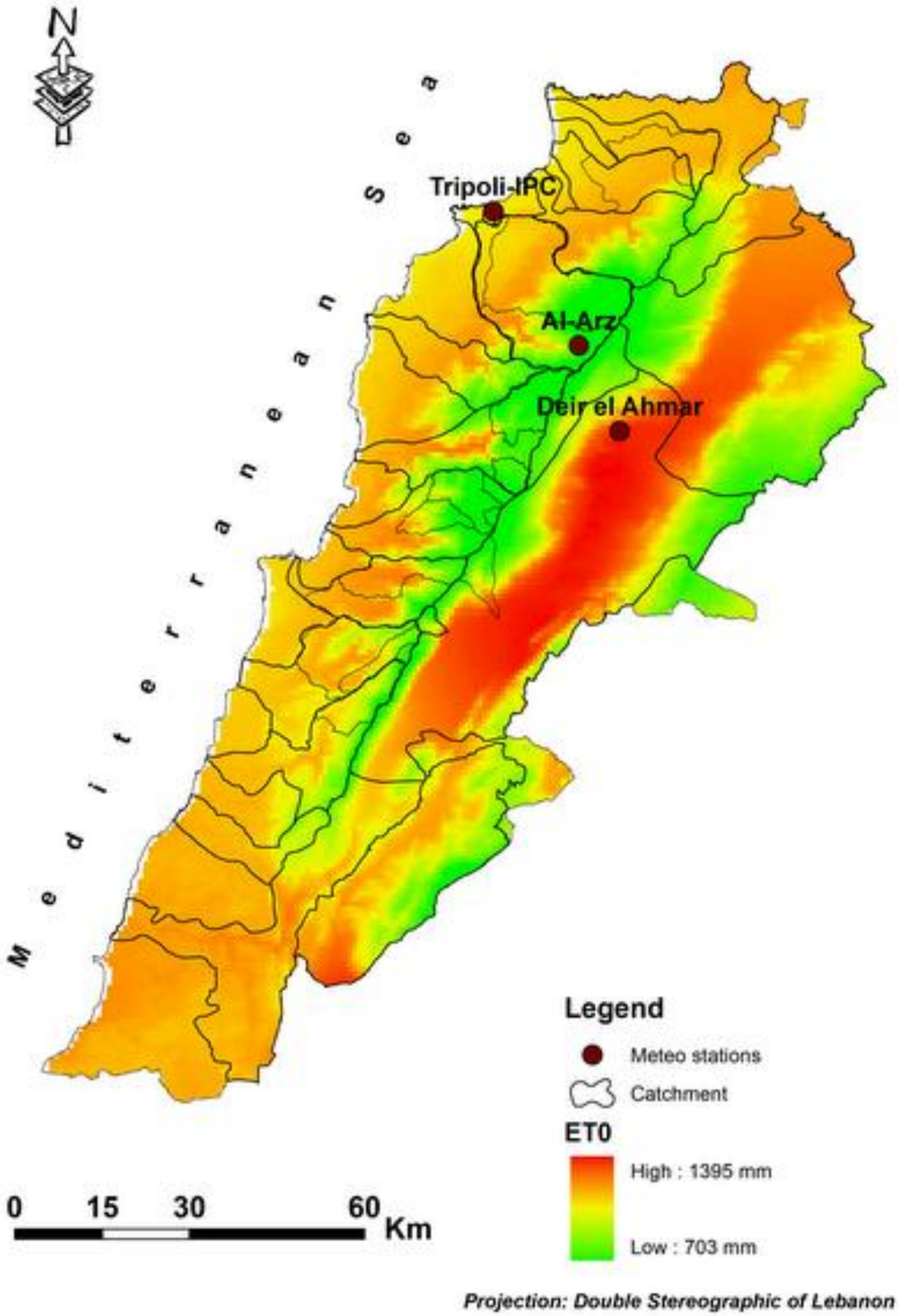


Fig. 3.5 (a) Spatial distribution of annual ET0 for the period 2000 – 2010 (source: MODIS 2010).

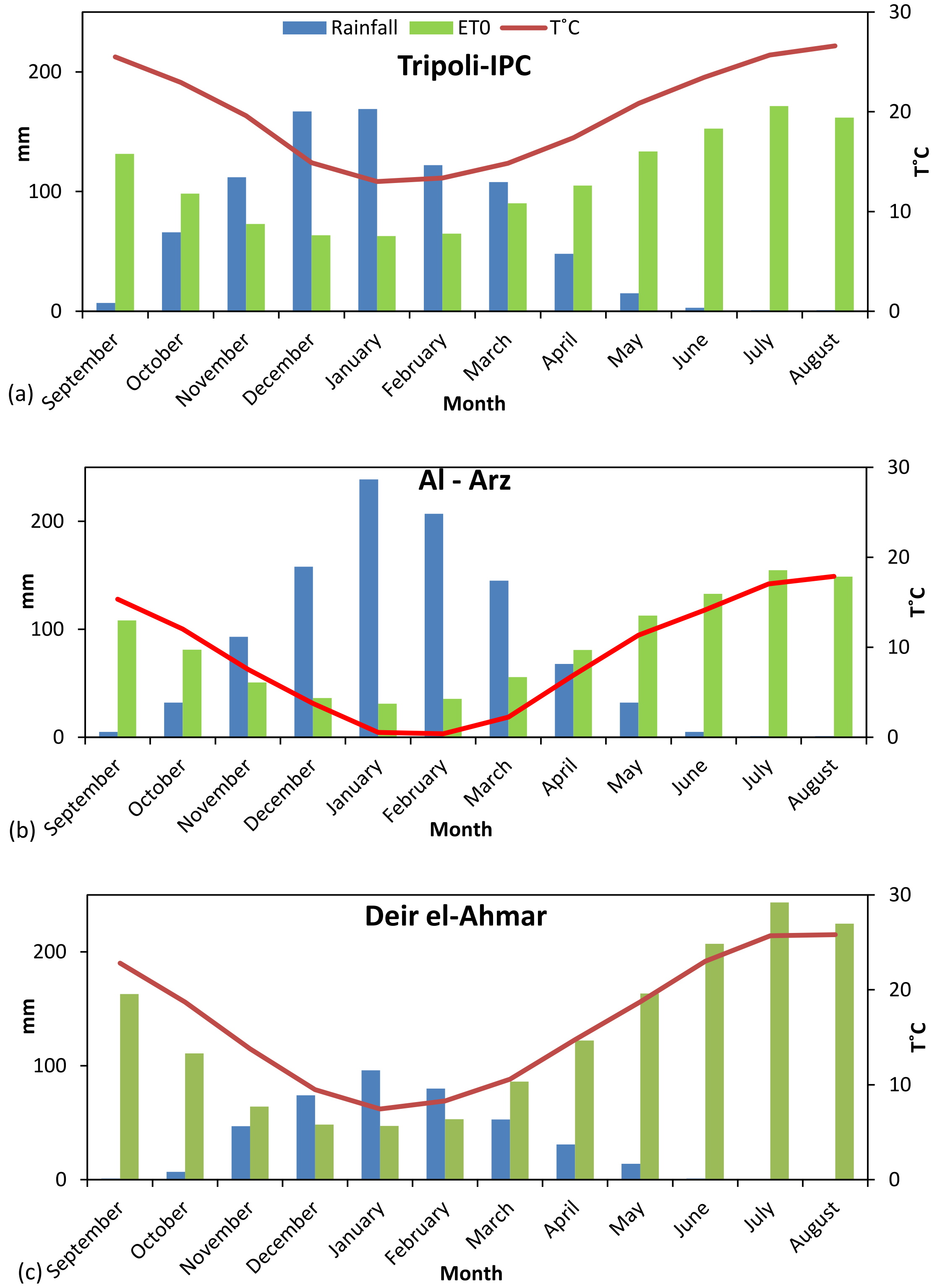


Fig. 3.5 (b) Monthly variation of mean monthly (2001 – 2011) Temperature, ET0 and Precipitation for three stations located at a West-East transect in Northern Lebanon. (a)Tripoli-IPC; (b) Al-Arz; and (c) Deir el-Ahmar.

3.5 Spatial interpolation of precipitation

3.5.1 Methodology

In this section we present the methodology used to interpolate mean annual precipitation. The method used here was universal kriging for the spatial interpolation. Given the reduced number of stations in our study period (2001 - 2011) we analyzed the effects of reducing the number of stations for the period 1967 - 1970 –when there were 130 stations- on the spatial coherence of the rainfall interpolation and on the mean annual precipitation by catchment. Here we reduced the number of station while trying to keep a good spatial coverage (Fig. 3.6).

3.5.2 Results and Discussions

One can notices that the overall spatial distribution of rainfall is maintained while the number of stations is gradually reduced. Table 3.1 compares catchments mean annual precipitations for the 1967 - 1970 period using 130 and 32 stations respectively. The median absolute value of residual catchment mean annual precipitations resulting from the two interpolations (with 130 and 32 stations respectively) is 59 mm. The highest absolute residual is found for the semi-arid northeastern part of the country (Assi basin, station 25) and the high plateau of the Mount Lebanon at Kelb basin and the headwaters of Beirut catchment (stations 13, 14, 15 and 16) and Berdawni basin (station 26). In both these 2 regions the decrease (in northeastern Lebanon) and increase (Mount Lebanon) in precipitation occur very rapidly at very short distances which may require a higher density of rain gauging stations. Nevertheless, the general trend of catchments mean annual precipitations calculated using the 2 sets of stations show no major differences.

Seemingly, we compared catchments mean annual precipitations between the period 1967 - 1970 and 2001 - 2011. Here too and despite the fact that the period 1967 - 1970 was a humid period (Fig. 3.8) the overall trend gives acceptable results in term of the spatial distribution of rainfall (Fig. 3.7) and the catchments mean annual precipitations (Table 3.1). The median absolute residual between the two periods is 228 mm which is acceptable since the mean annual precipitation for the whole country is 1073 mm for 1967 - 1970 and 854 mm for 2001 - 2011. At a monthly scale the spatial distribution of rainfall is conserved for all months in both periods (Fig. 3.7 and 3.9). However, for the period 1967 - 1970 January exhibits the highest rainfall amount, while in 2001 - 2011 the highest monthly rainfall is recorded in February.

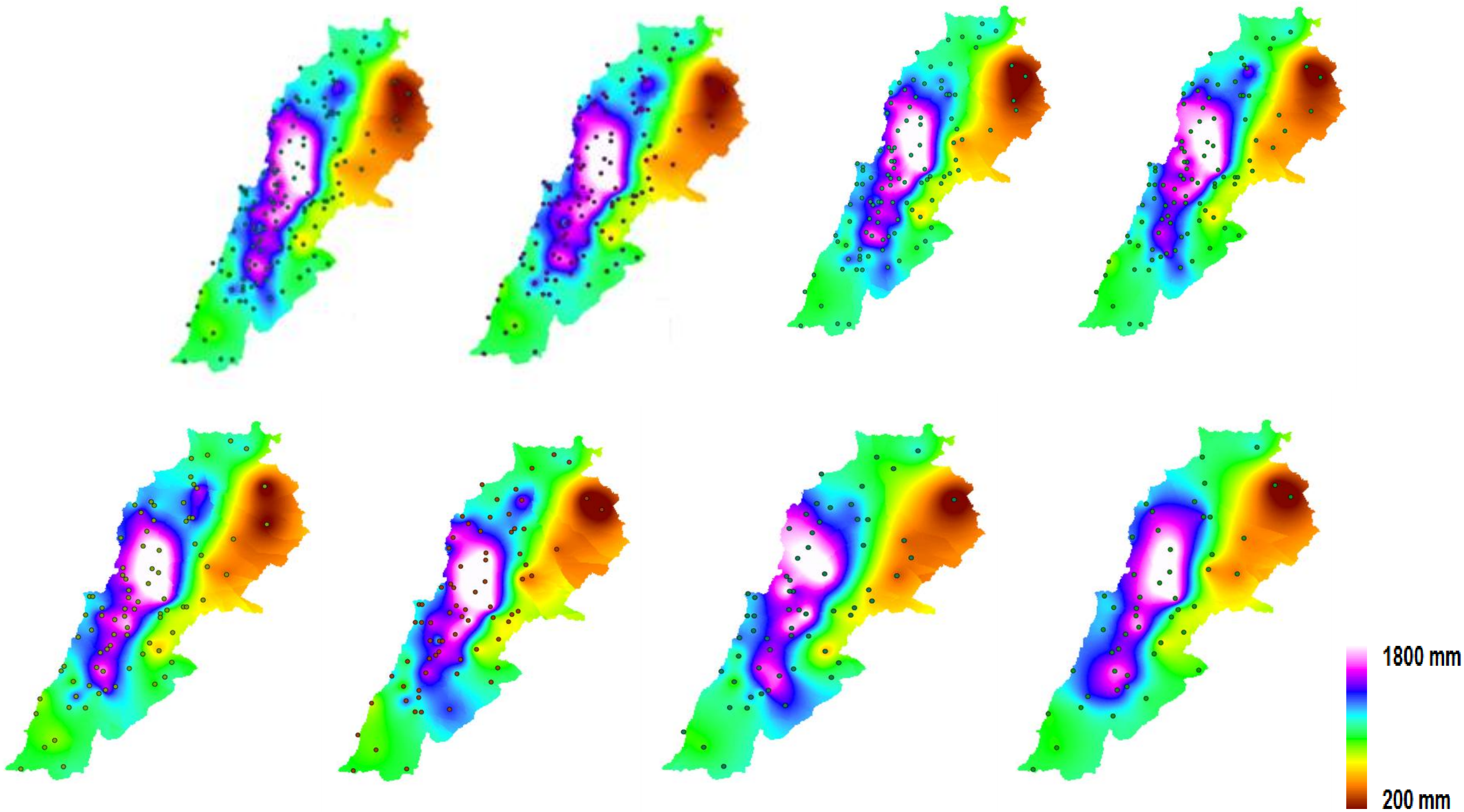


Fig. 3.6 Interpolation of average annual rainfall (1967-1970) using decreasing (10 %) number of stations (132 stations to 50 stations from right to left) Evaluation of the impact of a decreasing number of precipitation stations on the overall spatial distribution of precipitation. We used a decreasing number of stations for the period 1967 - 1970: from 132 (first map) to 50 stations (last) by removing 10% of stations in each step. Number of stations from left to right: 132, 120, 109, 98, 86, 73, 62 and 50.

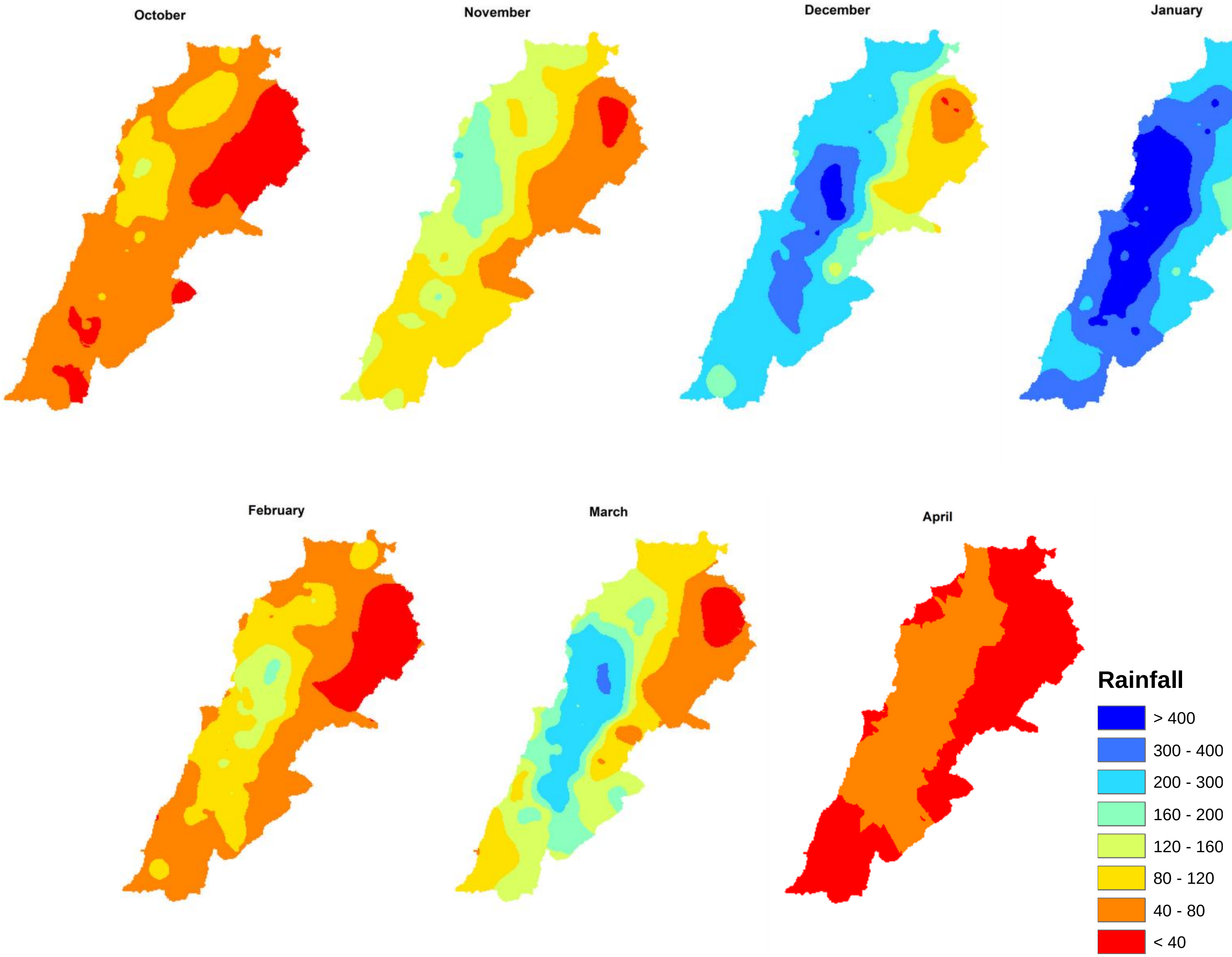


Fig. 3.7 Spatial Interpolation of average monthly rainfall (32 stations) for the period 1967-1970.

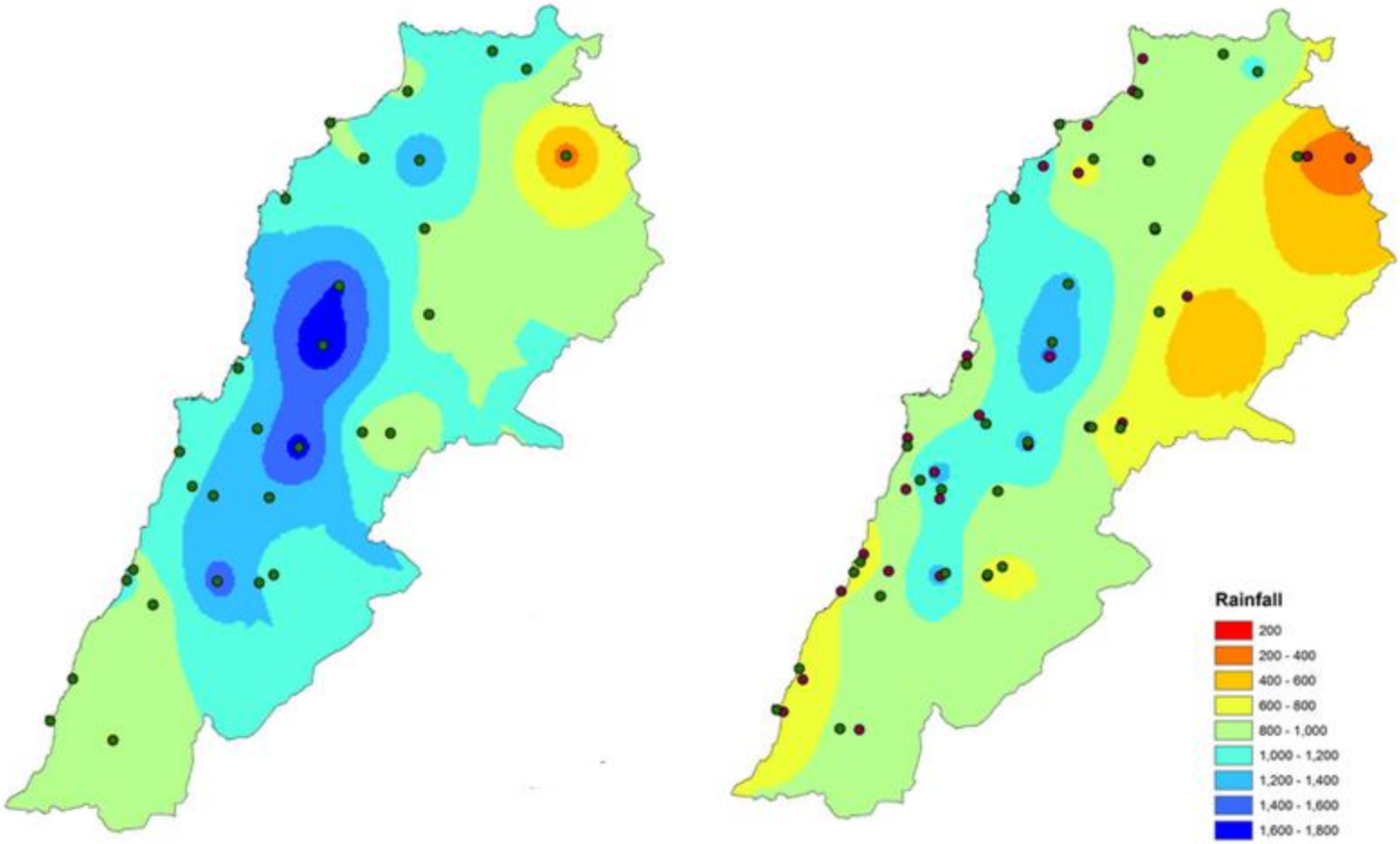


Fig. 3.8 Comparing the spatial distribution of mean annual precipitation (32 stations) for the periods 1967 – 1970 (left) and 2001 – 2011 (right).

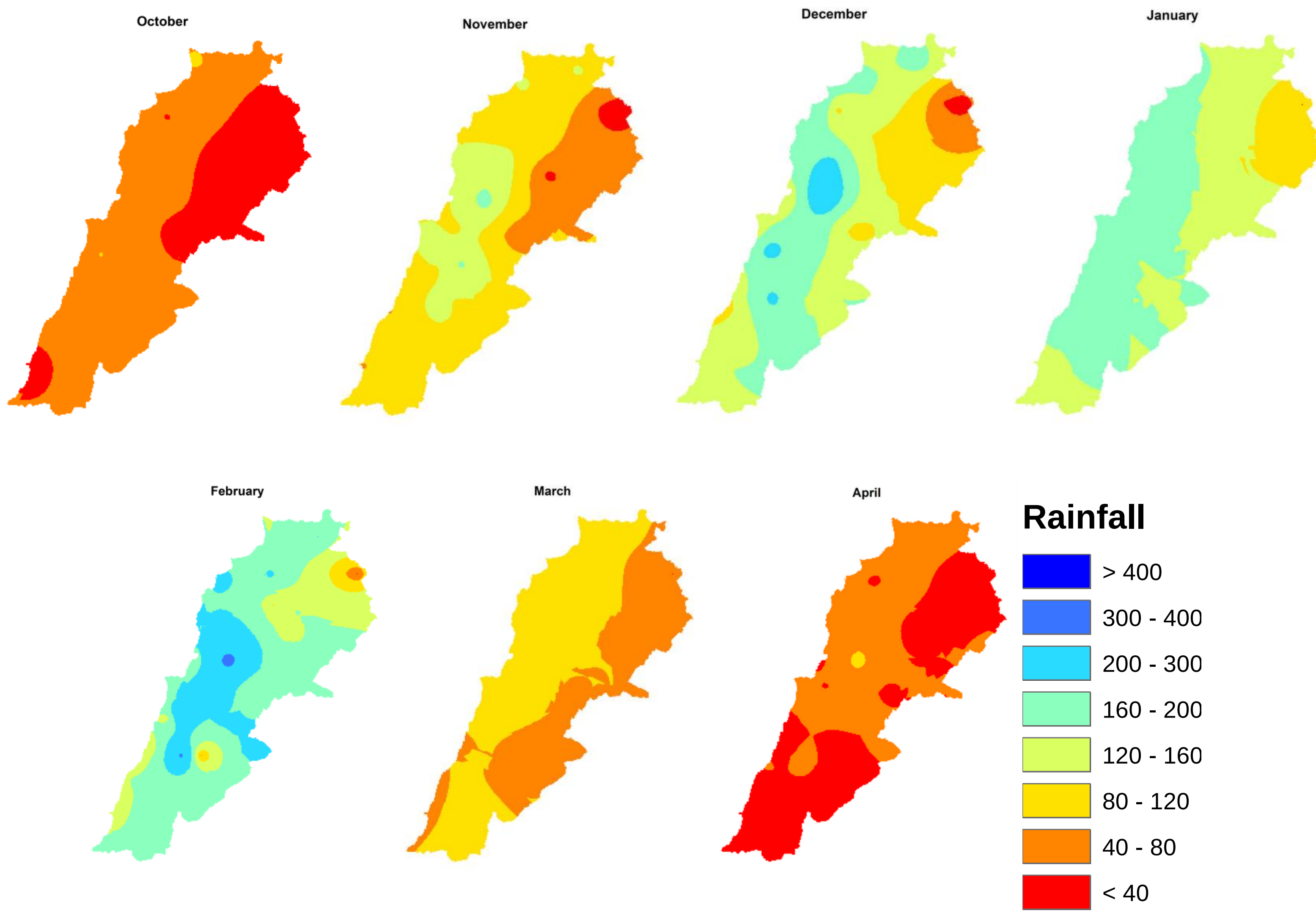


Fig. 3.9 Spatial Interpolation of average monthly rainfall (32 stations) for the period 2001-2011.

Table 3.1 Comparison of catchment MAP interpolation using different number of stations (132 stations (1) and 32 stations (2) for the period 1967 – 1970; column (3) gives the difference between columns (2) and (1). And between the periods 2001 – 2011 (4) and 1967 – 1970 using the same number of 32 stations; column (5) gives the difference between columns (4) and (2). MAP in mm.

Catchments	MAP 1967-1970 132 stations (1)	MAP 1967-1970 32 stations (2)	Column (2) – column (1) (3)	MAP 2001-2011 32 stations (4)	Column (4) – column (2) (5)
Oustuene at sm	972	1012	40	926	-86
Oustwene at Halba	975	1011	35	957	-53
Arka at Hakour	913	1018	105	917	-102
Bared at sm	994	1085	91	902	-182
Abu Ali at Rasheine	1097	1117	21	894	-224
Abu Ali at Abusamra	1084	1094	10	898	-196
Abu Ali at Daraya	1086	1069	-18	921	-148
Abu Ali at Kousba	1086	1069	-18	921	-148
Jaouz at sm	1317	1264	-53	1067	-197
Ibrahim at Roueiss	1237	1217	-20	998	-219
Ibrahim at Afqa	1348	1351	3	1053	-297
Ibrahim at sm	1471	1406	-65	1104	-302
Kelb at Hrajel	1755	1645	-110	1274	-371
Kelb at Daraya	1745	1620	-125	1292	-328
El Kelb sm	1645	1494	-150	1198	-297
Beirut at Jaamani	1490	1374	-116	1103	-271
Beirut at Daychounyeh	1449	1394	-55	1110	-285
Beirut at Jisr El Basha	1431	1382	-49	1099	-283
Damour at Wadi Sett	1482	1421	-61	1077	-344
Damour at Jisr Qadi	1416	1356	-59	1117	-239
Damour at sm	1335	1308	-27	1075	-233
Awali at Marj Bisri	1371	1318	-53	982	-336
Zahrani at sm	1087	1019	-68	919	-101
Orontes	418	848	430	569	-279
Berdawni at D.R.	1521	1185	-336	970	-215
Litani at Joubjannine	972	1068	96	926	-142
Hasbani at Wazzani	986	1097	111	870	-228

3.6 Conclusion

In this chapter we have presented the available data and discussed the methodology used to derive spatial rainfall over the studied catchments. We have tried to assess the impact of decreasing the number of rainfall stations on the spatial distribution of rainfall through interpolation. This step was necessary due to the decrease in the number of rainfall station across Lebanon between the pre-Lebanese civil war (the 1970s) and the current status of the Meteorological network. The methodology gives fair results proving that a rather small number of rainfall stations if distributed intelligibly may be enough. Moreover, we have presented the mean monthly snow coverage over Lebanon for the 2002-2012 periods and classified the country into elevation classes which will be used for snow water equivalent estimation necessary for any hydrological modeling trial in the country. The information derived from these data is used in the next chapters for hydrological response regionalization and modeling.

4 HYDROLOGICAL CHARATERISTICS AND DATA ANALYSIS

4.1 Introduction

In this chapter we will present the available hydrological data for twenty eight studied Lebanese catchments (fig. 4.1) and discuss their hydrological response characteristics in term of mean annual runoff and runoff coefficient, monthly runoff, distribution of daily flows and the maximum specific daily discharge. Finally we define a list of runoff signatures –derived from the literature- to be used for the classification of Lebanese catchments by their hydrological characteristics (see next chapter). Here, one should mention that this work does not take into account possible human impact on river discharges.

4.2 Dataset

Monthly discharge data are available for the 28 studied catchments for the period 2001 - 2012. However daily discharge data are only available for 24 of the 28 studied catchments for the same period (2002-2012). Another daily discharge records exist for the majority of the studied catchments for the period 1967-1974, this dataset will be used to control the quality of the data used in our work (the 2002-2012 period).

Finally, one should mention that the hydrometric network in Lebanon is under the control of the Litani River Authority.

4.3 Methodology

From the above-discussed hydrological information a list of variables (Table 4.1) that reflect different aspects of catchments hydrological responses (runoff signatures) were computed. These variables are widely used in the literature for catchments classification (Olden and Poff 2003, Alcazar and Palau 2010, Sawicz et al. 2011, 2014, Archfield et al. 2013, Viglione et al. 2013, etc.). They represent all aspects of river hydrological regimes: magnitude, frequency, duration, timing, and rate of change (see Poff and Zimmerman 2010). This permits the classification of catchments according to their hydrological characteristics. Table 4.1 summarizes the chosen variables. These runoff signatures will be used in the next chapter for the classification of Lebanese catchments according to their hydrological characteristics.

Table 4.1 Runoff signatures and their description.

Runoff Signatures	Description
RS1	Mean annual flow (m^3/s)
RS2	Mean annual runoff (mm)
RS3	Annual runoff ratio
RS4	Absolute minimum flow (m^3/s)
RS5	Average maximum annual flow (m^3/s)
RS6	Baseflow index, calculated as the ratio (in percentage) of the lowest mean monthly flow to the mean annual flow (Gordon et al., 1992)
RS7	Ratio Q90 %/Q50 %, used as an index of base flow contribution (Gordon et al., 1992)
RS8	Mean flow of Month with highest mean flow
RS9	Mean flow of Month with lowest mean flow
RS10	Slope of the flow duration curve
RS11-21	Number of times that the stream-flow is continuously below the 5 % (RS11), 10 % (RS12), 20 % (RS13), 30 % (RS14), 40 % (RS15), 50 % (RS16), 60 % (RS17), 70 % (RS18), 80 % (RS19), 90 % (RS20), and 95 % (RS21) of mean annual flow
RS22	Coefficient of variation of daily flows for the 10-year period
RS23	Average of coefficient of variation of daily flows for each year
RS24	Average of standard deviation of daily flows for each year
RS25	Coefficient of variation of mean annual flow
RS26	Coefficient of variation of annual runoff ratio
RS27	Variability index as proposed by Growns and Marsh (2000): [Q10 %-Q90 %]/Median

In the following we present some of the main runoff signatures that represent the main hydrological characteristics of the Lebanese catchments.

4.4 Results and discussions

4.4.1 Mean annual discharge, runoff and runoff ratio

Mean annual discharges for Lebanese rivers vary across the country with the highest value (12.2 m^3/s), surprisingly, at the Orontes River (station 25) in the semi-arid northeastern part of the country. It is a springfed river largely controlled by a very large karstic aquifer. Another inland river, the Upper Litani River (the lower part being regulated by a dam), also shows high value of mean annual discharge at station 27 (Joub Jannine). Although, the inland part of Lebanon (Bekaa Valley and the Eastern chain) is the less rainfed part of the country, relatively high values of rivers discharges in this region are plausible. On one hand, these rivers drain the largest catchments in the country; on the other hand, they are mainly springfed rivers with a baseflow index sometimes exceeding 90 % (Sene et al. 1999).

On the western slopes of Mount Lebanon, and in Mount Hermon (Hasbani basin), which have similar characteristics, the highest values of mean annual discharges are encountered in the central part of Mount Lebanon (Ibrahim and El-Kelb basins at station 12 and 15) and at station 5 in Northern Mount Lebanon (Abu Ali River). Ibrahim and El-Kelb Rivers drain the part of Mount Lebanon with the highest rainfall amount. And these rivers are also fed by karstic springs that discharge the high cenomanian plateau of Mount Lebanon. Abu Ali River is the largest catchment on the western slopes of Mount Lebanon and drains the largest and highest mountainous mass of Mount Lebanon (El-Mekmel Mountain which peaks at 3088 m above sea level). Likewise precipitation, annual flows are highly variable. In fact, the coefficients of variation of annual flows are in the range 0.4-0.5 which is "moderate to high" by international standards (McMahon and Mein 1986).

Catchments runoff yields (Fig. 4.1) and runoff ratios (Fig. 4.2) vary largely across the county with the runoff ratio being relatively high. The mean and standard deviation are 629 mm and 381 mm for the runoff, 0.67 and 0.39 for runoff ratio. Moreover, the first, second (median) and third quartiles are respectively 379, 535 and 773 mm for the runoff, 0.47, 0.60 and 0.77 for runoff ratio. Catchments with the highest runoff yields and runoff ratios are the catchments of central (Ibrahim and Kelb: in order of magnitude, stations 11, 10, 12, 13, 14 and 15) and the headwaters of Abu Ali river (stations 7 and 8), while catchments with the lowest values are primarily the large inner catchments (Orontes (25), Litani (27) and to a lesser degree the Hasbani (28)) and the Zahrani in the southernmost part of Mount Lebanon.

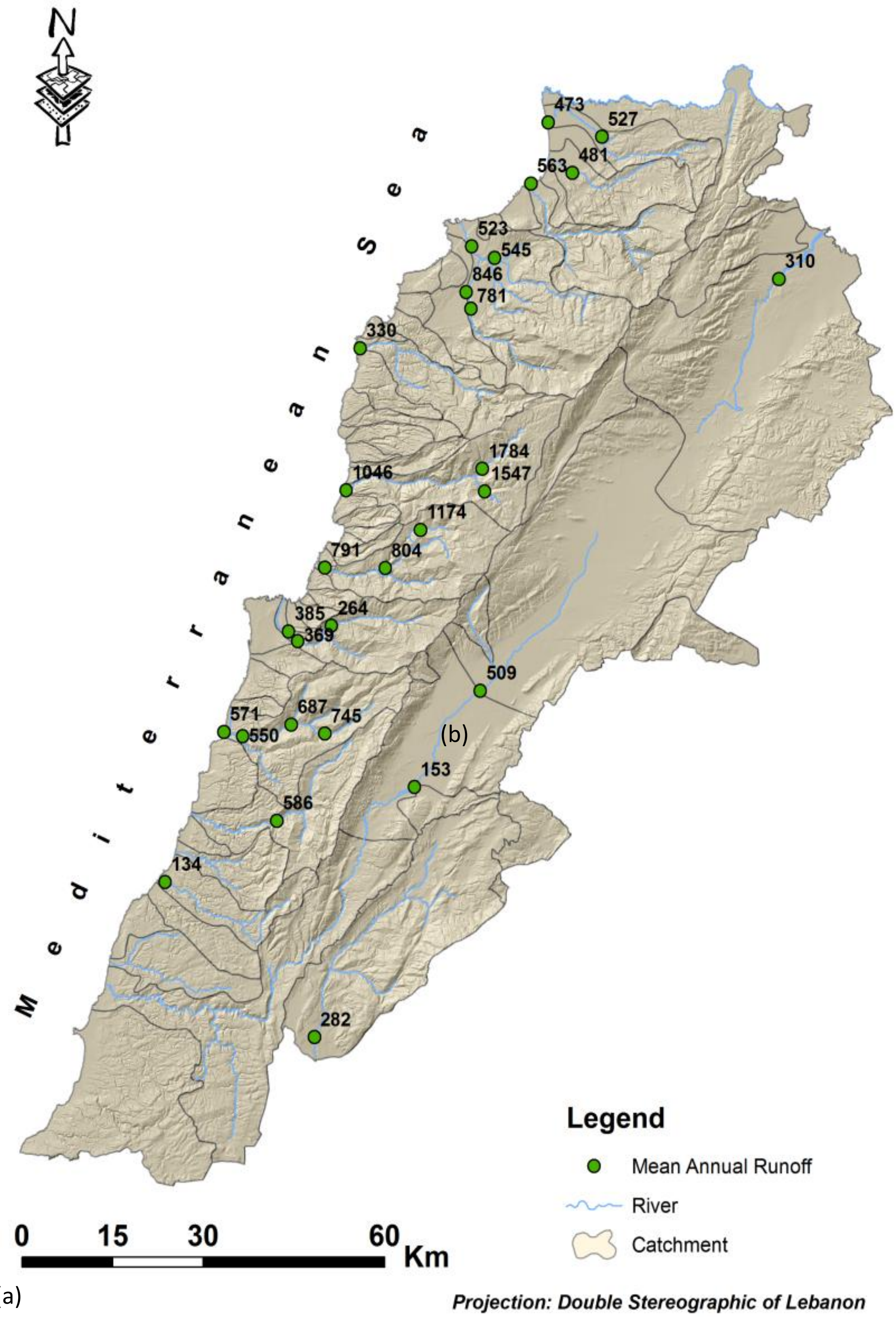


Fig. 4.1 Spatial distribution of mean annual runoff in mm (2001 – 2011).

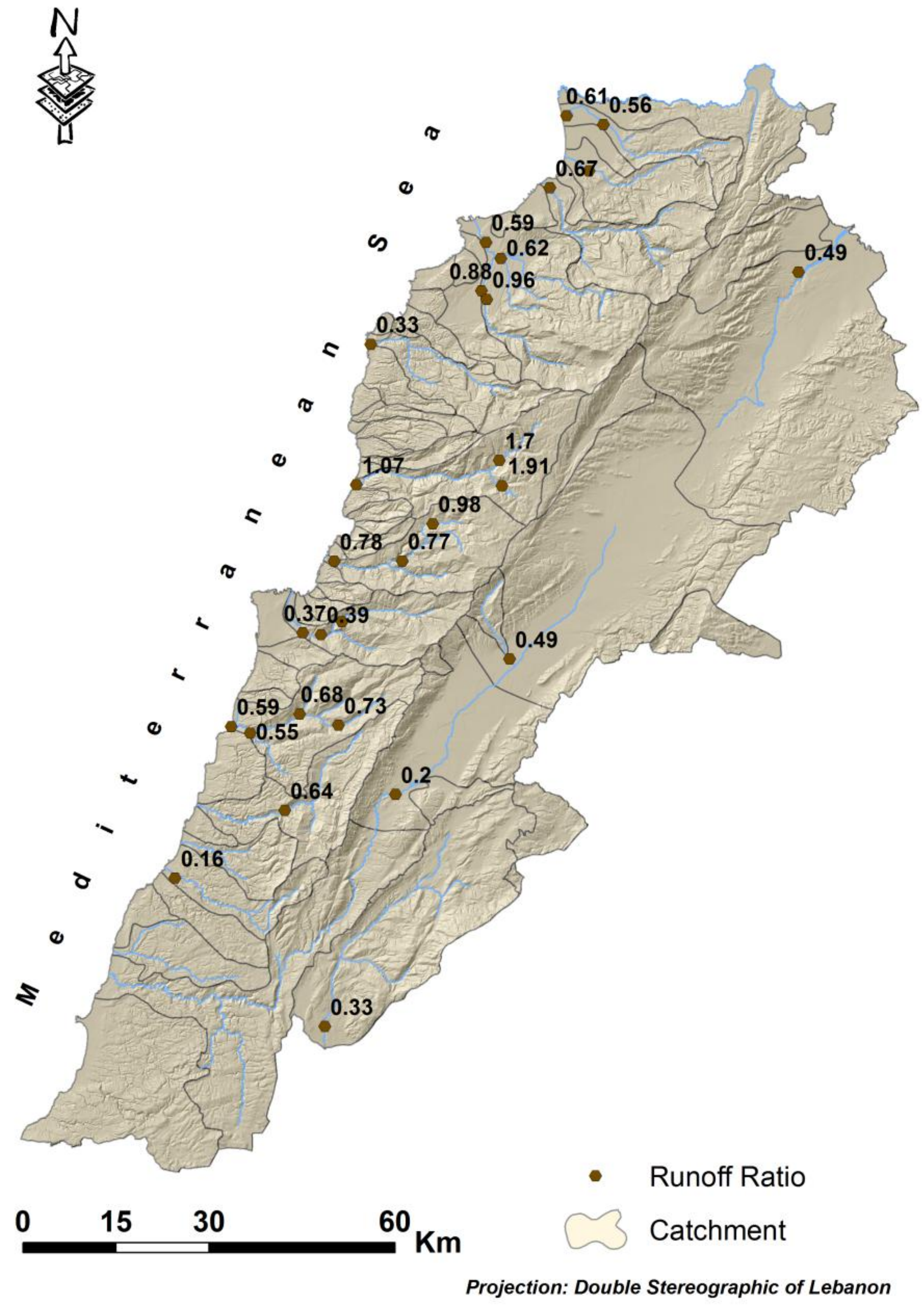


Fig. 4.2 Spatial distribution of mean annual runoff ratio (2001 - 2011).

4.4.2 Distribution of monthly runoff

Except for the particular case of the Orontes River that show almost a uniform distribution of discharge volume over the year, river discharges in Lebanon, likewise the precipitation exhibit a high intra-annual seasonality. Hence, for the large majority of Lebanese rivers more than 75 % of the total annual volumes of river discharges occur from December to April, whereas, less than 15 % of total annual volume occurs from June to November. River discharges began to increase slowly from the beginning of the rainfall season (October - November). The maximum monthly river discharge is reached in late winter (February) and spring (March and April) for the large majority of catchments. For some, especially headwater catchments with important spring discharge and snow melt contribution; a high discharge volume is maintained during May. After reaching its peak, monthly discharge volume began to decrease to reach less than 2 % of the total annual volume for August and September for the large majority of rivers (except the Litani and the Orontes).

According to the monthly distribution of total annual discharge volume for the Lebanese catchments, one can notice 3 main different hydrological regimes (Fig. 4.3):

- Rainfall dominated hydrological regime: here, the main climatic input regulating the hydrological response of catchments is rainfall, thus maximum discharge volume is primarily from the contribution of rainfall, and hence it is reached in February. We can find this type of hydrological response in the Akkar plain, Oustuene River (“a”, 1 and2); Arka River (“a”, 3) In the southern part of Mount Lebanon starting from Beirut catchment (“d”, 17 and 18), Damour (“d”, 19, 20, 21 and 22) and Zahrani (“e”, 24)

- Hydrological regime with important snow melt contribution: here, snow accumulation and melt are a main contribution to the total discharge volume alongside with rainfall. Thus, maximum discharge volumes occur in March. These regimes are found in Abu Ali ((b) 5), El-Jaouz ((b) 9), El-Kelb ((c) 15), the headwaters catchments of Beirut ((d) 16), Awali ((e) 23), in the Litani catchment ((f) 26 and 27) and the Hasbani basin ((f) 28).

- Snow dominated hydrological regime: here, it is snow accumulation and melt is the main contributor to the river discharge. Maximum discharge volume is encountered in April and a high discharge volume is maintained during May. These regimes are found in the most elevated catchments in Lebanon, such as El-Bared ((a) 4), the headwaters of Abu Ali River ((b) 6, 7 and 8), Ibrahim ((c) 10, 11 and 12) and the headwaters of El-Kelb River ((c) 13 and 14).

Finally, the Orontes River is a special case with uniform distribution of monthly discharge volume. It reaches a maximum in May ((f) 25).

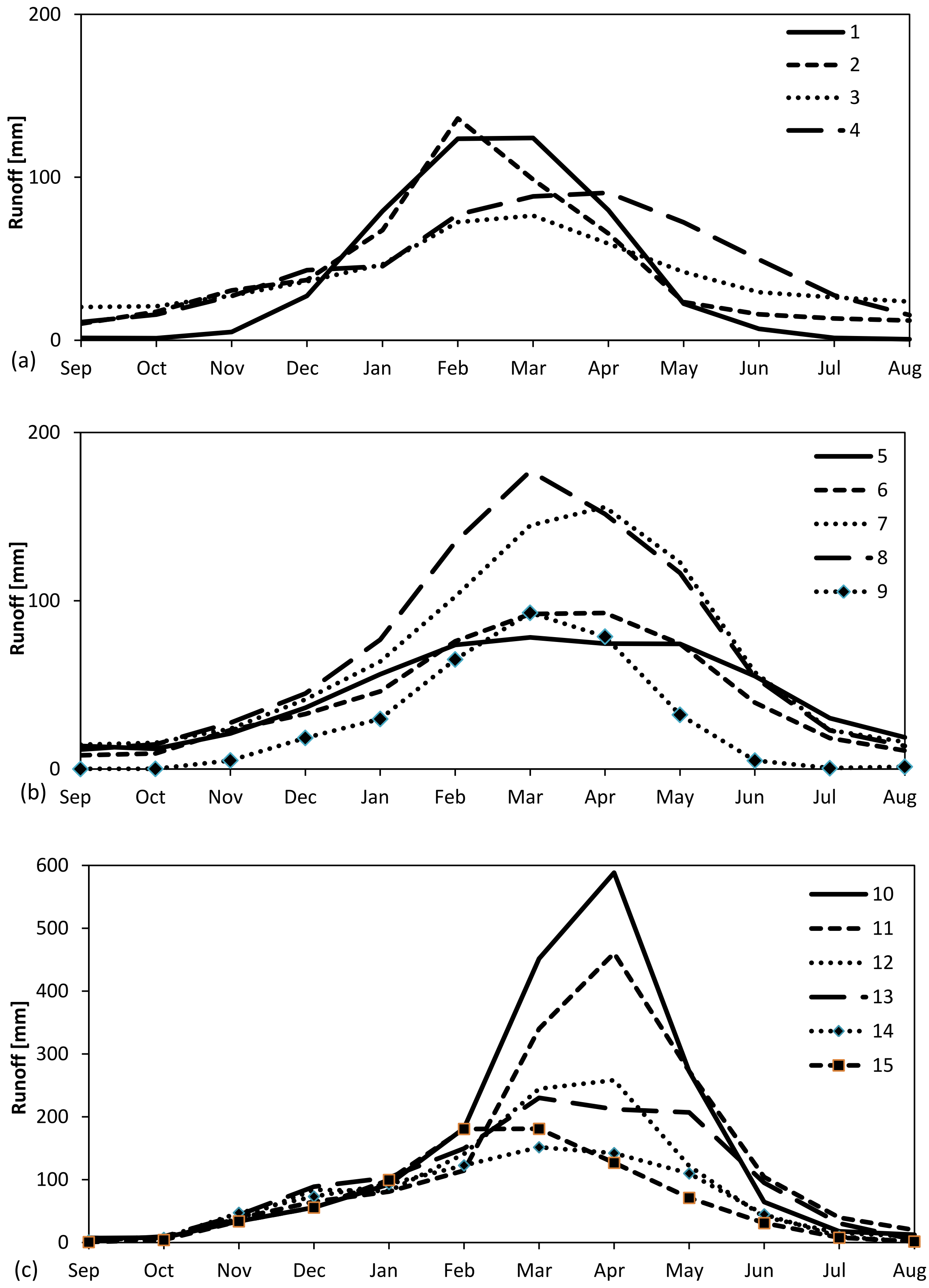
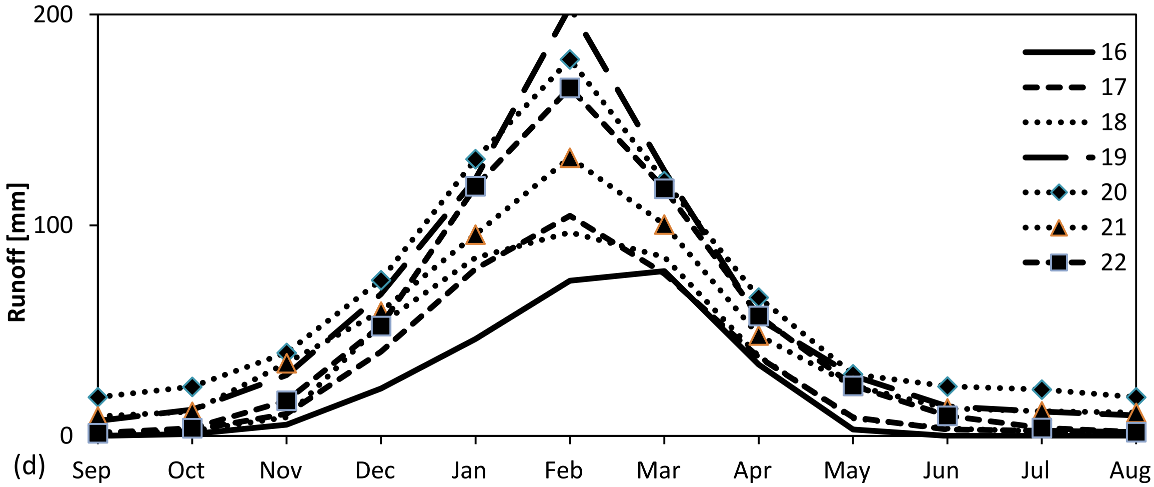
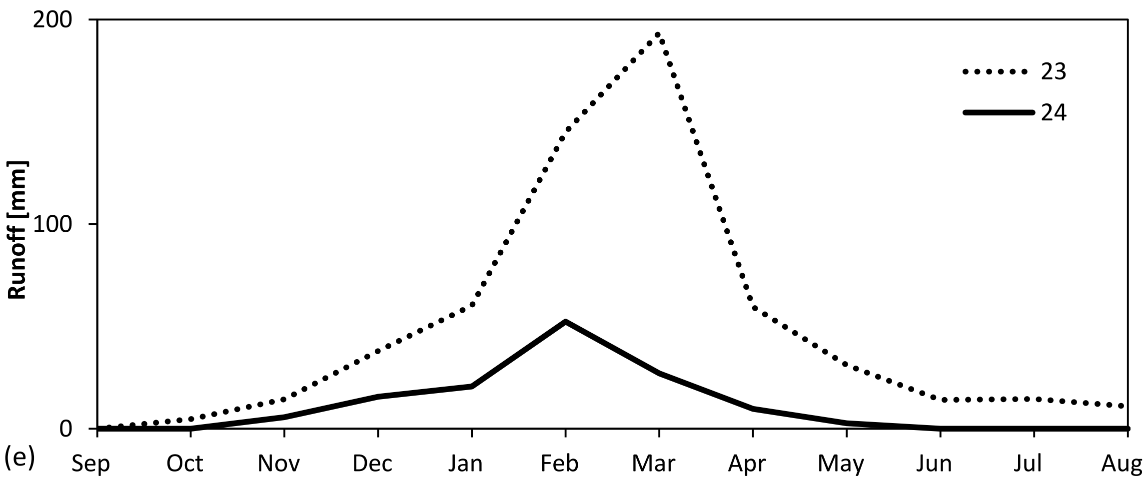


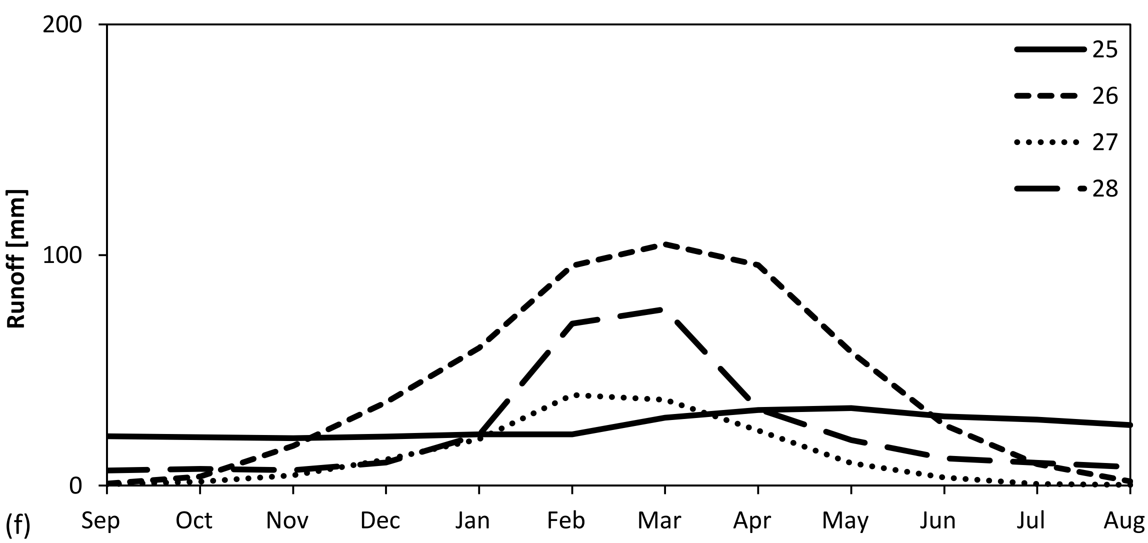
Fig. 4.3 Distribution of mean monthly runoff (mm) for the studied catchments; (a) Oustwene (stations 1 and 2), Arka (3), and Bared (4); (b) Abu Ali (5, 6, 7, and 8) and Jaouz (9); (c) Ibrahim (10, 11, and 12) and Kelb (13, 14, and 15).



(d)



(e)



(f)

Fig. 4.3 Distribution of mean monthly runoff (mm) for the studied catchments: (d) Beirut (16, 17, and 18) and Damour (19, 20, and 21); (e) Awali (23) and Zahrani (24); (f) Orontes (25), Berdawni (26), Litani (27) and Hasbani (28).

4.4.3 Distribution of daily discharge

A flow duration curve (FDC) presents the percentage of time (duration) that a streamflow value is exceeded for a given gauging station at a select time step. Figure 4.4 presents FDCs of daily discharge for stations were daily data are available. Here we compare – when available- FDCs for 2 different periods (1967-1974 and 2002-2012). The aim is to detect any change in the daily distribution of discharge between our study period (2002 – 2012) and a reference period (1967 – 1974). The general allure of the FDCs for the rivers, were data are available, do not change much between the 2 periods except for the stations 11, 13, 15, 17, 18, 20 and 21. In these stations the changes are mainly in the highest durations (lowest flows), here one can attribute these differences to drier conditions or an increase in anthropogenic impact especially for the period 2002-2012, or to gauging problems (non recorded low flows but replaced by zero values instead).

The shape of the FDCs can give a good idea on the hydrological regime of the studied river. Hence a FDC with a steep slope reflects a great contribution from extreme events. This is the case of most of the Lebanese rivers -with the stations in the Central part of Mount Lebanon (Ibrahim, Kelb, Beirut, Damour, and Awali) showing the highest daily discharges values- except for the Orontes River. This could be attributed to the nature of rainfall events in the Mediterranean region where rainfall occur mostly as short duration high intensity rainfall events that are concentrated in winter months (mainly from October to April). Moreover, low flows represent a great part of discharge records. This is due to the long summer dry periods (more than five months) where discharge is only maintained through permanent spring contributions.

One river, the Orontes (25), shows a very gentle slope with very little variation in daily discharges for all durations. This river located in the semiarid northeastern part of Lebanon is maintained throughout a year by a very large karstic spring (Ain Zarqa) with a very deep and well developed karstic system with a very residence time (about 24 years) (El-Hakim and Bakalowicz 2007).

The importance of FDCs in representing the distribution of daily discharges makes it necessary to extract variables that represent different aspect of this curve such as the main durations (representing low flows, high flows and general flow conditions) and the rate of change represented by the slope of the FDC.

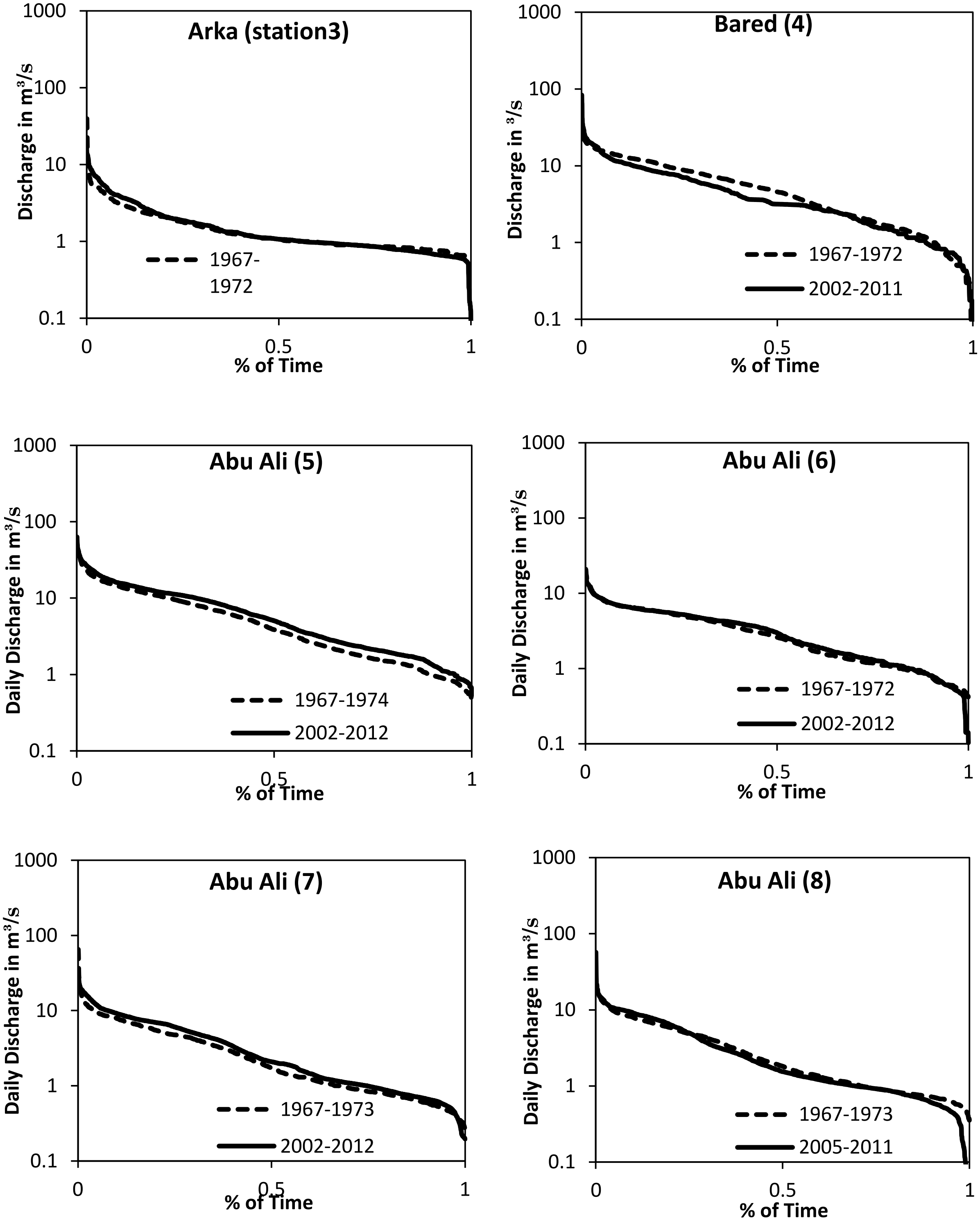
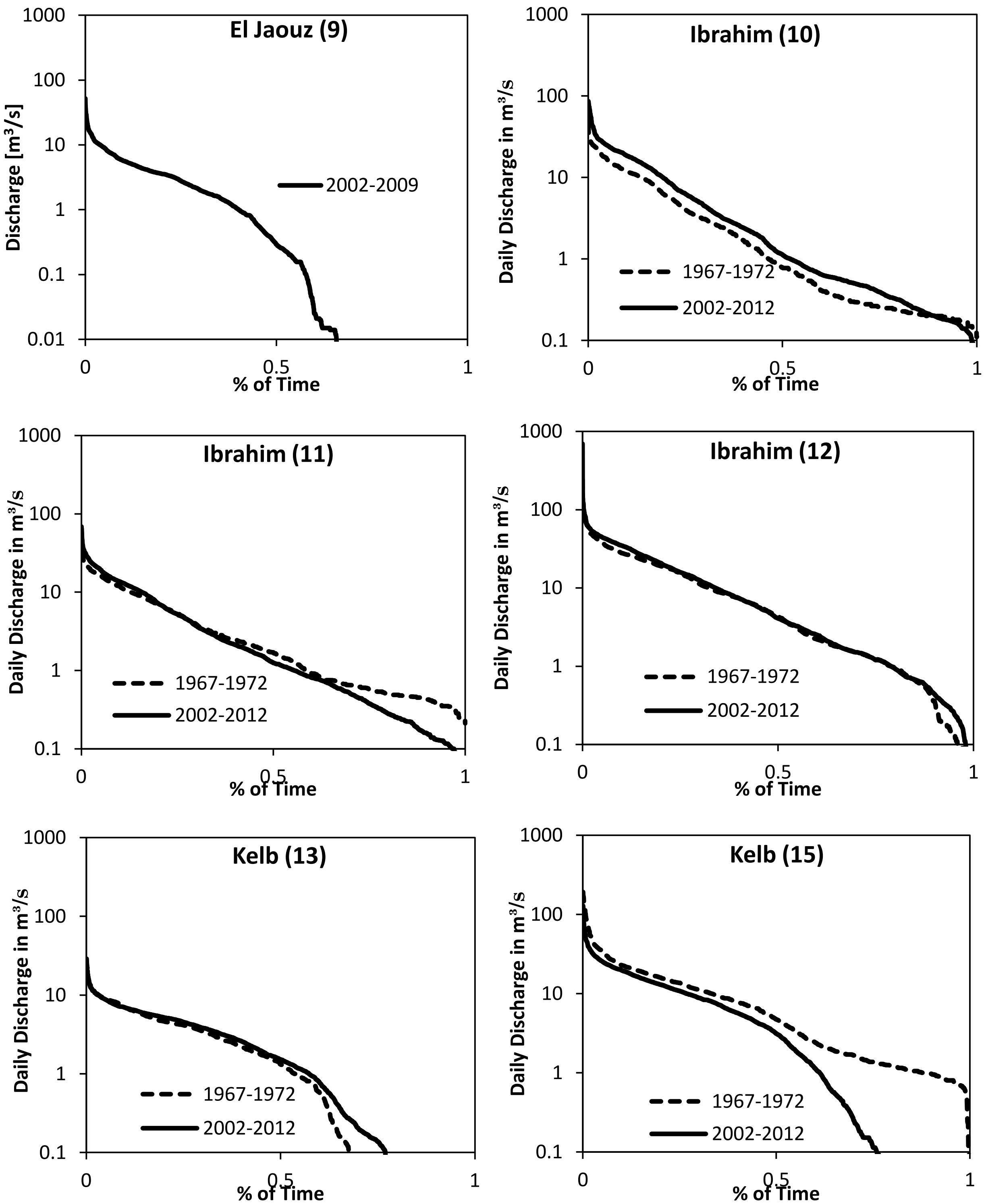
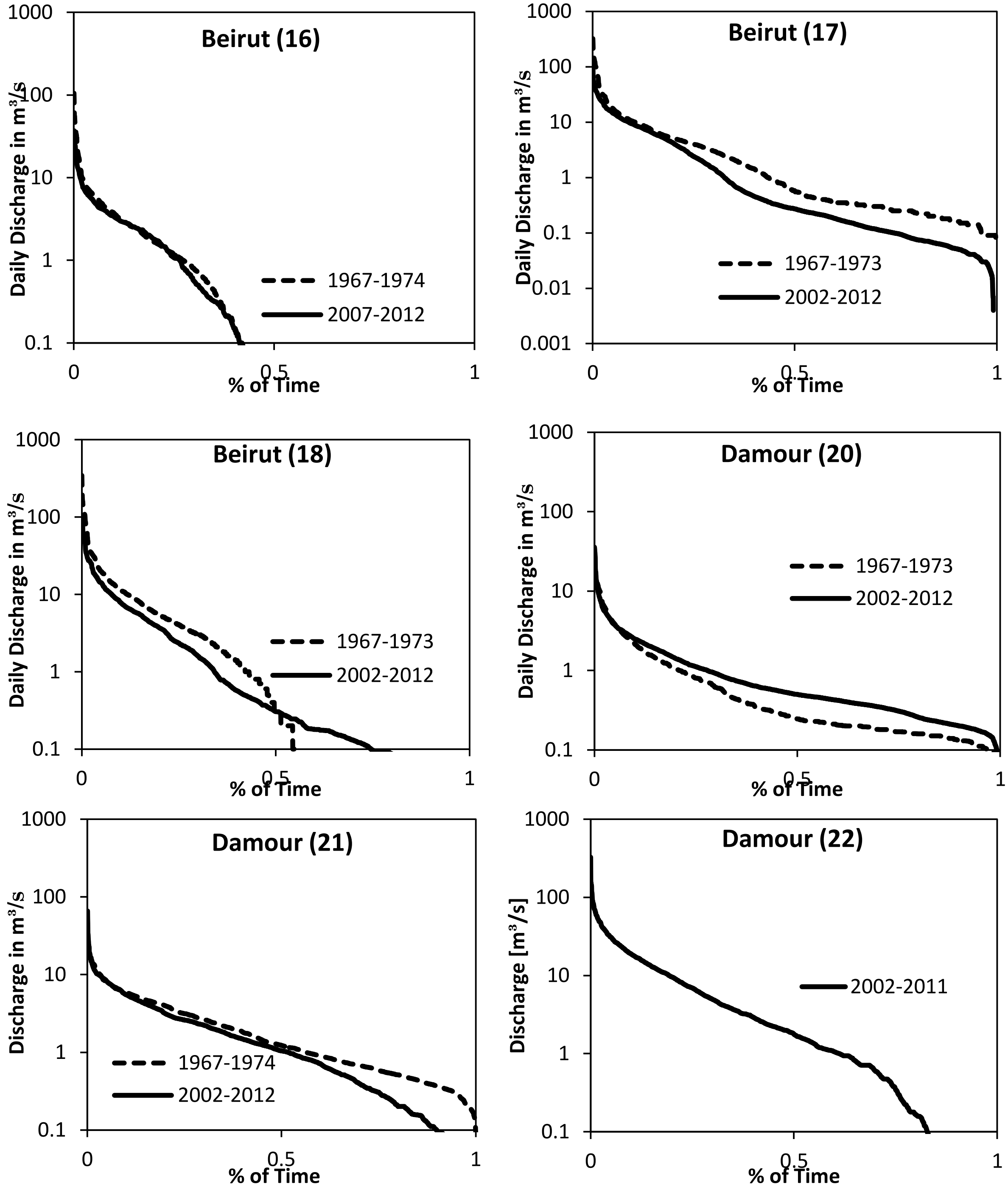


Fig. 4.4 Flow duration curves.


El Jaouz (9)
Discharge [m3/s]
2002-2009
% of Time
Ibrahim (10)
Daily Discharge in m3/s
1967-1972
2002-2012
% of Time
Ibrahim (11)
Daily Discharge in m3/s
1967-1972
2002-2012
% of Time
Ibrahim (12)
Daily Discharge in m3/s
1967-1972
2002-2012
% of Time
Kelb (13)
Daily Discharge in m3/s
1967-1972
2002-2012
% of Time
Kelb (15)
Daily Discharge in m3/s
1967-1972
2002-2012
% of Time


Beirut (16)
Daily Discharge in m³/s
% of Time
1967-1974
2007-2012
Beirut (17)
Daily Discharge in m³/s
% of Time
1967-1973
2002-2012
Beirut (18)
Daily Discharge in m³/s
% of Time
1967-1973
2002-2012
Damour (20)
Daily Discharge in m³/s
% of Time
1967-1973
2002-2012
Damour (21)
Discharge in m³/s
% of Time
1967-1974
2002-2012
Damour (22)
Discharge [m³/s]
% of Time
2002-2011

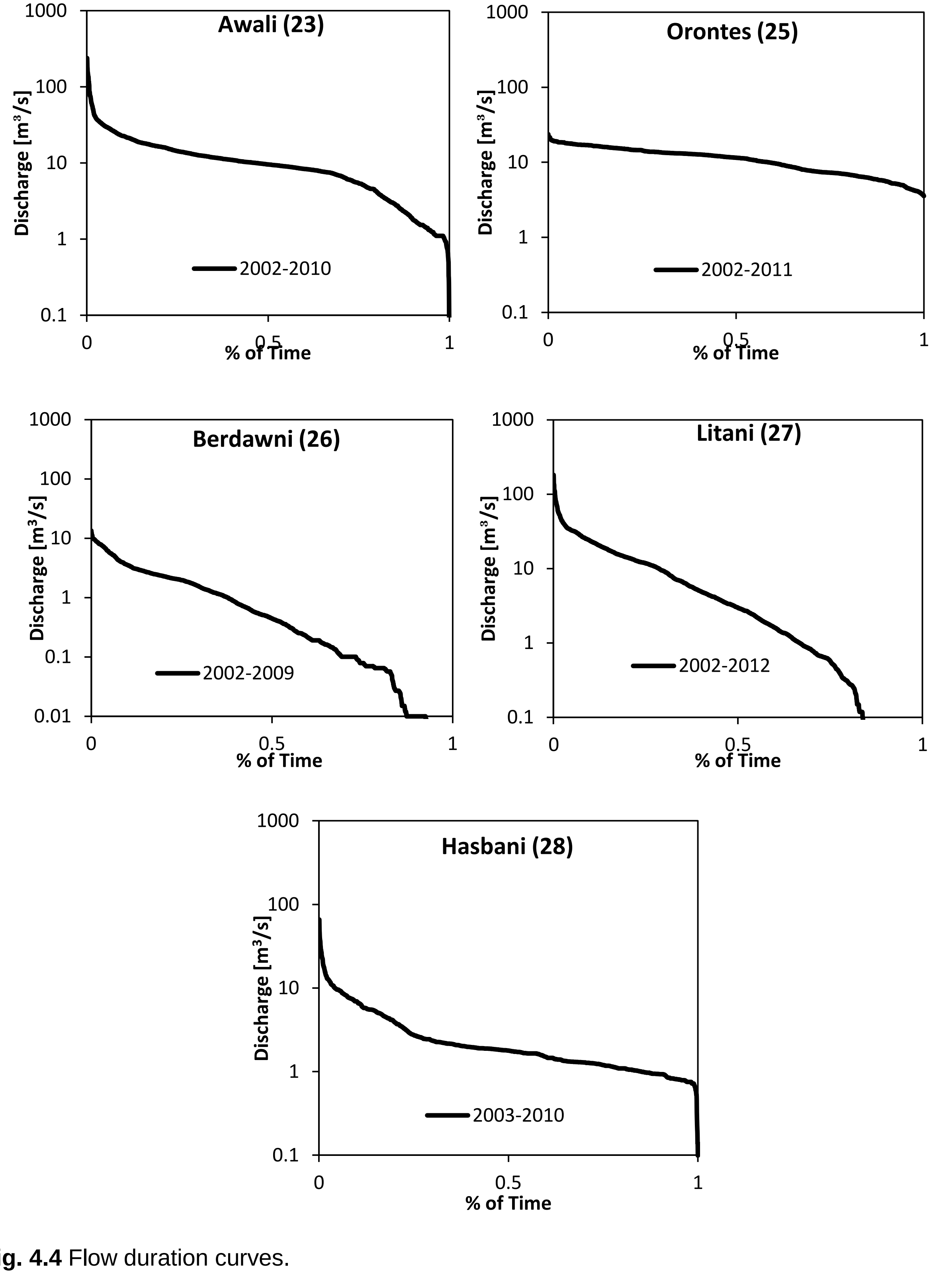


Fig. 4.4 Flow duration curves.

4.4.4 *Maximum specific daily discharges*

Extreme hydro-meteorological events are common under Mediterranean climate. However, the severity of these events depends not only on the meteorological disturbance that induces the event, but also on the physical characteristics of the catchment.

Figure 4.5 represents the Maximum specific daily flow (in m^3/s) for the studied Lebanese catchments for the period 2002 – 2012.

The maximum specific daily discharges in Lebanon exhibit a sort of regional grouping. The highest values being those of the catchments in Central Mount Lebanon (Ibrahim, El-Kelb, Beirut, Damour, Awali) and of the Hasbani, whereas, the lowest are those of the inland part of Lebanon (Litani and Orontes basins). The remaining rivers in northern Lebanon form an intermediate class. This primarily grouping of Lebanese catchments is quiet plausible, given the fact that the central part of Mount Lebanon are formed mainly of small basins (less than 500 km^2) with steep slopes and receive the highest amount of precipitation in the country, and the Hasbani basin have similar characteristics (but a little greater area). Moreover, the inner part of Lebanon is formed by 2 large basins ($Ac > 1000$ km^2) with more gentle slopes and less precipitation.

4.5 Conclusion

In this chapter we have presented the available dataset used for extracting runoff signatures that represent the hydrological characteristics of the Lebanese catchments. The main hydrological characteristics of the Lebanese catchments shows a sort of regional tendencies across in the country with catchments in the central part of Lebanon (the most humid region) exhibiting the highest values in term of both mean annual runoff, runoff ratio and specific daily discharge. Moreover, in term of daily discharge distribution these same catchments have higher percentage with high values of daily discharges. On the other extreme, catchments in the inner part of the country appear to exhibit the lowest values of the mean annual runoff, runoff ratio and daily discharge which are due to both larger basin area and lesser amount of precipitation. Catchments in the northern Lebanon appear to form an intermediate class.

These regional tendencies witnessed here will be re-emerge further ahead when we classify the Lebanese catchments according to their hydrological characteristics.

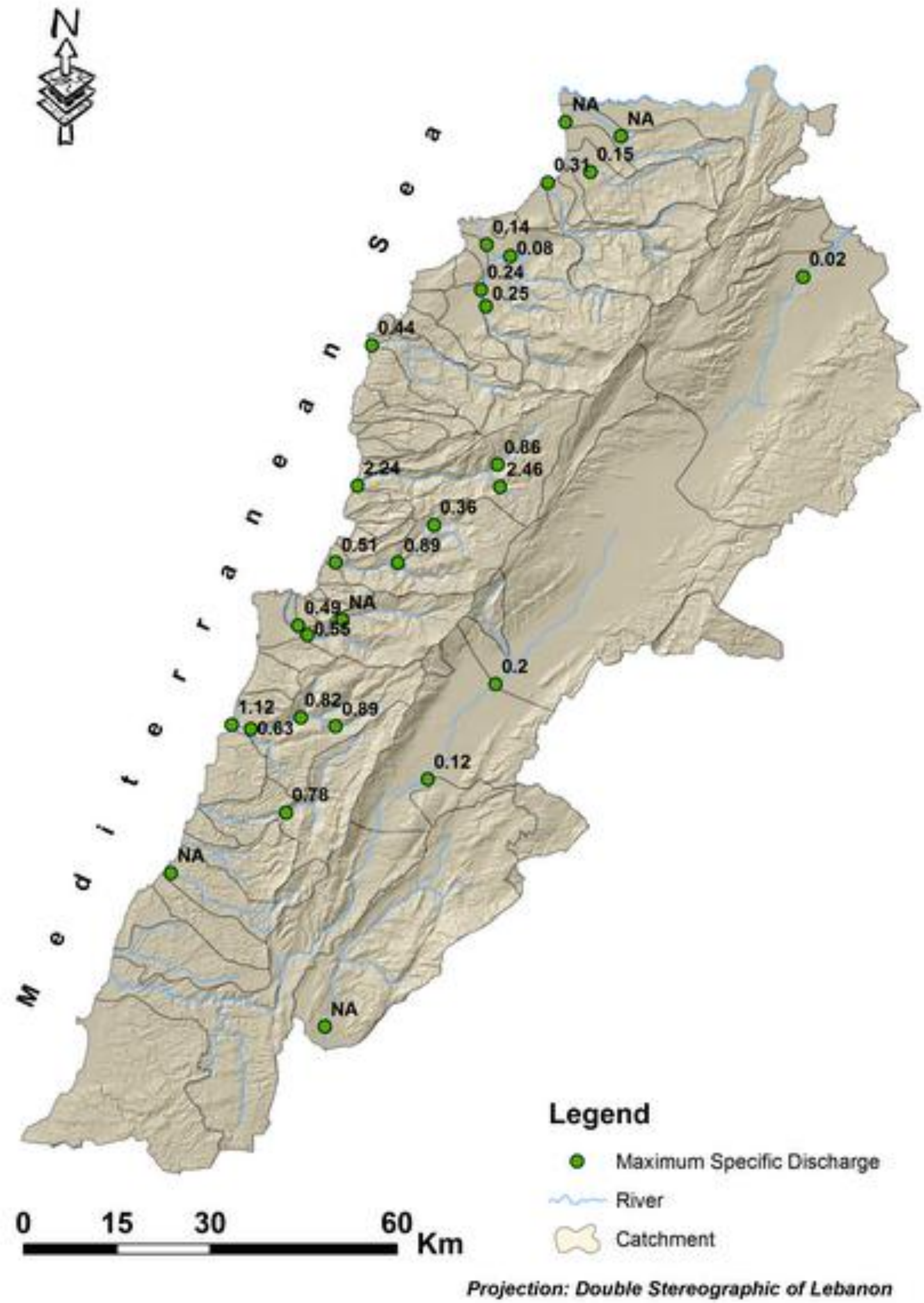


Fig. 4.5 Spatial distribution of maximum specific daily discharge in $m^3/s/km^2$.

5 LEBANESE CATCHMENTS IN THE MEDITERRANEAN

5.1 Introduction

This chapter analyzes the hydrological response of the Lebanese catchments at the annual water balance scale and the event scale. Furthermore, throughout this chapter the Lebanese catchments are compared to other Mediterranean catchments in term of annual water balance and climatic conditions and rainfall-runoff events characteristics. The aim is not only to characterize the Lebanese catchments response to rainfall inputs at the annual and event scale and to compare it to the larger Mediterranean context, but also to compensate the lack of high-resolution data. Comparing different catchments permit one to learn from their differences and similarities and also could be used as a tool for data quality control in poorly-gauged locations. In the following we will (i) present the applied methodology and characterize the Lebanese catchments response at the (ii) annual water balance scale and the (i) event scale. When the information is available, the studied catchments are compared to other Mediterranean catchments.

5.2 Materials and Methods

For the annual water balance scale, mean annual precipitation, reference evapotranspiration and mean annual runoff are calculated from the data presented in the previous chapters for the period 2001 - 2011.

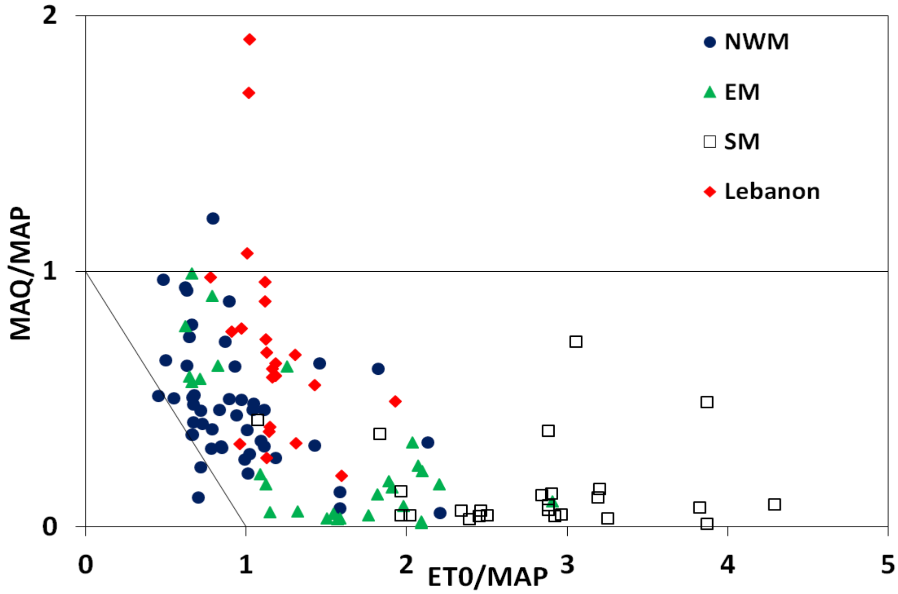
Daily discharge data and precipitation data (with big gaps in the data) are available for the period 2002 - 2011. The rainfall-runoff event selection was based upon the highest maximum daily flow in the record where daily precipitation data are available. So the maximum daily flow is located than the base flow is separated using a one-parameter recursive digital filter. Afterwards the entire runoff event corresponding to the maximum daily flow is extracted: the runoff event is considered from the first day of increase in direct runoff to the last day where direct runoff re-established the pre-event value (normally zero direct runoff). The corresponding rainfall event is assumed to start one day before the rising in direct runoff and to end at the last day with rainfall before the end of the direct runoff.

5.3 Annual water balance

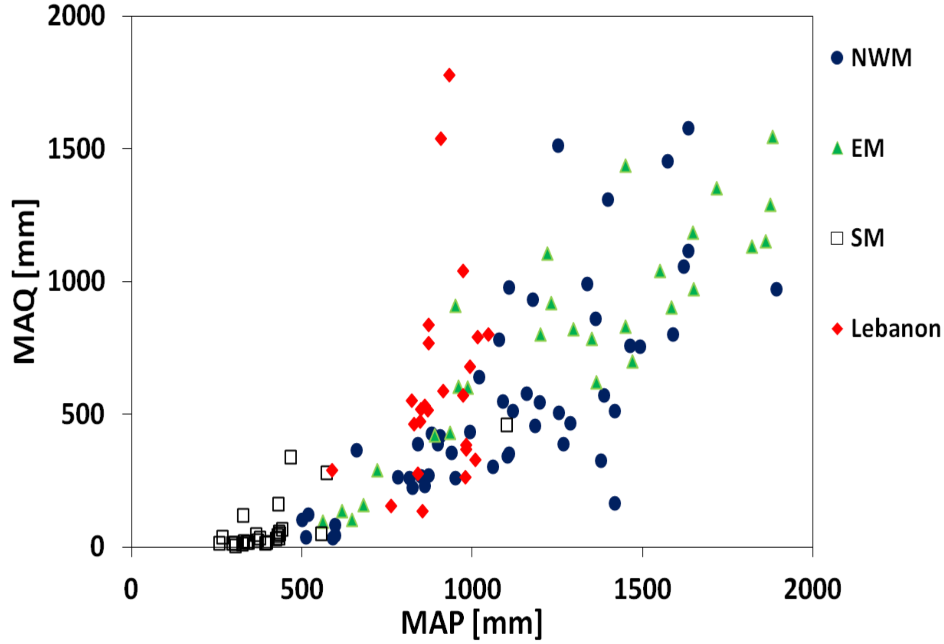
The climatic characterization is carried out here by the mean of the Budyko climatic classification scheme (Budyko 1974) (Fig. 5.1a). It shows the mean annual runoff coefficient MAQ/MAP as a function of the aridity index AI = ET0/MAP. When ET0/MAP<1, wet conditions prevail. When ET0/MAP>1, dry climatic conditions prevail. The lines MAQ/MAP=1 and MAP = MAQ + ET0 represent the water and energy limits respectively. Catchments are expected to fall within these limits for a closed water balance. Otherwise, the catchment is either gaining (catchment with MAQ/MAP>1) or losing (catchment with MAP<MAQ+ET0) water, or there might be under or over-

estimation of mean annual precipitation. Moreover, Fig. 5.1a presents the Lebanese catchments among other Mediterranean catchments. Furthermore, the relationship between mean annual precipitation and mean annual runoff is plotted in Fig. 5.1b and a comparison between Lebanese catchments and other Mediterranean catchments are also presented. Information about Mediterranean catchments was obtained from the literature (see chapter 1).

The majority of the Lebanese catchments are under dry conditions (only four catchments have an aridity index slightly lower than 1). The concentration of Lebanese catchments under arid conditions may suggest that these catchments are under water-limited conditions; however this is not the case with only seven catchments showing low annual runoff yield (MAQ/MAP < 0.5). This can be attributed to three main factors: the fact that precipitation and evapotranspiration under Mediterranean conditions are in opposite phase which mean that although reference evapotranspiration might be high, actual evapotranspiration are much lower, moreover, precipitation in Lebanon are quiet abundant with the majority of catchments (except for the two internal catchments: Orontes and Litani) have a MAP greater than 800 mm and can reach 1200 mm and more (Fig. 5.1b); secondly, an important amount of rainfall occur as snow that accumulates during winter and are slowly released during the spring and early summer which largely increase MAQ, and finally the prevalence of karstic conditions results in large karstic aquifers with recharge areas extending outside the border of the surface catchments and discharge in karstic springs that maintain river flows through the dry season. Hence, the impact of snow and karst are well obvious in catchments exhibiting an annual runoff ratio greater than 1. These are karstic mountainous catchment with snowfall dominated precipitation.



(a)



(b)

Fig. 5.1 (a) Plot of mass balance data on the Budyko's diagram: the mean annual runoff coefficient MAQ/MAP function of the aridity index ET0/MAP for the studied Lebanese catchments among other Mediterranean catchments (from chapter 1), the lines MAQ/MAP=1 and MAP = MAQ + ET0 represent the water and energy limits respectively; and (b) relationship between the mean annual runoff and the mean annual precipitation for the Lebanese catchments among other Mediterranean catchments. MAP: Mean Annual Precipitation; MAQ: Mean Annual Runoff; ET0: Mean Annual Reference Evapotranspiration.

A comparison of summary statistics of climatic and hydrological variables for the studied Lebanese catchments and other Mediterranean catchments in the 3 Mediterranean sub-regions is presented in Table 5.1. As for ET0, it is quite in the range of values recorded in other Mediterranean catchments especially in the EM. However mean annual precipitation values for the Lebanese catchments appears to have a narrow range of variation reaching only a maximum of 1200 mm while in EM subregion values up to 1718 mm are recorded alongside a third quartile of 1394 mm. This apparently low mean annual precipitation values across Lebanon with comparison to other Mediterranean catchments could be almost certainly attributed to a low estimation of precipitation in term of both rainfall and snowfall. This possible under-estimation of mean annual precipitation may result in a relatively higher than usual annual runoff coefficient values.

Nevertheless, the high annual runoff ratio of Lebanese catchments could not be attributed solely to an under-estimation of precipitation since MAQ values across the country are high. Indeed the Lebanese catchments MAQ values are in the range of values recorded in the more humid NWM subregion (rather than the EM catchments). In fact, some of these studied Lebanese catchments are karstic springs with a recharge area greater than the hydrological catchment which can explain the high values of MAQ.

Table 5.1 Summary statistics of climatic and hydrological variables for the studied Lebanese catchments and for catchments in the three Mediterranean sub-regions (NWM, EM and SM) defined in Chapter 2. MAP: Mean Annual Precipitation; ET0: reference evapotranspiration; MAQ: Mean Annual Runoff.

		MAP (mm)	ET0 (mm)	MAQ (mm)	ET0/MAP (-)	MAQ/MAP (-)
Lebanon	Min-Max	588 - 1200	920 - 1212	133 -1777	0.78 – 1.93	0.16 – 1.91
	Median	931	1081	552	1.14	0.62
	Interquartile range	859 - 980	973 - 1121	367 - 790	1.02 – 1.18	0.39 – 0.78
NWM	Min-Max	589 -1892	775 -1617	33 -1579	0.45 - 2.21	0.06 - 1.21
	Median	1113	933	485	0.84	0.46
	Interquartile range	891 -1366	868 - 990	319 - 763	0.67 -1.04	0.32 - 0.62
EM	Min-Max	428 -1718	957 - 1517	12 - 1437	0.62 - 2.91	0.02 - 0.99
	Median	924	1391	105	1.56	0.17
	Interquartile range	713 -1294	1120 -1444	105 - 649	1.02 - 1.99	0.06 - 0.57
SM	Min-Max	257 -1100	519 - 2382	4 - 460	1.07 - 4.29	0.01 - 0.73
	Median	376	1157	33	2.88	0.08
	Interquartile range	327 - 433	811 - 1272	15 - 56	2.39 - 3.19	0.05 - 0.14

Finally, some studies have shown that an increasing dryness index result in high variability of events runoff coefficients (Norbiato et al. 2009; Tarolli et al. 2012), so we might expect a large scatter in runoff response for our catchments. Furthermore, the high variability of the dryness index and runoff yield across the Lebanese basins would certainly impact flood response.

5.4 Rainfall-runoff events characterization: Rainfall and flood response

5.4.1 Selected Rainfall-Runoff events

A summary of the selected rainfall-runoff used in this work is presented in table 5.1. The monthly distribution of these events is shown Fig. 5.2. The month with the maximum number of events is February (about 30 % of the total events), followed by November (26 %) and December (18 %). The remaining events are distributed quite evenly on three other months: January, March and April (about 8 % each).

Table 5.2 Summary characteristic of the selected rainfall-runoff events.

Catchment	Event	Area (km^2)	Rainfall (mm)	Runoff (mm)	Max. daily dis. m^3/s	Spec. max dis.($m^3/s/km^2$)	Runoff Ratio
Arka at Hakour	24 to 27 Nov 2011	102	82	14	15	0.15	0.17
Bared at sm	21 to 23 Nov 2011	281	41	20	64	0.23	0.49
Abu Ali at Racheine	18 to 27 Feb 2003	202	314	57	20	0.10	0.18
Abu Ali at Abusamra	25 to 27 Nov 2004	466	117	16	63	0.14	0.13
Abu Ali at Kousba	25 to 27 Nov 2004	142	117	26	34	0.24	0.22
Abu Ali at Daraya	17 to 19 Feb 2011	144	61	45	57	0.40	0.74
Jouz at sm	16 to 21 Dec 2002	189	198	26	52	0.28	0.13
Ibrahim at Roueiss	31 Mar to 5 Apr 2006	101	225	315	86	0.86	1.41
Ibrahim at Afqa	25 to 27 Nov 2004	29	117	201	64	2.26	1.72
Ibrahim at sm	15 to 21 Dec 2002	327	200	207	696	2.13	1.04
Kelb at Hrajel	31 Mar to 5 Apr 2006	75	222	64	27	0.37	0.29
Kelb at Daraya	9 to 13 Dec 2009	143	129	77	58	0.41	0.60
Kelb at sm	25 to 27 Nov 2004	257	117	58	128	0.50	0.50
Beirut at Jaamani	14 to 24 Feb 2009	127	211	47	36	0.29	0.22
Beirut at Daychounyeh	20 to 28 Jan 2004	209	342	98	115	0.55	0.29
Beirut at Jisr El Basha	16 to 27 Mar 2003	217	225	157	104	0.48	0.70
Damour at Jisr Qadi	15 to 18 Dec 2009	185	274	128	151	0.82	0.47
Damour at Wadi Sett	17 to 22 Feb 2003	40	159	112	35	0.90	0.70
Damour at sm	18 to 21 Feb 2011	293	187	137	275	0.94	0.74
Awali at sm	18 to 27 Mar 2003	308	376	233	238	0.77	0.62
Berdawni at D.R.	19 to 28 Feb 2003	77	228	43	13	0.18	0.19
Litani at Joubjannine	19 to 28 Feb 2003	1433	228	29	182	0.13	0.13
Hasbani at Wazzani	20 to 28 Jan 2010	566	251	29	66	0.12	0.12

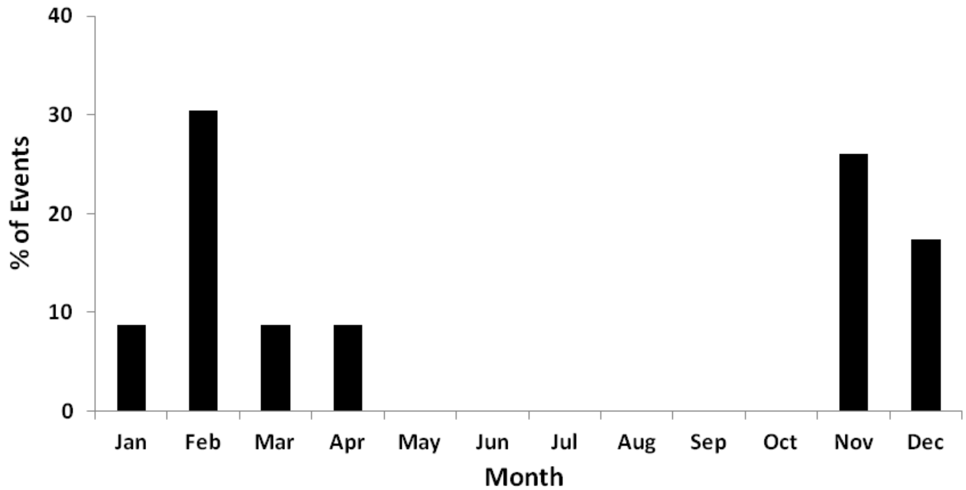
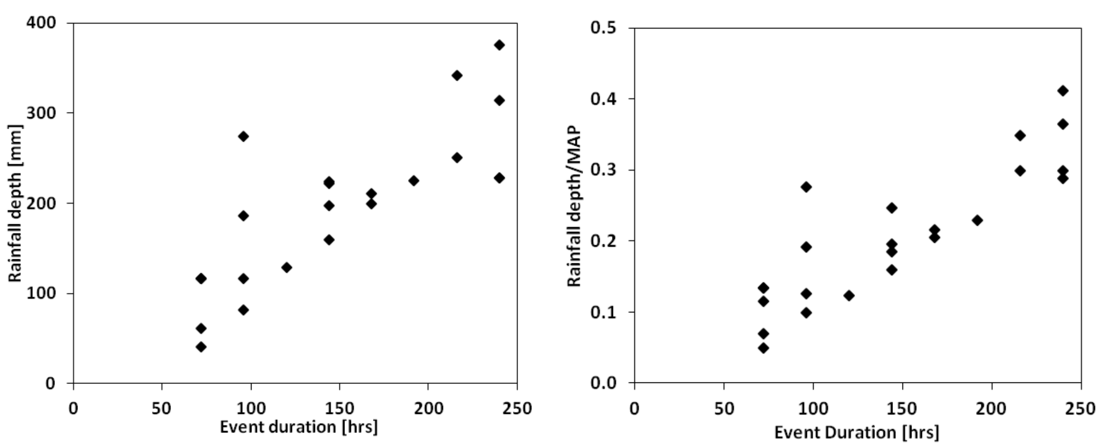


Fig. 5.2 Monthly distribution of the selected rainfall-runoff events.

5.4.2 Rainfall amount and duration

This section describes the rainfall responsible for catchment response in term of two variables: rainfall duration and amount. For the 23 events presented here, the duration of the runoff generating rainfall event varies between 3 and 10 days. Similarly, event rainfall amounts show great variability, from 41 mm in the Bared catchment to 376 mm in the Awali catchment.



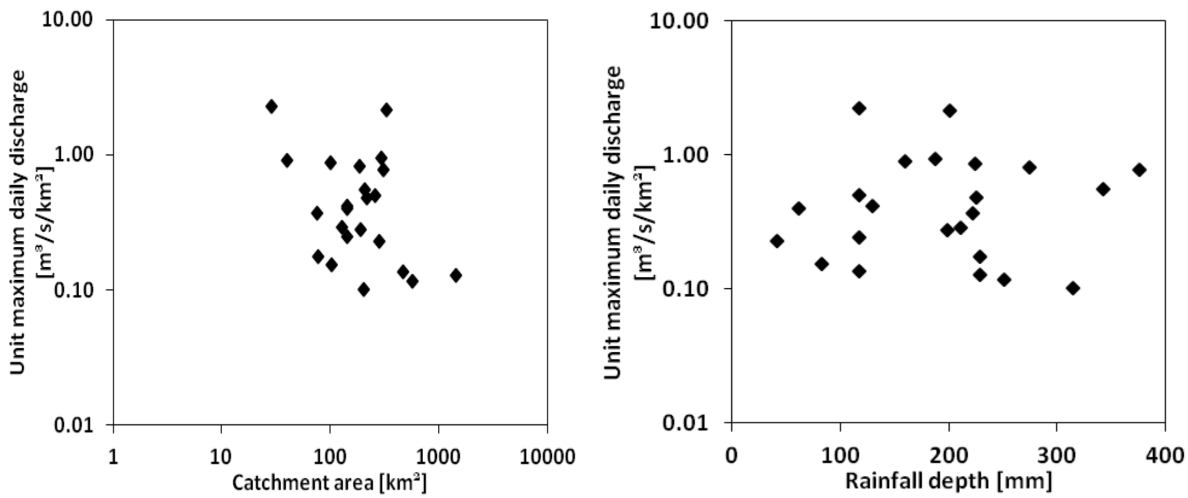
(a) (b)

Fig. 5.3 Event rainstorm characteristics: (a) rainfall event duration versus event rainfall depth and (b) event duration versus ratio of event rainfall depth to mean annual precipitation.

Figure 5.3a represents the cumulative event rainfall as a function of the event duration, with scattering in the relationship. For the same event duration, the total amount of cumulative rainfall can vary. Furthermore, the plot of rainfall duration versus the ratio of event rainfall to the mean annual precipitation presented in Fig. 5.3b permit the comparison between catchments taking into account the difference in mean annual precipitation. As for the event distribution, one can notice no significant differences between Fig. 5.3a and b. Nevertheless, Fig. 5.3b shows how important a single event rainfall amount on the annual water balance for Mediterranean catchments. Hence, in our dataset, event rainfall can represent up to 0.41 of the mean annual precipitation with a mean value of 0.21 and an inter-quartile range of 0.13 – 0.28. This is a characteristic of the Mediterranean climate where rainfall is concentrated in one or two short rainy seasons across the year (Cortesi et al. 2012).

5.4.3 Unit maximum daily discharge

Event peak discharge is widely used as an indicator of the hydrological response of catchments. Unfortunately information about event peak flow is not available herein, so we used the mean daily discharge. Figure 5.4a represents a log-log diagram of the maximum mean discharges of our catchment database: for each catchment, the mean discharge for the day with maximum daily discharge.



(a) (b)

Fig. 5.4 Unit maximum daily discharge versus (a) drainage area and (b) event rainfall depth.

In our dataset, the highest unit maximum daily flow was recorded for Ibrahim at Afqa with a value of 2.26 $m^3/s/km^2$ (A_c = 28 km^2). The inter-quartile range is about 0.2 – 0.8 $m^3/s/km^2$. However, the unit discharges decrease rapidly with the increasing catchment area. This rapid decrease in the unit peak discharge with the increase in the catchment area may reflect the high heterogeneity in the hydrological responses of different locations in the same catchment (Latron and Gallart 2007, 2008). Thus, for a given catchment and a given rainfall event, the runoff-generating processes are not the same in all parts of the catchment. Here one most not that a certain geographical clustering exist in the distribution of maximum daily flow values with the highest recorded in the central part of Mount Lebanon (catchments Ibrahim, Kelb, Beirut, Damour and Awali). These catchments are located in the part of the country that receives the highest amount of annual rainfall. Similar findings were reported in Sene et al. 2001.

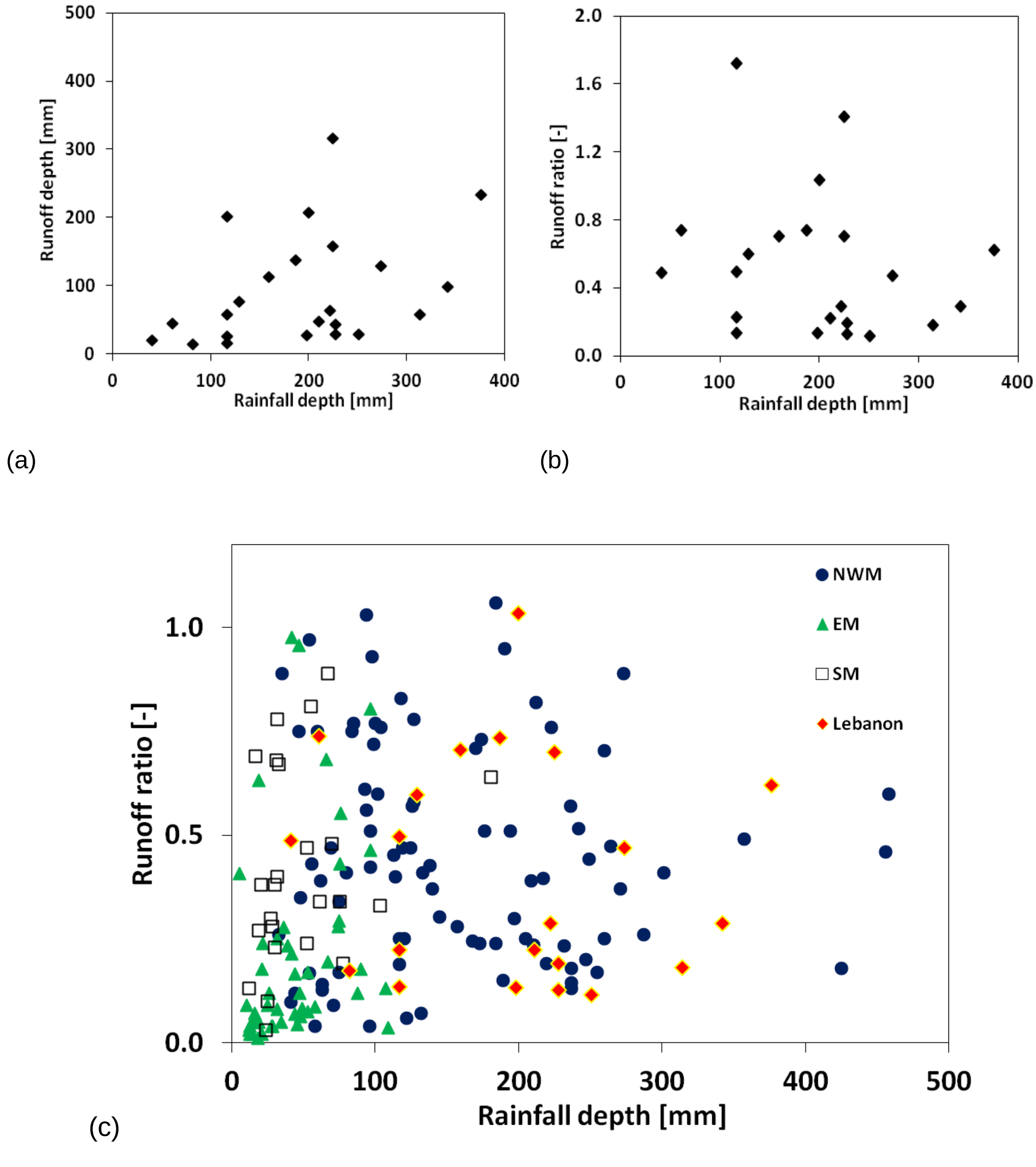
Catchment unit maximum daily discharges as a function of event rainfall depth (Fig. 5.4b) are highly scattered for a given amount of cumulative rainfall. Therefore, no correlation could be found between event rainfall depth and event maximum daily flow.

5.4.4 Runoff ratio

The runoff ratio is defined as the ratio of the event runoff volume to the event rainfall volume. It is a very important concept for assessing the catchment hydrological response. Figure 5.5 presents the runoff depth (Fig. 5.5a) and the runoff ratio (Fig. 5.5b) of the studied Lebanese catchments as a function of the cumulative event rainfall, and Fig. 5.5c compares the event runoff ratio of Lebanese catchments to others Mediterranean catchments. There is clear scattering in the response. Thus, for a given rainfall depth, both the runoff and runoff ratio may greatly vary.

In the studied catchments, event runoff depth and runoff ratio vary over a large range (Fig. 5.5). For instance, runoff depth varies from 14 mm in Arka at Hakour to 315 in Ibrahim at Roueiss with an Interquartile range of 29 – 133 mm. Seemingly, runoff ratio varies from 0.12 in Hasbani at Wazzani to 1.7 in Ibrahim at Afqa with an Interquartile range of 0.19 – 0.7 and median value of 0.47 while runoff ratio's mean and standard deviation are 0.51 and 0.42 respectively. The Lebanese catchments median runoff ratio is in the range of NWM catchments (median for NWM region is 0.4) and much higher than values recorded in EM catchments (median for EM is 0.12). This is clear in Fig. 5.5c where the Lebanese catchments appear to be in the same range of catchments in the NWM. High events runoff ratios recorded for the Lebanese catchments can be attributed to the fact that the majority of these events occur during the wet season, thus, the initial moisture conditions could trigger the generation of important runoff amounts.

The relatively low dependency of the runoff ratio on the cumulative rainfall depth could be explained by many factors. First, under Mediterranean climatic conditions, Hortonian flows are dominant; thus, the catchment hydrological response is rather controlled by rainfall intensity than depth. Moreover, for different events (even with the same amount of rainfall), the initial moisture conditions are different and trigger different hydrological responses. Furthermore, the temporal and spatial distributions of a rainfall event certainly play a role in shaping the catchment hydrological response. Furthermore, In Mediterranean catchments, the temporal and spatial distributions of a rainfall event are highly variable with heterogeneous runoff-generating processes and the percentage of the catchment area that actually contributes to runoff can vary (Latron and Gallart 2007, 2008, Molina et al. 2014).



(a) (b) (c)

Fig. 5.5 (a) Event runoff depth versus event rainfall depth and (b) event runoff ratio versus event rainfall depth for the Lebanese catchments and (c) comparison with other Mediterranean catchments.

5.5 Conclusion

This chapter presented an analysis of the hydrological response of the Lebanese catchments at the annual water balance and the event scale.

The analysis shows that the majority of the Lebanese catchments are mountainous with high relief ratio and drainage density which favors the rapid concentration of runoff along flow lines. Although under Mediterranean climate these catchments do not exhibit water-limited conditions, in fact annual runoff ratio/aridity index values are higher/lower than recorded in other EM catchments. The amount of rainfall in a given event could present up to 40 % of the total annual rainfall. Estimation of the unit peak flows are in the range of those recorded in other EM catchments however, events runoff ratios (mean = 0.39) are more in the range of the NWM catchments (mean runoff ratios are 0.4 for NWM, 0.35 for SM and only 0.12 in EM); this could be attributed to the karstic nature of the Lebanese terrains. Moreover, in Lebanon and all across the Mediterranean, unit peak flow and event runoff ratio are not correlated to event rainfall depth. Finally, antecedent soil moisture conditions appear to have a major impact on the catchment response especially in term of event runoff ratio.

Finally, one should not that comparing catchments in the same climatic region does not only permit to deepen our understanding of the hydrological processes under these particular climatic conditions but also to assess the data quality especially in poorly-gauged environments such as Lebanon. Nevertheless, it does not omit the need for higher resolution data that permits more in-depth investigation of the mechanism that trigger Lebanese catchment response.

PART III.

CLASSIFICATION AND MODELING OF LEBANESE CATCHMENTS

This part presents a classification of the Lebanese catchments according to their physical and hydrological characteristics. The variables defined in the previous part were used here for the classification. Moreover, a simple modeling approach were undertaken to test the robustness of the classification. The part ends by a proposition of conceptual models that represents the different groups.

Chapter 6 presents the classification of the Lebanese catchments by their physical and hydrological characteristics. Here, the physical and hydrological variables extracted in chapters 2 to 4 were used for the classification using an agglomerative hierarchical clustering analysis.

Chapter 7 presents a simple modeling approach at a monthly time scale for the Lebanese catchments. A simple but robust monthly time step model, GR2M, was used to assess the modeling quality of the Lebanese catchments and to compare different regionalization approaches.

6 CLASSIFICATION OF LEBANESE CATCHMENTS

6.1 Introduction

Regionalization studies in the country are very preliminary. Sene et al (1999, 2000) studied the spatial of baseflow index and the regional distribution of maximum instantaneous flows in Lebanon. They found a certain regional pattern. Abou Daher (2006) established global linear regression models for the estimation of annual runoff ratio. These preliminary studies suggested that all across Lebanon when structural characteristics are not varying, hydrologic parameters shows a remarkable degree of spatial coherence. Therefore, with an integration of more structural and functional characteristics of basins, a regionalization procedure could be undertaken for the Lebanese watersheds.

In the previous part we have analysed the physical, climatic and hydrological characteristics of the Lebanese catchments and compare the hydrological response characteristics of these catchments to their Mediterranean counterparts. In this chapter we used the catchment physical descriptors and runoff signatures previously derived from the data in order to classify the studied catchments accordingly. The aim is to compare catchments and learn from the differences and similarities between physical and hydrological characteristics in order to better understand catchments hydrological functioning and to transfer and generalize this understanding.

In the following we present the methodology applied here for the classification of Lebanese catchments. Afterwards, we present and discuss the results.

6.2 Materials and Methods

The catchment physical descriptors and runoff signatures derived from the data in part II (Data Analysis) are used to classify the Lebanese catchments according to their physical and hydrological characteristics.

The method used here for catchment classification is a hierarchical cluster analysis where groups are built according to distance connectivity (Archfield et al., 2013). It is similarity-based classification approach where the most similar individual are grouped together. The variables used as input to the cluster analysis were the principal components resulting from the initial set of variables (catchments descriptors and runoff signatures).

Principal component analysis (PCA) was applied to each set of variables (catchment physical descriptors and runoff signatures) independently using the correlation matrix as the input to the PCA. The aim is to reduce the dimension of the data set by retaining characteristics that contribute most to its variance (i.e. lower-order principal components, usually containing the most important aspects of the data). PCA permits minimizing redundancy and multicollinearity among the chosen variables (Olden and Poff 2003). It reduces the dimension of the datasets by transforming the n-dimensional space (n=

number of initial variables) into a new m-dimensional space, where m (1<= m <= n) is the number of new variables which are the principal components. These principal components are uncorrelated and orthogonal to one another and ordered as such the first component represents the largest amount of variance in the original dataset.

A hierarchical cluster analysis using a dissimilarity matrix based on Euclidean distance was then carried out to group the gauging stations into clusters of relatively homogeneous catchments with similar physical or hydrological response characteristics. Clusters were generated by minimizing the sums of square distance to the center mean (Ward 1963). This Agglomerative Hierarchical classification is the most commonly used clustering method for catchments classification (Olden et al. 2011). The variables used in the cluster analysis were the principal component axes identified in the PCA for catchments physical descriptors and runoff signatures separately, using the loadings of the original data of each station on each significant principal component.

Finally, catchments that are simultaneously in a group of physically similar catchments and a group of hydrologically similar catchments are put together in one group of physically and hydrologically similar catchments.

6.3 Results and Discussions

6.3.1 Catchment classification

The results of the PCA show that for the two groups of variables (runoff signatures and catchment descriptors) the first three to four principal components (for each group respectively) are statistically significant and explain most of the total variances in the variables (Table 6.1).

So, for the catchment physical characteristics the first four principal components (PC1, PC2, PC3, and PC4) explain about 77 % (40 %, 18 %, 11 % and 8% respectively) of the total variance. While for the catchment hydrological response characteristics (runoff signatures) the first four principal components (PC1, PC2, PC3 and PC4) explain about 86% (44 %, 26 %, 9 % and 7 % respectively) of the total variance in the dataset. Moreover, Table 6.1 shows that for each principal component the variables with the largest loadings are different among axes, therefore there are no redundancies in the new variables (the PC axes) and these variables carry most of the information available in the initial sets of variables.

Table 6.1 Results from the principal components analysis on the correlation matrix of the studied physical and hydrological variables showing the cumulative percentage of variation explained by each lower-order principal component as well as the variables exhibiting the largest absolute loadings.

Group of variables	Principal component	Cumulative % of variations explained by Principal components	Variables with largest loadings on PC
Physical descriptors	PC1	40	Bare, Zc>1800, Sc and MIS
	PC2	58	MAP, Ac, AI and HIS
	PC3	69	MPR, LPR, Min Zc and LIS
	PC4	77	Shrub, AK, HPR and Dd
Runoff signatures	PC1	44	RS16, RS17, RS19 and RS15
	PC2	70	RS24, RS5, RS11 and RS12
	PC3	79	RS10, RS22, RS25 and RS2
	PC4	86	RS3, RS2, RS10, and RS28

The importance of the PCA stands from the fact that the resulting principal components axes are orthogonal, thus the new variables used for catchment classification are relatively independent from one another within the single PCS (Olden and Poff 2003). So, the principal components identified for each group of variables were used to classify the studied catchments in groups of physically or hydrologically similar catchments using the agglomerative hierarchical clustering technique. Mahalanobis distance was used in the cluster analysis to avoid multicollinearity problems on the combined PCA scores (Alcazar and Palau 2010). The results of the two classifications (physical similarity and hydrological similarity) are presented in the following sections.

6.3.2 *Physically similar catchments*

The cluster analysis revealed five groups of physically similar catchments; except for two exceptions (Awali and Damour in groups 1 and 3 respectively) all groups form rather geographical differentiated area. (Fig. 6.1 a and b):

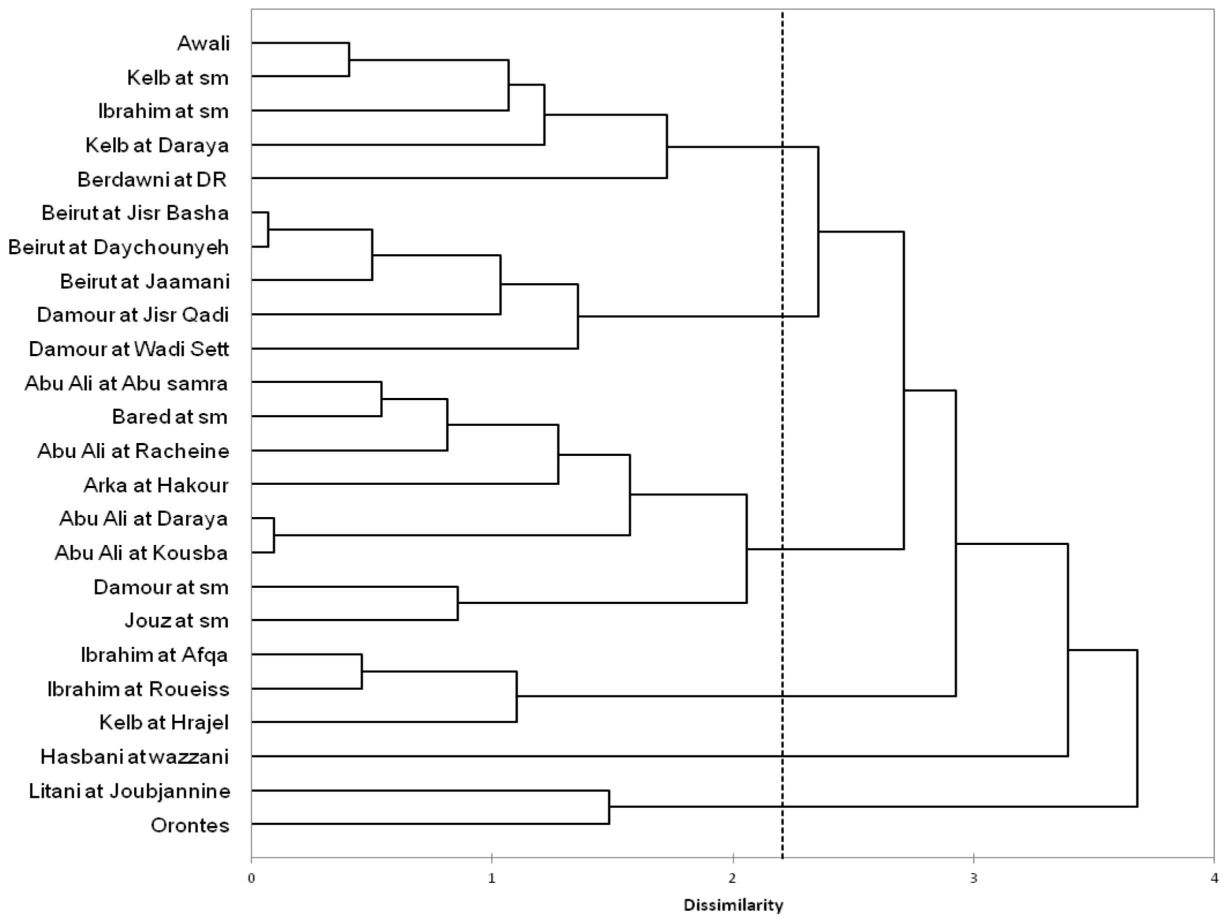


Fig. 6.1a Results of the cluster analysis for physical similarity of the studied catchments using the principal components axes identified in the PCA for catchments physical descriptors.

- Group P1. Five catchments (Awali and Ibrahim at sea mouth; Kelb at sea mouth and at Daraya and Berdawni) that are geographically connected (except for the Awali). These are highly fractured (Apparent karst always greater than 82 %) medium size catchments (maximum Ac of 320 km^2 for the Ibrahim) with mean elevations in the range of 1200-1700 m and steep slopes. Well developed deep soils with agricultural activities covers at least 20 % of catchments areas. At least 50 % of the total catchment area are barelands or/and covered with herbaceous vegetations (grass and shrubs). Mean annual precipitation values ranges from 800 to 1000 mm while annual reference evapotranspiration are slightly lower than mean annual precipitation. The nature of precipitation (rainfall or snowfall) depends upon the elevation.

- Group P2. Five catchments (Beirut at three stations: Jaamani, Daychounyeh and Jisr El Basha; and Damour at two stations: Jisr El Qadi and Wadi Sett). These are small to medium size catchments (40 < Ac < 217 km^2) with gentler slope (Sc around 10 %) and relatively medium elevation (mean Zc around 1000m and less than 3 % of Ac above 1800m). Approximately 50 % of the catchments areas are formed of karstified highly permeable rocks. Deep soils suitable for agriculture are present in these catchments (more than 10 %). At least 12 % of the total Ac is agricultural area, and more than 10 % are urban areas. Forest covers up to 40 % of catchments areas. These catchments receive good amount of precipitation (mean annual precipitation around 950 mm) mostly as rainfall, while reference evapotranspiration values are in the same order of mean annual precipitation.

- Group P3. Eight catchments (Damour, Jaouz, and Bared at sea mouth; Arka at Hakour, Abu Ali at all 4 stations), seven (except the Damour) are in a geographically differentiated region (northern Mount Lebanon). These are highly fractured (AK always greater than 65 %) medium sized catchments (Ac ranges from 102 to 466 km^2). Mean elevation ranges from 750 m for Arka to 1300 m at Abu Ali stations. This group is quite similar to the previous one. However, here deep well developed soils cover at from 20 to 40 % of catchments surfaces with agricultural lands occupying at least 20% of total basins areas. Moreover forests covers from 18 to 37 % of catchments areas. Mean annual precipitation values are in the range of 800-1000 mm while mean annual reference evapotranspiration values are slightly higher than its counterpart. The nature of precipitation (rainfall or snowfall) depends upon the elevation.

- Group P4. Three catchments (Kelb at Hrajel, Ibrahim at Afqa and Roueiss) form this group. These are highly fractured (AK > 85 %) small and steep high elevation mountainous catchments (Ac < 100 km^2, Sc > 16 %) with a mean altitude exceeding 1700 m and 60 to 85 % of catchment area above 1800 m. Soils are shallows with barelands covering about 50 % of total catchments area while the rest is mainly covers by grass and shrubs (to a lesser extent). Moreover, these catchments exhibit the wettest conditions in the country with the largest amount of precipitation (mean annual precipitation around 1200 mm) mostly occurring as snowfall, and a low reference evapotranspiration.

- Group P5. Two catchments (Litani at Joubjannine and the Orontes). These are the 2 largest catchments in the country with Ac exceeding 1200 km^2. They have a mean elevation of about 1300 m (with 10 to 30 % of catchment area above 1800 m for Litani and Orontes respectively).These are more gentle catchments (Sc < 6.5 %) with a good part of the catchment occupied by agricultural plains (21% for the Orontes and 48 % for the Litani) with well developed soils. However highly permeable karstified rocks are always present (50 to 60 % of catchment area). Due to the rain shadow effects of Mount Lebanon, these catchments exhibit the driest conditions in Lebanon. Mean annual precipitation values reach 760 mm for the Litani and a minimum value of 580 mm in the Orontes catchment; while reference evapotranspiration values are in the range of 1100-1200 mm, the highest values in the country.

- One catchment does not fit in any group. The Hasbani is a medium-sized catchment however relatively larger than others (Ac = 560 km^2), highly karstified. Mean elevation is around 1200 m with a maximum elevation at 2810 m, nevertheless only 9 % of catchment area is above 1800 m. Sc is gentle (along 5 %). Deep well developed soils are common in the catchment (more than 50 % of area) alongside agricultural activity. About half the Hasbani area is covered with herbaceous vegetation. It is an inland catchment, however, contrary to the other 2 inland catchments (Litani and Orontes) and due to its southern position (where Mount Lebanon decreases in elevation) it receives a good amount of precipitation with mean annual precipitation around 850 mm. Finally mean annual reference evapotranspiration is relatively high (around 1100 mm). Precipitation occurs as rainfall or snowfall depending on elevation.

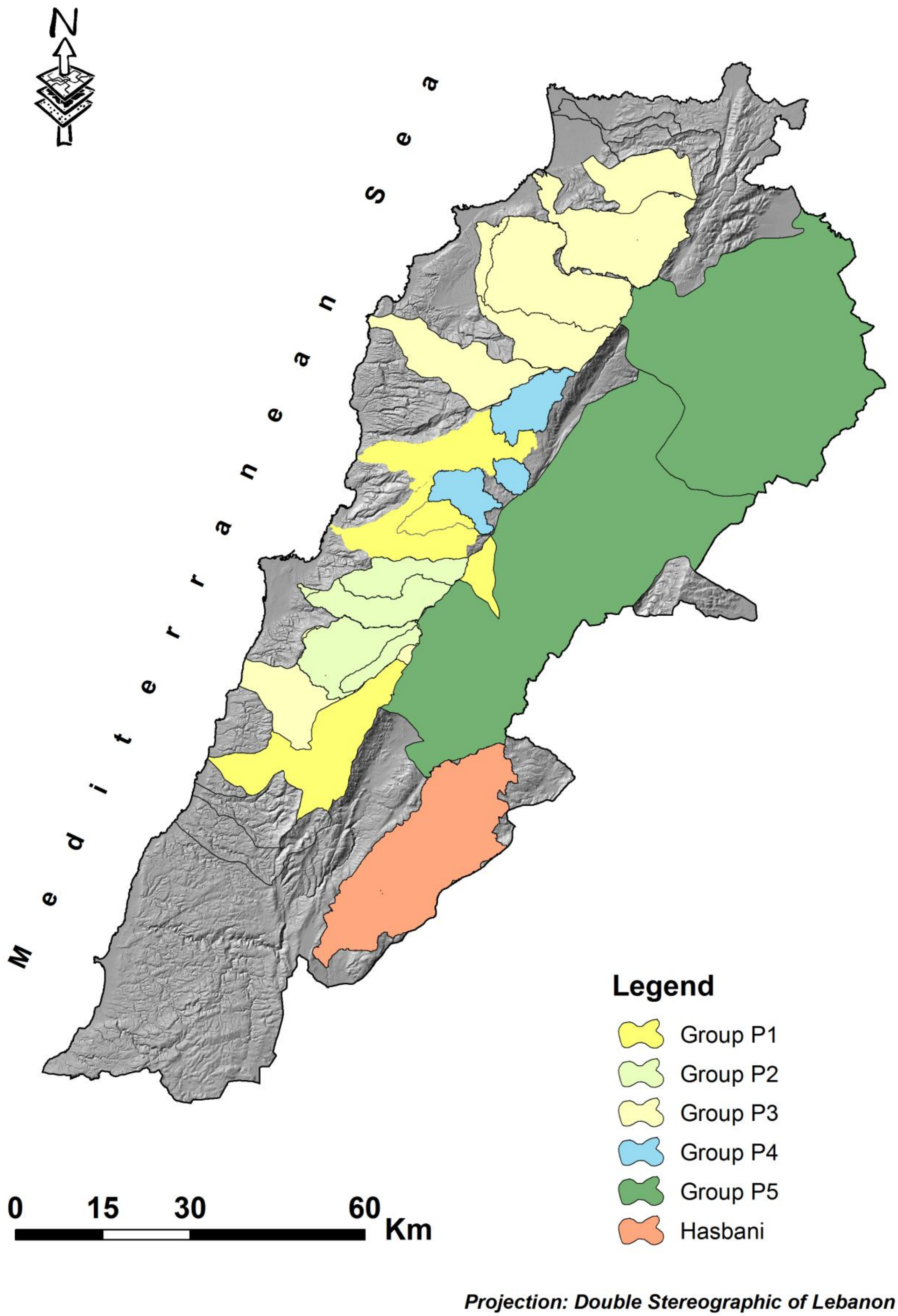


Fig. 6.1b Physically similar catchments.

6.3.3 *Hydrologically similar catchments*

The cluster analysis revealed 3 groups containing many catchments that are not necessarily geographically close, one group including the 2 headwaters of Ibrahim catchment (Roueiss and Afqa) and one catchment that does not fit in any group (the Orontes River (Fig. 6.2 a and b)

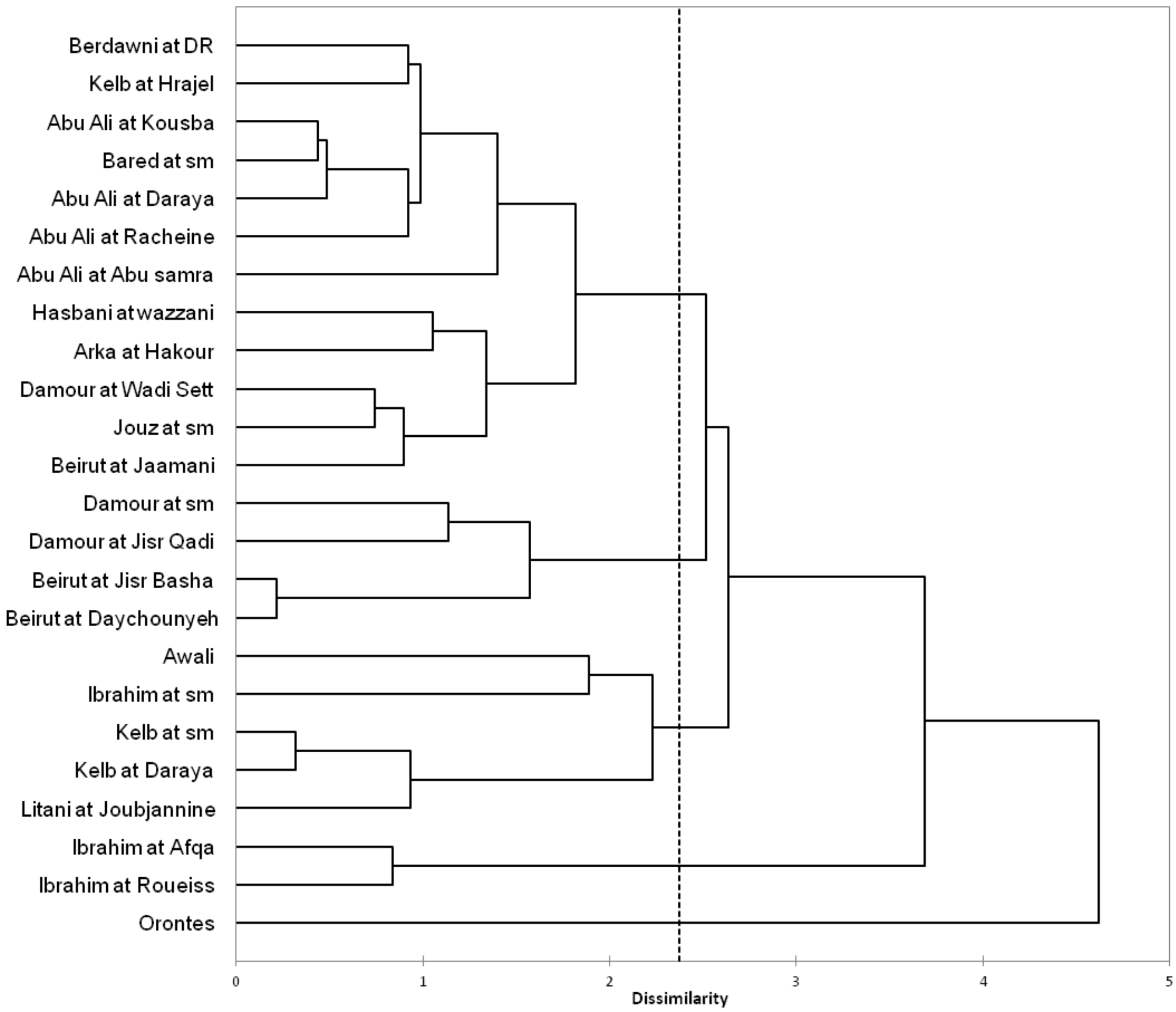


Fig. 6.2a Results of the cluster analysis for hydrological similarity of the studied catchments using the principal components axes identified in the PCA for catchments Runoff Signatures.

- Group H1 (Fig. 6.3). It includes twelve catchments: all catchments in the north (Arka at Hakour, Bared at sea mouth, Abu Ali at all four stations, and Jaouz at sea mouth), the headwaters of catchments in central Lebanon (Kelb at Hrajel, Beirut at Jaamani and Damour at wadi sett) and inland (Berdawni) along with the Hasbani in the inner part of the country. The rivers in this group are influenced by both rainfall and snow melt, here peak runoff is reached in the period between

February and April depending on the main precipitation input (rainfall or snowfall) with a relatively high runoff volume maintained through May and even in June. The runoff volume in the February-April period is somewhat constant (around 15 to 30 % of total annual volume) and about 10 to 15 % of the total annual volume is yielded in the dry season which emphasizes the role of snow and groundwater recharge in the hydrological processes of these catchments. Moreover, for a majority of these catchments minimum flows (below the mean) represent 60 to 80 % of the total daily discharges; and represents 10 to 45 % of the total volumes. However, some differences exist with the headwaters of Kelb, Beirut and Damour, the Jaouz and Berdawni where rainfall input appears to be greater than snowmelt (peak runoff in February) and the response is more extreme. Here mean daily flows exceeding 10 times the mean occur 2 to 5 % of time and contribute to about 10 to 22 % of total volume.

- Group H2 (Fig. 6.4). It includes four catchments (Damour at sea mouth and Jisr el Qadi, and Beirut at Daychounyeh and Jisr el Basha). Here rainfall is the main contributor to river discharges and catchment response to rainfall input is quiet rapid with a sharp increase in runoff that peaks in February(about 30 % of total volume) than decrease rapidly. Here discharge exceeding 10 times the mean occurs about 2% of the time but contribute from 18 to 25 % of the total annual discharge volume.

- Group H3 (Fig. 6.5). Five catchments (Awali, Ibrahim and Kelb at sea mouth; Kelb at Daraya and Litani at Joubjannine). Rivers in this group are quiet similar to those of group 1 however the main differences are the lower contribution of low flows (only 10 to 25 % of the total volume) with minimal runoff volume in the dry season and a greater contribution of high flows with more than 70 % of total volume from flows exceeding the mean.

- 3 catchments (Fig. 6.6) Ibrahim at Afqa and Roueiss, and Orontes: the first two make one group of high mountain active karst springs with a low infiltration rate and short residence time (2.5 months), Snow is the main contributor to water yield with the maximum runoff volume reached in April. And the Orontes River at Ain zarqa spring, this is a large karstic spring with a very deep karstic systems, a very low infiltration rate and a huge residence time reflected in a very low discharge seasonality reflected in relatively stable monthly runoff volume and daily flows.

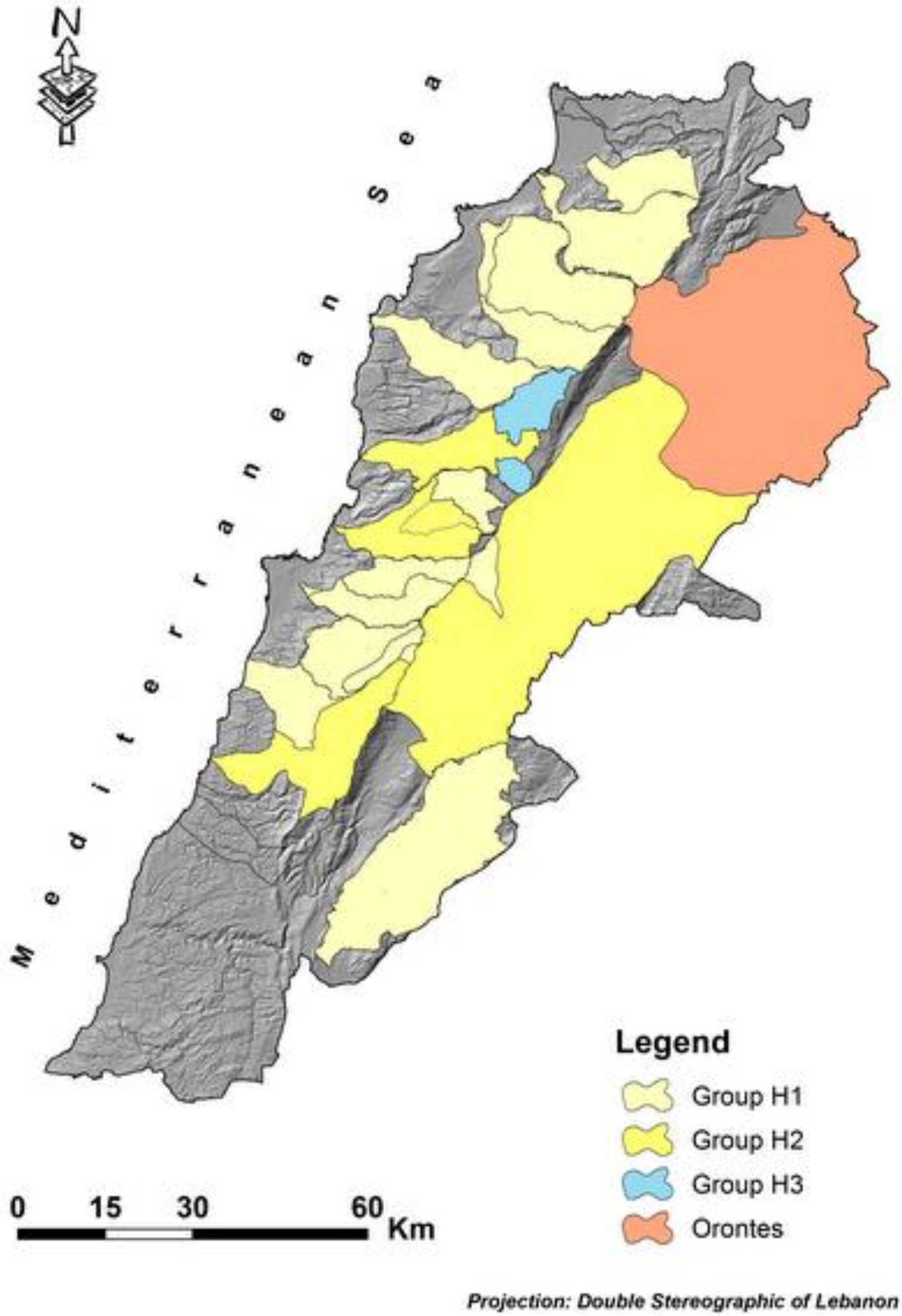


Fig. 6.2b Hydrologically similar catchments.

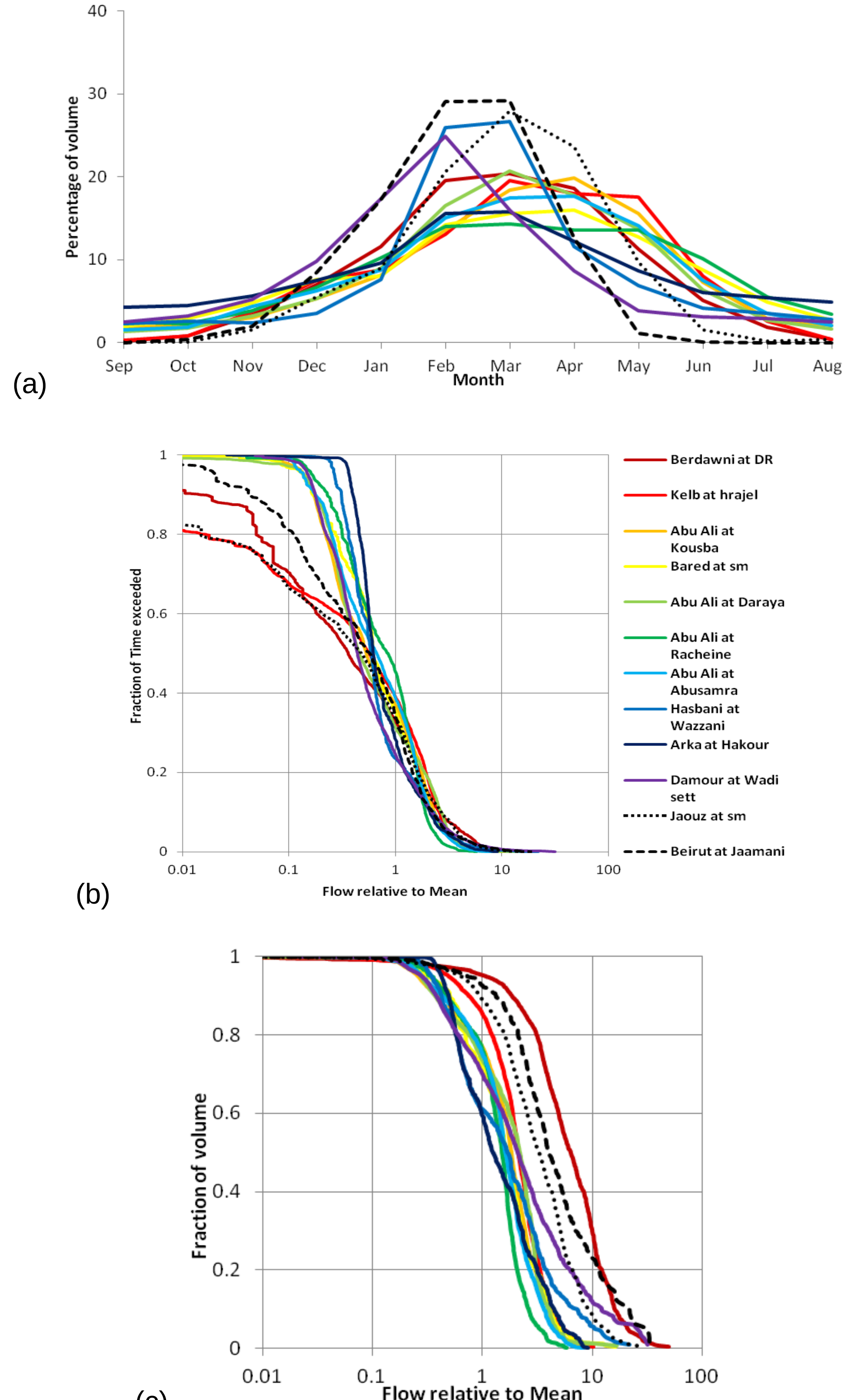
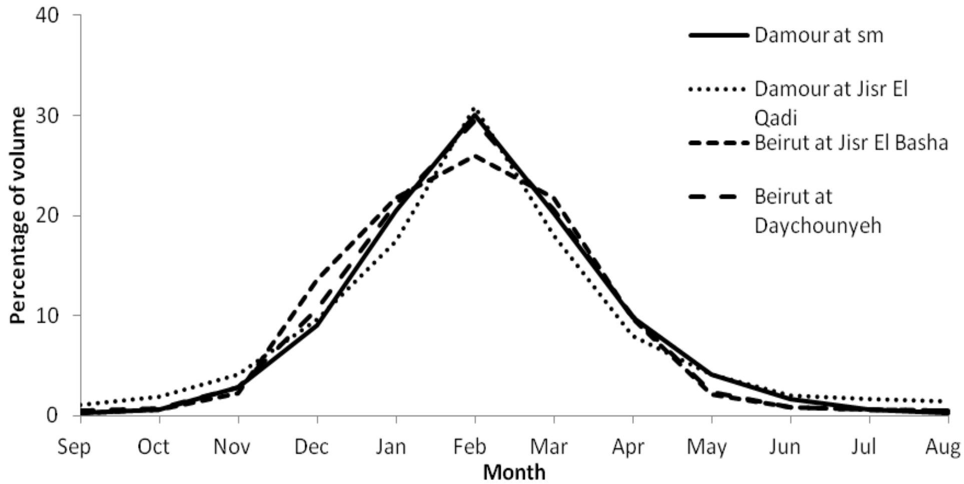


Fig. 6.3 Mean flow distribution of stations in group 1: a) Fraction of monthly flow volume, (b) 1-day flow duration curve and (c) volume-flow curves. (a) Fraction of monthly volume: monthly runoff volume divided by total annual runoff; (b) Flow relative to mean: mean daily flow divided by mean flow for the whole record; (c) Fraction of daily volume: daily runoff volume divided by total volume.



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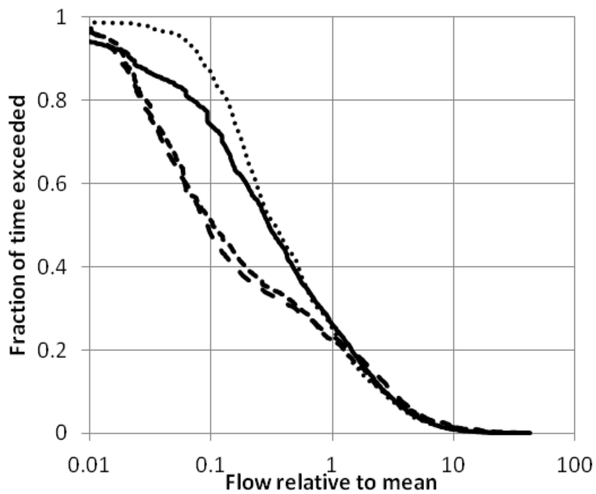

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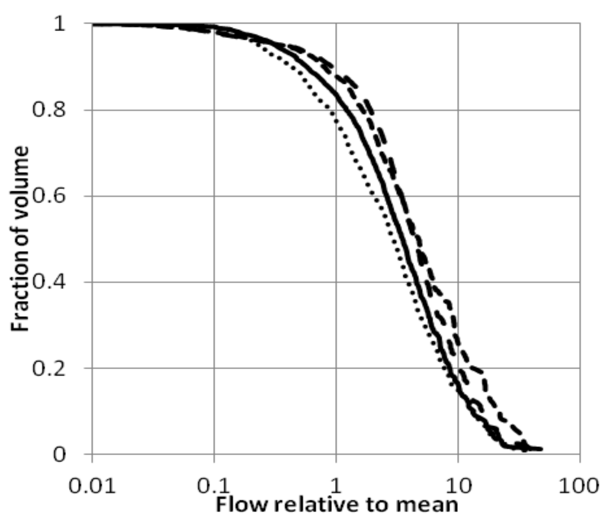


(c)

Fig. 6.4 Mean flow distribution of stations in group 2: a) mean monthly flow, (b) 1-day flow duration curve and (c) volume-flow curves.

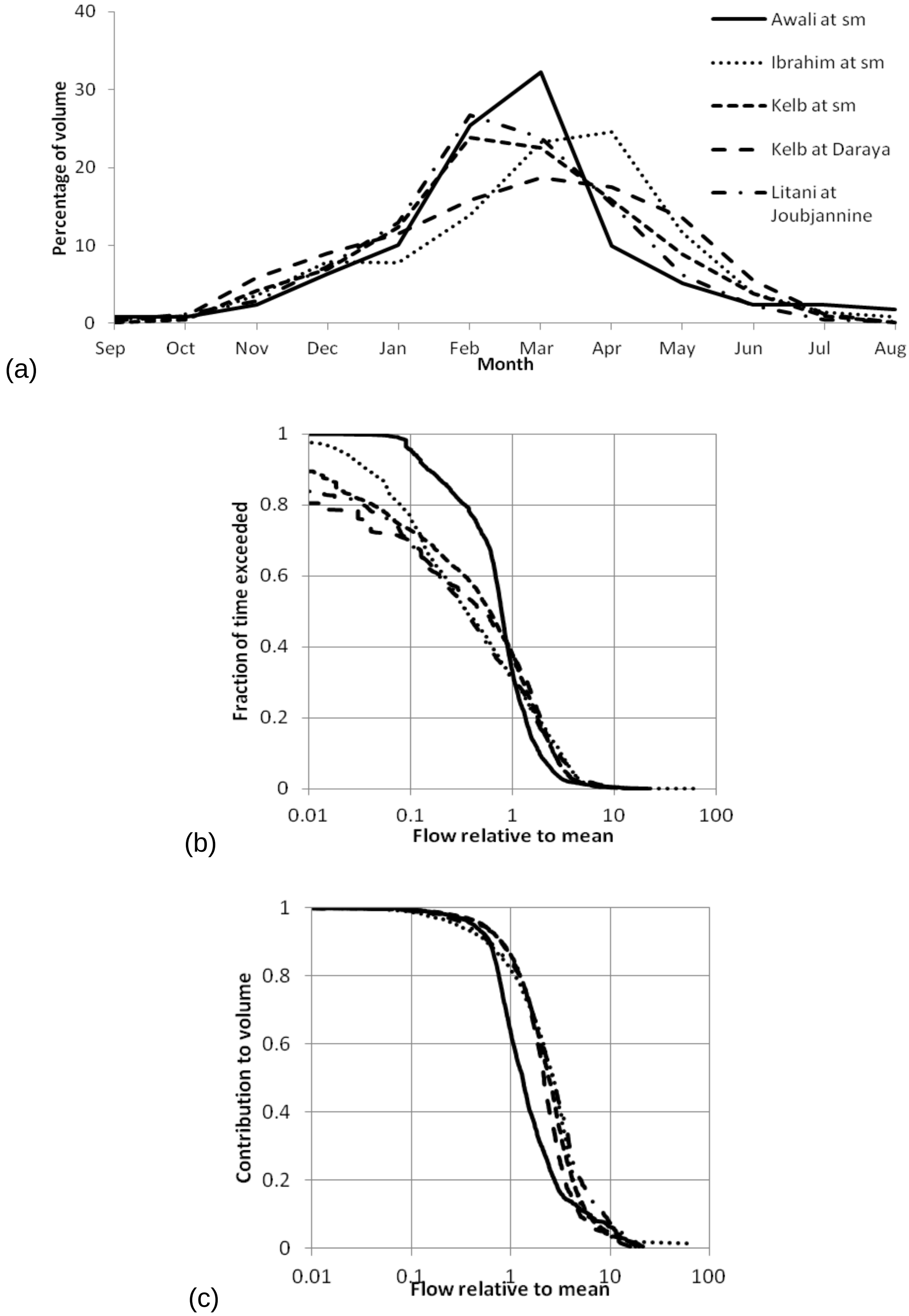


Fig. 6.5 Mean flow distribution of stations in group 3: a) mean monthly flow, (b) 1-day flow duration curve and (c) volume-flow curves.

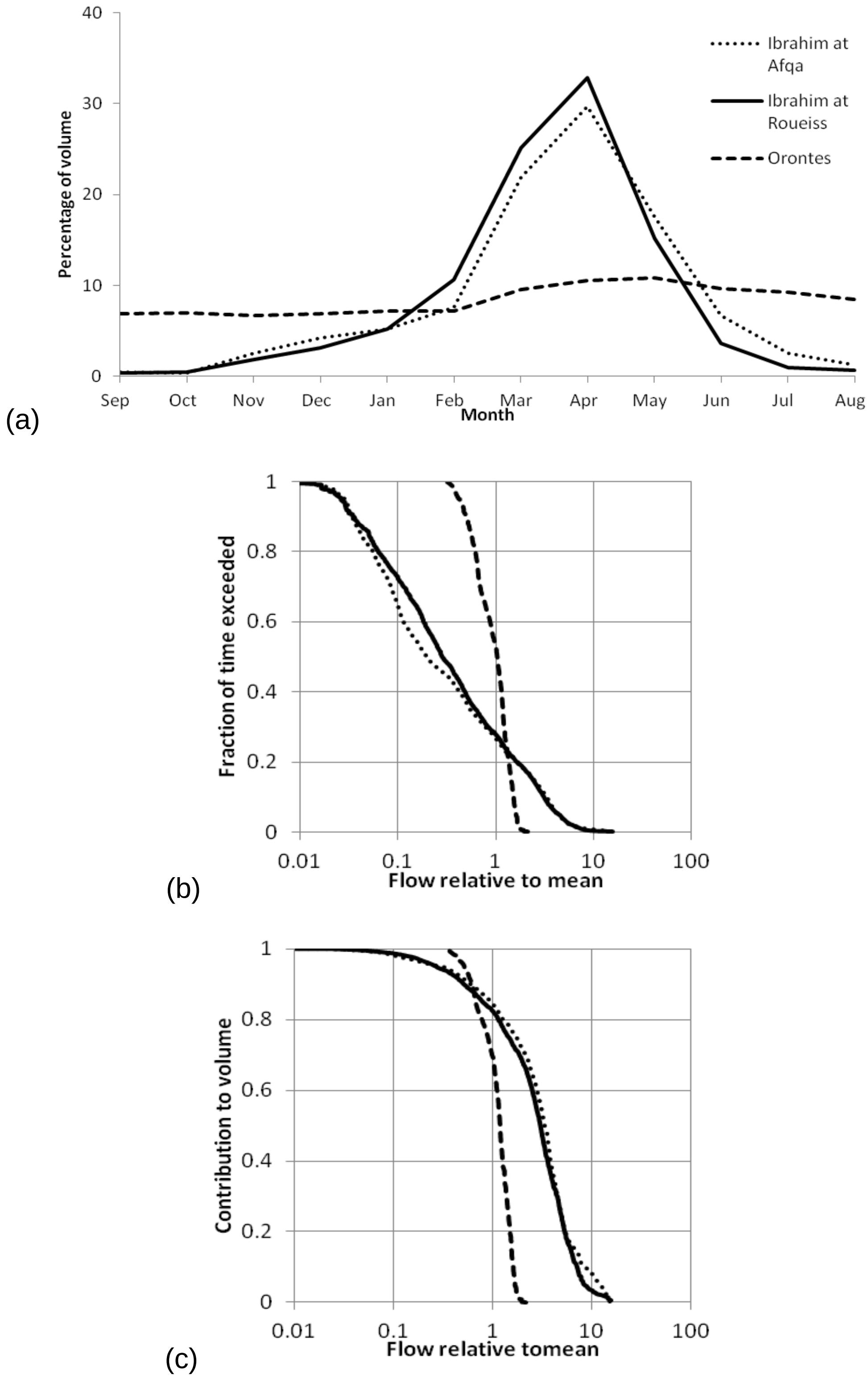


Fig. 6.6 Mean flow distribution of 3 particular stations (Ibrahim at Afqa and Roueiss, and Orontes): a) mean monthly flow, (b) 1-day flow duration curve and (c) volume-flow curves.

6.3.4 *Physical similarity Vs hydrological similarity*

So the catchments that are simultaneously in a group of physically similar catchments and a group of hydrologically similar are grouped together forming a group of physically and hydrologically similar catchments. Five groups of catchments which are simultaneously physically and hydrologically similar can be identified (Fig. 6.7):

- Group PH1. The catchments in northern Lebanon (Arka at Hakour, Bared at sea mouth, Abu Ali at all stations and Jaouz at sea mouth). These are medium-sized catchments with a considerable fraction of surface affected by snow. Hydrological response is induced by both rainfall and snowmelt while groundwater contributions maintain a good amount of runoff volume during the dry season.

- Group PH2. Very similar to the previous group, however here main springs in mountainous area heavily affected by snow constitute the headwaters of the catchments and at the same time rainfall impact downstream is more important in the previous group due to both steeper slopes and more humid conditions (higher mean annual precipitations.

- Group PH3 and PH4. Rainfall is the main contributor to river discharges however snow contribution is not absent especially in the headwaters catchments that constitutes group IV.

- Group PH5. Here we have the two karstic springs where Ibrahim River emerges. Their main input is snowmelt. Both high and low flows contribute to total springs discharges. The former represent rapid spring discharges (to rainfall or a rise in temperature that induce a great amount of snowmelt) while the latter represents slow response.

- Non similar catchments. Six catchments do not fit in any group: Kelb at Hrajel is a springfed stream with groundwater recharge as main contributor, it is rather similar to the group V however here the gauging station does not capture only spring discharge but also contribution of surface runoff, seemingly is the Berdawni at Damascus Road. The Orontes is a very clear special case that wad described earlier. Litani and Hasbani have hydrologically similar catchments but are mainly isolated because of their quite specific physical characteristics among other the prevalence of agricultural areas and area.

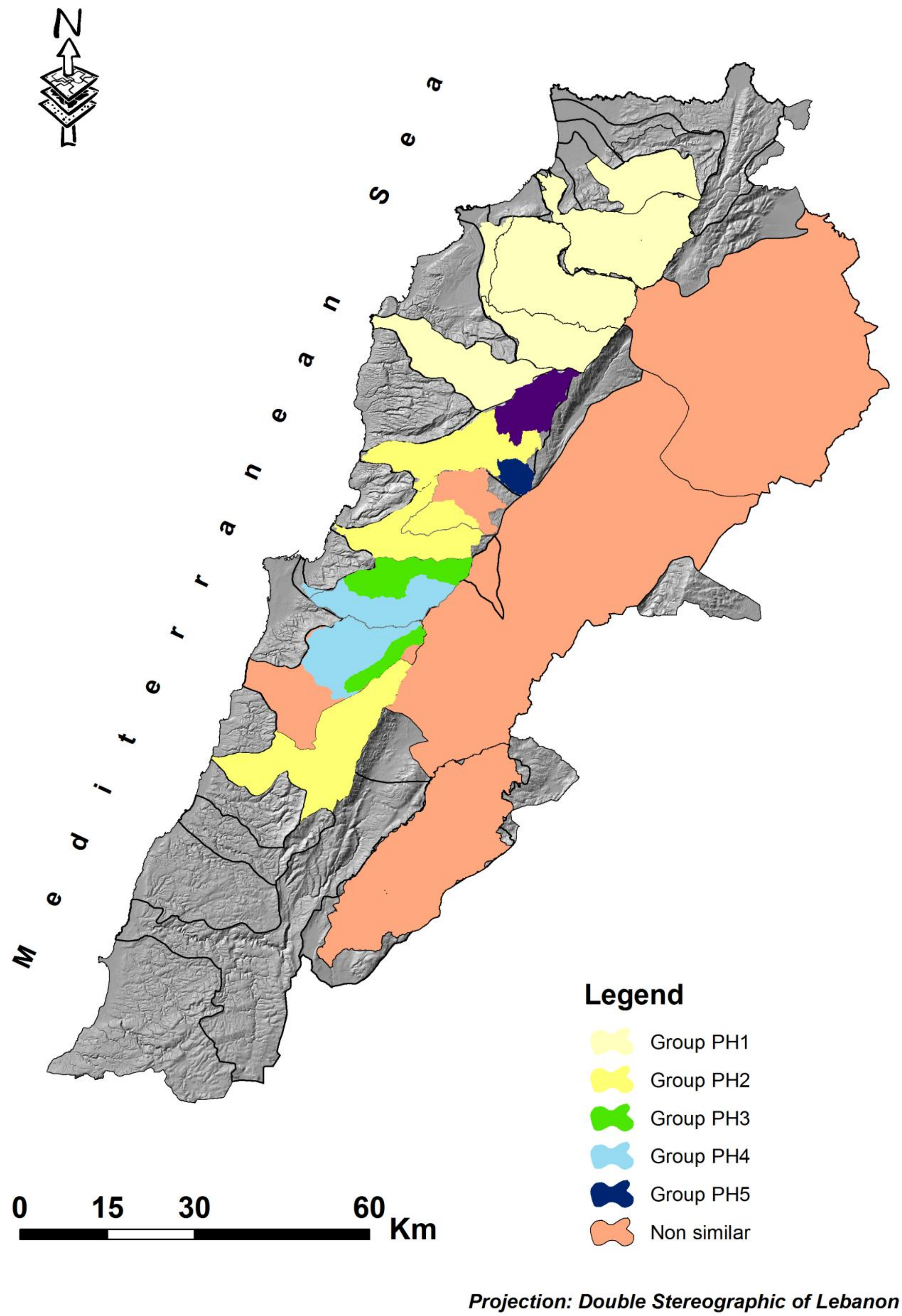


Fig. 6.7 Physically and hydrologically similar catchments.

6.4 Conclusions

In this chapter we presented a classification of Lebanese catchments using principal component analysis and agglomerative hierarchical clustering. Catchments physical descriptors and runoff signatures were transformed separately using PCA. The lowest order principal components were then used as an entry in the clustering process.

This method enables us to define groups of physically or hydrologically similar catchments. Catchments that are in the same time in a physically similar group and hydrologically similar group were joined together in a group of physically and hydrologically similar catchments. Five groups were so identified, while six catchments do not fit in any group.

The obtained results were quite coherent. Hence, catchments in northern Lebanon were runoff regime is mostly snow dominated form one group. Another group is made mainly by the steepest and most humid catchments in the country located in north central Mount Lebanon, while catchments in the southern central Mount Lebanon were the runoff regime is mostly rainfall dominated form a single group and their headwaters catchments form another group. Moreover, snow dominated mountainous karstic spring constitutes one single group. The inner catchments which are much larger with lowest precipitation and highest evapotranspiration and more agricultural areas have many particularities each and do not fit in any group.

So through catchments classification we were able to understand the reasons behind the similarities and differences in the hydrological responses characteristics of the studied catchments and see how the physical characteristics influence catchments hydrological response.

Finally, this classification constitutes a step forward toward the regionalization of the hydrological response of the Lebanese catchments. Hence, runoff signatures could be transferred from one catchment to another inside the same group. Moreover, this classification brings together catchments that have similar hydrological behavior thus could be represented by one conceptual model.

7 MODELING THE HYDROLOGICAL RESPONSE OF LEBANESE CATCHMENTS

7.1 Introduction

In the previous chapter we classified the Lebanese catchments according to their physical and hydrological characteristics. Five classes were defined.

This chapter investigates the hydrological response of Lebanese catchments through hydrological modeling taking into account the five above-defined classes. To achieve this, a well known global hydrological model, GR2M, was used. The choice behind using GR2M is not only from its simplicity and availability but also the fact that it was widely used and has proven its capabilities for many studies with different objectives. The range of GR2M utility is pretty wide from data analysis and construction of missing discharge data to water resources assessment and management studies and impact of global anthropogenic changes on basin hydrological response.

The GR2M is used in this study as a simple tool to assess the modeling quality of Lebanese catchments, and to compare different regionalization approaches across the studied catchments. Afterwards, GR2M simulation is used as a reference state compared to the observed data for each catchment separately. From the divergence between simulation and observation one can draw some conclusions about the processes that govern the hydrological behavior of the catchments.

In the following, the methodology of work of GR2M model is presented. Then, the results of GR2M application are presented at three levels. First, the overall results for all catchments are presented, followed by a comparative assessment of different regionalization approaches. Finally, the results are presented by group of similar catchments (physically, hydrologically and both).

7.2 Methodology

GR2M (modèle de Génie Rurale à 2 paramètres Mensuel) is a global two parameters monthly time step model, It was developed in the 1980s by the Cemagref, The version presented here is from Mouelhi et al. (2003).

It is an empirical model however it structure resembles conceptual reservoir models. It associates 2 reservoirs: one for production and one for rooting. Hence the production function of the model is based on the production reservoir that simulates the soil moisture conditions. The capacity of the reservoir is represented by a parameter X1. Another parameter -X2- associated to the rooting reservoir opens an exchange with the exterior of the basins (Figure 7.1).

The inputs to the model are rainfall and reference evapotranspiration in mm. The two parameters of the model are calibrated using the observed river runoff in mm. The multi-criteria function used for the calibration is the Nash and Sutcliffe efficiency criteria. The model gives Nash values in term of mean monthly observed runoff Nash (Q) but also in term of ($\sqrt{Q}$) which permits to analyze how good is the model in simulating high flows and also ln (Q) for low flows simulation assessment. And finally the model also gives the error on water volume.

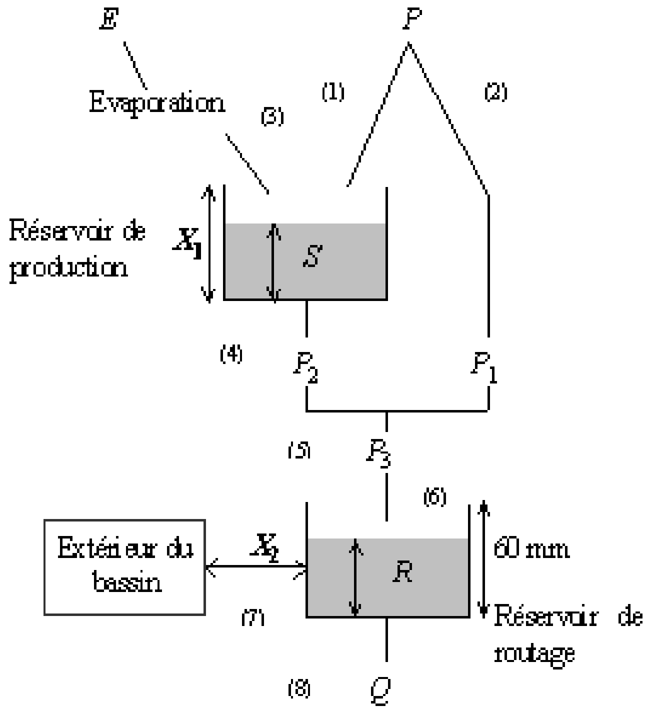


Fig. 7.1 GR2M structure.

The GR2M was applied on the Lebanese catchments for the period 2001-2011. The time series data (2001-2011) where split in two halves; from 2001 to 2005 for calibration and from 2006-2011 for validation, the process was then reverted. Nevertheless, three of the datasets (sub-basins) described before were excluded; they are Ibrahim at Afqa, Ibrahim Roueiss, and Orontes at Ain Zarqa. These are karstic springs that need to be treated separately.

Accordingly, the GR2M model was first applied separately on each basin (calibration/validation) and the results for all catchments were then discussed. In the next step, different regionalization approaches were compared. Afterwards, the results by groups of similar catchments (physically similar, hydrologically similar, and simultaneously physically and hydrologically similar catchments) are discussed. Finally, a detailed description of each catchment modeling result is presented.

7.3 Results and Discussions

7.3.1 GR2M modeling Results

GR2M results across the simulated Lebanese catchments have a wide range. Nash coefficient values range from 0.18 to 0.89 in calibration (2001 - 2006) and 0.02 to 0.74 in validations (2006 - 2011); and from 0.14 to 0.86 in calibration (2006 – 2011) and 0 to

0.84 in validations (2001 – 2006). Figure 7.2 shows the cumulative frequency distribution of GR2M simulation results for the calibration and validation periods. The results are quite consistent between the calibration/validation periods with a median Nash values in calibration and validation around 0.65 and 0.55 respectively for both. Moreover, the parameters values seem not to vary significantly when changing the calibration period (Fig. 7.3). However, the inter-quartile range for the 2001-2006 calibration /2006-2011 validation set appears to be slightly better (Table 7.1). Thus the rest of analysis will be presented on this dataset.

The worst results were obtained for mountainous catchments in the north of Lebanon heavily affected by snow (Nash (Q) < 0.1), while the best results (Nash (Q) > 0.7) were found in the inner catchments and in catchments located at the southern part of Mount Lebanon. In the former (inner catchments: Litani and Hasbani), the large area of these basins smooth the hydrological response making their simulation easier. Whilst in the latter, precipitation mostly occurs as rainfall (lower elevation) with limited snowfall which makes the simulation more efficient. In term of high flow simulation -Nash (√Q) - the results are in the same order of the Nash (Q) with a median result in validation around 0.5. However, for low flow simulation the results deteriorate with a median Nash ln (Q) of only 0.27.

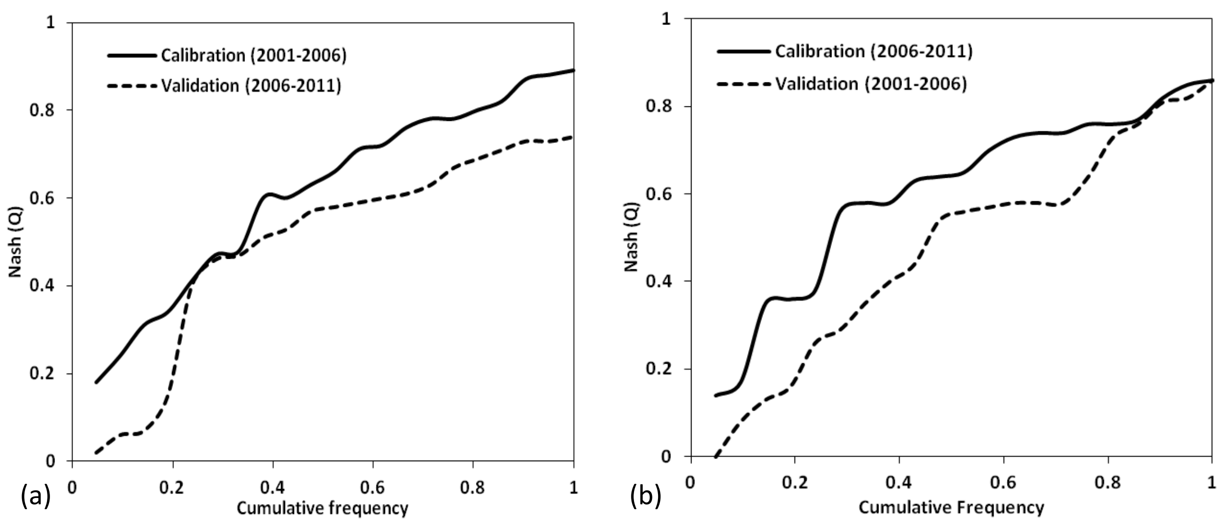


Fig. 7.2 Cumulative frequency distribution of GR2M performances over the studied Lebanese catchments for the study period (2001-2011) in term of Nash (Q); (a) model calibrated on 2001-2006 data and validated on 2006-2011. (b) Calibrated on 2006-2011 and validated on 2001-2006.

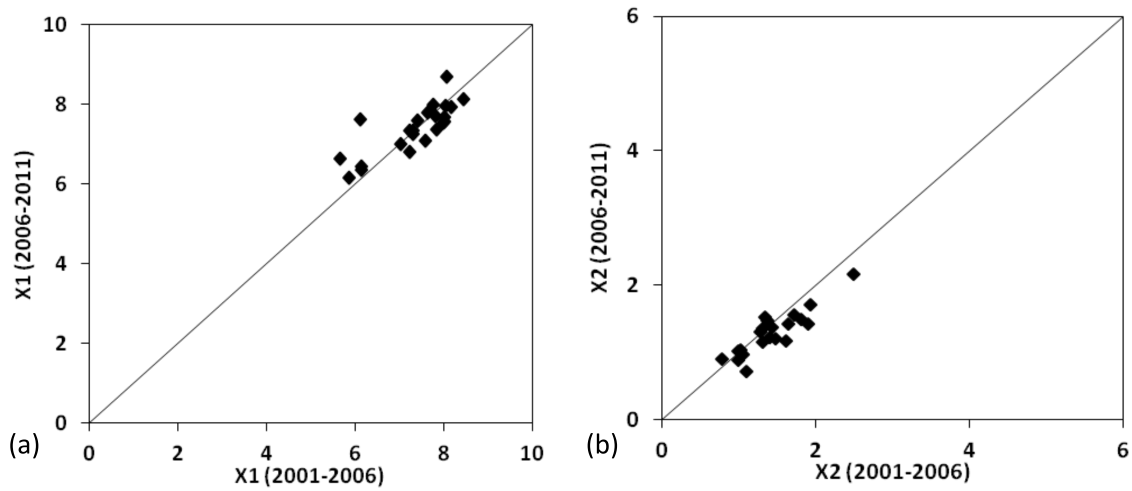


Fig. 7.3 Relationship between model parameters for 2 different calibration periods; (a) parameter X1, and (b) parameter X2.

Table 7.1 The range of GR2M parameters values and results of GR2M in term of median and inter-quartile range for 2 calibration and validation periods.

Group	X1 range	X2 range	Median Nash	Inter-quartile Nash range
Calibration (2001- 2006)	5.66 – 8.43	6.15 - 8.68	0.66	0.47 - 0.78
Validation (2006-2011)			0.58	0.46 – 0.67
Calibration (2006-2011)	0.79 - 2.49	0.72 – 2.16	0.65	0.56 – 0.76
Validation (2001-2006)			0.56	0.29 – 0.64

In order to investigate the impact of catchments characteristics on GR2M simulation efficiency we plotted the Nash (Q) values in validation against the catchment area, the catchment mean elevation and the catchment proportion of elevation greater than 1800 m (heavy snow impact) (Fig. 7.4). Despite the scatter in the data a slight tendency is felt toward a better simulation for catchments with large areas. This is clear given that the highest value of Nash is found for the biggest studied catchment, the Litani at Joubjannine. Moreover, in term of catchment elevation and snow impact (proportion of area above 1800 m), it is clear (except for some few exception, that the more elevated the catchment and the more high altitude are it covers the worst are the GR2M simulation results. Hence, the mountainous catchments of the north and central Mount Lebanon exhibit some of the worst Nash values.

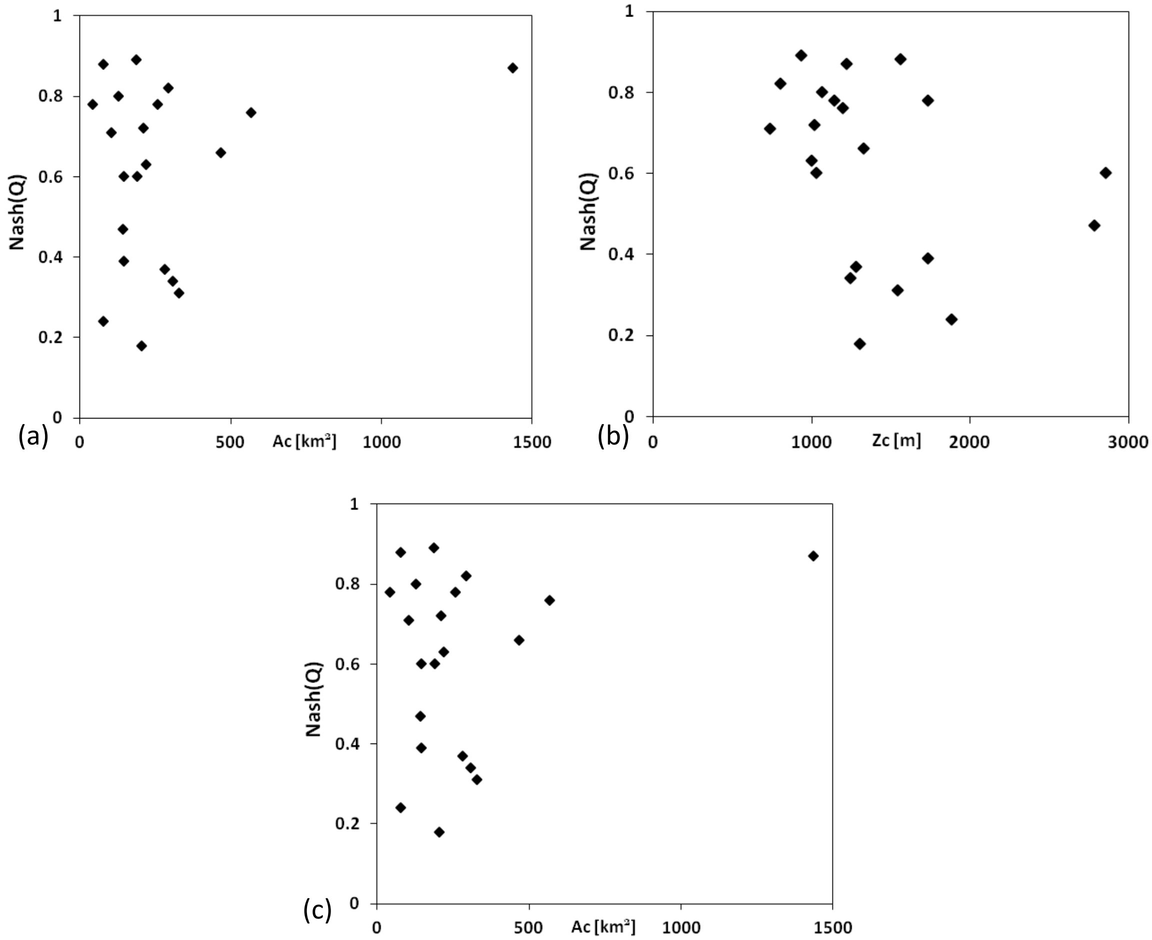


Fig. 7.4 Nash coefficient in calibration (2001-2006) versus (a) catchment area and (b) mean catchment elevation and (c) portion of catchment area above 1800 m for group of similar catchments.

7.3.2 Regionalization

Furthermore, we applied different regionalization approaches on the studied catchments. Hence, we validated the model on each catchment, using: (i) the parameters of its nearest neighbor (spatial proximity), the global mean parameters values, the mean parameter value for each group of similar catchments. The results compared to site validation (parameters calibrated on the same catchment) are presented in Fig. 7.5 and table 7.2. Despite the fact that the spatial proximity method is often reported in the litterature with the best performance, it yielded the poorest results. However, the good performance attributed with this method is usually associated with a high density of gauging stations (Parajka et al. 2005, Oudin et al. 2008, Andréassian et al. 2012, etc.) which is not the case here. For the similarity-based methods and the global mean, 60 % of the catchments results do not deviate considerably from the reference (site validation). At all levels, mean parameters of the physically similar groups and hydrologically similar groups yield very similar results and are better than the results from those yielded for both the physically and hydrologically similar groups (PH) mean parameters, and the global mean; with the PH groups being slightly better than the latter. While, it is expected for the global mean to yield poor results, mixed results for similarity-based methods are widely reported in the literature (see the review by Parajka et al. 2013). However, for the remaining 40 % of the catchments the results deteriorates dramatically in all types of grouping with negative Nash values for about 20 % of catchments.

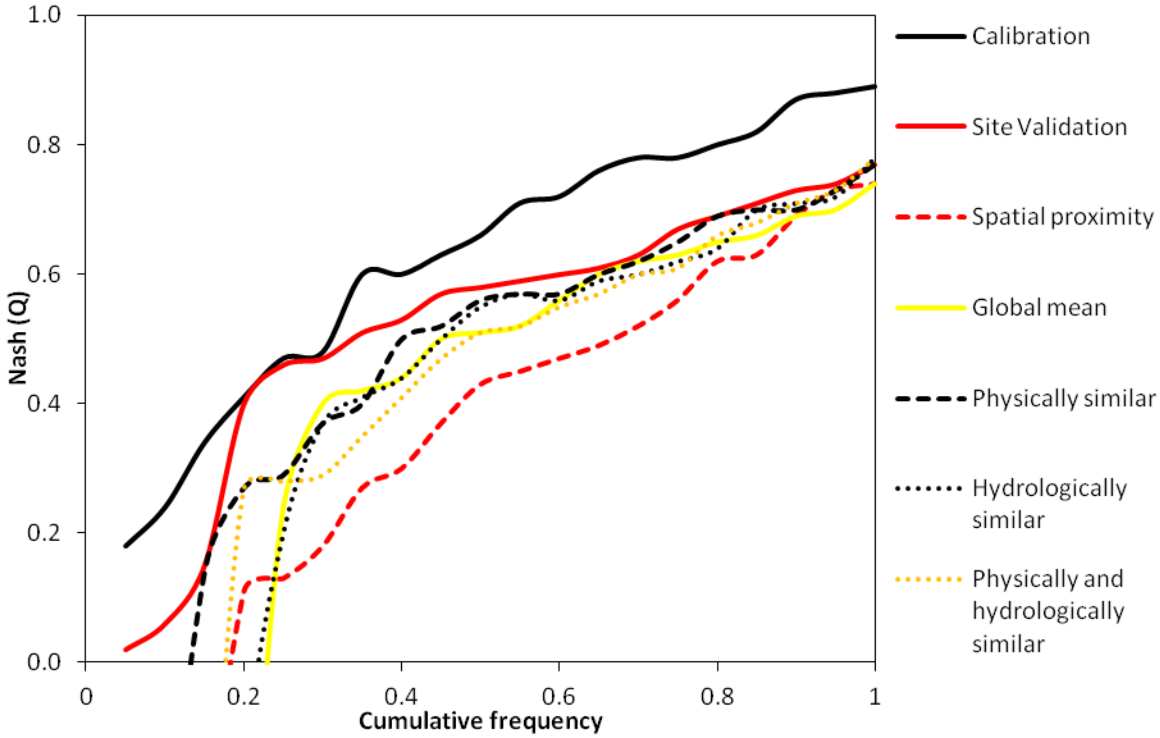


Fig. 7.5 Comparison between GR2M performances in term of Nash (Q) for the on site calibration, validation and for different regionalization approaches.

Table 7.2 Results of GR2M on term of median and inter-quartile Nash (Q) values for different regionalization methods.

	Median Nash (Q)	Inter-quartile Nash range
Calibration	0.66	0.47 - 0.78
Validation	0.58	0.46 – 0.67
Spatial proximity	0.44	0.17 – 0.58
Global mean	0.52	0.36 – 0.64
Group mean for physically similar	0.57	0.35 – 0.66
Group mean for hydrologically similar	0.56	0.33 – 0.63
Group mean for physically and hydrologically similar catchments	0.53	0.29 – 0.62

7.3.3 GR2M Results by group of similar catchments

For the physically similar groups (Table 7.3), the best performances are found in two catchments that do not fit in any particular group. These are the two internal catchments with the largest area. For the 3 remaining groups, all groups exhibit fair performances with the median Nash in the same order (around 0.55), however slightly better results are found for P1.

Table 7.3 The range of GR2M parameters values and results of GR2M in term of median and inter-quartile range by group of physically similar catchments.

Group	X1 range	X2 range	Median Nash	Inter-quartile Nash range
Group P1	7.0 – 7.6	1.3 – 2.3	0.55	0.5 – 0.63
Group P2	6.0 – 7.0	1.0 – 1.3	0.53	0.51 – 0.54
Group P3	6.23 – 8.29	0.91 – 1.67	0.54	0.53 – 0.59
Non similar	7.32 – 8.37	0.85 – 1.39	0.71	0.59 – 0.72

The hydrologically similar catchments “group H2“, (Table 7.4) comprises 4 neighboring and nested catchments in the southern central Mount Lebanon exhibits better Nash results with a narrow parameters range than the other two remaining groups.

Table 7.4 The range of GR2M parameters values and results of GR2M in term of median and inter-quartile range by group of hydrologically similar catchments.

Group	X1 range	X2 range	Median Nash	Inter-quartile Nash range
Group H1	6.87 – 8.37	0.91 – 1.67	0.48	0.21 – 0.55
Group H2	6.01 – 6.29	0.94 – 1.41	0.61	0.53 – 0.68
Group H3	7.32 – 7.87	1.01 – 2.32	0.55	0.50 – 0.63

For the third type of classes, catchments that are at the same time physically and hydrologically similar (Table 7.5), one can notice that the so defined group exhibit narrow parameter ranges (narrower than both previous classification) except of course for the non similar catchments, however, the median Nash results are mixed and not necessarily better than in previous grouping. Again group PH1 are mainly northern catchments with great snow impact, PH2, PH3 and PH4 almost correspond to P1 and P2. The non similar catchments are the inner catchments and the Damour at sea mouth which explain their high Nash values.

Table 7.5 The range of GR2M parameters values and results of GR2M in term of median and inter-quartile range by group of physically and hydrologically similar catchments.

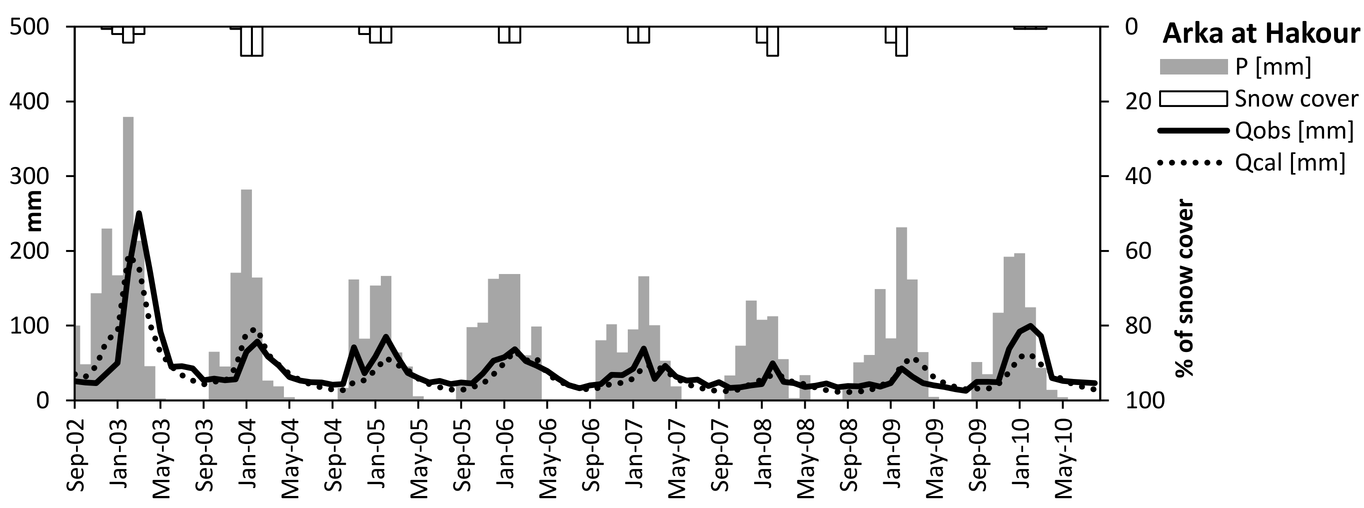
Group	X1 range	X2 range	Median Nash	Inter-quartile Nash range
Group PH1	7.49 – 8.28	0.91 – 1.66	0.4	0.15 – 0.47
Group PH2	7.28 – 7.87	1.4 – 2.32	0.52	0.39 – 0.57
Group PH3	6.87 – 7.02	1.00 – 1.64	0.55	0.53 – 0.57
Group PH4	6.01 – 6.25	1.40 – 2.32	0.52	0.39 – 0.57
Non similar	6.29 – 8.37	0.85 – 1.42	0.71	0.69 – 0.73

7.3.4 GR2M simulation analysis

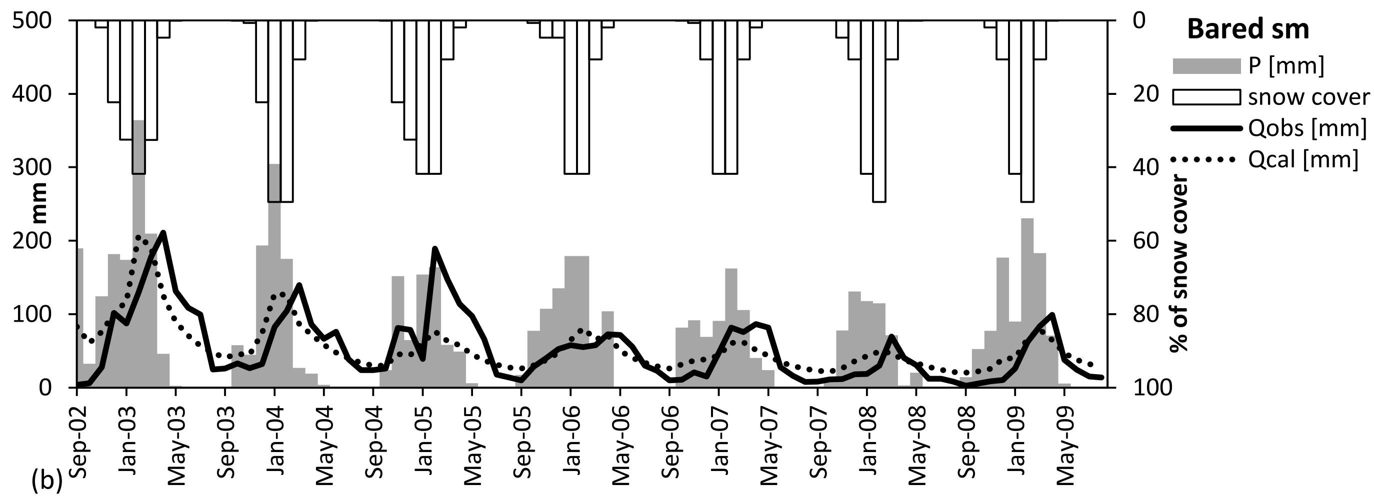
In order to look into the details of the GR2M simulation we present here the details hydrographs of the simulated catchments with the simulation results. Alongside the GR2M simulation the hydrograph presents the observed monthly runoff, precipitation and the % of catchment surface covered in snow.

Group PH1

A shift in the runoff peak from February to March-April is noticed. This can be attributed to the prevalence of snow dominated runoff regime. Snow covers 40 to 60% of this class catchments' (except Arka catchment) and can not be seized by the GR2M model. Arka catchment simulation gave fair Nash validation results (Nash (Q) = 0.61). A simple shift in the observed data for the Bared catchments increased the Nash (Q) from 0.37 to 0.6 in calibration and 0.02 to 0.3 in validation. So did Abu Ali at Rasheine.

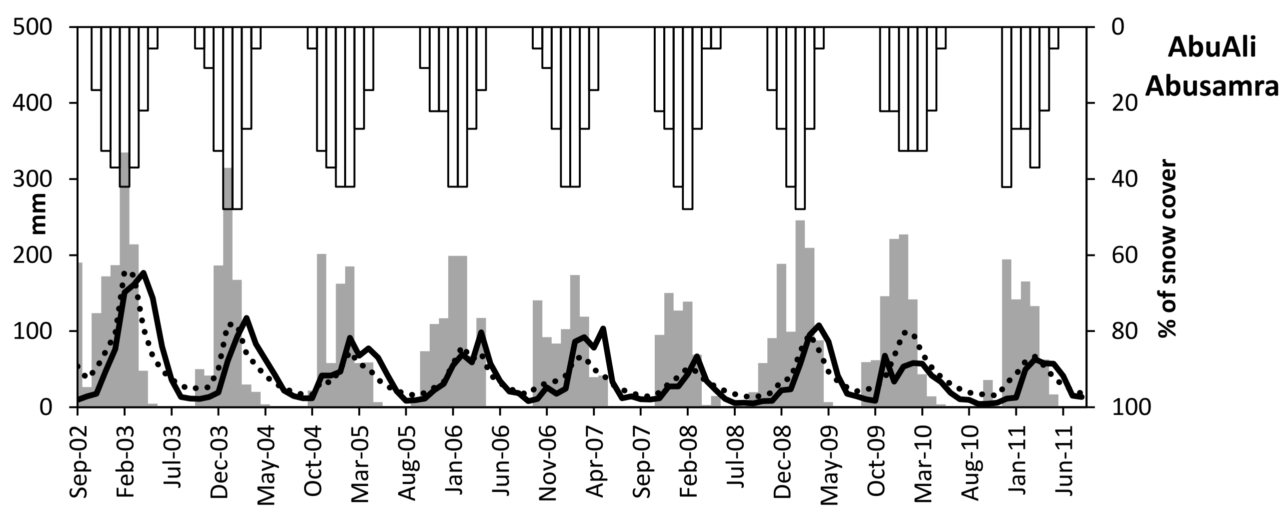


	Calibration (2002-2006)	Validation (2007-2010)
P (mm)	3804	2816
Qobs (mm)	2424	1723
Qcal (mm)	2321	1356
Nash(Q)	72.1	60.9
Nash(√Q)	65.9	46.2
Nash(lnQ)	55.0	17.6
Water Balance (%)	96.0	111.4

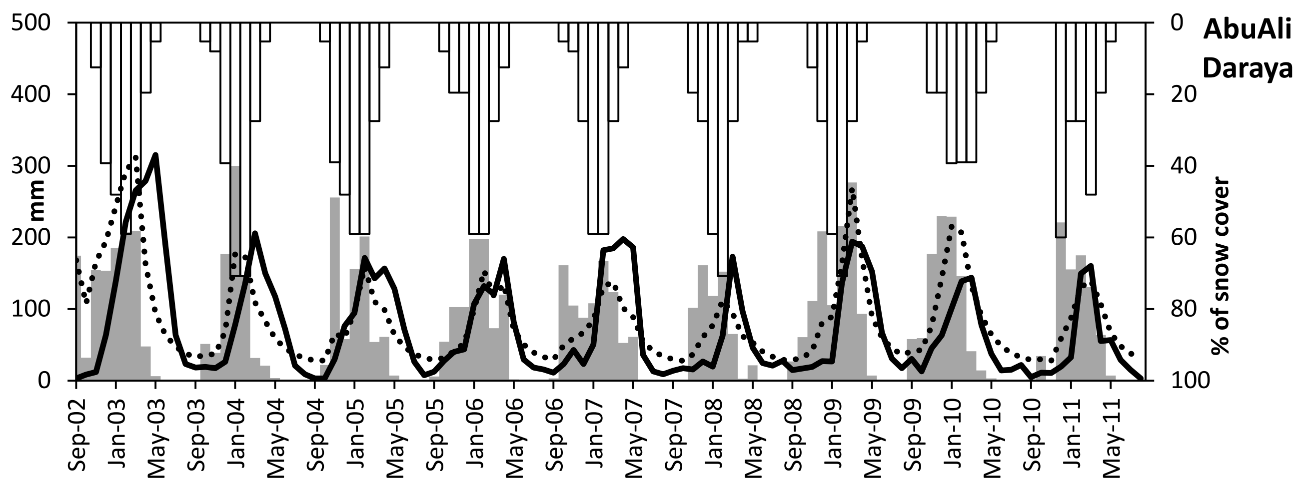


(b)

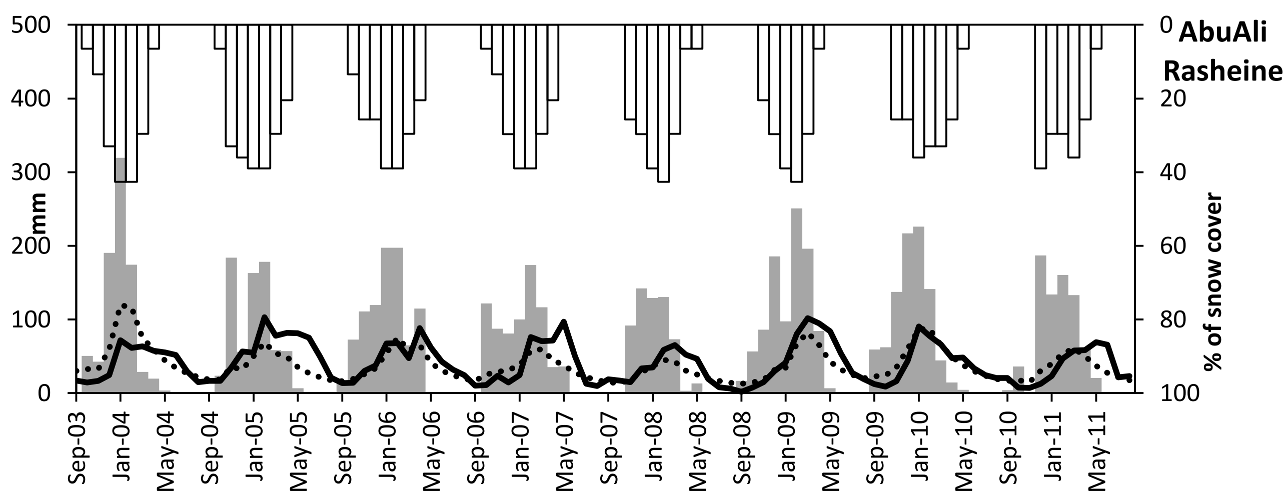
	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	3681	2967
Qobs (mm)	3291	1399
Qcal (mm)	3146	2284
Nash(Q)	37.8	2.7
Nash(√Q)	39.1	-16.2
Nash(lnQ)	31.0	-33.6
Water Balance (%)	95.6	161.9



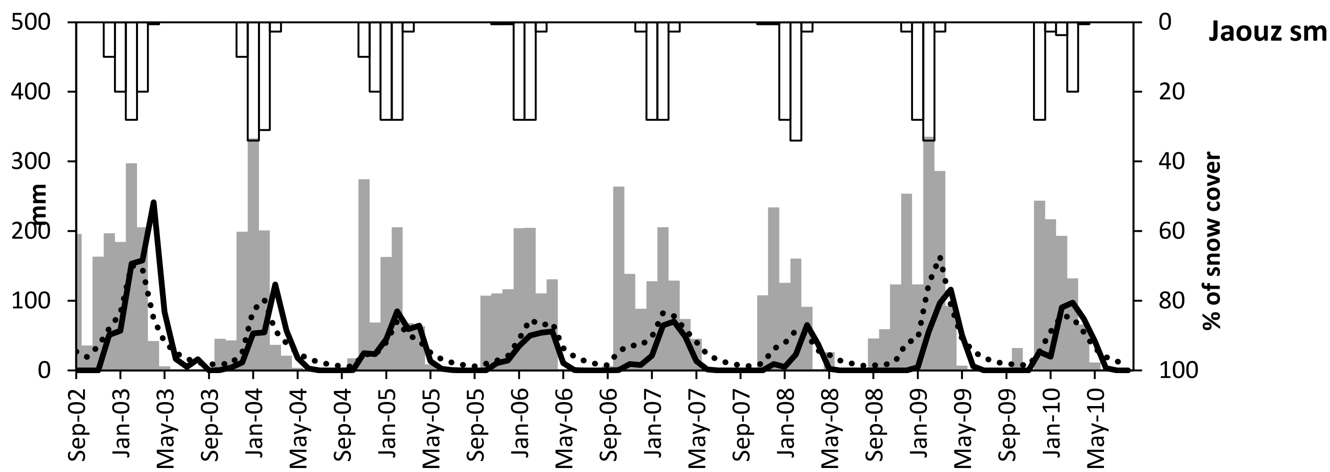
	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	3764	3764
Qobs (mm)	2493	1503
Qcal (mm)	2452	1959
Nash(Q)	66.4	49.5
Nash(√Q)	68.0	51.1
Nash(lnQ)	64.2	42.4
Water Balance (%)	98.4	130.4



	Calibration (2003-2006)	Validation (2007-2011)
P (mm)	2438	3472
Qobs (mm)	2575	2680
Qcal (mm)	2564	3730
Nash(Q)	60.2	40.8
Nash(√Q)	64.6	45.1
Nash(lnQ)	55.1	37.0
Water Balance (%)	99.5	137.6



	Calibration (2003-2006)	Validation (2007-2011)
P (mm)	2449	3208
Qobs (mm)	1674	1834
Qcal (mm)	1544	1847
Nash(Q)	81.6	63.3
Nash(√Q)	48.0	65.0
Nash(lnQ)	-24.9	65.4
Water Balance (%)	113.9	76.8

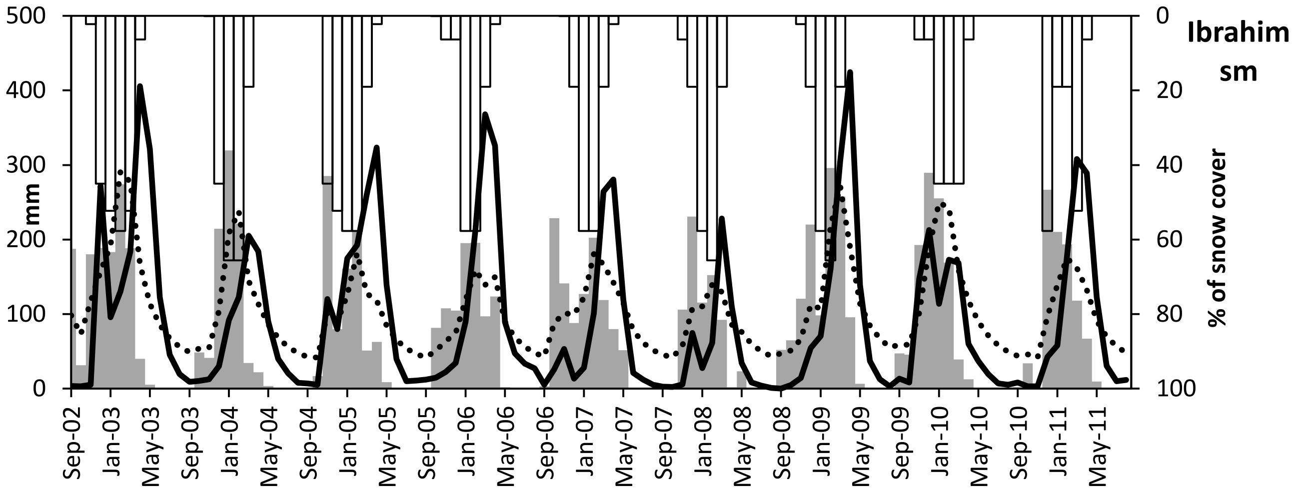


	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	4072	4075
Qobs (mm)	3391	3391
Qcal (mm)	1657	856
Nash(Q)	60.6	46.0
Nash(√Q)	59.9	31.1
Nash(lnQ)	29.3	-14.5
Water Balance (%)	107.8	158.1

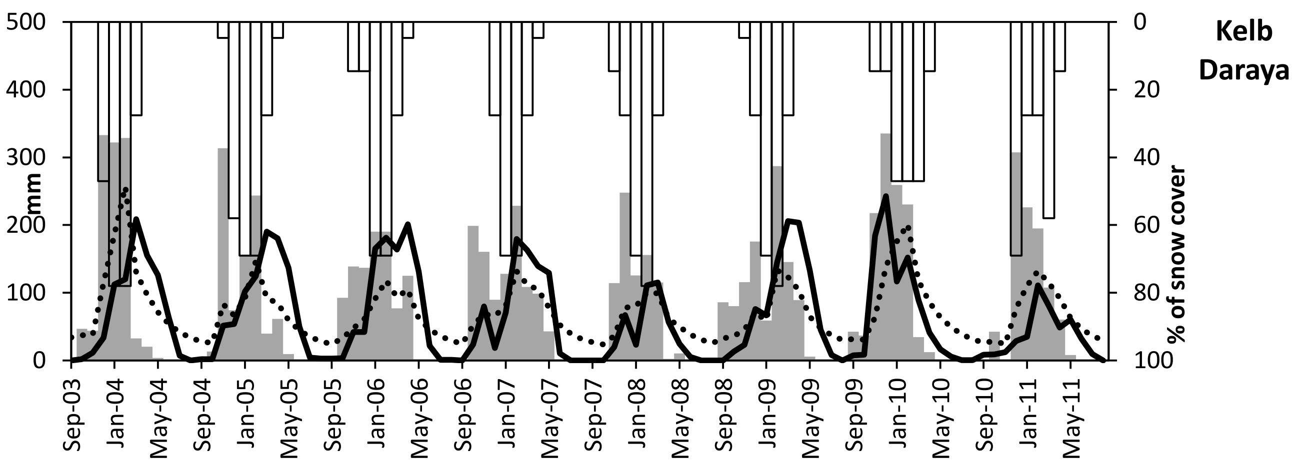
Fig. 7.6 GR2M simulation results for different group of similar catchments with observed runoff, precipitation and % of snow cover (Group PH1).

Group PH2

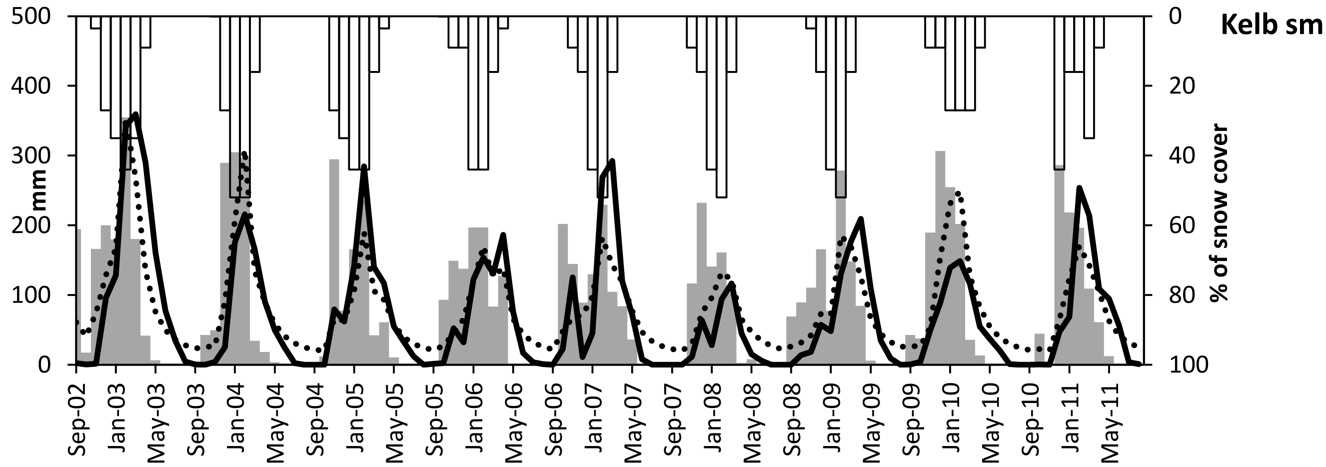
Similarly to the previous group, snow covers an important portion of the catchment total area (more than 50 % of catchments area). Here two main problems obviously appear in the hydrograph: a shift in the runoff peak from February (simulated) to March or April (observed) and a rapid recession during the dry period that is not captured well by the model. While the first problem (the shift in the peak) could be attributed to the snow impact, the reasons behind the rapid recession may be attributed to the over-exploitation of surface and groundwater in this period of the year. Nevertheless, the simulation gives relatively fair results with Nash (Q) in the range of 0.5, and reaches 0.63 for kelb at sea mouth.



	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	3970	3889
Qobs (mm)	5073	3817
Qcal (mm)	5059	4979
Nash(Q)	31.3	50.5
Nash(√Q)	39.9	38.1
Nash(lnQ)	26.4	4.4
Water Balance (%)	99.7	130.5



	Calibration (2003-2006)	Validation (2007-2011)
P (mm)	2995	3936
Qobs (mm)	2696	2641
Qcal (mm)	2627	3334
Nash(Q)	39.6	55.3
Nash(√Q)	48.7	44.1
Nash(lnQ)	29.2	11.5
Water Balance (%)	97.4	115.8



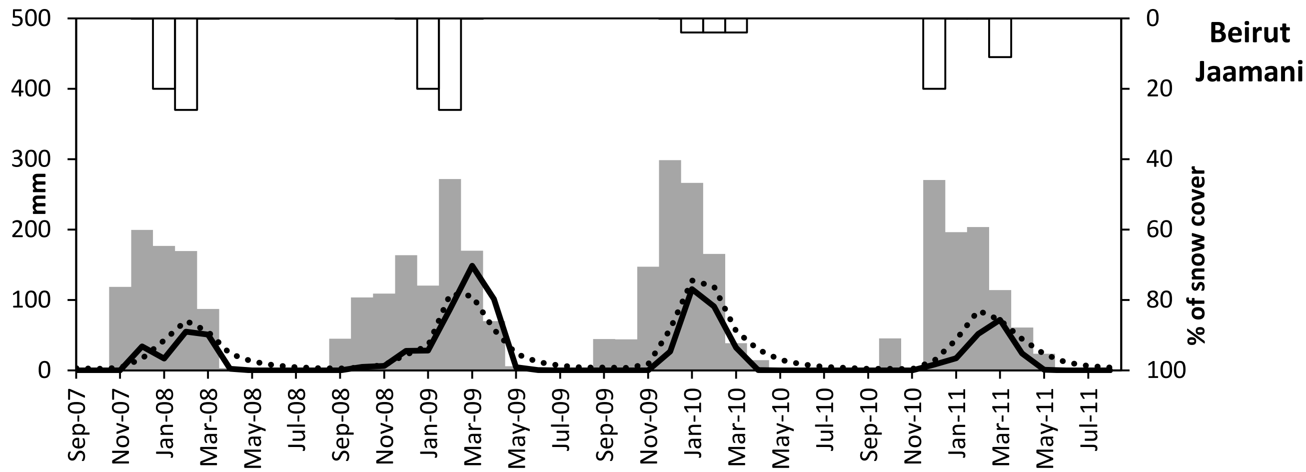
	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	4269	3809
Qobs (mm)	3955	2698
Qcal (mm)	4174	3543
Nash(Q)	78.1	63.2
Nash(√Q)	67.3	55.1
Nash(lnQ)	36.4	22.1
Water Balance (%)	105.5	131.3

Fig. 7.7 GR2M simulation results for different group of similar catchments with observed runoff, precipitation and % of snow cover.

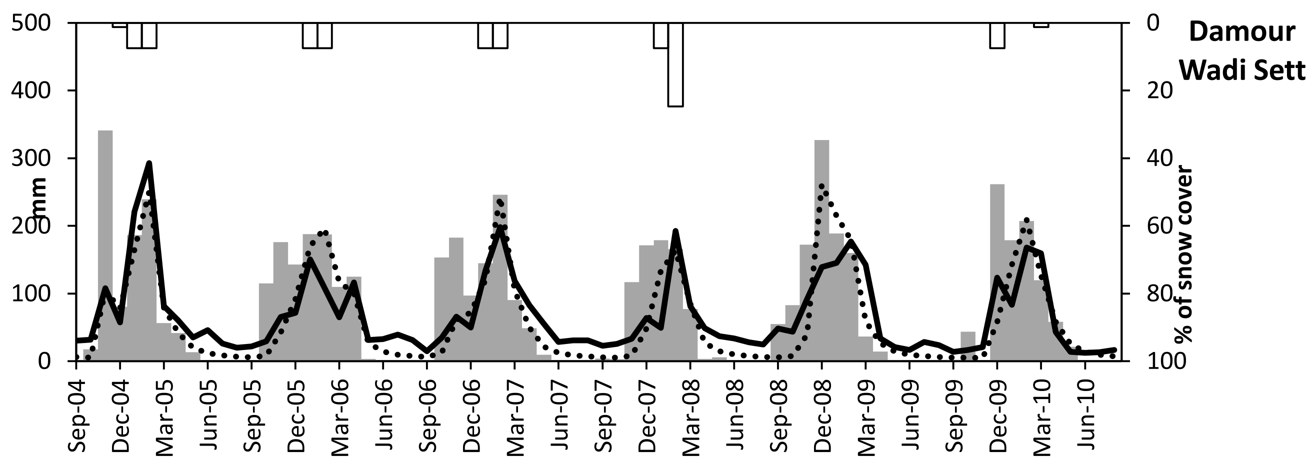
Groups PH3 and PH4

In these two groups, GR2M simulation results are satisfactory. The runoff generating mechanism is rainfall dominated. Snow cover is very limited and barely exceeds 20 % of total catchment area and for a very brief period of time. Nash ((Q) yields fair to good results with values ranging from 0.51 in Beirut at Jaamani to 0.67 for Damour at Jisr Qadi.

Group PH3



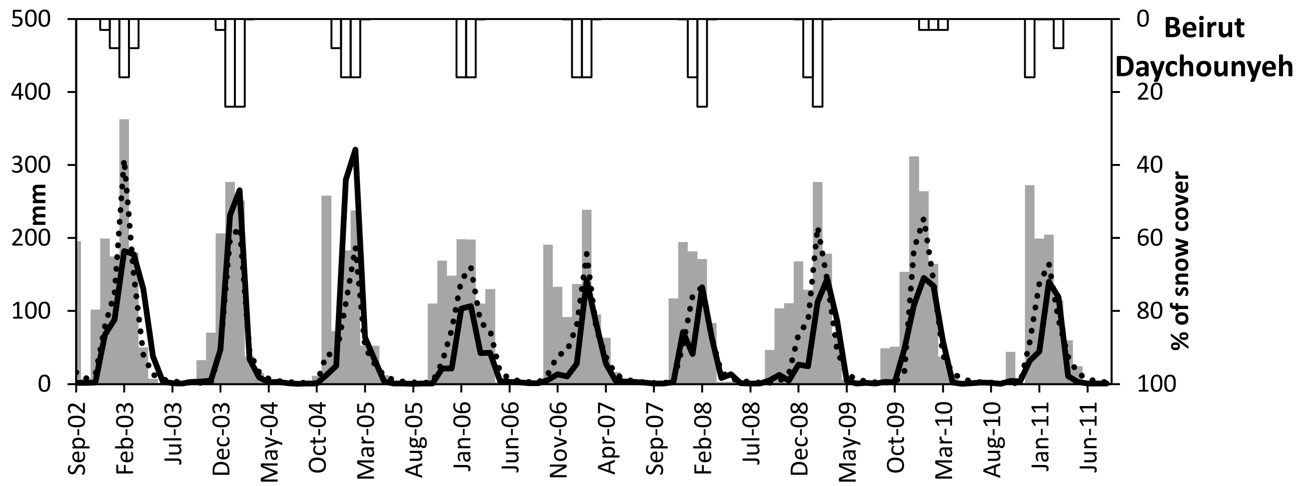
	Calibration (2006-2009)	Validation (2009-2011)
P (mm)	2788	1935
Qobs (mm)	768	438
Qcal (mm)	1226	746
Nash(Q)	80.9	51.1
Nash(√Q)	70.2	45.0
Nash(lnQ)	36.7	8.9
Water Balance (%)	111.6	179.4



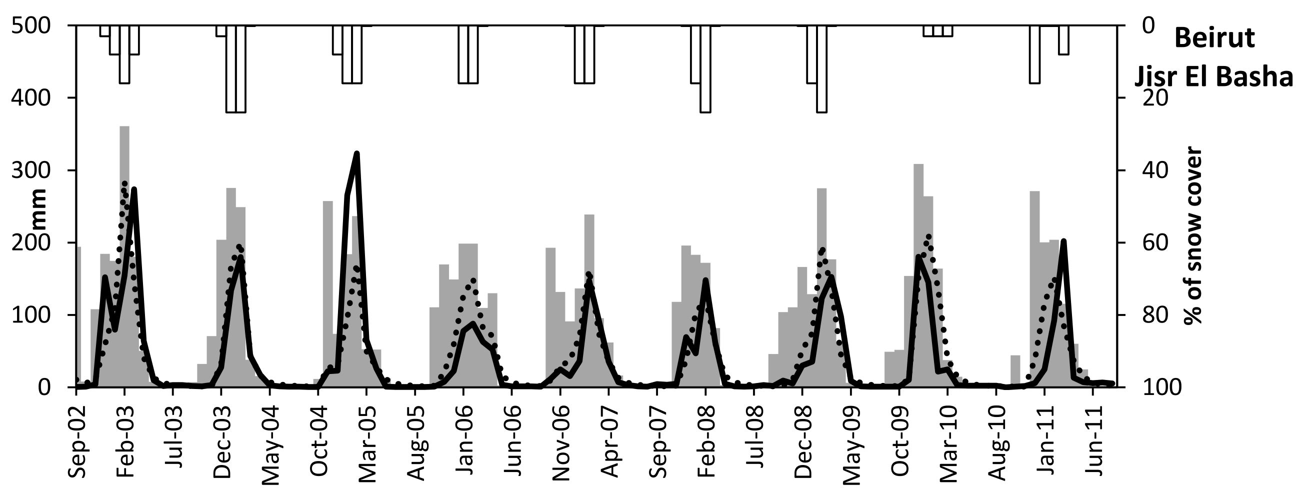
	Calibration (2004-2006)	Validation (2006-2010)
P (mm)	2024	3625
Qobs (mm)	1783	3061
Qcal (mm)	1570	2722
Nash(Q)	78.4	59.9
Nash(√Q)	82.2	67.8
Nash(lnQ)	80.7	59.8
Water Balance (%)	104.2	92.4

Fig. 7.8 GR2M simulation results for different group of similar catchments with observed runoff, precipitation and % of snow cover (Group PH3).

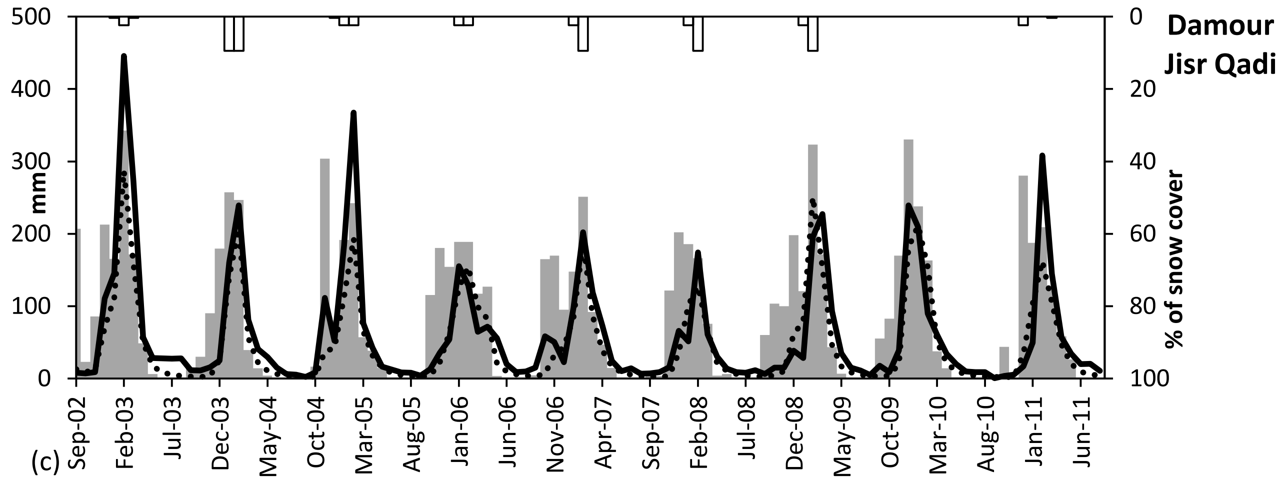
Group PH4



	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	4129	3809
Qobs (mm)	2388	1627
Qcal (mm)	2384	2174
Nash(Q)	72.0	53.4
Nash(√Q)	83.4	75.0
Nash(lnQ)	82.1	74.3
Water Balance (%)	99.8	133.6



	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	4111	3802
Qobs (mm)	2204	1574
Qcal (mm)	2133	1941
Nash(Q)	62.8	54.6
Nash(√Q)	82.1	70.6
Nash(lnQ)	82.0	74.6
Water Balance (%)	96.8	123.3

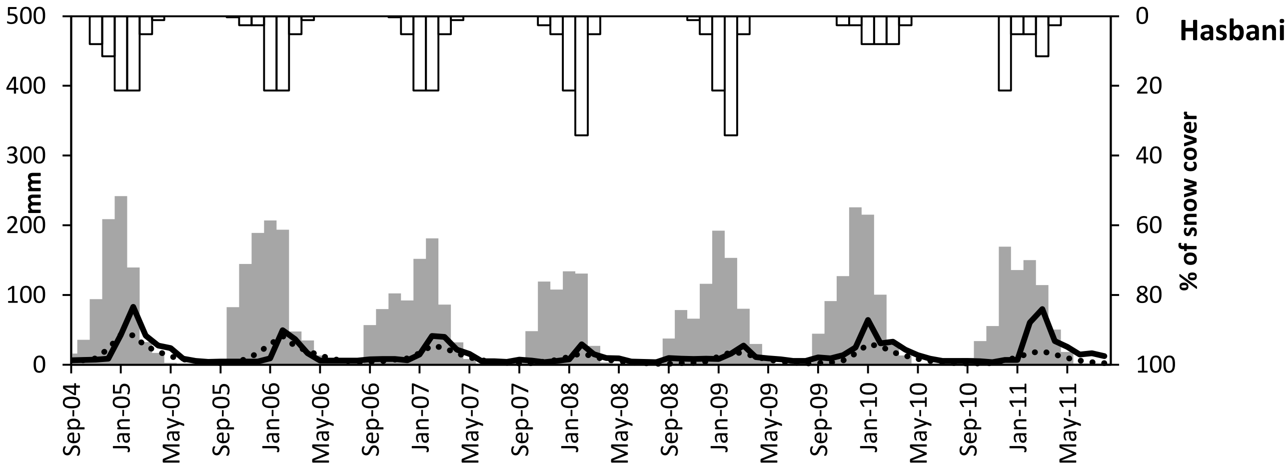


	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	4156	3920
Qobs (mm)	3311	2554
Qcal (mm)	3440	3242
Nash(Q)	89.7	67.3
Nash(√Q)	90.3	76.8
Nash(lnQ)	85.8	79.4
Water Balance (%)	103.9	126.9

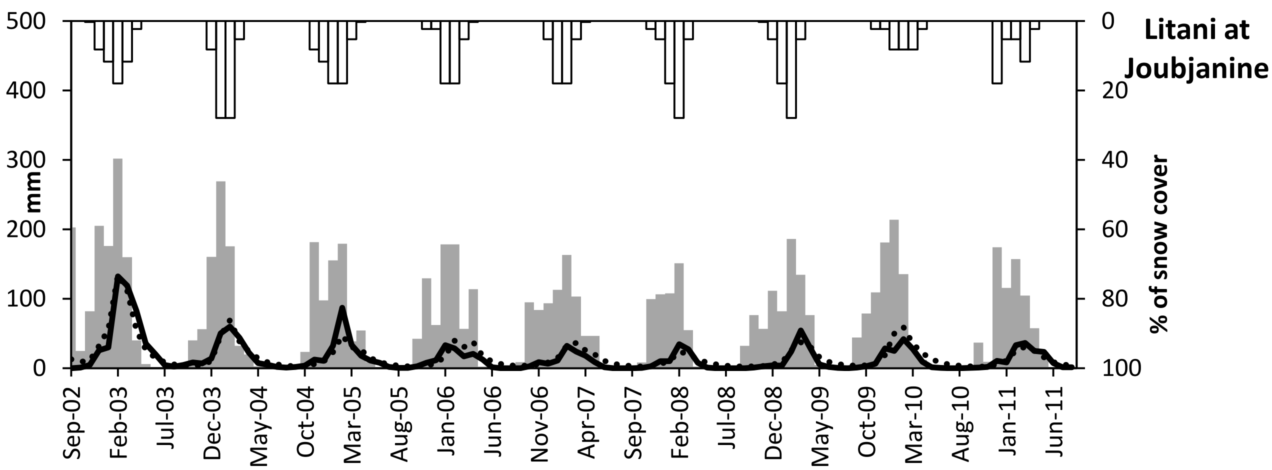
Fig. 7.9 GR2M simulation results for different group of similar catchments with observed runoff, precipitation and % of snow cover (Group PH3).

Non similar catchments

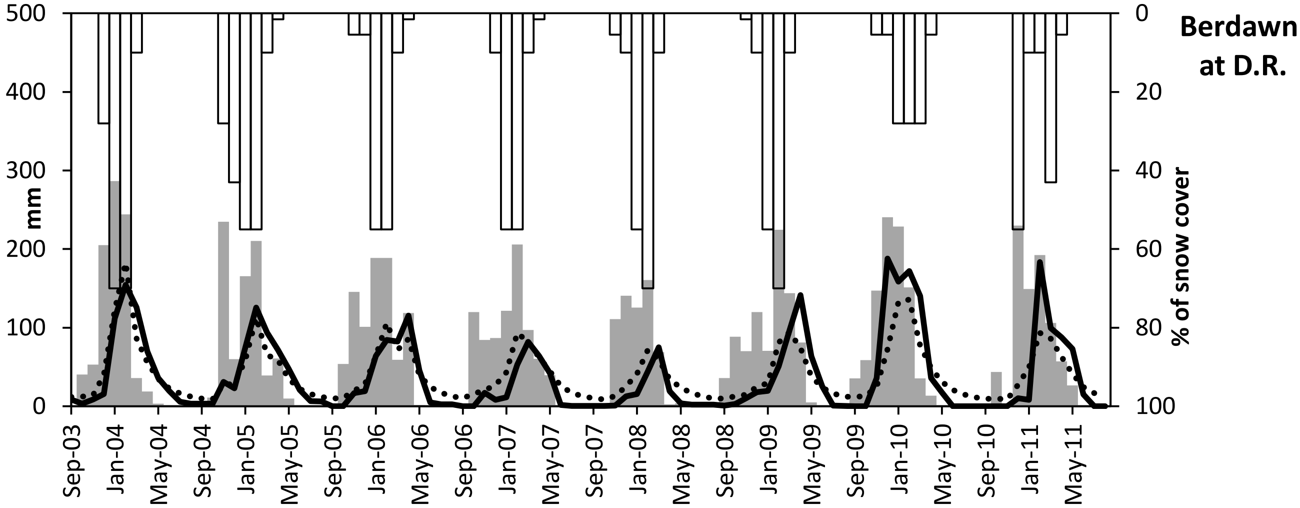
Four out of five non similar catchments exhibit a good modeling performance. Nash (Q) are around 0.70 and higher. The simulation yields also fair to good results in term of high flows (Nash(√Q)) and the error on volume. However, the simulation deteriorates for low flows (Nash (lnQ)) except in the case of Damour at sea mouth. Many factors could explain the good modeling performance in these cases. Both Hasbani and Litani have large surface areas that smooth the response and the snow cover rarely exceed 20 % of the area. For the Berdawni, and even though the catchment is small with important snow cover, snow melt appears to follow the same dynamics of rainfall with highest snow contribution coinciding with the rainfall peak. Both snow melt peak and rainfall peak occurs in February (no delay due to snow accumulation). Finally, for the Damour catchment, the negligible snow impact seems to be a major drive for the good modeling performance. One catchment, Kelb at Hrajel, yields poor results with Nash (Q) = 0.47. This is small mountainous catchments with heavy snow impact.



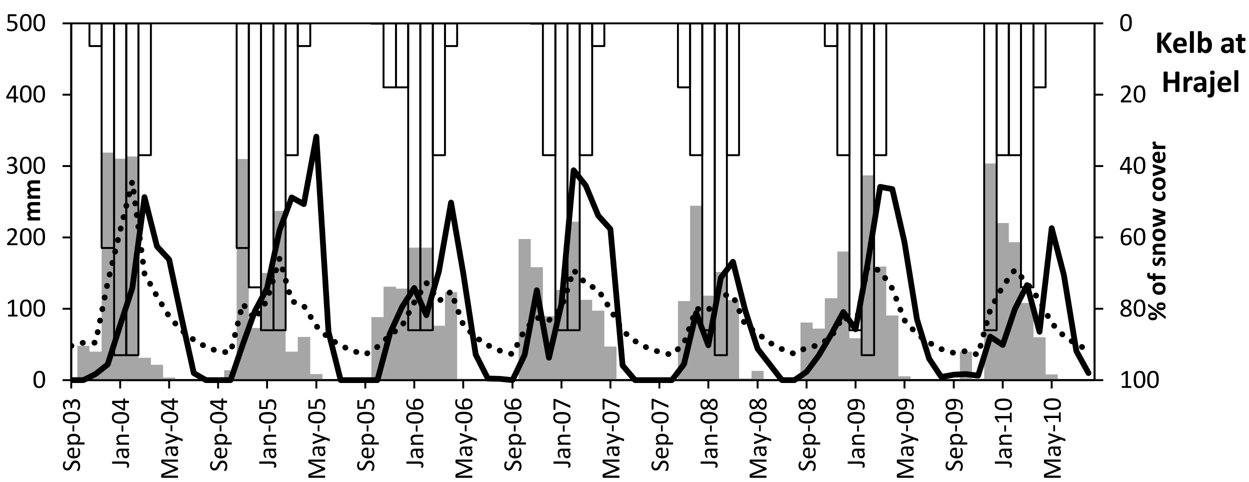
	Calibration (2003-2006)	Validation (2007-2011)
P (mm)	2559	2921
Qobs (mm)	515	747
Qcal (mm)	531	444
Nash(Q)	76.6	71.2
Nash(√Q)	77.9	52.0
Nash(lnQ)	66.2	-6.7
Water Balance (%)	102.3	82.6



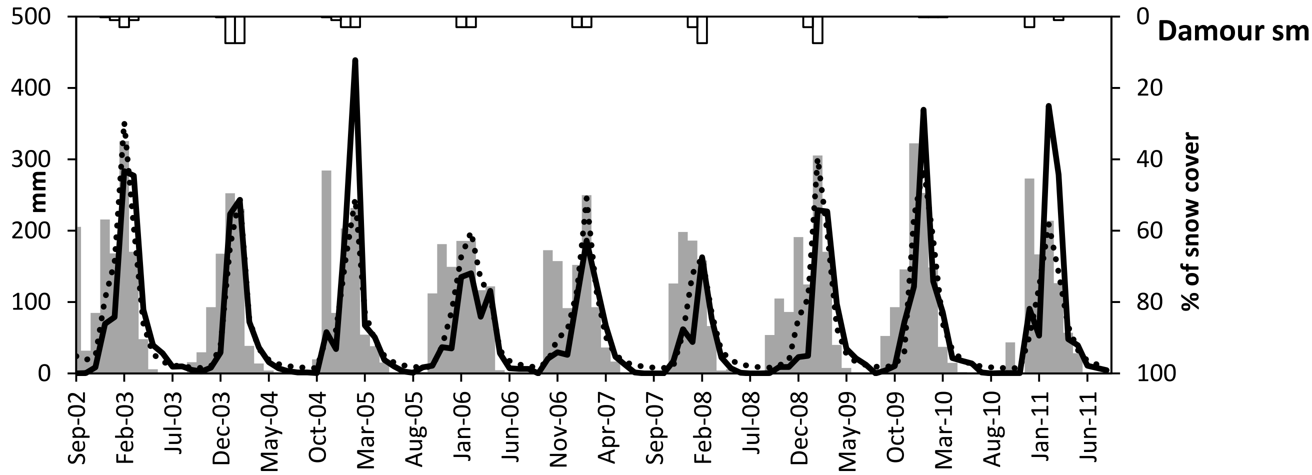
	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	3459	2781
Qobs (mm)	1033	511
Qcal (mm)	1066	635
Nash(Q)	87.8	73.0
Nash(√Q)	80.7	64.2
Nash(lnQ)	58.4	31.0
Water Balance (%)	103.2	124.2



	Calibration (2003-2006)	Validation (2007-2011)
P (mm)	2536	3170
Qobs (mm)	1505	1833
Qcal (mm)	1552	1814
Nash(Q)	88.7	69.6
Nash(√Q)	83.3	63.3
Nash(lnQ)	63.7	28.2
Water Balance (%)	103.2	99.0



	Calibration (2003-2006)	Validation (2007-2011)
P (mm)	2898	3868
Qobs (mm)	3323	2772
Qcal (mm)	3224	4200
Nash(Q)	23.9	47.1
Nash(√Q)	32.8	42.5
Nash(lnQ)	11.7	19.7
Water Balance (%)	97.0	106.1



	Calibration (2002-2006)	Validation (2007-2011)
P (mm)	4087	3813
Qobs (mm)	3037	2829
Qcal (mm)	3208	2981
Nash(Q)	82.4	74.6
Nash(√Q)	86.0	78.2
Nash(lnQ)	72.5	64.7
Water Balance (%)	105.6	105.4

Fig. 7.10 GR2M simulation results for different catchments with observed runoff, precipitation and % of snow cover.

7.4 Conclusions

In this chapter we presented the results for the modeling the Lebanese catchments hydrological response at a monthly time scale using a robust, parsimonious and well documented global model the GR2M. Here GR2M was used as a tool to assess the capability of a simple but robust model to simulate the hydrological response of complex karstic basins such as the Lebanese catchments and to compare different regionalization approaches.

The overall GR2M results give a median value of the Nash-Sutcliffe criteria around 0.55. The comparison of different regionalization approaches yield mixed results for similarity-based methods, while the spatial proximity method yields the worst result.

GR2M yield a Nash-Sutcliffe (Q) between 0.5 and 0.65 for nine catchments, while for five catchments (Litani, Hasbani, Berdawni, Damour at Jisr Qadi and sea mouth) GR2M yield quite good results (> 0.7). For the remaining catchments GR2M simulation results are poor (Nash (Q) < 0.5). When looking into the details of the simulation one can notice two main elements that may have a role in the poor performance of the GR2M. One is a shift in the runoff peak between February and March due to the snowmelt; another is the rapid recession during the dry period. So any amelioration of the GR or the proposition of new conceptual models must take these two factors into account.

The relatively fair simulation performances obtained for the Lebanese catchments using GR2M are understandable. Looking in details to the hydrographs of the catchments with the poorest results, one can notice the great impact of snow that could cover more than a half of the catchment area. This is the case for the majority of catchments in groups PH1 and PH2. Another important element is the karstic nature of these catchments. Catchment surface is not necessarily the entire contributing area to the river discharge. This is very obvious in the case of group PH5, where two mountainous karstic catchments are in fact karstic spring with a much larger recharge areas. Cases like this are reported in the literature. This is the case as an example of Torano at Piedimonte Matese, Sarno at S. Valentino Torio, and Fibreno at Brecco in southern Italy (Longobardi and Villani 2008), and Koiliaris River in Crete (Kourgialas et al. 2010). Here, catchment hydrological surface is much smaller than the recharge area that contributes to the river discharge which results in high annual runoff ratio (higher than 1). Seemingly, the Orontes river in the northeastern part of the country finds it source in a huge karstic spring with very large storage capacity (see annex 3) that can maintain a stable flow throughout the year. These three cases when simulated with GR2M (not presented here) give very poor results as it would be expected.

These particularities (snow + karst) are not confined to Lebanon and one can find in literature similar cases that had been studied across the Mediterranean (Rimmer and Salingar 2006, Tzoraki and Nikolaidis 2007, Fleury et al. 2007, Kourgialas et al. 2010, Nikolaidis et al. 2013, among others). These cases are generally treated by separating surface flow and groundwater flow. The surface flow component is than modeled using classical hydrological models, while the groundwater component (karstic springs) is modeled using a two-reservoir Maillet karstic model (Maillet 1905): the upper reservoir is responsible for the spring's rapid response simulation, while the lower one for slow response. When snow is a major component of the water balance, a snow module is also added to the modeling framework. However, such detailed models need a large amount of data, at least at a daily time step which is not available in our case neither for rainfall nor for snow.

Another element that makes the modeling of the Lebanese catchments a challenge is the uncertainty on the data. The quality of the available hydro-meteorological data is questionable and the uncertainty of the data is yet to be assessed. Therefore, there is an urge to assess the uncertainty of the available data, and its impact on any modeling procedure. Furthermore, the country is in great need for a more advances monitoring system with not only higher temporal and spatial resolution, but also enhanced measurements' quality.

GENERAL CONCLUSIONS AND PERSPRCTIVES

General conclusions

In this work we presented a classification framework for the Lebanese Mediterranean catchments. It begins by a state of the art review of Mediterranean catchment hydrology at different time scale. Afterwards, a detailed data analysis for the Lebanese catchments in term of physical, climatic and hydrological characteristics is presented, than we compare the hydrological response of Lebanese catchments with other Mediterranean catchments. Finally catchments descriptors and runoff signatures are used to define classes of physically and/or hydrologically similar catchments and to develop conceptual models to better simulate and understand the hydrological functioning of the studied catchments.

The review on the Mediterranean catchments hydrology showed regional discrepancies (between NWM, EM and SM sub-regions) in the distribution of climatic and hydrological response characteristics at the annual and the event scale. The NWM sub-region exhibits the most extreme rainfall regime in the Mediterranean region, especially in an arc that extends from Northeastern Spain to Northeastern Italy. A tendency towards decreasing water resources driven by both anthropogenic (mostly land covers change) and climatic pressure (decrease in precipitation, increase in temperature) and towards a more extreme rainfall regime with higher frequency of extreme rainfall events despite the reduction in the total annual amount of witnessed rainfall. Additionally, catchment responses at the event scale are very heterogeneous in time and space. Hence, major limitations confront classical modeling approaches that aim to simulate the Mediterranean catchment response especially during flooding events due to the specific features of the Mediterranean rainfall events. Furthermore, regionalization studies in the region are scarce even in term of low flows and FDCs which is surprising in a water-stresses region that witnesses long low-flows periods. In term of performance, predictions of runoff hydrograph give poor results under Mediterranean conditions. For FDCs and low flows predictions, statistical methods and Geo-statistical methods appear to outperform parametric approaches and regression models respectively. Mixed results were found for regional flood analysis which appears to be the most common regionalization practice in the region.

An inventory of the available spatial and temporal data was carried out and followed by a detailed data analysis of twenty eight Lebanese catchments through extracting the physical and hydrological response characteristics. The spatial data concerns the morphometry, drainage system, geology, karst, soils and land cover. The temporal data concerns the precipitation (32 stations at a daily –when available- and monthly time step), evapotranspiration (remote sensing data at a monthly time step) and discharge data (24 discharges at a daily time step and 4 at a monthly time step). Gathering the available temporal data was a real challenge since these data are not always available for the same period and precipitation data is expensive. The 2001-2011 temporal data was analyzed and compared with a database from the pre-war period.

A comprehensive list of variables describing the physical (geographical and climatic) characteristics of the Lebanese catchments was extracted from the available data. The great majority of the studied Lebanese catchments are small to medium sized catchments with area never exceeding 500 km^2. Only 2 catchments (Litani and Orontes) have an area exceeding 1000 km^2. Median slope is 8.3 % while a quarter have a slope exceeding 14 %. Furthermore, due to their small area and relative steepness, longest flow paths are usually short; never exceeding 60 km and drainage density is high with a median value of about 3.38 km/km^2. In addition, all are mountainous catchments with the great majority having a mean elevation over 1000 m, and more than half of them with at least 20 % of total basin area above 1800 m. Moreover, the geology of the country is mainly composed of highly karstified carbonate rocks. The substratum is made primarily of highly permeable rocks and all studied catchments have at least 50 % of their surface karstified. Furthermore, given the mountainous nature of Lebanon, soils are generally shallows with medium to high infiltration capacity. Deep well developed soils are mostly common in catchments with agricultural terrains. The distribution of land use classes varies largely. Finally, mean annual precipitation ranges from around 500 mm in the Orontes in the northeastern part of the country to more than 1200 mm in the central part of Mount Lebanon. Aridity index (defined as the ratio of mean annual precipitation to mean reference evapotranspiration) follows the same spatial distribution of rainfall.

The 2001-2011 available hydrological dataset were used for extracting runoff signatures that represent the Lebanese hydrological characteristics. The latter shows a sort of regional tendencies across the country with catchments in the central part of Lebanon (the most humid region) exhibiting the highest values in term of both mean annual runoff, runoff ratio and specific daily discharge. Likewise, the daily discharge distribution of these catchments showed higher percentage of days with high discharge values. While catchments in the inner part of the country appear to exhibit the lowest values of mean annual runoff, runoff ratio and daily discharge. This is due to large basin areas and lower precipitation amount, whereas, catchments in the north of Lebanon appear to form an intermediate class.

Compared to other Mediterranean catchments, annual runoff ratio values were high across the country. These high values are not solely attributed to the underestimation of the mean annual precipitation (maximum mean annual precipitation in Lebanon is lower than in other EM catchments) but also to the high values of mean annual runoff that is explained by a combination of snow accumulation and karstic springs that affect the water balance in the country. At an event scale, it is obvious that the rainfall amount may reach up to 40 % of the total annual rainfall. The maximum peak flows were not available; hence, the maximum daily flows were used in characterizing the catchment response. As expected, unit maximum daily discharge decreases with catchment area and is not correlated with event rainfall depth. However, it does show certain geographical clustering with the highest values recorded in the more humid central part of Mount Lebanon. Event runoff ratio is high even when compared to other Mediterranean catchments; in fact it is much higher than values recorded in the EM and is in the range of the NWM catchments. The latter could be attributed to both rainfall underestimation and the karstic nature of the studied catchments along with the antecedent soil moisture conditions.

The extracted catchments descriptors and runoff signatures were used separately for the classification of catchments according to their physical and hydrological characteristics. The method used for catchment classification is a hierarchical cluster analysis where groups are built according to distance connectivity. It is a similarity-based classification approach where the most similar individuals are grouped together. Catchments holding simultaneously the same physical and hydrological similarities were grouped together forming five “physically and hydrologically similar” catchments’ classes. The first group “PH1” -mainly catchments from north Lebanon- is composed of five medium-sized catchments with snow-dominated runoff regimes. In this group, hydrological response is induced by both rainfall and snowmelt while groundwater contributions maintain a good amount of runoff volume during the dry season. The second group “PH2” is very similar to the previous one, however downstream rainfall impact is more important than the previous group due to both steeper slopes and more humid conditions (higher mean annual precipitation). While the third and fourth group “PH3” and “PH4” are composed of catchments sharing the same hydrological characteristics and having the rainfall as the main contributor to river discharges, however, these groups differ in their physical characteristics (catchment size, elevation, land cover). The last group “PH5” is composed of two small mountainous catchments heavily affected of snow with large groundwater contribution. Five catchments (Litani at Joubjannine, Orontes, Hasbani, Berdawni at Damascus Road, and Damour at sea mouth) did not share any of the physical and hydrological similarities and consequently did not fit in any group.

Finally, the overall GR2M results are fair with a median value around 0.55. The comparison of different regionalization approaches yiled mixed results for similarity0based methods, while the spatial proximity method yields the worst result. GR2M yield fair results (Nash (Q) between 0.5 and 0.65) for nine catchments, while for five catchments (Litani, Hasbani, Berdawni, Damour at Jisr Qadi and sea mouth) GR2M yield quite good results. For the remaining catchments GR2M simulation results yielded Nash values lower than 0.5. When looking into the details of the simulation one can notice two main elements that may have a role in the poor performance of the GR2M. One is a shift in the runoff peak between February and March due to the snowmelt; another is the rapid recession during the dry period. So any amelioration of the GR or the proposition of new conceptual models must take these two factors into account. On the other hand, for the classification of catchments according to their hydrological and physical characteristics; catchments in the same group exhibit same modeling function, particularly for groups of physically and hydrologically similar catchments (PH).

The particularities (snow + karst) of the studied catchments that make their simulation with GR2M difficult are not confined to Lebanon and one can find in literature similar cases that had been studied across the Mediterranean. Models that deal specifically with such situations were proposed and implemented with satisfactory results. Nevertheless, such detailed need a large amount of data, at least at a daily time step which is not always available in our case neither for rainfall nor for snow. Further, the uncertainty on the data is another element that makes the modeling of the Lebanese catchments a challenge. The quality of the available hydro-meteorological data is questionable and the uncertainty of the data is yet to be assessed.

Perspectives

This study has highlighted various aspects of the hydrological and physical characteristics of the Mediterranean catchments in general and the Lebanese catchments in particular. And identified research challenges and gaps that need to be addressed in future works.

The review on Mediterranean hydrology showed disproportionality in the distribution of studies across the Mediterranean. There is a need for more hydrological studies in the Eastern and Southern Mediterranean, since the event scale studies at a high spatial and temporal resolution are rare. Moreover, new hydrological models based on observational data that take into account the high spatial and temporal variability of rainfall and heterogeneity of catchment response is also needed. On the other hand, most of the regionalization studies in the Mediterranean are based on the countries political boundaries and does not take into account the diversity of climates that that same country may encounter. Thus, studies that encompass countries borders and permit the comparison of catchments from different part of the Mediterranean will be useful for understanding the regional hydrology. Additionally, this work gathered information on a great number of the Mediterranean catchments, a follow-up on this work would be to find twins catchments across the Mediterranean. Nevertheless, this work was limited to the Mediterranean region; future work that may extent the angle to regroup all Mediterranean climate areas or undertake different climatic regions is recommended.

Concerning the Lebanese catchments, there are many problems that exist and need to be addressed. First, in term of data acquisition, the current spatial extent of the Meteorological network does not permit the full coverage of the entire country especially in the areas that might receive the highest amount of precipitation (mountainous areas) and in remote areas such as the Eastern chain. This can run also on the spatial extent of the hydrometric network with only permanent rivers being gauged while no information whatsoever is available for small intermittent streams. Furthermore, the temporal resolution for both networks needs to be higher in timescale (in minutes or even hours) in order to capture the rapid variation in precipitation and the rapid response of the Lebanese catchments. Additionally, snow contributes to a great extent to river discharge; hence snow accumulation and melt has to be closely monitored in order to establish a credible water balance of the country. Some work leaded by the CNRS is being conducted in the last couple of years with the construction of some snow monitoring stations. Last and not least, one should note that great efforts need to be placed to improve the quality of these measurements.

Lebanon has not developed a national data sharing policy. Data on water resources are neither sufficient nor available for everyone. However, some things could be done to improve the current situation. Remote sensing techniques can be one of the solutions that produce high resolution grids of rainfall spatial distribution on a daily and hourly time scale. Similarly, satellite imageries can be used to monitor the spatial distribution of the snow and its relative depth if appropriate tools are being used. This information could be used to build taylor-made model that better represent the hydrological functioning of the Lebanese catchments.

Finally, when gathering data on the Mediterranean catchments, the great heterogeneity of the used descriptors especially in regionalization studies was a real challenge. The same remark is made when defining the physical descriptors and runoff signatures of the Lebanese catchment. There exist a huge number of variables in the literature. Accordingly, each author defines his own variables. This doesn’t only make the classification less objective but also of a great challenge towards comparative hydrology and the development of a global classification schemes. Thereof, there is an urge to agree on a minimal number of variables to be used in catchment classification. Perhaps the development of an interactive international database with an identity card (made of the so defined variables) for each catchment would be a great step towards a global classification schemes in hydrology.

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ANNEXES

Annex A.
Acronyms

Ac	Catchment area (km²)
AI	Aridity index (AI= ET0/MAP)
Agr	Agricultural areas (%)
Ak	Apparent karst (%)
Bare	Bareland areas (%)
CC	Climate change
D	Deterministic approach
Dd	Drainage Density (km/km^2)
EM	Eastern Mediterranean
ET0	Mean annual evapotranspiration (mm)
Fc	Forested areas (%)
G	Geo-statistical methods
GR	Global regression
Grass	Grassland areas (%)
Group H	Hydrologically similar catchments
Group P	Physically similar catchments
Group PH	Physically and hydrologically similar catchments
HIS	High infiltration capacity soils (%)
HPR	High permeability rocks (%)
IM	Index methods
Lflow	Longest flow path (km)
LIS	Low infiltration capacity soils (%)
LPR	Low permeability rocks (%)
LUC	Land use change
MA	Model averaging
MAP	Mean annual precipitation (mm)
MAQ	Mean annual runoff (mm)
Max Zc	Maximum elevation (m)
Min Zc	Minimum elevation (m)
MIS	Moderate infiltration capacity soils (%)
MPR	Moderate permeability rocks (%)
Nc	Number of catchments
Ne	Number of events
NSE	Nash-Sutcliffe efficiency criterion
NWM	North-western Mediterranean
P	Event rainfall depth (mm)
PSBI	Physiographic space-based interpolation

R	Two-step regression
R^2	Coefficient of determination
RC	Regional calibration
RMSE	Root mean square error
RR	Regional regression
S	Similarity
Sc	Slope along the Lflow (m/m)
Shrub	Shrubland areas (%)
SM	Southern Mediterranean
SP	Spatial proximity
Uc	Urban areas (%)
Zc	Catchment mean elevation (m)
Zc>1800	Area above 1800 m (%)

Annex B.
Hydrological modeling

Introduction

Hydrological modeling could be defined as a simple representation of hydrological processes at a certain scale, generally at catchment scale. Hydrological modeling may simulate continuous hydrological processes at the catchment scale, or simulate hydrological processes induces by a single event, such as a storm.

Different approaches for hydrological modeling

1- Physically-based models or process-based models: these models are based on the understanding of physical processes and their mathematical description, such models required a large set of data (e.g. Green and Ampt 1911; Morel-Seytoux 1996). Physically-based models represent the component hydrological processes such as evapotranspiration, infiltration, overflow, and saturated and unsaturated zone flow using the governing equations of motion. In theory, physically-based models are defined by wholly measureable parameters and can provide continuous simulation of the runoff response without calibration (Beven 2001).

2- Conceptual models: these models are based on the conceptualization of physical processes (e.g. Horton 1933). According to Wheater et al. (1993), conceptual models are based on two criteria: firstly, the structure of the model is specified prior to any modeling being undertaken, and secondly not all of the model parameters have a direct physical interpretation. Therefore at least some conceptual model parameters have to be estimated through calibration against observed data. Conceptual models generally represent all of the component hydrological processes perceived to be of importance in catchment scale input-output relationships (Wheater 2002).

3- Empirical models: are based on statistical analysis of observed data, and they are usually applicable only to the same conditions under which the observations were made (e.g. Soil Conservation Service SCS 1972). The simplicity of such models has allowed them to be applied relatively easily to ungauged catchments by regional analysis, relating model properties to physical and climatic descriptors of the catchment.

Much widely used hydrological modeling software are based on one or more of these models, e.g. Morel-Seytoux model which is a simplification of the famous Green and Ampt equation (Chahinian et al. 2005) is used among others in WEPP (Raclot and Albergel 2006) and KINEROS (Woolhiser et al. 1990); Horton's model is used by example in MARINE (Roux et al. 2011), SCS is used among other in SWAT (Arnold et al. 1998) and HEC-HMS.

Based on the degree of model spatial representativeness, one can dedifferentiate lumped model and spatially distributed model. Lumped models are simple model that represent the whole basin as one entity, thus, does not account for spatial variability inside the catchment and for small-scales processes. On the contrary, spatial distributed model or distributed hydrological models (e.g. Moussa et al. 2007) are more complex models that take into account catchment subdivisions, and the variability of catchment physical characteristics from one subdivision to another.

In Hydrology, models have become essential for study of the water cycle at the catchment scale. These models are used by hydrologists to test hypothesizes and to understand hydrological processes (Beven 2001). They have become useful tools in water resources planning and management, providing capability to predict stream flow form routinely used climatic data. One hydrological models application that have been largely developed in recent years is the assessment of the hydrological impact of land cover changes. Whereas land cover change influence on water yield have become a major concern for hydrologists, hydrological modeling aiming to respond to this problematic has flourished in the last few years.

Model calibration and validation procedure

Model calibration is the process of selecting suitable values of model parameters such that hydrological behavior of the catchment can be simulated closely (Moore and Doherty 2005). Validation takes place after calibration to test if the model performs well on a portion of data, which was not used in calibration. Model verification aims to validate the model’s robustness and ability to describe the catchment’s hydrological response, and further detect any biases in the calibrated parameters (Gupta *et al*. 2005).Special attention should be paid to model calibration procedure since the role of calibration is to determine the model parameters. The rainfall-runoff record for the study area is usually divided into calibration and validation groups; while it is generally advisable that both groups should be large enough and represent the climatic and hydrological variability, more importance is usually given to the calibration group due to the calibration direct role in determining the model parameters. In general, records used for validation are not included in the calibration group; this is to asses independently the performance of the calibrated model (Bahat et al. 2009). Many objectives criteria are used in the literature for model calibration, these criteria usually measure agreement between the observed and the simulated runoff. Volume conservation, peak flow reproduction and global agreement between observed and computed curves are taken into account in the objectives criteria.

Two main objectives criteria used for calibration and validation procedures are the the Nash and Sutcliffe (1970) efficiency measure and the Root Mean Square Errors RMSE.

The Nash-Sutcliffe efficiency index is calculated as:

$$NSE = 1- \frac{\sum_{i=1}^{n}(Oi-Si)^2}{\sum_{i=1}^{n}(Oi-O)^2}$$

Oi is the observed discharge at timestep *i*, *Si* the simuated discharge, and *O* the mean value of observed discharges *Oi*.

Nash–Sutcliffe efficiencies can range from −∞ to 1. An efficiency of 1 (*NSE* = 1) corresponds to a perfect match between observed and simulated data. Essentially, the closer the model efficiency is to 1, the more accurate the model is.

As an example of the Root Mean Square Error:

$$\text{RMSEV} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Voi - Vsi)^2}$$

Where

RMSEV *the root mean square error for the overall runoff volume*

n *number of events in the calibration group*

I *index representing a flood event*

Voi *observed runoff volume for the event i (m^3)*

Vsi *simulated runoff volume for the event i (m^3)*

Here, one should mention that due to the high variability in events magnitudes, RMSE may be sensitive to large events, thus the representativeness of such criteria is questioned. As an example Bahat et al (2009) found that the optimal parameters based on RMSLQ (root mean square error for peak flow) for 12 rainfall-runoff events are 9 mm and 1 mm/h for the initial loss and infiltration capacity, respectively. If the largest runoff volume event is removed from this group, the calibration yields values of 6 mm and 8 mm/h. They notice that by adding a log-based function to the objective criteria equation, as example,

$$\text{RMSELV} = \sqrt{\frac{1}{n}\sum_{i=n}^{n}((logVoi + 1) - (logVsi + 1))^2}$$

(constants considerably smaller than any observed values are added to the logarithmic function to avoid the analysis of a zero in a log function), the sensitivity of the RMSE to large events decreases, as such, the parameters obtained for the RMSELV objective function are 4 mm and 3 mm/h for groups with or without the largest event.

The calibration is done by finding the optimal parameter values for each objective function, by scanning the parameter space at constant intervals and finding the parameter set with the best objective function value.

Models limitations

Since the models are the mathematical representations of natural processes, they are limited by many factors:

Empirical models based on statistical analysis of observed data are limited to the fact that they can only be used in the same conditions under which observations were made; otherwise, the model parameters will need intense calibration to fit in for the new environment were the model is applied. Moreover, one should mention, that the fact that these models are based on statistical analysis is a limitation, since statistical analysis are always liable for a certain degree of subjectivity. Furthermore, statistical techniques have their own limitations, sampling procedure, overweighting (sometimes the representativeness of a sample could be altered by the presence of extreme, very rare events), etc.

Physically-based models are highly demanding in term of data. Although these models describe the physical processes inside a catchment, it can only be applied on a very small scale; otherwise, one will need an immense data gathering networks. Such models are usually used in experimental catchment were data measurements are available. Moreover, such models most be applied on short time-steps to account for the continuous variation of physical parameters in the study area.

The limitations of a conceptual model lie in the reality that these models are a simplification of very complex natural process which is reduced to a mathematical formula. Conceptual models also required an immense parameterization.

In term of lumped and distributed hydrological models, the former is a simplification of a very complex situation; it neglects the effect of relief, and the influence of rainfall variability which make runoff less predictable especially in mountainous region (Moussa et al. 2007). While the latter, which is a more realistic approach for hydrologic simulation, is limited by data availability especially in term of rainfall and soil moisture distributions, which are two important variables that control runoff generation and serve as input to models (Nikolopoulos et al. 2011). A distributed model also required rigorous parameterization, calibration and validation procedures, with some test of internal consistency of the distributed results on subcatchments (Moussa et al. 2007).

One should also mention that in practice, complex models often do not provide more accurate runoff predictions relative to simpler and less detailed ones. For example, Michaud and Sorooshian (1994a), for the 150 km^2 semi-arid Walnut Gulch experimental watershed in Arizona, found similar performance of simple Soil Conservation Service (SCS 1965). Al-Qurashi et al. (2008) modeled a 734 km^2 arid watershed in Oman with the complex Kineros model but performance was poor and inferior to that of a simple empirical model.

Input errors

The biggest problems for modelers are input data. It is said that the quality of the results is more dependent on the quality of the input data than the model chosen for use (Boughton 2005). Two major problems are measurement errors and sampling errors (when the selected input data are not representative for the whole catchment (Boughton 2005).

Another issue is the spatial variability and distribution of input data, especially rainfall. Rainfall spatial distribution over the catchment is often not well represented by rain-gauge networks (Faures et al. 1995). Actually, radar technology has allowed the representation of rainfall variability and distribution. However, this method has always its limitations: on one hand, several corrections should be performed on the initial radar signal so that it can be used as an input to the hydrological model, on the other hand, which is more important, Nikolopoulos et al. (2011) has demonstrates that for rainfall resolution greater or equal to 8 km, the different in peak discharge and runoff volume between simulated and observed results, for all simulated catchment, are non-acceptable. This indicates that rainfall radar resolution should be considered when using radar data for runoff simulation.

Annex C.
Regionalization in hydrology

Introduction

Although the definition of the term "regionalization" has slightly changed over the years (He et al. 2011), it is mostly used to refer to any approach that permit the transfer of hydrological information from gauged catchments to ungauged ones (Oudin et al. 2010).

During the last decade (named the PUB decade by the International Association of Hydrological Sciences), hydrologists worldwide emphasize on developing, applying and comparing new methodologies for regionalization of hydrological information (Merz and Blöschl 2004, 2005; Parajka et al. 2005; Young 2006; Bardossy 2007; Gotzinger and Bardossy 2007; Oudin et al. 2008; etc.). This emphasize was driven by the fact that the majority of basins worldwide are ungauged and that "*in the presence of data scarcity it would be compelling to infer hydrologic function from the metric of catchment form*" (Hrachowitz et al. 2013). Moreover, hydrologists became aware that the, already in use, hydrological models and empirical methods are unable to predict in ungauged sites (Sivapalan, 2003a), which reflect their insufficiency in representing the underlying hydrological processes.

The importance of regionalization comes, not only from the necessity of prediction in ungauged basins, but also from its ability to compare between large samples of catchments across different hydro-climatic conditions. Andréassian et al. (2006) emphasizes the importance of working with a large number of basin datasets; the aim is to compare and learn from catchments differences and similarities in different locations (Parajka et al. 2013; Salinas et al. 2013). Hence, regionalization studies contribute enormously to the ongoing work towards the development of a global classification scheme which still lacking in hydrology (Sivapalan 2005; Wagener 2007). Furthermore, the application of regionalization approaches proved to be valuable in constraining model uncertainties (Yadav et al. 2007).

As referred to earlier, regionalization is "any method used to transfer hydrological information from gauged to ungauged sites". However, there are many types of hydrological information. In some cases, hydrological information could be limited to some hydrological indices (also called runoff signatures) that represent aspects of catchment response (see Olden and Poff 2003 for a detailed review of hydrological indices) such as low flows (Longobardi and Vallini 2008; Mehaiguene et al. 2012, etc.) or floods (Farquharson et al. 1992; Saf 2009; etc.). While in other cases, the aim of regionalization is a continuous streamflow simulation (Kay et al. 2006; Andréassian et al. 2012; etc.). In the first case, regionalization is model independent (hydrological indices are directly regionalized), in the latter, regionalization is model-dependent. This means that the parameters of a hydrological model are calibrated on one (or more) donor catchment (gauged site) and then transferred to the target catchment (ungauged site) where the model is run to predict the runoff hydrograph.

Model-independent or dependent, there are many regionalization approaches available in the literature. They can be summarized into 3 major groups: geographical distance-based regionalization, similaqrity-based methods and regression-based methods. Moreover, one can implement regionalization in many different manners. This largely depends on the number of donor catchments used to transfer hydrological information to the target one. Hence, one can talk about, global regression, regional regression, model averaging, output averaging, regional calibration, etc.

These regionalization methods do not perform equally well (Oudin et al. 2008, 2010; Parajka et al. 2013; Salinas et al. 2013; etc.). They have their limitations and they depend on the available data and the underlying climatic and catchments characteristics.

In the following we will present an overview of the widely used regionalization methods, their limitations and a comparison assessment of their performances.

Regionalization methods

There are many regionalization approaches mentioned in the literature. However, they can be grouped into 3 main classes of regionalization methods: geographical distance-based methods, similarity-based methods and regression-based methods.

Geographical distance based methods

a) Spatial proximity

This approach assumes that catchments in the same geographical region have similar climatic and physical conditions. Therefore, one can transfer hydrological information from one (or more) gauged sites to an ungauged catchment in the same geographical region (Parajka et al. 2005; Oudin et al. 2008; etc.). The spatial proximity between catchments is measured as the Euclidian distance between catchments outlets or centroids (Eq.1) (Parajka et al. 2005; Andréassian et al. 2012).

$$dist(t,d) = \sqrt{(Xt - Xd)^2 + (Yt - Yd)^2} \qquad (1)$$

Where Xt, Yt and Xd, Yd are the coordinates of the centroids (or outlets) of the target and donor catchments respectively.

b) Geo-statistical methods

As for the spatial proximity approach, geo-statistical methods also assume that geographically close catchments present similar behavior. These are a set of methods (such as “Kriging” and “inverse distance weighting”) developed to interpolate point observations (i.e. runoff signature, model parameter at the donor catchment outlet) over the geographical space (Vandewiele and Elias 1995; Parajka et al. 2005; Samuel et al. 2011; etc.). However, classical kriging (and other geo-statistical methods) does not take into account stream network organization and nested catchments (Skoien et al. 2006). Therefore, a new approach was developed: Topological kriging or Top-kriging (Skoien et al. 2006; Skoien and Blöschl 2007). Top-kriging combines the continuous process in space defined for point variables (classical kriging) and the topology of the channel network and the organization of nested catchments.

Similarity-based methods

a) Physical similarity

This approach assumes that catchments having similar climatic and physical characteristics must have similar hydrological behavior, thus, one can transfer hydrological information from one (or more) catchment to a "similar" ungauged target catchment. Physical characteristics of catchment are measured in term of catchment attributes or descriptors. However, the choice of these attributes varies from one study to another. Hence, Oudin et al. (2010) defined the most similar catchments in term of seven catchments descriptors (aridity index, catchment area, mean slope, median altitude, drainage density, fraction of forest cover and soils). Merz and Blöschl (2004) also added information about geological units, porous aquifers and Lake Index. Others, such as Kay et al. (2006) use a very large set of catchment descriptors (22 catchments descriptors relative to catchment from, drainage organization, land use, soil, geology, etc.) while, on the other hand, some authors define physical similarity with very few descriptors such as, catchment area, mean annual precipitation and baseflow index (McIntyre et al. 2005) or even with only one descriptor such as the drainage area (Masih et al. 2010).

Similarity is calculated as the root mean square difference of all catchments descriptors, these descriptors are standardizes by their standard deviations (Eq. 2).

$$dist(a,b) = \sqrt{\sum_{j=1}^{j} \left(\frac{Xa,j - Xb,j}{\sigma x,j}\right)^2} \qquad (2)$$

Where j is one of j catchments properties, Xa,j is the value of that catchment properties at the ath catchment, while σx,j is the standard deviation of the property across all sites.

b) Hydrological similarity

What really define catchment hydrological behavior and how to assess catchments hydrological similarity is still a problem for hydrologists (Wagener 2007). As pointed out by Oudin et al. (2010), a model-independent definition would be preferable, such definition is based on catchment hydrological response indices (also called runoff signatures) such as flow duration curves (Masih et al. 2010), or baseflow index (Longobardi and Vallini 2008), etc. However, runoff signatures represent only aspects of the catchment behavior, thus, to cover all aspects of the flow regimes, some authors rely on model parameters transferability to define hydrological similarity. Therefore, 2 catchments are considered hydrologically similar if the streamflow of one catchment is adequately simulated using the parameter set calibrated on the other catchment (Kokkonen et al. 2003; Oudin et al. 2010).

c) Transformed coordinates

These approaches measure the similarities between catchment in a transformed space of the catchments physical and climatic descriptors (He et al. 2011).

One of the most well known examples of such methods is the Principal Component Analysis (PCA). PCA is a multivariate statistical method usually applied to reduce the dimension of large datasets by transforming the n-dimensional space (n= number of initial variables) into a new m-dimensional space, where m (1<= m <= n) is the number of new variables which are the principal components. These principal components are linear correlations of the initial variables; they are uncorrelated and orthogonal to one another and ordered as such the first component represents the largest amount of variance in the original dataset. Individual catchments can then be projected into this space and grouped accordingly (Mehaiguene et al. 2012). PCA is generally applied in combination with other methods such as regression or with kriging. The former method is referred to as Principal Component Regression (PCR) (Eslamian et al. 2010) and the latter, Physiographic Space-Based Interpolation (PSBI) (Castiglioni et al. 2009, 2011).

Another multivariate statistical method used for regionalization is the Canonical Correlation Analysis (CCA). Here we have 2 sets of random variables X= (X1, X2, …, Xn) and Y= (Y1, Y2, …, Ym), and there are correlations between the variables. CCA will find combinations of Xi and Yj which have the best linear correlations. In other worlds, CCA allows us to find the dominant linear model of covariability between the 2 sets of variables X and Y (Ouarda et al. 2001). Correlations between catchments descriptors and catchments response signatures (ex: low flows, floods) (Ouarda et al. 2001) or model parameters (Hundecha et al. 2008) could be found via CCA. These so found relationships (correlations) are than replaced by canonical variables. As for the principal components of the PCA, these canonical variables are uncorrelated and orthogonal, thus, can be used as coordinates axes that define a canonical space where distance between catchments can be computed using Euclidean metrics (He et al. 2011).

As for the PCA, CCA can also be used for a Physiographic Space-Based Interpolation (Ouarda et al. 2001). Here, similarity measures are performed in the canonical space using geo-statistical methods such as kriging.

All of the similarity measures presented in this work exhibit a limitation represented by the fact that these measures describe dependencies or bivariate correlations between random variables. Thus, these relationships will change if the marginal distribution of the random variable changes. To overcome this problem, some authors introduced the usage of copulas (Chowdhary and Singh 2010;

Samaniego et al. 2010). Copula is a multivariate distribution with uniform marginal distribution. In other words, copula is a measure describing dependency regardless of the marginal (He et al. 2011). Copula based similarity measure outperform Euclidean distance measures and reduce uncertainty in streamflow prediction (Samaniego et al. 2010).

Regression-based methods

Hydrological indices and/or model parameters are related to catchments descriptors via empirical relationships, the latter are used to estimate hydrological indices/model parameters in ungauged catchments. These types of regionalization methods are the mostly commonly used approaches (Nash 1960;; Kokkonen et al. 2003; Merz and Blöschl 2004; Parajka et al. 2005; Kay et al. 2006; Yadav et al. 2007; Oudin et al. 2008; Longobardi and Vallini 2008; Vezza et al. 2010; Mehaiguene et al. 2012; etc.). As for the physical similarity approach, one can relate catchment response indices (hydrological indices or model parameters) to a large range of catchments descriptors. Thus, as for the similarity-based methods, an important issue is raised: what are the catchments attributes that control the catchment hydrological response, and therefore need to be included in the regression model.

Regression could be directly applied to whole set of studied catchments; here we talk about global regression. Or, one can first subdivide the initial set of catchments into groups of catchments of similar characteristics using different grouping techniques, such as cluster analysis (Mehaiguene et al. 2012), or Principal Component Analysis (Eslamian et al. 2010) or based on pattern identification (e.g. seasonality of runoff) or even geographical distribution: here we talk about regional regression.

Other Regionalization methods

A set of regionalization methods widely used in regional flood studies (Farquharson et al. 1992; Javelle et al. 2010; etc) is: *"Index Methods*" (Salinas et al. 2013). These approaches are applied over regions that are assumed homogenous. The flood distribution function (of the region of interest) is than scaled by an index flood (such as mean annual flood) so we obtain a regional-scaled flood distribution function. For the ungauged catchment, the index flood is first estimated and multiplied by the regional-scaled flood distribution function afterwards.

Another approach used for regionalization is cluster analysis. Here, the initial set of individuals (catchments) is re-arranged into groups in such a way that each group (cluster) contains individuals that are the most similar. There are multiple algorithms to perform clustering. One can mention the distance-based model, such as hierarchical clustering, where groups are built according to distance connectivity (Archfield et al. 2013). Another algorithm is K-means clustering where individuals are grouped in clusters in which every individual belong to the cluster with the nearest mean (Mehaiguene et al. 2012). Many other clustering algorithms exist and are in use by hydrologists, such as hybrid cluster analysis and fuzzy cluster analysis (Ramachandra Rao and Srinivas 2006).

Finally, some authors use the arithmetic mean of model parameters as a regionalization method (Kokkonen et al. 2003; Parajka et al. 2005; Oudin et al. 2008; etc). This method is generally applied as the simplest regionalization method to compare with other more sophisticated approaches.

Implementation of the regionalization methods

The implementation of the regionalization methods can be model-dependent or independent. It depends on the method in use, the parameters to be regionalized (model parameters or runoff signatures) and the number of donor catchments.

For model parameters regionalization, many implementation techniques are in use:

- *Model Averaging*: this technique is applied with geographical distance based methods and similarity based methods. Here, more than one donor catchment is in use. An average parameter set computed from parameter sets of many donor catchments (Goswami et al. 2007; Oudin et al. 2008; Samuel et al., 2011).

- *Output Averaging*: Also used with a group of donor catchments, and with the spatial and similarity based methods. Here, instead of averaging the model parameters, the streamflow is averaged over the donor catchments and transferred to the target site (McIntyre et al. 2005; Oudin et al. 2008). The advantage is that all the information of the locally calibrated model parameters is used (Oudin et al. 2008).

- *Two-step regression*: this regression technique is applied, as the noun implicate, in two steps. First, model parameters are calibrated on the gauged catchments; secondly, model parameters are related to catchment descriptors. This technique is the most popular regression (Kokkonen et al. 2003; Merz and Blöschl 2004; Wagener and Wheater 2006; Young 2006; etc).

- *One step regression/regional calibration:* this technique combines the two steps of the previous one. Here, the model is not calibrated independently form catchment descriptors. On the contrary, the performance of the multiple regression (between model parameters and catchment descriptors) are simultaneously taken into account (Hundecha and Bardossy 2004; Hundecha et al. 2008, etc). This method allows one to find more liable parameters and make use of the information contained in the catchment descriptors (Parajka et al. 2013).

- *Sequential regression;* here instead of calibrating all the model parameters simultaneously, the calibration is performed sequentially from the most identifiable parameter to the least one (He et al. 2011). In fact this method is developed to overcome the issue of poor model parameters identifiability (Hogue et al. 2000; Wagener and Wheater 2006).

The performance of regionalization methods are usually assessed with the leave-one-out cross validation procedures (also known as pseudo-ungauged catchment procedure or jack-knife procedure). Here, each basin is used in turn as if it was ungauged (Parajka et al. 2005; Oudin et al. 2008; Samuel et al. 2011; etc). Statistical tests are then applied to test the performance of the prediction in the pseudo-ungauged catchments. One of the most commonly in use efficiency criterion is the Nash and Sutcliffe (1970) criterion (Cutore et al. 2007; Oudin et al. 2008, 2010; etc). Other efficiency tests are also in use such as the coefficient of determination (Castiglioni et al. 2011; Vezza et al. 2010; etc), the root mean square error (RMSE) (Saf 2009; Chokmani and Ourda 2004, etc), volume error, mean bias, etc.

Limitations

Although regionalization approaches seem promising for prediction in ungauged basins, for constraining uncertainties related to model parameterization and for comparing large set of catchments (which is most valuable for the development of a unified hydrological theory and a general classification scheme). These methods have their limitations. They are either due to the regionalization approach itself, to the model in use, or to the underlying climate and physical conditions and the data availability.

Limitations due to the regionalization methods

A main issue with the *geographical-distance based* methods is that we do not understand how this approach works. In fact, as pointed by He et al. (2011), we do not yet know the underlining causes behind catchments similarity. Many authors have discussed the fact that geographical proximity does not necessarily reflect hydrological similarities which make spatial proximity a *"vague indicator"*. Hence, one can find in the literature contradictory results, with geographical distance approach sometimes yielding good results (Parajka et al. 2005; Oudin et al. 2008; Andréassian et al. 2012) or poor results (McIntyre et al. 2005; Young 2006).

Similarity-based approaches also exhibit important limitations: how can we define catchments similarity? What catchments attributes should we choose? What similarity measures should we apply?

Many authors rely on physical similarity assuming that physically similar catchments might exhibit similar hydrological behavior, hence, new questions are raised: are physically similar catchments really hydrologically similar? And how we measure physical similarity and hydrological similarity?

Physical similarity is usually measured by Euclidean distance between catchment attributes (see section 2.2.a). However, no universal rules are set for the choice of attributes, and choices are usually made according to the author knowledge of the system and/or the available data. Hence, there exist, in the literature, a wide range of catchment descriptors to choose from. Furthermore, in a study by Oudin et al. (2008) of 913 catchments in France, seven catchments attributes were chosen (aridity index, catchment area, mean slope, median altitude, drainage density, fraction of forest cover and soils), the author then apply different combination of these descriptors, 3 descriptors were enough to yield optimal results.

To answer the question of whether physically similar catchments are really hydrologically similar, Oudin et al. (2010) grouped 903 catchments (893 in France and 10 in the UK) according to their physical similarity and hydrologic similarity (based on model parameter transferability (see section 2.2.b). Only 60 % of the studied catchments were both physically and hydrologically similar. The author emphasized on the need to define new catchment attributes that better describe the underlining geological and soils characteristics of the basins. Other studies also find no improvement in the prediction in ungauged basins by grouping of catchments according to their physical-climatic characteristics (McIntyre et al. 2005).

Another similarity approach is the *transformed coordinates*. A first limitation of these methods lies in the fact that any transformation (projecting data from one space to another) involves a loss of information. Hence, in PCA, the individuals (catchments) are usually projected in the space created by the first and second principal component. However, these 2 components represent the largest amount of variance in the original variables, but not the whole variance. Moreover, Canonical Correlation Analysis, as pointed out by He et al. (2011), is subject to 3 main limitations: (1) the original variables should be normally distributed, (2) non-linear relationships are not captured, and (3) the linear correlation is not unique and hard to interpret.

Regression-based approaches share some limitations with the similarity approaches. Here again, no rules for the choice of catchment attributes against which model parameters or hydrological indices are regressed. Nonetheless, some catchment attributes seems to be more in use than other, such as drainage density, land cover/use, slope, soil and elevation (He et al. 2011). However, if a catchment descriptor is widely in use, this does not mean that it is crucial in defining catchment hydrological response. In fact, regression-based methods do not improve our understanding of catchment hydrological behavior. They may correctly estimate model parameters or catchment response indices, but they are still empirical relationships that may or may not come up with good estimations.

Limitations due to the model in use

In a study by Parajka et al. (2013), authors compared different regionalization approaches (for continuous streamflow simulation) involving 3874 catchments across different climates. These studies used different rainfall-runoff models with different degree of complexities, which was very valuable to determine the limitations induced by model structure on the performance of regionalization approaches. Model complexity was expressed in term of number of model parameters. Results indicate no strong dependency of the performance on model complexity. However, one most notes that in these studies compared by Parajka et al. (2013), different regionalization methods were used with different models. Moreover, other authors (e.g. Oudin et al. 2008) found a slight decrease in regionalization performance with an increasing number of model free parameters. In the UK, Kay et al. (2006) compared 3 regionalization methods using 2 models (PDM and TATE) with 6 free parameters. Authors found that physical similarity outperforms regression for PDM, while, regression performs better with TATE. They concluded that model structure does influence the performance of regionalization methods.

A well known problem of model-dependent regionalization is the problem of model parameters equifinality (different sets of model parameters yield the same optimum result). Another is the interdependency of model parameters. In order to overcome this problem, Bardossy (2007) discussed a new approach where the whole sets of catchment parameters are transferred from the donor catchments to the target catchments. The approach was presented as trial and error procedure. Where some target catchments delivered good results and other don't. Further work is needed to develop this approach.

Impact of data availability, climatic conditions catchment characteristics on regionalization efficiency

Geographical-distance based methods and physical similarity methods seem to improve with an increasing density of gauged basins (Parajka et al. 2005; Oudin et al. 2008; Andréassian et al. 2012). In fact, the impact of the streamgage network density on the efficiency of the geographical-based methods is crucial. Oudin et al. (2008) progressively decreases the network density of the possible donor catchments. The efficiency of the spatial proximity largely decreases with the decrease of the network density. The same results were presented by Andréassian et al. (2012). This limitation is very undermining since the whole point of regionalization is prediction in "ungauged basins".

Parajka et al. (2013) and Salinas et al. (2013) compared regionalization methods for runoff hydrograph prediction, and low flows and floods predictions respectively. The former used 3874 catchments from 34 international studies on continuous streamflow simulation across different climates. The Latter used 3112 catchments (14 studies) for low flows predictions and 3023 catchments (20 studies) for floods prediction across different climates. They concluded -for all regionalization methods and all regionalized parameters- that regionalization methods perform better in humid areas than in arid areas. This is mainly due to the fact that hydrological processes are more linear under humid conditions. Arid regions are more spatially heterogeneous and hydrological processes tend to be more non-linear and variable in time. Other authors gave the same conclusion. Hence, Bao et al. (2012) compared regionalization methods across different climates in China. They found better performance in humid regions. Oudin et al. (2008) found the better performance of regionalization methods in western France, while the catchment in the Mediterranean southern part of the country yielded the poorer results. However, in cold environments regionalization yielded a very wide range of performance. This may be due to the complexity of such environments where snow is a major control on hydrological processes.

In the same works, Parajka et al. (2013) and Salinas et al. (2013) studied the effect of catchment characteristics (for a lesser number of catchments/studies) on the regionalization method performance. They found that the impact of elevation goes in the same direction of climate, in other word when the increase in elevation tend to enhance more humid conditions (e.g. France), the performance increases, whereas, when it enhance arid conditions (e.g. Austria) the performance decreases. For all methods, an increase in catchment scale always increases method performance. This can be attributed to 2 main reasons: (1) the increasing number of raingauge in a large catchment, and more importantly (2) to the aggregation effect of runoff, as the catchment area increases, hydrological variability is averaged out (a smoothing effect).

Comparative assessment of regionalization methods

Comparing the performance of regionalization methods is very problematic. On the one hand, regionalization methods performance depend on the model in use, the available data, the used catchment descriptors, catchments characteristics and the climatic conditions. However, studies comparing different regionalization methods are always limited in one or another of the above mentioned criteria. As an example of this dilemma: Parajka et al. (2005) compared different regionalization methods in Austria, however Austria has only a cold climate, by which the comparison is limited. Moreover, the streamgage network in Austria is well developed which may favor one methods over another (geographical based over similarity). These same comments could be make for many other studies (e.g. Goswami et al. 2007; Oudin et al. 2008 [France]; Kay et al. 2006; Young 2006 [UK]; Viviroli et al. 2009 [Switzerland]; Kokkonen et al. 2003 [North Carolina, USA]; Samuel et al. 2011 [Ontario, Canada]; etc). Furthermore, Parajka et al. (2005) and Merz and Blöschl (2004) compared spatial proximity and kriging for the same sets of catchments in Austria. However, the former used an improved version of the model (HBV) used by the latter. Parajka et al. (2005) found that kriging slightly outperform spatial proximity, while with Merz and Blöschl (2004), the results favored spatial proximity.

On the other hand, studies that compare regionalization methods across different geographical locations (i.e. different climates) by synthesizing other works (e.g. Parajka et al. 2013; Salinas et al. 2013) have also their constrains. Different studies use different kind of datasets, different catchment descriptors and different models.

All the above-mentioned factors make it very difficult to generalize on the comparative performance of regionalization methods. However, some conclusions could be drawn from the literature:

- All regionalization methods perform better in humid climates than in arid climates and in large catchments than in small ones (Parajka et al., 2013; Salinas et al. 2013; Bao et al. 2012).

- For the geographical distance based methods, geo-statistical approaches (mainly kriging) more often outperform spatial proximity approaches (Vandewiele and Elias 1995; Parajka et al. 2005; Castiglioni et al. 2009).

- Geographical distance based methods are dependent on the streamgauge density, and seem to outperform other methods when streamgauge density is high (Parajka et al. 2005; Oudin et al. 2008; Parajka et al. 2013). The performance of these methods increases when the number of neighbors increases (Andréassian et al. 2012).

- Regression-based methods are the most commonly used. However, they tend to exhibit lower performances when compared to other methods (Kokkonen et al. 2003; Merz and Blöschl 2004; Parajka et al. 2005; McIntyre et al. 2005; Oudin et al. 2008; Samuel et al. 2011). One can find some exceptions as in Young (2006) and Kay et al. (2006).

- In comparison with other approaches, mixed performances are reported for the physical similarity approach and it is hard to draw a general conclusion. It is somewhat in between geographical-distance based approaches and regression. It seems that the choice of catchment attributes and the model have a great impact on the performance of this method (Kokkonen et al. 2003; Kay et al. 2006; Oudin et al. 2008).

- Physical similarity does not necessarily implicate hydrological similarity (Oudin et al. 2010) and using model-independent approaches to measure hydrological similarity seems to be more accurate (Masih et al. 2010) than model parameters transferability approaches.

- When implemented via output averaging, spatial proximity and physical similarity seems to yield better results than with the model averaging approach (McIntyre et al. 2005; Oudin et al. 2008).

- New approaches combining different regionalization methods (Samuel et al. 2011; Bao et al. 2012) and other using more sophisticated statistical techniques such as PCA (Castiglioni et al. 2009), CCA (Ouarda et al. 2001), copulas (Samaniego et al. 2010) or geo-statistical based approaches such as Top-kriging (Skoien et al. 2006; Skoien and Blöschl 2007) or even a combination of both such as the PSBI (Physiographic space-based interpolation) (Castiglioni et al. 2009, 2011) seems to be very promising.

However, more work is needed to further develop these approaches and learn about their potentialities and limitations.

Conclusion

During the last decade, prediction in ungauged basins has been a main arena for research development in the field of hydrological sciences. Its importance stands from many factors: (1) the majority of catchments around the globe are ungauged, (2) the need to develop a global classification scheme for classification in hydrology, (3) and the necessity to compare large number of catchments in order to deepen our knowledge and understanding of catchment organization and the hydrological patterns and responses that govern catchment hydrological behavior.

Prediction in ungauged basins can be model dependent or independent. Many approaches are undertaken by hydrologists in order to optimize prediction in ungauged basins. In this work, we have presented an overview of the most commonly used regionalization methods, their limitations and their relative performances. One can summarize as follow:

- Regionalization methods could be grouped into 3 main approaches: geographically-based approaches, similarity-based approaches and regression. They can be implemented as model-dependent or independent. They are applied for continuous streamflow simulation or for specific runoff signatures.

- Regionalization approaches have many limitations. These limitations are due to the philosophy (assumption) behind the approach; data availability; catchment descriptors and model complexity, and the underlining climatic and catchments characteristics.

- The relative performances of regionalization methods vary with climatic conditions, catchments attributes, the model and the data. However, although the most commonly in use, regression based methods appears to be the least successful. Whereas the geographical based approach (mainly geo-statistical methods) tends to be the most successful especially in regions with dense streamgauge network.

- Catchment attributes most commonly in use for similarity and regression based methods are not necessarily the main factors influencing catchment hydrological behavior. More work is needed to fully understand what govern the hydrological response of catchments in order to optimize the choice of catchment attributes.

- New promising regionalization approaches are being developed (CCA, PSBI, copulas, Top-kriging, etc.). However, more work is needed to fully explore the potentiality of these methodologies.

Annex D.

On regionalization studies in the Mediterranean

Introduction

Although the definition of the term “regionalization” has slightly changed over the years (He et al., 2011), it is mostly used to refer to any approach that permit the transfer of hydrological information from gauged catchments to ungauged ones (Oudin et al., 2010).

During the last decade (named the PUB decade by the International Association of Hydrological Sciences), hydrologists worldwide emphasize on developing, applying and comparing new methodologies for regionalization of hydrological information (Merz and Blöschl, 2004, 2005; Parajka et al., 2005; Young, 2006; Bardossy, 2007; Gotzinger and Bardossy, 2007; Oudin et al., 2008; etc.). This emphasize was driven by the fact that the majority of basins worldwide are ungauged and that “*in the presence of data scarcity it would be compelling to infer hydrologic function from the metric of catchment form*” (Hrachowitz et al., 2013). Moreover, hydrologists became aware that the, already in use, hydrological models and empirical methods are unable to predict in ungauged sites (Sivapalan, 2003a), which reflect their insufficiency in representing the underlying hydrological processes.

The importance of regionalization comes, not only from the necessity of prediction in ungauged basins, but also from its ability to compare between large samples of catchments across different hydro-climatic conditions. Andréassian et al. (2006) emphasizes the importance of working with a large number of basin datasets; the aim is to compare and learn from catchments differences and similarities in different locations (Parajka et al., 2013; Salinas et al., 2013). Hence, regionalization studies contribute enormously to the ongoing work towards the development of a global classification scheme which still lacking in hydrology (Sivapalan, 2005; Wagener, 2007). Furthermore, the application of regionalization approaches proved to be valuable in constraining model uncertainties (Yadav et al., 2007).

As referred to earlier, regionalization is “any method used to transfer hydrological information from gauged to ungauged sites”. However, there are many types of hydrological information. In some cases, hydrological information could be limited to some hydrological indices (also called runoff signatures) that represent aspects of catchment response (see Olden and Poff, 2003 for a detailed review of hydrological indices) such as low flows (Longobardi and Vallini, 2008; Mehaiguene et al., 2012, etc.) or floods (Farquharson et al., 1992; Saf, 2009; etc.). While in other cases, the aim of regionalization is a continuous streamflow simulation (Kay et al., 2006; Andréassian et al., 2012; etc.). In the first case, regionalization is model independent (hydrological indices are directly regionalized), in the latter, regionalization is model-dependent. This means that the parameters of a hydrological model are calibrated on one (or more) donor catchment (gauged site) and then transferred to the target catchment (ungauged site) where the model is run to predict the runoff hydrograph.

Model-independent or dependent, there are many regionalization approaches available in the literature. They can be summarized into 3 major groups: geographical distance-based regionalization, similarity-based methods and regression-based methods. Moreover, one can implement regionalization in many different manners. This largely depends on the number of donor catchments used to transfer hydrological information to the target one. Hence, one can talk about, global regression, regional regression, model averaging, output averaging, regional calibration, etc.

These regionalization methods do not perform equally well (Oudin et al., 2008, 2010; Parajka et al., 2013; Salinas et al., 2013; etc.). They have their limitations and they depend on the available data and the underlying climatic and catchments characteristics.

In the following we will present an overview of the widely used regionalization methods, their limitations and a comparison assessment of their performances.

Database

A total of 32 studies on the Mediterranean region published over the last two decades were analysed.

To study regional tendencies in the Mediterranean zone, the study region was divided into the northwestern Mediterranean (NWM, encompassing Mediterranean Albania, Croatia, France, Italy, Montenegro, Portugal, Slovenia and Spain; 102 studies), eastern Mediterranean (EM, encompassing Cyprus, Egypt, Greece, Israel, Lebanon, Palestinian territories, Syria and Turkey; 35 studies) and southern Mediterranean (SM, encompassing Algeria, Egypt, Libya, Morocco and Tunisia; 15 studies).

The studies were divided into three groups to focus on the annual water balance (68 studies), flood events (48 studies) and droughts (36 studies). In each group, studies on individual catchments (120 studies) and regionalization studies for predictions in ungauged basins (32 studies) were analysed separately.

For each study, key information includes (*i*) the reference and coordinates of the basin location; (*ii*) the objectives of the study; (*iii*) the basin characteristics, such as the area, mean elevation, mean slope, land use, soil classes, geology and the possible presence of karst; (*iv*) the hydro-meteorological data characteristics, such as the rainfall-runoff measurement period, the time step of the measurements, the mean annual precipitation, the reference evapotranspiration, the mean annual runoff, the runoff coefficient and the snow contribution; for event-based studies, detailed information on catchment responses (rainfall, runoff, peak discharge) for each event was also extracted when available; (*v*) the model characteristics, such as the model name and original reference, the simulated hydrological processes, the spatial resolution (lumped, semi-distributed or distributed), the time step and the model evaluation criteria; for regionalization studies, information on the regionalization methods and their relative performances was also obtained.

Continuous streamflow simulation

Regionalization studies concern either the prediction of the runoff hydrograph for ungauged basins or the prediction of flow duration curves (FDC), which characterize the discharge distribution.

Runoff hydrograph studies

A predicted runoff hydrograph in ungauged basins is usually achieved through regionalization of hydrological model parameters. Hence, model parameters are transferred from the gauged (donor) catchment(s) to the ungauged (target) catchment(s) (Blöschl 2005). Definitions and details of each method are presented in Parajka et al. (2013) and Goswami et al. (2007).

Six studies on runoff hydrograph predictions in Mediterranean countries are presented in Table D.1. Three of these studies were undertaken specifically in the Mediterranean region, while three other Mediterranean catchments were part of a larger set of catchments. All of the presented studies used conceptual rainfall-runoff models for the regionalization of the runoff hydrograph. Four of the six studies performed regionalization for the daily runoff hydrograph, while monthly runoff hydrographs were predicted for the remaining two studies (Cutore et al. 2007; Vicente-Guillén et al. 2012).

Table D.1 Summary of existing regionalization studies for continuous runoff simulation in the Mediterranean. Statistical evaluation indicates the leave-one-out assessment of the regionalization approach performance with the Nash-Sutcliffe (NSE) efficiency criterion. Nc: total number of catchments and the number in brackets represents the number of Mediterranean catchments in the larger dataset. Methods used for transfer of hydrologic model parameters include: SP: physical similarity; S: similarity; MA: model averaging; R: two-step parameter regression; and RC: regional calibration. The performances of the regionalization approaches are not reported when they were available for the whole set of catchments and not particularly for the Mediterranean cases.

Study	Country	Nc	Hydrologic model	Time step	Regionalization method	Performance (NSE)
Castiglioni et al. 2010	Italy (Central)	52	HYMOD	Daily	R	0.53
Cutore et al. 2007	Italy (Eastern Sicily)	9	Regression-based RR model	Monthly	R; RC	0.59; 0.66
Oudin et al. 2010	France	850	GR4J; TOPMO	Daily	S	-
Oudin et al. 2008	France	913 (162)	GR4J; TOPMO	Daily	SP, S, R	-
Goswami et al. 2007	France	12 (3)	Combination of models	Daily	MA, RP	-
Vicente-Guillén et al. 2012	Spain	8	Exponential model	Monthly	R	0.9

When assessing the relative performances of regionalization approaches, Oudin et al. (2008) proved that the spatial proximity method yielded the best results, the two-step regression had the worst performance, and the physical similarity provided intermediate results. Here, one must note that the relatively dense discharge network in France may have favoured the spatial proximity approach (Oudin et al. 2008, Andréassian et al. 2012). This result was also found by Parajka et al. (2013) in their review on runoff hydrograph studies across climates. The unfavourable performance of two-step regression methods was also shown in Castiglioni et al. (2010), in which the median NSE value did not exceed 0.53. Even at a monthly time step, the two-step regression yielded poor results. Cutore et al. (2007) examined the two-step and one-step (regional calibration) methods and proved that the median NSE performance of the method slightly increased from 0.59 (two-step) to 0.66 (one-step). A comparison between the model average and regional pooling (Goswami et al. 2007) shows that the latter has a better performance in all catchments, possibly because this method preserves the response of each donor catchment.

Generally, regionalization approaches perform poorly in Mediterranean catchments. In Goswami et al. (2007) and Oudin et al. (2008), regionalization approaches yielded poor results in Mediterranean catchments when compared with catchments in other French regions. The authors state that the high temporal and spatial variability of extreme rainfall events caused highly variable streamflow discharges over time and that the catchment responses in relatively arid areas are heterogeneous (Parajka et al. 2013, Salinas et al. 2013).

Flow duration curves

A flow duration curve (FDC) presents the percentage of time (duration) that a streamflow value is exceeded for a given gauging station at a select time step (e.g., daily). A FDC is commonly used because it is a convenient and informative method for displaying the entire range of streamflow discharges from low flows to floods (Castellarin et al. 2004). Many available approaches exist for the regionalization of FDCs. These methods can be summarized as statistical approaches, parametric approaches and geographical approaches. For details on each approach, please refer to Castellarin et al. (2004).

Despite the importance of FDCs for water management plans, particularly in water-stressed environments, few studies that deal with the regionalization of FDC have been published (Table D.2). This body of literature for FDC predictions in ungauged basins is scarce for the Mediterranean and globally, as shown in Parajka et al. (2013) and Salinas et al. (2013). Table D.2 summarizes the main FDC regionalization studies undertaken in the Mediterranean region.

Table D.2 Summary assessment of existing regionalization studies for Flow Duration Curve (FDC) in the Mediterranean. Statistical evaluation indicates the leave-one-out assessment of the regionalization approach. NSE: Nash-Sutcliffe efficiency criterion; MSE: mean square error; RMSE: root mean square error;

Study	Country	Nc	FDC approach	Predicted variable	Performance criterion	Performance
Sellami et al. 2014	France (South)	10	Modelling	FDC	NSE	-
Longobardi and Vallini 2013	Italy (South)	28	Statistical	FDC	RMSE	0.014 - 0.498
Mendicino and Senatore 2013	Italy (South)	19	Statistical Parametric	FDC	NSE	>0.75 for more than 78% of cases for all models; >0.75 for more than 52% of cases for all models
Rianna et al. 2011	Italy (Lazio)	28	Statistical	FDC	NSE	>0.95 for 54% of cases
Viola et al. 2011	Italy (Sicily)	53	Parametric	FDC	RMSE	0.24 – 0.38
Castellarin et al. 2007	Italy (Eastern Central)	18	Statistical	FDC	NSE	As figure
Castellarin et al. 2004	Italy (Eastern Central)	51	Statistical Parametric Graphical	FDC	NSE	>0.75 for 29 % of cases; >0.75 for 31% of cases; >0.75 for 22% of cases
Franchini and Suppo 1996	Italy (Molise)	16	Parametric	FDC	-	-
Croker et al. 2003	Portugal	67	Statistical	FDC	BIAS (%)	12 sites with BIAS > 75%
Mimikou and Keamaki 1985	Greece	11	Parametric	FDC	MSE (%)	3 - 10

Except for Sellami et al. (2014), who used hydrological model parameter regionalization for the prediction of FDC, all classical approaches for the regionalization of FDC perform well. These results may be surprising, particularly compared with the poor performance of runoff hydrograph regionalization under the same Mediterranean conditions. However, FDC is much simpler than a runoff hydrograph, and one could expect a better regionalization performance.

When assessing the relative performances of different FDC regionalization approaches, mixed conclusions are reported. Hence, statistical approaches appear to yield the best results according to Mendicino and Senatore (2013), while Castellarin et al. (2004) reported better performances for parametric approaches. However, for all approaches, the results deteriorate for the lowest duration of the FDC (high streamflow values). Moreover, the catchment area, mean annual precipitation, and indices representing the catchment permeability are reported as the most redundant variables in regression models. This finding emphasizes the important role of the catchment shape and geological features along with climatic characteristics in catchment responses represented by the FDC. Finally, given the extreme variability in climatic and hydrological responses in Mediterranean catchments that complicates modelling and results in a poor performance of runoff hydrograph regionalization techniques, the good performance of FDC regionalization is very promising.

Floods

Flood regionalization is a common practice in the Mediterranean region. The main methods used are index methods (IM), process-based approaches, and regional regression (RR). Definitions and details of these methods are available in Salinas et al. (2013). Eleven flood regionalization studies undertaken in various areas in the Mediterranean were analysed (Table D.3).

Table D.3 Summary of existing regionalization studies for floods in the Mediterranean. Statistical evaluation indicates the leave-one-out assessment of regionalization approach. Methods used include: IM: Index Methods; PB: Process based methods; RR: Regional Regression models (RR). Notations: Nc : number of catchments ; Q(2, 10, 100) : flood of 2, 10 and 100 years return period; Q100/Qm : Q100 normalized by the mean annual flow ; MAF : maximum annual flow; (-): information not retrievable.

Study	Country	Nc	Regionalization method	Predicted Variable	Performance criterion	Performance
Artigue et al. 2012	France (South)	1	PB	Peak flow	NSE and % of Peak Discharge	-
Javelle et al. 2010	France (South)	160	PB	Peak flow	Peak Error	-
Shentsis et al. 1997	Israel	67	RR	Peak flow	RMSE	-
Bocchiola and Rosso 2009	Italy (Northwest)	16	IM	Peak flow	Dimensionless MSE (%)	8 - 69
Aronica and Candela 2007	Italy (Sicily)	6	IM	Peak flow	Comparison with observed	-
Ferro and Porto 2006	Italy (Sicily)	43	IM	MAF	MSE	-
Portela and Dias 2005	Portugal	120	IM	Q2	Correlation coefficient	0.774 - 0.929
Mediera and Kjeldsen 2014	Spain	93	IM	Q(2, 10, 100)	RMSE	-
Cherif and Bargaoui 2013	Tunisia	32	IM	Q100	RMSE	0.29 - 0.46
Saf 2009	Turkey (West)	47	IM	Q100/Qm	RMSE	0.43
Topaloglu 2005	Turkey	50	IM	MAF	Prediction Error (%)	49 - 56

The most common technique for flood prediction in ungauged basins is index methods. The maximum annual flood is usually taken as the index flood. Here, differences between studies are often related to the method used to identify homogenous regions, the choice of the suitable flood frequency distribution function, and the regression models used to estimate the index flood. This group of statistical approaches appears to yield relatively satisfactory results. However, these results deteriorate for large return-period floods. This is true for all regionalization approaches. Moreover, the catchment area and antecedent soil moisture (when available) constitute the main parameters in regional regression models. However, it must be emphasized that the development of new descriptors that better describe the hydrological function of Mediterranean catchments (Mediera and Kjeldsen 2014) appear to improve the overall performance of the regionalization approach. These descriptors will not only help predictions in ungauged basins but also permit a deeper understanding of the highly variable and heterogeneous runoff-generation processes during rainfall events in Mediterranean conditions.

Low flows

Five recent regionalization studies on low-flow indices undertaken in the Mediterranean region were analysed (Table D.4). Four of these studies were conducted in Italy, and one study was conducted in northwestern Algeria. The hydrological indices include the discharge over 355 days (Q355), a daily discharge equal to or greater than 95% and the base flow index (BFI).

Table D.4 Summary of existing regionalization studies for low flows in the Mediterranean. Statistical evaluation indicates the leave-one-out assessment of the regionalization approach. Methods used include: PSBI: Physiological Space-Based Interpolation; G: Geo-statistical methods; GR: Global Regression; and RR: Regional Regression. Notations: Nc: number of catchments; BFI: baseflow index; Q355: discharge associated with duration of 355 days; Q95%: discharge equalled or exceeded 95% of the time.

Study	Country	Nc	Regionalization method	Predicted Variable	Performance criterion	Performance
Mehaiguene et al. 2012	Algeria (Northwest)	24	GR RR	BFI	R^2	0.32; 0.82 - 0.92; 0.70 - 0.99
Castiglioni et al. 2011	Italy (Centre)	51	PSBI G	Q355	NSE	0.78 - 0.83 0.89
Vezza et al. 2010	Italy (Northwest)	41	GR RR	Q95%	R^2	0.657 0.531 - 0.687
Castiglioni et al. 2009	Italy (Centre)	51	D G GR	Q355	NSE	0.64 - 0.65 0.31 - 0.81 0.72
Longobardi and Vallini 2008	Italy (South)	28	GR	BFI	R^2	0.230 - 0.678

The methods used for predicting low-flow indices in ungauged basins in the region are applicable worldwide. These methods are geo-statistical methods (G), deterministic interpolation (D), global regression (GR), and regional regression (RR). For detailed definitions of these methods, see Salinas et al. (2013). Geo-statistical methods and regression-based methods have been applied in transformed spaces of physical and climatic catchment characteristics (e.g., principal component analysis). Here, we discuss physiological space-based interpolation (PSBI) following Castiglioni et al. (2011).

Because the Mediterranean region is water-stressed, and low flows constitute a major component of the hydrological response of Mediterranean catchments, numerous studies on low-flow regionalization are expected in the region; however, few articles address this subject.

When assessing the relative performances of low-flow regionalization approaches, Castiglioni et al. (2009) showed that interpolation approaches (both deterministic and geo-statistical approaches) yielded better results than global regression (except for ordinary kriging). The performances of both approaches improved when applied in the transformed space of catchment’s physical and climatic characteristics (PSBI) (Castiglioni et al. 2011). When comparing global regression and regional regression, the latter always outperform the former (Vezza et al. 2010, Mehaiguene et al. 2012). Moreover, the choice of catchment descriptors highly impacts the results of regression models. Attributes that describe catchment permeability are particularly important in the case of low flows. The use of a permeability index, which takes into account catchment land cover, slope and geology, greatly increases the performance of the regression model (Longobardi and Vallini 2008). Nevertheless, the number of studies available here and the extent of the areas are very limited for generalizing the entire Mediterranean. One can definitely say that there is a need for many more low-flow regionalization studies in this region.

Discussion and Conclusion

Regionalization studies specifically undertaken in the Mediterranean are rare. Several studies were conducted at the national scale (e.g., in France), in which the Mediterranean is only a part of the study. Runoff hydrograph studies are the least common, and a majority of these studies were conducted at the national scale rather than the Mediterranean only. The results from these studies show that runoff hydrograph regionalization in the Mediterranean produces relatively poor results, possibly because these methods are model-dependent; thus, uncertainty from the regionalization approach is added to the already-discussed hydrological modelling limitations in the Mediterranean.

Relative evaluations of different regionalization methods show no specificity for the Mediterranean region. Regionalization studies on FDCs, particularly on low flows, are scarce. Regional flood studies appear to be the most common type of regionalization.

Statistical approaches for FDCs and floods appear to yield satisfactory results. However, these results deteriorate for the lowest duration of the FDC (high streamflow values) and seemingly for large return-period floods. Parametric approaches and regression analysis for FDC and low flows, respectively, produce mixed results.

Nevertheless, regionalization studies are important because they present an idea of the catchment attributes that impact the catchment hydrological responses. In FDC regionalization studies, the catchment area, mean annual precipitation, and indices that represent catchment permeability are the most relevant variables. The catchment shape and geological features, along with climatic characteristics, are important to the catchment response presented by the FDC. In low-flow models, catchment permeability appears in most regression equations. Groundwater plays a role in maintaining streamflows during dry periods.

In flood studies, the catchment area and antecedent soil moisture conditions (when available) constitute the main parameters in regional regression models. However, it must be emphasized that new descriptors that better describe the hydrological function of Mediterranean catchments are needed (Mediera and Kjeldsen 2014).

Annex E.

Lebanese data collection and availability

Introduction

In order to pursue a hydrological study, a set of data is required. This data goes from the meteorological and hydrometric measures, to the physical characteristics of the study area.

However, such data are not always available or/and accessible. In Lebanon, while getting the spatial data seems to be relatively easy, having access to available meteorological and hydrometric data is a real dilemma. Moreover, huge gaps exist in the series of temporal data due to political and military conflicts that took place in the country.

Herein, we are going to present the temporal and spatial extent of the available meteorological and hydrometric data, the available spatial data.

Temporal data

The temporal data consist of the series of meteorological and hydrometric data available for the country.

Meteorological data

General information

The American University of Beirut (AUB) meteorological station was the first to operate in Lebanon in 1891 and is still in use. However, available information from this station is limited to daily precipitation and temperature series from 1920 to 1974.

By the year 1928, six meteorological stations were operating in Lebanon: AUB and Beirut Nazareth in Beirut, El-Qraye and Jezzine in the Central part of Mount Lebanon, and Rayak and Ksara in the Bekaa valley. During the 1930s the number of meteorological stations in the country increases, and in the year 1940, 31 stations were operating. However, due to the Second World War, no meteorological data exists for the period between September 1941 and August 1944. In the years following the war, the number of stations increases enormously and by 1950, 55 stations were operating throughout Lebanon. This network of meteorological stations expands more and more during the 1950s and 1960, and by 1970, a dense network of 134 meteorological stations covers the whole country.

For climatic and orographic considerations, the Lebanese territory was divided into 3 major parts. The coastal region: from sea level to 800m, it was further divided into "Littoral North (LN), "Littoral Centre" (LC), and "Littoral South" (LS). The mountainous region, from 800m to the crest line of Mount Lebanon, further divided into "Mountainous North" (MN), "Mountainous Centre" (MC). The Internal region, from the crest line of Mount Lebanon downward to the Bekaa valley, this region also includes the Lebanese part of the Anti-Lebanon and Mount Hermon ranges, it was further divided into "Interior Oronte" (IO), "Interior Litani" and "Interior Hasbani". The meteorological stations were classified according to this climatic division of the country. Hence, fig. E.1 shows the expansion of the Meteorological Network at its peak in the year 1970. On the map, the stations were indexed from North to South in each geo-climatic class. Information regarding the name, altitude and the starting date for each station in fig. E.1 is presented in Table E.1. Available records from these station end in the year 1970.

Although this meteorological network provided a large set of climatic data such as precipitation, temperature, humidity, wind, etc. These parameters are only available on hard copies and need to be digitized. We were able only only to digitize monthly precipitation data.

Moreover, one should also notice, regarding the spatial and temporal extent of the pre-1970 meteorological network, that the spatial density and the length of the available data series vary from one region to another. Hence, the maximum spatial coverage of the Network is in the Central part of Mount Lebanon, the Interior Litani region and in the Littoral Centre. These three regions also benefits from the longest available records. Hence, in 1970, among 134 deployed throughout the country, 63 stations were concentrated in the above-mentioned three regions (33 in the Central part of Mount Lebanon, 22 in the Interior Litani, and 18 in the Littoral Centre). Moreover, from a total of 79 stations with records length of 10 years and more, 55 stations are located in these three geo-climatic zones.

In 1975, the Lebanese Civil War started causing a big gap in the data. For about 15 years and more only very few Meteorological stations remain operating (Tripoli-IPC, Beirut International Airport, Al-Arz and Rayak). One should wait until the year 2000 for a new Meteorological Network to be established for the whole country, however, with only 32 stations, the spatial coverage of this Network is far from the one of the pre-war network. Table E.2 represents details about these stations and their available meteorological data. The spatial extent of this Network is represented in fig. E.2. Daily precipitation and monthly temperature records are available from these stations from the department of meteorological services of the directory of civil aviation but not free of charge. In fact, these data cost a fortune and we were only capable of obtaining these data through a project financed by the UNDP. Afterwards, the data were examined to look for outliers and shift in the record.

Fortunately, around 20 stations from the pre and post-war period are almost in the same exact location (stations highlighted in yellow in tables E.1 and E.2).

At least but not last, it is worth-mentioned that the pre and post-war Meteorological stations are controlled by the National Meteorological Service of The General Directory of Civil Aviation of the Ministry of Public works and Transport.

At last, in 2009 the Lebanese Agronomic Research Institute (LARI) starts the establishment of its own Meteorological Network. Daily precipitation, temperature, humidity, wind speed and direction, and sunshine are available from these stations. Unfortunately, the records are too short, and there are a lot of missing data in the available record.

Meteorological data used in this work

This work was limited to the period 2002 - 2011. For this period precipitation data were available at a daily time step for 32 stations (Table E.2).

These data were used at two different levels:

- Daily precipitation data were used to characterize the hydrological response of the Lebanese catchments at the event scale. Fere, we have only worked on the most extreme event during the study period. The daily precipitation was averaged on the catchment during the event using the arithmetic mean of daily precipitation recorded in the stations located inside or directly near the border of the catchment.
- Monthly precipitation data were calculated from these data and used for rainfall-runoff modeling with GR2M for the period 2002 - 2011. Here monthly precipitations were calculated using all 32 stations for the whole country using interpolation methods (see chapter 3). Afterwards, monthly values were extracted for each catchment.

Temperature was only available at a monthly time scale (table E.2). However, due to the large gaps in the record we used ET0 values retrieved from MODIS imageries for the GR2M modeling.

Missing precipitation data

The gaps in the precipitation record for the study period (2002-2011) were completed using a simple arithmetic mean method. Hence the precipitation P at a given station x is given by:

$$P_x = \frac{1}{n}\sum_{i=1}^{n} Pi$$

Where 'n' is the number of nearby stations, 'P_i' is precipitation at ith station and 'P_x' is the missing precipitation.

Hydrometric data

Hydrometric network in Lebanon is under the control of the Litani River Authority. Hydrometric measures start in Lebanon in the early 1930s, with stations on the Litani and the Orontes Rivers. Afterwards, the number of hydrometric stations increases and by the year 1967, all of the main Lebanese rivers had at least one hydrometric station. Due to its importance, the Litani River has the densest hydrometric network, with 16 hydrometric stations on the main river and its tributaries. Unfortunately, with the civil war starting in 1975, the hydrometric records stopped for about 15 years. After 1990, the hydrometric Network was reestablished gradually, and by the year 2002, the Network count about 48 stations installed on the main Lebanese rivers.

Hydrometric data are available from a large number of hydrometric stations, however for the pre-1975 period; this record is short (about 8 years). The spatial extension of stations are available is presented in fig. E.3. Table E.3 gives details about each station in fig. E.3. Daily records are available for 24 stations and only monthly records for another 4 stations. However, getting these data were not easy, it was possible through personal connections.

Spatial data

Three forms of spatial data are in use in this study: Digital Elevation Model, Thematic maps and Satellite imageries.

Digital Elevation Model

A 10 m resolution Digital Elevation Model is developed for Lebanon at the Remote Sensing Center of the Lebanese National council for Scientific Research (CNRS). This DEM was developed from the topographic maps of Lebanon, with 10m contour lines interval. This DEM is in use for the delineation of watersheds, and the extraction of basins morphometric characteristics.

Thematic maps

Many thematic maps exists for Lebanon, the one in use in this study for the extraction of the physical characteristics of basins are:

- A 1/200000 geological map of Lebanon elaborated by Dubertret in 1955.
- A 1/50000 Karst map of Lebanon elaborated in 2011 by the CNRS.
- A 1/200000 soil map of Lebanon elaborated by Geze in 1956.
- A series of 1/20000 urban expansion map of Lebanon from 1963 to 2010, elaborated by the CNRS.

Satellite images

Due to the huge development in Remote Sensing technologies during the last few decades, satellite imageries had become an important aid in hydrological studies.

In the context of our study, we are using MODIS images at 500 m spatial resolution and 8-days temporal resolution from 2002 to 2012, to monitor the extent of snow cover over the Lebanese mountains and to calculate monthly ET0.

Conclusion

In this annex, we have briefly presented the temporal and spatial data available for our study area, Lebanon.

Temporal data exists from the early 1930s with different spatial coverage that increases over time and that is not evenly distributed all over the country. The maximum extent of the temporal data coverage was reached in the late 1960s. Unfortunately, few years later, in 1975, the Lebanese Civil War destroys the Meteorological and Hydrometric Network of the country, and it is not until the year 2000 that a new Meteorological and Hydrometric Networks were reestablished.

However, these post-war Networks are not as dense as the pre-war Networks, and the quality of the measurements are questioned.

As for spatial data, these data are available and easily accessible, however, some issues does exist with these data: the geological and soil map of the country, were developed over a half century ago on a very large scale (1/200000). The land cover/use maps developed for the country do not use all the same classification systems.

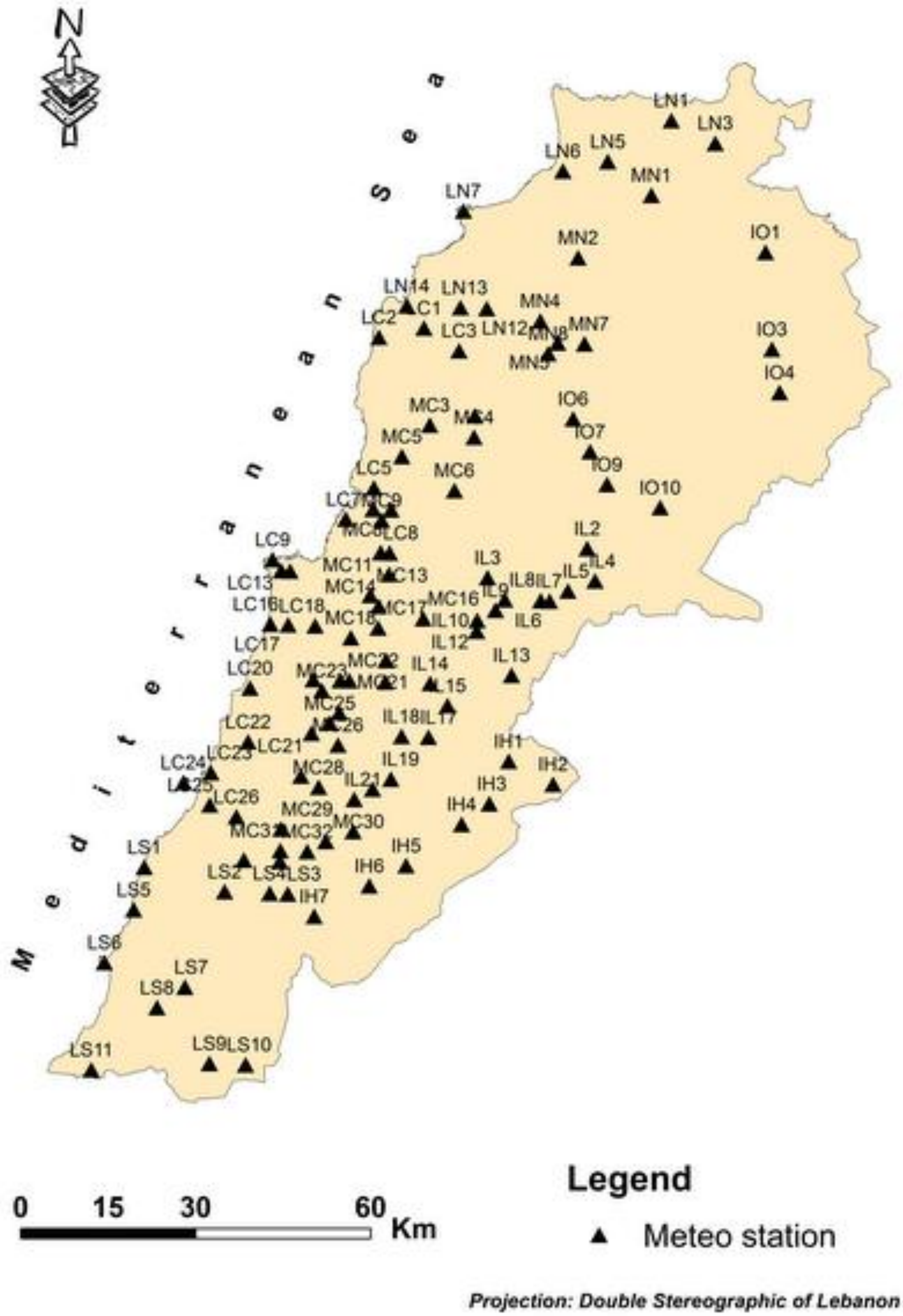

Fig. E.1 Meteorological Network at its peak in 1970; details of measurements period are given in table E.1

Table E.1 Details of pre-war Meteorological stations; *The measurements ended in 1974 due to the civil war (1975-1990) that causes a gap in the data. The highlighted stations are those re-established after the civil war (the same as the highlited stations in table E.2); as an example, the Qlaiaat station operated from 1931 to 1974 and than was re-established in 2003 (details in table E.2).*

Station number	Station name	Altitude (m)	Starting date	Station number	Station name	Altitude (m)	Starting date
LN1	Kouachra	400	1962	**MC5**	Ghebale	970	1944
LN2	Qlaiaat	5	1931	**MC6**	Faraya-village	1320	1962
LN3	Qaabrin	25	1966	**MC7**	Faraya-Mzar	1840	1965
LN3	Qoubayat	540	1962	**MC8**	Rayfoun	1050	1949
LN4	Beino	510	1966	**MC9**	Qlaiaat-Kesewan	1050	1939
LN5	Halba *	160	1938	**MC10**	Beskinta	1220	1966
LN6	El-Abde	40	1954	**MC11**	Bikfaya	900	1949
LN7	Tripoli-Mina	20	1960	**MC12**	Jouar-el-haouz	1290	1966
LN8	Bared-Moussa	250	1955	**MC13**	Ras-el-Maten	920	1944
LN9	Bakhaoun	630	1966	**MC14**	Arsoun	750	1945
LN10	Zgharta	110	1966	**MC15**	Falouga	1250	1966
LN11	Bechmezzin	275	1966	**MC16**	Dahr-el-Baidar	1510	1952
LN12	Abou-Ali	250	1938	**MC17**	El-Qraye	1010	1928
LN13	Amioun	300	1945	**MC18**	Bhamdoun	1090	1946
LN14	Chekka	15	1951	**MC19**	Ain-Zhalta	1080	1940
LC1	Kaftoun	215	1951	**MC20**	Fraidis	1250	1966
LC2	Batroun	20	1939	**MC21**	Kafar-Nabrakh	1020	1944
LC3	Kafar-Halda	580	1940	**MC22**	Majdel-Maouch	810	1946
LC4	Amchit	135	1966	**MC23**	Beit-ed-din	880	1940
LC5	Ghazir	390	1950	**MC24**	Jdeidet-ech-chouf	770	1944
LC6	Ghosta	650	1950	**MC25**	Moukhtara	810	1940
LC7	Zouq-Mikayel	70	1944	**MC26**	Jbaa-ech-chouf	1130	1964
LC8	qornet-Chehwan	605	1948	**MC27**	Beit-eddine-loqch	835	1965
LC9	Un.Americaine (Bey)	35	1891	**MC28**	Jezzin	945	1928
LC10	Arbaniye-jisr	510	1960	**MC29**	Jbaa-halawi	800	1964
LC11	Fanar	255	1969	**MC30**	Dahr-Darje	1150	1964
LC12	Nazareth (Bey)	90	1928	**MC31**	Jarjouaa	850	1964
LC13	Un.Saint-Joseph (Bey)	45	1933	**MC32**	Rihan	1090	1965
LC14	Ins.de Geographic (Bey)	55	1933	**IO1**	Hermel	700	1932
LC15	Jamhour	410	1955	**IO2**	El-qaa	650	1966
LC16	Aeroport (Bey)	15	1933	**IO3**	Fakehe	1060	1970

LC17	Choueiffat	100	1956	**IO4**	Arsal	1400	1961
LC18	Souq-el-Ghareb	700	1948	**IO5**	Nabha	1100	1966
LC19	Jisr-el-Qadi	260	1948	**IO6**	Yammoune	1370	1939
LC20	Dmit	350	1946	**IO7**	Chlifa-Flawi	1120	1944
LC21	Gharife	680	1965	**IO8**	Younin	1200	1966
LC22	Katermaya	380	1964	**IO9**	Haouch-Dahab	1010	1960
LC23	Saida	5	1962	**IO10**	Baalbek	1150	1931
LC24	Sfarai	570	1962	**IL1**	Kafar-dan	1080	1966
LC25	Maghdouche	230	1964	**IL2**	Haouch-snaid	995	1958
LC26	Anqoun	380	1965	**IL3**	Qaa-el-rim	1320	1940
LC27	Arab-salim	580	1964	**IL4**	Sarain	1000	1946
LC28	deir-el-zahrani	450	1964	**IL5**	Haouch-el-Ghanam	955	1951
LC29	lebaa	360	1969	**IL6**	Rayak	920	1928
LS1	Insariye	160	1964	**IL7**	Tell-Amara	905	1953
LS2	Douair	380	1962	**IL8**	Zahle	990	1950
LS3	Jarmaq	400	1964	**IL9**	Ksara	920	1928
LS4	Nabatiye	410	1964	**IL10**	Chtaura	920	1953
LS5	El-Qasmiye	30	1951	**IL11**	Terbol	890	1954
LS6	tyr	5	1955	**IL12**	Taanayel	880	1958
LS7	Jouaya	300	1964	**IL13**	Anjar	925	1951
LS8	Qana	300	1964	**IL14**	Ammiq	870	1962
LS9	Ain-Ebel	765	1960	**IL15**	Mansoura	860	1939
LS10	Aitaroun	680	1939	**IL16**	Soultan-Yaaqoub	1400	1965
LS11	Alma-Chaab	385	1960	**IL17**	Joub-Janin	920	1948
MN1	Michmich	1080	1964	**IL18**	Kherbe-Qanafer	950	1955
MN2	Syr-ed-Denniye	915	1940	**IL19**	Qaraoun-village	950	1953
MN3	Bouhairet-Toula	1135	1966	**IL20**	Qaraoun-Barrage	0	1963
MN4	Kafar-Sghab	1310	1964	**IL21**	Machghara	1070	1939
MN5	Bcharre-Ville	1460	1938	**IL22**	Markabe	670	1964
MN6	Bcharre-Usine	1400	1966	**IH1**	Yanta	1500	1961
MN7	Les Cedres	1925	1937	**IH2**	Deir-el-Achayer	1280	1965
MN8	Hasroun	1375	1963	**IH3**	Kafar-Qouq	1210	1961
MC1	Maifouq	875	1966	**IH4**	Rachaya	1235	1933
MC2	Laqlouq	1700	1940	**IH5**	Kfair-ez-Zait	940	1944
MC3	Tourzaya	880	1940	**IH6**	Hasbaya	750	1944
MC4	Qartaba	1140	1939	**IH7**	Marjayoun	760	1944

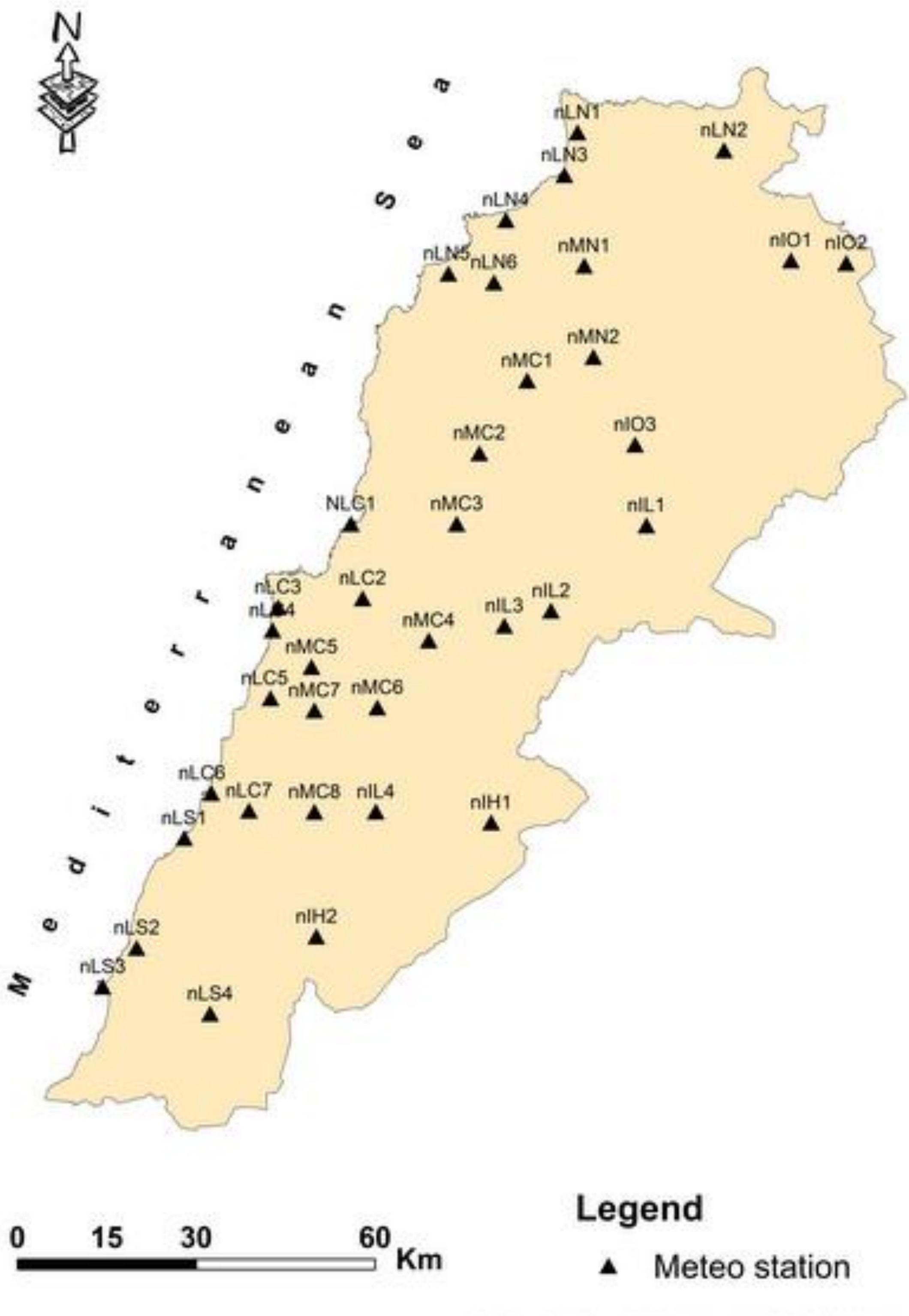

Fig. E.2 Post-war (after 1990) Meteorological Network; details of measurements period are given in table E.2

Table E.2 Post-war (after 1990) Meteorological stations; the highlighted stations are those that operated before the civil war (see Fig. and Table E.1)

Station number	Station name	Altitude (m)	Daily Rainfall Record	Missing Rainfall data	Monthly Temperautre record	Missing Temperature data
nLN1	El Qlaiat-Akkar	5	Mar 2003 to Dec 2011		Mar 2003 to Dec 2011	Sep 2006, May and Jun 2007
nLN2	El Qoubayat	497	Jan 2001 to Dec 2011		Jun 2000 to Dec 2011	Jan and Feb 2003, Sep 2003 to Mar 2005, Jun to Sep 2006, Aug 2010
nLN3	El Abde	37	Jan 2001 to Dec 2011		Jan 1998 to Dec 2011	Mar 2002 to Dec 2002, Oct 2003 to Sep 2004
nLN4	Tripoli-IPC	5	Aug 1940 to Dec 2010	Mar 1958 to Jul 1962, Mar 1976 to Dec 1976	May 1940 to Dec 2011	1941, May 1958 to June 1968, Mar to Dec 1976, May 1981, Jan to Apr 1982, Aug and Sep 1982, Sep 1984 to Mar 1994
nLN5	Balamand	359	Jan 2001 to Jan 2012		May 2000 to Dec 2011	Oct 2001 to Aug 2003, Nov 2004 to Mar 2005,
nLN6	Kafar Chakhna	260	Apr 2003 to Mar 2012		May 2003 to Dec 2011	Nov 2003 to Feb 2004, May to Sep 2004, Dec 2004 to Mar 2005, Nov and Dec 2005Mar and Apr 2008
NLC1	Kaslik Jounieh	41	Aug 2001 to Dec 2011		Jul 2001 to Dec 2011	Jul to Oct 2004, Feb 2005, Dec 2010, Mar, Apr and May 2011
nLC2	El Qoussaiba h	584	Jan 2001 to Dec 2011		Nov 2000 to Dec 2011	Feb, May and Jun 2001; Oct 2001 to Feb 2002, July to Sep 2002, Dec 2002 to Feb 2003, Jun to Dec 2003, Jul to Sep 2005, Feb to2010
nLC3	Beyrouth-Golf	14	Feb 1999 to May 2012		Feb 1999 to Dec 2011	
nLC4	Beirut Internation al Airport	12	Jul 1932 to Dec 2009		May 1931 to Dec 2011	1941, 1977
nLC5	El Meshref	395	Jun 2003 to Feb 2012		Jun 2002 to Dec 2011	Sep 2004, Aug 2005, Jan 2008 to

						Jan 2009
nLC6	Saida	14	Jan 2001 to Feb 2012		May 2000 to Dec 2011	Aug-10
nLC7	Lebaa	331	Jan 2001 to Feb 2012		Jun 2000 to Dec 2011	Oct 2001 to Oct 2002, Feb to Sep 2004, Aug and Sep 2010
nLS1	Zahrani	10	Jan 2001 to Feb 2012		July 2000 to Dec 2011	Feb, Jun and Jul 2001, Dec 2001 to Feb 2002, Sep 2002 to May 2004, Sep 2005 to Mar 2006
nLS2	El Quasmiye	9	Jan 2001 to Feb 2012		Apr 2000 to Dec 2011	Fen to Aug 2001, Jul 2002 to Jan 2003, Mar 2004, Jan to Mar 2005, Jun 2007, Sep 2010, Aug and Sep 2011
nLS3	Sour	4	Jan 2001 to Sep 2011		Jan 1999 to Dec 2011	Aug 1999 to Jan 2000, Mar to May 2000, Dec 2002 to May 2003, Sep 2003, Oct 2004
nLS4	Kafar Dounine	560	Sep 2004 to Feb 2012		Sep 2004 to Dec 2011	May, Aug and Sep 2005, May to Dec 2006, May and Jun 2007, Jan to Jul 2008,
nMN1	Syr-Ed-Denniye	926	Feb 2001 to Aug 2012	Sep 2006 to Oct 2007	Jan 2001 to Dec 2011	Jul 2004 to May 2005, Oct 2006 to Oct 2007
nMN2	Al Arz-Les Cedres	1891	Jan 1982 to Apr 2011	Jan 1988 to Mar 1996	Jan 1947 to Dec 2011	1949, Jun 1951 to Feb 1956, 1962, 1976, 1977, Jan 1984 to Feb 1996
nMC1	Tannourine	1838	Jan 2001 to Dec 2011		Dec 2000 to Dec 2011	Sep 2002 to Jul 2003, Nov 2004 to Jan 2005, Jan to Apr 2006, Sep 2006 to Apr 2007, Nov 2007 to Apr 2008, Oct 2008 to Sep 2009
nMC2	Qartaba	1222	Jan 2001 to Dec 2011		Apr 2000 to Dec 2011	Jun-06
nMC3	Faqra	1655	Jan 2001 to Dec 2011		Jul 2000 to Dec 2001	Oct 2001 to Oct 2002, Jun and Jul 2003, Apr to Aug 2004, Jun to Se 2006
nMC4	Dahr El Baidar	1516	Jan 2001 to Dec 2011		Jun 1962 to Dec 1972, Dec 1998 to Dec 2011	Jun and Aug 1967, Oct 1969, Oct 2004 to Jan 2005; May and Sep 2005; Jun

						to Oct 2006; Apr and May 2008, Nov and Dec 2010
nMC5	Bayssour	940	Jan 2001 to Dec 2011		Jun 2000 to Dec 2011	May and Jun 2006
nMC6	Barouk Fraidis	1114	May 2000 to Jan 2009		Mar 2000 to Apr 2009	Nov 2004 to Mar 2005; Jan, Mar, Apr and Sep 2006
nMC7	Deir El Kamar	794	Jan 2001 to Feb 2012		Mar 2000 to Dec 2011	Oct 2002 to Sep 2004, Aug 2010
nMC8	Jezzin	1070	Aug 2001 to Feb 2012		Jul 2001 to Dec 2011	Oct 2001 to Mar 2002, Jul 2002 to Feb 2003, Jun to Nov 2003, Jun to Nov 2003, Mar to Jul 2004, Nov 2004 to Jan 2005, Sep and Oct 2006
nIO1	El Hermel	605	Jan 2011 to Dec 2011		Aug 2004 to Dec 2011	Oct to Dec 2005, Jun to Oct 2006
nIO2	El Qaa	513	Jan 2004 to Dec 2009		Jan 2004 to Dec 2011	Jan 2006, Jun and Jul 2007, Apr to Dec 2008
nIO3	Deir El Ahmar	943	Jan 2001 to Dec 2011		Oct 1999 to Dec 2011	Oct 2004 to Mar 2005, Jun 2008
nIL1	Douris	1009	May 2003 to May 2006		Oct 2004 to May 2006	
nIL2	Rayak-Amara	852	Feb 1932 to Feb 2010	1941, Feb 1976 to Dec 1977, Jan 1986 to Dec 1997	Jan 1932 to Dec 2011	Apr 1932, 1933, 1935, 1939, 1941 to 1943, Jul 1947, Oct 1969, 1970, 1976, 1977, Feb 1986 to Jul 1989, Jun to Sep 1995, Jan 1996, May 1996, Feb to Jun 1997
nIL3	Houch El Oumara-Zahle	926	Jul 1998 to Dec 2011		Jan 1998 to Dec 2011	
nIL4	El Qaraoun	843	Mar 2001 to Mar 2012		Mar 2002 to Dec 2011	Jun-06
nIH1	Kafar qouq/Rachaya	1205			Apr 2003 to Dec 2011	Apr and Nov 2005
nIH2	Marjeyoun	827	Aug 2009 to Mar 2012			

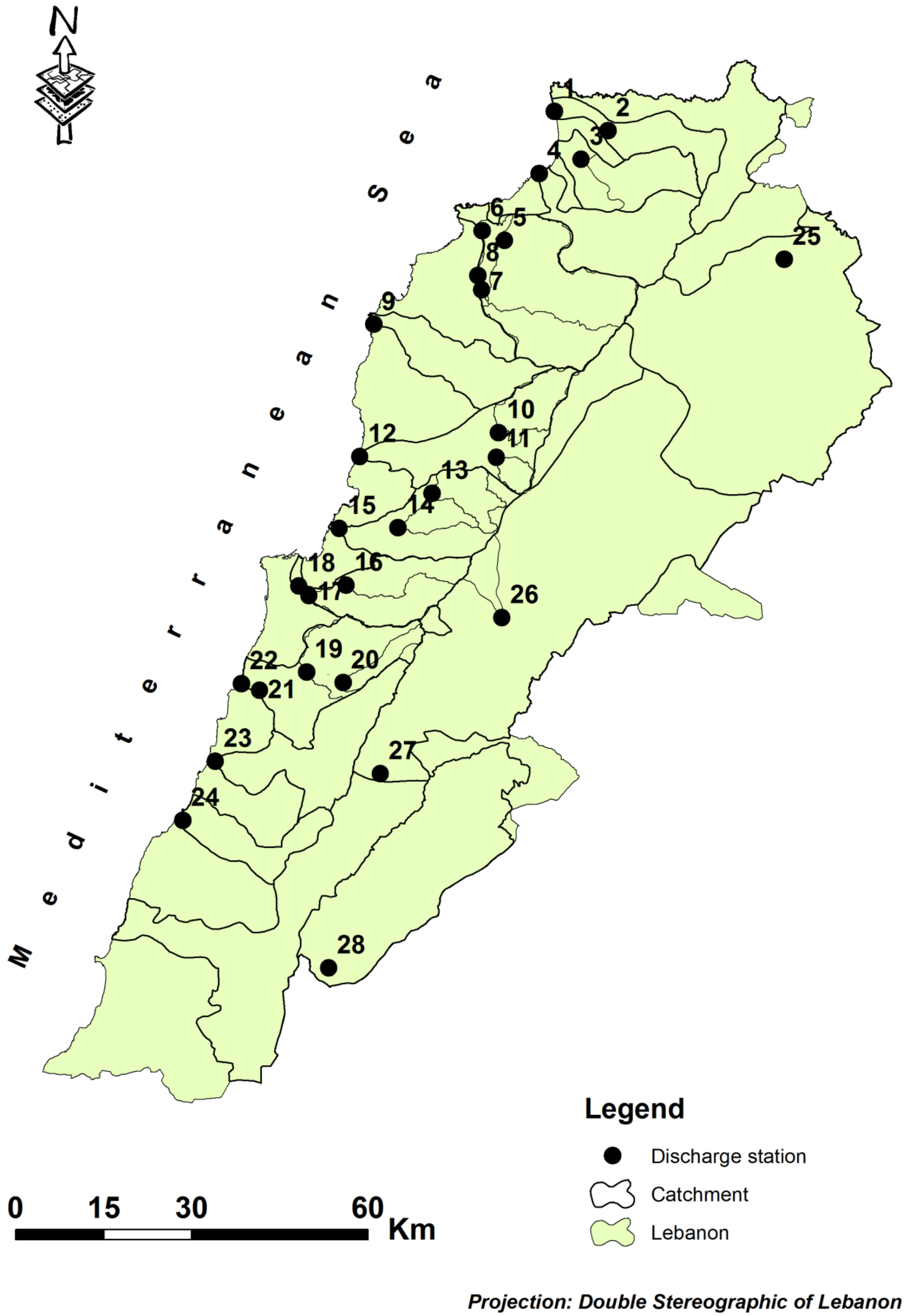

Fig. E.3 Hydrometric Network of stations with daily flow records; details of measurements period are given in table E.3

Table E.3 Hydrometric stations with daily records; the highlighted cells are stations were only monthly data is available.

Station number	Basin	River	Station name	Operating years	Missing data
1	Ostouene	Ostouene	Sea Mouth	2002-2012	
2	Ostouene	Ostouene	Halba	2002-2012	
3	Arka	Arka	Hakour	1967-1974 and 2002-2012	
4	Bared	Bared	Sea Mouth	1967-1974 and 2000-2012	
5	Abou Ali	Racheine	Zghorta Bridge	1967-1974 and 2002-2012	1972/1973
6	Abou Ali	Abou Ali	Abou Samra	1967-1974 and 2000-2012	
7	Abou Ali	Abou Ali	Kousba	1967-1974 and 2002-2012	1972/1973
8	Abou Ali	Abou Ali	Daraya	1967-1973 and 2002-2012	
9	El jouz	El Jouz	Sea Mouth	2000-2012	
10	Ibrahim	El Rouaiss	Majdel Bridge	1967-1972 and 2002-2012	
11	Ibrahim	Afka Spring	After The Spring	1967-1974 and 2002-2012	1972/1973
12	Ibrahim	Ibrahim	Sea Mouth	1967-1974 and 2000-2012	
13	Kelb	El Mougharah	Hrajel	1967-1974 and 2002-2012	1972/1973
14	Kelb	El Kelb	Daraya	1967-1974 and 2002-2012	1972/1973
15	Kelb	El Kelb	Sea Mouth	1967-1972 and 2000-2012	
16	Beirut	El Joamani	Ras El Metn Bridge	1967-1974 and 2006-2012	
17	Beirut	Beirut	Dachounieh	1967-1973 and 1992-2012	
18	Beirut	Beirut	Jiser El Bacha	1967-1974 and 1990-2012	
19	Damour	Damour	El Qadi Valley	1967-1974 and 1992-2012	1996/1997, 1997/1998 and 1998/1999
20	Damour	Es Safa	Es Sitt Valley	1967-1973 and 1998-2012	
21	Damour	Damour	connection	2002-2012	
22	Damour	Damour	Sea Mouth	1994-2012	
23	Awali	Awali	Saida	2000-2012	
24	Zahrani	Zahrani	Sea Mouth	2002-2011	2009/2010
25	Oronte	Oronte	Hermel	1967-1974 and 1991-2012	
26	Litani	Berdaouni	Damascus Road	1967-1974 and 1990-2012	1970/1971
27	Litani	Joub Janine	Joub Janine Bridge	1998-2012	
28	Hasbani	Hasbani	After Wazzani Spring	2002-2012	

Annex F.

Lebanese catchments' characteristics

Table F.1 Physical characteristics of the studied Lebanese catchments (refer to annex A and G for variable description and calculation)

St	Catchments	Min Zc	Ac	Dd	Lflow	Zc	Max Zc	Zc>1800	Sc	AK	HPR	MPR	LPR	HIS	MIS	LIS	Fc	Uc	Bare	Shrub	Grass	Agr
1	Outuene at sm	10	151	3.0	19	516	1923	0.6	10	43	42	5.8	52	8.2	61	30	24	6.3	0	3.3	19	46
2	Oustuene at Halba	89	100	3.4	17	651	1923	0.7	9.6	61	60	8.2	31.8	0.2	52	43	33	6.2	0	4.1	18	38
3	Arka at Hakour	77	102	3.8	16.2	737	1951	0.75	11	73.6	66.8	9.2	24	0.5	60.6	38.9	24.2	8	0	6.9	13.8	46.6
4	Bared at sm	29	281	4	42	1278	2878	21	6.7	6	61.7	15.7	22.6	1.5	50.8	47.7	37.4	2.8	1.6	12	17.2	26.8
5	Abu Ali at Racheine	80	202	4.6	26.7	1302	3081	48	11	79	71.4	6.6	22	4.2	50.2	45.6	19.4	4.6	8.8	15.6	27.2	24
6	Abu Ali at Abu samra	46	466	3.4	35	1328	3081	32.5	8.6	73	64	5.5	30.5	3.5	56.5	40	18.4	4.9	8.8	11.9	28.5	27.3
7	Abu Ali at Kousba	240	142	4.2	16	1650	3081	38	17	69	59.6	3	37.4	2.8	78.2	19	19.8	4.3	10.8	5.3	36.9	22.7
8	Abu Ali at Daraya	174	144	4.2	18.2	1670	3081	37.5	15	68	59.2	3.2	37.6	2	77.2	20.8	19.8	4.6	10.7	5.3	36.6	22.7
9	Jouz at sm	9	189	4.8	29	1032	2342	10.5	4.6	87	64.4	7.6	24.9	10.6	26.6	62.8	28.5	6.2	1.2	21.2	20.7	21.4
10	Ibrahim at Roueiss	1073	95	5.7	9.6	2024	2660	83.6	16	95	94	1	5	0	100	0	0.6	0.2	42	2	51	3
11	Ibrahim at Afqa	1113	28.6	6.4	4.2	1894	2130	85.6	24	100	100	0	0	0	100	0	4	0.7	35	1.3	58	0
12	Ibrahim at sm	3	326	2.4	36.7	1541	2658	40.8	7.2	92	83	6	11	11.3	66.4	22.3	20	3.8	20.6	11	36	8.5
13	Kelb at Hrajel	1178	75	3.2	5	1886	2622	61.6	28	91	81	10	9	19	80	1	1.26	3.5	39	2.8	43	9
14	Kelb at Daraya	557	143	2.4	11.7	1733	2622	39.3	17	85	77	15	8	29	63	18	8.5	5.4	28	8.4	35	14.5
15	Kelb at sm	12	257	3.0	28.3	1733	2622	26.7	9.2	84	77.8	14.4	7.8	21.3	51	27.7	21	14	15.7	12.4	23.2	13.4
16	Beirut at Jaamani	270	127	2.5	13.3	1064	2062	3	13	67	65	33	2	36	27	37	46.4	9	2	10	20	12
17	Beirut at Daychounyeh	73	209	3.4	24.2	1018	2086	3	8.3	62	58	38	4	37	37	26	42	10.6	1.6	11.4	19.5	14.4
18	Beirut at Jisr Basha	22	217	3.3	27	1003	2086	2.9	7.6	62	59	37	4	37	37	26	41.8	11.2	1.6	11.2	19.2	14.4
19	Damour at Jisr Qadi	254	185	3.1	43	938	1941	0.4	3.9	75	47	49	4	21.6	75.4	3	14.6	14	2.3	13	26	29
20	Damour at Wadi Sett	536	40	4.5	28.3	1143	1771	2	4.3	58	44	39	17	27	60	13	9.5	17.6	8	11	26	27
21	Damour at connection	19	77	3.4	12	828	1941	4	13	79	55	41	4	17	78	5	20	15	1.7	14	20	28
22	Damour at sm	9	293	3.7	56.7	802	1941	0.3	3.4	79	57	4	39	18	7.8	74.2	20	15	1.7	14	22	26
23	Awali at Marj Bisri	308	78	4.5	9.9	1247	1949	5	15	98	76	23	1	4	78	18	21	10.6	0.3	24.5	26.6	16.7
24	Zahrani at sea mouth	3	152	1.6	15	534	1670	0	9	81	78	15	7	25	18	57	11	16	1	18	17	36
25	Orontes	590	1241	2.9	39	1393	3081	30.2	6.3	60	64.8	31.4	3.8	2	73.2	24.8	5.4	2	11	6.4	53	21
26	Berdawni at DR	880	77	0.9	15.7	1560	2501	16.2	10	88	87	10	3	15	63	22	0.7	8.6	9.6	13	47	20
27	Litani at Joubjannine	859.7	1433	2.5	65.6	1223	2551	9.6	2.5	53	44	26	30	11	41	48	5.4	4.7	2.7	6.6	32	48
28	Hasbani at wazzani	281	566	2.1	47.5	1198	2810	8.1	5.3	82	79.5	13.4	7.1	10	27	63	6	3.6	0.7	22	43	24

Annex G.
Variables' calculation

Notation	Description
Ac (km²)	Catchment area calculated from digital elevation model
Lflow (km)	The longest drainage line from the crest to the outlet
Dd (km/km²)	Total drainage length in km divided by catchment area in km^2
Sc (%)	MaxZc – MinZc / Lflow
Min Zc (m)	The elevation of the catchment outlet
Zc (m)	Average elevation calculated by averaging pixel elevations on the DEM
Max Zc (m)	The elevation of the highest point in the catchment
Zc>1800	Percentage of Ac with elevation above 1800 m
AK (%)	Percentage of Ac with apparent karst
HPR (%)	Percentage of Ac with High Permeability Rocks
MPR (%)	Percentage of Ac with Moderate Permeability Rocks
LPR (%)	Percentage of Ac with Low Permeability Rocks
HIS (%)	Percentage of Ac with High Infiltration Capacity Soil
MIS (%)	Percentage of Ac with Moderate Infiltration capacity Soil
LIS (%)	Percentage of Ac with Low Infiltration Capacity Soil
Fc (%)	Percentage of Ac covered by Forests
Uc (%)	Percentage of Ac covered with Urban areas
Bare (%)	Percentage of Ac covered with Bareland
Shrub (%)	Percentage of Ac covered with Shrubland
Grass (%)	Percentage of Ac with Grassland
Agr (%)	Percentage of Ac with Agricultural areas
RS1	Mean annual flow (m^3/s) averaged over the study period
RS2	Mean annual runoff (mm) averaged over the study period
RS3	Annual runoff ratio averaged over the study period
RS4	Absolute minimum flow (m^3/s) which the lowest flow recorded over the study period
RS5	Average maximum annual flow (m^3/s): the average of the maximum flow in each year of the record
RS6	Baseflow index, calculated as the ratio (in percentage) of the lowest mean monthly flow to the mean annual flow (Gordon et al., 1992)
RS7	Ratio Q90 %/Q50%, used as an index of base flow contribution (Gordon et al., 1992)
RS8	Mean flow of Month with highest mean flow (averaged over the whole study period record)
RS9	Mean flow of Month with lowest mean flow (averaged over the whole study period)
RS10	Slope of the flow duration curve: [Q30% - Q70%] / 40Qd where Qd is the mean daily runoff
RS11-21	Number of times that the stream-flow is continuously below the 5 % (RS11), 10 % (RS12), 20 % (RS13), 30 % (RS14), 40 % (RS15), 50 % (RS16), 60 % (RS17), 70 % (RS18), 80 % (RS19), 90 % (RS20), and 95 % (RS21) of mean annual flow
RS22	Coefficient of variation of daily flows for the 10-year period
RS23	Average of coefficient of variation of daily flows for each year
RS24	Average of standard deviation of daily flows for each year
RS25	Coefficient of variation of mean annual flow
RS26	Coefficient of variation of annual runoff ratio
RS27	Variability index as proposed by Growns and Marsh (2000): [Q10 %-Q90 %]/Median flow

Annex H.
Hydrogeology of Lebanon

The underlining geology of the country is made mainly of carbonate rocks which are highly karstified and fractured.

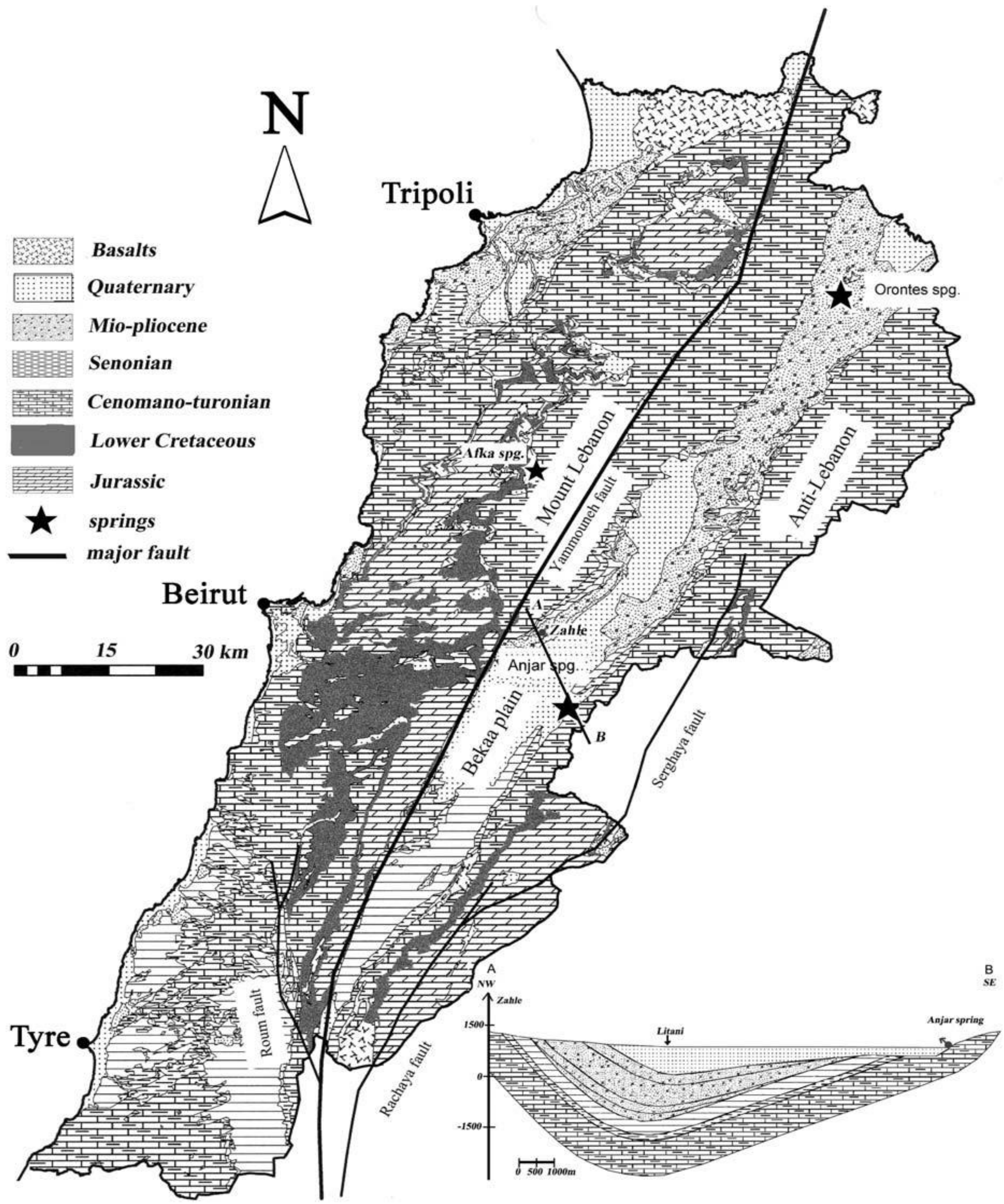

Fig. H.1 The Lebanese faulting system on the major geological formations of Lebanon (El-Hakim and Bakalowicz 2007)

Karstic systems in Lebanon are deep and well developed. This is clear from cave systems such as Jeita which exists at almost sea level, indicating the surface karstification has cut deep through the thick Jurassic carbonate sequence. Some large springs even exist below sea level such as offshore from Ras Chekka (Edgell 1997, Bakalowicz et al. 2008). Figure H.1 shows a geological cross-section of the Ain Anjar spring karstic system (a source for the Litani River) that discharges a cenomanian aquifer in the Bekaa valley. One can notice how large and deep (1500 m) is this karstic system. This emphasize on the great importance of groundwater contribution to river flows in Lebanon. In fact, the high areal extent of the well fractured and highly karstified carbonate rocks, favorites infiltration. In fact, in a study for determining recharge potential zone in Occidental Lebanon (an area of about 5000 km^2, about 50 % of the total surface of the country), Shaban et al. (2006) classified 56 % of the total studied are as having high to very high infiltration capacity, while only 28 % of this area have low infiltration capacity. Therefore, according to FAO (1967), in areas with high to very high infiltration capacity, about 30 to 50 % of total rainfall is estimated to infiltrates. And the geological history of the country favored the development of deep and highly developed (in some cases deep below the base level) karstic systems (Fig. H.2).

So, groundwater contribution to surface flow is crucial. In fact, Base Flow Index (BFI) for the period 1968 - 1972 (Sene et al. 1999) represents more than 70 % of the total flow for the majority of stations in northern Lebanon and in the internal region where it can reach more than 90 %. In other parts of the country BFI rarely drops below 40 %. It only reaches value below 30 % in the southern part of Mount Lebanon where snow contribution is minimal. Hence, a large number of aquifers (Fig. H.1) discharge in many hundreds of mostly karstic springs across Lebanon (El-Fadel 2000). Many of these springs have large discharges and contribute largely to river flows (e.g. Ain Zarqa: the main source for the Orontes River, it has a discharge of 14 m^3/s; Afqa (1-2 m^3/s) and Roueiss (0.5-1 m^3/s) are the main sources of the Ibrahim River; Nabaa el Laban (0.5-1 m^3/s) and Jeita Grotto (1-2 m^3/s) contributes to El Kelb River; Qob Elias (0.5-1 m^3/s), Chamsine (1-2 m^3/s) and Faour (0.5-1 m^3/s) contributes to the Litani River; etc.). However these karstic systems functions differently. El-Hakim and Bakalowicz (2007) classified some karstic aquifers in Lebanon (the aquifers of Ain Anjar Spring, Chamsine spring, Afqa spring and Ain Zarqa spring) according to two index: ***i*** and ***k***. The index ***i*** represents the infiltration delay ($0<i<1$), a high value of ***i*** indicates a low infiltration rate; while ***k*** is the residence time in years. ***K*** highlights the storage capacity of the aquifers, an aquifer with a high residence time have a large storage capacity. Their findings provide some insight to the functioning and capacities of some Lebanese karstic aquifers. The ***i*** index was found to be 0.83, 0.90, 0.80 and 0.98 for Anjar, Chamsine, Afqa and Zarqa respectively. This high i index means that low infiltration is dominant due to snow cover which constitutes the main source of groundwater recharge (El-Fadel 2000). As for the ***K*** index, one can distinguish two cases: on one hand, Afqa spring with k = 0.21 years (2.5 months); and on the other hand, Anjar, Chamsine and Ain Zarqa with k = 1.6, 3 and 24 years respectively. The value of $k<0.5$ is very common in active karstic aquifers such as high-mountain karstic system (Fig. H.2a), however the values of $k>1$ are very unusual, carbonate aquifers which such huge storage capacities are very uncommon. This could be explained by a very deep well karstified phreatic zone, partially or totally confined under impermeable sediments (Fig H.2b). This very high phreatic zone storage capacity is responsible for the seasonally low variable discharge of the Orontes River.

In conclusion, karstic aquifers developed all around the country in various carbonate formations largely contribute to surface water via springs. However, these aquifers do not respect the boundaries of surface water catchments. In fact, many aquifers such as Cenomanian aquifer stretch over many catchments. Hence, the cenomanian aquifer underline most of the northern half of the country extending on almost all the basins of this area. Not only the cenomanian, but also other aquifers such as the Jurassic extend over the area of many adjacent surface basins (Fig. H.1).

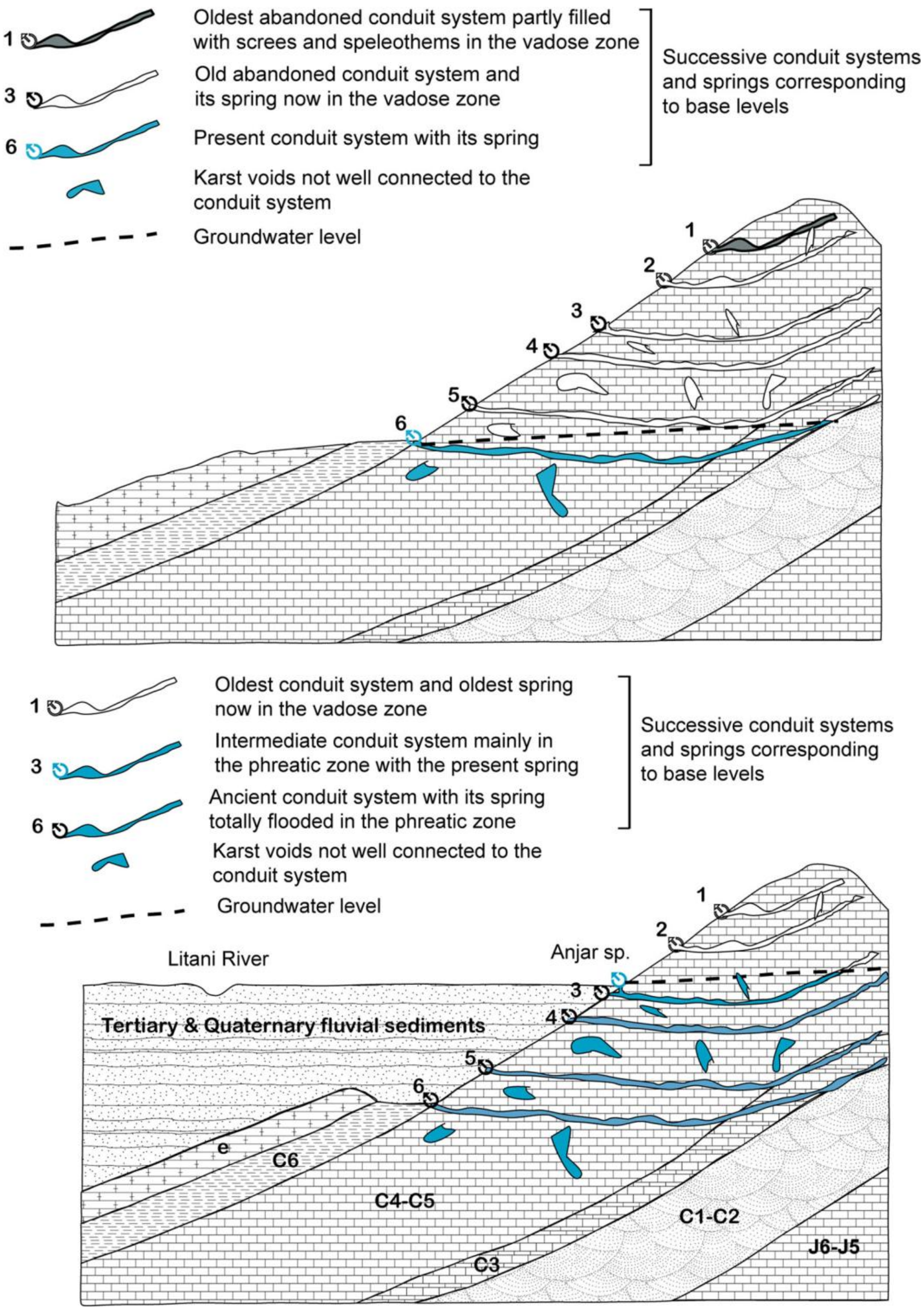

Fig. H.2 (a) High-mountain karst system (e.g. Afqa spring) and (b) Karst systems related to basins and grabens. Conduit systems developed during a regional uplift followed by the closing and the sediment infilling of the basin. From the example of the Anjar–Chamsine system, the Bekaa plain (source: Bakalowicz 2015.