NATIONAL TECHINCAL UNIVERSITY OF ATHENS

SCHOOL OF CIVIL ENGINEERING

DEPARTMENT OF WATER RESOURCES & ENVIRONMENT

Diploma thesis:

“Pseudo-continuous stochastic simulation framework for flood flows estimation”

Moustakis Yiannis

Supervisor: Efstratiadis Andreas, Lab Teaching Staff, NTUA

Responsible Professor: Koutsoyiannis Demetris, Professor, NTUA

Athens, July 2017

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Ευχαριστίες / (Acknowledgments in Greek)

Η εκπόνηση και παρουσίαση της παρούσας διπλωματικής εργασίας αποτελεί την τελευταία πράξη της εξαετούς φοίτησής μου στη Σχολή Πολιτικών Μηχανικών ΕΜΠ και σηματοδοτεί την απαρχή ενός νέου, σημαντικού κεφαλαίου της ζωής μου.

Μέσα σε έναν κυκεώνα συναισθημάτων που κυμαίνονται από τη χαρά της αποφοίτησης, τα όνειρα και τις ελπίδες για τη συνέχεια, τις γλυκές αναμνήσεις από τη φοίτηση, μέχρι τις φοβίες για το άγνωστο και αβέβαιο αύριο, αλλά και τη συγκίνηση για τον αποχωρισμό από τη Σχολή και τους χώρους της, στους οποίους έζησα, ωρίμασα, μορφώθηκα, πολιτικοποιήθηκα και ερωτεύτηκα, αισθάνομαι μια πολύ έντονη ανάγκη να ευχαριστήσω τους ανθρώπους που χάραξαν ανεξίτηλα τα τελευταία έξι χρόνια της ζωής μου, εκείνους που με ενέπνευσαν και με στήριξαν και, προφανώς, όλους όσοι συνέβαλαν στην εκπόνηση της παρούσας εργασίας.

Όλοι τους, ο καθένας σε διαφορετικό χρονικό σημείο, με άλλη ένταση και διαφορετικό ρόλο, βοήθησαν στο να διαμορφωθώ σε αυτό που είμαι σήμερα. Κάθε πτυχή του εαυτού μου, περισσότερο ή λιγότερο ελλαττωματική, φέρει, σε μεγαλύτερο ή μικρότερο βαθμό το αποτύπωμα των ανθρώπων αυτών και για αυτό είμαι απόλυτα ευγνώμων.

Πρώτα και κύρια θα ήθελα να ευχαριστήσω των επιβλέποντα καθηγητή και κοσμήτορα της Σχολής Πολιτικών Μηχανικών ΕΜΠ κ. Δημήτριο Κουτσογιάννη για την ανάθεση ενός εξαιρετικά ενδιαφέροντος θέματος και τις χρήσιμες συμβουλές του σε κρίσιμα ζητήματα που αφορούσαν την εργασία. Πολύ δε περισσότερο, θα ήθελα να τον ευχαριστήσω, καθώς από κοινού με τον κ. Νικόλαο Μαμάση, αναπληρωτή καθηγητή ΕΜΠ, με τις συνεχείς τους προσπάθειες τα τελευταία χρόνια, έχουν δημιουργήσει ένα ελεύθερο ακαδημαϊκό περιβάλλον υψηλού επιπέδου, δυσεύρετο στα ελληνικά πανεπιστήμια, στα πλαίσια του οποίου η γνώση τοποθετείται στο επίκεντρο, οι επιστημονικές απόψεις και οι ιδέες διακινούνται ελεύθερα και οι «ανήσυχοι» φοιτητές, όπως ο γράφων, βρίσκουν ελεύθερο ζωτικό χώρο να μάθουν, να εκφραστούν και να εμπνευστούν. Τους ευχαριστώ για τα κίνητρα που μου έδωσαν, το χρόνο που αφιέρωσαν σε εμένα και, φυσικά, για την ανοχή τους.

Στα πλαίσια της εργασίας, καθοριστικός ήταν ο ρόλος του κ. Ανδρέα Ευστρατιάδη, Δρ Πολιτικού Μηχανικού, ΕΔΙΠ ΕΜΠ, οποίος με πολλή όρεξη και υπομονή με καθοδήγησε βήμα-βήμα καθ΄όλη τη διάρκεια εκπόνησής της. Θα ήθελα να τον ευχαριστήσω θερμά, καθώς ένιωσα ότι με εμπιστεύτηκε απόλυτα, δίνοντάς μου μεγάλη ελευθερία κινήσεων, ενώ ήταν πάντα διαθέσιμος και κατάφερε να ανεχτεί τις ιδιοτροπίες μου. Ο «κύριος Αντρέας», τον οποίον γνώρισα πρώτη φορά κατά τη διάρκεια των κινητοποιήσεων για την υπεράσπιση του Ιδρύματος το 2013, αποτελεί σημείο αναφοράς για την φοίτησή μου στη Σχολή. Είναι ο άνθρωπος που κατάφερε με το πάθος του να μου κεντρίσει το ενδιαφέρον για το αντικείμενο του Υδραυλικού Μηχανικού, στα πλαίσια του μαθήματος των «Αστικών Υδραυλικών Έργων», σε μια περίοδο όπου είχα βρει μικρό μόνο ενδιαφέρον για τη Σχολή, ενώ, με ενέπνευσε σημαντικά στα πλαίσια των «Υδροηλεκτρικών Έργων». Το διδακτικό έργο και το ήθος του τον καθιστούν πολύτιμο για το ίδρυμα και την επιστήμη και τον ευχαριστώ θερμά για όλα.

Θα ήθελα επίσης να ευχαριστήσω τους Τσουκαλά Γιάννη (Υ.Δ.), Κοσσιέρη Παναγιώτη (Υ.Δ.) και Ηλιοπούλου Άννυ (Υ.Δ.), για την πολύτιμη βοήθεια και τις συμβουλές τους κατά την *εκπόνηση της εργασίας και, φυσικά, τον Δημητριάδη Παναγιώτη (Υ.Δ.), που αποτελεί πρότυπο επιστήμονα και πηγή έμπνευσης για τους φοιτητές, με τον οποίον είχα την τύχη να συνεργαστώ και να μοιραστώ πολλές ώρες συζητήσεων τα τελευταία δύο χρόνια.*

Σε αυτό το σημείο θα ήθελα να κάνω μια ιδιαίτερη αναφορά στον Μαρκόνη Γιάννη, Δρ. Μηχανικό Περιβάλλοντος, ο οποίος κατάφερε να μου μεταδώσει το σπάνιο πάθος και την όρεξή του για την επιστήμη και με βοήθησε να γνωρίσω τον ακαδημαϊσμό, όπως αυτός πραγματικά είναι, με τις όμορφες, αλλά και άσχημες πτυχές του. Αισθάνομαι έντονα ότι σε οποιαδήποτε επιλογή κληθώ να πάρω στο μέλλον, οι συμβουλές του φίλου μου Γιάννη, οι συζητήσεις που έχουμε κάνει μαζί, αλλά και ο τρόπος σκέψης και προσέγγισης της επιστήμης που μου μετέδωσε, θα παίξουν καθοριστικό ρόλο. Τον ευχαριστώ βαθύτατα για όλα.

Ακόμη, θα ήθελα να ευχαριστήσω πολύ τη Θεοδωροπούλου Δέσποινα, που με στήριξε τα τελευταία χρόνια, τους καλούς μου φίλους και συναδέλφους Μπαρδάκα Δημήτρη και Λεοντάρη Κωσταντίνο, τους εκλεκτούς φίλους και συντρόφους Δήμα Παναγιώτη, Νικολάου Τάσο και Πουλιάση Γιώργο για την κοινή μας πορεία τα τελευταία χρόνια εντός και εκτός Σχολής, καθώς και τον παιδικό μου φίλο Κοκκίνη Γιώργο με τον οποίο βιώσαμε μαζί το μεγαλύτερο μέρος της φοιτητικής μας ζωής.

Φυσικά, οφείλω ένα μεγάλο ευχαριστώ σε όλους τους συντρόφους, παλιούς και νέους, του Εγκέλαδου Πολιτικών Μηχανικών ΕΜΠ, οι οποίοι με εμπιστεύτηκαν, με ανέχτηκαν και με στήριξαν σε δύσκολες στιγμές. Μέσα από τη συλλογική δράση απέκτησα έντονες εμπειρίες, που με διαμόρφωσαν ανεξίτηλα. Είμαι περήφανος για τις μάχες που δώσαμε και τυχερός για τους ανθρώπους που γνώρισα στον Εγκέλαδο.

Ακόμη, θα ήθελα να ευχαριστήσω τη συντονιστική ομάδα, αλλά και κάθε απλό, ανώνυμο ή επώνυμο μέλος της διαδικτυακής κοινότητας του «MQN.gr», όχι μόνο για την πολύτιμη βοήθεια στα μαθήματα, αλλά κυρίως για τον θαυμαστό ιντερνετικό κόσμο αλληλεγγύης που έχουν στήσει.

Τέλος, τίποτα από όλα αυτά δεν θα είχε συμβεί αν δεν υπήρχε η ηθική και υλική στήριξη από τους γονείς μου, Μουστάκη Ηλία και Μαρίνου Σωτηρία, οι οποίοι μου συμπαραστάθηκαν όλα αυτά τα χρόνια και αποτελούν σταθερό σημείο αναφοράς στη ζωή μου. Η τυφλή εμπιστοσύνη που δείχνουν στο χαρακτήρα και τις ικανότητές μου, αποτελεί πηγή δύναμης για εμένα. Παράλληλα, θα ήθελα να ευχαριστήσω την αδερφή μου, Μουστάκη Αγγελική, με την οποία ζήσαμε μαζί τα τελευταία έξι χρόνια και δεν σταμάτησε ποτέ να με στηρίζει και να με πιστεύει.

Μουστάκης Ιωάννης

Αθήνα, Ιούλιος 2017

Abstract

Typically, flood modelling in the context of everyday engineering practices is addressed through event-based deterministic tools, e.g., the well-known SCS-CN method. A major shortcoming of such approaches is the ignorance of uncertainty, which is associated with the variability of soil moisture conditions and the variability of rainfall during the storm event.

In event-based modelling, the sole expression of uncertainty is the return period of the design storm, which is assumed to represent the acceptable risk of all output quantities (flood volume, peak discharge, etc.). In the meantime, the varying antecedent soil moisture conditions across the basin are represented by means of scenarios (e.g., the three AMC types by SCS), while the temporal distribution of rainfall is represented through standard deterministic patterns (e.g., the alternative blocks method). Furthermore, time of concentration is considered as a constant characteristic feature of a basin, which has actually been proved to be an invalid assumption.

In order to address these major inconsistencies, while simultaneously preserving the simplicity and parsimony of the SCS-CN method, we have developed a pseudo-continuous stochastic simulation approach, suitable for ungauged basins, comprising the following steps: (1) generation of synthetic daily rainfall time series; (2) update of potential maximum soil retention, on the basis of accumulated five-day Antecedent Precipitation; (3) estimation of daily runoff through the SCS-CN formula, using as inputs the daily rainfall and the updated value of maximum soil retention;(4) daily update of the value of time of concentration according to the runoff generated; (5) selection of extreme events and application of the standard SCS-CN procedure for each specific event.

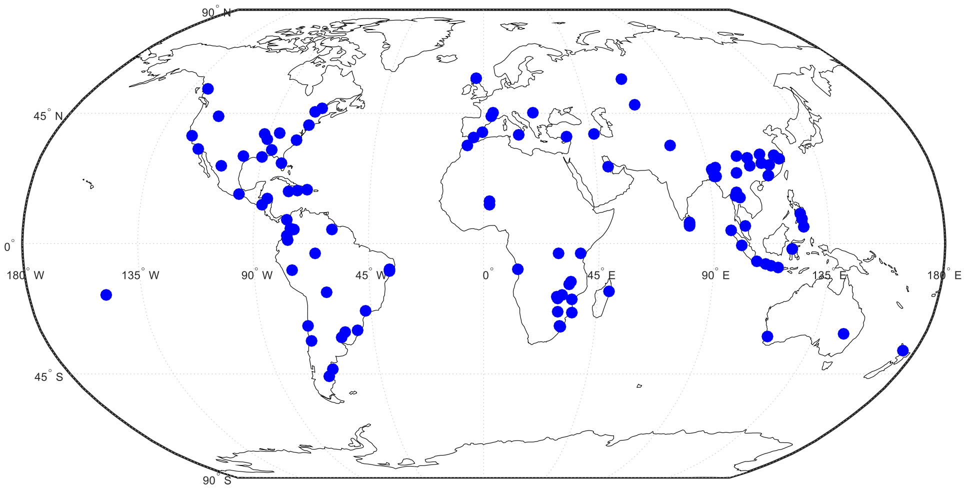
This scheme requires the use of two stochastic modelling components, namely the CastaliaR model, for the generation of synthetic daily data, and the HyetosMinute model, for the stochastic disaggregation of daily rainfall to finer temporal scales. Outcomes of this approach are a large number of synthetic flood events, allowing for expressing the design variables in statistical terms and thus properly evaluating flood risk.

The proposed pseudo-continuous stochastic simulation framework, along with a series of model variations is thoroughly investigated, in order to examine its response, prove its consistency and suggest further improvements and topics for future work.

Εκτεταμένη Περίληψη / (Extended abstract in Greek)

Παρά το γεγονός ότι η επιστήμη και ηα τεχνολογία έχουν σημειώσει ραγδαία πρόοδο τις τελευταίες δεκαετίες, ο άνθρωπος αγωνίζεται ακόμα να αντεπεξέλθει στις προκλήσεις που του θέτει η φύση με τις απρόβλεπτες δυνάμεις της. Οι φυσικές καταστροφές συνεχίζουν να προκαλούν θανάτους και καταστροφή περιουσιών.

Μεταξύ αυτών, οι πλημμύρες έχουν εξέχουσα θέση. Ενδεικτικό είναι ότι μόνο στο πρώτο εξάμηνο του 2017 περισσότεροι από 1 100 θάνατοι που αποδίδονται σε πλημμυρικά γεγονότα έχουν καταγραφεί παγκοσμίως, η γεωγραφική κατανομή των οποίων δεν περιορίζεται αυστηρά σε χώρες του τρίτου κόσμου ή/και αναπτυσσόμενες χώρες.



Σχήμα 1 : Γεωγραφική απεικόνιση με τη χρήση του λογισμικού Matlab® των καταγεγραμμένων μεγάλων πλημμυρών, κατά το πρώτο εξάμηνο του 2017

Το γεγονός ότι μεγάλες και θανατηφόρες πλημμύρες συμβαίνουν και στις οικονομικά εύρωστες χώρες, όπου τα μέσα και οι πόροι για τον αντιπλημμυρικό σχεδιασμό είναι επαρκή και, εν πολλοίς, διατίθενται, καταδεικνύει ότι υπάρχει πολύς ακόμα δρόμος που πρέπει να διανύσει η ανθρωπότητα, για να προστατευθεί από τα ακραία γεγονότα.

Παρότι η επιστημονική κοινότητα αναμβίφολα έχει καταβάλει σημαντικές προσπάθειες προς αυτή την κατεύθυνση, οι πολύπλοκοι μηχανισμοί που καθορίζουν την παραγωγή πλημμυρικής απορροής δεν μπορούν να περιγραφούν με ακρίβεια, όχι μόνο επειδή το επιστημονικό πεδίο της υδρολογίας είναι σχετικά νέο και εν μέρει αχαρτογράφητο, αλλά και, κυρίως, λόγω της εγγενούς αβεβαιότητας των υδρομετεωρολογικών μεταβλητών και υδρογεωλογικών διεργασιών, που δεν επιτρέπουν τις ακριβείς προβλέψεις.

Μέσα σε αυτά τα πλαίσια, παρά το γεγονός ότι οι πιο εξελιγμένες μέθοδοι που έχουν αναπτυχθεί τα τελευταία χρόνια και περιλαμβάνουν μοντέλα συνεχούς προσομοίωσης των υδρολογικών διεργασιών μιας λεκάνης απορροής, έχουν καταφέρει να δώσουν αξιόπιστες προβλέψεις, η χρήση τους παρουσιάζει ακόμα προβλήματα. Πιο συγκεκριμένα, τέτοιες μέθοδοι απαιτούν βαθμονόμηση βασισμένη στην ύπαρξη πραγματικών μετρήσεων βροχής –

απορροής που στην πλειονότητα των περιπτώσεων δεν είναι διαθέσιμες. Ακόμη και στην περίπτωση που τέτοιες μετρήσεις υπάρχουν, η ποιότητά τους είναι αρκετές φορές αμφισβητήσιμη. Τέλος, η χρήση τέτοιων προσομοιωμάτων είναι αφενός πολύπλοκη και απαιτεί ιδιαίτερες γνώσεις, ενώ, ταυτόχρονα, η χρήση αρκετών παραμέτρων ως δεδομένα εισόδου αυξάνει την αβεβαιότητα των συστημάτων αυτών.

Ως εκ τούτου αυτά τα συστήματα προσομοίωσης δεν έχουν καθολικά καθιερωθεί και η χρήση τους δεν είναι εύκολη. Έτσι, η διεθνής κοινότητα των μηχανικών –ακόμη και για λόγους κουλτούρας, που έχουν να κάνουν με την αδράνεια στην επιστημονική πρόοδο- στην πλειοψηφία της συνεχίζει να χρησιμοποιεί τις κλασικές μεθόδους προσομοίωσης γεγονότων, παρότι έχει αποδειχθεί ότι βασίζονται σε ορισμένες αρκετά ασυνεπείς και θεωρητικά αβάσιμες υποθέσεις.

Οι μέθοδοι προσομοίωσης γεγονότων, που συναντώνται στις συνήθεις πρακτικές των μηχανικών, δεν λαμβάνουν υπ΄όψην τους την αβεβαιότητα που υπάρχει εγγενώς στις υδρομετεωρολογικές μεταβλητές, καθώς και τη μεταβλητότητα των συνθηκών εδαφικής υγρασίας. Σε αυτά τα πλαίσια, η πιθανοτική έκφραση των πλημμυρικών όγκων και των αντίστοιχων πλημμυρικών αιχμών αρκείται στο να ταυτίζεται με την περίοδο επαναφοράς της βροχόπτωσης σχεδιασμού, η χρονική εξέλιξη της οποίας ακολουθεί ένα αυθαίρετα προκαθορισμένο μοτίβο.

Οι σημαντικές ασυνέπειες των μεθόδων αυτών, αλλά και οι δυσκολίες και τα εμπόδια στη χρήση των πιο συνεπών, αλλά πολύπλοκων συστημάτων συνεχούς προσομοίωσης, ορίζουν και τον προσανατολισμό της παρούσας διπλωματικής εργασίας.

Ειδικότερα, σκοπός της παρούσας δουλειάς είναι η ανάπτυξη ενός πλαισίου στοχαστικής προσομοίωσης σε ψευδο-συνεχή χρόνο για την εκτίμηση πλημμυρικών παροχών, το οποίο θα αποτελεί μία ενδιάμεση προσέγγιση, μεταξύ των παραπάνω. Ένα τέτοιο πλαίσιο, αφενός θα πρέπει να υπερβαίνει τις σοβαρότατες ασυνέπειες και τα ελαττώματα των κλασικών αιτιοκρατικών προσομοιωμάτων και, αφετέρου, να παραμένει απλό στη σύλληψη, αλλά και φειδωλό, ώστε να μην απαιτούνται βαθμονόμηση ή ειδικές γνώσεις για τη χρήση του, όπως συμβαίνει στα μοντέλα συνεχούς προσομοίωσης.

Στα πλαίσια της παρούσας διπλωματικής εργασίας, ως «τυπικό αιτιοκρατικό πλαίσιο προσομοίωσης» ορίζεται εκείνο το πλάισιο σύμφωνα με το οποίο:

- Η καταιγίδα σχεδιασμού επιλέγεται με βάση τις όμβριες καμπύλες, για την επιθυμητή περίοδο επαναφοράς και διάρκεια
- Η χρονική εξέλιξη της καταιγίδας σχεδιασμού καθορίζεται με βάση τη μέθοδο των εναλλασσόμενων μπλοκ (alternating blocks method), με ταυτόχρονη επιφανειακή απομείωση της βροχόπτωσης μέσω του δείκτη φ (Aerial Reduction Factor)
- Υπολογισμός των υδρολογικών ελλειμάτων με την ευρέως διαδεδομένη μέθοδο NRCS-CN, για μία από τις τρεις διαφορετικές πιθανές συνθήκες υγρασίας (υγρές, μέσες ή ξηρές συνθήκες)
- Μετασχηματισμός της ενεργού βροχόπτωσης σε πλημμυρογράφημα με τη χρήση μοναδιαίου υδρογραφήματος. Εν προκειμένω χρησιμοποιείται μοναδιαίο

υδρογράφημα παραμετρικό ως προς τον χρόνο συγκέντρωσης, ο οποίος θεωρείται σταθερός και υπολογίζεται με τη γνωστή μέθοδο Giandotti

Τα βασικά μειονεκτήματα της παραπάνω προσέγγισης έχουν να κάνουν με την αυθαίρετη επιλογή συνθηκών υγρασίας, την εξίσου αυθαίρετη επιλογή ενός προκαθορισμένου μοτίβου, όσον αφορά τη χρονική εξέλιξη της καταιγίδας σχεδιασμού, την υπόθεση ότι ο χρόνος συγκέντρωσης είναι σταθερός, αλλά και την ίδια την αντιμετώπιση των υδρολογικών διεργασιών της λεκάνης, που υποτίθεται ότι διέπεται από πλήρως αιτιοκρατικές σχέσεις.

Πιο συγκεκριμένα, τόσο η βιβλιογραφία, όσο και η ίδια η εμπειρία των μηχανικών, καταδεικνύει ότι η εδαφική υγρασία επηρρεάζει κατά κύριο λόγο την παραγόμενη απορροή, για μια δεδομένη καταιγίδα. Η εφαρμογή της παραπάνω μεθοδολογίας συνήθως εντάσσεται σε μια λογική υπερδιαστασιολόγησης, όπου επιλέγονται οι υγρές συνθήκες χάρην ασφαλείας, παρ΄ότι έχει παρατηρηθεί ότι τα ακραία γεγονότα μπορούν να συμβούν ακόμα και σε ξηρές συνθήκες. Ειδικότερα στην Ελλάδα και, πολύ δε περισσότερο στην ανατολική Ελλάδα, οι ξηρές συνθήκες επικρατούν έναντι των υγρών (Pontikos, 2014). Συγχρόνως, σε μια περίοδο που η ανθρωπότητα αγωνίζεται να διατηρήσει πόρους, η κατασπατάλησή τους και, άρα, η κουλτούρα της υπερδιαστασιολόγησης θα έπρεπε να αποφεύγεται.

Καθίσταται επομένως σαφές ότι ένα πλαίσιο στο οποίο περιγράφεται η πραγματική φύση της μεταβλητότητας της εδαφικής υγρασίας, είναι σίγουρα πιο συνεπές και αναπαριστά πιο πιστά το πραγματικό καθεστώς της εκάστοτε περιοχής μελέτης. Επιπλέον, η διακριτοποίηση των συνθηκών εδαφικής υγρασίας σε τρεις τύπους είναι προφανές ότι είναι εξαιρετικά μη ρεαλιστική, αφού στην πραγματικότητα το έδαφος μπορεί να βρεθεί σε οποιαδήποτε κατάσταση. Βέβαια, μια πιο συνεπής περιγραφή της μεταβλητότητας αυτής δεν μπορεί να γίνει αναθέτοντας αυθαίρετα μία κατανομή στις συνθήκες υγρασίας, αλλά, αντιθέτως θα πρέπει να σχετίζεται με τις διεργασίες εντός της λεκάνης.

Ταυτόχρονα, η αυθαίρετη επιλογή ενός προκαθορισμένου μοτίβου, όσον αφορά τη χρονική εξέλιξη της καταιγίδας σχεδιασμού, έχει αποδειχθεί ότι είναι όχι μόνο μη ρεαλιστική, αλλά οδηγεί και σε εξαιρετικά απίθανες καταιγίδες, καθώς βασίζονται στην υπόθεση ότι το ύψος βροχής σε κάθε χρονική διάρκεια αντιστοιχεί στην ίδια περίοδο επαναφοράς. Συνεπώς, η χρήση ενός πλαισίου στο οποίο μπορούν να παραχθούν πιο ρεαλιστικά προφίλ βροχόπτωσης, τα οποία θα μπορούν να διατηρούν τα στατιστικά χαρακτηριστικά και τη δομή αυτοσυσχέτισης της βροχόπτωσης της περιοχής μελέτης καθίσταται απολύτως αναγκαία.

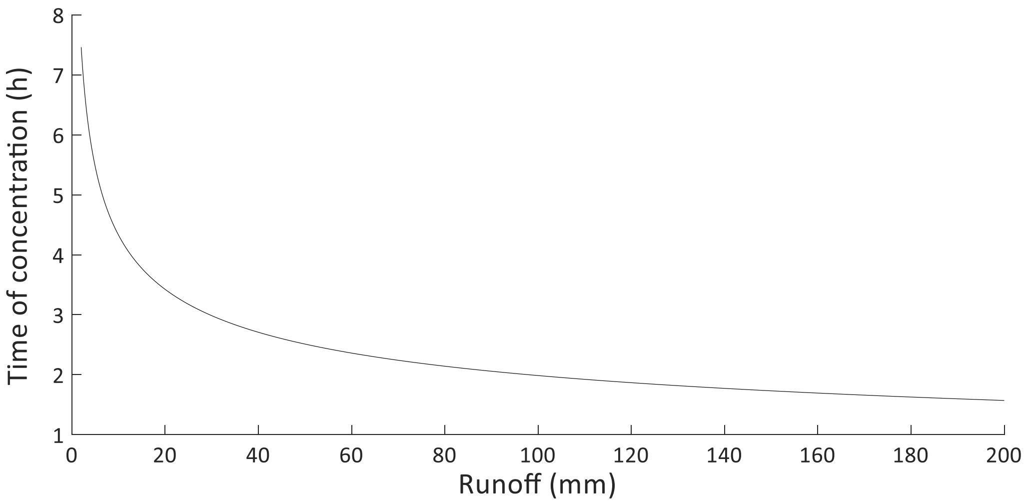
Παράλληλα, σύμφωνα με τη βιβλιογραφία (π.χ. Grimaldi κ.α. (2012)), αλλά και την εμπειρία των μηχανικών, ο χρόνος συγκέντρωσης δεν μπορεί να θεωρείται σταθερός. Είναι προφανές ότι όταν αυξάνεται η απορροή και, άρα, αυξάνονται οι παροχές και οι ταχύτητες της επίγειας ροής, καθώς και της ροής στο υδρογραφικό δίκτυο, ο χρόνος συγκέντρωσης είναι μειωμένος. Σε αυτή την κατεύθυνση, πρόσφατα η Αντωνιάδη (2016) ανέπτυξε μία μεθοδολογία, σύμφωνα με την οποία ο χρόνος συγκέντρωσης μεταβάλλεται και συσχετίζεται με το ύψος της παραγόμενης πλημμυρικής απορροής.

Τέλος, ακόμα και ένα πλαίσιο το οποίο θα αντιμετώπιζε τα παραπάνω, δεν θα μπορούσε να είναι αξιόπιστο, παρά μόνο αν λάμβανε υπ΄όψη και την εγγενή αβεβαιότητα των υδρομετεωρολογικών διεργασιών και των υδρογεωλογικών μηχανισμών που σχετίζονται με αυτές και επηρρεάζουν την απόκριση της λεκάνης. Συνεπώς, μόνο μία στοχαστική προσέγγιση, μπορεί να προσφέρει πιο αξιόπιστες λύσεις, κατά την οποία τα μεγέθη σχεδιασμού μπορούν να προσεγγιστούν πιθανοτικά.

Λαμβάνοντας υπ΄όψηην τα παραπάνω προτείνεται το πλαίσιο στοχαστικής προσομοίωσης σε ψευδο-συνεχή χρόνο το οποίο περιλαμβάνει αναλυτικά τα ακόλουθα βήματα:

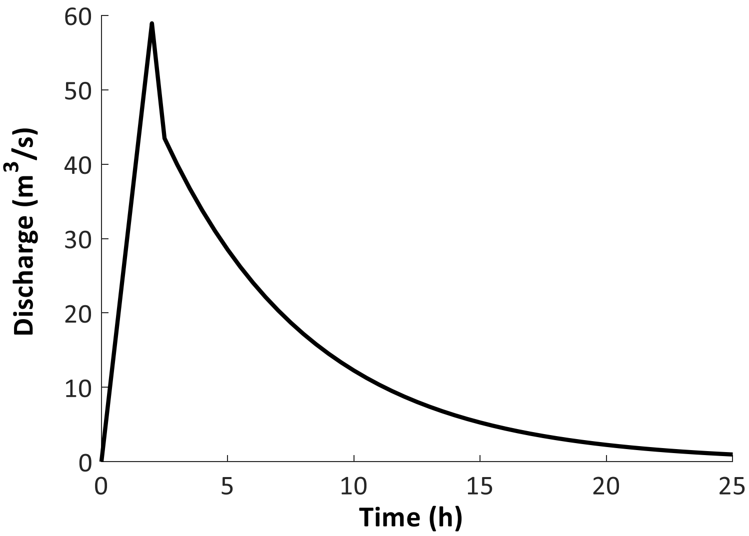
1) Μελετώνται τα φυσιογραφικά χαρακτηριστικά της λεκάνης και καθορίζεται η τιμή αναφοράς για την παράμετρο CN

2) Με τη χρήση του Ψηφιακού Μοντέλου Εδάφους της περιοχής υπολογίζεται η σχέση της απορροής με τον χρόνο συγκέντρωσης. Αυτό γίνεται με βάση τη μεθοδολογία που προτείνει η Αντωνιάδη (2016), σύμφωνα με την οποία η απορροή συνδέεται με το χρόνο συγκέντρωσης μέσα από μία εκθετική σχέση, της μορφής $P=at_c^{-b}$, όπου a,b>0 και P η απορροή σε χιλιοστά.



Σχήμα 2 : Η σχέση του χρόνου συγκένετρωσης με την παραγόμενη απορροή για τη λεκάνη της Ραφήνας

3) Καθορισμός των παραμέτρων του Παραμετρικού Συνθετικού Μοναδιαίου Υδρογραφήματος, όπως αυτό αναπτύχθηκε στα πλαίσια του ερευνητικού προγράμματος «ΔΕΥΚΑΛΙΩΝ» (2014).



Σχήμα 3 : Το ΜοναδιαίοΥδρογράφημα της λεκάνης της Ραφήνας για χρόνο συγκέντρωσης που έχει υπολογιστεί με τη μέθοδο του Giandotti

4) Επιλογή κατάλληλης ιστορικής χρονοσειράς βροχοπτώσεων

5) Βαθμονόμηση του πακέτου στοχαστικού επιμερισμού HyetosMinute (2016) με βάση την ιστορική χρονοσειρά

6) Παραγωγή συνθετικής χρονοσειράς ημερήσιων βροχοπτώσεων με τη χρήση του λογισμικού Castalia (Efstratiadis, et al., 2014). Η επιλογή του μήκους των συνθετικών χρονοσειρών γίνεται με βάση την επιθυμητή περίοδο επαναφοράς (10 000 χρόνια παράγονται για τον αξιόπιστο υπολογισμό πλημμύρας σχεδιασμού με περίοοδο επαναφοράς ίση με 1 000 χρόνια).

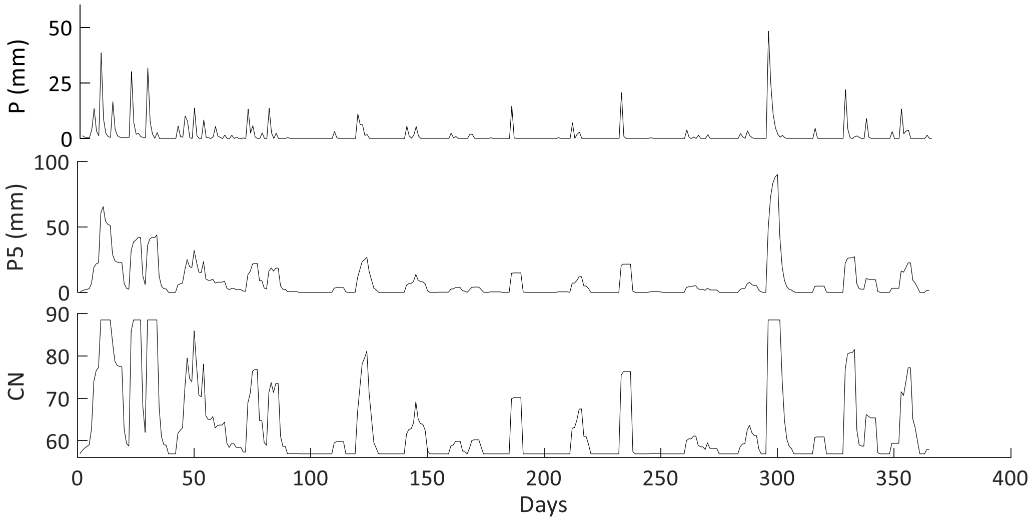
7) Στοχαστικός επιμερισμός των ημερήσιων βροχοπτώσεων σε λεπτότερες χρονικές κλίμακες (π.χ. 15 λεπτά) με τη χρήση του πακέτου HyetosMinute (Kossieris, et al., 2016).

8) Υπολογισμός της εδαφικής υγρασίας (τιμή της παραμέτρου CN^i και κατ΄επέκτασην της μέγιστης δυνητικής κατακράτησης) για κάθε ημέρα *i*, με βάση την αθροιστική βροχή των προηγούμενων πέντε ημερών, P_5. Σε αυτά τα πλαίσια, οι ξηρές συνθήκες αντιστοιχίζονται στο χαμηλότερο 10% των P_5, ενώ οι υγρές συνθήκες στο υψηλότερο 10%. Για κάθε ενδιάμεση κατάσταση, γίνεται γραμμική παρεμβολή μεταξύ των δύο, με βάση την εκάστοτε τιμή P^i_5, όπως φαίνεται στις ακόλουθες σχέσεις.

$$\frac{P_5^i - P_5^{dry}}{P_5^{wet} - P_5^{dry}} = \frac{CN^i - CNI}{CNIII - CNI}, \qquad for\ P_5^{dry} < P_5^i < P_5^{wet}$$ **Eq. (1-1)**

$$CN^i = CNI, \qquad for\ P_5^i \le P_5^{dry}$$ **Eq. (1-2)**

$$CN^i = CNIII, \qquad for\ P_5^i \ge P_5^{wet}$$ **Eq. (1-3)**



Σχήμα 4 : Παράδειγμα όπου φαίνονται η χρονοσειρά των βροχοπτώσεων, τα αντίστοιχα P_5 και οι τελικές τιμές του CN που ανατίθενται

9) Υπολογισμός της ημερήσιας απορροής, με βάση την τιμή του CN που υπολογίστηκε στο βήμα (3), με χρήση της μεθόδου NRCS-CN.

10) Επιλογή των ετησίων μεγίστων της απορροής

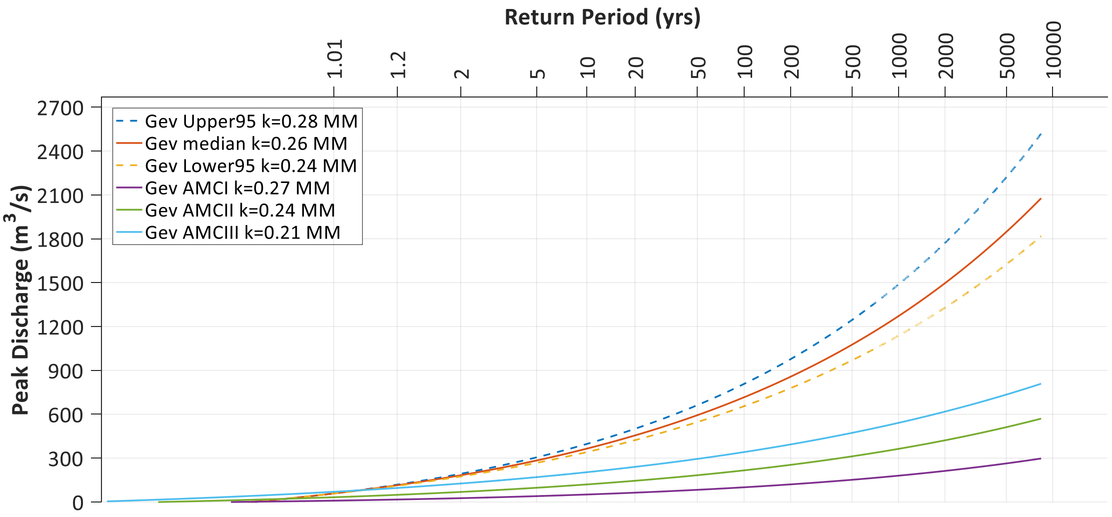
11) Υπολογισμός του χρόνου συγκέντρωσης, δεδομένης της παραγόμενης απορροής και, επομένως του μοναδιαίου υδρογραφήματος που προκύπτει για κάθε επιλεγμένο επεισόδιο

12) Υπολογισμός της χρονικής εξέλιξης των υδρολογικών ελλειμάτων με χρήση της μεθόδου NRCS-CN στην κλίμακα του επεισοδίου και παραγωγή των πλημμυρογραφημάτων.

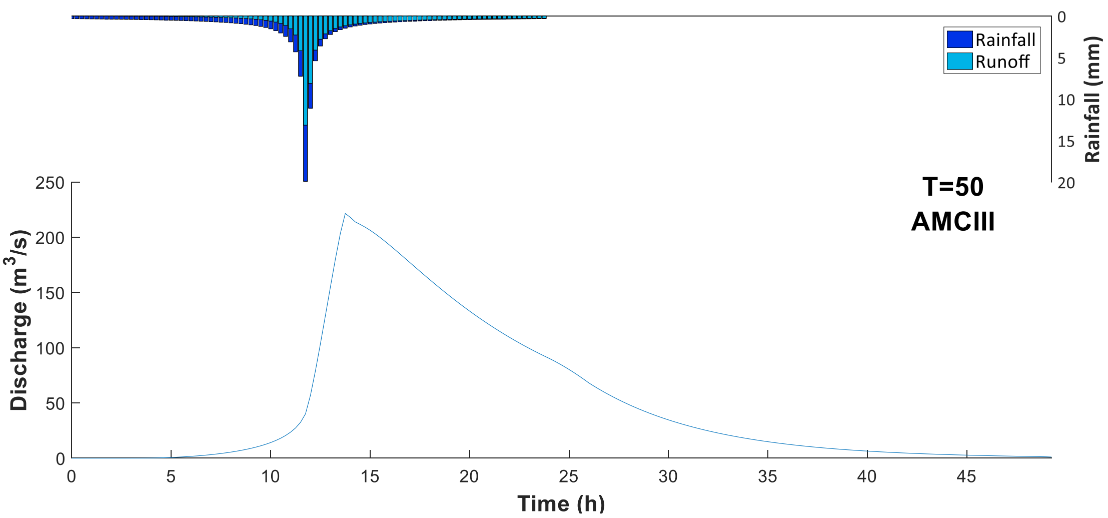
13) Επανάληψη των βημάτων (1) έως (12) στα πλαίσια μίας προσομοίωσης Monte-Carlo, προκειμένου να εξαχθούν οι περιθώριες κατανομές των αποτελεσμάτων.

Οι παραπάνω προσεγγίσεις εφαρμόστηκαν στη λεκάνη της Ραφήνας και τα αποτελέσματα της βασικής ανάλυσης παρουσιάζονται στο ακόλουθο διάγραμμα, όπου φαίνεται πως το κλασικό ντετερμινιστικό πλαίσιο υποεκτιμά αρκετά τις πλημμυρικές αιχμές, με τη διαφορά των δύο μεθόδων να αυξάνεται, καθώς αυξάνεται η περίοδος επαναφοράς. Παράλληλα, το προτεινόμενο πλαίσιο, λόγω της μεθόδου επιμερισμού της βροχής που χρησιμοποιείται, δίνει αρκετά ρεαλιστικά πλημμυρογραφήματα, σε αντίθεση με τα τυποποιημένα πλημμυρογραφήματα που παράγονται από το κλασικό πλαίσιο.

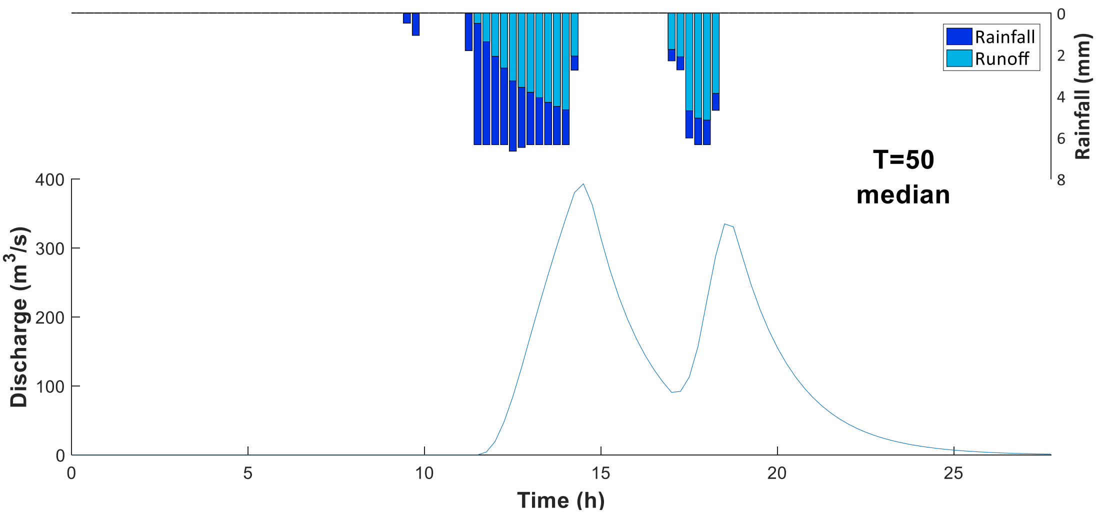
Φυσικά, το προτεινόμενο πλαίσιο είναι αρκετά εύκολο στη χρήση του και χρησιμοποιεί λίγες παραμέτρους, χωρίς να απαιτεί την ύπαρξη μετρήσεων βροχής – απορροής και είναι, συνεπώς, κατάλληλο για λεκάνες χωρίς μετρήσεις, όπως είναι η πλειονότητα των λεκανών παγκοσμίως.



Σχήμα 5 : Οι κατανομές των πλημμυρικών αιχμών υπολογισμένες με βάση το προτεινόμενο πλαίσιο και την κλασική ντετερμινιστική μεθοδολογία. Φαίνονται οι περιθώριες κατανομές του προτεινόμενου πλαισίου (άνω –κάτω όρια για όρια εμπιστοσύνης 95% και ενδιάμεση εκτίμηση) και οι κατανομές του ντετερμινιστικού πλαισίου για τους τρεις τύπους εδαφικής υγρασίας (AMCI-II-III).



Σχήμα 6 : Πλημμυρογράφημα που αντιστοιχεί σε περίοδο επαναφοράς 50 έτη, υπολογισμένο με το ντετερμινιστικό πλαίσιο

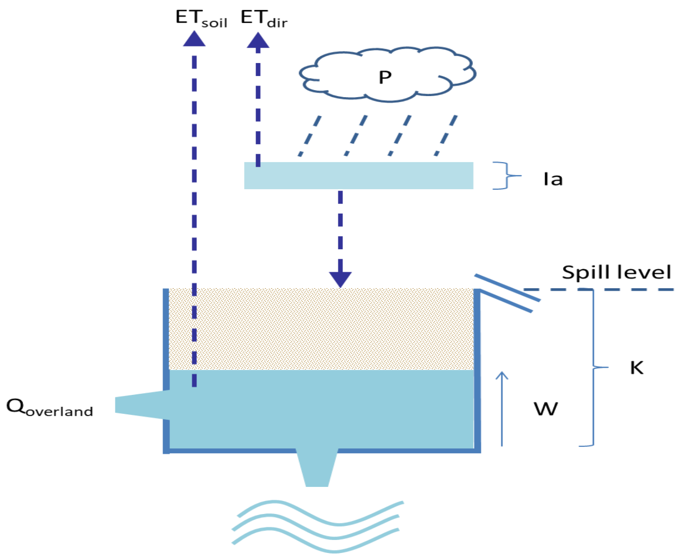


Σχήμα 7 : Πλημμυρογράφημα που αντιστοιχεί στην ενδιάμεση εκτίμηση για περίοδο επαναφοράς 50 έτη, υπολογισμένο με το προτεινόμενο στοχαστικό πλαίσιο

Με αυτά κατά νου, διενεργήθηκε παράλληλα μία σωρεία αναλύσεων με βάση αρκετές τροποποιήσεις στις διάφορες πτυχές του προτεινόμενου μοντέλου, τα αποτελέσματα και τα συμπεράσματα των οποίων καταλαμβάνουν έναν σημαντικό όγκο πληροφορίας και σε καμία περίπτωση δεν μπορούν να παρουσιαστούν στην παρούσα περίληψη, αλλά παρουσιάζονται εκτενώς στα κεφάλαια της εργασίας που ακολουθούν.

Οι αναλύσεις αυτές πραγματοποιήθηκαν προκειμένου να διερευνηθεί η επιρροή που έχουν στο παραγόμενο αποτέλεσμα οι διάφορες υποθέσεις του προτεινόμενου πλαισίου και ανα αναζητηθούν ενδείξεις που να στηρίζουν την ορθότητα των επιλογών μας.

Οι διαφοροποιήσεις αφορούν τον επιμερισμό της βροχής (με τη μέθοδο των εναλλασσόμενων μπλοκ ή με μία απλή ομοιόμορφη κατανομή), τη θεώρηση του χρόνου συγκέντρωσης ως σταθερού, ενώ μελετήθηκε και το φειδωλό συνεχές εννοιολογικό προσομοίωμα Annie-model που αναπτύχθηκε από τους Παπουλάκο κ.α (2017).



Σχήμα 8 : Σχηματική απεικόνηση των διεργασιών της λεκάνης σύμφωνα με το Annie-model

Μεταξύ πολλών ευρημάτων και συμπερασμάτων, αναφέρουμε εδώ ενδεικτικά ότι ο χρόνος συγκέντρωσης φαίνεται να έχει την πιο έντονη επιρροή στο αποτέλεσμα, ενώ το πακέτο HyetosMinute, που παράγει πιο συμπαγή και περιορισμένα στο χρόνο συσσωματώματα βροχής, μπορεί να παράξει πιο δυσμενή υδρογραφήματα από ό,τι οι άλλες μέθοδοι επιμερισμού.

Παράλληλα, αν και το μοντέλο υπολογισμού της εδαφικής υγρασίας του προτεινόμενου πλαισίου φαίνεται να μπορεί να αναπαραστήσει σε πολύ αδρές γραμμές το καθεστώς της περιοχής, που είναι κατά κανόνα ξηρό, προκύπτει, ύστερα από μια ποιοτική σύγκριση με το πιο πλήρες Annie-model, ότι μια προσέγγιση βασισμένη στην αθροιστική βροχή των 60 ή 90 –αντί των 5- προηγούμενων ημερών ίσως ήταν πιο αξιόπιστη.

Κλείνοντας, σε γενικές γραμμές μπορεί να θεωρηθεί ότι το προτεινόμενο πλαίσιο έχει ικανοποιητική λειτουργία. Παρ΄όλα αυτά σίγουρα πρέπει να γίνουν προσπάθειες για τη βελτίωση ορισμένων πτυχών του.

Οι πρώτες κατευθυντήριες γραμμές τόσο για τη βελτίωση του προτεινέμενου πλαισίου, όσο και για περαιτέρω αυτόνομη έρευνα, αλλά και βελτίωση των διάφορων εργαλείων που χρησιμοποιήθηκαν έχουν τεθεί αναλυτικώς στα κεφάλαια που ακολουθούν.

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1 Introduction

1.1 General Context

Despite the fact that human societies have tremendously grown spiritually, scientifically and technologically, thus dramatically changing all aspects of everyday life to the better, human nature is still having trouble coping with the unpredictable and occasionally devastating forces of nature -among which floods have a prominent position.

Driven by the urging need of safer and less expensive flood control works in modern societies, that would protect human life and property, flood engineering has significantly changed in the past decades. The progress made in the field of hydrology, along with the computational capabilities provided by the rapid developments in computer science, have paved the way for the establishment of better and more consistent flood modeling schemes.

However, not only in the underdeveloped or developing countries, but also in the most developed, where the necessary resources and means for protection are adequate, floods continue to pose a great threat, as severe events causing casualties and mass destruction keep occurring. In particular, according to the United Nations Office for Disaster Risk Reduction (2015) since 1995, floods have accounted for 47% of all weather-related disasters killing 157 000 and affecting 2.3 billion people, while the globally recorded economic damage reaches totally up to662 billion US $.

Specifically in Europe, between 1998 and 2009, over 213 major floods occurred, causing destruction, including the catastrophic floods along the Danube and Elbe rivers in summer 2002. Severe floods also occurred in 2000 in Italy, France and the Swiss Alps, as well as in the United Kingdom, during the summer of 2007. In total, during this period 1 126 people died, about a half million were displaced and and the total economic loss was at least 60 billion € in total. (EEA, 2010)

In the first half of 2017 alone, up to the moment this study was written, over 100 different major flood events all over the world (as depicted in the following map)had been recorded, raising the death toll at approximately over 1 115 people totally.

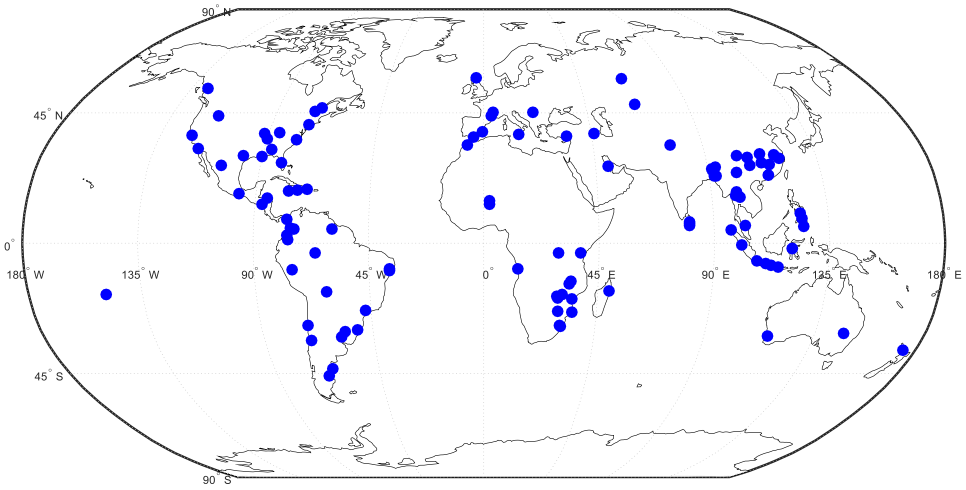

Figure 1-1: Depiction of major floods recorded during the first half of 2017

Moreover, the findings indicate that there has been an increase in observed floods worldwide, which is quite intriguing, since humanity has had an apparent impact upon them. Intense urbanization and deforestation have increased flood runoffs in many places across the world, while cities have been constructed in many cases on flood plains. As a result, even though the nature of precipitation, which is the driving force of floods, has not been altered, floods nowadays have more devastating effects on lives and property. In other words, anthropogenic changes have increased the flood magnitude for particular precipitation events, and also have amplified the flood damage potential.

Moreover, apart from the loss of human life, residencies getting flooded, great numbers of people-even whole communities-being forced to evacuate their homes and valuable property being destroyed, the recurrent flooding of agricultural land, particularly in Asia, has also taken a heavy toll in terms of lost production, food shortages and rural under-nutrition.

In addition to economic and social damage listed above, floods may have severe environmental consequences as for example when waste water treatment plants are inundated or when factories holding large quantities of toxic chemicals are also affected. Floods may also destroy wetland areas and reduce biodiversity.

In this context, in order to protect our societies from floods and before turning to flood engineering, which is the subject of this study, it is essential that humanity understood that there are yet urgent things that need to be done.

First and foremost, it should be made a priority that cities are expanded farther from river banks, thus avoiding construction on flood plains, where possible, while deforestation should be restricted to the minimum necessary, or even reversed, when possible. Urbanization should be carefully planned, providing enough space for the construction of adequate drainage systems that could propagate major floods, communities should be designed and constructed in a more flood-resilient way, taking advantage of modern technology and, of course, the natural streams or rivers that cross cities should under no circumstances be constrained.

Simultaneously, safety guidelines and plans should be designed and the population along with the authorities should be trained and well prepared, in order to behave in the best possible, most efficient and quickest manner, when it comes to evacuating cities and rescuing people under threat, thus minimizing the risk on human lives.

In the framework of planning in order to keep our cities safe, it is essential that the flood risk could be calculated. Flood hazard maps, showing the extent and expected water depths/levels of a flooded area, as well as flood risk maps, showing potential population, economic activities and the environment at potential risk from flooding, should be prepared.

However, even though flood engineering has dramatically advanced, over the past decades, there are yet major shortcomings to be found in the methods and formulas used in everyday engineering practices, that lead to significant over or underestimations of flood risk, thus resulting in over or undersizing flood control structures respectively. Such shortcomings, apart from deriving from the core weaknesses of the field of hydrology itself, are also indicative of another major misconception in typical engineering, which is engineer's inertia of grasping the inherent uncertain nature of hydrometeorological variables and accepting the fact that they cannot be described in deterministic ways.

On the one hand, hydrology is mostly an empirically developed field of science, where the complexity of the mechanisms governing the processes under study remains -to its full extent- elusive. In addition, the established methods and formulas are not only based on experiments conducted exclusively on watersheds, where measurements were available, but have also been derived from the investigation of specific –tremendously short, compared to Earth's age- time intervals of the past, which ,in a non-deterministic universe, cannot be fully representative of the true nature of any hydrometeorological variable.

On the other hand, even in a fully deterministic world, where the twists and turns of every complicated natural process would be completely analyzed and easily predictable, humans would also have to decide upon an accepted level of flood risk. Extremely low levels of acceptable risk would require massive flood control works, thus wasting resources that could be spent more wisely on other sectors, such as healthcare or education, while higher levels would leave human lives and property exposed.

In this context, it becomes quite clear already, that in order to deal with the challenges set by nature, we should embrace the fact that, not only are our methods usually inconsistent, misled by the scarcity or unreliability of measurements and not adequately theoretically founded, but that there also is an inherent uncertainty underlying all hydrometeorological processes.

1.2 Objective and structure

Given the above, the scope of this thesis is to propose a stochastic simulation framework for calculating flood risk, in an attempt to address the inconsistencies found in everyday flood engineering.

The main goal of this work is to propose a framework that opposes the deterministic view on hydrological processes and is also simple and parsimonious enough, so that it can be implemented in studying ungauged basins, opposed to the more complex continuous models developed over the past decades that require calibration.

In the second chapter, a literature review is conducted, in order to document the theoretical background regarding flood engineering.

In the third chapter, the materials and methods used in the context of this study are presented. A more complete, yet equally simple and parsimonious hydrological model, for calculating the generated runoff is also presented in this chapter. Although this model needs calibration, thus being not appropriate for ungauged basins, its simplicity allows its implementation in watersheds with limited measurements, where calibrating a fully distributed, more complex model would require more data.

In the fourth chapter, the typical deterministic approach is described, its shortcomings are analyzed and some of its key assumptions that lack a stable theoretical background are questioned.

In chapter five, the need for a stochastic approach that would remedy the inconsistencies of typical deterministic flood engineering is stated. Moreover, the shortcomings of more complex continuous model are documented, which support our choice of implementing a midrange approach. Finally the proposed pseudo-continuous stochastic simulation framework is thoroughly presented.

In chapter six, Rafina stream basin, which is the study case of this thesis is presented and the model parameters are set.

In chapter seven, the analyses and investigations regarding the proposed framework are conducted and the results are presented. The analyses involve presenting the results of the typical deterministic scheme, as well as the outcome of the proposed framework and comparing them; examining the continuous, as well as the event based parts of the model; investigating different variations of the proposed framework; testing the response of Annie-model, which is presented in this thesis; and finally, examining the influence of CN upon the resulting floods.

In chapter eight, the proposed scheme is improved, based on the results of our investigations and the response of the improved version is also tested.

In the ninth chapter, summary and conclusions of this diploma thesis are presented. That chapter consists of a summary of the topics treated in this thesis, final remarks regarding the conclusions made from all analyses and, finally, suggestions for further investigation.

It should definitely be noted that the proposed framework is based mostly on methods, software and tools developed over the past years by teaching staff, researchers and students of the School of Civil Engineering, of National Technical University of Athens (from now on NTUA) and more specifically the Department of Water Resources and the Environment.

2 Literature review

In this chapter, a review on the literature regarding flood engineering and more specifically the part of hydrologic design is conducted, in order to define the necessary theoretical background and concepts. The main hydrological procedures governing runoff generation, along with the flow mechanisms determining flood propagation are described. Moreover, the key steps in hydrologic design -from determining the design rainfall to calculating the flood at the outlet of the basin- are presented.

2.1 Floods

2.1.1 Definitions, causes and effects

The flow regime in rivers and streams has a changing and uncertain nature, and floods are actually only a part of the natural variability of river discharges. As a result, the phenomenon referred to as flood is mostly used to distinct only that part of the wide spectrum of that natural process,which posesa threat to human lives and property. Thus, since "threat" cannot be easily quantifiedand is quite subjective, it is difficult to determine above what extent, the rise of water level should be considered as a flood. That is why, one can find a wide variety of definitions of floods in the literature, the most prominent of which are listed below.

According to the International Glossary of Hydrology (WMO, 2012) a flood is "*(a) the rise, usually brief, in the water level of a stream or water body to a peak from which the water level recedes at a slower rate (b)Relatively high flow as measured by the stage height or discharge.*", while flooding is also defined as "*(a)Overflowing by water of the normal confines of a watercourse or other body of water (b)Accumulation of drainage water over areas which are not normally submerged (c)Controlled spreading of water*" –with the latter one being not suitable in our case.

In the meantime, European Commission, in its Flood Directive 2007/60 (EC, 2007) provides a more parsimonious definition, according to which flood "*means the temporary covering by water of land not normally covered by water*". In an attempt be more descriptive, the EC states that the above "*shall includefloods from rivers, mountain torrents, Mediterranean ephemeral water courses and floods from the sea in coastal areas, and may exclude floods from sewerage systems*".

Moreover, according to the National Weather Service of the United States of America, floods are defined as "*any high flow, overflow, or inundation by water which causes or threatens damage*".

Floods, based on their causes, as well as effects, may be described by one of the following types:

Table 2-1: Types of flood, Causes and effects (EXIMAP, 2007)

Type of flooding	Causes of flooding	Effect of flooding	Relevant parameters
River flooding in flood plains	• Intensive rainfall and/or snowmelt • Ice jam, clogging • Collapse of dikes or other protective structures	• Stagnant or flowing water outside the channel	• Extent (according to probability) • Water depth • Water velocity • Propagation of flood
Sea water flooding	• Storm surge • Tsunami • High tide	• Stagnant or flowing water behind the shore line • Salinisation of agricultural land	• Same as above
Mountain torrent activity or rapid runoff from hills	• Cloudburst • Lake outburst • Slope instability in watershed • Debris flow	• Water and sediments outside the channel on alluvial fan; erosion along channel	• Same as above; • Sediment deposition
Flash floods in Mediterranean ephemeral water courses	• Cloudburst	• Water and sediments outside the channel on alluvial fan • Erosion along channel	• Same as above
Groundwater flooding	• High water level in adjacent water bodies	• Stagnant water in flood plain (long period of flooding)	• Extent (according to probability) • Water depth
Lake flooding	• Water level rise through inflow or wind induced set up	• Stagnant water behind the shore line	• Same as above

2.1.2 Floods in Europe

In Europe 222 flood events have totally occurred between 1970 and 2005, according to Barredo (2006). From 1998 to 2009 alone, more than 1 100 people died and more than 3 million people were affected by catastrophic flooding events, while the total economic losses in the same period were more than 60 billion €.

Between 2003 and 2009, 320 fatalities were caused by floods in the continent, most of which occurred in Romania (85 deaths in 2005), Turkey (47 deaths in 2006) and Italy (35 deaths in 2009) (EEA, 2010). In the following figure, the total deaths from 1970 until 2008 are depicted.

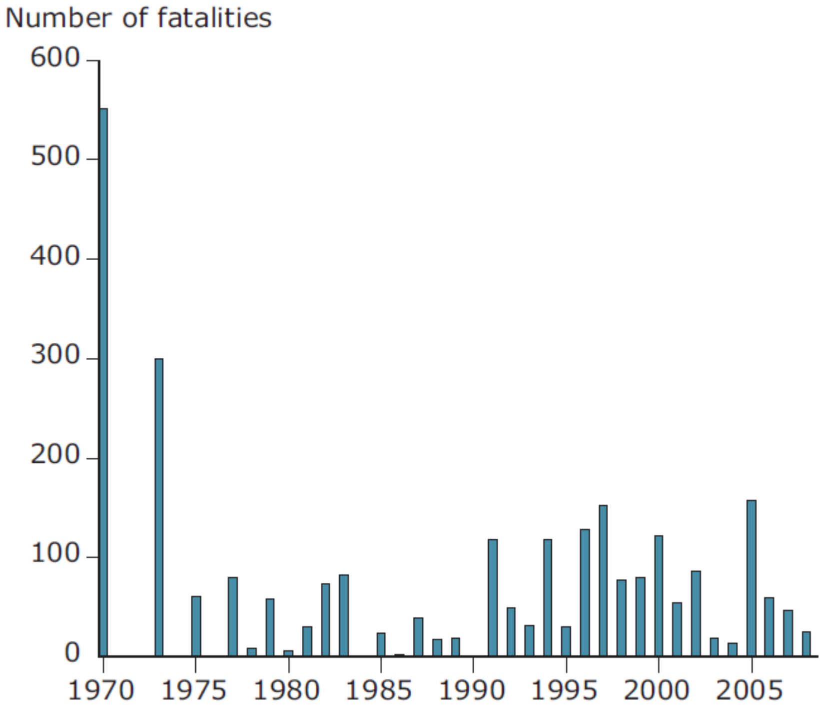

Figure 2-1 : Number of fatalities caused by flood disasters in Europe, 1970 -2008 (Barredo, 2006) –edited by (EEA, 2010)

As already stated,the intensification of deforestation, urbanization and changes in land use, over the past years, have altered the flow regime in many basins, resulting in the generation of larger, more frequent and more disastrous floods. It is important to note that we cannot yet imply that this change is due to any climatic trend.

In the same context, it is reported that economic losses in Europe caused by floods in the past 20 years are 10 times higher than in the 1960s –considering the inflation- (Barredo, 2006). This escalation of the destruction and the amplification of the economic losses is the result of several shifts of the socio-economic, political and the environmental system. In particular, according to Kundzewicz (2005) the causes can be summarized as follows:

- Population trends in exposed areas,
- Increase in exposed values
- urbanization and development in flood-prone areas (land use change),
- increase in the vulnerability of structures, goods and infrastructure,
- failure of flood protection systems and
- changes in environmental conditions

2.1.3 Floods in Greece

It is estimated that in Greece approximately 145 006 people are exposed to floods, which is significantly higher -up to 44%- than previous decades (Pesaresi, et al., 2017).

The long and intricate coastline, and the abundance of islands in Greece, lead to the formation of numerous small-sized steep hydrological basins. The large majority of the streams have ephemeral flow, characterized by non-permanent surface runoff, often increased percolation, since karstic formations cover 40% of the Greek territory.

In the meantime, the mountain range of Pindos, in Greece, serves as a hydrological boundary between Western and Eastern parts of Greece, since it stops the movement of clouds towards the Eastern parts. Consequently, the western regions are more wet than the eastern. However, even in the driest basins of the east, rainfall intensities remain high. In particular, a single rainfall event may have a total depth equal to 25% of the cumulative annual rainfall.As a result, in drier areas, where rainfall is rarer, the flood risk may become higher than in the wetter ones, where people are more familiar with the more frequent rainfall. (Koutsoyiannis, et al., 2012)

Such a steep, mountainous and/or hilly topography fitted in small basins, if combined with intensive and rapid rainfall, provides the ideal framework for generating flash floods.Such flooding events are mostly local, scattered in time and space and are caused by excessive rainfall in a short period of time –less than 6h approximately- and are usually characterized by violent torrents immediately after heavy rains that rip through river beds, urban streets, or mountain valleys sweeping everything before them. These floods are quite dangerous since they occur within several seconds to several hours with little to no warning and have an extremely sudden onset, with the fall of water levels being rapid as well.Urban areas are also susceptible to flash floods, since the imperviousness of the surface facilitates high run-off velocity.

Flash flooding mostly occurs in autumn –summer. In particular, about 52% of the reported flash floods (between 1950 and 2005) occurred in autumn and 39% in summer (Barredo, 2006).

Furthermore, the chaotic and unplanned urbanization in Greece over the past decades, during when the economy grew, with little regard to the environment, has left Greek cities with little resilience against floods.Unfortunately, the natural streams with an ephemeral nature were in many cases converted into road network. At the same time, many buildings have been illegally constructed over or very close to the stream banks. Even some of the larger streams were covered, despite the fact that the flow had a continuous flow and their natural bed was replaced by artificial channels, the discharge capacity of which was inadequate to convey extreme floods.

Given not only the above, but also the ongoing deep economic crisis that has stroke the country the future seems gloomy.The state is currently unable to allocate adequate funds for emergency planning and proper maintenance of the drainage networks and it is more than obvious that flash floods (and floods in general) pose a great threat in Greece and would cause massive death and destruction, once they occurred, unless we got properly prepared.

The most recent deadly flood in Greece occurred in the wider region of Messinia at 7 September of 2016 and is a typical example of flooding in the country. Actually it is of specific interest, since it is representative of the devastating results that economic difficulties have, combined with negligence, as well as with some questionable decisions regarding the acceptable risk in flood engineering.

As recorded, the total rainfall depth of the episode reached up to 278 mm in 24 hours, which equals a mean rainfall intensity of 11.58 mm/h. Consequently, many parts of the natural drainage networks of the area, such as Pamisos and Nedontas rivers, along with some of the smaller creeks and streams flooded, causing major damages.

In particular, two people died from the flood, hundreds of cars were swept away by water, houses and agricultural land were inundated, and slope landslides as well as subsidence in the surface of the earth were recorded.

Image 2-1 : Cars swept away by floods in Messinia (Source: www.ert.gr)

According to the regional authorities the total economic loss caused by the flooding reached approximately up to 2 million €, while the responsible ministry was only able to allocate funds only equal to 250 000 € as compensation for the damage done.

In the meantime, locals accused the authorities of having done nothing or little to maintain and clear the natural, as well as the artificial drainage network of the region. In addition, they claim that there have not been enough flood control works in the area such as dykes that could have prevented or constrained the damage.

It is necessary in this point to note that the recorded rainfall was quite a big one, given the historic records of the wider region. More specifically, at some time intervals, the intensities measured were as much as three times larger than the corresponding values of a return period equal to 50 years, which is used in the hydrologic design of many flood control works. As a result, the flood control works such as channels and pipes, had not the adequate capacity in order to route the flood.

A characteristic example was the newly constructed major highway linking Messinia to the capital of Greece, Athens, which was flooded, since its drainage network could not propagate a flood bigger than the one with a 50-year return period, thus suddenly cutting the city off. Of course that is not a responsibility of the constructor, who followed the directives suggesting a 50-year return period and, since a less frequent rainfall occurred this cannot be considered a failure in paper, however, such problems question whether the responsible authorities should dictate higher return periods for design.

2.2 EC flood directive

A game changer in flood engineering in Europe was the directive 2007/60/EC of the European Parliament and the council of 23 October 2007, on the assessment and management of flood risk, since it requires all EU member states to assess if all water courses and coast lines are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk.

Flood risk is defined as "*the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event"* (EC, 2007).

The aim of the directive is "*to reduce the adverse consequences on human health, the environment, cultural heritage and economic activity*" (EC, 2007) caused by floods, or, in other words, to reduce *flood risk.*

According to the Directive, EU Member States should assess the flood risk and need for further action in each watershed and provide for the establishing of flood hazard maps and flood risk maps showing the potential adverse consequences associated with different flood scenarios, while assessing also activities that increase flood risk. Moreover, flood risk management plans should be developed, focusing on prevention, protection and preparedness. Such plans would include measures aiming to give rivers more space, considering where possible the maintenance and/or restoration of floodplains, the establishment of flood forecasting techniques and early warning systems, the promotion of sustainable land use practices, the improvement of water retention, the controlled flooding of certain areas and a wide range of other measures in order to prevent and reduce the consequent destruction.

More specifically, flood hazard maps should depict the inundated areas, water depths and flow velocities, according to the following scenarios:

a) Floods with low probability (extreme events, without determining the return period)
b) Floods with a medium probability (likely return period ≥100 years)
c) Floods with a high probability (without determining the return period)

In the meantime, flood risk maps should determine the potential adverse consequences associated with the aforementioned scenarios, which include the number of people affected, the type of economic activity potentially disrupted and information on possible sources of pollution, such as the flooding of a wastewater treatment plant.

It is important to know, that flood risk management plans, combined with river basin management plans under Directive 2000/60/EC, which aim for a good ecological and chemical status of the water bodies of a watershed, constitute an integrated river basin management, providing a more holistic approach for managing the water resources at a given area, along with potential threats.

2.3 Hydrologic design in the context of flood engineering

As aforementioned, the development of flood risk management plans aiming to reduce the adverse consequences of flooding requires the preparation of flood hazard and flood risk maps, which, among others, depict the inundated areas, the corresponding water levels and the velocity of the flow.

It is quite clear that determining which regions will be flooded and the flow regime on spot is the most essential part in assessing flood risk, since the above indicate whether an asset (fields, structures, road networks, agricultural land) will be flooded and if so, the severity of the consequences, according to the water depth and velocity of the flow.

In this context, the necessary framework for flood mapping defines approximately that field of engineering which is called flood hydrology and focuses on the processes governing flood generation, from the initiation of a storm, to the propagation of the flood.

The key difference between flood hydrology and the general field of hydrology is the time scale under study. In the first one, the time scale is the same with that of a storm, usually ranging between several minutes, until several days. During that period, the analysis is based mostly on direct runoff, since the ongoingprocesses of evapotranspiration, infiltration to soil and percolation through it, with the consequent changes in water volumes in the soil, as well as the flow velocities in the aquifers are of no importance, compared to surface runoff.

In flood hydrology, on the other hand, one cannot underestimate the importance of mechanisms governing the flood propagation scheme, such as the response time, the density of the drainage network and its geometrical characteristics, which in general hydrology are completely ignored.

In general, flood hydrology consists of the hydrologic and the hydraulic design. Hydrologic design, which is the subject of this thesis, is about determining the design storm, causing the flood, as well as the generated flood hydrograph, while, hydraulic design determines the spatial and temporal propagation of the generated runoff, thus defining the inundated areas and the corresponding flow regime, using as input the generated flood hydrograph.

Hydrologic design is strongly correlated with the probabilistic (and stochastic) nature of storms and the resulting floods. The designing process is based on an extreme analysis, in the context of which, each event is studied independently from others, sinceaccording to the extreme theory, the distribution of extremes of a hydrometeorological variable, consists of uncorrelated values.

Given the above, it becomes clear, that the probabilistic nature of extreme events must be somehow implemented in choosing the design element for any project, in the context of flood control, as a quantification of the importance of the project under study and the safety that it is designed to provide. In particular, the more significant a flood controlwork is, which means that it is required to cope with more hazardous, rather than ordinary events, the lowest the exceedance probability of the event must be.

The exceedance probability, *F*, of a variable is closely linked to the easily conceivable concept of return period, *T*:

$$T=1/F \quad \textbf{Eq. (2-1)}$$

In small scale projects of no significant importance, such as secondary and tertiary drainage network channels and pipes, only the peak discharge is needed as a design element, which is estimated by simplistic deterministic approaches such as the rational method and the return period used for the design is usually of low value.

However, in the context of studying larger scale projects such as dykes, dams and spillways for flood protection that are of significant importance for human lives and property, hydrologic design is not only interested in the peak discharge of the event, but also aims for calculating the design flood hydrograph, thus determining the complete temporal evolution of the flood. This level of detail is necessary, since the key assumptions found in the rational method, such as the storm duration being at least equal to the time of concentration and the rainfall intensity being constant throughout the episode are quite unrealistic. In addition, the routing of the incoming flood through a dam spillway, for example, is a non-linear process, dependent on the volume-elevation characteristics of the reservoir and the outflow-elevation relationship for the spillway, which makes the calculation of the complete temporal evolution of the flood a necessity, for the purpose of designing the spillway.

2.4 Design flood hydrograph estimation

As aforementioned, hydrologic design in the context of studying larger scale projects, which is the subject of this thesis, is about estimating the design flood hydrograph which is in turn used as input in a hydraulic design model.

A proper scheme for determining the design hydrograph starts with generating a design hyetograph. For the required return period a single design hyetograph is produced, which is considered the most severe, given that specific exceedance probability. Usually the chosen storm profiles are empirically determined by the engineer, based upon some basic assumptions.

Afterwards the hydrologic deficits must be abstracted from gross rainfall and then the generated runoff is transformed into a hydrograph, with models such as the unit hydrograph.

The described procedure constitutes the so-called event-based modeling, while, there are other, more complex schemes, which are based on hydrological models operating on continuous time. Such models roughly describe the basic hydrometeorological processes and the mechanisms that govern runoff generation, thus calculating floods more accurately. The downside of such models is that they need calibration, which is dependent on the availability and quality of measurements in a basin.

2.5 Event-based hydrologic design

The basic elements of event-based hydrologic design are listed below.

2.5.1 Design rainfall

The design rainfall represents the evolution of a hypothetical storm event of the desirable duration and temporal resolution, which corresponds to the required return period. The duration, D and resolution, Δt, are characteristic temporal properties of the design rainfall. These two quantities determine the simulation period and time step of the hydrological analysis, respectively. The Intensity-duration-frequency curves are a well-known tool for estimating rainfall depths, for the required duration and return period.

There is a wide range of models developed for producing typical rainfall profiles that are divided in four categories:

- Deterministic patterns: Singe pre-selected time distribution curves, such as uniform, triangular or bimodal triangular hyetographs, with little or none probabilistic basis.
- Almost-deterministic probabilistic: Such are empirically developed dimensionless patterns describing the percentage of water precipitated during each time step. They are linked to a probability and have mostly regional applicability, since they are based on measurements of locally recorded events.
- Intensity- Duration- Frequency curve based methods: The hyetograph synthesized by these methods has the property that the maximum rainfall depth for every duration equals the depth given by the IDF curve for that duration. The most well-known methods of this category are the alternating blocks and the worst profile methods.
- Stochastic disaggregation schemes: These involve generating more than one rainfall profiles that preserve the statistical characteristics and the autocorrelation structure of rainfall in the region. A typical stochastic disaggregation scheme is achieved with the use of Poison –cluster models.

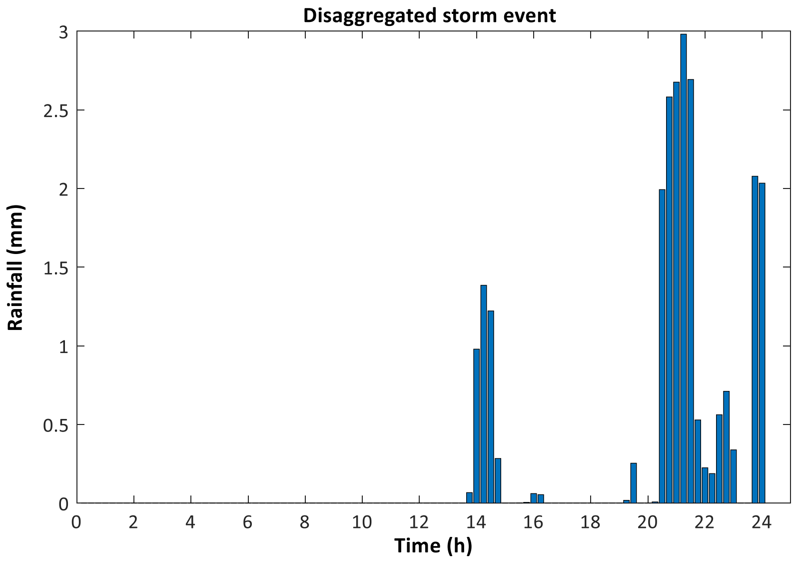

Figure 2-2 : A stochastically generated storm profile

2.5.2 Hydrologic deficit estimation

During a storm, only a portion of the total rainfall depth becomes runoff. Getting to know the mechanisms that govern the runoff ratio is really crucial for hydrologic design, while, one must approximately determine the amount of generated discharge without seriously over or underestimating it. Significant overestimations result in expensive constructions, wasting not only financial, but also natural resources, while considerable underestimations pose a serious threat to human safety, particularly when it comes to flood control.

Before reaching the ground, a part of the precipitated water may get intercepted by plants, trees, grass or other human constructions. The water that actually reaches the soil starts to fill the cavities on its surface, thus creating a layer of water, known as surface detention. The water that does not get evaporated, while staying in the surface, starts gradually infiltrating the soil.

When the infiltration water reaches the subsurface water horizon of a layer of lower hydraulic conductivity, subsurface flow occurs, during which water travels literally above that interface and reappears on the surface as a seep or spring. This type runoff is often called quick return flow because it contributes to the hydrograph during or soon after the storm.

After the initial demands of interception, infiltration and surface storage have been satisfied and/or once the rainfall rate becomes greater than the infiltration rate, surface runoff occurs (or overland flow), during which the water flows on the soil surface and through channels.

At the same time, water being precipitated directly on a flowing stream is obviously entirely considered as generated runoff.

The three aforementioned flow generating mechanisms i.e. subsurface flow, surface runoff and channel runoff, are in total referred to as direct runoff (or effective rainfall, or rainfall excess), which is actually the total amount of water consisting the flood during and until shortly after the storm event. The precipitated water that is not a part of direct runoff, consisting the hydrological deficits, gets evaporated and/or refreshes the underground aquifers, which provide the stream baseflow throughout the whole year.

During a flood, the generated runoff is significantly larger –up to two or three orders of magnitude- than the usual discharge of a river, which constitutes its baseflow.

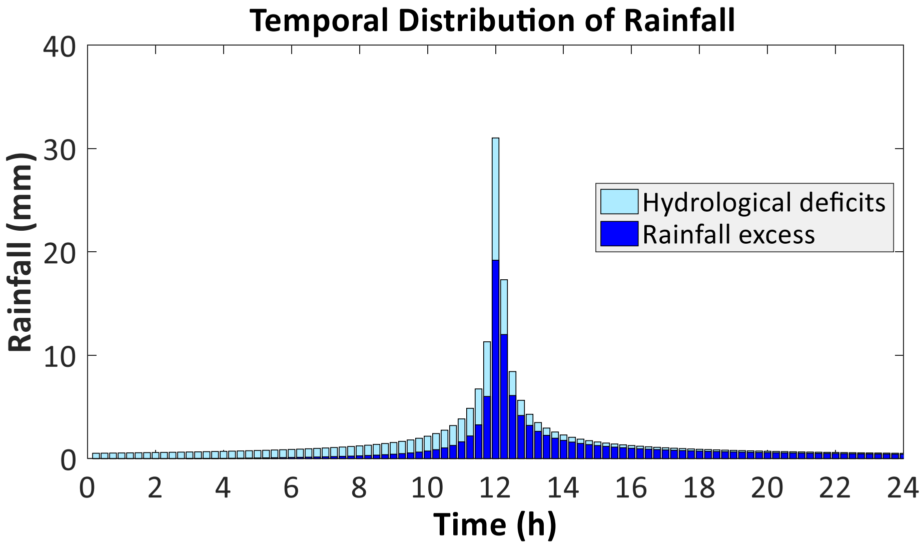

Figure 2-3 : Hydrological deficits calculated in a storm event

2.5.3 Design Flood Hydrograph estimation

The runoff generated by a storm event is propagated to the reference point of a basin by means of overland flow through the existing hydrographic network, as well as subsurface flow through the soil, until the water reaches the surface, entering a creek or stream.

In non-distributed and semi-distributed models, where no Digital Elevation Models are used, the time-area transformation of runoff to flood flow at the basin or sub-basin outlet respectively, is performed under the implementation of the unit hydrograph theory.

Another essential feature of a basin that governs the flood regime, thus being crucial for hydrological and hydraulic design is the time of concentration t_c.

2.5.3.1 Unit Hydrograph

Unit Hydrograph (from now on UH) of a given storm duration *D*, is the flood Hydrograph (i.e. without representing the baseflow) observed at the basin outlet, generated by a total rainfall excess h_e equal to 10 mm. Therefore, the area of the UH, which is, by definition equal to the flood volume *V*, will be $V=h_eA$, where *A* is the basin area. According to the classic UH theory, the UH is characteristic of a basin remaining constant in time. However, in the framework proposed in this study, the above is questioned and a varying UH is finally implemented.

The UH theory is based on the following fundamental assumptions:

- The rainfall intensity $i=h_e/D$ is is constant during the storm event and the water gets uniformly precipitated throughout the whole basin.
- In a given basin, the flood generated by any storm is independent of previous events
- Superposition: The hydrograph resulting from a given pattern of rainfall excess can be built up by superimposing the unit hydrographs due to the separate amounts of rainfall excess occurring in each unit period
- Proportionality: The ordinates of the hydrograph are proportional to the volume of rainfall excess

Consequently, for a given total amount of rainfall excess h_e, with a known temporal distribution of the storm represented in discrete time intervals Δt, the flood generating scheme using the UH of duration Δt is easily accomplished, based on the principles of superposition and proportionality. Specifically for every time interval $[t, t + \Delta t]$, a flood hydrograph is extracted, by multiplying the corresponding rainfall depth h_t to the UH ordinates. For a total storm duration D, $N=D/\Delta t$ amount of hydrographs are generated and superpositioned, in order to produce the final flood hydrograph.

2.5.3.2 Time of concentration

Time of concentration has been the subject of many studies and a tremendous amount of work has been conducted in order to detect the underlying mechanisms that determine its value. However, the accurate behavior of concentration time still remains elusive, since it is the outcome of a great number of complex processes, dependent on a wide range of different factors that concern the physiographic, hydrologic and hydraulic characteristics, as well as the urbanization degree and the –natural or artificial- drainage network of a basin.

In the literature, one can find multiple definitions regarding the time of concentration, with the most common one dictating that "*time of concentration is the travel time required for a rain drop to flow from the hydraulically most remote point of a basin to its outlet*". Consequently, for any rainfall uniformly distributed over a basin, time of concentration is the moment, after which, every inch of the basin contributes to runoff generation, thus maximizing the flow rate at the outlet, given that the duration of the storm is at least equal to t_c and that it is also uniformly spatially distributed.

In watersheds where measurements of rainfall and generated runoff are available, it is possible to determine t_c, whereas in ungauged basins there is a wide range of regional formulas that can be implemented. Such formulas are mostly empirically developed and are established upon a weak or non-existent theoretical background, thus usually under or overestimating t_c and it can absolutely not be implied that any formula could be globally applicable.

Among the abundance of regional formulas the most known and well-tested are Kirpich, Giandotti and SCS, followed by their variances and modifications.

2.5.4 Typical event-based modelling procedure

Summarizing the above, the typical event-based modeling scheme in the context of hydrologic design aiming for the estimation of the design flood hydrograph consists of the following steps:

- **Step 1:** An extreme analysis of the parent rainfall timeseries is conducted, usually the IDF curves are calculated and the UH of the basin under study, as well as the time of concentration are determined
- **Step 2:** The design storm corresponding to the desirable return period is determined, with duration larger than the time of concentration of the basin. The storm temporal evolution is also user defined.
- **Step 3:** The hydrological deficits are estimated, thus calculating the effective rainfall
- **Step 4:** Given the rainfall excess and the chosen storm profile, the flood hydrograph is calculated, based on the UH

It must be noted that the aforementioned typical scheme is only a general description of event-based modeling. There are actually a wide range of methods and tools that can alter and enrich the above. The most prominent ones will be used for establishing the classic –deterministic- approach that will be described in the following chapters.

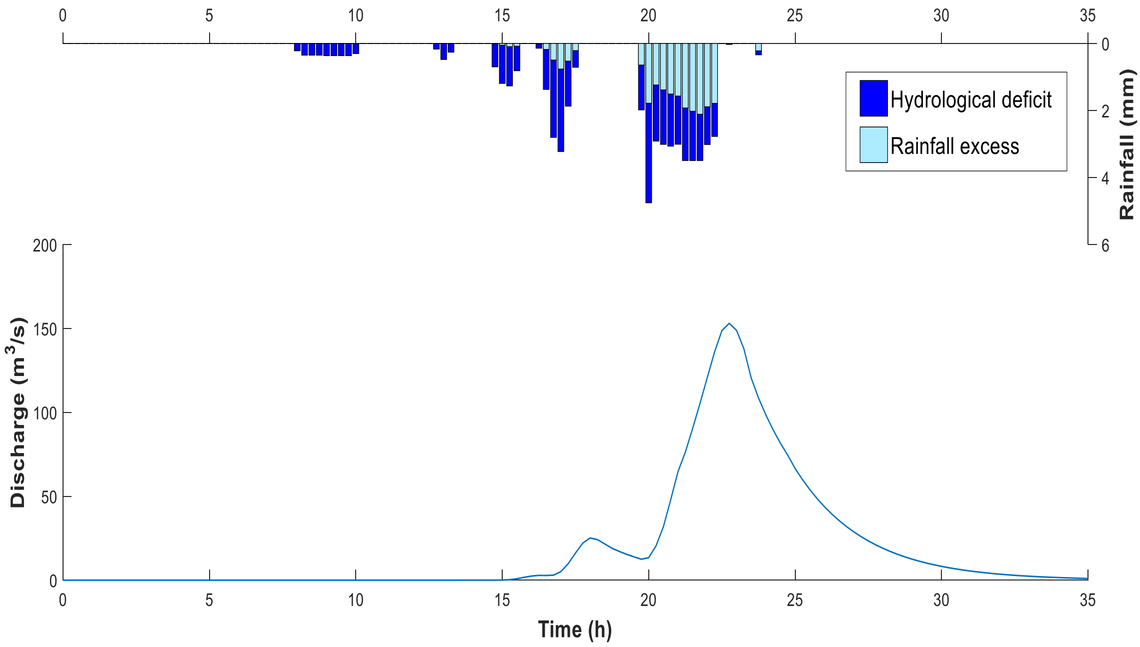

Figure 2-4 : A hyetograph and its corresponding flood hydrograph, as estimated through event- based modelling

2.6 Continuous simulation frameworks

Most of the study conducted worldwide is focused on continuous simulation. According to Boughton et al. (2003) the term 'continuous simulation' when used in flood hydrology "*refers to the estimation of losses from rainfall and the generation of streamflow by simulating the wetting and drying of a catchment at daily, hourly and occasionally sub-hourly time steps*".

An abundance of such frameworks can be found in the literature, most of which are based on the combination of a synthetic timeseries generation scheme, used for producing a synthetic rainfall timeseries, with a rainfall-runoff model, which generates the corresponding synthetic discharge timeseries. The design flood is estimated from the statistical analysis of the produced discharge timeseries.

A continuous model represents the important hydrological procedures that govern runoff generation in a sub-daily time scale (hourly or even sub-hourly), during a simulation length which depends on the desirable return period. For instance, in order to produce statistically reliable results for a required return period equal to 1 000 years, the necessary simulation length should be several thousand years.

Continuous simulation systems mainly involve a loss model to determine the runoff generated from rainfall, and a flood hydrograph model to determine the flood hydrograph at the outlet of the catchment.

More specifically, precipitation, evapotranspiration, temperature, soil infiltration and percolation through it, snowmelt, stream baseflow and runoff propagation through the basin are the most commonly represented hydrometeorological variables and procedures in continuous modeling, since these are the most essential elements governing floods. Of course there is a wide variety of continuous models ranging from more complex to simpler ones, each of them describing the aforementioned functions of a basin in a different manner. Simpler models ignore some of these procedures or conceptually link them in a way that could be described by single parameters, while more complex models fully represent them.

Continuous models are usually fully distributed, taking advantage of the Digital Elevation Models that are very helpful in estimating the spatially discretized hydrological and hydraulic response of a watershed. However, semi-distributed models are also used, especially in less complex frameworks, while, in the cases of small basins even the use of undistributed models can be suggested.

It is important to note that continuous simulation does not have any start or finish of flood events—all durations of rainfall are calculated in every flood event- and the stream baseflow is not treated discretely from the runoff generated during an event

It becomes quite evident, given the above, that continuous simulation is more realistic and takes into consideration the joint probability of precipitation, temperature and soil moisture conditions. The combination of the above, as well as the preservation of the cross-correlation structure of the hydrometeorological variables under study, provide a quite faithful representation of the actual hydrological regime of the basin in a small time-scale proper for flood engineering.

Even though such a simulation scheme, describing the most essential processes and mechanisms that determine flooding, provides more accurate and reliable results than event-based models, continuous models require massive computational power particularly if a large simulation length is desired.

Moreover, because of their complexity such frameworks need calibration, which means that a large dataset of rainfall-runoff, temperature and evapotranspiration measurements is usually required. In addition, even if such measurements exist, one cannot ignore their bias and quality.

As a result, despite the fact that continuous simulation frameworks are at the edge of science nowadays, engineers still need to further develop more simplistic and parsimonious schemes that could be implemented in basins where measurements are not available, as is the case for the vast majority of basins worldwide.

3 Materials and methods

The typical hydrologic design scheme of event-based flood modeling has already been described. In this chapter the specific methods and software used during this study are described. Some of them have been developed during the past years by teaching staff, researchers and students of the School of Civil Engineering, of National Technical University of Athens (from now on NTUA) and more specifically the Department of Water Resources and the Environment, while others are well-tested methods widely used worldwide.

3.1 Methods used

3.1.1 Intensity – Duration – Frequency curves

The most common approach for determining the design storm involves the intensity- duration –frequency (from now on IDF) curves, which are actually a mathematical relationship between rainfall intensity (or depth), desirable duration and the frequency (or return period) required for design.

The IDF curves are developed through a frequency analysis of rainfall measurements at a site. For each duration selected, the annual maximum rainfall depths are extracted from the historical timeseries and a frequency analysis is conducted.

According to Flood Directive specifications (common for entire Greece), the expression proposed by Koutsoyiannis (1998) is implemented, representing the average rainfall intensity *i* over a timescale (also referred to as duration) *d*, for a given return period *T*, as the ratio of a Generalized Pareto distribution for rainfall intensity over some threshold at any time scale to a duration function, i.e.:

$$i(d,T) = \frac{\lambda'(T^{\kappa} - \psi')}{(1 + d/\theta)^{\eta}} \qquad \textbf{Eq. (3-1)}$$

,where λ′, ψ′, κ are the scale, location and shape parameters of the Pareto distribution respectively, while η, θ are parameters related to time scales.

The methodology for estimating the aforementioned parameters is beyond the scope of this thesis and is therefore not presented. A more accurate analysis has been conducted within the framework of Deucalion project by Efstratiadis (2012) .

3.1.2 Areal Reduction Factor

Since the parameters of IDF curves are estimated based on point (i.e. station) records, it is reasonable assuming that IDFs refer to the point scale. However, hydrologic design always involves basin or sub-basin studying as a whole, and therefore mean regional values for rainfall are necessary. In the meantime, it is known that for any given return period and duration, the spatially averaged rainfall over a specific area is less than the maximum point rainfall depth. In this context, the adjustment (i.e., reduction) of point rainfall estimations (in terms of depths or intensities) is essential, in order to provide areal estimations over the corresponding catchments.

A commonly used practice in everyday engineering for the purpose of regionally adjusting point values is the employment of the so-called areal reduction factor (ARF), φ, defined as the ratio of areal to point rainfall. This factor, which is by definition less than unity, is a decreasing function of area and an increasing function of time scale. A well-tested formula, used in the context of this thesis, is the one developed by Koutsoyiannis and Xanthopoulos (1999):

$$\varphi = 1 - \frac{0{,}048A^{0{,}36-0{,}01lnA}}{d^{0.35}} \geq 0.25$$ **Eq. (3-2)**

, where φ is the dimensionless reduction factor, A is the catchment area in km^2, and d is the rainfall duration in h. The above empirical relationship has been formulated based on data capturing a wide range of durations(from 1 minute to 25 days) and catchment sizes (from 1 to 30 000 km^2). The above formula resulted to significantly reduced values of rainfall, particularly for small durations. We remark that the peak intensity corresponds to the smallest time scale, i.e. $d = \Delta t$. As the time scale increases, the rainfall intensity decreases, while the areal reduction factor, φ, increases.

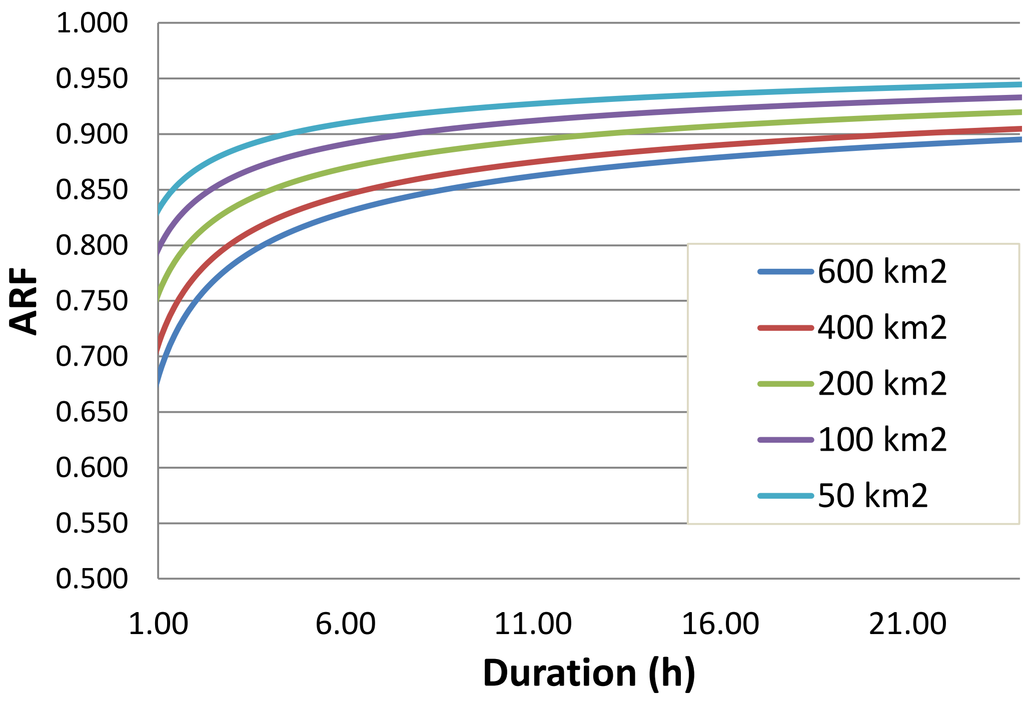

Figure 3-1 : Graph depicting ARF versus duration for different area basins

3.1.3 Alternating Block Method

The alternating block method is a method for producing a typical rainfall profile based on the Intensity –Duration –Frequency curves of a region. The hyetograph generated by this method describes the rainfall pattern at *N* time intervals of duration Δt, such as the product $N \Delta t$ equals the total storm duration, *D*. As already stated, the hyetograph synthesized by this method has the property that the maximum rainfall depth for every duration equals the depth given by the IDF curve for that duration.

The necessary procedure for creating the rainfall profile according to this method, includes the following steps:

- From the IDF relationship the average intensity for each duration Δt, $2\Delta t$, ..., $N\Delta t$, and the given return period, *T* are calculated;
- The cumulative rainfall depths are computed by multiplying all intensities by the corresponding durations;
- The partial rainfall depths (i.e. the amounts of rainfall during each additional unit of time interval Δt), are computed as differences between consecutive cumulative depth values;
- The rainfall increments are reordered into a time sequence with the maximum intensity occurring at the center of the storm, and the remaining partial depths arranged in descending order, alternately to the right and left of the central block;

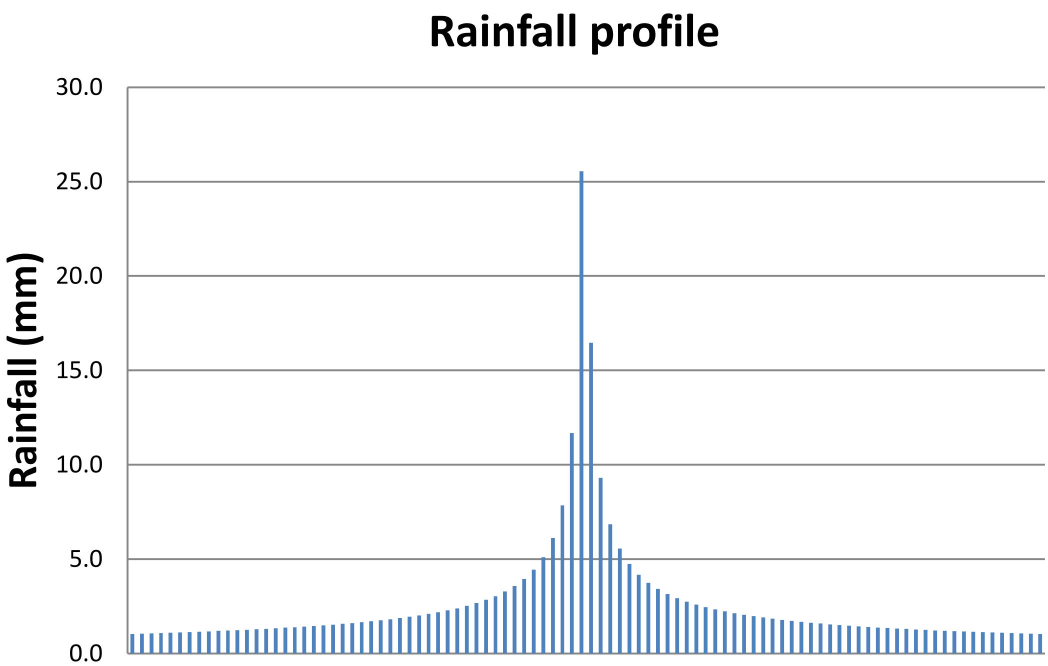

Figure 3-2 : Typical rainfall profile produced via the Alternating Blocks Method

3.1.4 Uniform distribution of rainfall

For the purpose of this thesis a simplistic approach was implemented, according to which the temporal evolution of rainfall was considered as being uniformly distributed.

Such a distribution does not preserve the statistical characteristics and the autocorrelation structure of the actual temporal evolution of rainfall in the area. As a result, this approach obviously fails to represent the rainfall regime of the region.

However, this scheme is used for academic purposes only. More specifically, a uniformly distributed rain produces smoother flood hydrographs and without any rapid peaks, serving as a "lower bound" for the purposes of our analyses.

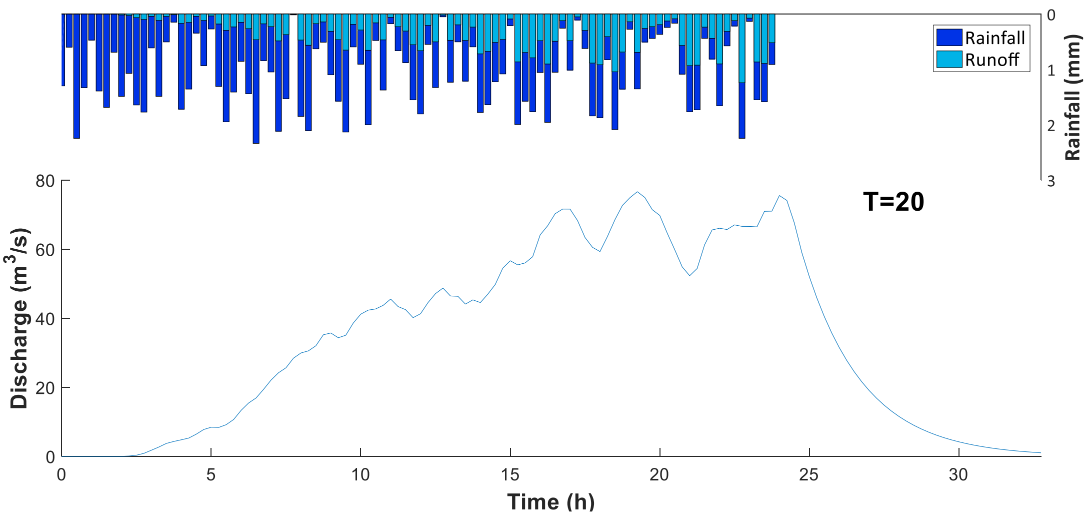

Figure 3-3 : A typical flood hydrograph generated by uniformly distributed rainfall

3.1.5 The Bartlett-Lewis model – HyetosMinute package

HyetosMinute (Kossieris, et al., 2016) is a package created to allow for the temporal stochastic simulation of rainfall process at fine time scales, i.e. from daily down to 1-minute, based on the Bartlett-Lewis Rectangular Pulse model. The software was coded in the programming language R, with some parts of code implemented in C. It operates on several modes and combinations of them (depending on data availability), such as the operational or the testing mode, and simple sequential simulation or disaggregation. In the latter case, it uses the Bartlett-Lewis model to generate rainfall events along with proven disaggregation techniques that adjust the finer scale (e.g., hourly) variables in order to obtain the given coarser scale (e.g., daily) value. The package comprises various variants of the Bartlett-Lewis model, graphical capabilities, import/export tools as well as an optimization tool for the estimation of model parameters.

The Bartlett-Lewis Rectangular Pulse (BLRP) model belongs to the general category of Poisson-cluster models that simulate rainfall events via clusters of rectangular pulses that occur in continuous time. The model is appropriate for disaggregation frameworks in which different time scales are involved, while it has the ability to reproduce the characteristics of rainfall at multiple time scales, even in cases where some of these time scales are not preserved explicitly by a fitting procedure.

The basic assumptions of the Bartlett-Lewis clustering mechanism are:

- Storm origins t_i occur in a Poisson process with rate k and each storm i is associated with a random number of cells.
- Within each storm i, the origin t_{ij} of each cell j occurs following a second Poisson process with rate b, whereas the origin of first cell coincides with the storm origin. The time intervals of successive storm and cell origins are independent and identically distributed random variables that follow an exponential distribution.
- Within each storm, the generation of cells terminates after a time span v_i following the exponential distribution with rate c. This implies that the number of cells per storm has a geometric distribution of mean $\mu_c = 1 + b/c$.
- Each cell has a duration w_{ij} following the exponential distribution with rate g.
- Each cell has an intensity x_{ij} with a specific distribution. In the simplest version of the model, the exponential distribution with mean μ_X is assumed.

The BLRP model has been further extended to allow the reproduction of high variability of rainfall profile giving a total of 7 parameters.

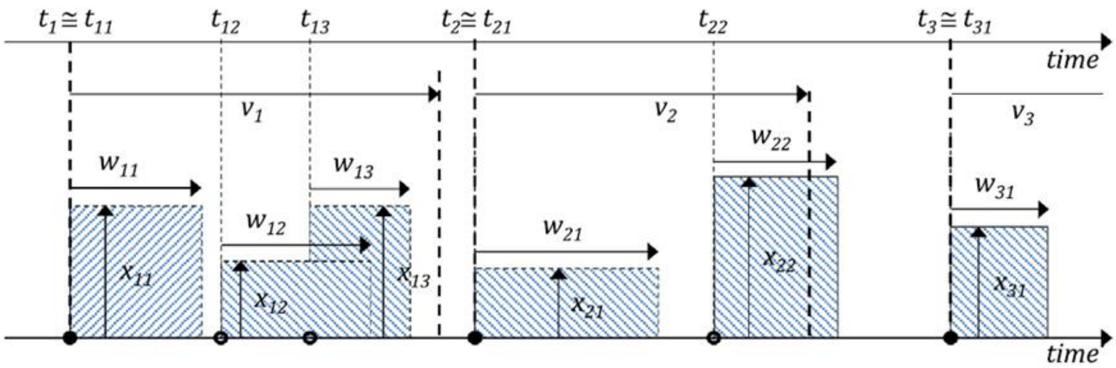

Image 3-1 : Schematic representation of the Bartlett-Lewis clustering mechanism. Filled circles denote storm origins while open circles denotes cell arrivals. (Kossieris, et al., 2016)

Different sequences (clusters) of wet days, preceded and followed by at least one dry day, can be assumed stochastically independent, hence treated as such. For each cluster of wet days, the Bartlett-Lewis model runs several times to establish, in the first phase, the appropriate wet/dry structure, and in a second phase the intensity profile of the event.

For a cluster of L wet days, the disaggregation of daily rainfall into any sub-hourly depths (e.g., 5-min) comprises the following steps:

1. The Bartlett-Lewis model generates sequences of storms and cells, at the specific sub-hourly time scale (e.g. 5-min), until a cluster of exactly L wet days, followed by one or more dry days, is obtained. In the case that the cluster has been formed successfully within an allowed number of repetitions, n_0, the process continues to Step 2. Otherwise, the cluster of L wet days is sub-divided randomly into sub-clusters with smaller lengths. In this case, the disaggregation process applied to each cluster independently, starting from the current Step 1.
2. For the formed sequence of storms and cells, the cell intensities are generated and the synthetic daily depths are calculated. The synthetic daily depths are compared to the original ones and the difference must be below the chosen limit *0.* If so, then the process continues to Step 3. Otherwise, new sequences are generated, until the difference is within the acceptable limit.
3. For the generated sequence, the rainfall depths are adjusted according to the ratio of the given daily rainfall depth and the synthetic one.
4.

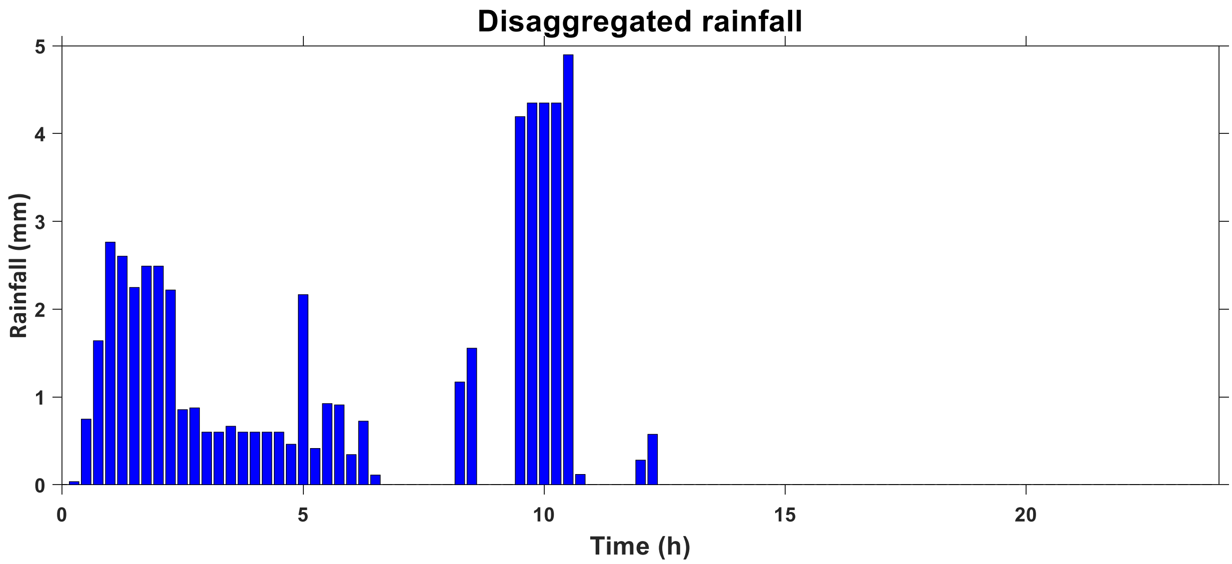

Figure 3-4 : Rainfall disaggregated with HyetosMinute

3.1.6 NRCS-CN

The NRCS-CN method (NRCS, 2004)is a well-known method for subtracting the hydrological deficits and, thus, determining the effective rainfall, developed by the National Resources Conservation Service of the United States Department of Agriculture. It has its origins in the investigations of *Mockus* (Mockus V., 1949) who realized that a curve drawn through a plot of total storm runoff versus total storm rainfall for many storms on a watershed is concave upward and shows that no runoff occurs for small storms. It was also apparent that the trend as storm size increases is for the curve to become asymptotic to a line parallel to a line of equality. Ever since, Mockus's work has been further investigated and improved based on a tremendous amount of experimental work and scientific feedback, resulting in the NRCS-CN method in its current state, which has been integrated into several rainfall-runoff models, thus being nowadays widely used in the United States and across the world.

The NRCS-CN approach is a simplistic and empirically developed hydrological model that estimates the direct surface runoff depth from a given rainfall event, based on the following assumptions:

- During an initial time interval $t_{\alpha 0}$, the entire gross rainfall is transformed to deficit (initial deficit), without producing any effective rainfall. Therefore, aftertime, the maximum effective rainfall depth cannot exceed the potential quantity P-I_a, where P is the total gross rainfall.
- The additional to I_a deficit during a very large storm event cannot exceed a maximum quantity S, called potential maximum retention.
- At any time t>$t_{\alpha 0}$, the ratios of the cumulative effective rainfall and the total minus the initial deficit to the corresponding potential quantities P-I_a and S, respectively, are equal.

More specifically:

$$P = I_a + Q + F \quad \textbf{Eq. (3-3)}$$

$$\frac{P - I_a}{Q} = \frac{S}{F} \quad \textbf{Eq. (3-4)}$$

The combination of the above yields the common form of the NRCS-CN equation:

$$Q = \begin{cases} \dfrac{(P - I_a)^2}{S + P - I_a}, & P > I_a \\ 0, & P \leq Ia \end{cases} \quad \textbf{Eq. (3-5)}$$

Where I_a is the initial abstraction, P is the cumulative rainfall depth, Q is the generated runoff and S is the potential maximum retention. In order to maintain the model's simplicity, an empirical relationship between initial abstraction and potential maximum retention is established, according to which, I_a is a proportion of S with a ratio λ, which is called initial abstraction ratio.

$$I_\alpha = \lambda S \quad \textbf{Eq. (3-6)}$$

Eq. (3-5)was justified on the basis of measurements in watersheds less than 10 acres in size. Despite the measurements showed that there was a considerable scatter in the data, Soil Conservation Service (now known as NRCS) reported that 50% of the data points lay within the limits $0.095 \leq \lambda \leq 0.38$, which led to adopting a standard value of $\lambda = 0.2$. However, several studies encompassing various geographical locations have documented values varying in the range $0.0 \leq \lambda \leq 0.3$, while other studies have demonstrated that the initial abstraction is neither constant in time nor in space, since it varies from storm to storm as well as from watershed to watershed (Ponce, et al., 1996). In particular, recent analyses of flood events in a number of catchments in Greece and Cyprus have estimated λ values less than 0.05 (Efstratiadis, 2014), which is also approved by other researchers (Baltas, et al., 2007).

For further convenience, parameter *S* was transformed into a new dimensionless parameter (curve number *CN*) that represents the average soil type, cover and hydrological conditions.

$$CN = \frac{25400}{S + 254}$$ **Eq. (3-7)**

, where *S* is expressed in mm.

CN varies from 0 to 100 and embraces the physiographic characteristics of the basin that are associated with runoff generation into a single value. In the context of flood studies, CN is determined from lookup tables using two inputs, namely soil types and land use/land cover.

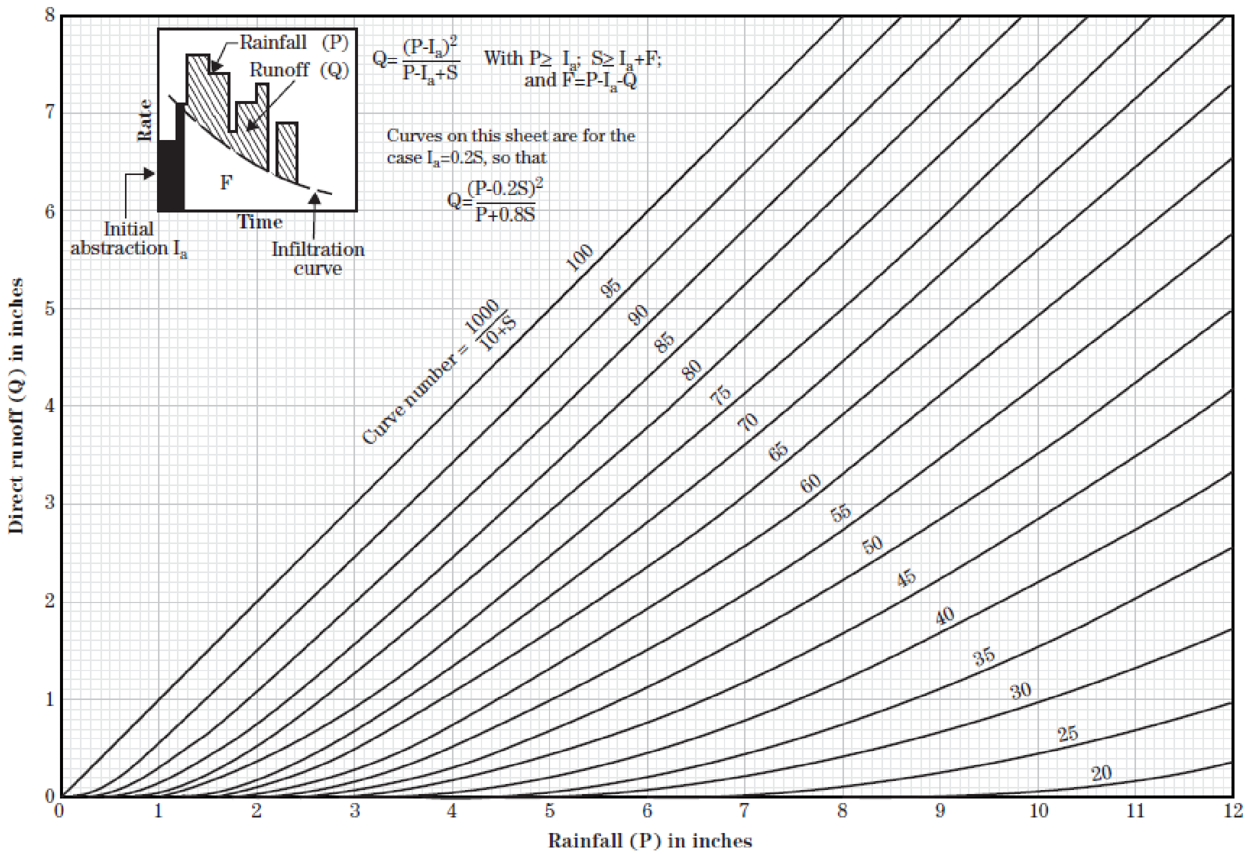

Figure 3-5 : Graphical solution of NRCS-CN method (NRCS, 2004)

The curve number embraces the physiographic characteristics of the basin that are associated with runoff generation into a single value. In the context of flood studies, CN is determined from lookup tables using two inputs, namely soil types and Land Use/Land Cover (LU/LC).

Primarily, NRCS identifies four hydrological soil groups, based on their infiltration and transpiration rates. Soils falling in group A, B, C and D exhibit high, moderate, low, and very low rates of infiltration, respectively, thus CN increases as the soil type changes from A to D. The classification is made as follows:

Group A: Typical soil types are sand, loamy sand or sandy loam types of soils. Such soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sands or gravels and have a high rate of water transmission.

Group B: Typical soil types are silt loam or loam. Such soils have a moderate infiltration rate when thoroughly wetted and consists chiefly or moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.

Group C: Typical soil type is sandy clay loam. Such soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine structure.

Group D: Typical soil types are clay loam, silty clay loam, sandy clay, silty clay or clay. This group has the highest runoff potential. Such soils have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface and shallow soils over nearly impervious material.

Moreover, NRCS classifies three major classes of LU/LC as urban, cultivated, and woods and forests. These classes were further categorized into various subclasses, on the basis of land treatment practices such as contoured, terraced, straight row, bare, etc. The following table, shows CN values across all these different types of soils and LU/LC classes as proposed by Chow et al (1988).

Table 3-1: CN values for selected agricultural, suburban and urban land uses for different soil groups (Chow, et al., 1988)

Land Use Description		**Hydrologic Soil Group**			
		A	**B**	**C**	**D**
Cultivated Land:	without conservation treatment	72	81	88	91
	with conservation treatment	62	71	78	81
Pasture or range land:	poor condition	68	79	86	89
	good condition	39	61	74	80
Meadow:	good condition	30	58	71	78
Wood or forest land:	thin stand, poor cover, no mulch	45	66	77	83
	good cover	25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc.:					
good condition: grass cover on 75% or more of the area		39	61	74	80
fair condition: grass cover on 50% to 75% of the area		49	69	79	84
Commercial and business areas (85% impervious)		89	92	94	95
Industrial districts (72% impervious)		81	88	91	93
Residential:					
Average lot size	Average % impervious				
1/8 acre or less	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84

Paved parking lots, roofs, driveways, etc	98	98	98	98
Streets and roads: paved with curbs and storm sewers gravel dirt	 98 76 72	 98 85 82	 98 89 87	 98 91 89

For a watershed including various land uses on different soil types, each assigned with a different CN value, a composite CN can be calculated. More precisely, a weighted arithmetic mean of CN values is estimated, according the area covered by every land use, under the expression:

$$CN = \sum_{1}^{n} \left(\frac{A_i}{A} CN_i \right) \quad \textbf{Eq. (3-8)}$$

, where A_i is the area of each unit *I*, *A* is the whole area of the region and CN_i is the CN value assigned to every unit of the area. A typical example of a map depicting assigned CN values to an area is attached below.

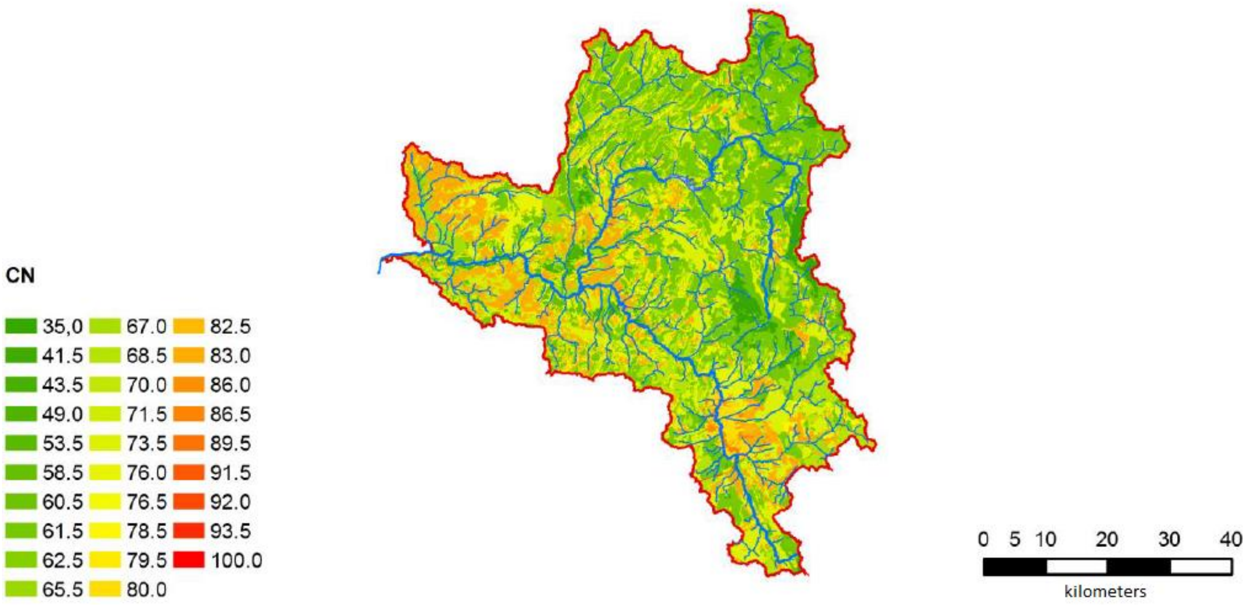

Image 3-2: Map depicting assigned CN values in Alfeios river basin, in West Peloponnese, Greece (YPAPEN, 2017)

It is well known, based on engineering experience through past decades, that the amount of generated runoff is highly dependent on the soil moisture conditions; more water gets infiltrated in a dry soil, thus producing less discharge, while a wet soil generates more runoff, since voids are filled with water and are incapable of abstracting more.

In terms of CN values, one realizes that a single CN which remains constant through time cannot faithfully describe the properties of a watershed. Hence, the CN values described above correspond to normal Antecedent Moisture Conditions (AMC II) and in the literature two additional AMC types can be found. In particular, AMC I refers to dry conditions, while AMC III refers to wet conditions, which in the absence of more complex calibrated soil moisture accounting models, are linked to the five-day antecedent precipitation (P_5), as listed below:

- AMC I: Dry conditions that correspond to P_5 less than 13 mm;
- AMC II: Normal conditions that correspond to P_5 ranging from 13 to 38 mm;
- AMC III: Wet conditions that correspond to P_5 more than 38 mm.

Curve Numbers of AMC I & III are linked to Curve Number of AMC II through the following relationships:

AMC I : $$CN_I = \frac{0.42CN_{II}}{1-0.0058CN_{II}}$$ **Eq. (3-9)**

AMC II: $$CN_{III} = \frac{2.3CN_{II}}{1+0.013CN_{II}}$$ **Eq. (3-10)**

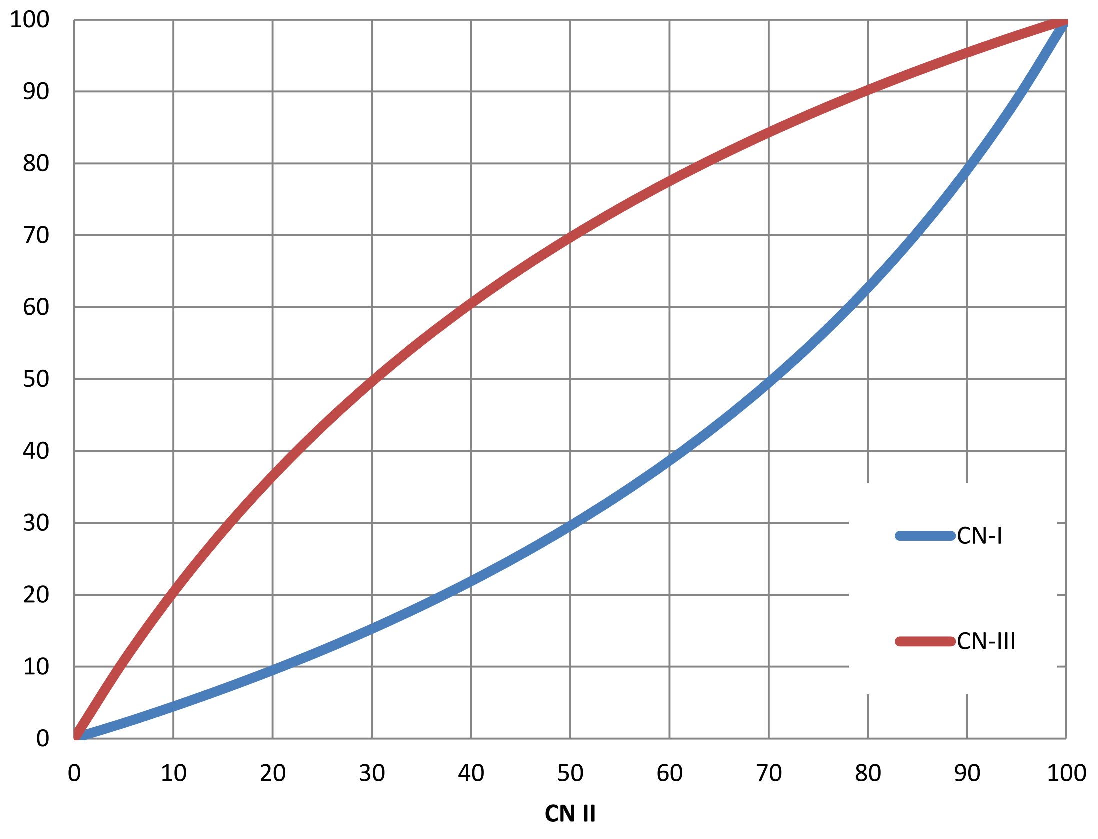

Figure 3-6 : Graph of CN II values versus CN I and CN III

In the literature it is suggested that the above dry, wet, and normal situations statistically correspond, respectively, to 90%, 10%, and 50% cumulative probability of the exceedance of runoff depth for a given rainfall (Hjelmfelt, et al., 1982).

The NRCS-CN method is applicable not only to the total rainfall depth, but can also be used at any time during a storm event, to its corresponding cumulative rainfall depth, thus allowing us to obtain the temporal evolution of the hydrological deficits and the associated surface runoff against time, as long as the temporal distribution of the storm is provided.

3.1.7 The Annie-model

The Annie-model is a lumped conceptual scheme representing the key hydrological processes of a river basin, in order to transform rainfall to actual evapotranspiration, surface runoff and underground losses to the sea. The model was initially developed by researchers and students of School of Civil Engineering of National Technical University of Athens, in the context of a wider simulation of water-energy fluxes for a remote Greek island, Astypalaia. This work was conducted in the framework of the European Geosciences Union's 2017 General Assembly, where the students of School of Civil Engineering participated. The model was tested among the analysis conducted for this thesis and the complete work regarding the Astypalaia Island can be found under Papoulakos et al. (2017). The name of the model was inspired by the name of one of the developers, namely, Theano (Annie) Iliopoulou.

In particular, the basin is vertically subdivided into two storage elements that represent the temporary interception processes on the ground and the soil moisture accounting across the saturated zone. Model inputsa are the daily precipitation, *P*, and daily potential evapotranspiration, *PET*. All fluxes are expressed in units of water depth (i.e. mm) per unit time (day), while storages are expressed in terms of water depths.

The proposed model is a simple and relatively parsimonious scheme, which uses three parameters. The model parameters are: (a) the interception capacity, I_a (mm), representing a rainfall threshold for runoff generation, (b) the soil capacity K (mm), and (c) the fraction *a* of the soil storage that outflows to the sea, which acts as a recession parameter. Initial condition of the model is the soil storage at the start of the simulation.

It is known that each model perceives reality in a different manner. As a result, we should definitely note that while the model incorporates the well-tested NRCS-CN – as presented below- method in order to calculate the generated runoff, the parameter I_a is not identical to the initial abstraction found in NRCS-CN, even though it remains strongly correlated to it.

Moreover, the initial condition of the model may be considered negligible (if the simulation starts at the end of the dry period) or expressed as fraction of K. Either way, initial conditions play absolutely no role in determining the outcome of continuous modeling where simulation lengths are big. In fact, after some time needed for adjustment, the model is fully independent of initial conditions. According to Berthet et al. (2009), a 1-year simulation run is an adequate warm-up period, after which it can be safely assumed that the model state obtained is fully independent of the initial conditions.

For given inputs and parameter values the simulation procedure is the following:

First, provided that P exceeds the interception capacity, I_a, the well-known NRCS-CN method for estimating overland flow is applied:

$$Q_{overland} = (P - I_a)^2/(P - I_a + K - W_0) \quad \textbf{Eq. (3-11)}$$

,where W_0 is the soil moisture level at the beginning of the time interval expressed in mm and, consequently, $K – W_0$ represents the so-called maximum potential soil retention (i.e. the empty space of the soil tank).

The remaining rainfall is by priority used for fulfilling the PET demand, thus generating direct ET i.e.:

$$ET_{direct} = \min(PET, P - Q_{overland}) \quad \textbf{Eq. (3-12)}$$

,while the remainder enters the soil moisture tank, thus increasing its current storage, i.e.:

$$W = W_0 + P - Q_{overland} - ET_{direct} \quad \textbf{Eq. (3-13)}$$

The actual evapotranspiration losses through the soil are then estimated via the conceptual formula:

$$ET_{soil} = (PET - ET_{direct})\tanh\left({W}/{K}\right) \quad \textbf{Eq. (3-14)}$$

Next, a fraction a of the current storage moves vertically, thus generating underground losses to the sea, i.e.:

$$L = a(W - ET_{soil}) \quad \textbf{Eq. (3-15)}$$

Finally, if soil moisture level, W, remains larger than the overall capacity of the soil, K, saturation excess runoff is produced by means of spill, i.e.:

$$Q_{excess} = \max(0, W - ET_{soil} - L - K) \quad \textbf{Eq. (3-16)}$$

The total runoff is the sum of the overland and excess flow, while the total actual ET is the sum of the direct and soil ET i.e.:

$$Q_{total} = Q_{overland} + Q_{excess} \qquad \textbf{Eq. (3-17)}$$

At the end of the time step, the final soil moisture storage, serving as the initial condition for the nex time step, is calculated:

$$W_0 = W - ET_{soil} - L - Q_{excess} \qquad \textbf{Eq. (3-18)}$$

In this point it should be highlighted that the need for developing a scheme where the NRCS-CN method could be coupled with a soil moisture accounting procedure that would also incorporate the scenario during which the soil is fully saturated, hence all excess water getting transformed into runoff, has also being successfully addressed by Michel et al. (2005) who proposed such a model. Later on, some important attempts in order to further develop the model proposed by Michel were made, the most prominent being the works of Singh et al. (2015) and Duran-Barroso et al. (2016).

The aforementioned attempts treat soil moisture accounting and runoff generation as two separate procedures. The water content is determined by a separate model of the engineer's choice and given that the generated runoff can be estimated using these models.

On the contrary, we tried to incorporate runoff generation and soil moisture accounting into one integrated scheme, where the processes of runoff generation, direct evapotranspiration, soil infiltration, evapotranspiration through soil, percolation through it and finally overspill, can actually interact. Even though these procedures may actually coincide in time, the prioritization we have established seems quit legit conceptually.

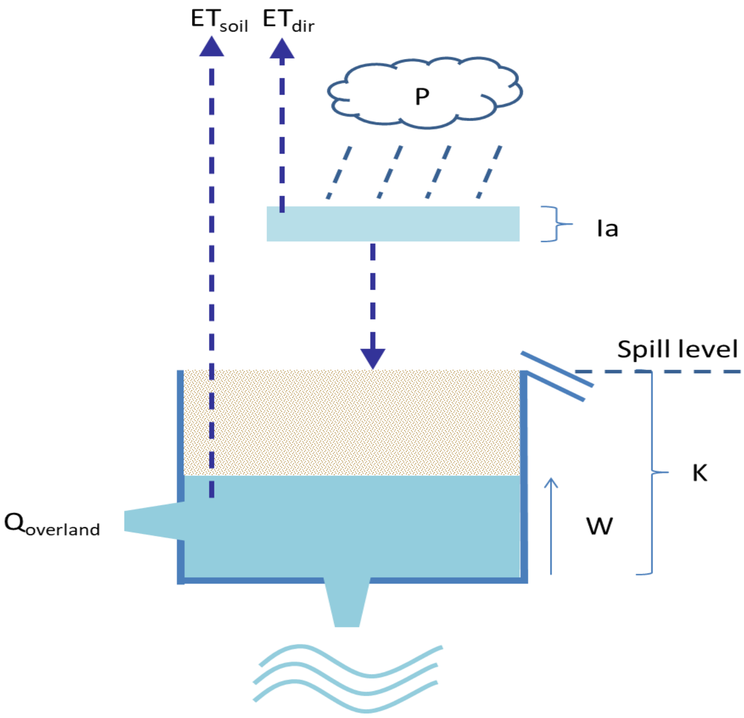

Figure 3-7 : Figure representing Annie-model

3.1.8 Time of concentration: The Giandotti formula

In Greece and Cyprus, it is found that the most suitable method for estimating the time of concentration in a watershed is the Giandotti formula, while other well-known methods, such as the Kirpich or the SCS formulas, significantly underestimate it, resulting in tremendously overestimated peak discharges (up to 100%) (Koutsoyiannis, et al., 2014).

According to the Giandotti formula, the time of concentration t_g is:

$$t_g = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{\Delta H}} \qquad \textbf{Eq. (3-19)}$$

, where A is the area of the watershed, L is the length of the main stream and ΔH is the difference between the mean elevation of the basin and the elevation of its outlet.

3.1.9 Variation of time of concentration according to runoff

Antoniadi (Antoniadi, 2016), according to the findings within the literature that t_c varies inversely with discharge and thus the rainfall intensity, established a methodology for quantifying the variability of the travel time across the longest flow path of a watershed against the rainfall excess produced during a storm. “*The methodology is based on the kinematic approach employed within typical design of urban sewer networks, which employs a semi-distributed schematization of the hydrological system and takes advantage of the rational method for the estimation of design peak discharge of each network element. The input data are derived through digital elevation model processing on geographic information systems.”* (Antoniadi, 2016)

Antoniadi, based on the suggestions of McCuen, examined not only the flow in the main stream, but also the overland flow. More specifically, McCuen (McCuen, 2009) stated that velocities of runoff at the watershed are lower than those on the principal flowpath, since the time of concentration, when determined by observations was generally longer, than estimations made using the principal flowpath. Consequently, in Antoniadi’s work, the maximum flow route, along which the flood is propagated, includes also the overland flow. In turn, the peak discharge is calculated, from upstream to downstream, using the rational formula and considering a temporally and spatially uniform distribution of effective rainfall.

Antoniadi suggests that travel time and rainfall excess depth, P, are strongly correlated and their relationship is approximated as a power type of the form $P=at_c^{-b}$, where a,b>0. Such a relationship dictates that an asymptotic behavior, which practically means that for extreme hydrological events the time of concentration converges to a minimum value. A very intriguing finding is that the widely used Giandotti formula, results in a time of concentration corresponding to a total rainfall excess depth of only 2 mm.

3.1.10 Parametric Synthetic Unit Hydrograph

Usually a wide range of existing Synthetic UH approaches are implemented, where the UH shape is based upon the physiographic characteristics of a basin. Such an approach was developed by the Itia Research Team, NTUA, in the framework of Deucalion project (Koutsoyiannis, et al., 2014), where a Parametric Synthetic UH (from now on PSUH) was proposed, based on the time of concentration t_c.

More specifically the time to peak t_p and base time t_b of the PSUH of a storm duration d, are calculated by the following formulas and are finally rounded up in order to be expressed as integer multiples of d:

$$t_p = d/2 + \beta t_c \qquad \textbf{Eq. (3-20)}$$

$$t_b = d + \gamma t_c \qquad \textbf{Eq. (3-21)}$$

, where β, γ are parameters with 0<β<1 and γ≥1.

Since t_p, t_b, β, γ are determined, the ordinates of the PSUH are calculated. In particular:

$$u(t) = q_p\, t/t_p \quad ,t \le t_p$$ **Eq. (3-22)**

$$u(t) = q_p \exp(-k\, t/t_b) \quad ,t \ge t_p$$ **Eq. (3-23)**

, where q_p is the peak discharge, and k is such, so as $u(t_b)=q_0=0.001A$, where A is the area of the basin. Consequently:

$$k = -\ln(q_0/q_p)$$ **Eq. (3-24)**

The determination of peak discharge q_p has no analytical solution and requires instead a repetitive arithmetic procedure, based on the continuity equation, which dictates that the flood volume calculated by the area of the PSUH should be equal to the total flood volume V generated by the storm, where $V=h_eA$.

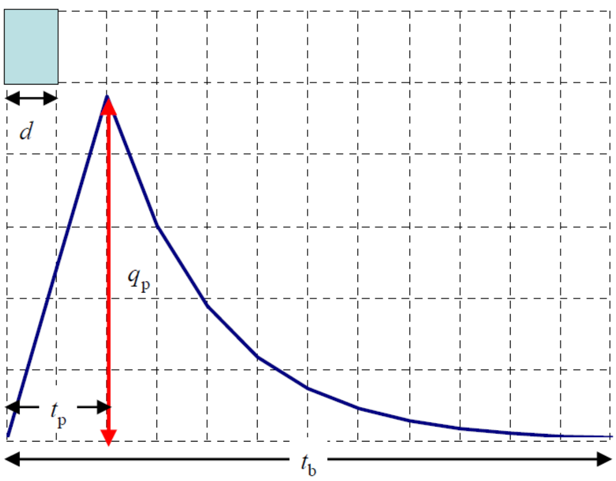

Figure 3-8: Parametric Synthetic Unit Hydrograph of a storm duration *d* (Koutsoyiannis, et al., 2014)

3.1.11 Monte Carlo Simulation

"*The first thoughts and attempts I made to practice [the Monte Carlo Method] were suggested by a question which occurred to me in 1946 as I was convalescing from an illness and playing solitaires. The question was what are the chances that a Canfield solitaire laid out with 52 cards will come out successfully? After spending a lot of time trying to estimate them by pure combinatorial calculations, I wondered whether a more practical method than "abstract thinking" might not be to lay it out say one hundred times and simply observe and count the number of successful plays. This was already possible to envisage with the beginning of the new era of fast computers, and I immediately thought of problems of neutron* *diffusion and other questions of mathematical physics, and more generally how to change processes described by certain differential equations into an equivalent form interpretable as a succession of random operations. Later [in 1946], I described the idea to John von Neumann, and we began to plan actual calculations."*(Ulam, recounting his inspiration)

In flood engineering all hydrological models involve the use of parameters as inputs, whose estimation is quite a difficult and highly uncertain procedure. In the meantime, the true nature of hydrometeorological variables is also inherently uncertain and the mechanisms governing flood generation are yet elusive. In this context it is absolutely necessary to highlight that recognizing uncertainty as an essential attribute of a system, especially when it comes to systems regarding hydrometeorological variables and natural hazards, is the only way to fully take into account and reproduce in a process-based framework the dynamics of hydrological systems (Montanari, et al., 2012).

Given the above, a Monte Carlo simulation model will be used in this study, in order to deal with the uncertainties regarding flood engineering.

The Monte Carlo simulation is a stochastic simulation model applied in all fields of science, from economy to nuclear physics. It is based on computational algorithms that rely on repeated random sampling to obtain numerical results. The essential idea that this model has established is using randomness in order to treat for the inherent uncertainty of model parameters, thus probabilistically approaching the solution to a problem and defining its confidence intervals.

The modern version of the Markov Chain Monte Carlo method was invented in the late 1940s by Stanislaw Ulam, while he was working on nuclear weapons projects at the Los Alamos National Laboratory. Being secret, the work of von Neumann and Ulam required a code name. A colleague of von Neumann and Ulam, Nicholas Metropolis, suggested using the name Monte Carlo, which refers to the Monte Carlo Casino in Monaco where Ulam's uncle would borrow money from relatives to gamble.

The benefits of using such a stochastic simulation framework, as well as the inconsistencies of everyday engineering practices that make the establishment and implementation of such schemes a necessity, will be documented in the following chapters

3.1.12 GEV-max theoretical distribution

The application of a specific distribution function depends not only on probability theory and the examination of the particular sample, but also the general hydrologic experience, which in our case dictates that the GEV-max distribution function is suitable. Of course, even such a choice could be further questioned and analyzed, since tremendous work has been conducted on the subject of fitting distributions, especially when it comes to extremes, where fitting a distribution with a heavier or lighter tail may have a great impact on the result. However such an analysis is beyond the scope of this thesis –one can find more under the study based on a large global dataset conducted by Papalexiou (2013).

The General distribution of Extreme Values (GEV maxima) is a generalization of the extreme values which combines the three types of Extreme Values (EVI & II & III) distributions. The distribution has three parameters; the shape parameter κ, the scale parameter λ and the location parameter ψ. When κ→0, the function corresponds to the EVI, whereas for κ>0 and ψ=1/κ we can obtain the EVII.

The relation of the GEV-max distribution is the following:

$$F(x) = e^{-[1+\kappa\left(\frac{x}{\lambda}-\psi\right)]^{-1/\kappa}}$$ **Eq. (3-25)**

The above relation holds for values of κ different than 0. When κ→0 the relation of EVI distribution function is used:

$$F(x) = e^{-e^{-\frac{x}{\lambda}+\psi}}$$ **Eq. (3-26)**

The inverse distribution function is expressed as follows:

$$x(u) = \lambda\psi + \frac{\lambda}{\kappa}[(-lnu)^{-\kappa} - 1] \quad , for\ \kappa \neq 0$$ **Eq. (3-27)**

$$x(u) = \lambda\psi - \lambda \ln(-lnu) \quad , for\ \kappa = 0$$ **Eq. (3-28)**

The parameters κ, λ, ψ of the distribution are estimated via the Moments and L-moments method for the purposes of this study.

3.1.12.1Moments method

The Moments method has been proposed by Koutsoyiannis (2004) and the parameters are estimated according to the following relationships:

$$\kappa = \frac{1}{3} - \frac{1}{0.31 + 0.91C_s + \sqrt{(0.91C_s)^2 + 1.8}}$$ **Eq. (3-29)**

$$c_1 = \kappa/\sqrt{\Gamma(1-2\kappa) - \Gamma^2(1-\kappa)}$$ **Eq. (3-30)**

$$\lambda = c_1\sigma$$ **Eq. (3-31)**

$$c_3 = [\Gamma(1-\kappa) - 1]/\kappa$$ **Eq. (3-32)**

$$\psi = \mu/\lambda - c_3$$ **Eq. (3-33)**

, where σ is the standard deviation, μ is the average and C_s is the skewness of the sample.

3.1.12.2 L-moments method

L-moments obtain their name from their construction as linear combinations of order statistics. Unlike product moments, the sampling properties for L-moments statistics are nearly unbiased -even though there are indications of bias regarding record length (Papalexiou, et al., 2013)- and are near normally distributed.

The L-moments are calculated as follows:

$$L_1 = \beta_0 \qquad \textbf{Eq. (3-34)}$$

$$L_2 = 2\beta_1 - \beta_0 \qquad \textbf{Eq. (3-35)}$$

$$L_3 = 6\beta_2 - 6\beta_1 + \beta_0 \qquad \textbf{Eq. (3-36)}$$

, where

$$\beta_0 = n^{-1} \sum_{j=1}^{n} x_j \qquad \textbf{Eq. (3-37)}$$

$$\beta_1 = n^{-1} \sum_{j=2}^{n} x_j \, [(j-1)/(n-1)] \qquad \textbf{Eq. (3-38)}$$

$$\beta_2 = n^{-1} \sum_{j=3}^{n} x_j \, [(j-1)(j-2)/(n-1)(n-2] \qquad \textbf{Eq. (3-39)}$$

, where the data $x_{1:n}$ are ranked from ascending order from 1 to n.

Having estimated the L-moments the parameters of the distribution as calculated as follows:

$$\kappa = 7.8c - 1.43c^2, \quad where \; c = \frac{ln2}{ln3} - \frac{2}{3 + \tau_3} \qquad \textbf{Eq. (3-40)}$$

$$\lambda = \frac{\kappa L_2}{\Gamma(1-\kappa)(2^{\kappa} - 1)} \qquad \textbf{Eq. (3-41)}$$

$$\psi = \frac{L_1}{\lambda} - \frac{\Gamma(1-\kappa) - 1}{\kappa} \qquad \textbf{Eq. (3-42)}$$

,where the coefficient of skewness τ_3 is defined as:

$$\tau_3 = \frac{L_3}{L_2}$$ **Eq. (3-43)**

In the analysis conducted in this thesis, the GEV-max distribution fitted to the data is depicted with the use of a transformation method. The aim of this transformation is the better depiction of the sample and of the distribution functions, as much linearly as possible, thus making it easier for the user to examine each graph, especially regarding higher return periods that normally have an asymptotic behavior.

The Gumbel paper is used for projection in this thesis.

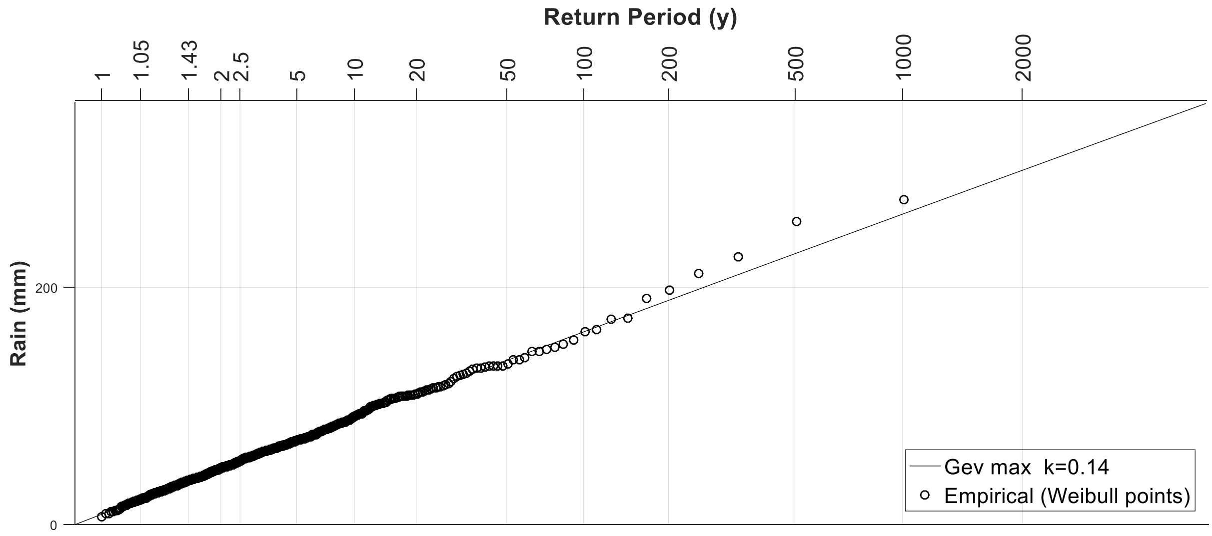

Figure 3-9 : GEV-max distribution fitted to a hydrometeorological variable using the L-moments method

3.2 Software used

3.2.1 Castalia: A stochastic scheme for synthetic timeseries generation

Hydrological processes, such as precipitation, are extremely complicated and difficult to reproduce. Upon generating a synthetic timeseries, one must not only preserve the basic marginal statistics and the joint second order statistics of the variable under investigation, but also several characteristic properties that are closely related to their temporal evolution, particularly:

a) Long-Term Persistence
   Long-Term Persistence (from now on LTP) was discovered by Hurst (Hurst, 1951) while studying Nile's discharge timeseries, within the framework of designing the Aswan High Dam. Hurst found out that wet years tend to cluster into multi-year wet periods and dry years tend to cluster into multi-year drought periods hence called "Hurst phenomenon". Since then, LTP behavior has been identified in a wide range of hydroclimatic and geophysical processes, including precipitation.
   LTP is quantified by the Hurst coefficient, H ($0<H<1$), defining a timeseries as persistent, for values greater than 0.5 or anti-persistent otherwise. A persistent timeseries exhibits a positive autocorrelation coefficient, while being negative in anti-persistent timeseries.
   As shown by (Iliopoulou, et al., 2016) there are notable indications of weak LRD in the annual rainfall globally, with a mean H of 0.58. For the 95% confidence interval, H values fluctuate between 0.4 and 0.8.
b) Periodicity
   Periodicity in precipitation appears at the sub-annual scale (e.g., monthly) and is due to the Earth motion
c) Intermittency
   Intermittency (often referred to as probability dry) of a hydroclimatic variable, such as precipitation, is the probability that the variable has a value equal to zero, within a time interval. Intermittency is an essential characteristic of the rainfall regime in a region, thus being very important for hydrological design. Intermittency also results in significant variability and high positive skewness of rainfall, which are difficult to reproduce by most generators.

Castalia (Efstratiadis, et al., 2014) is free software, developed and supported by the research team ITIA, in the National Technical University of Athens, that can faithfully generate a synthetic timeseries, whilst preserving the essential statistical characteristics of a hydroclimatic variable. The initial version of the program for monthly stochastic simulations was implemented as component of a decision support system for the management of the water supply system of Athens. The current version also supports daily simulations, through a three-level multivariate disaggregation scheme. For intermediate time scales (e.g., seasonal, weekly), synthetic data is straightforwardly provided by aggregating from the closest finer scale.

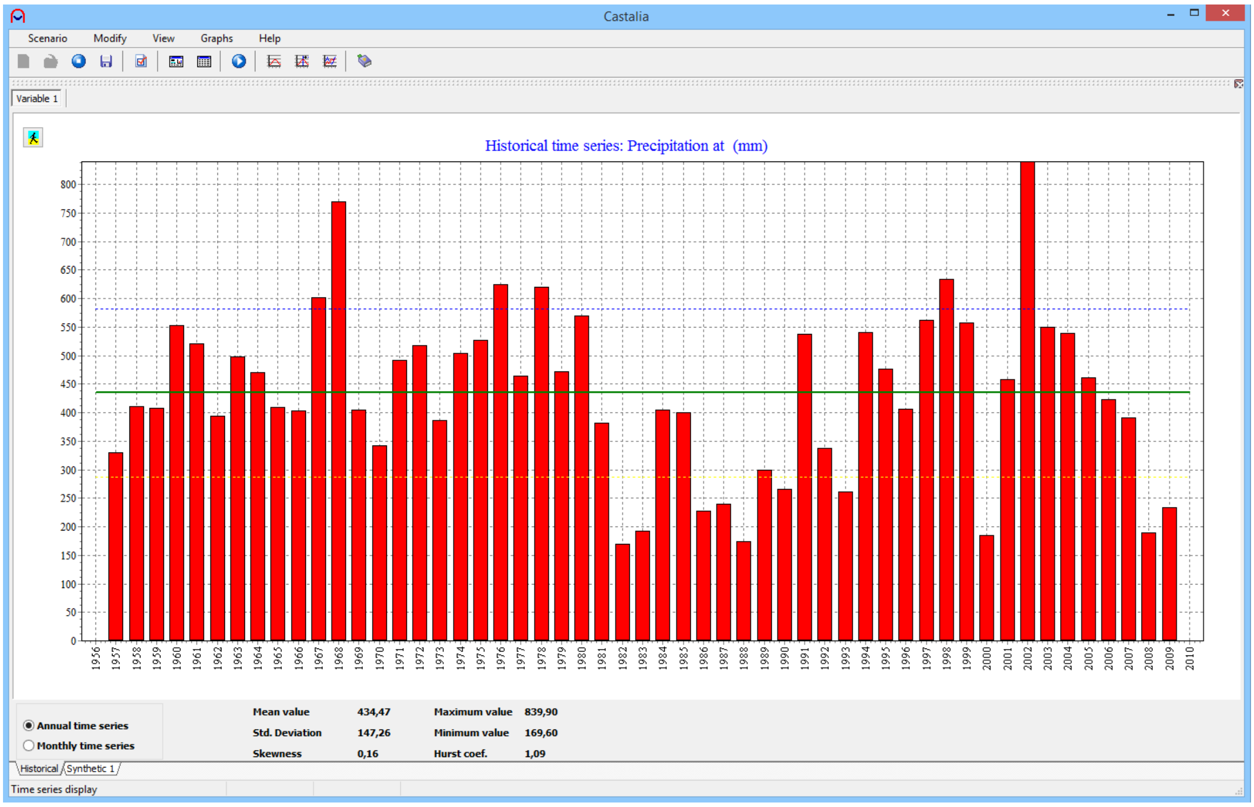

Image 3-3: The environment of Castalia Software

The generating procedure implemented in Castalia preserves the marginal statistics up to third order (mean, standard deviation, skewness) as well as the joint second order statistics, particularly the first order autocorrelations and lag zero crosscorrelations, at the daily, monthly and annual time scales. These are generally assumed as the essential statistical properties that should be preserved by stochastic hydrological models (Matalas, et al., 1976). Furthermore, the model reproduces LTP behavior at the annual and over-annual scales, the periodicity at the monthly scale, and the intermittency at the daily scale (in terms of preserving the probability dry of the process of interest).

The necessary model parameters are estimated by the statistical characteristics of the parent historical data. First, at the annual time scale, LTP is reproduced through a Symmetric Moving Average scheme that implements a user-defined autocovariance function, which enables the representation of a wide range of stochastic structures, i.e. from ARMA-type, which are characterized by short term persistence, to Hurst-Kolmogorov behavior, with as high long-term persistence as needed. For the monthly and daily time scales, auxiliary time series are initially provided by a multivariate periodic autoregression scheme. Daily values are generated through a gamma distribution.A disaggregation procedure is employed to establish statistical consistency between the three temporal scales; first the monthly series are adjusted to the known annual ones and then the daily time series are adjusted to the disaggregated monthly data, using a multivariate coupling scheme.

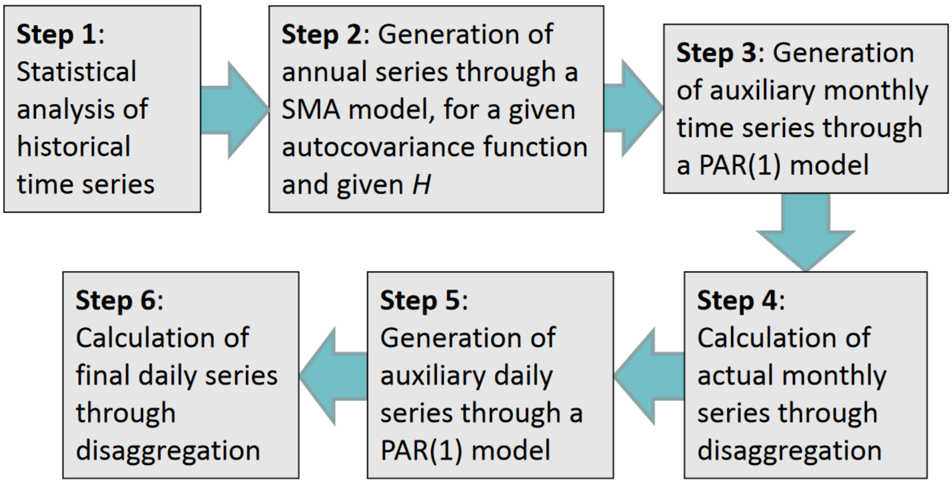

Figure 3-10: Flowchart of computational procedures of Castalia (Venediki, et al., 2013)

The length of simulations may reach several thousands of years, in order to represent statistically rare events and evaluate extreme probabilities.

Considering that Castalia software was initially developed for the simulation of rainfall and runoff, it is confirmed that this program can further conduct stochastic simulations of a wide spectrum of hydrometeorological variables. In particular, it can be used for multivariate stochastic simulation of hydrometeorological processes such as sunshine duration, wind speed and precipitation on annual, monthly and daily scale.

Castalia can be downloaded at http://www.itia.ntua.gr/en/softinfo/2/.

3.2.2 R software

Since HyetosMinute was coded in R programming language, the R software was used for the purpose of this thesis.

R is an open source programming language and software environment for statistical computing and graphics that is supported by the R Foundation for Statistical Computing. The R language is widely used all over the world among statisticians and data miners for developing statistical software and data analysis, while its popularity has significantly increased over the past years.

The R Foundation is a not for profit organization working in the public interest. It has been founded by the members of the R Development Core Team in order to:

- Provide support for the R project and other innovations in statistical computing.
- Provide a reference point for individuals, institutions or commercial enterprises that want to support or interact with the R development community.
- Hold and administer the copyright of R software and documentation.

R is an official part of the Free Software Foundation's GNU project, and the R Foundation has similar goals to other open source software foundations like the Apache Foundation or the GNOME Foundation.

Among the goals of the R Foundation are the support of continued development of R, the exploration of new methodology, teaching and training of statistical computing and the organization of meetings and conferences with a statistical computing orientation.

R is a GNU package. The source code for the R software environment is written primarily in C, Fortran, and R. R is freely available under the GNU General Public License, and pre-compiled binary versions are provided for various operating systems.

The fact that R is open source has allowed the community to rapidly burst and expand, creating a very vivid community-based scheme, where one can find innumerable functions and packages that are user-developed and, of course, available for free.

In this context, the capabilities of R have extended through user-created packages, which allow specialized statistical techniques, graphical devices, import/export capabilities, reporting tools etc. These packages are developed primarily in R, and sometimes in Java, C, C++, and Fortran.

In the meantime, even though R is an open source project supported by the community developing it, there are some companies providing commercial support and/or professionally developed extensions for their customers.

More information can be found at the official site, where the software is also available for downloading: https://www.r-project.org/

3.2.3 Rstudio

While R has a command line interface, there are several graphical front-ends available. Among them, Rstudio has a prominent position.

More specifically, RStudio is a free and open-source Integrated Development Environment (IDE) for R, written in the C++ programming language –it is also available in commercial editions. It includes a console, syntax-highlighting editor that supports direct code execution, as well as tools for plotting, history, debugging and workspace management, which constitute a more user-friendly and easy environment (as depicted in the following image) for programming in R.

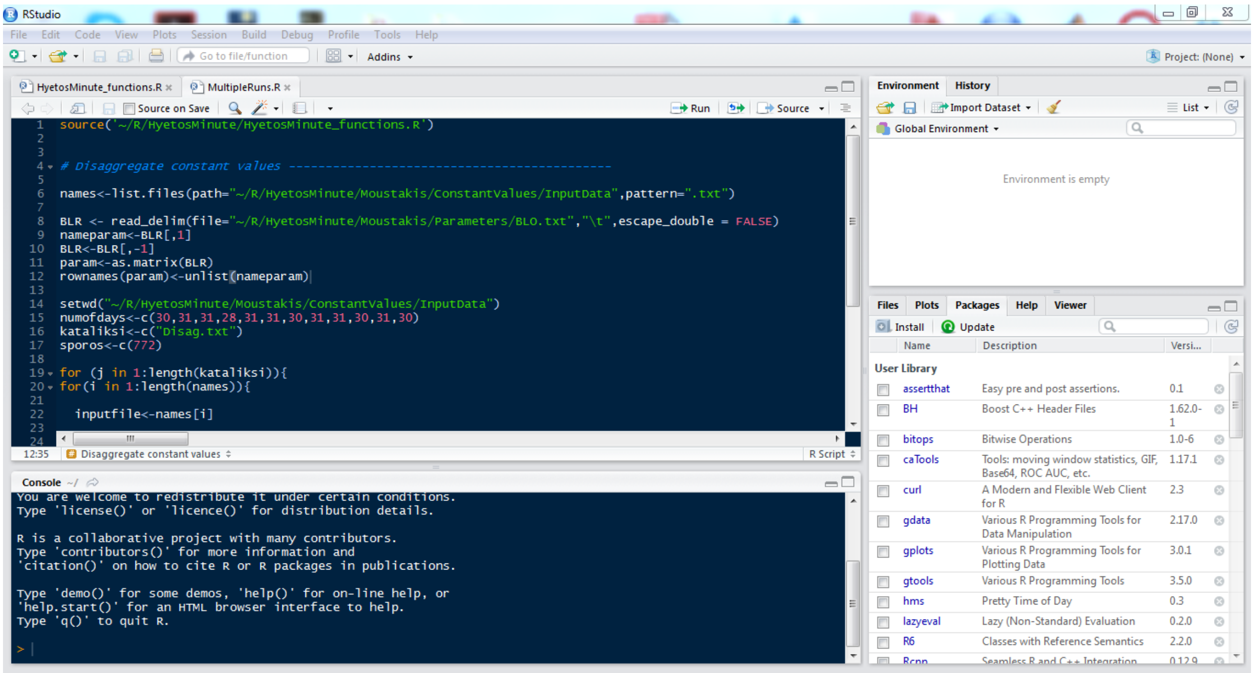

Image 3-4 : Rstudio Environment, while running HyetosMinute package

3.2.4 Matlab®

MATLAB® (MATrix LABoratory) is a multi-paradigm numerical computing environment and fourth-generation programming language, developed by MathWorks. While MATLAB® was initially designed for numerical linear algebra – as its full name indicates-, it has become a tool for all types of mathematical calculations in the meantime. Nowadays, MATLAB® is applied in nearly every field of scientific or technical calculations. In the academic branch there is almost no university where MATLAB® is not available. Of course, even though the use of MATLAB® has significantly expanded to almost all branches and fields of science, numerous linear algebra calculations are still available, such as inversion of matrices, eigenvalue and eigenvector determination, which can be applied to perform various tasks, for example, the solution of systems of linear equations.

In general, with MATLAB® all types of mathematical operations can be performed. One may perform basic statistics, numerical differentiation and integration, evaluate all types of functions, solve dynamical systems and partial differential equations, estimate parameters and so forth. MATLAB® is also suitable for matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python. All this is part of core MATLAB®, a collection of basic mathematical tools.

The user-friendly graphical interface, the quite detailed "help" section, where every function is analytically described along with practical examples, the abundance of useful tools , such as tools aimed for developing, managing and even error tracing, that consist of clusters of functions focused on solving specific complex problems and, finally, the well-developed

Graphical User Interface, which enables 2-D, 3-D high-end depiction of data in graphs, image editing and animation, are only some of the key features of MATLAB® that make it a state of the art tool for programming.

Given the above, and also taking into consideration the feedback procedure, where the community was successfully widely and thoroughly engaged in the process of further improving and developing the software, it is no wonder why MATLAB® has become in our days an excellent choice for solving problems in every scientific field.

The basic parts of the MATLAB® environment (as depicted in the following image) are the Command Window, where commands can be entered and immediately called, the Workspace, where the results of all calculations, as well as the variables created are shown, the "Current Folder" section, where one can access the project folders and files, the Editor, where scripts can be written and edited and the Toolbar, where all tools, toolboxes, function libraries, help sections, settings and actions can be found.

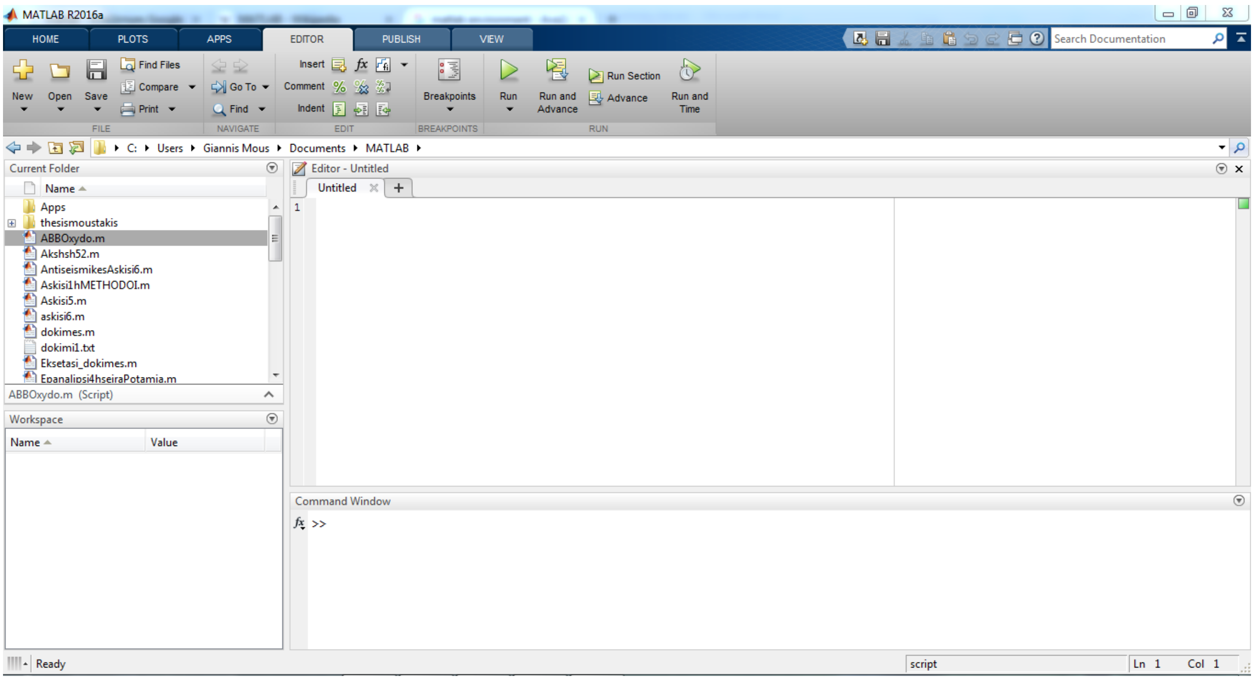

Image 3-5 : MATLAB® working environment

More information on MATLAB® can be found on the official site of the software developers, MathWorks: http://www.mathworks.com

3.2.5 Hydrognomon software

Hydrognomon is an independent software application for Microsoft Windows developed for time series processing by researchers of Department of Water Resources and the Environment of the School of Civil Engineering, NTUA.

The most important functions provided by the system, are among others the following:

- Time series transformation to one with a regular time step
- Aggregation to coarser temporal scales
- Standard consistency tests like homogeneity test, extreme values test and time consistency test
- Linear regression between time series, multiple regression, organic correlation and autocorrelation
- Estimation of missing values by means of linear regression, option to introduce a random term in order to maintain the statistical properties. Time series expansion
- Evapotranspiration and potential evapotranspiration calculation using analytical or semi – empirical methods.
- Time series sampling, statistical property estimation, statistical parameter adjustment, statistical predictions, statistical tests and confidence interval estimation. (This subsystem is known as Pythia.)
- Time series analysis of special rainfalls – Intensity - Duration - Frequency (IDF) curve estimation by means of consistent methodologies. (This subsystem is known as Omvros.).

The software, with the information and documentation necessary is available for free under www.hydrognomon.org.

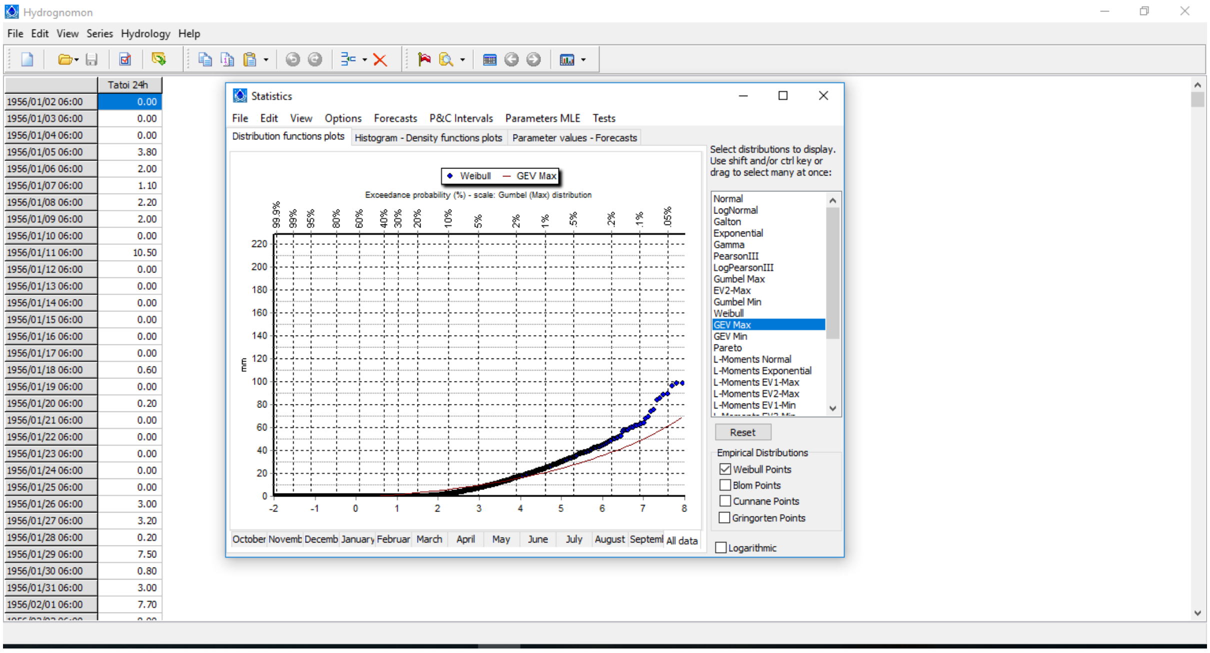

Image 3-6 : The environment of Hydrognomon software

4 Typical deterministic framework

The scope of this chapter is to describe the steps of a typical modeling framework regarding ungauged basins, used in everyday flood engineering all over the world. In turn, the theoretical inconsistencies of such a scheme, which make the establishment of a stochastic approach a necessity, are documented.

4.1 Framework description

The typical deterministic framework for flood engineering in ungauged basins, implemented in everyday practice all over the world, involves the most common tools and methods for every step of hydrological design. Of course, the framework described below, can be found in many different versions, with each step varying, since, as already stated, a wide range of widely used techniques are available in the literature. However, the core of such schemes, which is the implementation of event-based models only approached through a deterministic prism, remains the same to all possible variations, being the main reason why all of them remain highly inconsistent.

For the purpose of this thesis, we only list one typical framework among many, which consists of the following steps:

Step 1: The physiographic characteristics of the watershed are determined and the basic parameters are estimated. In particular the time of concentration is estimated through the Giandotti formula, the Unit Hydrograph is shaped and a CN value is assigned to the area.

Step 2: The point IDF curves are extracted from an appropriate hyrdrometeorological station. If no station exists in the basin under study, then the rainfall measurements of a nearby watershed may be used, as long as the climatic conditions of the measured region are similar and comparable to our case. In most cases, this task has already been carried through and the IDF curves can be found in the literature, under the responsible Ministry or local authority.

Step 3: The desirable return period is determined, according to the magnitude and the importance of the project under study. Sometimes this is dictated by the responsible authorities and if not, one can rely on suggestions based on engineering experience. It should be noted that when it comes to flood control, the choice also depends on the importance of the regions under threat. For instance, a flood control work such as a dyke protecting a cultural heritage site is of high importance and its design would require a larger return period, than any other structure protecting an ordinary asset, located on the flood plain of a river.

Step 4: For the determined return period and for the desirable duration, the design storm is produced via the alternating blocks method and the point rainfall is adjusted with the ARF. The duration is preferred to be at least equal to the time of concentration. A common choice is a duration of 24 hours.

Step 5: According to the importance of the flood control work, an Antecedent Moisture Condition (wet, normal or dry) is selected, thus the corresponding CN value is obtained.

Step 6: The hydrological deficits are estimated via the NRCS-CN method, thus calculating the rainfall excess.

Step 7: Given the temporal evolution of rainfall excess and the PSUH, the design flood hydrograph is estimated.

4.2 Documenting the inconsistencies

As already stated, hydrology is a relatively newly established filed of science which is mainly semi-empirically developed. In the meantime, hydrometeorological procedures have an inherently uncertain nature, thus making hydrological modeling a difficult task.

In the context of highlighting and documenting the inconsistencies of everyday flood engineering one could list hundreds of misconceptions of bigger or smaller importance, pointed out in the literature. Ranging from the errors in the measurements and the uncertainties even of the IDF curves, to the arbitrary choices of Unit Hydrographs or even the flaws of rainfall excess estimation, the spectrum of misconceptions and inconsistencies in hydrology is quite broad.

Obviously it is the hydrologist's duty to highlight those flaws and, fortunately, the work conducted in the purpose of further developing and improving our tools and methods has been tremendous, over the past decades.

However, in the framework of developing a simple and parsimonious modeling framework, suitable and easily applicable in everyday engineering, especially for ungauged basins, only the major inconsistencies are to be addressed.

After all, the true motivation of our thesis is our strong belief that significant improvement in approaching flood engineering can be made, without the implementation of complex, multi-parametric, fully distributed continuous models being necessary. It is known that the complexity of such schemes possibly imposes great uncertainty to a system, especially when measurements and available data cannot be fully trusted, or are not provided at all, while the use of such models in ungauged basins, that are calibrated in other "similar' regions, is not a wise choice.

To summarize, in this chapter only the most significant inconsistencies will be documented. For the remedy of these inconsistencies the stochastic simulation framework, which will be discussed in the following chapters, will be proposed.

4.2.1 Antecedent Moisture Conditions

It is well-known that rainfall events of equal cumulative depths do not necessarily produce the same flood hydrograph neither in terms of the temporal evolution, nor regarding the total amount of flood volume. On the one hand, the shape of the flood hydrograph is obviously governed by a wide variety of factors, the most important of which being the temporal evolution of the storm and the time of concentration, which control the hydraulic response of a watershed.

On the other hand, when it comes to comparing the total amount of generated runoff between storms of equal cumulative depth or even of identical rainfall profiles, differences are mostly due to the varying initial moisture conditions at the beginning of the event, which have been found to be of significant importance.

As already stated in the chapter describing runoff generation mechanisms, direct runoff occurs only after the initial demands of interception, infiltration and surface storage have been satisfied and/or once the rainfall rate becomes greater than the infiltration rate. Consequently more wet soils have a small capacity of withholding water, thus generating more runoff compared to a dry earth layer, where the soil voids are still empty and more water can be abstracted and percolated through them. Moreover, while the voids of an initially dry soil get more and more saturated during a storm, direct runoff gets generated more intensively.

As a result, it is quite evident, that the hydrological cycle and more particularly the sequences of dry and wet periods fully govern the hydrological response of a watershed, in terms of determining the initial soil moisture conditions.

In the literature the importance of estimating the initial soil moisture conditions in event-based modeling has been excessively highlighted. According to Berthet et al. (2009) who conducted a study on 178 watersheds where measurements were available, event-based strategies can be efficiently used for operational flood forecasting purposes, since the loss in performance compared to a continuous model is not substantial and the difference is actually not significant.

However, as Berthet (2009) states event-based models can only be reliable in cases where the analysis is conducted on a short pre-forecast period, since only under this scheme the initial soil moisture conditions can be properly estimated.

In any other case, where the initial soil moisture conditions are arbitrarily chosen – as happens in everyday engineering practice- the generated flood can be significantly over or underestimated, because of the heavy dependence of event- based models on soil moisture levels. In addition, since hydrological processes and the models representing them are essentially nonlinear, even a slight change on initial conditions could lead to significantly heavier discrepancies in the results.

It has been found that "*catchments with a more uniform hydrological response are less sensitive to antecedent soil water conditions. Thus, the role of the initial soil water content is more important in catchments where the presence of plant cover increases the spatial variability of soil characteristics and produces a mixture of runoff and run-on sites that are determined by soil wetness*" (Castillo, et al., 2003)

Especially in regions where flash floods are the prominent type of flooding, characterized by rather rapid peaks, the initial conditions have been found to be really crucial in peak discharge estimations.

As already stated, in the context of taking into account the variability of soil moisture conditions, the NRCS-CN method provides for three different Antecedent Moisture Condition (AMC) types assigning a CN value for each of them, according to the CN determined for the normal AMC type.

Given the above, when designing with event-based models, the arbitrary choice of an AMC type is inevitable. A common practice in everyday flood engineering practice, in the context of overengineering, is selecting the AMC III type (i.e. wet condition), thus usually resulting in overestimating peak discharges and consequently oversizing flood control works.

Such an approach, not only overestimates the flows in the basin outlet, but also ignores the actual rainfall regime of a region, since it does not take into consideration the autocorrelation structure of rainfall (i.e. the tendency of wet days occurring in clusters and the correlation between the sequential rainfall depths), nor the intermittency which are really crucial for determining the soil moisture levels. For instance, according to Curtis et al. (2013) who studied the rainfall regime of Phoenix, AZ-US, dry conditions can be safely assumed and are recommended for design.

To summarize, one of the main inconsistencies that make event-based modeling unreliable is the lack of a procedure that could adequately determine the initial conditions at the beginning of a storm, based on the rainfall regime of the region, rather than using recipes or arbitrary setting conditions in the context of overengineering.

4.2.2 Alternating Blocks Method

The hyetographs synthesized by the Alternative Blocks Method have the property that the maximum rainfall depth for every duration equals the depth given by the IDF curve for that duration. This actually means that the probability of rainfall observed for various durations within a storm is constant.

Even though this method produces a unique hyetograph requiring no additional assumptions and depends on local data, instead of transferring rainfall profiles from other regions, which make it an easily applicable and not complex tool for everyday engineering practices, it has some significant shortcomings.

The ABM method is not capable of providing any probability measure for the unique and unusual arrangement it implies and the basic assumptions upon which it is established are not the outcome of observed rainfall profiles or any physical reasoning. Of course, it is highly inconsistent to assume that the frequency of occurrence of rainfall observed for various durations within a storm is the same for all durations. (Koutsoyiannis, 1994)

Moreover, this method was established in the purpose of creating rainfall profiles that tend to maximize the resulting flood hydrographs and completely ignores the actual autocorrelation structure of rainfall, dictating the rainfall regime of the region.

Consequently, it becomes quite clear that not only is such a storm temporal evolution highly unrealistic, nearly impossible and physically un-based, but that it also results in a significant increase in joint uncertainty of the final outcome, when other sources of uncertainty are also taken into consideration.

In the meantime, the fact that this technique leads to the generation of a unique hyetograph prevents us from conducting a probability-based study of the peak discharge. Such an approach could only be done in the context of a stochastic disaggregation scheme where the production of a series of probable profiles – and, of course, realistic -, instead of a single event, would be possible.

4.2.3 Time of concentration

As mentioned, the true nature of the time of concentration and the mechanisms governing it remain elusive, thus rendering time of concentration a quite ambiguous concept in hydrology. For ungauged basins, t_c is usually estimated by empirical formulas which are based on the basin response time as function of its lumped geomorphological characteristics, such as the Giandotti formula previously described.

Apart from the underlying uncertainty in determining the physiographic, geomorphologic and geometric characteristics of the watershed and its drainage network, the most misleading hypothesis is treating time of concentration as a constant.

According to Grimaldi (2012), who studied observed rainfall-runoff events in four watersheds, there is an inherent variability in time of concentration, changing through events, leading to a variability up to 500% in its estimation, if only a partial event set is available. Moreover, the study indicates that it is not possible to accurately predict even the lower and upper bounds to t_c, due to discrepancies and misconceptions in definitions and estimation procedures. However, Grimaldi found out that the variability of time of concentration could be described as a function of the return period and peak flows.

4.2.4 Exceedance probability

Taking into consideration the above, it becomes quite clear that rainfall is not the sole factor that governs runoff generation. The temporal evolution of a storm, the initial soil moisture conditions and the time of concentration play also a significant role in shaping the hydrological and hydraulic response of a watershed. These factors have a significant variability and it is important to consistently represent them, rather than arbitrarily determining them and/or treating them as constant characteristics of the basin, despite their true nature.

The deterministic framework actually assumes that the return period of the peak discharge observed at the outlet of the basin equals the return period of the cumulative rainfall depth of the storm (i.e. The 100-year storm generates the 100-year discharge). However, in reality this is absolutely not the case. The specific temporal evolution, initial conditions and time of concentration during an episode, have also separate exceedance probabilities that ought to be accounted for.

As a result, the deterministic approach presented in this chapter, which is widely used in everyday engineering across the globe, is severely lacking in terms of estimating the joint probability of a flood hydrograph occurring.

5 Pseudo-continuous stochastic simulation framework

As already stated, the typical deterministic event-based approaches used in everyday flood engineering are established upon some major misconceptions. Such inconsistencies inevitably affect the outcome of any analysis and need to be addressed, since more accurate and realistic predictions are required for properly protecting human lives, property and the environment against floods.

The engineers across the globe should be using consistent modeling schemes, avoiding physically un-based assumptions that usually involve highly unrealistic design storms and even more unlikely flood hydrographs. Even though in the context of overengineering such modeling frameworks, combined with oversizing during construction – for example construction of free boards that add capacity beyond design - could be proved adequate in terms of safety, such engineering practices should not be implemented in an era when humanity must desperately struggle to preserve resources.

On the contrary, the use of more complex continuous models is not an easy task, especially in ungauged basins. Such models need calibration based on adequate rainfall-runoff measurements which are usually unavailable or unreliable. A common practice which involves implementing model parameters in a watershed which have been estimated in different regions through calibration should be avoided, since physical and hydrologic similarity are actually elusive and widely misconceived concepts.

In this chapter, a pseudo-continuous stochastic simulation framework will be proposed, in order to address the aforementioned inconsistencies.

At first the theoretical and technical issues regarding our choice will be documented and, in turn, the proposed framework will be described in detail.

Before continuing in the presentation and documentation of the proposed framework, we should note that here, the term “ungauged” is related to watersheds that lack discharge observations, while it is assumed that common Digital Elevation Models (DEMs) with a standard resolution, soil-use digital support (i.e. CORINE 2000) and rainfall raingauge data are accessible.

5.1 Towards a pseudo-continuous stochastic model

5.1.1 Addressing the inconsistencies of event-based modeling: Continuous simulation

As already stated, the tremendous advance in the field of hydrology, combined with the significant technological progress over the past years have paved the way for the development of continuous models, that remedy most flaws and inconsistencies of event-based modeling.

Continuous simulation represents the basic procedures of a basin, governing runoff generation in a continuous time, usually at a sub-daily time scale and, as Blazkova and Beven (2009) indicate "*This approach has the potential to represent properly the way in which rainfall characteristics, antecedent conditions in a catchment, and flood runoff generation processes change with time and severity of an event*".

The inputs of such models are usually -depending on the complexity of the model- stochastically generated and cross-correlated synthetic rainfall, temperature and potential evapotranspiration timeseries at the desirable timescale and length, as well as parameters regarding the hydraulic response and the physiographic characteristics of a watershed.

The main benefit of continuous simulation in contrast with event-based modeling is that, since continuous models fully represent the basic processes of a basin, they treat for the estimation of the initial conditions at the start of every storm event, which are of great importance in determining the amount of generated runoff.

The initial soil moisture conditions are estimated via a Soil Moisture Accounting (SMA) procedure that continuously calculates the level of saturation in the soil, with the use of simpler or more complex hydrological models that account for evapotranspiration, soil infiltration and percolation through it.

In the previous chapters it was highlighted that since soil moisture plays the most important role in runoff generation, storms of larger cumulative depths do not necessarily generate greater floods. For instance a 100-year storm occurring under completely dry conditions could possibly generate a smaller flood than a 50-year storm occurring when the soil is saturated. As a result, in a continuous simulation framework with an underlying SMA procedure, the arbitrary assumption, commonly found in event-based modeling, that the storm of a given return period generates flood of equal return period is no longer made.

The generation of rainfall timeseries in temporal scales finer than daily is usually the case in such models, which means that the actual rainfall regime of a region is taken fully into consideration and, in addition, any arbitrary choices between recipes regarding the temporal evolution of storms are avoided.

Furthermore, such models also allow for accounting for the variability of some important intrinsic model parameters such as the time of concentration. As already mentioned, time of concentration has been found not to be a constant of a catchment, but rather a varying characteristic, mostly linked to the amount of generated runoff.

As a result, besides from faithfully representing the hydrologic response of a watershed, continuous models can also provide for estimating its ever-changing hydraulic response.

To summarize, it becomes quite evident that continuous simulation frameworks can be the solution to the flaws, misconceptions and inconsistencies that are found in common deterministic frameworks, implemented in everyday engineering practice.

5.1.2 The shortcomings of continuous simulation frameworks

A faithful representation of the essential hydrological processes governing flood generation and the mechanisms related to flood propagation in a watershed is not an easy task. Continuous models are more complex and require more parameters as inputs, than event-based ones. Hence, apart from establishing a consistent conceptual framework that can include the above and at the same time take into consideration the specific characteristics of a basin, we also need to calibrate these models.

The establishment of a conceptual model and the choice of the essential processes that should be represented demands a deep knowledge of the hydrological regime, soil layers, as well as the hydraulic characteristics of the basin under study.

It is quite obvious that we cannot implement the same model in a mountainous steep watershed with nearly impermeable soils and in one with a smoother topography, significant snowmelt and karstic soil formations filled with cavities. In the first case the hydraulic response of the watershed is immediate and flash floods are most likely to occur. In the latter one, subsurface flow through the karstic cavities, which reaches the outlet of the basin after a significant time lag and the process of snowmelt play an important role, extending floods in time beyond the end of a storm. As a result, soil formations and snowmelt play a key role in shaping the hydraulic response of the watershed and absolutely need to be represented in the model. However, such a model would be of no use for the first basin.

Luckily, in the literature a substantial number of different continuous models can be found, with each and every one of them being targeted towards different types of watersheds and needs and, even though one could choose an appropriate model the problem of calibration still remains.

In ungauged basins, where there are no recorded rainfall-runoff data available, model calibration is impossible. Hence, it is common to use models with parameters calibrated upon other, "similar" catchments and regional recipes found to be appropriate for them. However, even if this sounds a good engineering practice, there is actually a major inconsistency underlying the sole concept of "similarity".

It is yet uncharted under which premise, criteria and metrics two areas should be considered as similar. Even though significant scientific work has been conducted in the context of determining similarity, collapsing the vast complexity of environmental factors that define the hydrologic regime of natural catchments into a few parsimonious numbers, distributions or models, remains a difficult and ambiguous task and further improvement is still needed (Wagener, et al., 2007). According to (Oudin, et al., 2010) the physical descriptors classically used in regionalization studies ignore a number of important features of hydrological behavior and new descriptors should be developed to characterize the role of underground catchment properties, process dynamics at the catchment scale, or catchment heterogeneity and complexity.

Scientists nowadays also focus on determining how many measurements are needed in order to calibrate an ungauged basin if gauges are to be installed. As Seibert et al. (2009) suggest, a hydrologically intelligent choice of only a small number of observations –instead of regularly or randomly choosing measurement times- could perform well. However, such approaches still need further investigation.

While in ungauged basins the use of continuous models is quite ambiguous and uncertain, in gauged basins, where rainfall-runoff measurements are available, thus enabling calibration, problems still occur, having to do with the uncertainty and quality of the provided data.

Since floods are, by definition, rare phenomena that occur without advance warning, it is important that the monitoring systems operate automatically, measuring at preset time intervals and logging the data that must be accessible remotely via telecommunication systems.

However this is not always the case. Usually flow gauges are primarily designed for measuring low flow conditions. As a result, during extreme floods they might get inundated. According to Escarameia et al. (2001) when a flow measurement structure or rated channel section is drowned or out-flanked by a flood flow the uncertainties associated with flow measurement rise from the 3% for in-bank flow to 30% or more for out-of-bank flood conditions and estimates of flood frequency may be significantly biased.

Moreover, historical records can be significantly biased even if the measurements are correct. For example rapid changes in the built environment during a historically recorded flood, such as a dyke failure, could have led to substantially misleading measurements which, even if true, do not actually represent the response of the watershed. Moreover, in some cases records may have even been possibly acquired at a moment prior to the time when the peak discharge occurred, thus underestimating it.

Apart from gauges being inundated and measurements being biased regarding time, there is yet one reason why available data are not always reliable. In most cases river discharge is indirectly calculated by measuring the river stage and converting it into river discharge by means of a stage-discharge relationship, namely, the so-called rating curve. According to Baldassarre et al. (2011) errors in the individual stage and discharge measurements used to parameterize the rating curve; uncertainty inherent to the least squares estimation of its parameters; presence of unsteady flow conditions; extrapolation of the rating curve beyond the range of measurements used for its derivation and temporal changes in the geometry of the channel, make such measurements uncertain. Baldassarre also indicates that such uncertainty could lead to 10% or in some cases 20% over or underestimation.

However, even if it could be assumed that measurements were completely correct and reliable and the underlying uncertainty ignored, the difficulties regarding calibration and its inherent uncertainty are yet to be overcome. In many cases continuous models require several parameters, whose estimation is not based on any kind of measurement techniques. Such parameters do not reflect reality directly but are distorted representations of the real world as seen by the model.

In everyday engineering practice, a monte carlo simulation is used in order to identify the optimum parameter set. However, according to Beven (1993) such an approach is flawed in a number of ways, the most important being that it discourages the consideration of uncertainty in parameter values and predictions. In addition, there could even be multiple optima for a single calibration method.

Beven, who addressed most of the major inconsistencies and the uncertainty regarding parameter estimation of continuous distributed models, sarcastically indicated that the predictions of such models should be treated more as an exercise in prophecy rather than prediction and proposed a scheme in order to account for model uncertainty.

It is quite evident, that modeling uncertainty in continuous modeling schemes, where great computational power is already necessary, when treated in a deterministic manner, is quite a difficult task. Given also that simulations of length reaching up to several thousands of years are needed in order to obtain statistically reliable and consistent results, the consequent cost in resources and time is quite heavy.

Finally, Makropoulos et al. (2007) come to the quite interesting conclusion that *"in typical practical applications, parameter parsimonious conceptual models, with a simple mathematical structure, may yield better results than physically based ones, which are restrained by the large amount of spatially distributed data required to represent heterogeneity of physical processes and the intrinsically deficient knowledge of the physical system"*.

5.1.3 The need for a stochastic approach

In deterministic frameworks the outcome of a model is uniquely determined through fully described relationships and equations. A given input will always result in the same output and uncertainty is not taken into consideration. Of course, this applies not only to simple event-based models, but also to more complex continuous schemes.

However, it has become quite evident up until now that in flood modeling there are many sources of uncertainty ranging from the inherent uncertainty in hydrometeorological processes, to the uncertainty in initial conditions, measurements, model parameters estimation and the mechanisms regarding the hydraulic response of a basin and many more.

As a result, the outcome of deterministic models, which is obviously fully dependent on the model inputs, is heavily biased. For example, even in a continuous model where a stochastically generated rainfall timeseries is used as input, the storm of a certain return period corresponds to a specific set of initial conditions, as calculated by the model. However, it could possibly be that these were different and the model itself cannot account for this possibility.

Hence, it is quite evident that integrating uncertainty into our analysis is not just a persistence of academics and researchers, but actually an attribute that should be taken seriously into consideration in flood modeling.

The necessity of taking uncertainty into consideration tends to be fully accepted among the scientific community nowadays. In this point, it should be once more highlighted that, instead of trying to avoid uncertainty, which is actually unavoidable, recognizing it as an essential attribute of a system is the only way to fully take into account and reproduce the dynamics of hydrological systems (Montanari, et al., 2012).

The modern engineer must be able not only to trace the sources of uncertainty, but should also try and integrate uncertainty in modeling, in order to estimate the confidence level of the results. Even though such a task is not quite easy and requires knowledge and effort, it is the only way if we aim for capturing the true nature of floods.

According to Montanari et al. (2012) any deterministic scheme can be converted into a stochastic one, therefore incorporating randomness in hydrological modeling as a fundamental component. In particular they propose such an approach that results in replacing the single output of a deterministic model with the probability distribution thereof, which is estimated by stochastic simulation.

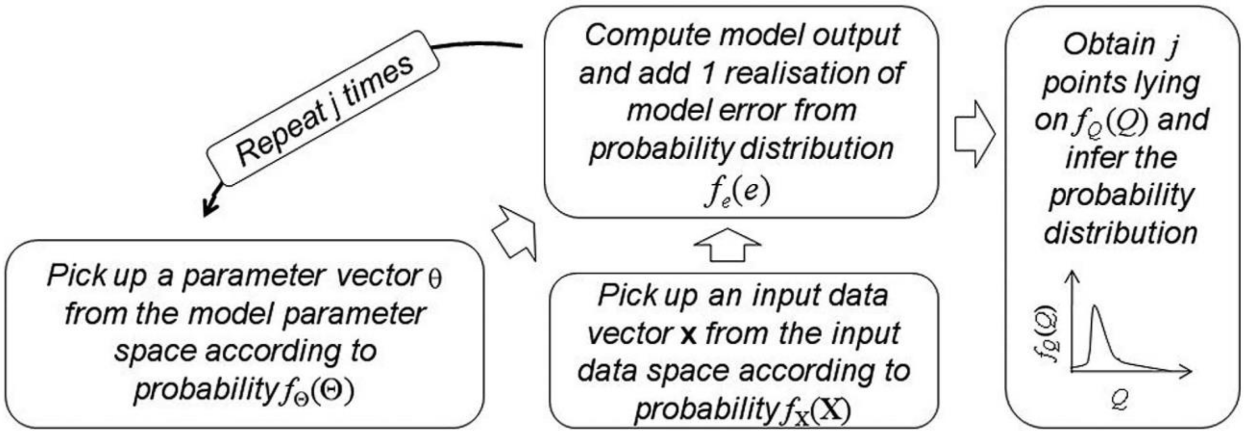

Figure 5-1 : Flowchart of the proposed Monte Carlo simulation procedure proposed by Montanari et al. (2012)

5.1.4 The need for a pseudo-continuous approach

As already stated continuous modeling can address most of the inconsistencies found in event-based modeling. However, in ungauged basins things are more complicated and the use of such frameworks is not suggested, while even when the required data are available, the implementation of such models is yet difficult, as already stated, especially when it comes to everyday engineering practice.

According to Boughton et al. (2003) "*continuous simulation is unlikely to be used for the design of minor works in the foreseeable future. Event-based methods using generalized rainfall statistics will continue to be the main approach to design of minor works whose cost* *and consequences of failure will not justify the effort of data preparation and calibration of a continuous simulation system*".

In addition, the complexity of continuous simulation frameworks requires knowledge and skills that are mostly found in the research and academic environment, rather than in ordinary engineers, who mostly need to rely on simple and parsimonious schemes. As a result, the engineering community worldwide prefers using event-based models that are easily implemented, since their (few) parameters can be directly obtained from bibliographic sources (Efstratiadis, et al., 2014).

In the meantime, Berthet et al. (2009) suggest that besides being a matter of knowledge and complexity, the tendency of engineers to favor event-based approaches might be even cultural. More specifically they note that "*Some endusers, who traditionally use hydraulic propagation methods, are culturally in favor of an event-based approach. Despite all the good reasons advanced by hydrologists for using continuous approaches, practitioners often continue using event-based models and see them as the only solution*".

Given the above, the scope of this thesis is to propose a framework that is neither event-based, nor continuous, but rather takes a midrange approach by combining the basic elements of event-based analysis with some of the key features of continuous modeling. As a result, we regard the proposed framework as a 'pseudo-continuous' simulation scheme. The most important goal of this work is to propose a framework as described above that, however, still remains simple and parsimonious enough.

More specifically, the proposed framework is an undistributed model, which involves the synthetic generation of daily rainfall; its disaggregation into finer temporal scales; a very simplistic procedure for the estimation of initial soil moisture conditions based on 5-day Antecedent Precipitation; runoff calculation; selection of annual maxima of generated runoff; and finally the calculation of the design flood hydrograph for the selected events.

The specifics of the proposed simulation scheme will be described in detail in the following chapter.

5.2 The proposed pseudo-continuous stochastic simulation framework

The proposed stochastic simulation framework is actually a mid-range approach between event-based and continuous modeling. A very simplistic Soil Moisture Accounting procedure is incorporated in continuous time, the daily generated runoff is estimated and the annual maxima events are extracted. From then on, the selected events are transformed into flood hydrographs according to event based modeling. The Monte Carlo Simulation scheme, allows for accounting for the uncertainty.

The main benefits of the model is that it remains simplistic and parsimonious enough, for everyday engineering practice, while simultaneously addressing some of the major shortcomings of event-based modeling and accounting for uncertainty.

5.2.1 The basic steps

Step 1: The physiographic characteristics of the watershed are studied and a CN value is assigned to the area.

Step 2: A Digital Elevation Model of the region is incorporated in order to estimate the relationship of time of concentration versus generated runoff. This is done according to the work of Antoniadi (2016) that suggests a power type relationship of the form $P=at_c^{-b}$, where a,b>0 and P is the generated runoff.

Step 3: A Parametric Unit Hydrograph that uses time of concentration as a parameter is shaped. In our case we use the Parametric Synthetic Unit Hydrograph presented in the Methods chapter. It is obvious that since time of concentration is varying according to the amount of generated runoff, the shape of the PSUH will be varying too.

Step 4: A rainfall timeseries is extracted from an appropriate hydrometeorological station.

Step 5: HyetosMinute model is calibrated using the historical timeseries

Step 6: Using the historical timeseries as input to the Castalia model, a synthetic daily timeseries is stochastically generated.

Step 7: The stochastically generated synthetic daily rainfall timeseries is disaggregated into finer temporal scales (i.e. 15 minutes) via the HyetosMinute stochastic disaggregation scheme

Step 8: The value of CN is treated as a continuous variable and is updated daily, based on the 5-day Antecedent Precipitation, thus updating the value of maximum potential soil moisture retention S, which is a function of CN

Step 9: The daily runoff is estimated through the NRCS-CN method, using as inputs the synthetic daily rainfall and the updated value of soil moisture retention S.

Step 10: The annual maxima of daily runoff are extracted

Step 11: Time of concentration, based on the calculated daily runoff and the corresponding Parametric Synthetic Unit Hydrograph are estimated for every selected event.

Step 12: The flood hydrographs of the selected events are produced, since the temporal evolution of rainfall and the PSUH are provided. The temporal evolution of hydrological deficits is estimated via the NRCS-CN method.

Step 13: Steps 6 through 12 are repeated in a Monte Carlo simulation scheme, in order to estimate the confidence intervals of the results and obtain a set of design flood hydrographs for the desirable return period.

5.2.2 Important notes on the proposed framework

5.2.2.1 Defining the term "ungauged"

As already stated, the term "ungauged" is related to watersheds that lack discharge observations, while it is assumed that common Digital Elevation Models (DEMs) with a standard resolution, soil-use digital support (i.e. CORINE 2000) and rainfall raingauge data are accessible.

It is quite obvious that if no rainfall measurements are available, the proposed framework cannot be implemented.

5.2.2.2 Rainfall measurements

If no station exists in the basin under study, then the rainfall measurements of a nearby watershed may be used, as long as the climatic conditions of the measured region are similar and comparable to our case. One should definitely keep in mind the aforementioned regarding the concept of hydrological similarity.

5.2.2.3 Desirable return period

The desirable return period is determined, according to the magnitude and the importance of the project under study. Sometimes this is dictated by the responsible authorities and if not, one can rely on suggestions based on engineering experience. It should be noted that when it comes to flood control, the choice also depends on the importance of the regions under threat. For instance, a flood control work such as a dyke protecting a cultural heritage site is of high importance and its design would require a larger return period, than any other structure protecting an ordinary asset, located on the flood plain of a river.

5.2.2.4 Simulation length

The length of the generated timeseries in order to obtain statistically consistent and reliable results depends on the desirable return period. For instance, for a return period of 1 000 years, a timeseries of length equal to 10 000 years is generated.

5.2.2.5 Parametric Synthetic Unit Hydrograph

In order to take into consideration the varying hydraulic response of a watershed, it is important that a Synthetic Unit Hydrograph that uses time of concentration as a parameter is incorporated. In our case we propose the Parametric Synthetic Unit Hydrograph presented in the Methods chapter that has been developed in National Technical University of Athens and is well-tested.

However, different PSUH's could be used, if needed, depending on the physiographic characteristics of a watershed.

5.2.2.6 Calibrating HyetosMinute

In the context of calibrating the HyetosMinute model, measurements of finer –than daily-temporal scales need to be available. If the historical timeseries of the region is of coarser scale, then the timeseries of a different yet hydrologically similar region can be used.

5.2.2.7 Daily updating of CN value

CN is treated as a continuous variable that is daily updated based on the 5-day cumulative Antecedent Precipitation, which is the cumulative rainfall depth received the last 5-days leading up to the event.

This is actually one of the key elements differentiating our approach from event-based modeling, since a continuous procedure for soil moisture accounting is introduced. However, such an approach, based on antecedent precipitation is quite simplistic and by no means can perform better than a calibrated more complete continuous hydrological model.

The use of antecedent precipitation as an indicator for initial conditions has been widely criticized and poor results have been mentioned [(Tramblay, et al., 2010), (Brocca, et al., 2007) and others] when compared to continuous hydrological models. However, none of these writers suggest the abolishment of methods based on antecedent precipitation.

In the framework proposed in this thesis we incorporate a method based on 5-day antecedent precipitation, since we consider it suitable enough for the midrange approach between event-based and continuous modeling that we wish to establish. Given that a basin is ungauged, a complete hydrological model cannot be trusted and the best choice is to take into consideration the actual rainfall regime, affecting soil moisture, even if performed in a simplistic manner. The same is suggested by Berthhet et al (2009) who indicates that such approaches are the best and most informative available, when it comes to event-based modeling.

Moreover, according to Aronica et al. (2007) the simplicity of treating the soil moisture conditions by using a very simple descriptor such as the Antecedent Precipitation Indexes, actually allows to have a robust modeling of the flood formation process.

The scheme regarding the daily update of CN values is performed with a simple linear interpolation between the typical dry and wet Antecedent Moisture Conditions (types I and III), corresponding to lower and higher 10% of the non-zero 5-day Antecedent Precipitation (P_5), respectively.

In order to do so, firstly the Index of P_5 throughout the synthetic timeseries is calculated and the lower and higher 10% of non-zero values are estimated based upon their empirical distribution. These values (expressed in mm) correspond to the AMCI and AMCII type and the CNI and CNII values are assigned to them respectively.

The daily value of P_5 determines the value of CN according to the above. In particular, for values of P_5 ranging between dry and wet P_5 values, CN is obtained through a simple linear interpolation between CNI and CNII. Moreover, in order to avoid extremely unrealistic conditions, where the soil might be completely saturated, hence fully impermeable or fully unsaturated, hence no runoff being generated, the values of CNI and CNII are used as lower and upper bounds of CN respectively.

The above can be expressed as follows:

$$\frac{P_5^i - P_5^{dry}}{P_5^{wet} - P_5^{dry}} = \frac{CN^i - CNI}{CNIII - CNI}, \quad for\ P_5^{dry} < P_5^i < P_5^{wet}$$ **Eq. (5-1)**

$$CN^i = CNI, \qquad for\ P_5^i \leq P_5^{dry}$$ **Eq. (5-2)**

$$CN^i = CNIII, \qquad for\ P_5^i \geq P_5^{wet}$$ **Eq. (5-3)**

, where P_5^{dry} and P_5^{wet} are the lower and upper 10% of non-zero P_5 values respectively, P_5^i is the value of P_5 calculated for the day i of the timeseries and CN_i is the value of CN finally assigned to the day i.

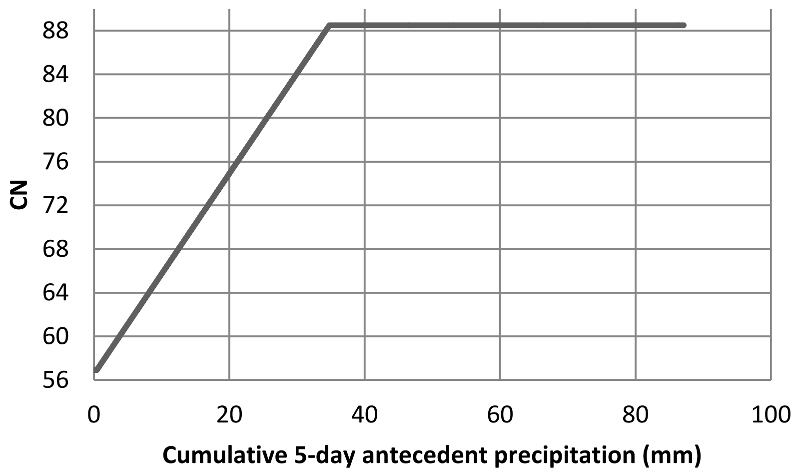

Figure 5-2 : Relationship of CN versus 5-day antecedent precipitation (P_5)

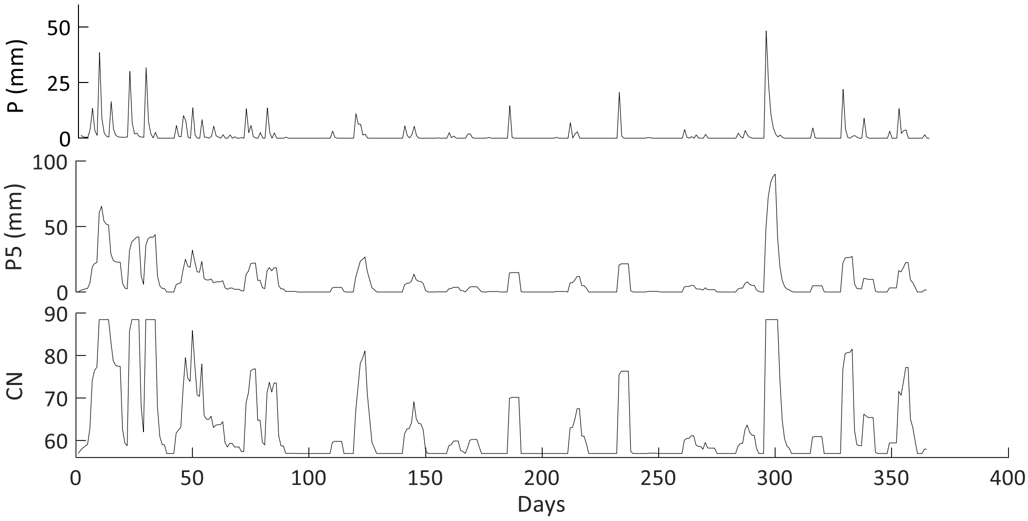

Figure 5-3 : Example of a rainfall timeseries (P) with its corresponding cumulative 5-day antecedent precipitation (P_5) and the resulting CN values

In the literature, more variations on Antecedent Precipitation approaches can be found that consider different weights for each antecedent day, being greater for the most recent precipitation, however further investigation is beyond the scope of this thesis.

5.2.2.8 Issues regarding the selection of annual maxima of daily runoff

By selecting the annual maxima of daily runoff it is straightforwardly assumed that greater flood volumes result in greater peak discharges, even though this is actually not the case. A greater flood volume that happens to be uniformly distributed in time can reach a peak discharge smaller than the one generated by a flood of smaller volume, but with a temporally more concentrated distribution.

However this cannot be addressed. Estimating the flood hydrograph of each day separately (treating each day independently) and then selecting the most severe flood would require massive computational power and would be extremely time consuming, given the necessary simulation lengths and the repetition in the context of the Monte Carlo simulation.

After all, the great simulation lengths and the Monte Carlo simulation, can remedy this minor inconsistency.

5.2.2.9 The Monte Carlo simulation scheme

The rainfall of a certain return period can occur under a wide range of possible initial conditions and temporal evolution profiles.

The Monte Carlo simulation scheme is conducted in order to account not only for the variability of Antecedent Moisture Conditions across days, but also the stochasticity of sub-daily rainfall. This is performed by generating more than one synthetic timeseries, each of them assigning a different CN value to the event of a certain return period and, in turn, running the selected daily events with multiple sub-daily rainfall patterns.

The above allow for estimating the joint uncertainty of varying daily rainfall (thus varying Antecedent Moisture Conditions, CN value, time of concentration and shape of Unit Hydrograph) and varying sub-daily rainfall.

6 Study basin

The scope of this thesis is the proposal and documentation of a simple and parsimonious pseudo-continuous stochastic simulation scheme for flood modeling that can be used in every-day engineering, instead of typical event-based modeling that has been found to be highly inconsistent.

Hence, the proposed scheme is not established upon a specific study basin, but is rather a general framework aimed for being easily implemented in every small or medium sized ungauged basin.

However, we selected a study basin in order to analyze and report the functionality and the results of the proposed model and also conduct further investigations.

In this chapter the study basin and the data available are presented and the input parameters are determined.

6.1 Rafina stream basin

The selected study area is Rafina watershed, a periurban area in the greater southeast Mesogeia region in Eastern Attica, Greece.

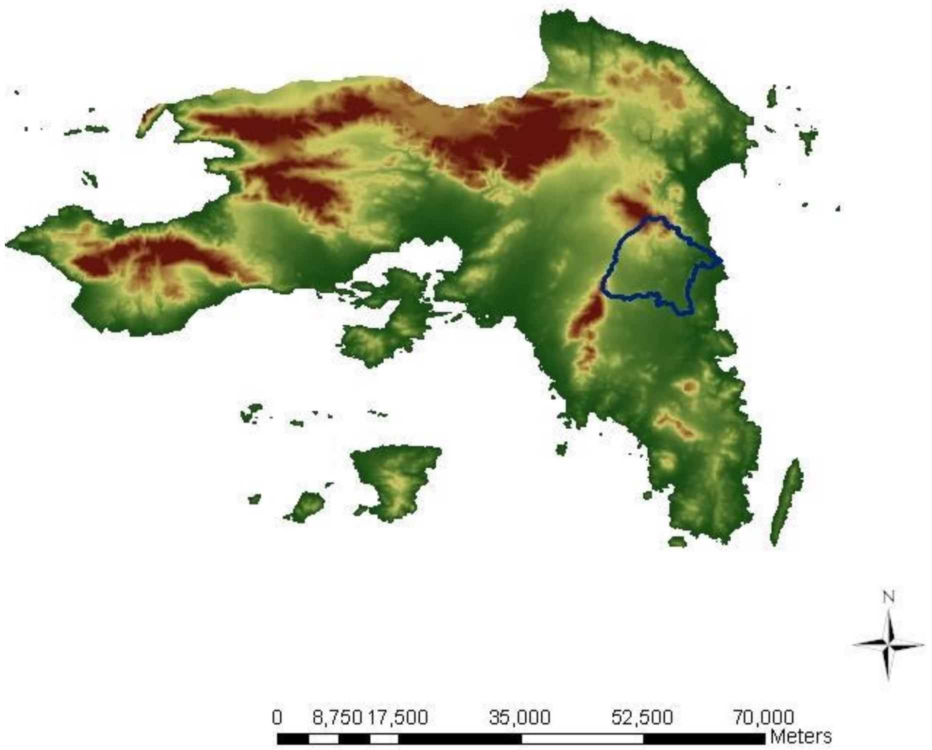

Image 6-1 : The DEM of Attica region and the boundaries of the study area (Papathanasiou, et al., 2013b)

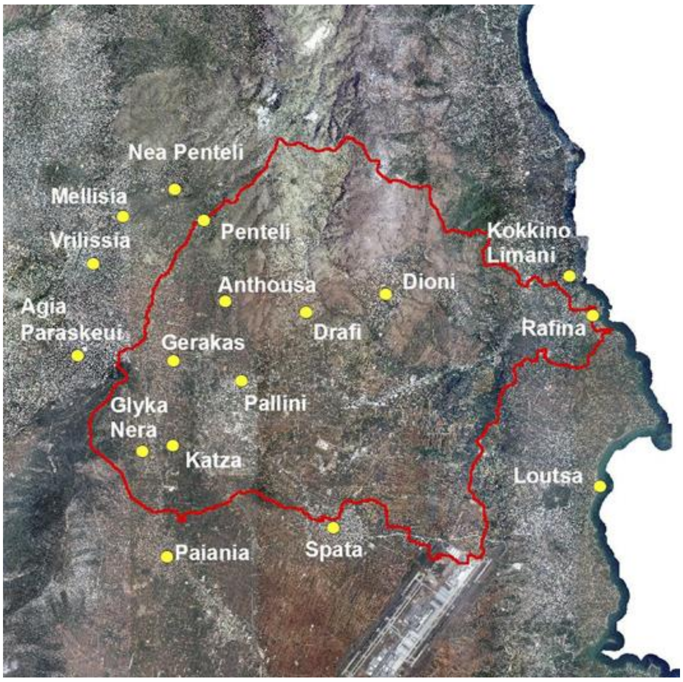

Image 6-2 : Satellite image of the study region with its boundaries and more important sites noted (www.flire.eu)

6.1.1 Topographic characteristics

The area covers 123.3 km^2 and geographically extends east of Ymittos mountain to the coastline of Evoikos Gulf. The mean altitude of the region is approximately 227 m, with the maximum value being 909 m and the minimum 0 m. The ground slope ranges from 0% to 37.8% and its mean value is approximately 7.5%. Increased slopes are mostly found in the upstream parts of the region and are clustered at its north part.

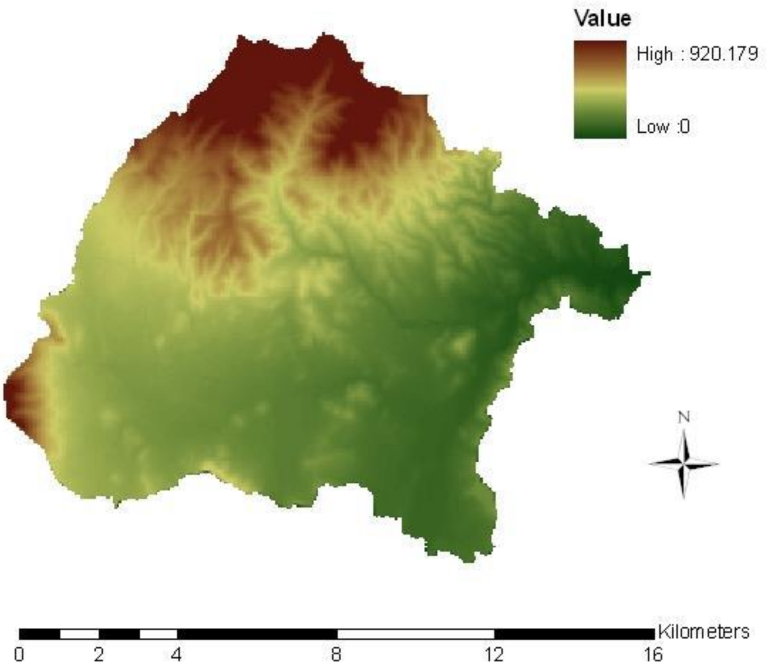

Image 6-3 : Detailed DEM of the study basin (Papathanasiou, et al., 2013)

6.1.2 Hydrographic network

The hydrographic network of the study basin is quite dense in the upstream, where the topography is more intense. The main water body of the area is the Rafina stream which collects smaller streams and creeks from the upstream and reaches the outlet of the basin, flowing towards the South Evoikos Gulf.

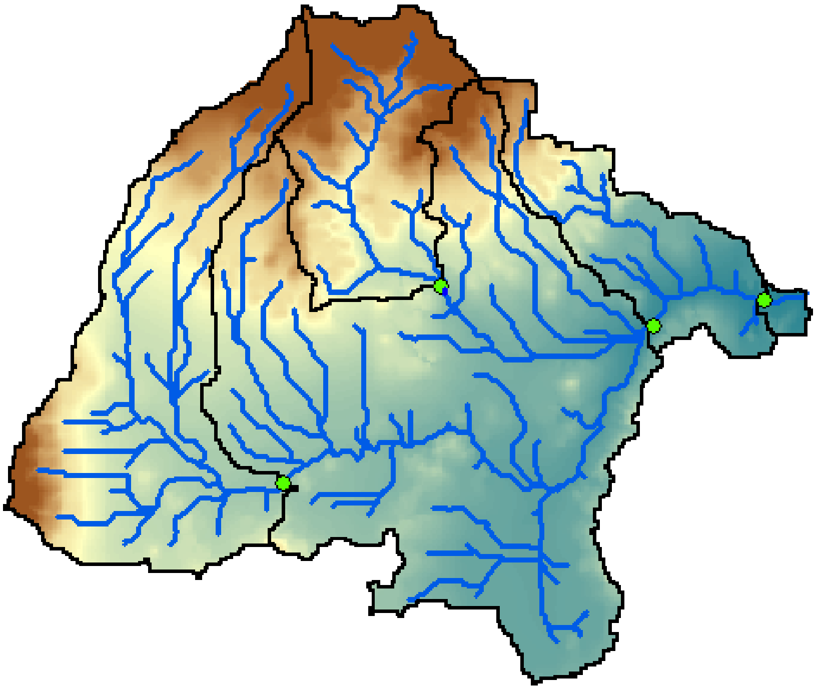

Image 6-4 : The hydrographic network of the study basin drawn on its DEM (Papathanasiou, et al., 2013)

6.1.3 Hydrometeorological regime

The climate in the region is characterized as a typical subtropical Mediterranean climate, with prolonged hot and dry summers succeeded by considerably mild and wet winters. Snowfall is rare in the region and the mean annual precipitation is estimated at 400 mm. The drought period usually starts in May and ends in October. The daily mean temperature ranges between 27°C during the summer months and 11°C during winter months.

6.1.4 Geological characteristics

The region is part of the Attico-Cycladic Massif. Two main units dominate in the geological structure of Attica, namely the crystalline basement (Paleozoic-Upper Cretaceous) and the Neogene-Quaternary clastic deposits. The basement consists of schists and carbonate rocks. The Neogene and Quaternary deposits fill up both the degradations and tectonic grabens of the East Attica basin and consist of maly limestones, marls, clays, sandstones, conglomerates and other coarse, unconsolidated sediments.

The greater area presents neogene sediments and the thickness of these deposits in the northern part of the study area exceeds 150 m and is estimated at about 80 m in the central part, decreasing towards the schists. The mio-Pliocene deposits are characterized by the presence of lignite in the upper parts. The thickness of the lignite-bearing layers is approximately 6 m to the west of Rafina. Schists, phyllites, limestones and crystalline marbles of Upper Cretaceous age occur in the southern part of the study area. According to oral information from borehole owners, deep drillings in the northern and eastern parts of the Spata basin also show the presence of lignite layers.

Tectonically, the entire region is controlled by a fault system with predominate east–northeast and west–northwest directions. The formation of the Mesogea tectonic graben is a result of the northeast–southwest faulting, whereas the Ymittos mountain marble massif tectonically controls the western part of the basin. The central part of the basin is highly affected by the great pre-alpine syncline fold of northeast–southwest direction and definitely formed by the post-alpine faulting. (Papathanasiou, et al., 2013b)

6.1.5 Land use

Rafina basin includes forests (~30%), arable soils and grasslands (~50%) mainly located upstream and urban cells (~20%) located downstream. (Alonistioti, 2011) The land cover properties of the study area are constantly changing and intense urbanization has been reported in the region, over the past decades.

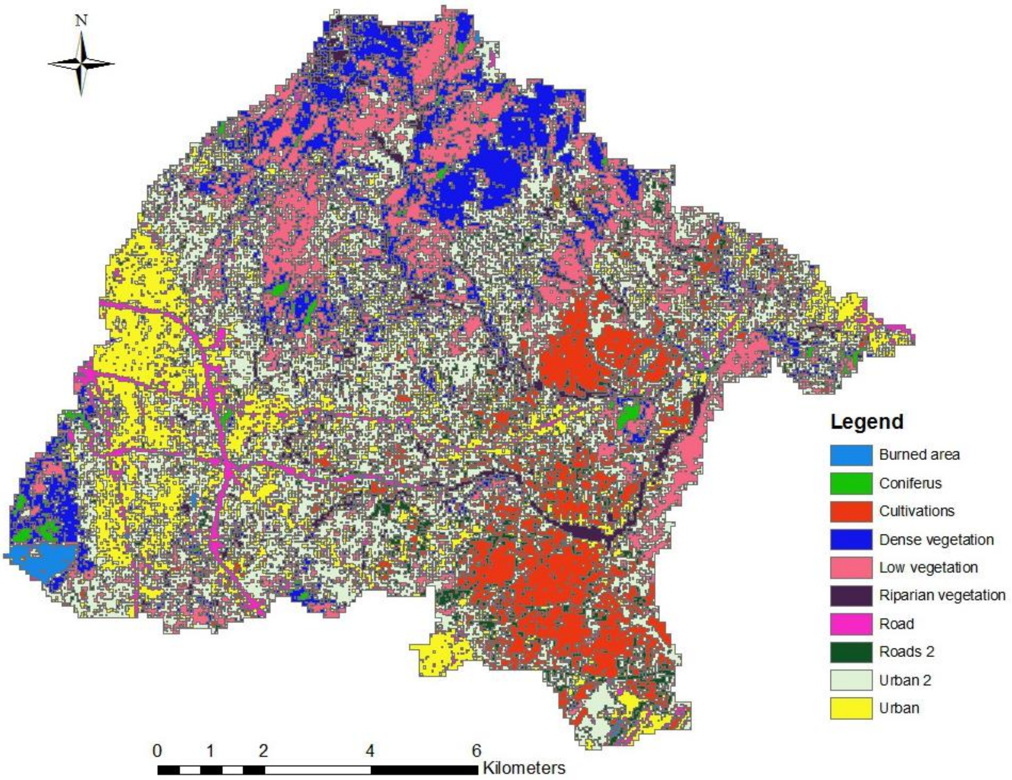

Image 6-5 : Land use map drawn in 2009 (Papathanasiou, et al., 2013)

6.1.6 Hydraulic response and floods in the region

The region presents medium to high flood risk becaouse of topography and urbanization levels, constituting flood control a necessity. Flood risk has greatly increased since extensive forested areas have been burned by wildland fires occurring over the past two decades.

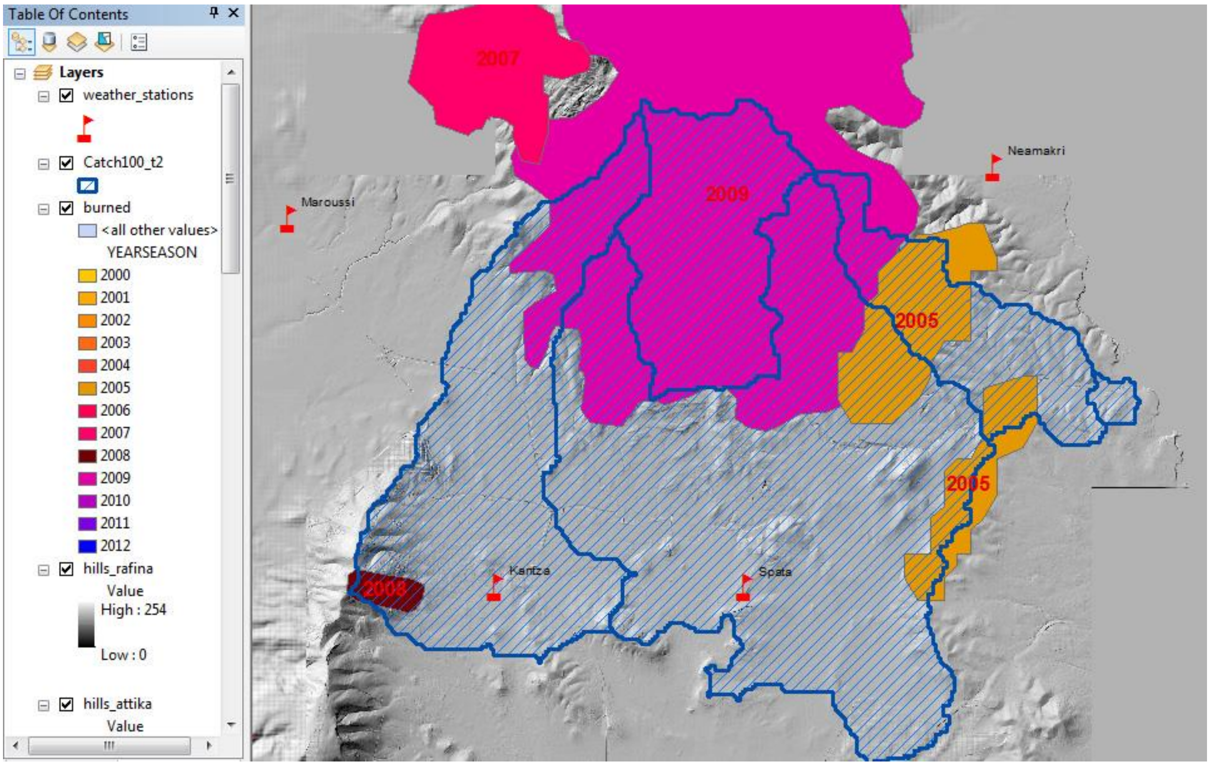

Image 6-6 : Forest fires in the study area for the period 2000-2012 (Papathanasiou, et al., 2013)

6.2 Parameters of the study basin

6.2.1 Historical timeseries

The historical timeseries is of daily timescale and was extracted by a nearby hydrometeorological station located in Tatoi, in the region of Attica. The historical timeseries and the fitted GEV-max distribution of its annual maxima are presented in the following graphs.

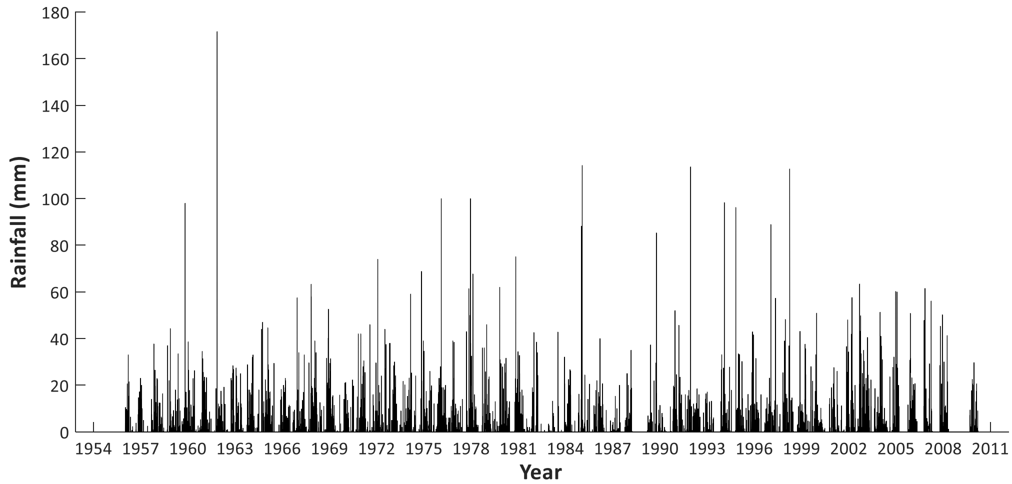

Figure 6-1 : Graph of the historical daily rainfall timeseries

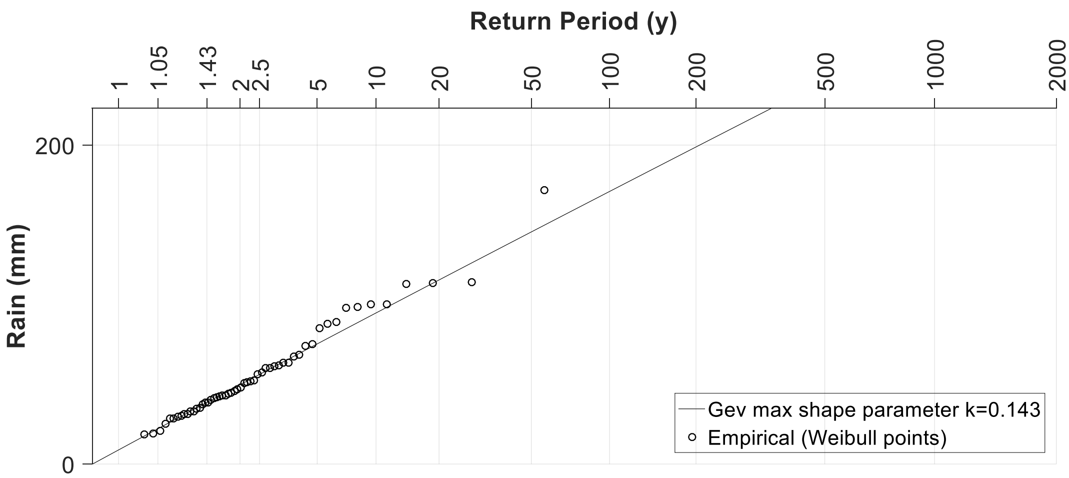

Figure 6-2 : The fitted GEV-max distribution of the annual maxima of the historical timeseries

6.2.2 NRCS-CN Parameters

The CN value of the Rafina stream basin is estimated as 60.

The runoff mechanisms of the region are best described with an initial abstraction I_a equal to 0.05*S, where S is the potential maximum retention. (Koutsoyiannis, et al., 2014)

6.2.3 Time of concentration

According to Antoniadi (2016) the relationship of time of concentration versus the generated runoff is described by the following expression:

$$P = 760.34 * t_c^{-2.956} \qquad \textbf{Eq. (6-1)}$$

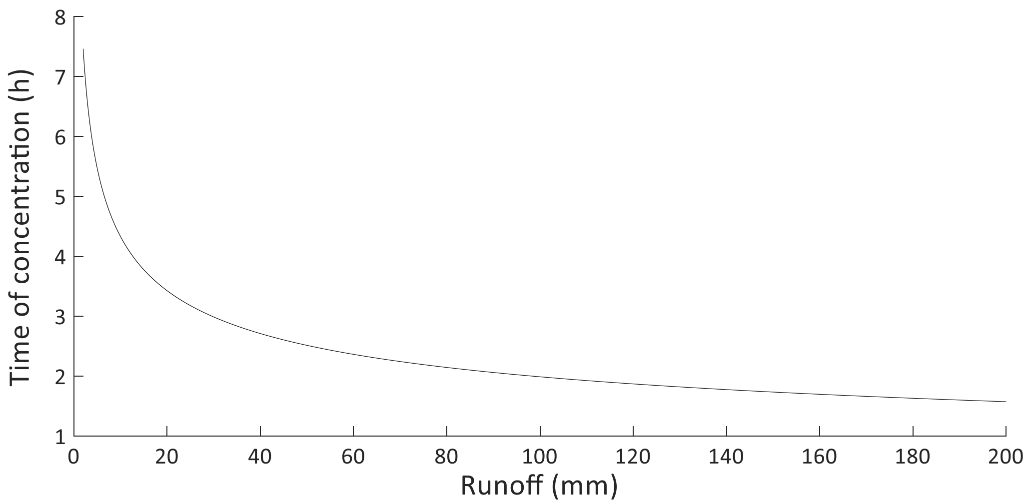

Figure 6-3 : The relationship of time of concentration versus the amount of runoff generated

6.2.4 Parametric Synthetic Unit Hydrograph

The Parametric Synthetic Unit Hydrograph of the Rafina basin is determined based on the suggestions of Koutsoyiannis in the Deukalion project (Koutsoyiannis, et al., 2014). In particular we determine the parameters as following;

β=0,3 and γ=5

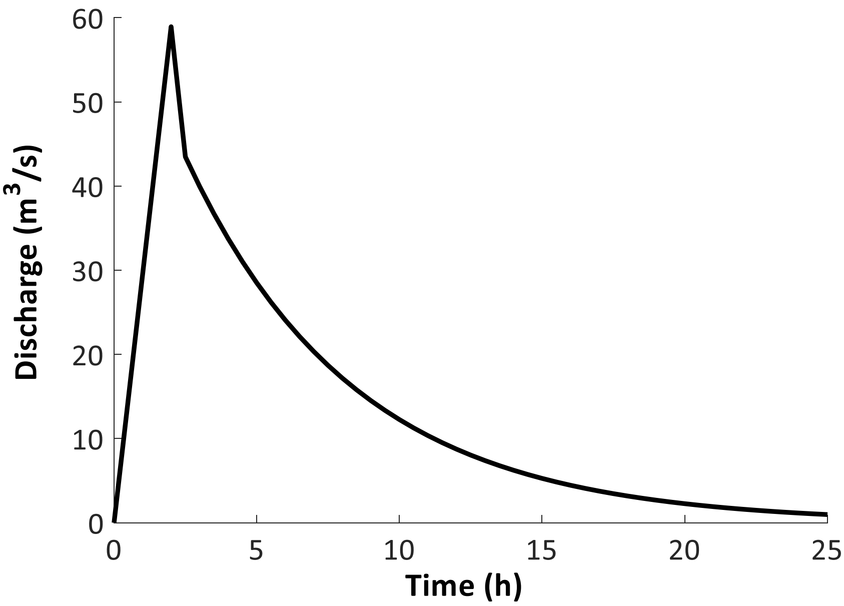

Figure 6-4 : The shape of the 15min Parametric Synthetic Unit Hydrograph of the Rafina basin, when time of concentration is calculated via the Giandotti formula

6.2.5 HyetosMinute parameters

HyetosMinute has been calibrated for the region of Attica and the model parameters are listed below.

Table 6-1 : Table of the HyetosMinute model parameters

	lambda	phi	kappa	alpha	v	mx	sxmx
Jan	0.2115	0.490071	0.061309	150	68.3091745	55.85088	1
Feb	0.179823	0.369566	0.079567	150	45.29799638	55.96484	1
Mar	0.175569	0.219374	0.065356	150	39.27718449	57.25784	1
Apr	0.105171	0.803011	0.071454	150	85.23040712	50.61669	1
May	0.116005	0.068099	0.03775	150	80.77257464	144.1119	1
Jun	0.043155	0.076942	0.047353	150	63.59520007	205.1426	1
Jul	0.031376	0.056437	0.038994	150	100.696013	190.7726	1
Aug	0.025476	0.026041	0.018823	150	67.95964156	138.9034	1
Sep	0.024085	1.1406	0.100049	150	115.5787362	167.9183	1
Oct	0.098127	0.119333	0.027722	150	46.21295957	128.7391	1
Nov	0.169945	0.25168	0.057052	150	57.78682077	94.79975	1
Dec	0.246718	0.362942	0.079427	150	45.62160533	63.25976	1

7 Analysis and results

In this chapter the results of the analyses conducted in the context of this thesis will be presented.

Our analyses involve the implementation of the proposed pseudo-continuous stochastic simulation framework and its comparison to the results obtained by the typical deterministic scheme, as well as further investigations regarding the variation of soil moisture conditions and the time of concentration.

Moreover, alternative, less complex approaches and model variations will be tested and compared to the proposed framework.

Among the presentation of the results, some preliminary conclusions will also be listed, which will be further discussed in the chapters to follow.

The analyses to their full extent were made with the use of the Matlab® programming language in the Matlab® environment.

7.1 Introduction

As already stated the pseudo-continuous stochastic simulation framework presented in this thesis is a midrange approach between continuous simulation and event-based modelling. This framework is established upon some essential assumptions regarding the key processes represented in the model, as well as the tools and methods used.

In the continuous part of the proposed framework, the key assumptions made, regard the variability incorporated in CN, which is treated as a continuous variable, rather a discrete one, hence accounting for every possible soil moisture condition instead of the three typical Antecedent Moisture Conditions represented in typical event-based modeling. This is performed through the 5-day cumulative Antecedent Precipitation.

When it comes to the event-based part of the proposed framework, the key elements that differentiate it from everyday engineering practices are the rainfall disaggregation scheme, used for obtaining the temporal evolution of the storm in finer (i.e. sub-daily) temporal scales and the implementation of a varying time of concentration in a daily basis, according to the amount of runoff generated daily. The variance of time of concentration results in a varying shape of the Parametric Synthetic Unit Hydrograph.

To summarize, the key aspects differentiating our approach than typical event-based models could be roughly sated as:

- Variance of soil moisture conditions
- Implementation of stochastic rainfall disaggregation scheme
- Variance of time of concentration

Moreover, a Monte Carlo Simulation scheme is incorporated in order to account for the uncertainty generated by the variability and inherent stochastic nature of the above.

Given the aforementioned, our analysis will be focused on each and every one of these key elements of the proposed framework and their impact on the outcome, while several approaches regarding the modeling of the above will be tested and compared to the proposed scheme. In addition, the response of the model for different sets of parameters will be tested.

The purpose of these analyses is, on the one hand, to compare the outputs of the proposed framework to the results of the typical deterministic scheme described in the previous chapters. On the other hand, it is also intended to present the significance of the changes that we implement in everyday flood modeling, by comparing different variations of the proposed model, regarding the methods used for treating for the above elements. In the meantime some preliminary conclusions will be made, that will be further discussed in the chapters to follow.

In most cases the flood hydrographs and other characteristics such as time of concentration and CN distributions for return periods equal to 5,10, 20,50,100,200,500,1000 years are examined. These values are selected, not only because it is practically meaningless to provide results for many different return periods, but also because they are commonly used in design.

7.2 Types of analysis

The types of analysis conducted are listed below and their respective results will be presented in the same order:

a) *The typical deterministic framework*
During this analysis the typical deterministic framework used in everyday engineering is implemented in the Rafina stream basin. The distribution of peak discharges, as well as the design flood hydrographs for different return periods and Antecedent Moisture Conditions is presented.

b) *The proposed pseudo-continuous stochastic simulation framework*
During this analysis the pseudo-continuous stochastic simulation framework proposed in this thesis is implemented in the Rafina stream basin. The distributions of peak discharges for the 95% confidence intervals are presented, the results will be compared to the typical framework and a set of flood hydrographs corresponding to the median estimation for some indicative return periods, usually implemented in design, are also provided. The sets of flood hydrographs corresponding to different confidence intervals are listed in Appendix A.

c) *Analysis and further investigation regarding the continuous part of the proposed framework*
This series of analysis includes investigations regarding the variability of Soil Moisture conditions, as indicated by the CN value assigned to each day of the

simulation, during the continuous (on a daily scale) analysis. The main scope of these investigations is to determine whether the proposed continuous simulation, combined with a Monte Carlo scheme represent the variability of Soil Moisture conditions in the region in a more faithful manner, rather than a more simplistic stochastic approach where a distribution is arbitrarily assigned to CN values instead.

Moreover, the distribution of the annual maxima of daily runoff with their corresponding rainfall events is presented and it is proved that annual maxima of rainfall do not produce the maximum flood volumes.

d) *Analysis and further investigation regarding the event-based part of the proposed framework*

This spectrum of analysis focuses on the event-based part of the pseudo-continuous stochastic simulation scheme that is presented in this thesis and includes testing and comparing different variations of the model, regarding the nature of time of concentration and the disaggregation of rainfall that could be implemented. More specifically, time of concentration can be treated as a constant, calculated via the Giandotti formula and the rainfall can be alternatively disaggregated through the alternating blocks method or randomly uniformly distributed. Consequently, five more variations of the main framework arise by combining the aforementioned alternatives, all of which are tested and compared to the proposed scheme and, of course, to the deterministic approach. The analysis is once again conducted for Rafina stream basin.

The main scope of the aforementioned analyses is to estimate the significance of the nature of concentration time and temporal evolution of storms to the outcome in flood engineering.

Moreover the distribution of time of concentration is estimated and issues regarding the difference between selecting the annual maxima of rainfall, rather than the annual maxima of daily rainfall are further discussed.

Instead of a daily approach, the response of the model is also tested and discussed, in occasions where the duration of the storm is determined alternatively (i.e. two or three days).

Finally, two different ways of estimating GEV distribution parameters, namely Moments and L-moments methods, are compared.

e) *The proposed pseudo-continuous stochastic simulation framework with the incorporation of Annie-Model*

The Annie-Model presented in this thesis is also tested, replacing the simplistic soil moisture accounting procedure performed via the 5-day cumulative Antecedent Precipitation. The distribution of maximum peak discharges is estimated and the flood hydrographs for different return periods are also listed.

In addition the distribution and the temporal evolution of soil moisture levels is examined and its link to Antecedent Precipitation is also investigated, in order to find a link that may imply the consistency of approaches based on Antecedent Precipitation.

Since the model is not calibrated based on measurements from Rafina stream basin we cannot conduct reliable comparisons with the proposed framework. However, the parameters of the model are arbitrarily set, in order to better reproduce the response of the proposed framework.

It is quite evident that calibrating Annie-Model without any measurements, but only in the context of reproducing –in terms of quality- the response of our framework is not actually reliable. As a result, only preliminary investigations are made in order to identify any apparent relationships and behaviors and safe conclusions can absolutely not be drawn.

f) *The influence of CN over the response of the model*

It is well known that the NRCS-CN method is non-linear. As a result, combined with the non-linearity of the rainfall disaggregation scheme, our framework is highly non-linear.

In order to check the non-linearity of our model, its response for different values of CN is examined. The relationship of CN values with the GEV distribution parameters of the resulting peak discharges is investigated and some indicative distributions are also presented.

7.3 Abbreviations

Before presenting the results, it is important to list the abbreviations used in the figures and graphs that follow.

Table 7-1 : Abbreviations used in the presentation of results

Abbreviation	Description
QpeakmaxQ	Peak Discharge abstracted from events where annual maxima of runoff occurred
Qpeakmaxrain	Peak Discharge abstracted from events where annual maxima of rainfall occurred
CNmaxQ	CN values assigned to events where annual maxima of runoff occurred
Cnmaxrain	CN values assigned to events where annual maxima of rainfall occurred
maxQ	Annual maxima of runoff
Qmaxrain	Runoff generated during events where annual maxima of rainfall ocurred
maxrain	Annual maxima of rainfall
rainmaxQ	Rainfall depth during events where annual maxima of rainfall occurred
WmaxQ	Soil moisture level in Annie-model, corresponding to days where runoff annual maxima occured
MM	GEV fitted using the Moments Method proposed by Koutsoyiannis (2004)
LM	GEV fitted using the L-moments method
AMCI	Deterministic model with Type I Antecedent Moisture Condition
AMCII	Deterministic model with Type II Antecedent Moisture Condition
AMCIII	Deterministic model with Type III Antecedent Moisture Condition
P5	5-day cumulative Antecedent Precipitation

As already mentioned, five model variations arise, by combining the aforementioned alternatives. Moreover, two model variations with the implementation of the Annie-model are also examined. For the purpose of showing the results, each variation was assigned an abbreviation, as listed in the following table.

Table 7-2 :Abbreviations assigned to the different model variations

Abbreviation	Rainfall Disaggregation	Time of concentration	Continuous part
HDI	HyetosMinute	Varying Daily - (Antoniadi, 2016)	Antecedent Precipitation
HCG	HyetosMinute	Constant - Giandotti	Antecedent Precipitation
ADI	Alternating Blocks	Varying Daily - (Antoniadi, 2016)	Antecedent Precipitation
ACG	Alternating Blocks	Constant - Giandotti	Antecedent Precipitation
UDI	Uniform distribution	Varying Daily - (Antoniadi, 2016)	Antecedent Precipitation
UCG	Uniform distribution	Constant - Giandotti	Antecedent Precipitation
Annie-HDI	HyetosMinute	Varying Daily - (Antoniadi, 2016)	Annie-Model
Annie-HCG	HyetosMinute	Constant - Giandotti	Annie-Model

7.4 The typical deterministic framework

The typical deterministic framework is implemented in the Rafina stream basin and the results are listed below. In particular, the distributions of the peak discharges for the three different Antecedent Moisture Condition types and the design flood hydrographs for the selected return periods are presented.

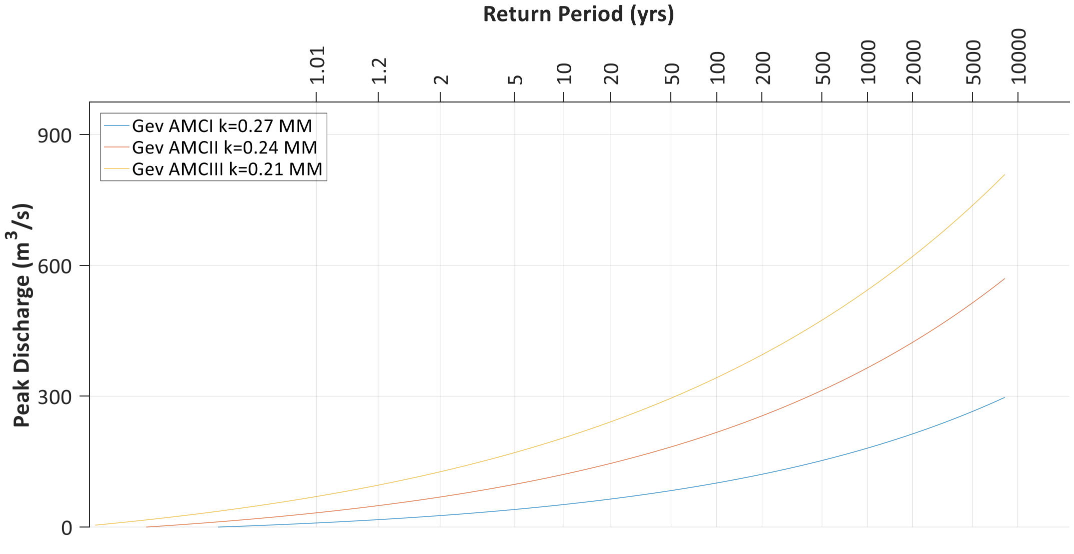

Figure 7-1 : Distribution of Peak Discharges estimated through the typical deterministic framework

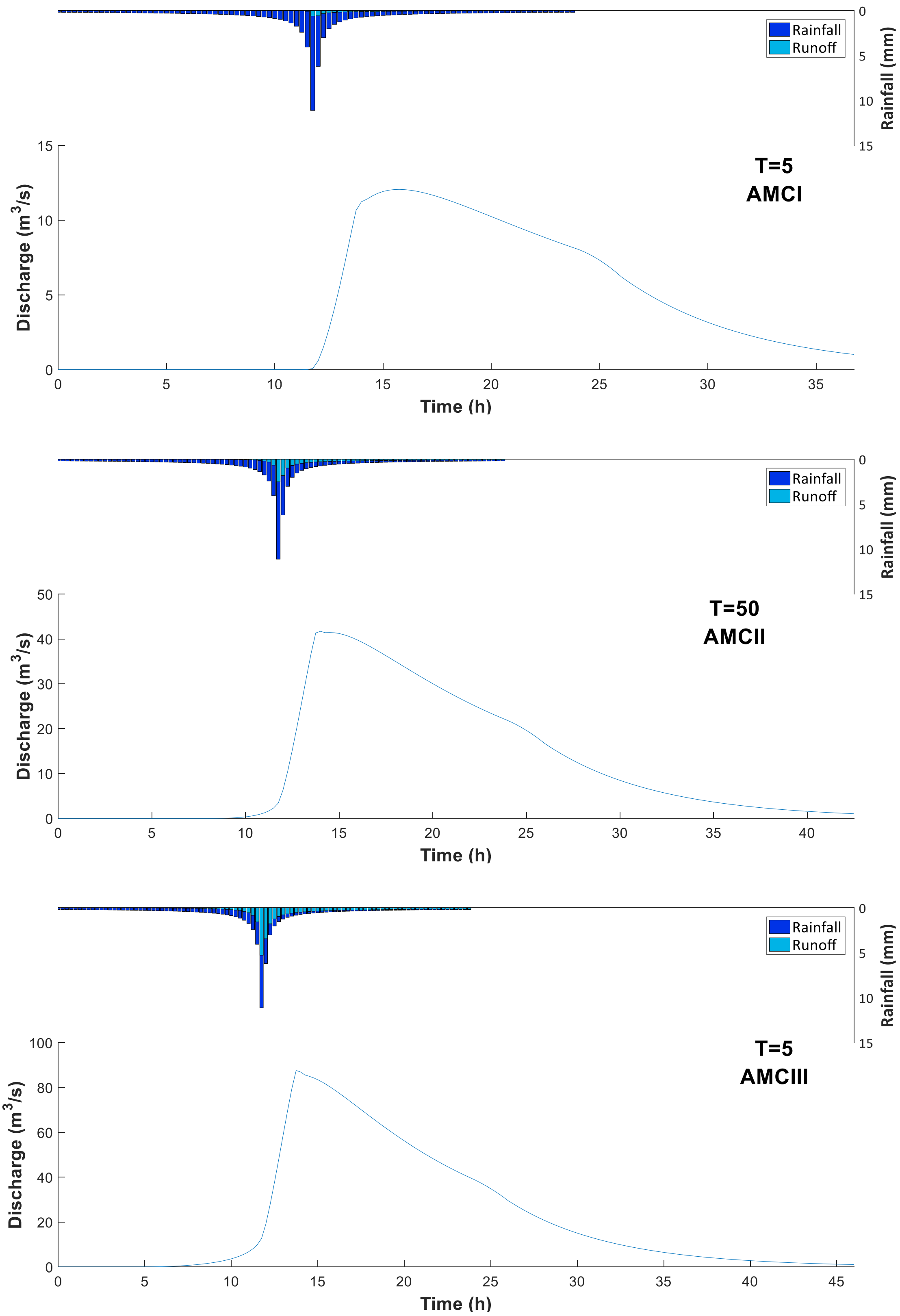

Figure 7-2: Flood hydrographs for the three different AMC types (T=5 years)

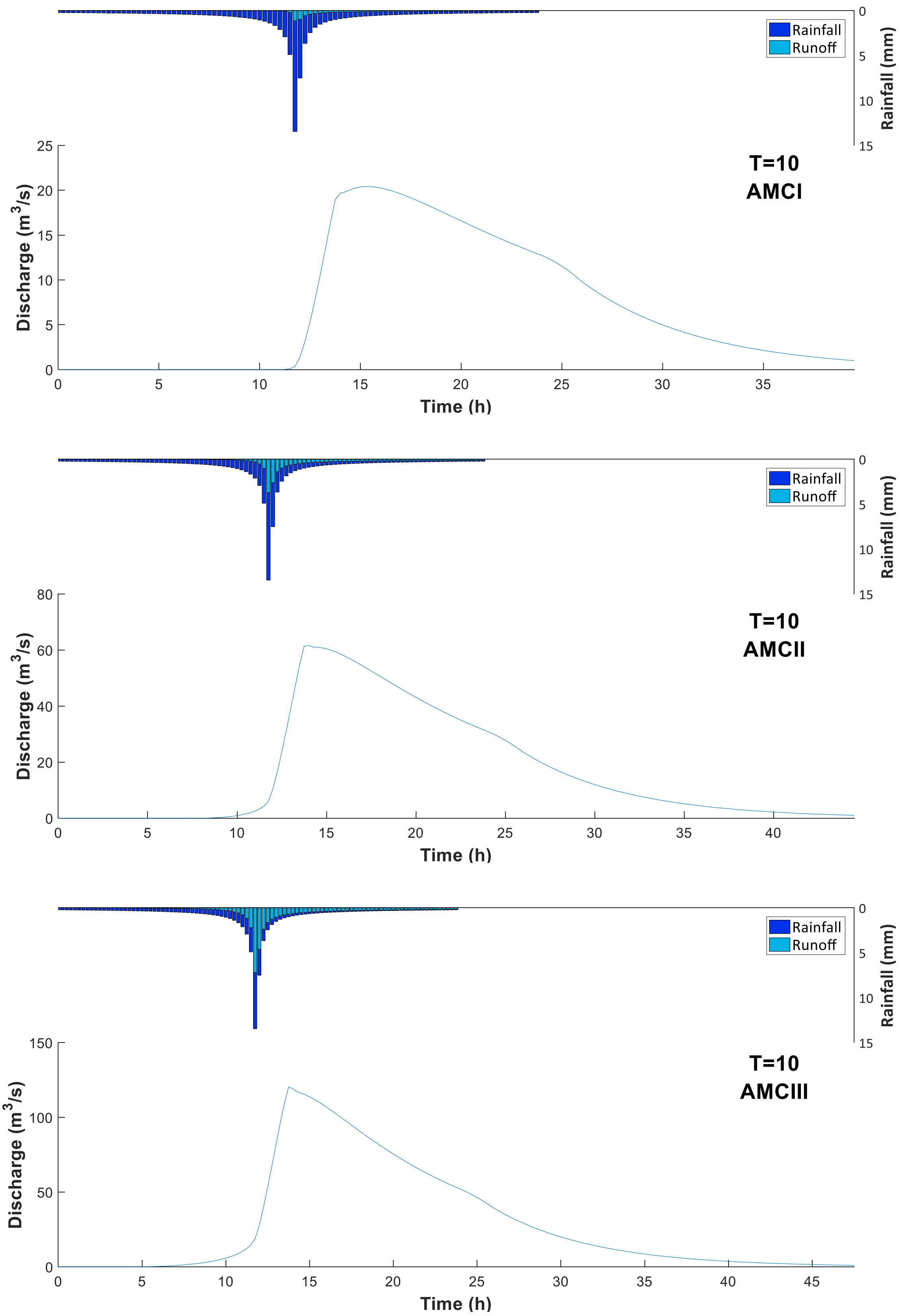

Figure 7-3 : Flood hydrographs for the three different AMC types (T=10 years)

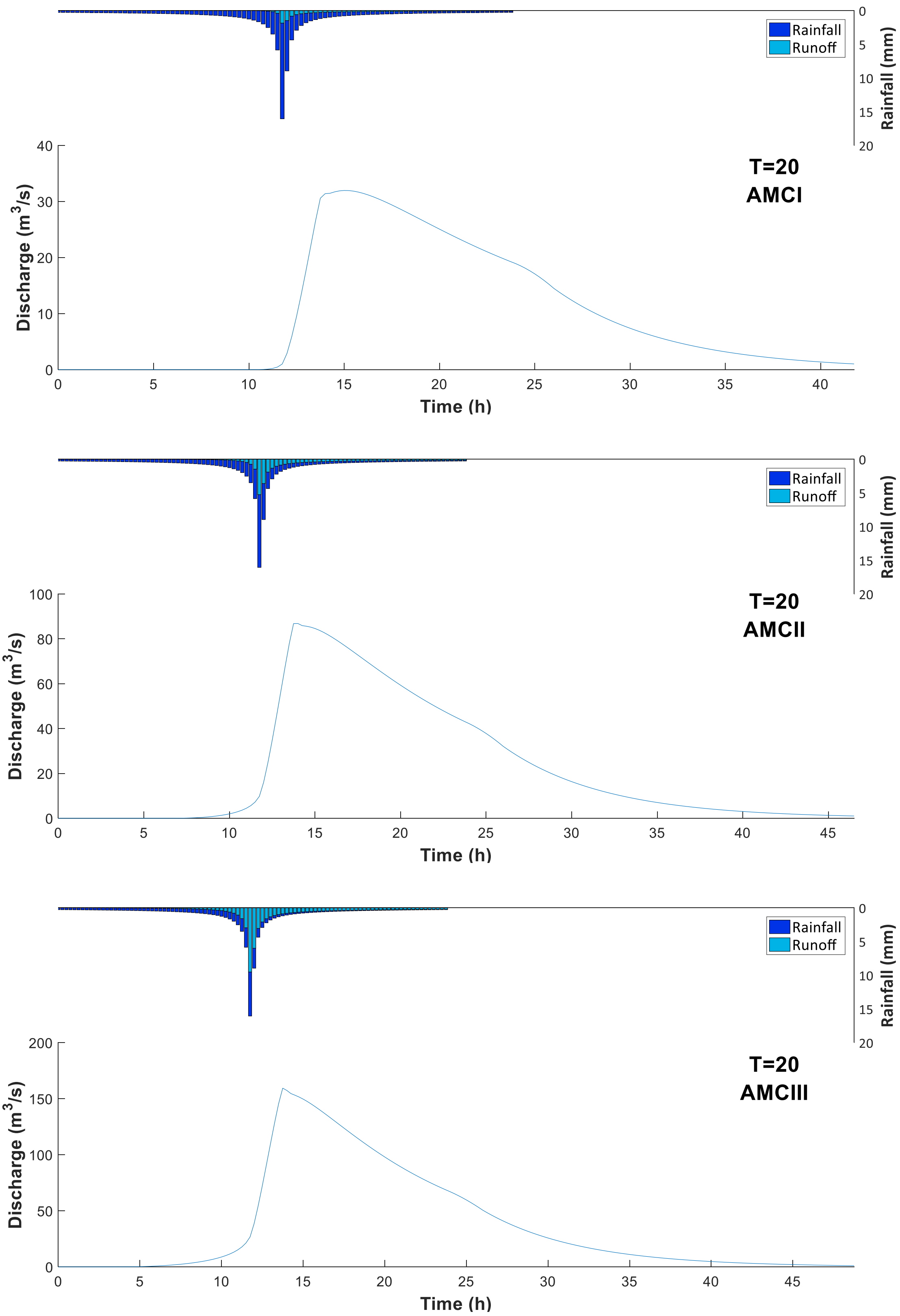

Figure 7-4 : Flood hydrographs for the three different AMC types (T=20 years)

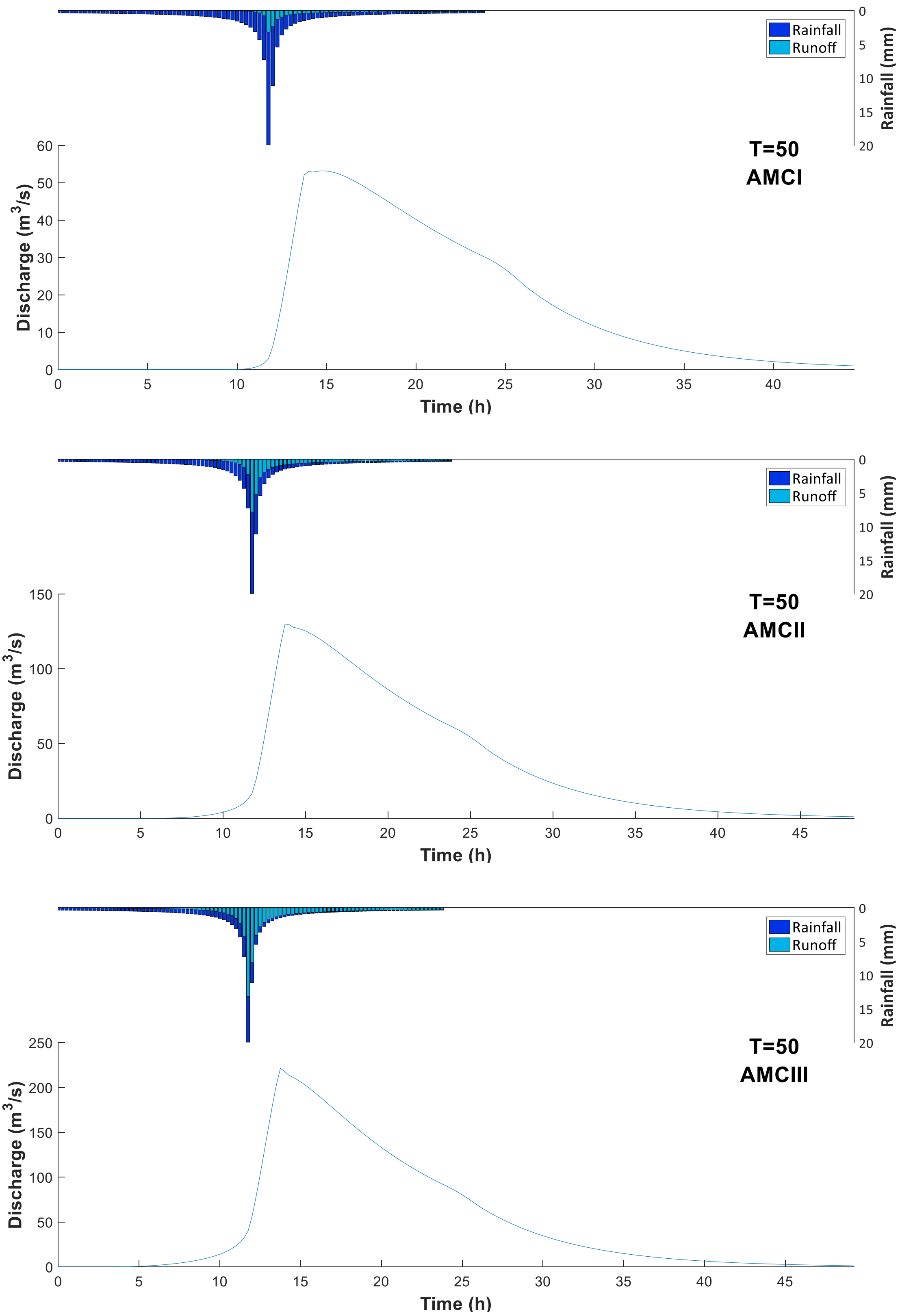

Figure 7-5 : Flood hydrographs for the three different AMC types (T=50 years)

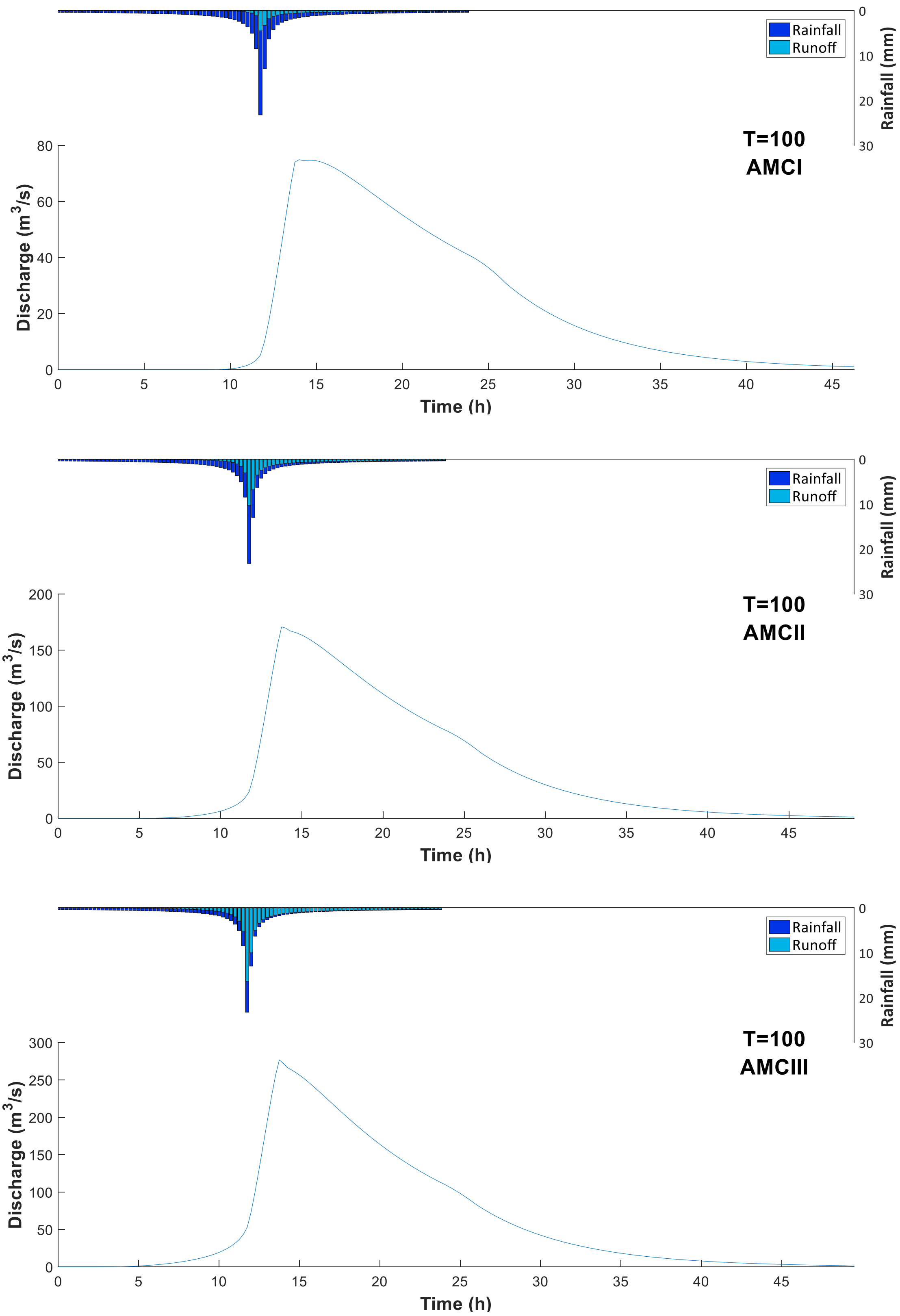

Figure 7-6 : Flood hydrographs for the three different AMC types (T=100 years)

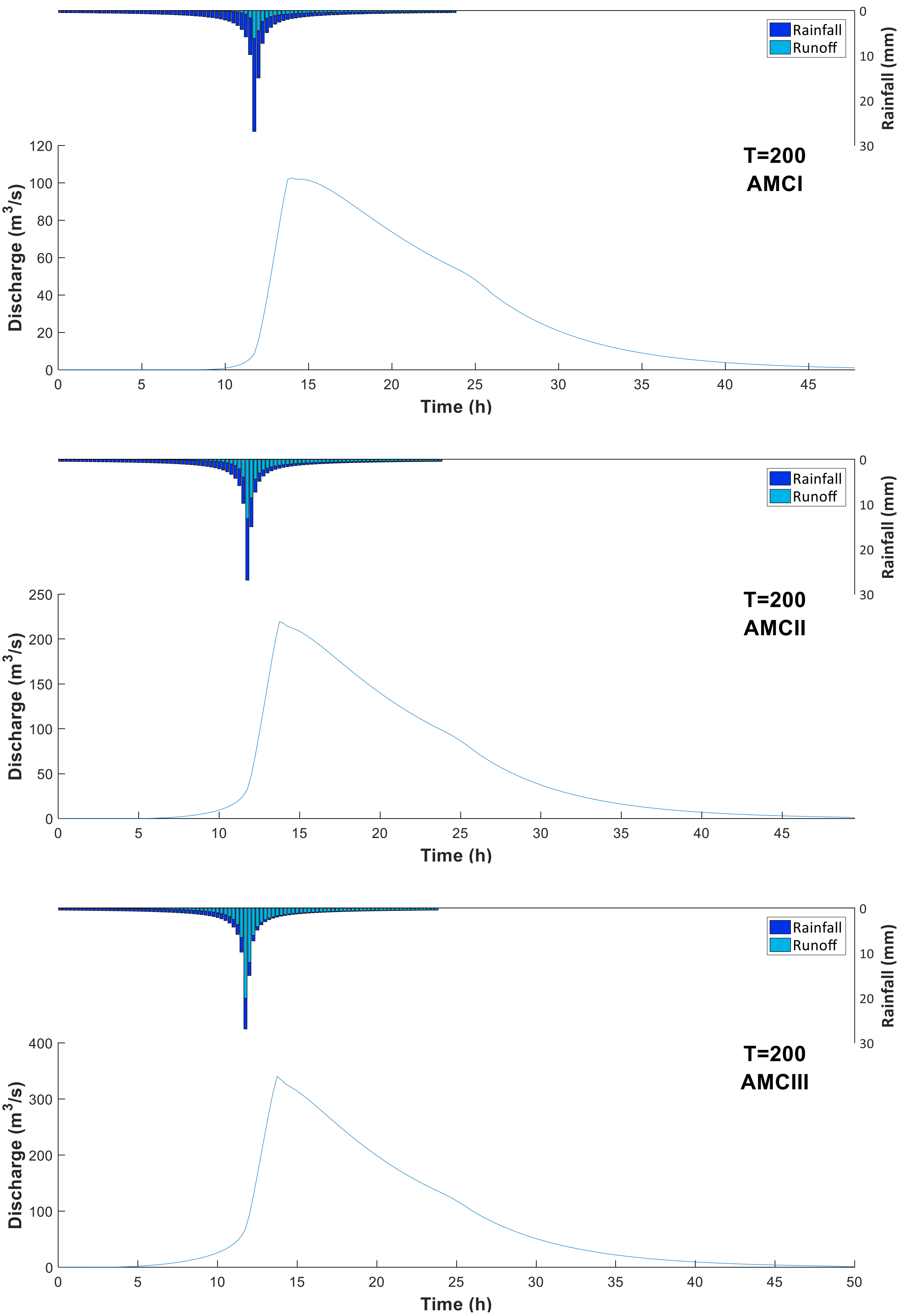

Figure 7-7 : Flood hydrographs for the three different AMC types (T=200 years)

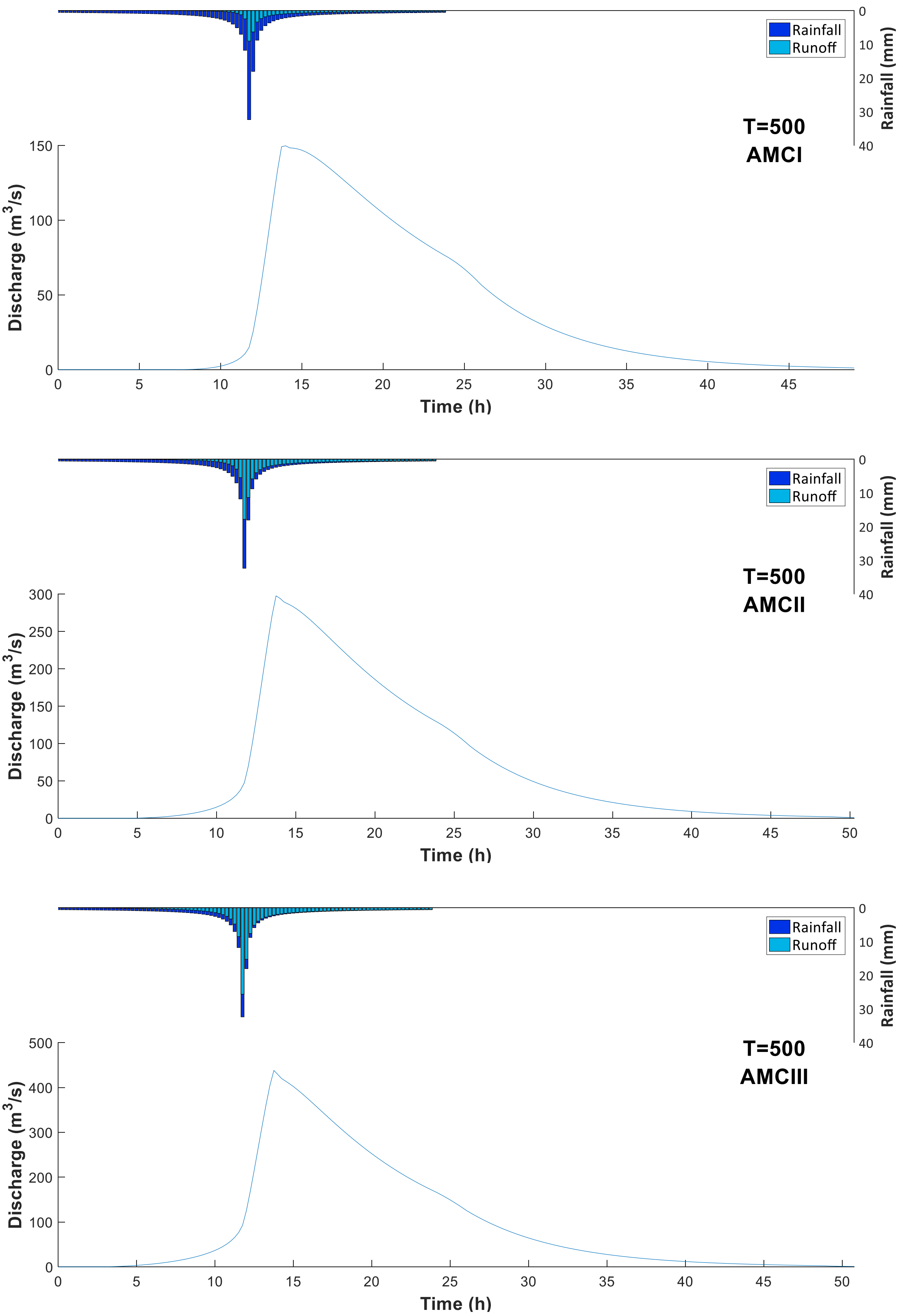

Figure 7-8 : Flood hydrographs for the three different AMC types (T=500 years)

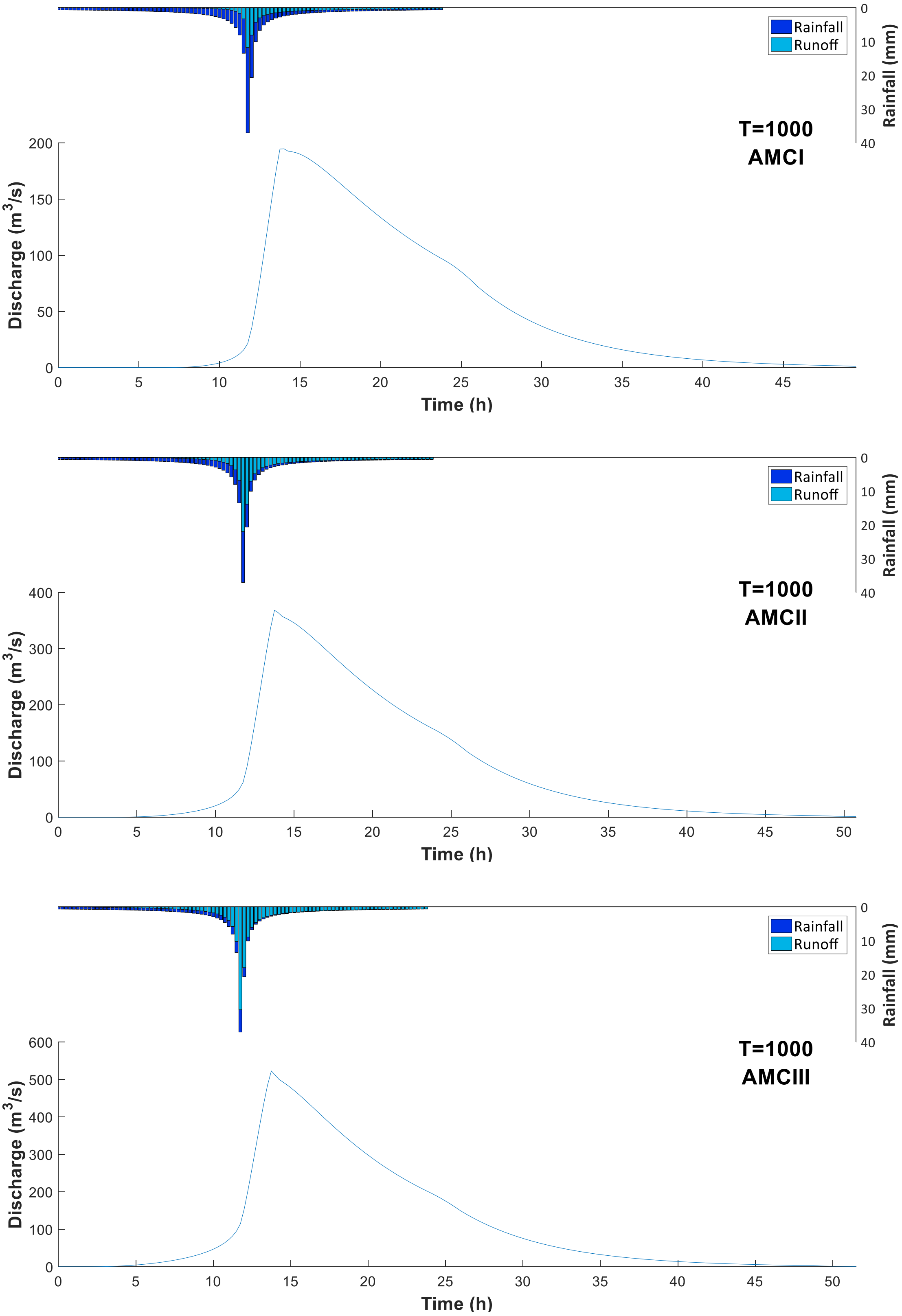

Figure 7-9 : Flood hydrographs for the three different AMC types (T=1000 years)

7.5 The proposed pseudo-continuous stochastic simulation framework

The proposed pseudo-continuous stochastic simulation framework is implemented in the Rafina stream basin and the results are listed below.

The analysis was conducted based on four different rainfall timeseries, with length equal to 10.000 years, each of which was disaggregated five times into finer into a 15 minute time scale. As a result, twenty different rainfall timeseries were produced. Under this Monte Carlo simulation scheme, the peak discharges were sorted in order to obtain the confidence intervals of our estimations, which are shown in the following graphs and tables.

Furthermore, the set of flood hydrographs corresponding to the median estimation will be presented here, while the sets assigned to confidence intervals equal to 95%, 70% and 50% will be listed in the Appendix.

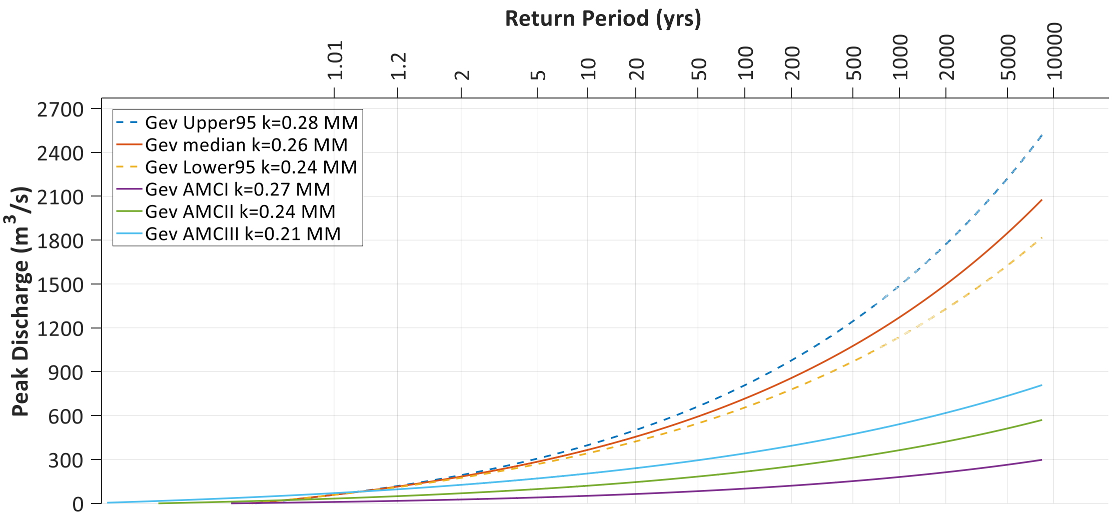

Figure 7-10 : Distribution of peak discharges, where the Upper and Lower bounds of 95% Confidence Interval, as well as the median estimation are depicted, along with the results of the typical deterministic framework

It is quite clear from Figure 7-10 that the proposed framework provides significantly greater floods, than the ones estimated through the typical deterministic framework. This difference in estimation becomes more intense while return period increases.

In the meanwhile, as shown in Table 7-3 and Table 7-4, the variability of the results produced by the pseudo-continuous scheme increases, as return period becomes larger. The variability is such that that the peak discharges assigned to 500 years return period, coincide and even exceed the value corresponding to the 95% Lower Bound of the estimations for a return period equal to 1 000 years.

Table 7-3 : Table showing the results properly sorted, in order to obtain the Upper and Lower bounds for the desirable Confidence Intervals

Return Period (yrs)	Peak Discharges (m^3/s)																			
		95% confidence interval																		
				70% Confidence interval																
						50% Confidence interval														
											Median									
5	84.1	84.7	84.9	85.1	85.2	85.3	85.4	85.5	85.5	85.6	85.7	86.0	86.3	86.4	86.5	86.5	86.9	87.3	87.4	87.8
10	148.2	149.3	150.0	150.0	150.4	150.7	150.8	150.9	150.9	151.2	151.2	151.4	151.5	153.1	153.2	153.3	154.3	154.4	155.3	155.9
20	229.6	232.5	234.2	234.8	235.0	236.3	236.9	237.0	237.5	238.1	238.2	240.1	240.3	240.6	240.8	241.3	241.3	242.4	243.0	245.7
50	361.9	371.8	372.1	375.4	377.6	385.9	388.2	388.6	391.5	392.3	393.1	393.4	393.6	396.3	396.9	397.2	398.4	399.1	400.1	408.3
100	517.9	520.5	520.7	523.8	525.1	526.2	527.6	528.3	531.2	536.8	540.0	546.8	551.6	553.2	558.2	559.4	559.5	566.9	568.6	594.3
200	658.9	685.5	693.0	696.6	698.0	701.0	707.3	710.4	713.4	715.6	728.9	751.8	759.6	763.4	764.5	765.4	769.5	771.6	779.3	799.2
500	902.1	913.8	925.7	950.5	978.0	982.5	986.2	988.7	1006.4	1018.3	1020.3	1024.8	1037.3	1041.0	1045.7	1049.1	1070.4	1083.5	1100.7	1101.0
1000	1070.3	1185.0	1196.6	1206.2	1228.0	1232.1	1244.3	1246.8	1248.9	1270.1	1286.4	1316.2	1321.8	1333.7	1344.6	1357.2	1358.0	1381.6	1419.7	1435.9

Table 7-4 : A compact Table showing the Boundaries for the desirable Confidence Intervals

Return Period (yrs)	Peak Discharges (m3/s)						
	95% Lower Bound	70% Lower Bound	50% Lower Bound	Median	50% Upper Bound	70% Upper Bound	95% Upper Bound
5	84.7	85.1	85.3	85.7	86.5	86.9	87.4
10	149.3	150.0	150.7	151.2	153.2	154.3	155.3
20	232.5	234.8	236.3	238.2	240.8	241.3	243.0
50	371.8	375.4	385.9	393.1	396.9	398.4	400.1
100	520.5	523.8	526.2	540.0	558.2	559.5	568.6
200	685.5	696.6	701.0	728.9	764.5	769.5	779.3
500	913.8	950.5	982.5	1020.3	1045.7	1070.4	1100.7
1000	1185.0	1206.2	1232.1	1286.4	1344.6	1358.0	1419.7

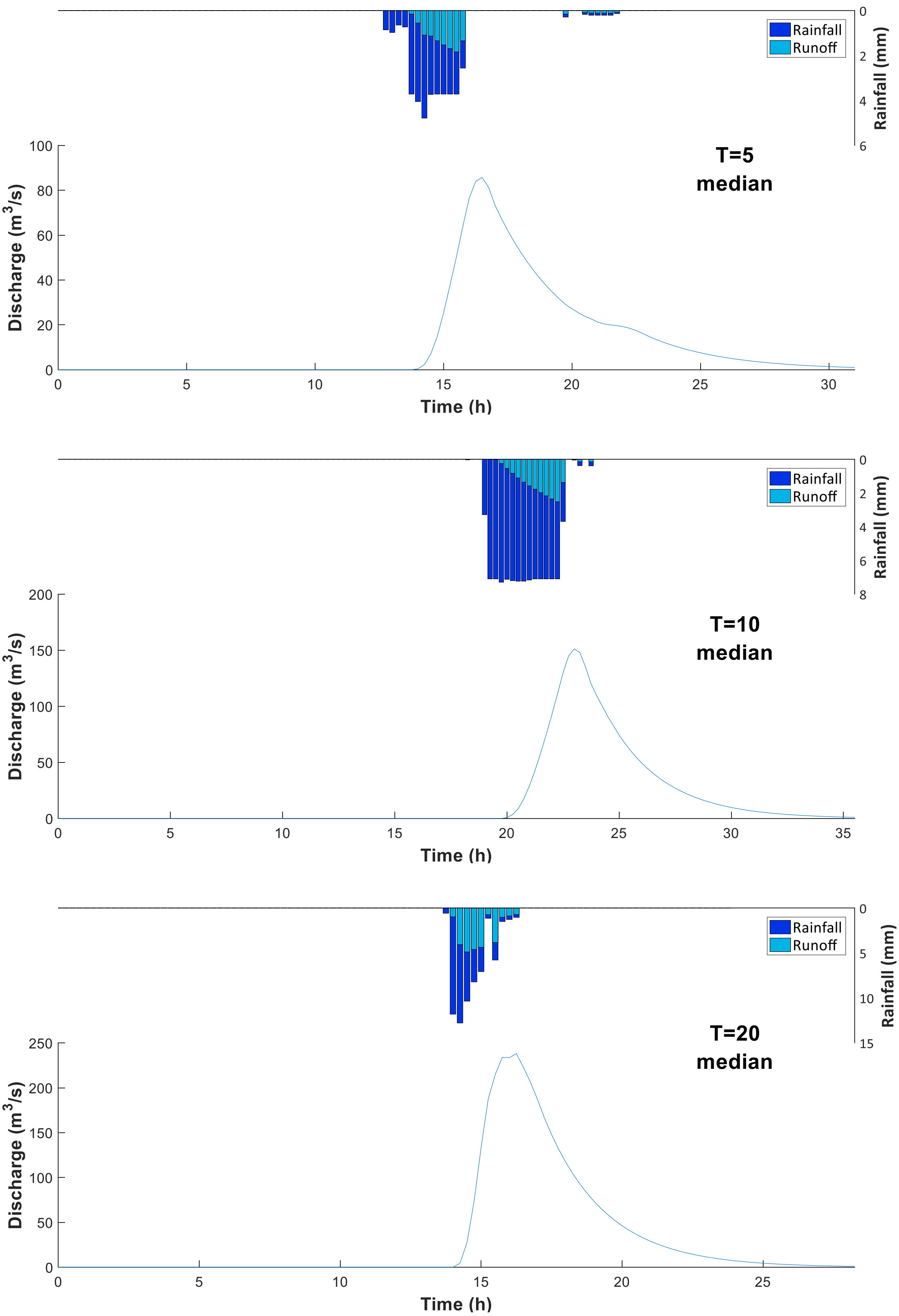

Figure 7-11 : Flood hydrographs for T=5, 10 and 20 years (median estimation)

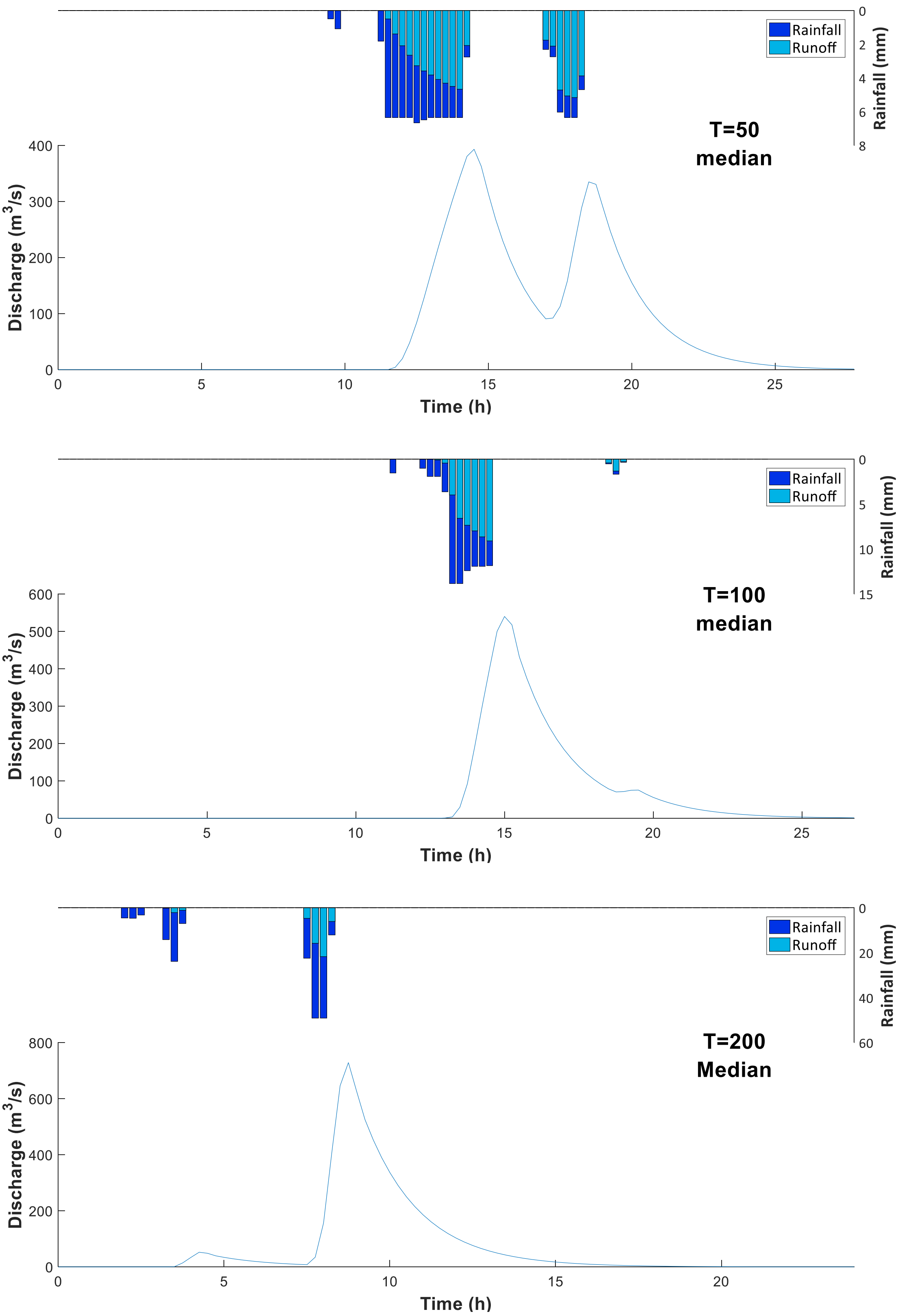

Figure 7-12 : Flood hydrographs for T=50, 100 and 200 years (median estimation)

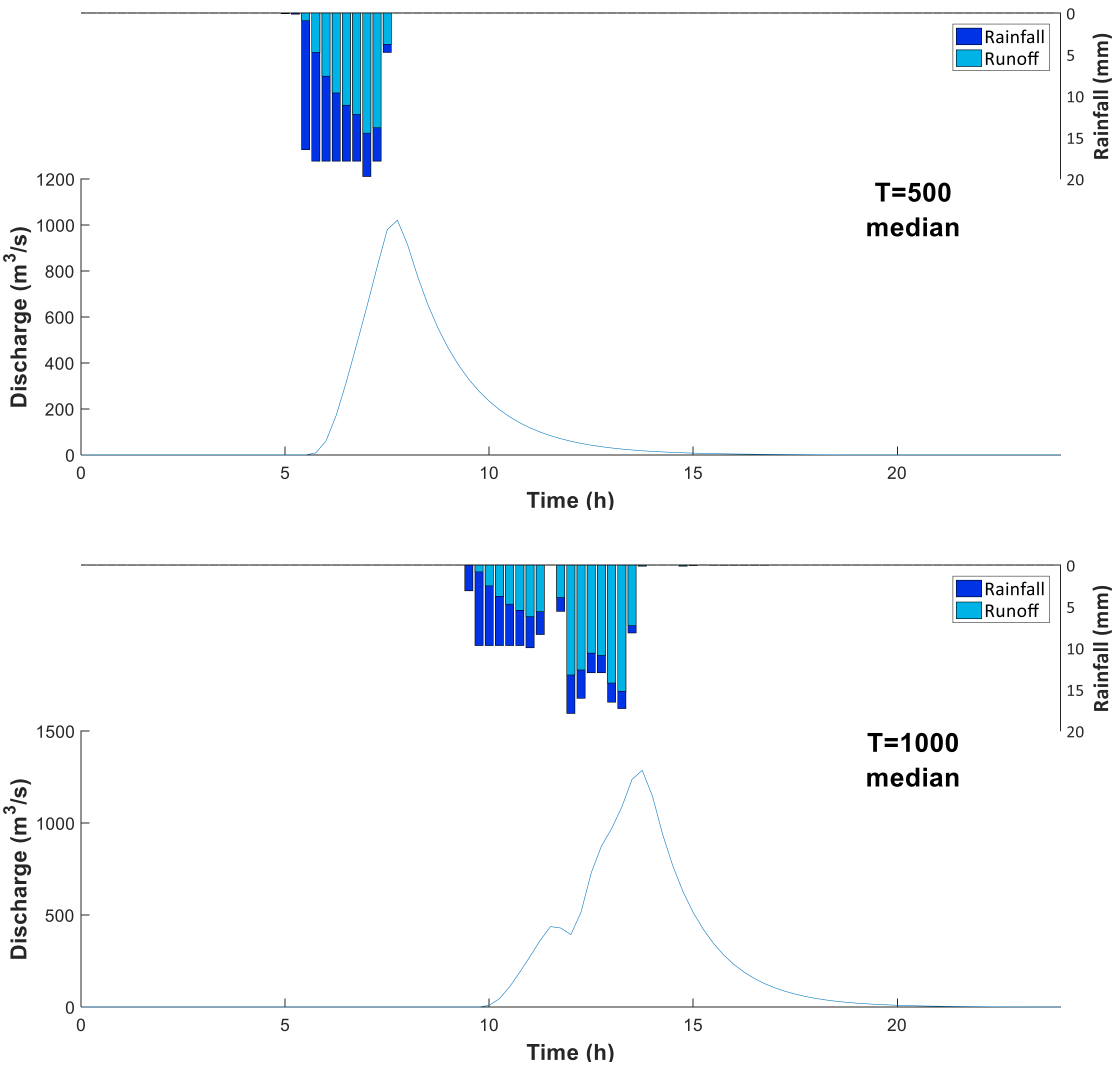

Figure 7-13 : Flood hydrographs for T=500 and 1 000 years (median estimation)

After having examined not only the set of flood hydrographs presented in this chapter, but also the hydrographs listed in the Appendix, it is easily assumed, based on engineering experience that such hydrographs are far more realistic than the ones provided by the typical deterministic framework. This is mostly due to the stochastic disaggregation scheme incorporated into the framework, which produces realistic rainfall profiles, contrary to the standard rainfall pattern produced via the alternating blocks method.

An indicative example of the above is the flood hydrograph corresponding to 50 years return period, when two peaks occur. Such a hydrograph shape cannot be obtained by any of the commonly used frameworks.

Of course, peak discharges are highly dependent on the temporal evolution of the storm. As anticipated, greater peak discharges occur when rainfall depth is more concentrated in smaller time intervals.

Finally, it should definitely be highlighted that, even if each simulation had a length equal to 10.000 years, only the results up until a return period of 1 000 years were considered reliable. The rest were omitted from our investigations.

7.6 The continuous part of the proposed framework

The continuous part of the proposed framework is implemented in the Rafina stream basin. Firstly the results from a single simulation with a length equal to 1 000 years are presented, regarding the generated runoff and the distribution of CN values across days. Moreover, the difference between selecting events of annual maxima of runoff and events of annual maxima of rainfall is investigated.

It should definitely be noted that among different simulations soil moisture conditions vary and not always the same CN values are assigned to rainfall of a given return period. Hence, a unique simulation is indicative and reliable only in terms of identifying coarser behaviors and apparent tendencies.

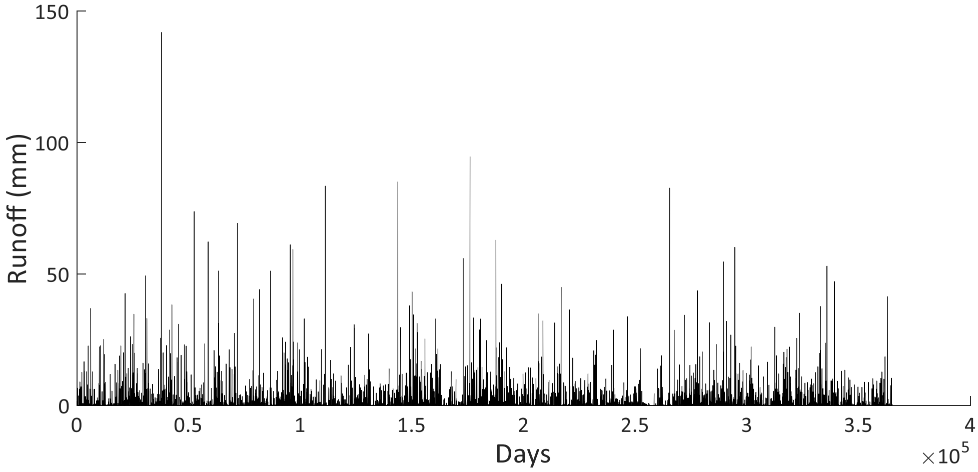

Figure 7-14 : Daily runoff calculated by the continuous simulation scheme

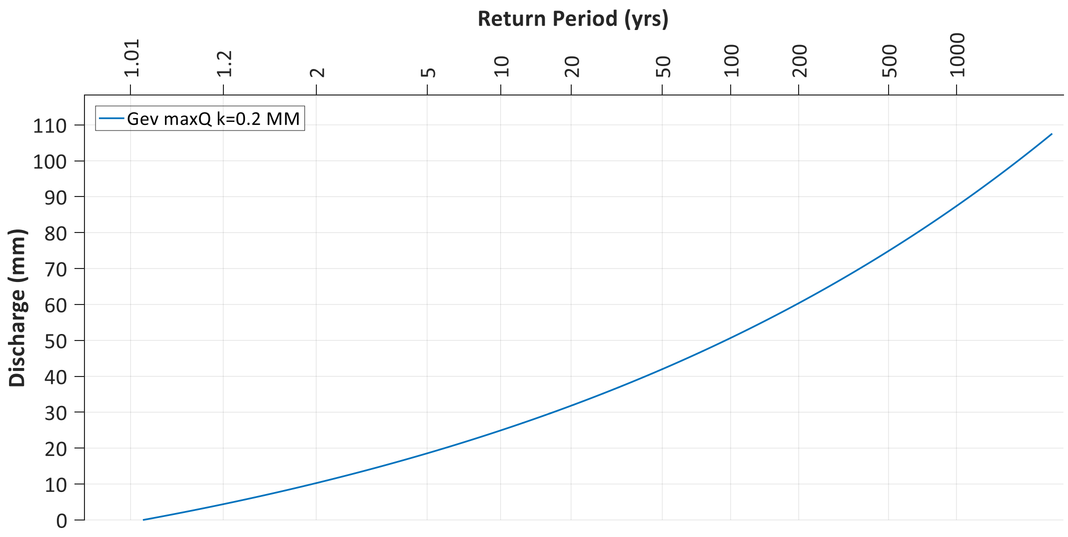

Figure 7-15 : Distribution of runoff annual maxima

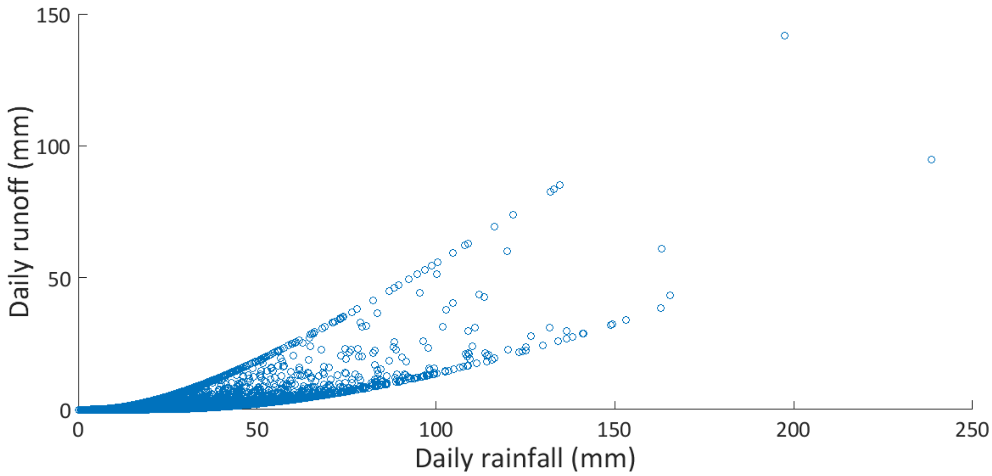

Figure 7-16 : A scatter of the daily rainfall versus the generated runoff

In Figure 7-16 the variability of soil moisture conditions is quite apparent. Two lines are distinct serving as the upper and lower boundaries of the graph that correspond to the CNIII and CNI values respectively. One can easily deduce that, of course, larger rainfall depths do not necessarily produce larger flood volumes, since, some of the largest storms, in terms of total depth, occur in dry conditions (i.e. bottom line).

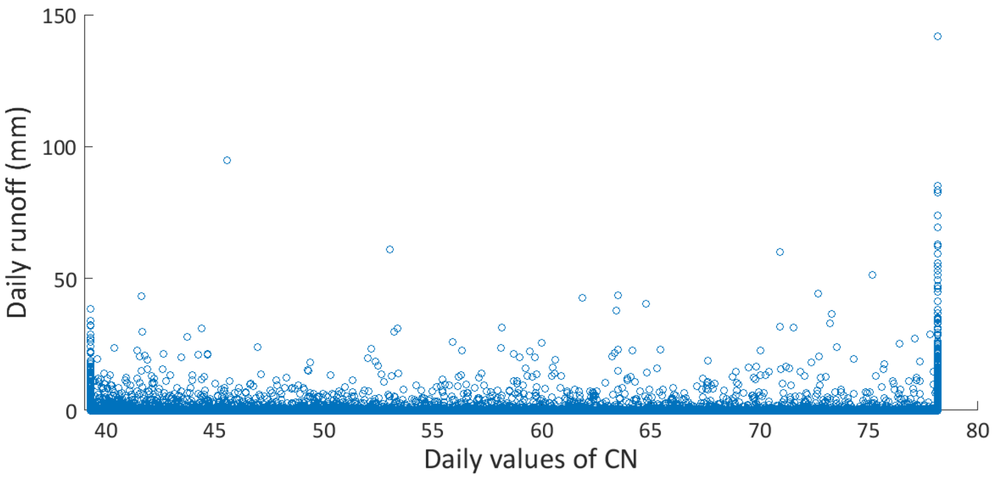

Figure 7-17 : Scatter of daily values of CN versus the daily runoff

In Figure 7-17 it is quite evident that, even though most of the greatest flood volumes are generated under wet soil, significant floods occur also under medium or even dry conditions.

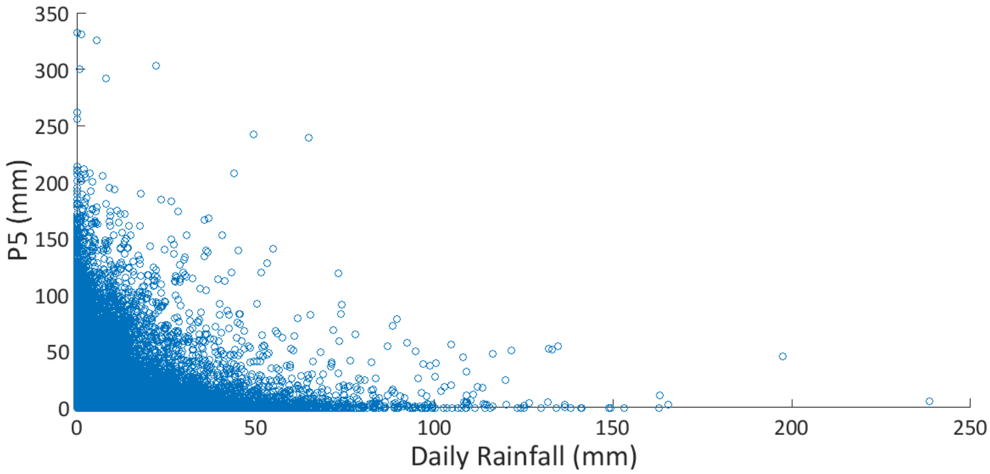

Figure 7-18 : Scatter of daily rainfall versus 5-day cumulative Antecedent Precipitation (P5)

In order to further investigate the circumstances under which rainfall occurs, Figure 7-18 is attached, where no apparent relationship between rainfall and the 5-day cumulative Antecedent Precipitation is evident. However, more indicative is the following figure, where the distribution of CN values across days is depicted.

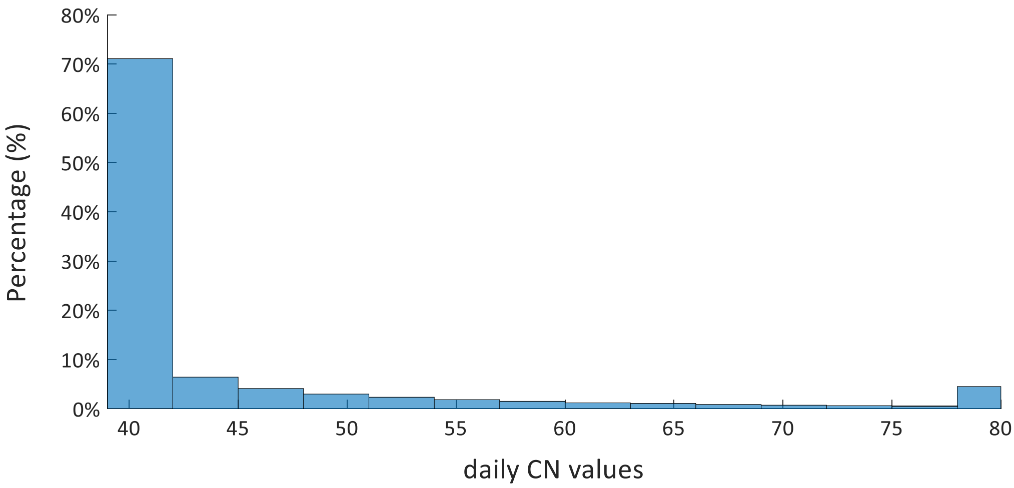

Figure 7-19 : Histogram of daily CN values

It becomes quite clear, based on Figure 7-19, that dry conditions are significantly the most prominent state in which the catchment can be found. However, this is highly biased by seasonality and dry periods, where no rainfall occurs, thus being of no interest for flood engineering.

What can be more helpful is Figure 7-20, which depicts the distribution of CN values only across wet days (i.e. days when rainfall has occurred). It should be noted that, even if dry conditions are still prominent, their frequency is significantly lower. This is indicative of the tendency of wet days to form clusters of multi-day wet periods. However, this distribution is still quite biased, since storms of extremely small rainfall depths that are still of no interest to flood engineering are still included.

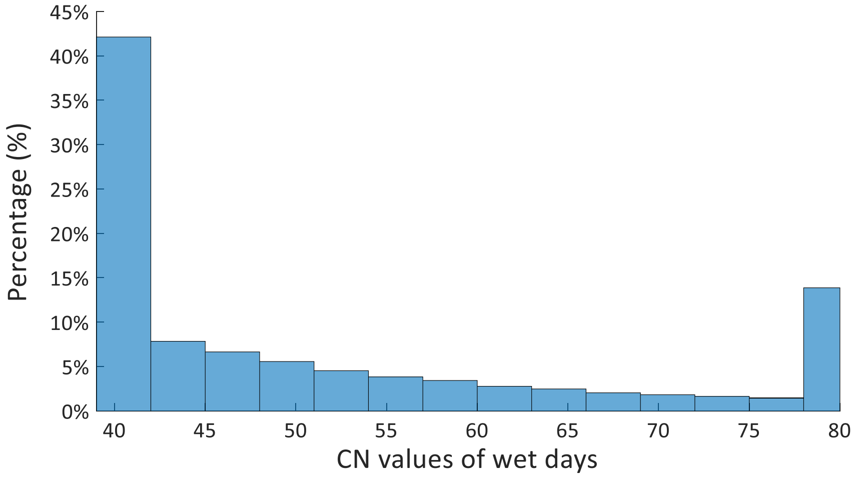

Figure 7-20 : Histogram of CN values across wet days (i.e. days when rainfall occurs)

The true state of the catchment area regarding the soil moisture conditions that highly affect the outcome is depicted in Figure 7-21 which follows. The figure shows the distribution of CN values across the events during which the annual maxima of runoff were generated. Here, it becomes quite clear that extreme events occur almost equally in dry as well as wet conditions. However, dry conditions still tend to be dominant.

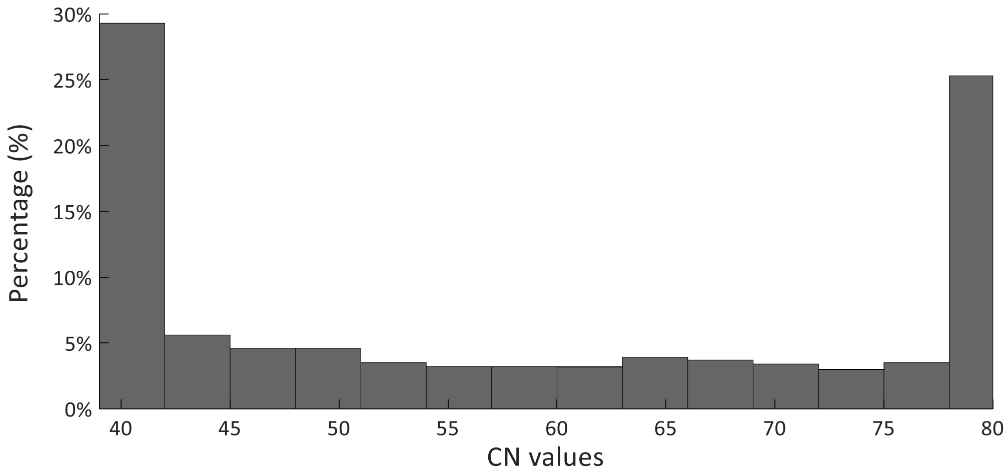

Figure 7-21 : Histogram of CN values for the selected events (where annual maxima of runoff occur)

In order to examine whether there is an apparent relationship between the total rainfall depth and the soil moisture conditions a scatter of CN values versus rainfall depths of the selected events is shown in Figure 7-22. It is clear that no evident relationship exists, even though it seems slightly more frequent for most extreme rainfalls to occur in drier conditions.

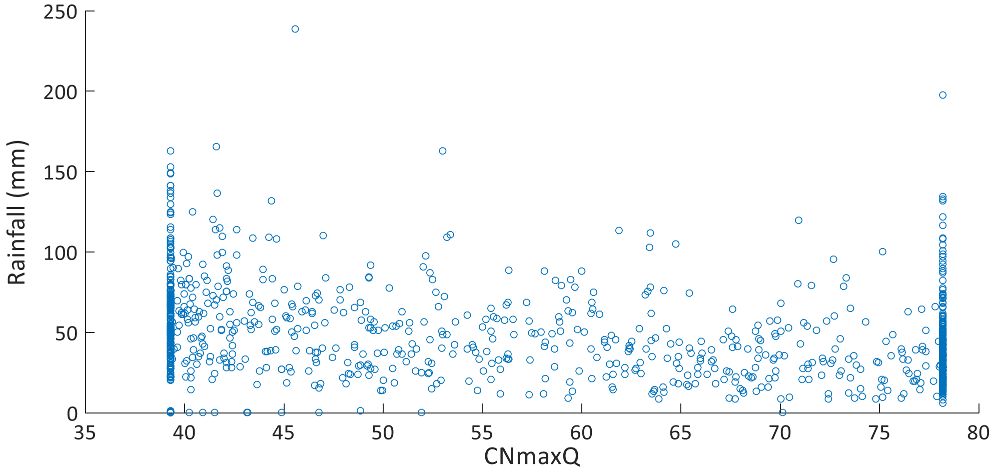

Figure 7-22 : Scatter of CN values versus rainfall depths for selected events

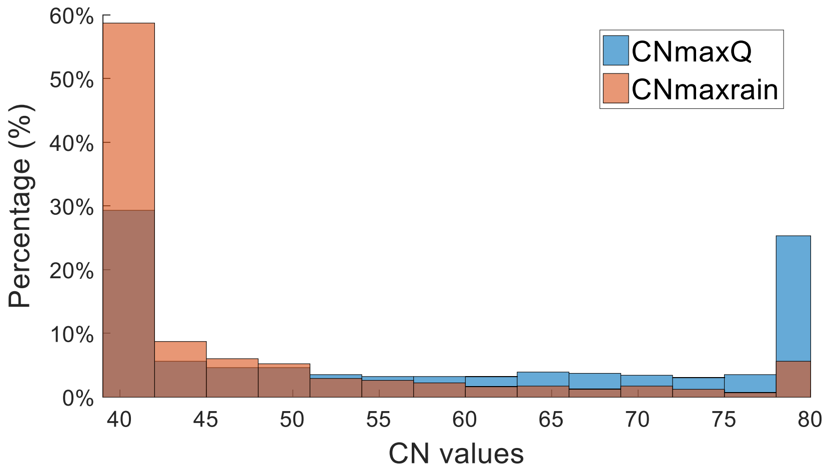

Figure 7-23 : Histograms of CN values for annual maxima of rainfall and annual maxima of runoff

In Figure 7-23 the distribution of CN values for the events when the annually maximum rainfall depths occurred, are compared to the selected events (annual maxima of runoff). It is obvious in the graph that the first occur mostly in dry conditions. This is characteristic of the rainfall regime of the region and is the reason why the two approaches provide different results.

In fact, the above comply with the findings of Pontikos (2014) who suggests that dry conditions are most prominent in eastern Greece and, consequently, arbitrarily choosing wet or medium conditions in the context of hydrological design may result in oversized expensive hydraulic works. On the contrary, he claims that the probabilistic nature of the soil moisture conditions must be taken into consideration, in order to conduct statistically consistent studies.

In this context, only a procedure including simulation is necessary in order to properly represent the actual probabilistic nature of soil moisture. We should note that a Monte Carlo scheme, with no simulation incorporated, during which a distribution (usually uniform) is arbitrarily assigned to soil conditions, is actually inconsistent and fails to represent the actual regime of the region.

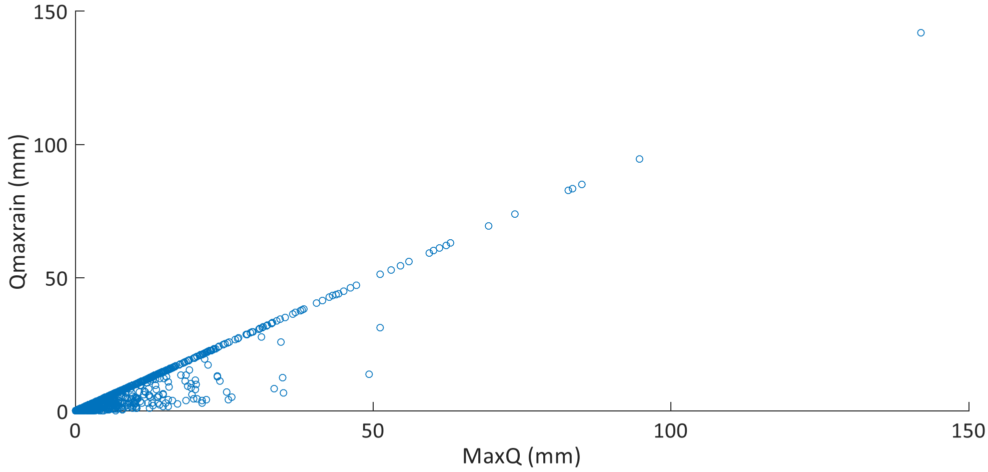

Figure 7-24 : Scatter of annual maxima of runoff (maxQ) versus the corresponding runoff generated by the events of annual maxima of rainfall (Qmaxrain) for every year

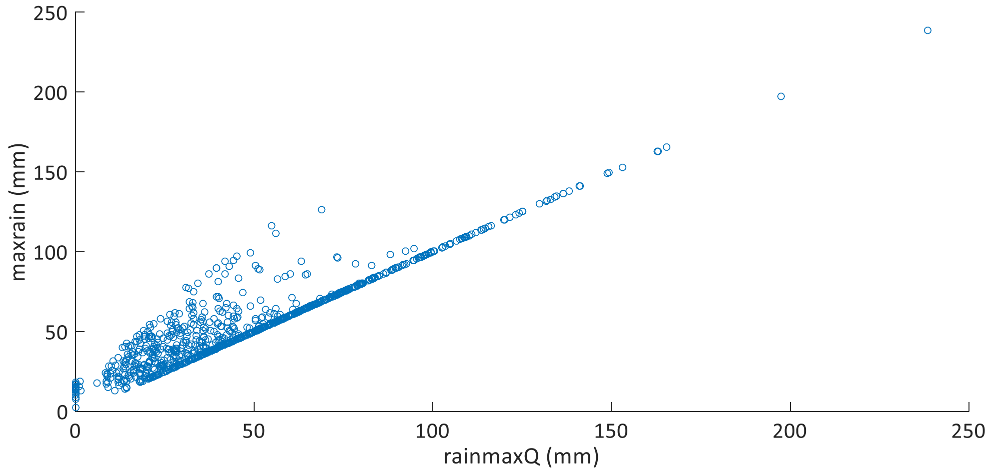

Figure 7-25 : Scatter of rainfall generating the annual maxima of runoff (rainmaxQ) versus the corresponding annual maxima of rainfall (maxrain) for every year

The difference between selecting the events where the largest runoff is generated, instead of the ones where the largest amount of water is precipitated, is depicted in Figure 7-24, as well as Figure 7-25. We should definitely note that differences arise mostly on small and medium return periods where some significant floods may be neglected if we select based on rainfall maxima. As a result, selecting based on runoff maxima rather than rainfall maxima is more appropriate, even if the two approaches coincide when it comes to the most extreme events.

7.7 The event-based part of the proposed framework

This chapter involves investigations regarding the event-based part of the pseudo-continuous stochastic simulation scheme.

The analysis is based on a single simulation with a length equal to 10 000 years, which, of course, is indicative and reliable only in terms of identifying coarser behaviors and apparent tendencies.

Different variations of the model, involving alternative approaches for estimating time of concentration and disaggregating rainfall will be implemented, in order to compare them with the proposed framework.

Firstly the impact of time of concentration in the results will be examined. As already stated, time of concentration, can alternatively be treated as a constant and calculated via the Giandotti formula.

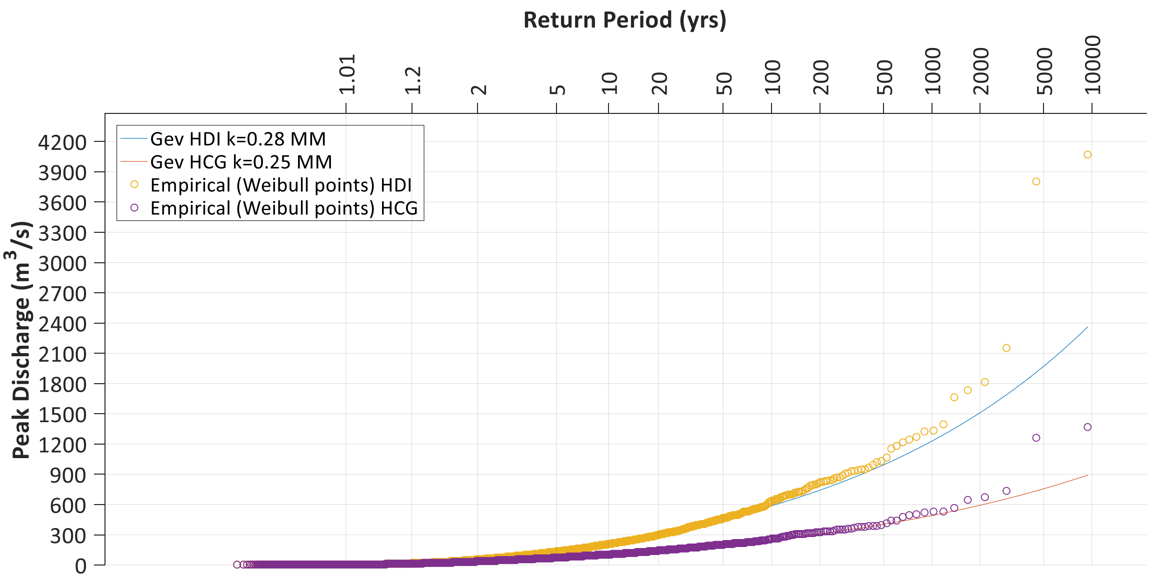

Figure 7-26 : Distribution of Peak Discharges estimated through HDI and HCG models

In Figure 7-26, where HDI and HCG models are compared, one can clearly notice the heavy impact that time of concentration has. HDI model, in the context of which time of concentration varies daily, produces far more significant floods than HCG model, where time of concentration is treated as a constant. Moreover, the non-linearity introduced in the model by the daily variation of time of concentration is also evident, since the shape parameter in HDI is larger than HCG.

When it comes to rainfall disaggregation, it can alternatively be conducted using the alternating blocks method, or by randomly uniformly distributing rainfall in time.

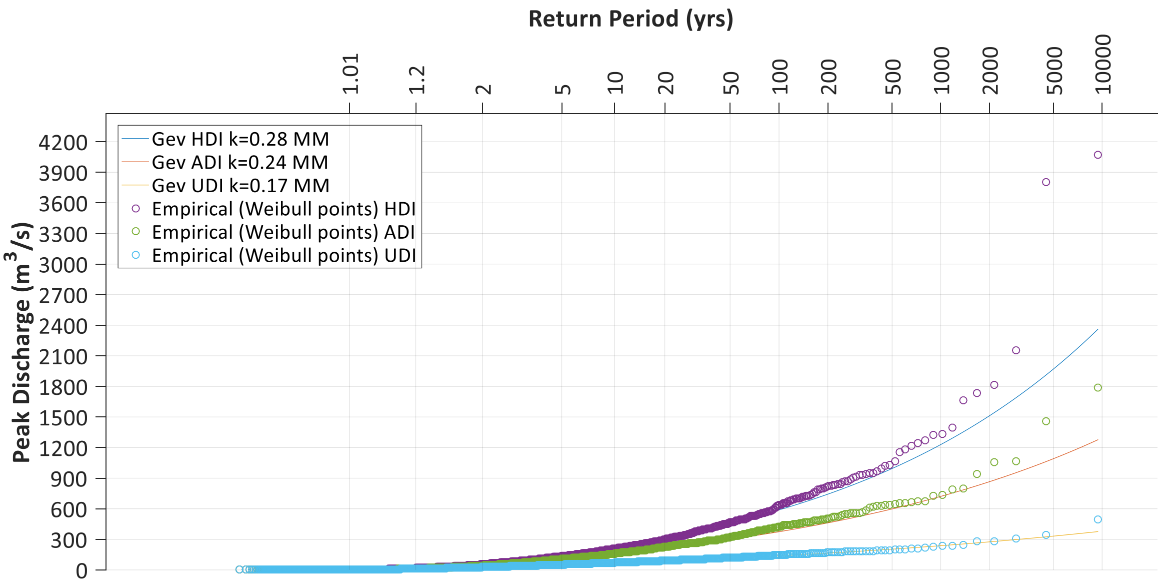

Figure 7-27 : Distribution of Peak Discharges estimated through HDI, ADI and UDI models

In Figure 7-27 the impact of the disaggregation scheme implemented in the model is presented. In particular, it appears that HDI model produces the most extreme floods, followed by ADI and UDI models. It seems that the patterns produced by the HyetosMinute model can produce greater peak discharges than the alternative blocks method, while a uniform distribution of rainfall produces the smaller floods.

Moreover the values of shape parameter are indicative of the non-linearity introduced by the stochastic disaggregation scheme, compared to the other two methods. Here, it is quite interesting that the uniform distribution of rainfall produces an “equally smooth” distribution of extremes.

In order to further examine the results between HDI, ADI and UDI models, the hydrographs corresponding to a return period equal to 20 and 100, years are presented in Figure 7-28 and Figure 7-29 that follow.

It is quite clear in these graphs that, on the one hand, a uniform distribution provides a smooth flood hydrograph extended in time, while, on the other hand, the HyetosMinute model provides rapid hydrographs, given that it happens that the rainfall depth is concentrated in small time intervals. The alternating blocks method provides a hydrograph that is not as rapid, since the rainfall increments are distributed throughout the whole day, rather than being concentrated in smaller scales, as in the second case.

The aforementioned are also validated by the findings presented in Figure 7-30, where HCG, ACG and UCG models are compared. In this comparison, time of concentration is constant; hence the observed differences appear due to the distribution of rainfall alone.

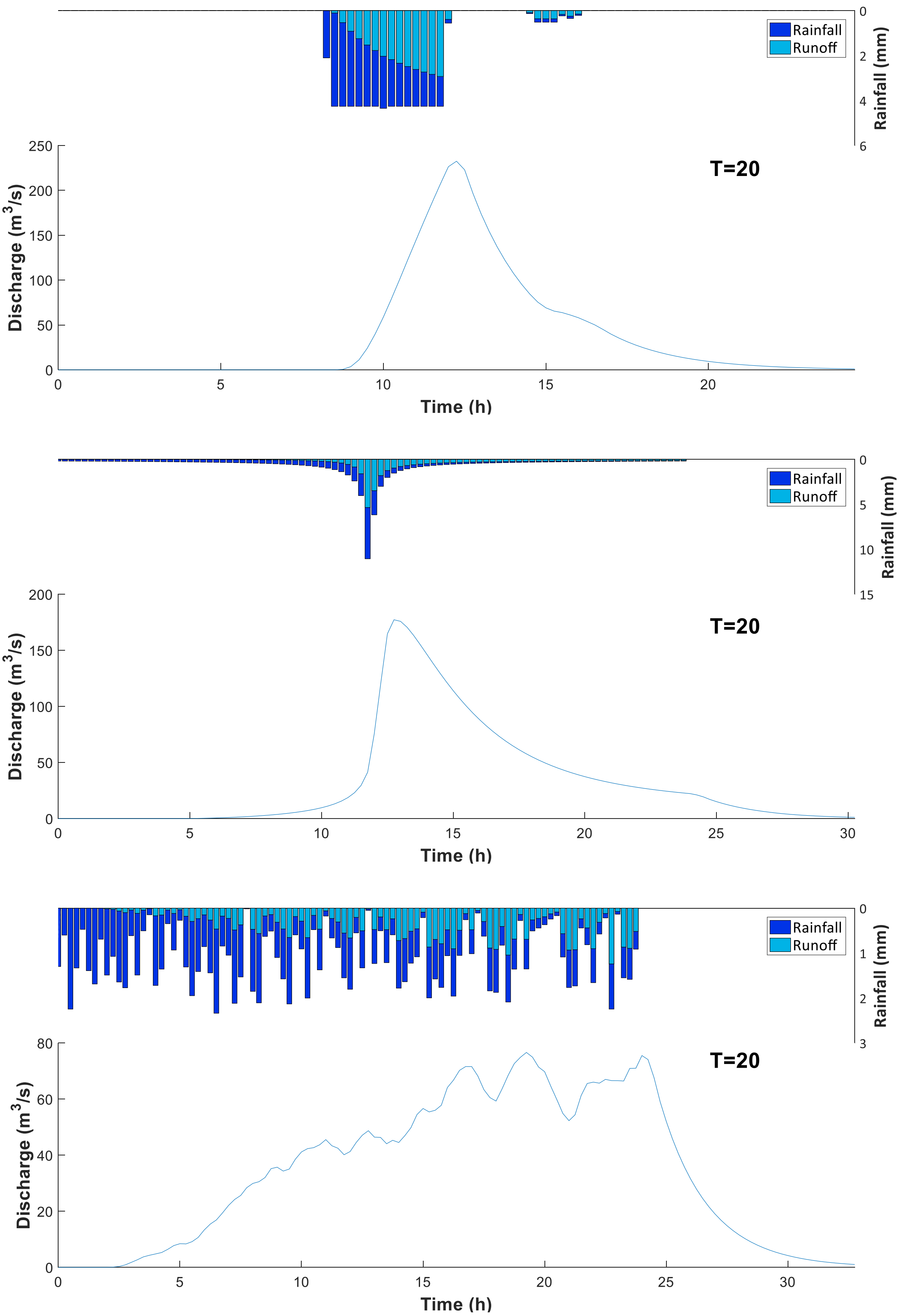

Figure 7-28 : Flood hydrographs produced by HDI, ADI and UDI (from top to bottom) - (T=20 years)

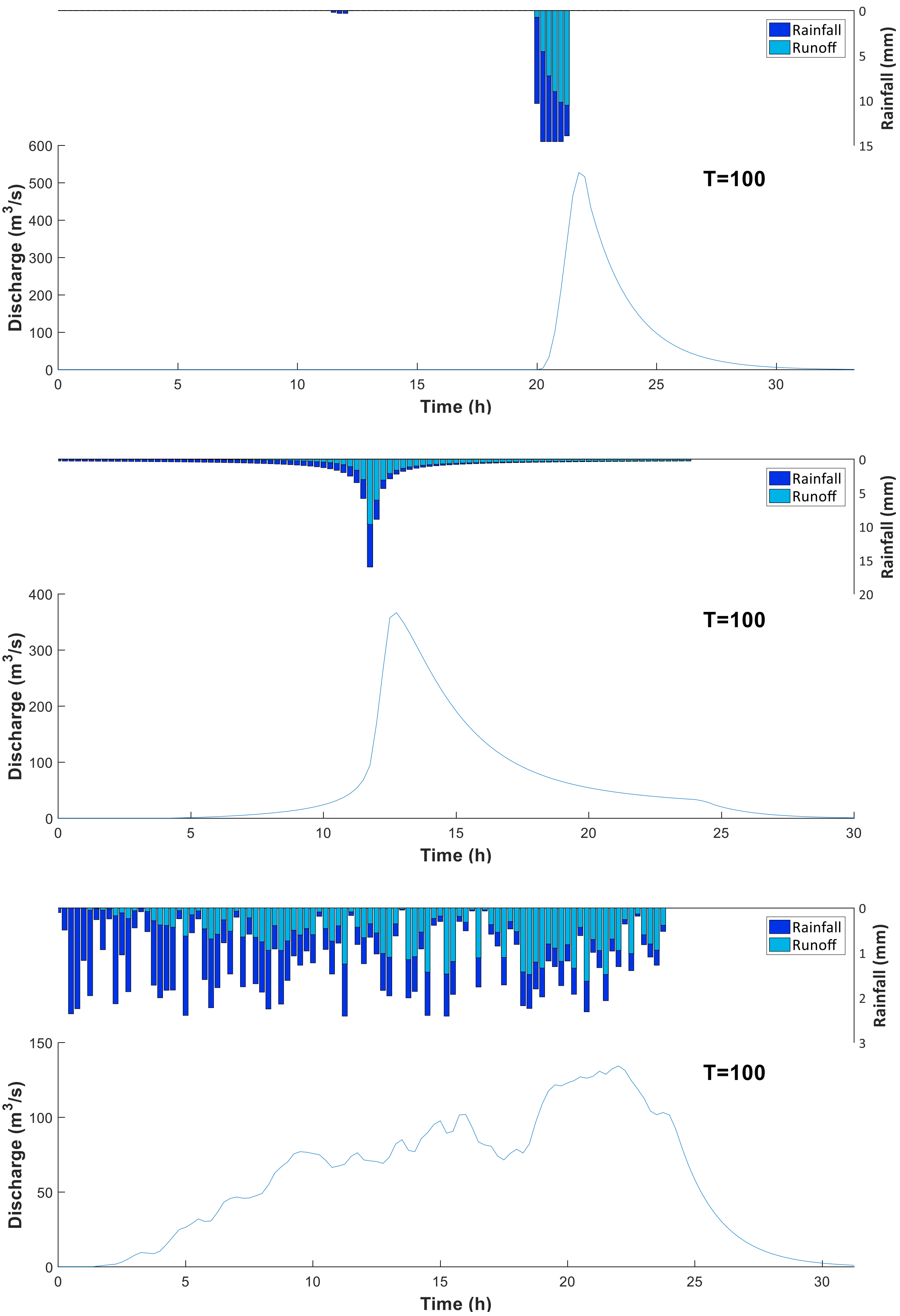

Figure 7-29 : Flood hydrographs produced by HDI, ADI and UDI (from top to bottom) - (T=100 years)

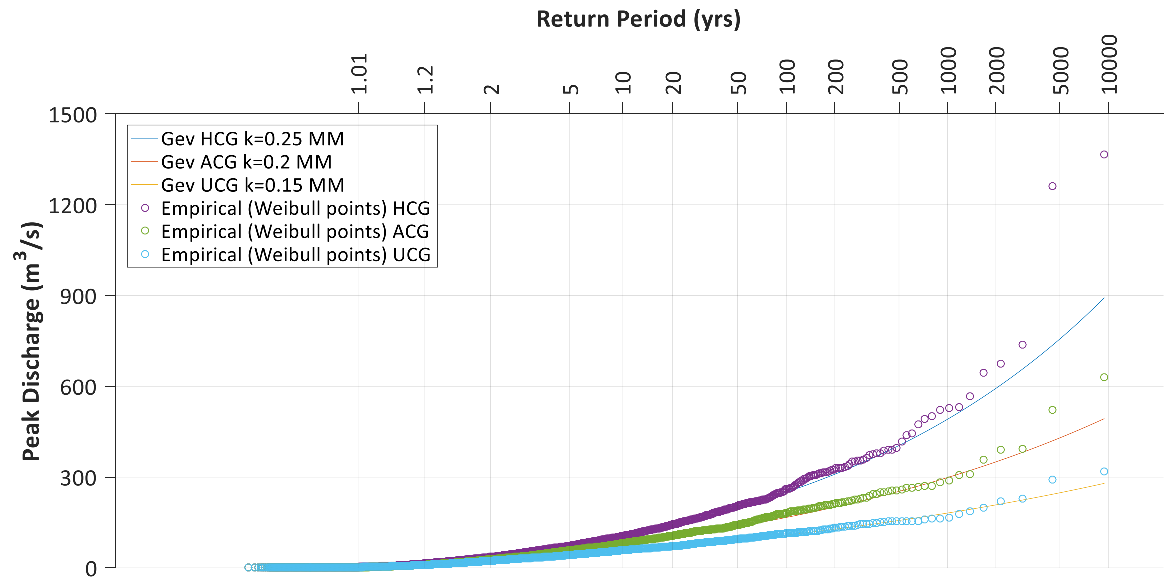

Figure 7-30 : Distribution of Peak Discharges estimated through HCG, ACG and UCG models

Finally, the following graph depicts a total comparison of all models examined in this chapter, including the results of the typical deterministic framework.

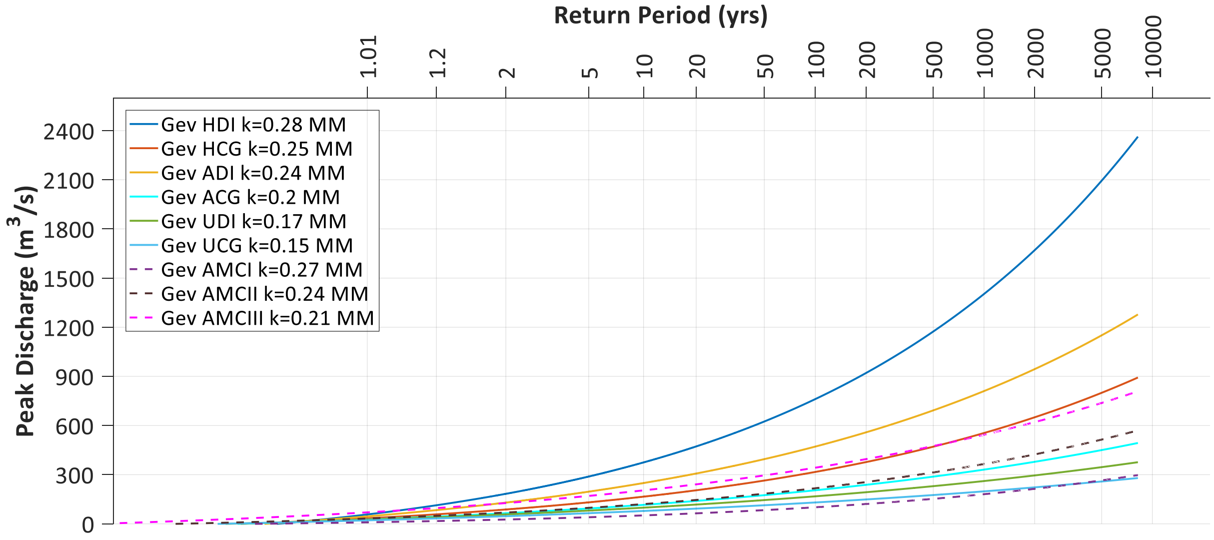

Figure 7-31 : Comparison of all the variations of the model, including the typical deterministic framework for the three AMC types

By examining Figure 7-31 we can see that HCG model and the deterministic framework for AMCIII, appear to provide quite similar results. In the following figure, a closer look in these two is taken.

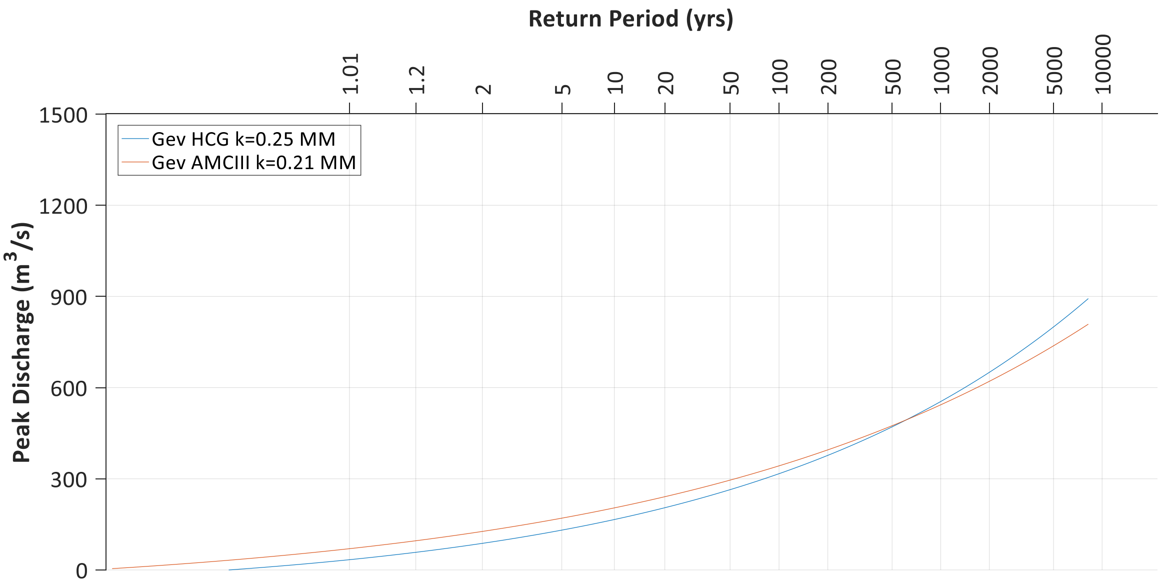

Figure 7-32 : Distribution of peak discharges estimated through HCG model and the typical deterministic framework for AMCIII

At this point the impact of treating time of concentration as a constant is apparent, even though in HCG model soil moisture conditions still vary daily. However, even if HCG model and the typical deterministic framework for wet conditions seem to provide similar results, the first is still more consistent, since it provides more realistic flood hydrographs, in contrast to the “standard” shape of the hydrographs produced by the latter one, because of the given pattern of rainfall.

The above may have significant influence when the produced hydrographs need to be used as inputs for any hydraulic model.

In Figure 7-33 and Figure 7-34the scatters of time of concentration and CN values versus the corresponding peak discharges are shown. These are extracted by the twenty simulations conducted under the Monte-Carlo scheme.

Not surprisingly, the relationship between time of concentration and peak discharges is quite similar to the relationship between time of concentration and runoff.

Meanwhile, as anticipated, the scatter of CN values versus peak discharges is very similar to the distribution of CN values across the days where the annual maxima of runoff are generated. Obviously, throughout the twenty simulations the most extreme floods in terms of peak discharge were generated under wet conditions. However, some of the greatest floods were produced under medium and even conditions as well.

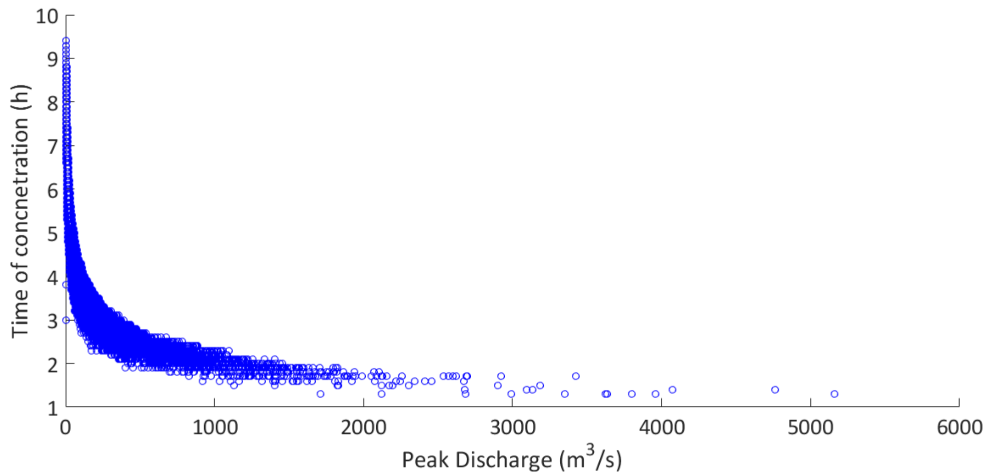

Figure 7-33 : Scatter of QpeakmaxQ values versus the corresponding time of concentration

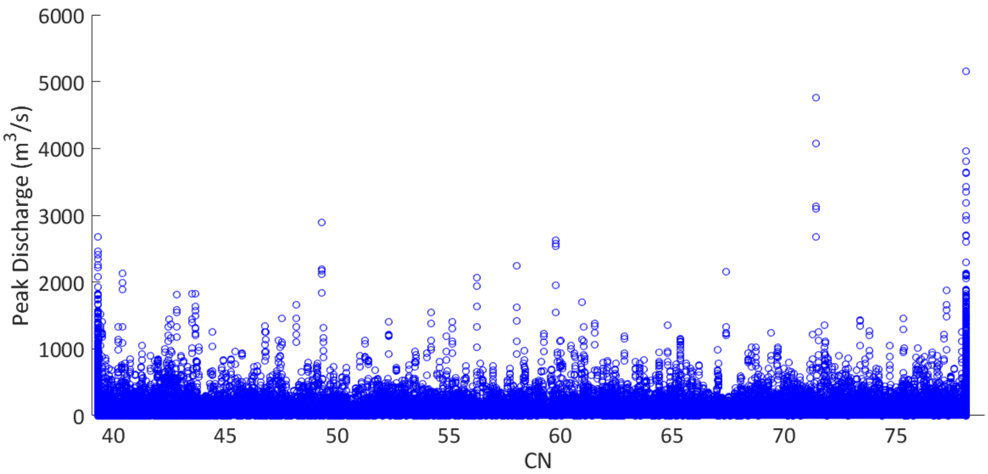

Figure 7-34 : Scatter of CN values versus the corresponding Peak Discharges

In turn, the analysis regarding the determination of the duration of storms is presented. As already stated, the HDI model will also be implemented in cases where the duration of a storm is determined as 2 and 3 days. The results are shown in Figure 7-35.

We should note that the initial conditions under these schemes are the conditions occurring at the beginning of every multi-day episode, which have been estimated through an implementation of the continuous part of the model in a daily scale.

Given the nature of the NRCS-CN method where the portion of rainfall turning into runoff gets higher while the storm develops, one would anticipate that duration equal to 3 days would provide the most extreme floods. However, this is not the case, since it appears that duration equal to 1 day still provides greater peak discharges, followed by two and three days.

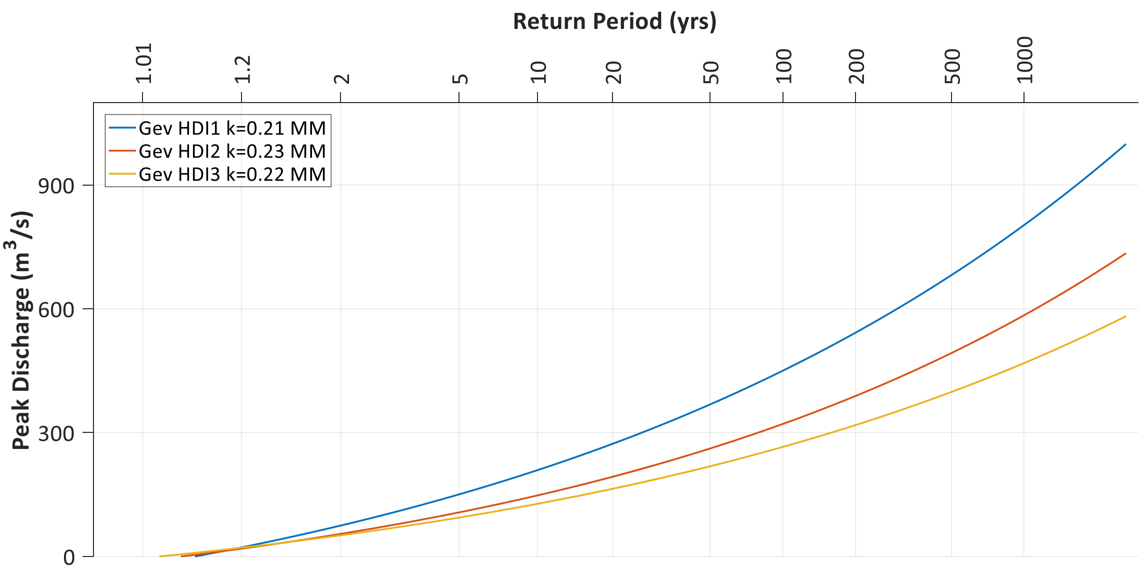

Figure 7-35 : Distribution of peak Discharges estimated through HDI model, where the duration of a storm is determined as 1, 2 and 3 days

The paradox mentioned above is mostly due to the rainfall disaggregation model which generates storms whose incremental depths are not necessarily distributed closely in time, as seen in the following flood hydrographs. As a result, the resulting hydrograph may have two or three peaks and a unique rapid peak is not observed instead. Figure 7-36 which depicts the flood hydrographs of the three models for a given return period is quite indicative.

A model providing storm temporal evolutions consisting of more compact clusters of rain, instead of separate pulses, would probably produce the anticipated results, however further investigation is beyond the scope of this thesis.

Moreover, we should also highlight an issue regarding the determination of the initial conditions as the conditions at the beginning of a multi-day storm. In order to better grasp this, an example will be provided.

The rainfall depth of a 3-day event, following a multi-day dry period, falls as follows; 5mm in the first day, 30 mm in the second day, and 50mm in the third day. The 50mm precipitated in the third day follows the 100 mm observed in the second one.

In a daily analysis these 100mm would be included in the estimation of the 5-day Antecedent Precipitation, thus, increasing the wetness of the soil. However in a multi-day analysis, the initial conditions of the event would be considered as dry. As a result less runoff would be generated by the same amount of rainfall.

Of course, the opposite can also happen (i.e. taking into consideration an antecedent day that would not otherwise affect the result). As a result, since the model is quite non-linear the outcome cannot be predicted and no safe results can be made.

In order to investigate the above, Figure 7-37,Figure 7-38and Figure 7-39 are listed below. These figures show that wet conditions are slightly more prominent when the analysis is based on duration equal to 3 days. However, this tendency is not apparent and may vary between different simulations.

Of course, we can safely deduce that the distribution of CN values is roughly the same in all three cases. Given that, it becomes clearer that the sole thing affecting the results is the distribution of rainfall.

Moreover, it would definitely be more consistent if the time of concentration and/or soil moisture conditions would gradually change during an event, providing smaller hydraulic response times and greater CN values, as the storm developed. However, such an investigation is beyond the scope of this thesis.

In addition, the applicability of NRCS-CN method in multi-day events is yet another question that needs to be addressed.

In the context of this thesis, a preliminary investigation was made and further research definitely needs to be conducted.

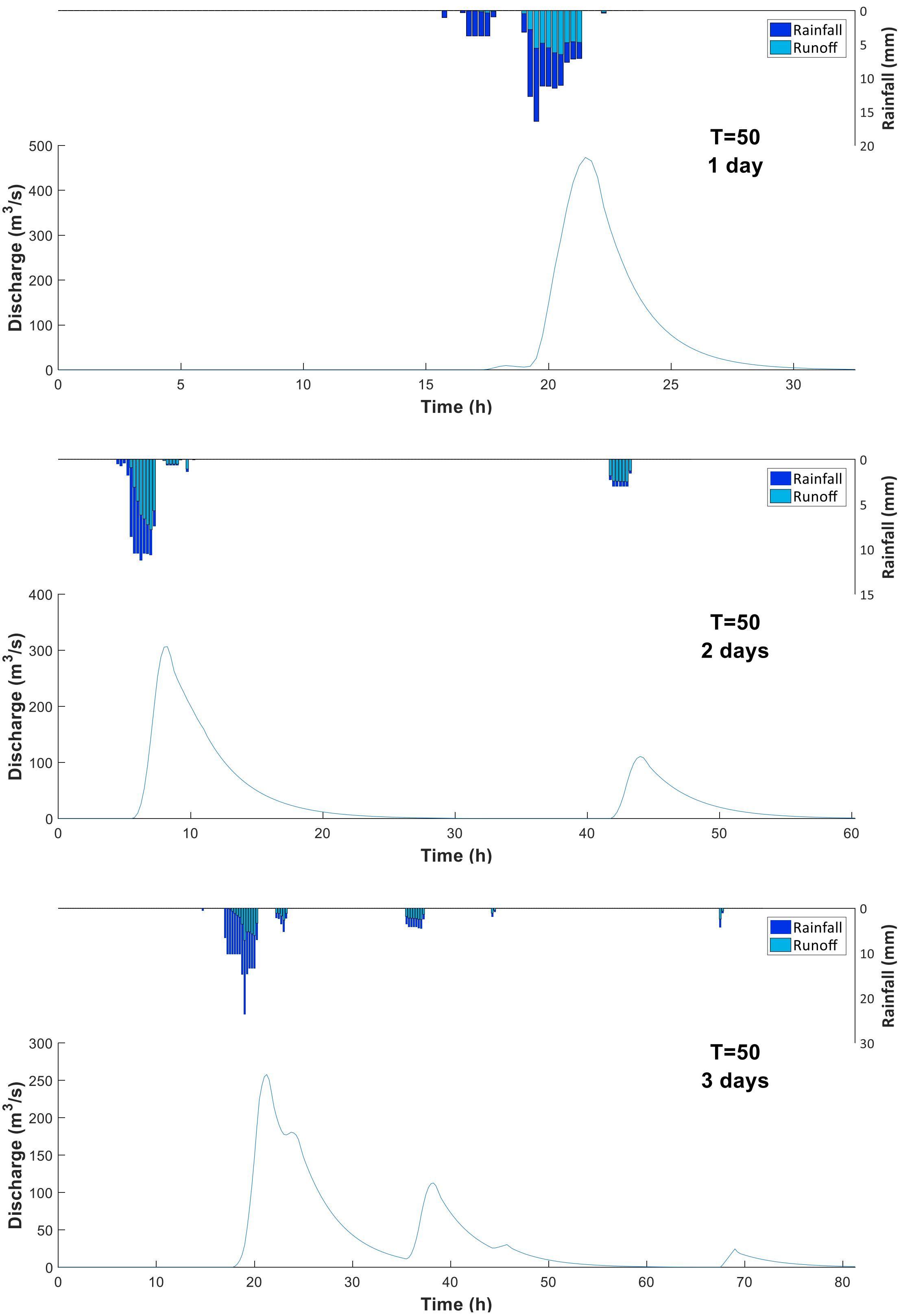

Figure 7-36 : Flood hydrographs estimated via HDI model, where the duration of a storm is determined as 1, 2 and 3 days

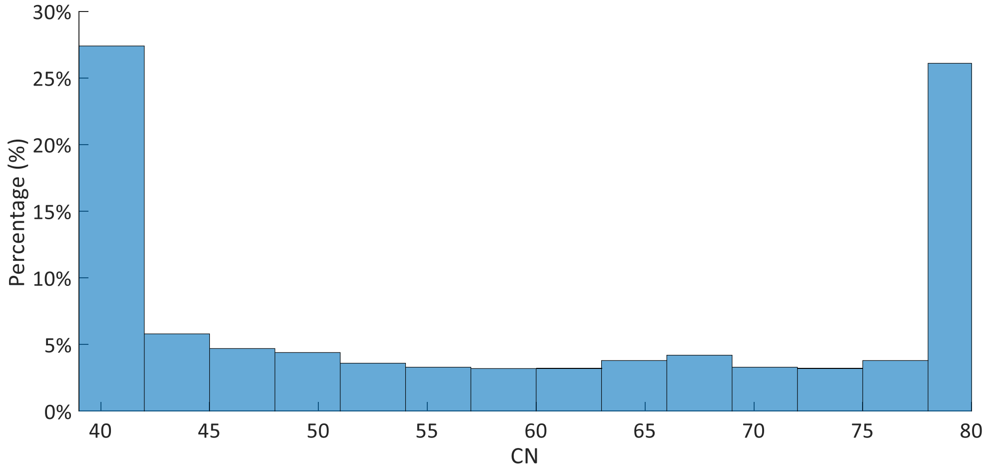

Figure 7-37 : Distribution of CNmaxQ values (duration of storm = 1 day)

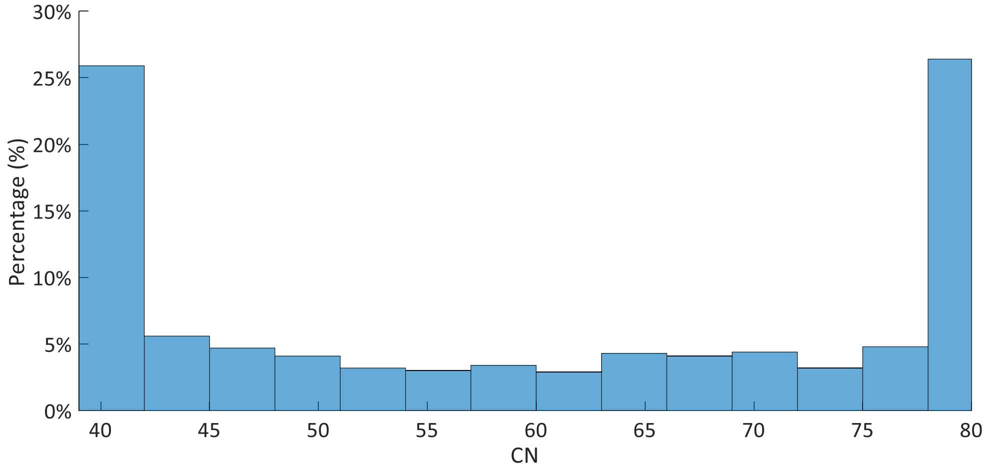

Figure 7-38 : Distribution of CNmaxQ values (duration of storm = 2 days)

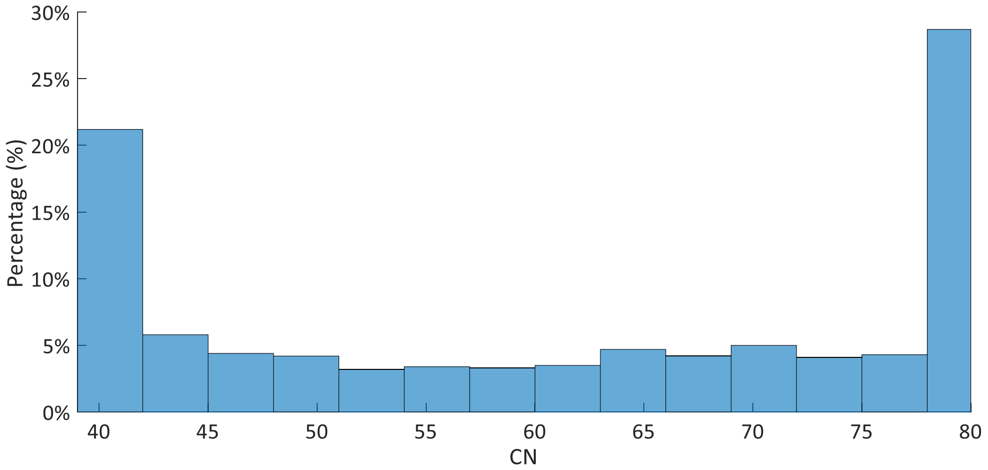

Figure 7-39 : Distribution of CNmaxQ values (duration of storm = 3 days)

Finally, the distributions of Qpeakmaxrain and QpeakmaxQ estimated through the HDI model are shown in Figure 7-40. As one can clearly notice the two distributions almost coincide and one would wonder whether an analysis based on selecting the events when the annual maxima of runoff occurred is actually better than an analysis based on the annual maxima of rainfall.

In order to further investigate this Figure 7-41 and Figure 7-42 are also attached. In the first graph, the scatter of QpeakmaxQ versus the corresponding Qpeakmaxrain values is depicted. Here, it is evident that the greatest events coincide in the two cases, as already stated in the previous chapters.

However, the second graph –which is actually the same scatter plot- is far more interesting, since it focuses only on events of smaller significance (i.e. with a return period no more than 50 years approximately). Here it is quite clear that when it comes to smaller return periods the two approaches greatly differ. One should also notice that there are also events where the Qpeakmaxrain is larger than QpeakmaxQ. This is of course natural, since smaller flood volumes can actually produce greater peak discharges, depending on the temporal distribution of rainfall.

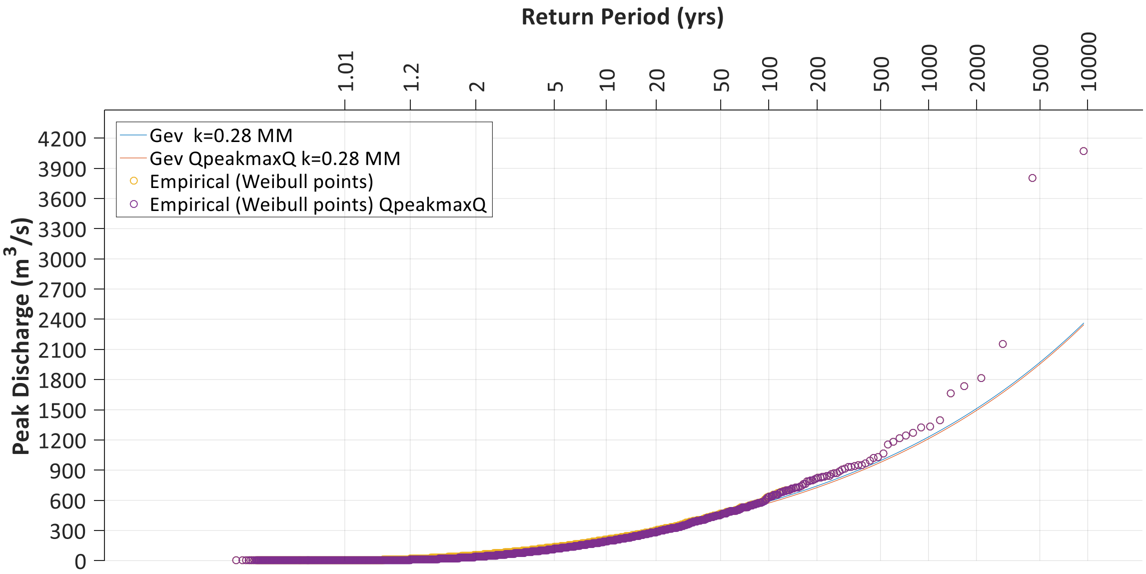

Figure 7-40 : Distributions of Peak Discharges estimated through the HDI model. In the first case QpeakmaxQ and in the latter Qpeakmaxrain are shown

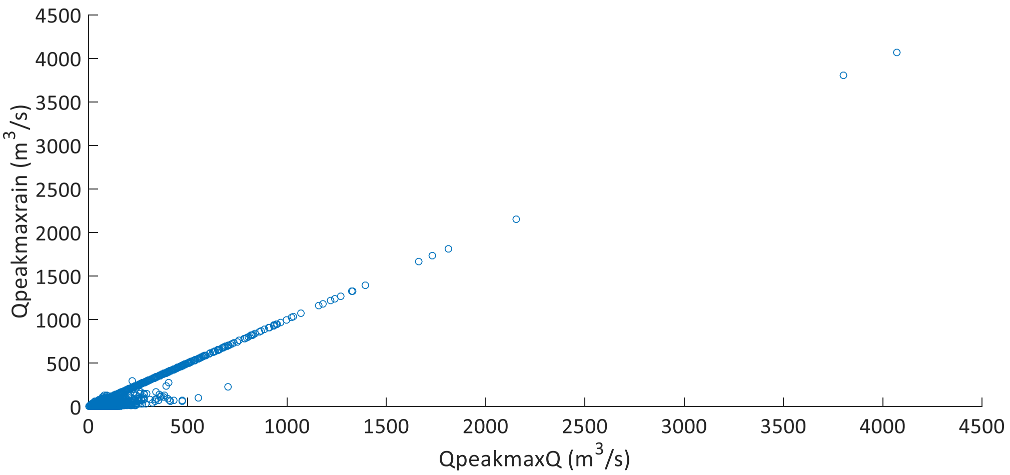

Figure 7-41 : Scatter of QpeakmaxQ versus the corresponding Qpeakmaxrain of every year

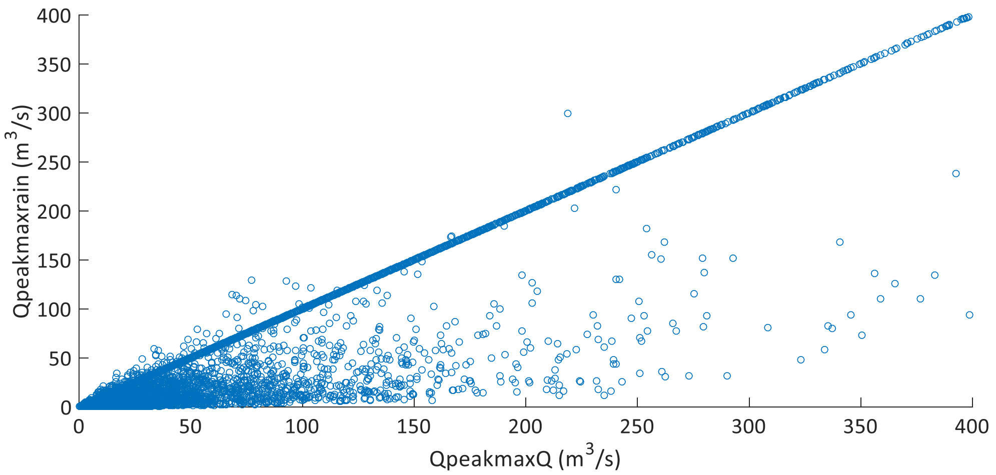

Figure 7-42 : Scatter of QpeakmaxQ versus the corresponding Qpeakmaxrain of every year focused on less significant events

Consequently, it is quite evident that the approach based on selecting annual maxima of runoff is better in terms of estimating floods of return periods smaller than 50 and provides the same results with selecting the annual maxima of rainfall, when it comes to estimating greater floods. As a result, the first approach is far more consistent and beneficiary.

Finally it should be noted that the GEV distribution cannot be properly fitted to the distributions of peak discharges, when the shape, scale and location parameters are estimated through the L-moments method, as shown in the following figure. The L-moments method seems to be insensitive to greater values and highly biased by the main body of the distribution.On the contrary, fitting the GEV distribution based on the Moments method proposed by Koutsoyiannis (2004) seems to provide better results.

Nevertheless, we should definitely state that maybe other distributions could be used instead. However, further investigation was not conducted since this is beyond the scope of this thesis.

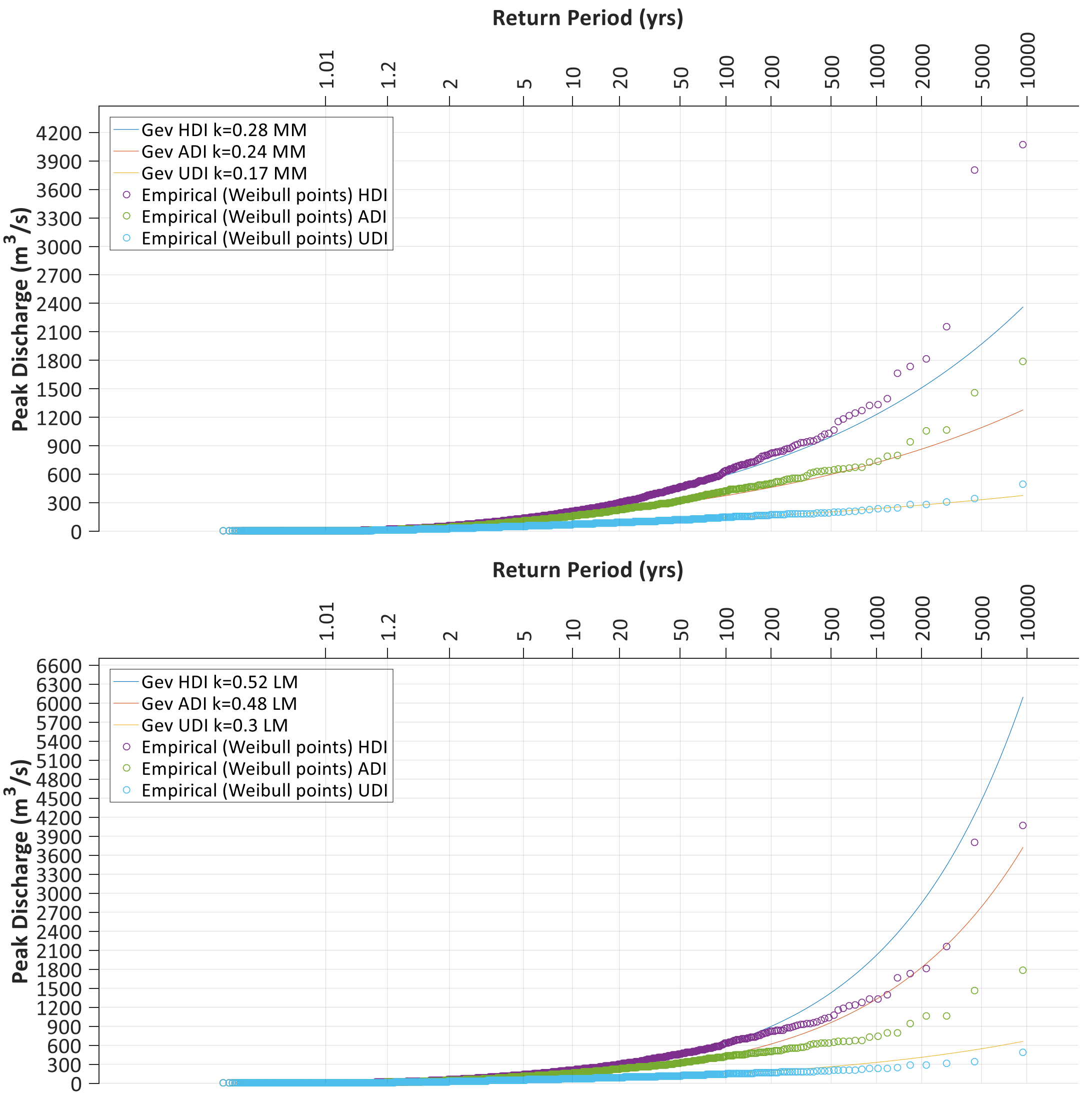

Figure 7-43 : Distributions of peak discharges provided by HDI, ADI and UDI models. In the first case, GEV is fitted through Methods Moment, while, in the latter case the L-moments method is used

7.8 Annie-Model integrated in the proposed framework

In this chapter the Annie-HDI model will be tested, which is actually the proposed framework, with the Annie-model incorporated instead of the continuous scheme based upon the Antecedent Precipitation.

As already stated in 7.2, since the model has not been calibrated based on measurements from Rafina stream basin we cannot conduct reliable comparisons with the proposed framework. However, the parameters of the model are arbitrarily set, in order to better reproduce the response of the proposed framework. The parameters were set such, that Annie-HDI would produce the same runoff/rainfall ratio with the HDI model, throughout a simulation.

More specifically, we have set the parameters as follows;

Table 7-5 : Parameter set for Annie-model

Parameter	Value
Initial abstraction (I_a)	10 mm
Soil Storage (K)	300 mm
Recession rate for percolation (a)	0.017

At this point we should definitely note that there are more than one parameter sets that may provide results similar to the HDI model, however further investigations are beyond the scope of this thesis and, after all, there are no measurements available. As already stated, there could be multiple optima for a single calibration method (Beven, 1993). Further investigation and a more complete Monte-Carlo scheme under which multiple sets of parameters were determined can be found under Papoulakos et al. (2017).

It is quite evident that calibrating Annie-Model without any measurements, but only in the context of reproducing –in terms of quality- the response of our framework is not actually reliable. As a result, only preliminary investigations are made in order to identify any apparent relationships or behaviors and safe conclusions can absolutely not be drawn. Hence, no comparison between the Annie-HDI and the proposed HDI model will be made, as they may prove to be quite misleading.

The analysis was based on a single simulation with a length equal to 1 000 years and a Monte-Carlo simulation with the use of more than one timeseries was not conducted, since the estimation of confidence intervals would be of no use to a non-calibrated model.

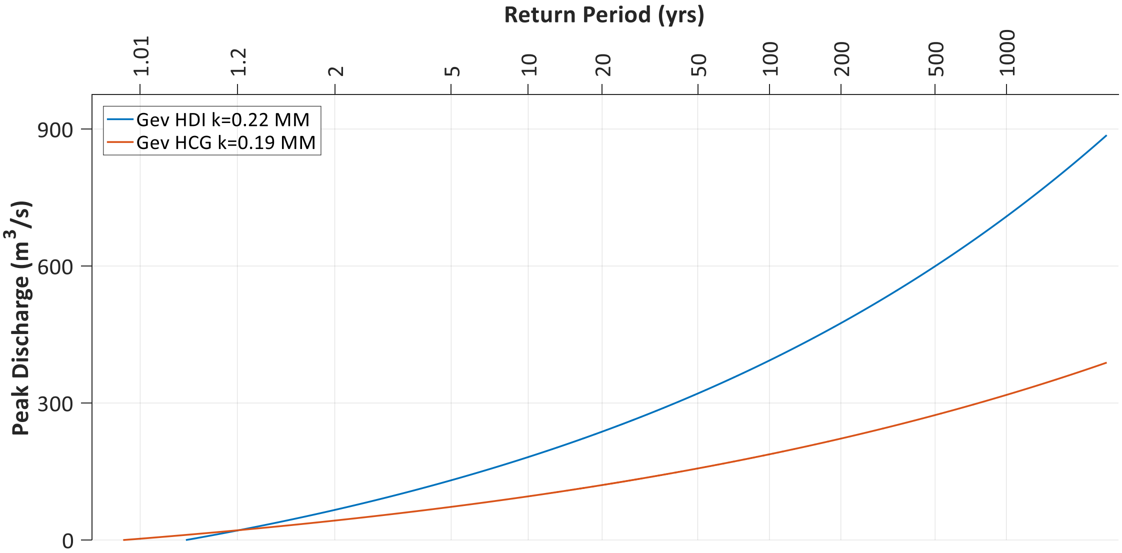

Figure 7-44 : Distribution of Peak Discharges estimated through Annie-HDI and Annie-HCG models

Firstly, the peak discharge distributions estimated through Annie-HDI and Annie-HCG models are presented in Figure 7-44. Since the only thing that changes from the proposed framework is the continuous part of the model regarding the estimation of initial conditions at the beginning of every event, the impact of time of concentration and rainfall disaggregation technique obviously remain the same.

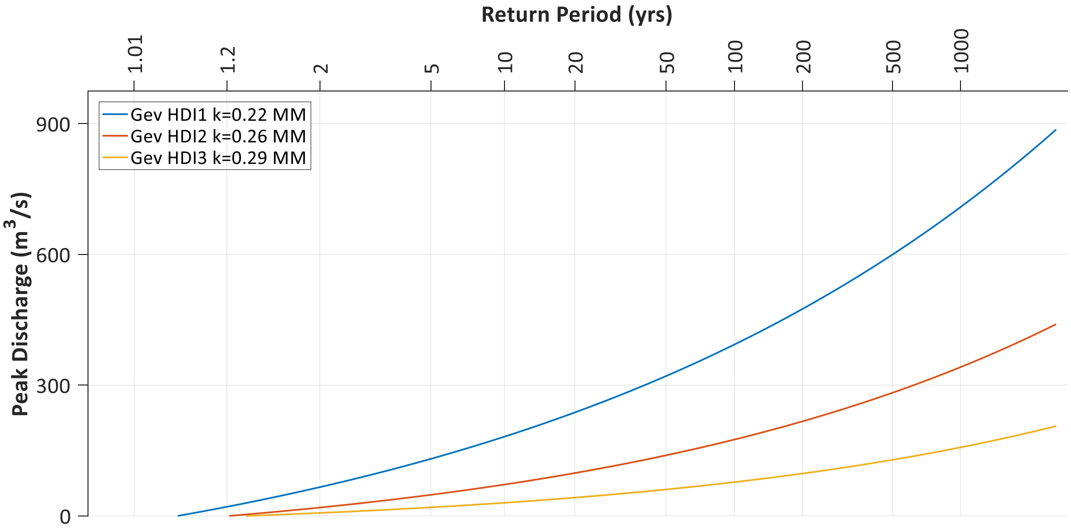

Figure 7-45 : Distribution of peak Discharges estimated through Annie-HDI model, where the duration of a storm is determined as 1, 2 and 3 days

The above is also implied by Figure 7-45, whose findings suggest that the relationship between the distributions of peak discharges, for durations determined as 1, 2 or 3 days, remains the shame, regardless of the continuous model incorporated. An analysis based on 1-day events still produces greater floods than 2-days, followed by 3-days analyses.

In turn, we will try to examine whether the results of Annie-model validate in any way the results that the continuous scheme which is based on Antecedent Precipitation produces. Of course, as already stated, the validation we are after, is only conceived by means of qualitative coarser relationships and behaviors. If such relations actually appear, this could be an indication implying that the model based on Antecedent Precipitation could be as efficient as a more complete continuous model would probably be.

However, it should be strictly highlighted that such any deductions made are only preliminary and further investigation is absolutely necessary.

The findings regarding soil moisture variability are depicted in Figure 7-46. There, dry conditions appear to be the most prominent, as happened in the HDI model.

Meanwhile, greater floods seem to occur mostly under medium and wet conditions, as shown in Figure 7-47. Extremely wet conditions do not occur, but, of course, this may not necessarily the case in Rafina stream basin, since the results are strongly dependent on the determination of K and I_a. Nevertheless, the tendency of dry conditions being prominent in the region still appears, as in the Antecedent Precipitation based approach.

It should be noted, that it is of highly importance that the actual rainfall regime appears to be properly taken into consideration, in terms of soil moisture variability. Dry periods followed by sudden storms under dry conditions are mostly the case in Greece and Attica in particular.

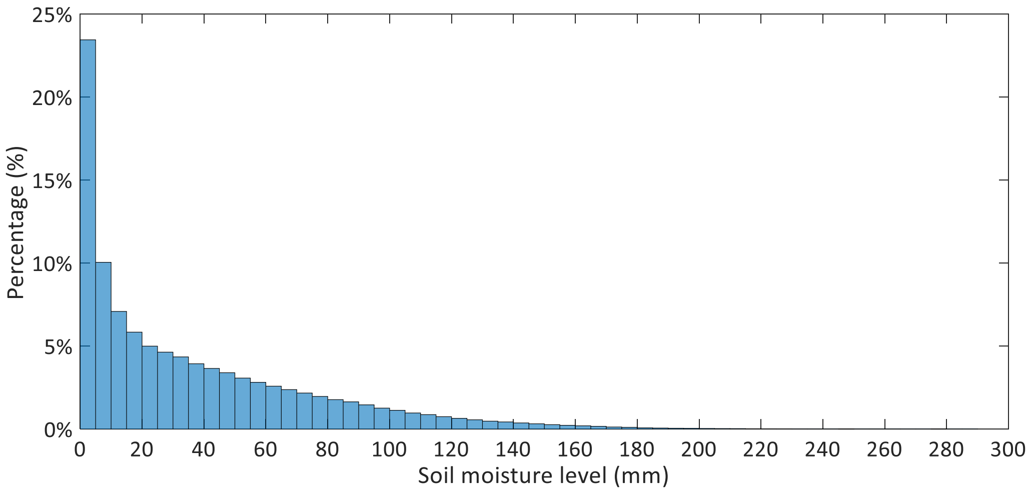

Figure 7-46 : Histogram of daily Soil moisture level

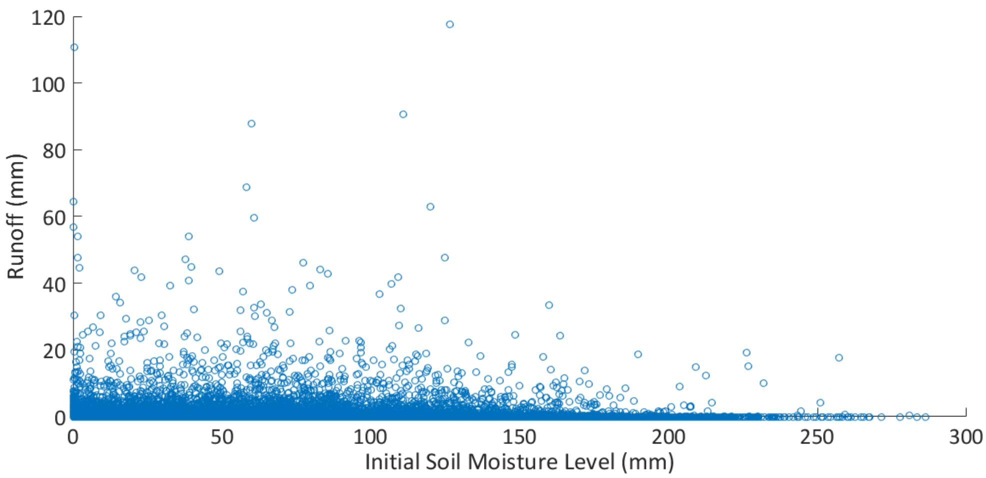

Figure 7-47 : Scatter of Initial Soil Moisture Level versus the corresponding generated runoff

In Figure 7-48 a scatter of the Soil Moisture Level at the end of every event, versus the corresponding generated runoff is depicted. Compared to Figure 7-48, where the same generated runoff is scattered versus the Initial Soil Moisture Level (i.e. at the beginning of a storm) it is quite evident that Figure 7-48 leans more to the right (i.e. towards more wet states). This comparison is indicative of the model's response regarding soil moisture variability and is better represented by Figure 7-49.

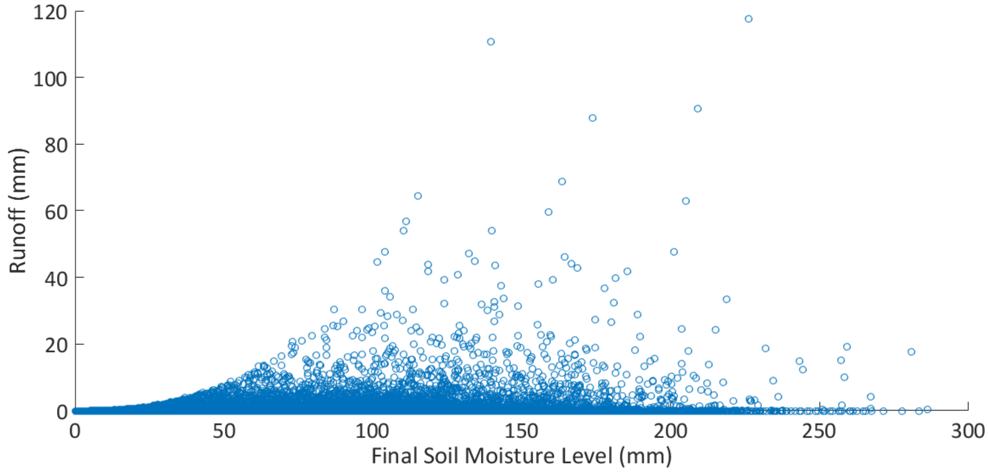

Figure 7-48 : Scatter of Soil Moisture Level at the end of an event versus the corresponding generated runoff

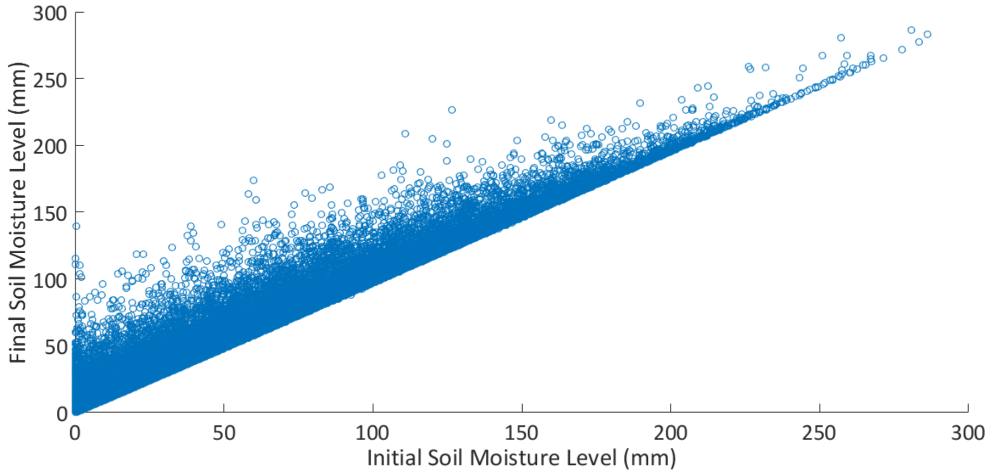

Figure 7-49 : Scatter of Initial Soil Moisture Level versus the corresponding Soil Moisture Level at the end of each event

Finally, the evolution of Soil Moisture Level will be examined and its possible relationship with Antecedent Precipitation will be investigated.

It is evident in Figure 7-50 that the evolution of soil moisture has a periodicity. This behavior is mostly due to the periodicity of temperature that governs Potential and actual Evapotranspiration. In addition, the distribution of rainfall depth throughout the year also plays a minor role in shaping the twists and turns of this behavior.

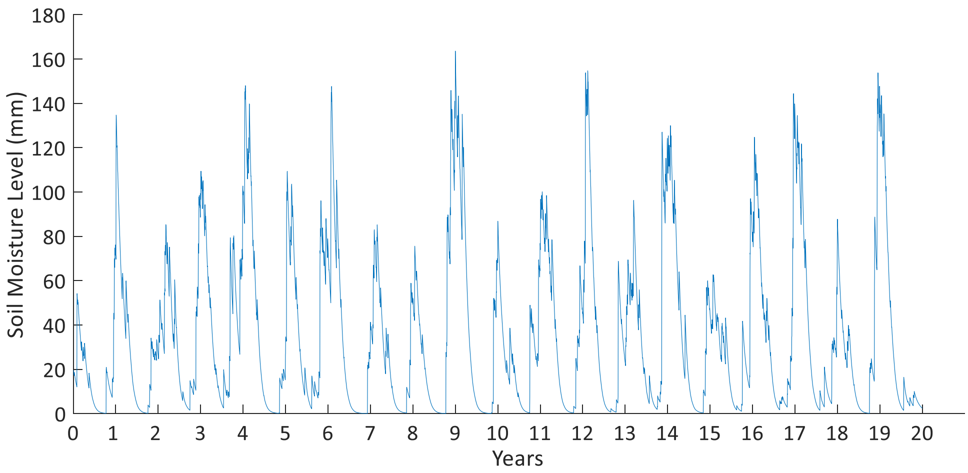

Figure 7-50 : The evolution of Soil Moisture Level over a time interval equal to 20 years

In Figure 7-51 the maximum retention *S* estimated through the 5-day cumulative Antecedent Precipitation is scattered versus the corresponding soil storage left (*K-W*), calculated through the Annie-model. Given that both schemes are based on the NRCS-CN method, the two variables should be correlated. Of course, as already stated, the model has not been calibrated, hence only coarser relations should be expected. In the figure it becomes quite evident that no correlation exists.

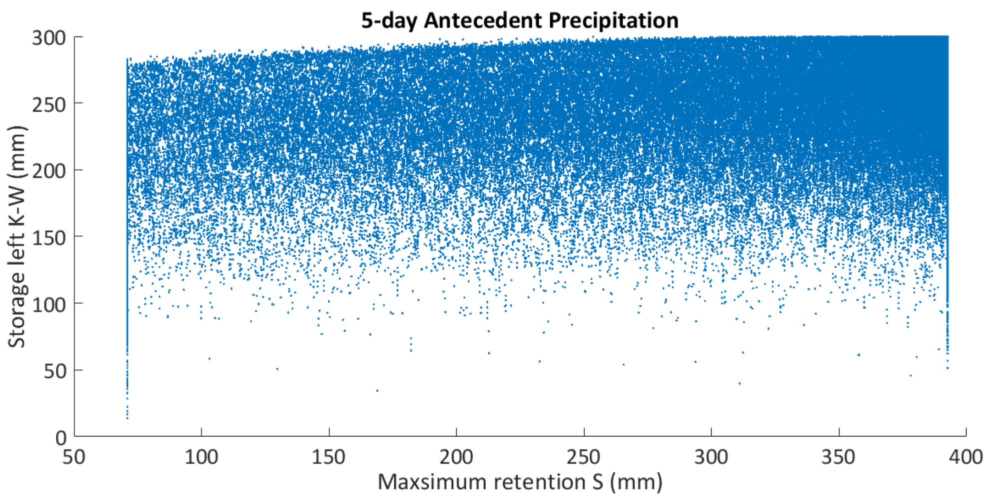

Figure 7-51 : Scatter of maximum retention S, calculated through the 5-day cumulative Antecedent Precipitation, versus the corresponding storage left in the soil, as calculated via the Annie-model

These findings agree with the following figure, where the evolution of 5-day Antecedent Precipitation over a time interval equal to 20 years is plotted. There it becomes quite clear that the shape of the plot is strongly variant, preserving approximately the daily variability of rainfall. Hence, the kind of periodicity characterizing the evolution of Soil Moisture Level – depicted in Figure 7-50- does not appear in this case.

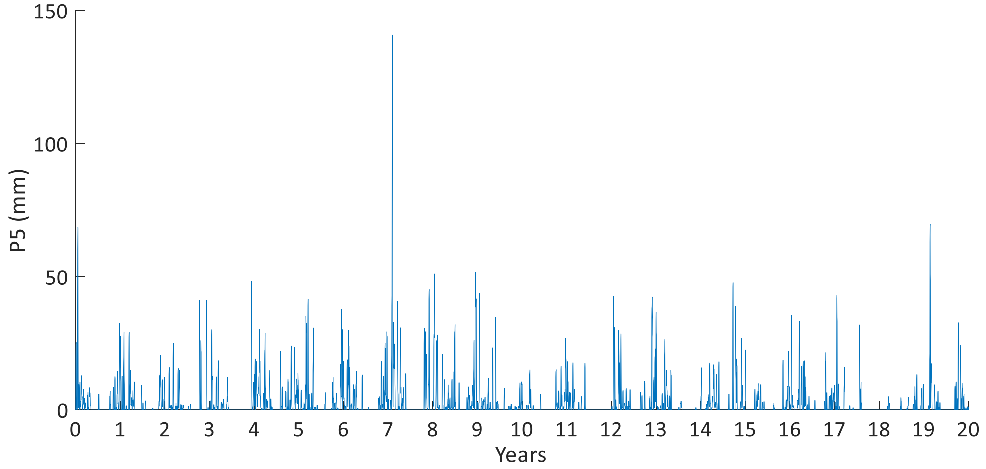

Figure 7-52 : The evolution of 5-day cumulative Antecedent Precipitation over a time interval equal to 20 years

In order to further investigate the above, we conducted a series of analyses using different numbers of days used for the calculation of Antecedent Precipitation each time. As shown in the following figures (from Figure 7-54 through Figure 7-59), calculations were conducted for 10, 20, 30, 60, 90, 120 and 150 days.

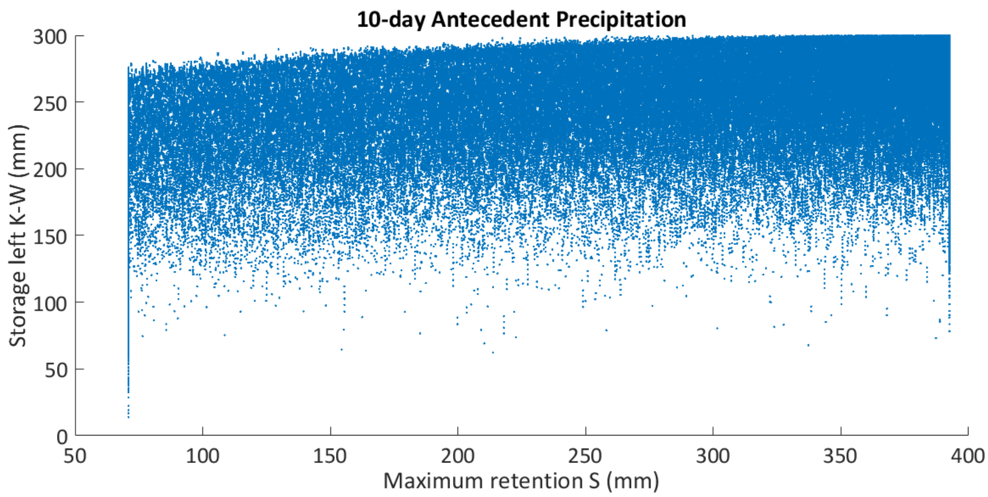

Figure 7-53 : Scatter of maximum retention S, calculated through the 10-day cumulative Antecedent Precipitation, versus the corresponding storage left in the soil, as calculated via the Annie-model

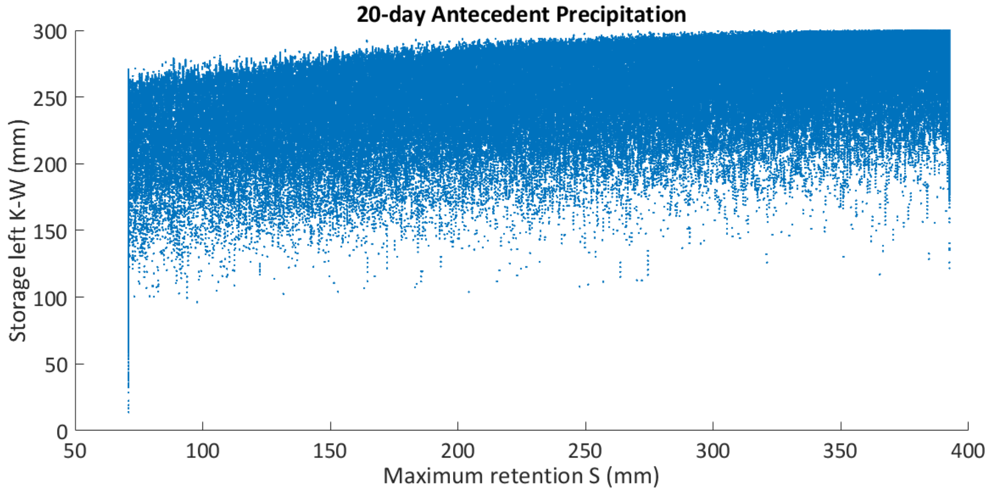

Figure 7-54 : Scatter of maximum retention S, calculated through the 20-day cumulative Antecedent Precipitation, versus the corresponding storage left in the soil, as calculated via the Annie-model

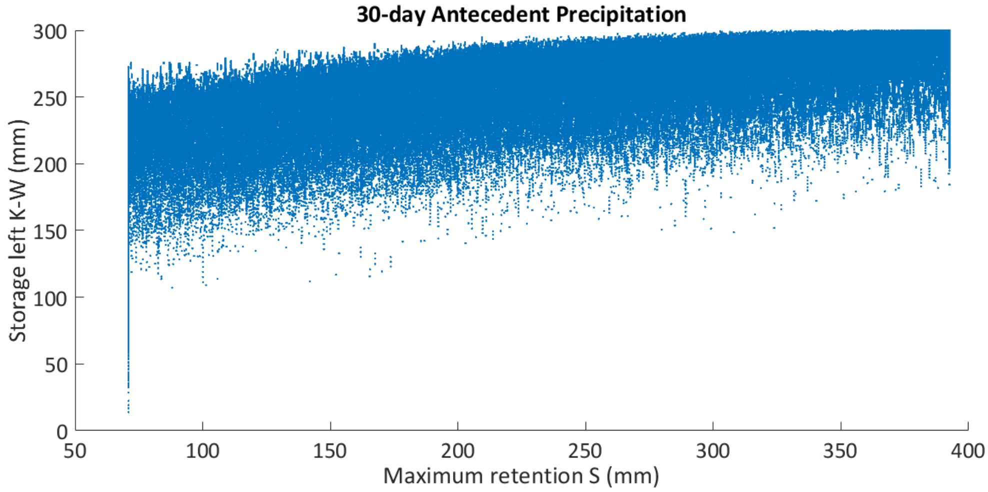

Figure 7-55 : Scatter of maximum retention S, calculated through the 30-day cumulative Antecedent Precipitation, versus the corresponding storage left in the soil, as calculated via the Annie-model

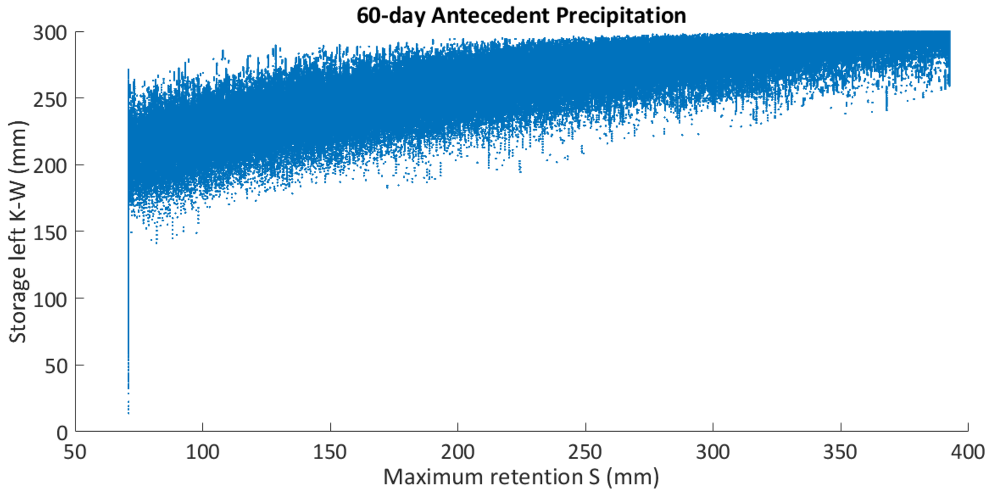

Figure 7-56 : Scatter of maximum retention S, calculated through the 60-day cumulative Antecedent Precipitation, versus the corresponding storage left in the soil, as calculated via the Annie-model

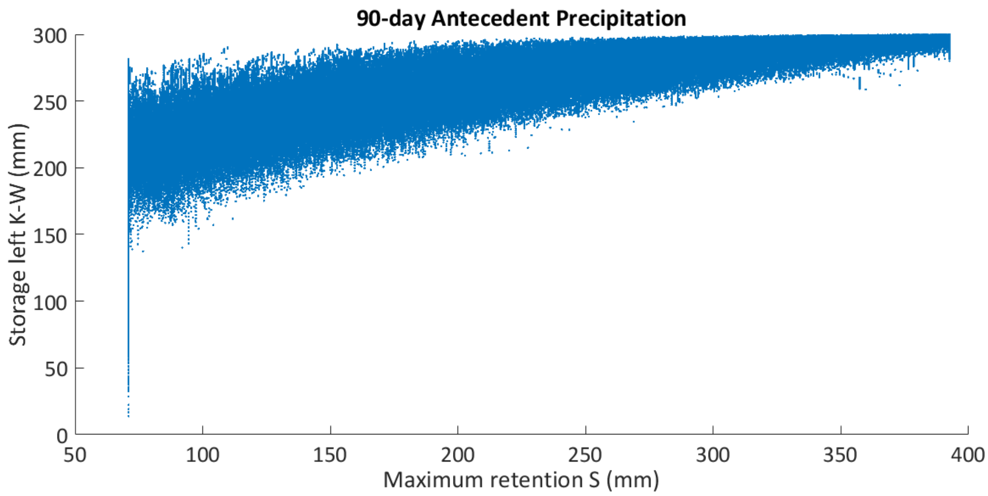

Figure 7-57 : Scatter of maximum retention S, calculated through the 90-day cumulative Antecedent Precipitation, versus the corresponding storage left in the soil, as calculated via the Annie-model

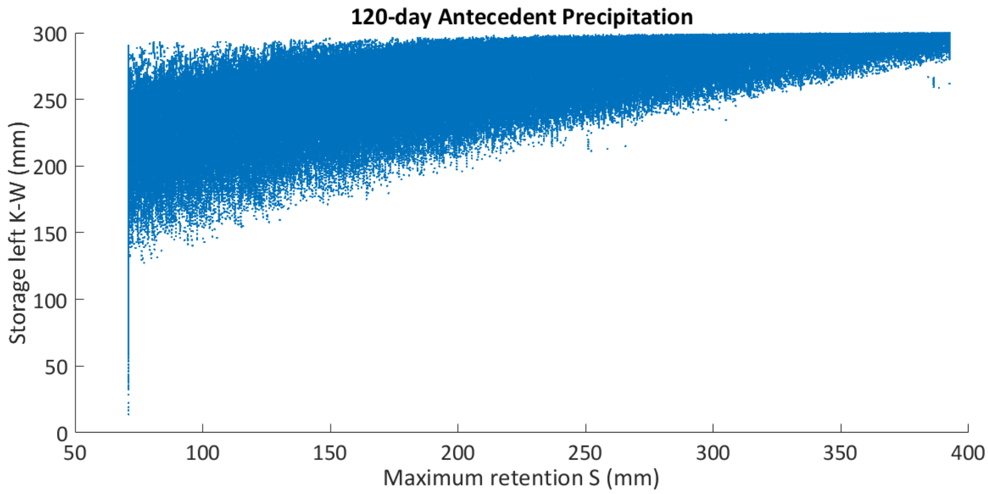

Figure 7-58 : Scatter of maximum retention S, calculated through the 120-day cumulative Antecedent Precipitation, versus the corresponding storage left in the soil, as calculated via the Annie-model

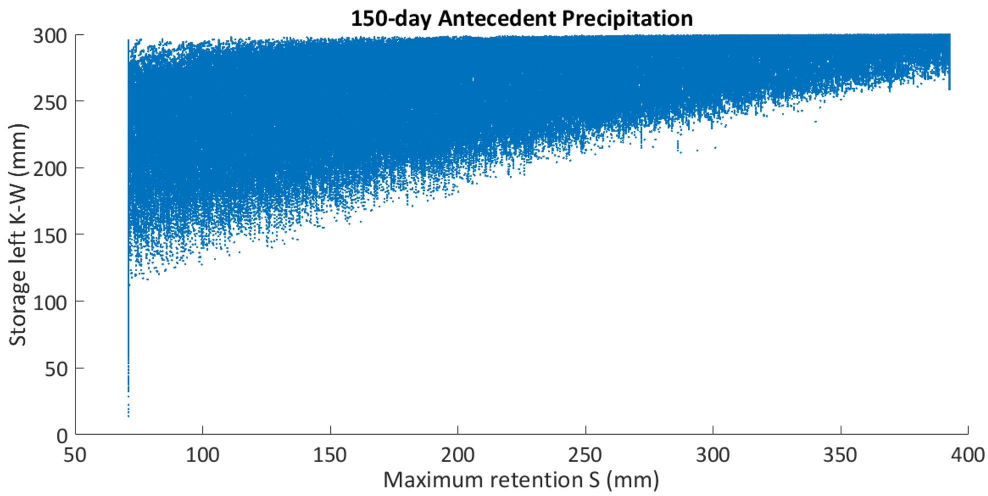

Figure 7-59 : Scatter of maximum retention S, calculated through the 150-day cumulative Antecedent Precipitation, versus the corresponding storage left in the soil, as calculated via the Annie-model

The figures listed above show that when the analysis is conducted based on 60 antecedent days, maximum retention is more strongly correlated to the soil storage left estimated through the Annie-model. This is only slightly better than the results provided when the analysis is based on 90 antecedent days.

In fact, the plots of the evolution of 60 and 90-days cumulative Antecedent Precipitation in Figure 7-60 and Figure 7-61 respectively are support the aforementioned allegations. It is quite evident that the shape of the plot presents a roughly similar periodicity to the one appearing in the evolution of soil moisture levels.

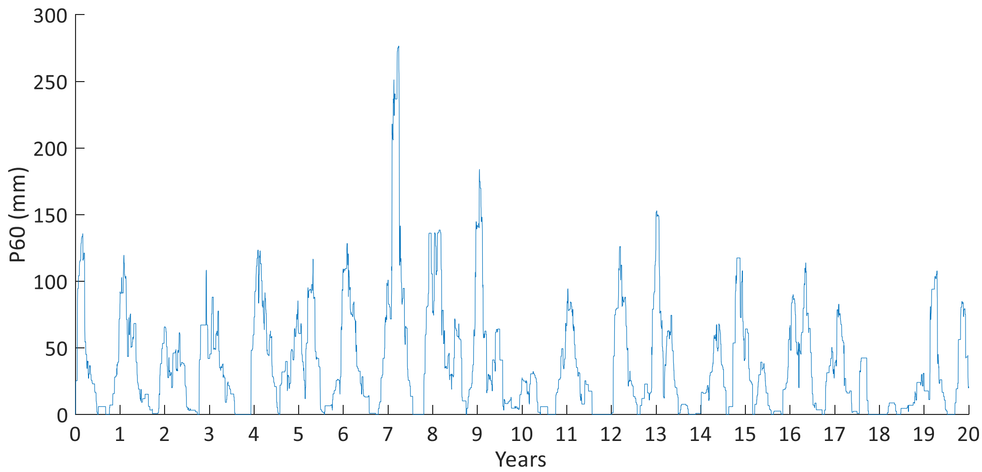

Figure 7-60 : The evolution of 60-day cumulative Antecedent Precipitation over a time interval equal to 20 years

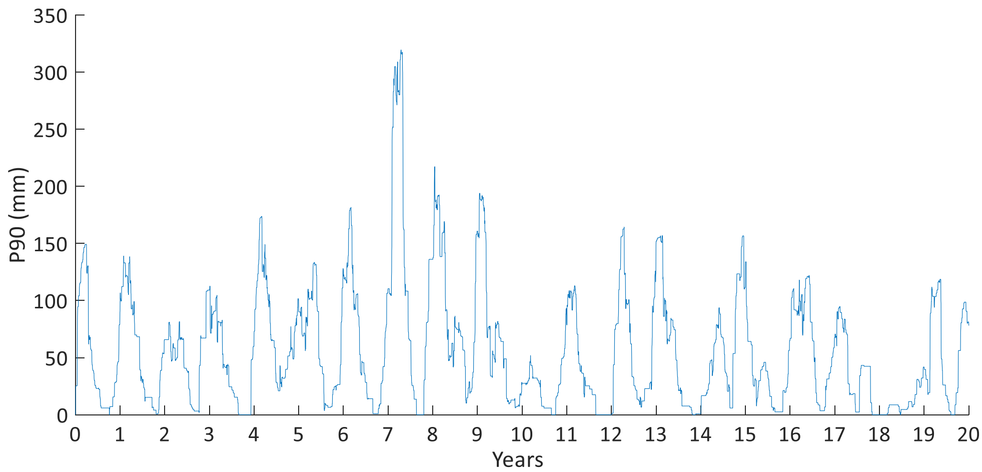

Figure 7-61 : The evolution of 90-day cumulative Antecedent Precipitation over a time interval equal to 20 years

The strong indications stated above actually suggest that there is a time interval equal to two months approximately, that governs the soil moisture regime of the region. In order to further investigate this, Figure 7-62 is attached. Here, it seems that the only months when the percentage of runoff maxima exceeds the percentage of rainfall maxima are December, January, February and March, which are the months that follow the most wet two or three-month periods. On the contrary, September and October (and probably November), are strongly dependent on the dry summer and early-autumn period.

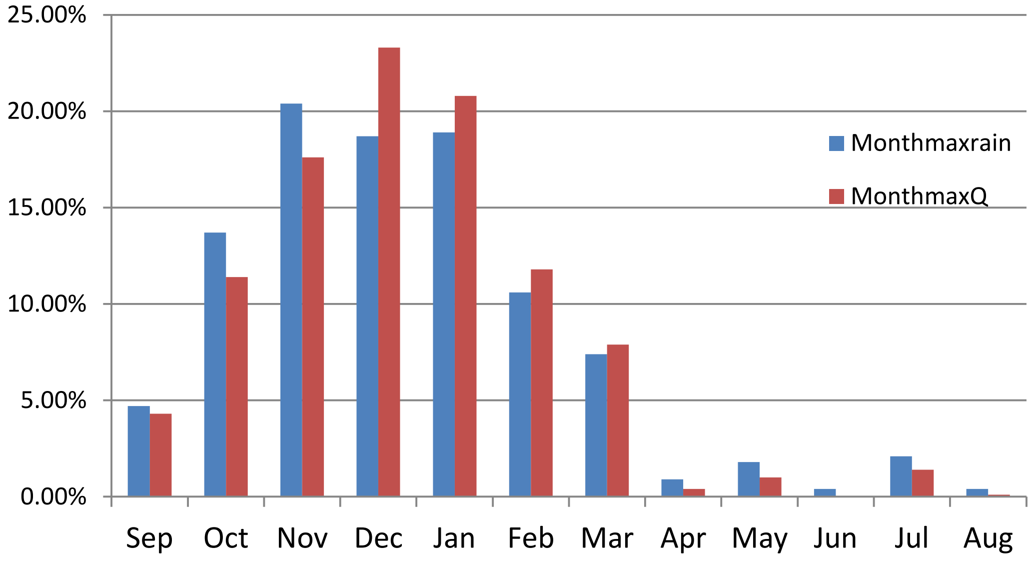

Figure 7-62 : Histogram of the months when the annual maxima of runoff and annual maxima of rainfall occurred

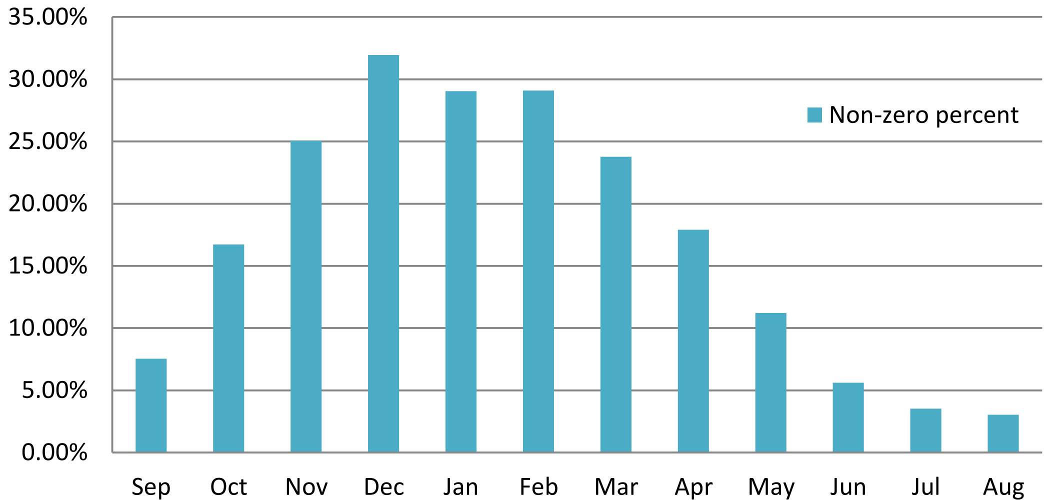

Figure 7-63 : Histogram depicting the percentage of non-zero values during each month in the historical rainfall timeseries

Figure 7-63 depicts the percentage of non-zero values during each month, recorded in the historical rainfall timeseries. This graph strongly supports our implications and the most indicative example is November. In particular, November is affected by September and October, which are relatively dry -especially the first-, despite being a wet month, during which extreme storms occur.

To summarize, the 60 or 90-days cumulative Antecedent Precipitation seems to be conceptually legit. However, further investigation needs to be done, in order to support this suggestion.

7.9 The influence of CN

In this chapter, the response of the proposed framework for different values of CN is examined. The analysis was conducted for all possible CN values ranging from 1 to 100.

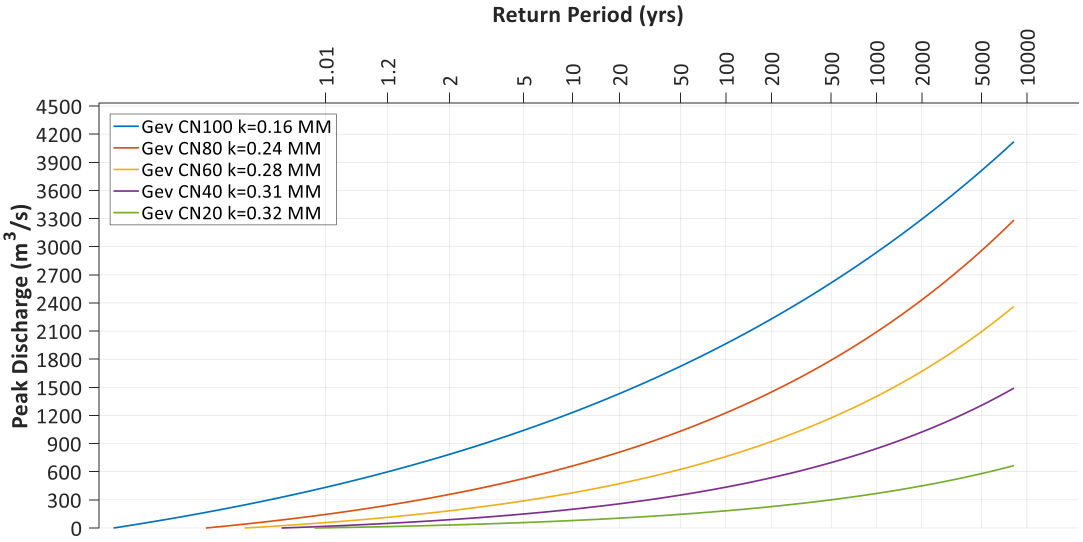

Figure 7-64 : Distributions of peak discharges estimated through the HDI model for different values assigned to CNII

In Figure 7-64 some indicative distributions are shown. As anticipated, greater CN values produce greater floods. However, the most interesting part of the previously shown figure is the differences found in shape parameter. It seems that non-linearity increases as CN decreases.

Of course, this is due to the inherent non-linearity of the NRCS-CN method which is incorporated into the HDI model. It is well-known that under this method, non-linearity increases as CN decreases. Nevertheless, non-linearity still exists even for a CN value equal to 100, because, not only a non-linear rainfall disaggregation scheme is used, but also due to the inherent non-linearity that underlies rainfall.

The impact of CN on the distribution of peak discharges is further investigated in the following figures, where the relations between CN and shape, scale and location parameters of the GEV distribution are examined.

We should note that GEV-parameters are estimated via the Moments Method proposed by Koutsoyiannis (2004).

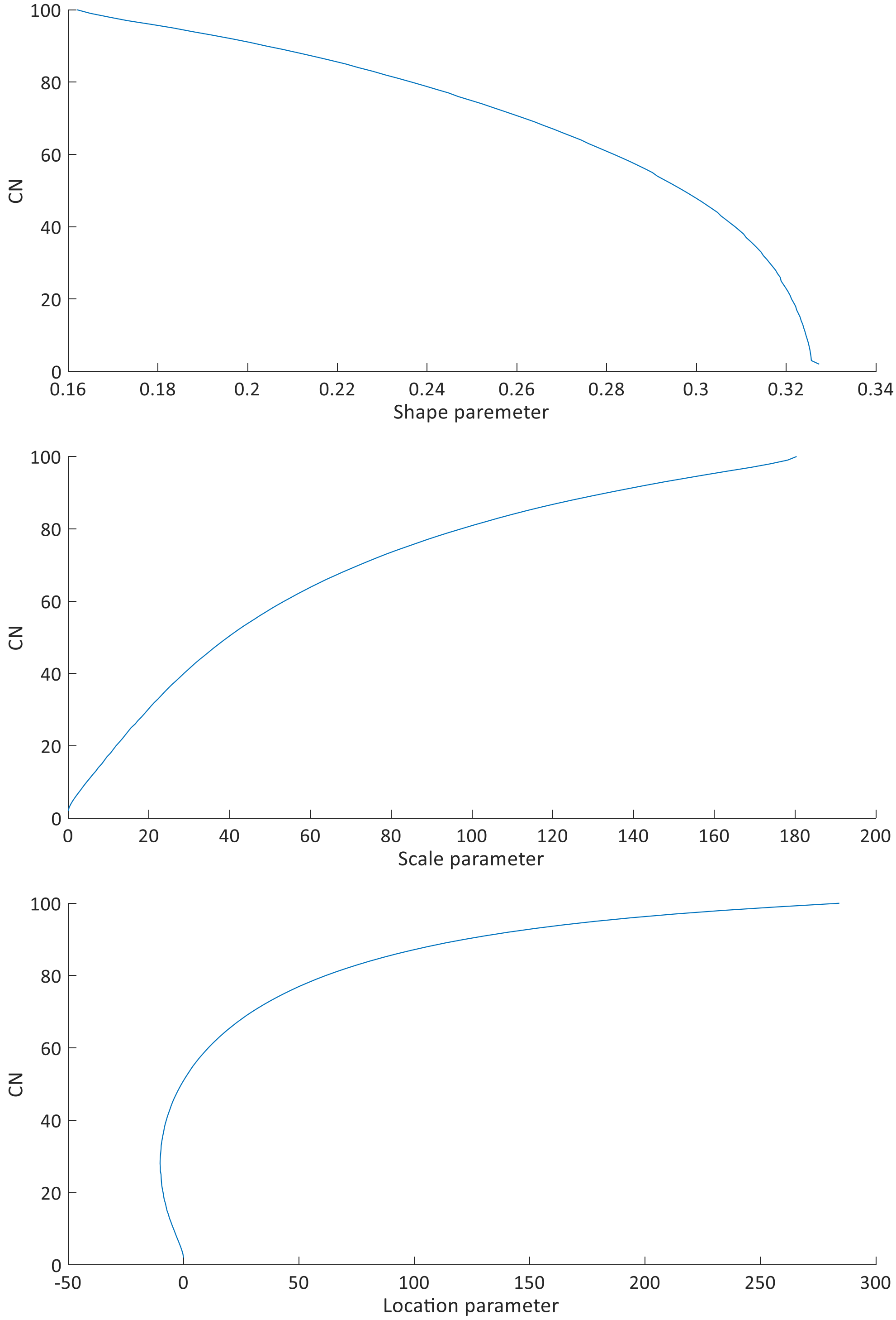

Figure 7-65 : Plots of Shape, Scale and Location parameters of the GEV distribution versus CN values

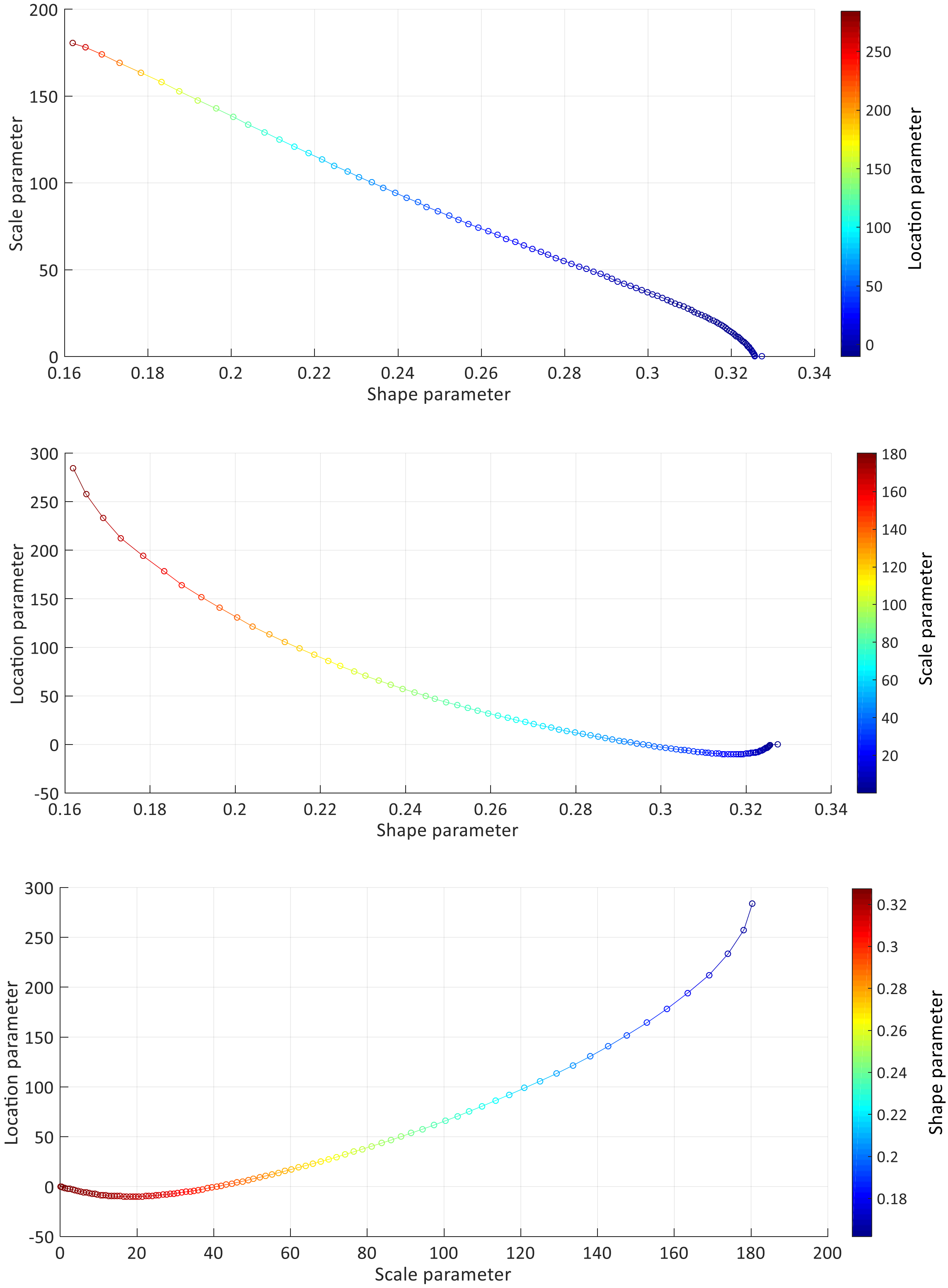

Figure 7-66 : 2D-Plots between Shape, Scale and Location parameters. Each time the third parameter is represented in colors

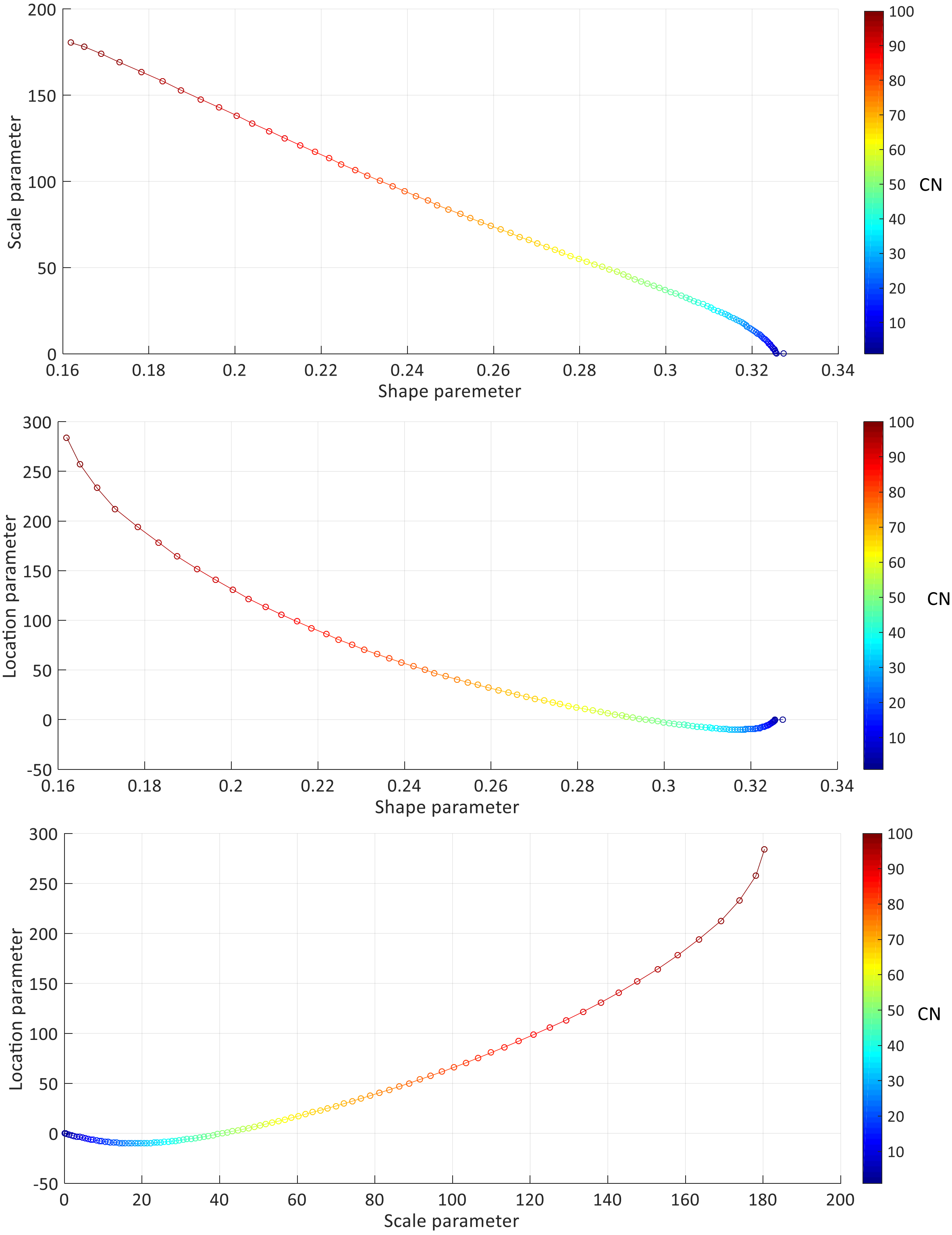

Figure 7-67 : 2D-Plots between Shape, Scale and Location parameters. Each time CN is represented in colors

It becomes clear that the parameters of the GEV distribution are a linear function of CN and are, hence, intercorrelated.

Moreover, it is proved, by examining the relationship of shape parameter and CN values, that non-linearity becomes more intense as CN decreases.

8 Improving the proposed framework

Based on the findings of the analyses conducted in the framework of this thesis, we have identified two elements of the proposed framework that could possibly be revised.

In this chapter, the framework is revised in order to remedy these shortcomings and the results are presented. However, it should be noted that the newer version is experimental only and its consistency is yet to be proved.

In particular, the proposed framework will be modified as follows:

- As suggested in the previous chapter, a 60 or 90 days period possibly describes more accurately the evolution of soil moisture across time. As a result, in this chapter a 60-day cumulative Antecedent Precipitation is used in order to estimate the initial soil conditions.

- During our analyses it became quite clear that considering initial abstraction I_a as a portion of maximum retention S should definitely be questioned.

  On the one hand, a daily variance of I_a does not seem consistent, based on engineering experience. Of course, I_a may vary, depending on vegetation state of development, however, such a variation could be merely seasonal.

  On the other hand, this daily variation, especially in a region where dry conditions are prominent, thus high values of S are being obtained, leads mostly in equally high values of I_a, while during wet days, smaller values of Ia are estimated, thus over or underestimating flood volumes.

  In this context, we treat I_a as a constant and equal to 10mm, which corresponds to the average initial abstraction estimated in the results of the proposed framework.

In Figure 8-1 the distribution of peak discharges estimated via the modified framework is presented alongside the results of the initial version of the model. It seems that the modified framework provides greater floods than the initially proposed model.

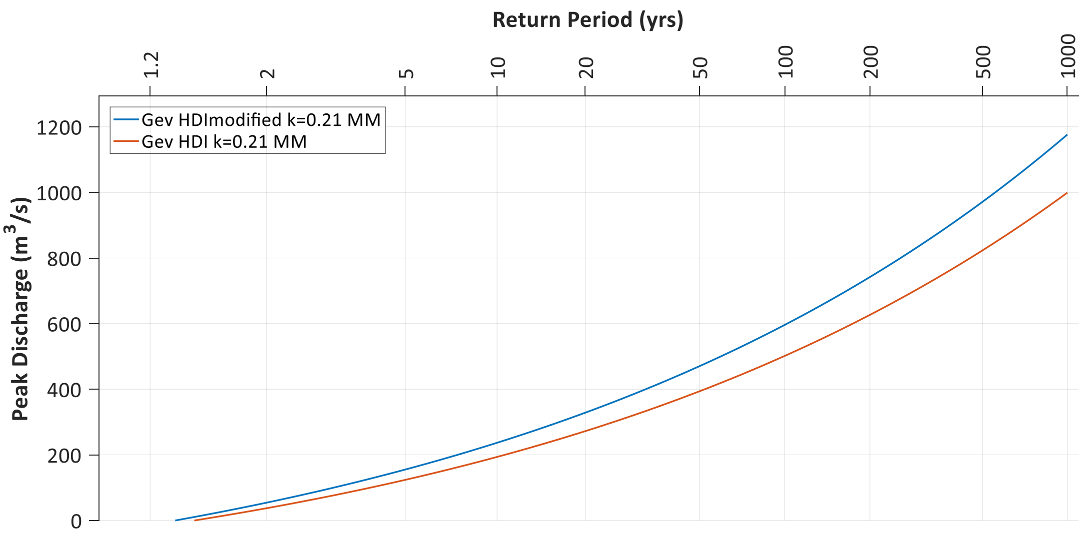

Figure 8-1 : Distribution of peak discharges estimated through the proposed framework (HDI) and its revised version (HDImodified)

In order to better understand the response of the modified model, Figure 8-2, Figure 8-3 Figure 8-4 are presented which explain the result. Here, it is quite evident that the distribution of CN values is similar –in terms of quality- to the distribution of Soil moisture levels estimated through the Annie-Model. In the meantime, even if dry conditions are still prominent, they occur less frequently than in the initial framework, where they reach a percentage equal to 70% approximately.

As a result, the modified model provides greater floods, since wet conditions occur more frequently than the initial framework.

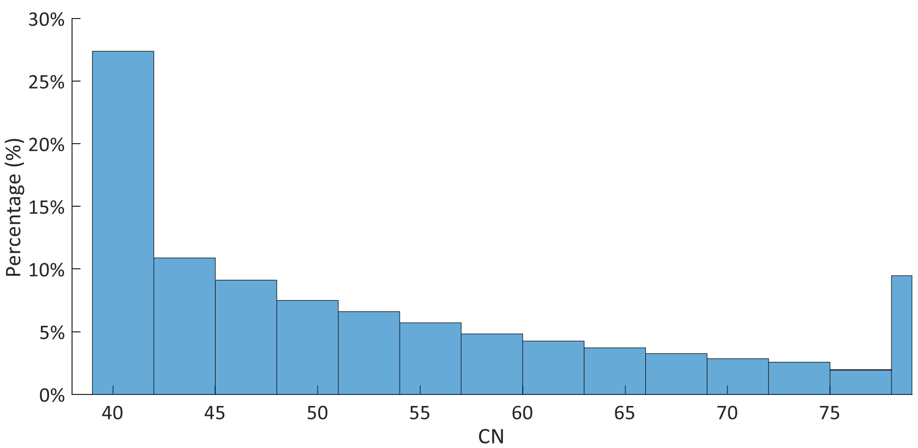

Figure 8-2 : Histogram of CN values across days estimated through the modified version

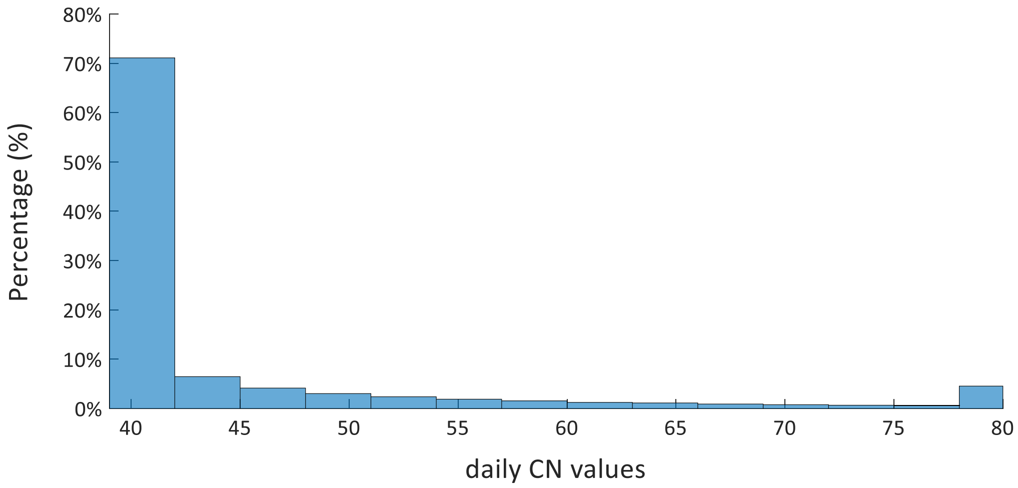

Figure 8-3 : Histogram of daily CN values estimated through the initially proposed framework

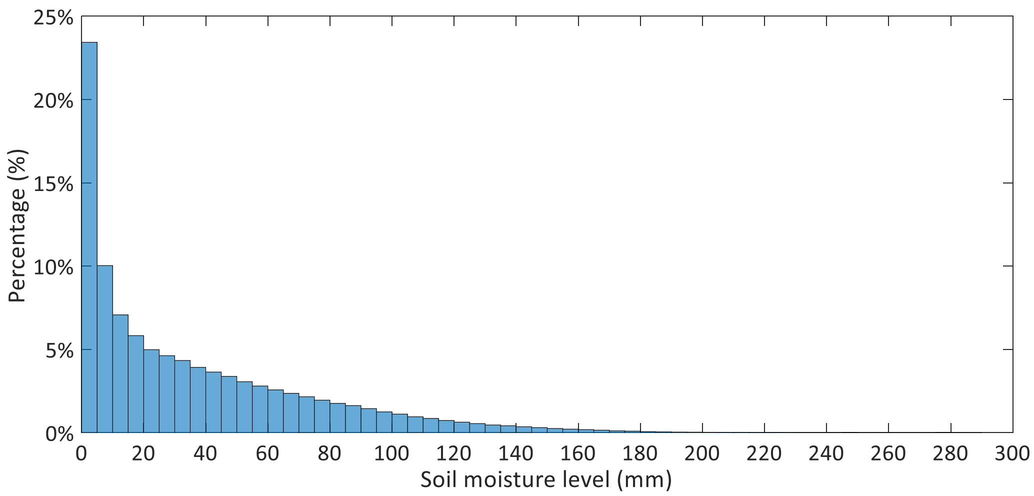

Figure 8-4 : Histogram of daily Soil moisture level estimated via Annie-Model

In addition, in order to examine the difference between estimating soil moisture through 60 or 90 antecedent days, Figure 8-5 is presented. Here, it seems that the two approaches have actually no difference.

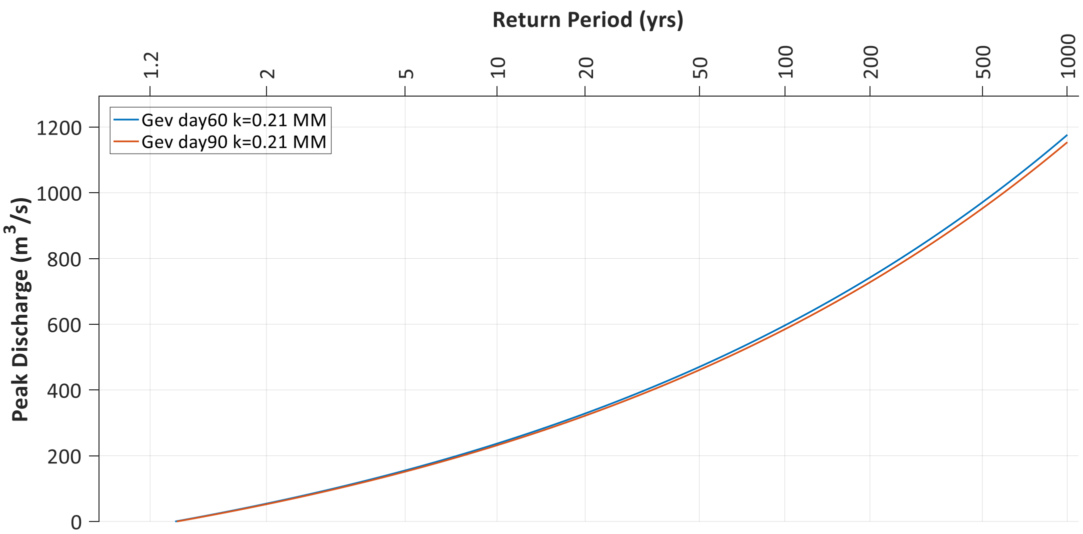

Figure 8-5 : Distribution of peak discharges estimated through the modified version of the proposed framework. In the first case Antecedent precipitation is based on a 60days interval, while in the latter case a 90days interval is used

In order to examine the impact of each improvement separately, Figure 8-6 is presented. Here it becomes quite clear that Ia plays no important role. However, this is due to determining Ia equal to the average initial abstraction estimated in the results of the proposed framework.

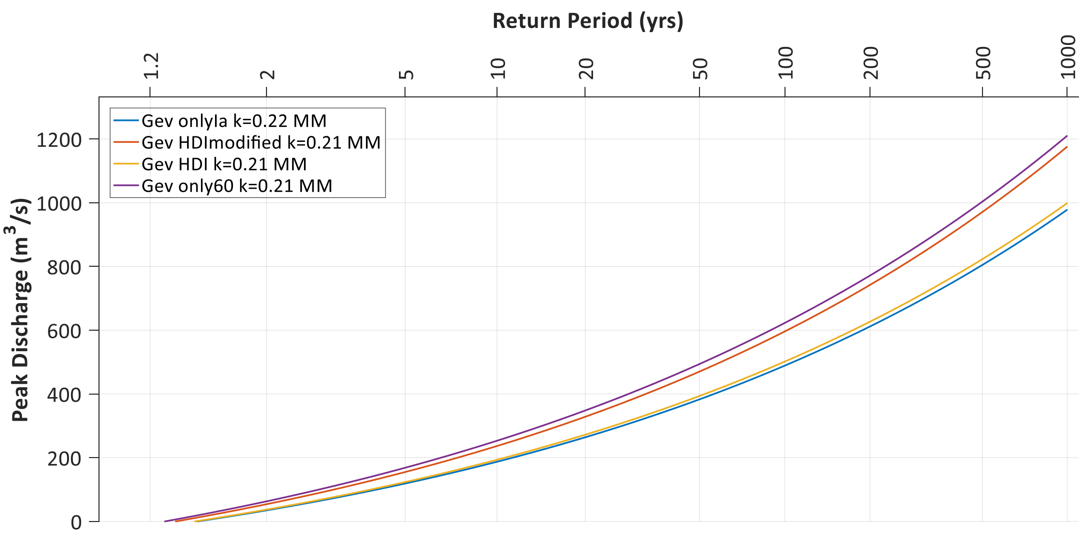

Figure 8-6 : Distribution of peak discharges estimated through the proposed framework (HDI), its revised version (HDImodified), the proposed framework with Ia treated as aconstant (onlyIa) and the proposed framework with 60days antecedent precipitation (only60)

Finally, it should be highlighted that treating I_a as a constant, or even considering a seasonal variability should be more thoroughly investigated, even though they seem consistent, based on engineering experience. Moreover, deeper examination is needed in order to test the validity of approaches based on antecedent precipitation and the number of antecedent days that need to be taken into consideration.

The necessary further work was not conducted in the context of this thesis, due to time limitations; however, this chapter was added in order to serve as a motive for future work.

9 Summary, conclusion and discussion

9.1 Summary

Despite crossing an era during which technological progress has been tremendous, humanity is still struggling with the forces of nature. Disastrous natural hazards, with floods being prominent among them, occur without warning causing deaths and destruction.

Significant efforts have been made by the engineering community in order to predict extreme events more accurately, in order to properly protect human lives and property. However, the exact mechanisms that govern runoff generation are yet elusive, while the natural variability of hydrological processes requires further investigation.

In the meantime, the methods developed by researchers are usually either too sophisticated and cannot be used by common engineers or require rainfall-runoff measurements that are usually unavailable or of bad quality. As a result, engineers across the world mostly use simplistic methods, which are proved to be highly inconsistent.

The main objective of the present study was to propose a simple and parsimonious stochastic simulation framework, suitable for ungauged basins that can be easily implemented in everyday flood engineering. Such a framework, should remedy the significant inconsistencies that underlie typical deterministic frameworks.

In this context, the shortcomings of typical deterministic flood engineering schemes, regarding the variability of soil moisture conditions, the disaggregation of rainfall into finer temporal scales and the variability of time of concentration, as well as the problems related to more complex models were documented, based not only in the literature, but also engineering experience.

The proposed method was presented and it was implemented on Rafina stream basin, comparing the results with the typical deterministic scheme. In turn, further analyses were conducted in order to check the model's response under different states and modifications.

9.2 Conclusions

Even if a wide range of analyses and a series of deductions were made in the framework of this thesis, the most important remarks are briefly listed below:

- The typical deterministic framework that is widely used in everyday engineering practice (i.e. NRCS-CN coupled with alternating blocks method and constant time of concentration) is highly inconsistent, because it ignores significant uncertainties associated with flood design.

- The complex continuous schemes that have been developed over the past years rely drastically on the availability and quality of data. Still, in cases where measurements pose no limitation, the calibration of such models is a difficult and uncertain procedure.

- The proposed framework attempts to address the major shortcomings found in typical deterministic schemes, while remaining simple and parsimonious. The actual response of a watershed is better described when accounting for inherently variable quantities, such as the antecedent soil moisture conditions, the time of concentration and the temporal distribution of rainfall events.

- Key issue of the methodology is the Monte-Carlo approach, which allows for describing all results in probabilistic terms and estimating the uncertainty bounds around each return period.

- The pseudo-continuous scheme, coupling the daily time step with finer scales, is an efficient equilibrium between significantly complex and computationally tedious continuous modeling and over-simplistic event-based methodologies.

- The well-known NRCS-CN method, is easily adapted in the modeling procedure by considering a daily varying CN value, according to the accumulated Antecedent Precipitation, and a daily varying time of concentration, based upon the effective rainfall of each day.

- Two distinguished stochastic tools are implemented i.e. Castalia for the generation of daily synthetic rainfall and HyetosMinute for disaggregating daily rainfall series into finer temporal scales.

- In contrast to the arbitrary hydrographs produced by specific temporal rainfall patterns (e.g. alternating blocks), our method provides flood hydrographs that are consistent with reality, since the statistical properties and autocorrelation structure of rainfall are preserved within the stochastic model.

- Due to soil moisture variability, rainfall of a certain return period does not necessarily produce a flood of equal return period. For this reason, selecting the annual maxima of runoff, instead of the rainfall annual maxima, is more suitable for floods of small and medium return periods, while the two approaches coincide for larger return periods.

- The key assumption that the time of concentration is a decreasing function of the daily runoff provides quite greater flood flows than the typical deterministic practice, particularly for large return periods.

- By ignoring the major hypothesis of varying time of concentration, thus considering a constant time estimated via the Giandotti formula, we obtain peak flood estimations that are close to the results of the deterministic scheme under wet conditions.

- The statistical behavior of extreme floods is highly dependent on the reference CN value of the watershed. In particular, the tail of the distribution as quantified by the shape parameter of the GEV distribution becomes heavier as CN decreases.

9.3 Suggestions for future work

The driving force of this thesis was an urge to combine in a single framework all the tools, methods and the knowledge produced over the past years in the Department of Water Resources and the Environment of School of Civil Engineering, NTUA. The work conducted during this study was mostly investigative in the purpose of highlighting problems, inconsistencies and flaws that could lead to further research.

In this context every aspect of the proposed framework was thoroughly investigated. Based on the results of the analyses and while the thesis was still ongoing, a wide spectrum of ideas for further investigation kept emerging, most of which were beyond the scope of this work, or could not be properly examined due to time limitation.

These ideas are listed below and some really interesting future work may be conducted upon them, in order to make the proposed framework more robust and improve the tools used.

In particular, the proposals for future work are listed below:

- In this method, the response and the mechanics of the proposed framework were investigated mostly in terms of engineering evidence and theoretical consistency. However, the results provided by the model should also be tested upon actual flood data from gauged catchments, in order to validate its predictive capacity in quantitative terms.

- The Monte-Carlo scheme can be generalized in order to also treat the uncertainty associated with several model inputs that have been considered as fixed quantities (e.g. the parameters of the Unit Hydrograph). Apparently such an extended Monte-Carlo analysis would definitely provide even wider uncertainty bounds. However, assigning a proper distribution to these parameters is not an easy task.

- The implementation of this model results in the generation of a wide series of flood hydrographs corresponding to each return period. These flood hydrographs can be used as input to a stochastic hydraulic model which accounts for parameter uncertainty. Under this scheme, the uncertainty of both hydrologic and hydraulic design can be taken into consideration and the joint probability of a flood occurring can be estimated.

- Since the variability of time of concentration has a great impact in the results, its relation to generated runoff needs to be further examined and tested. Significant work related to the issue is already being conducted by Michailidi et al. (2017), but further work is needed in order to develop a scheme under which the time of concentration would vary during the storm event.

- The daily generating scheme within Castalia software requires improvement in order to address some flaws that we came across. In particular, issues regarding intermittency emerged, since months with less than 10% probability-dry were occasionally being generated. During these months multi-day wet clusters with extremely small rainfall depths were generated. In addition, the extremes of the historical timeseries were not always faithfully represented, due to the use of Gamma Type III distribution for the generation of white noise, which fails to preserve the actual tail of the distribution.

- The Bartlett-Lewis model used for rainfall disaggregation fails to reproduce the actual variability of rainfall events, due to the overclustering of pulses associated with the overestimation of probability-dry (Kossieris, et al., 2013). This provides too intense rainfall clusters, thus tending to overestimate the peak flows. On the other hand, long dry time intervals tend to underestimate floods, for long storm durations (e.g. larger than 24 hours). The model should be revisited in order to remedy this problem.

- Treating initial abstraction, I_a as a portion of maximum retention should be questioned, because the variability of the two quantities should not be identical. Particularly in dry conditions –which are prominent in our case- high values are usually assigned to initial abstraction, thus resulting in very low runoff rates, even for extreme storms. In order to restore consistency, a seasonal variation of I_a could be considered, based on surface characteristics of the catchment and development stages of vegetation.

- Estimating soil moisture conditions based on 5-day cumulative Antecedent Precipitation cannot properly represent the dynamics of soil moisture storage across seasons. As shown with the help of Annie-model, an approach based on 60 to 90 daily intervals may be more accurate. However, further research should be made regarding this issue.

- The proposed framework does not treat properly for the spatial variability of both rainfall and the physiographic characteristics of the catchment. This is a well-known problem of non-distributed models that treat a catchment as a solid completely homogenous unit, all over which rainfall is uniformly distributed. In order to handle heterogeneities, multivariate stochastic models for rainfall coupled with semi-distributed hydrological models should be incorporated.

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Appendix A: Design flood hydrographs

The sets of flood hydrographs produced by the proposed framework for the Upper and Lower Bounds of 95%, 70% and 50% Confidence Intervals, are listed below. The hydrographs correspond to return periods equal to 5, 10, 20, 50, 100, 200, 500 and 1 000 years.

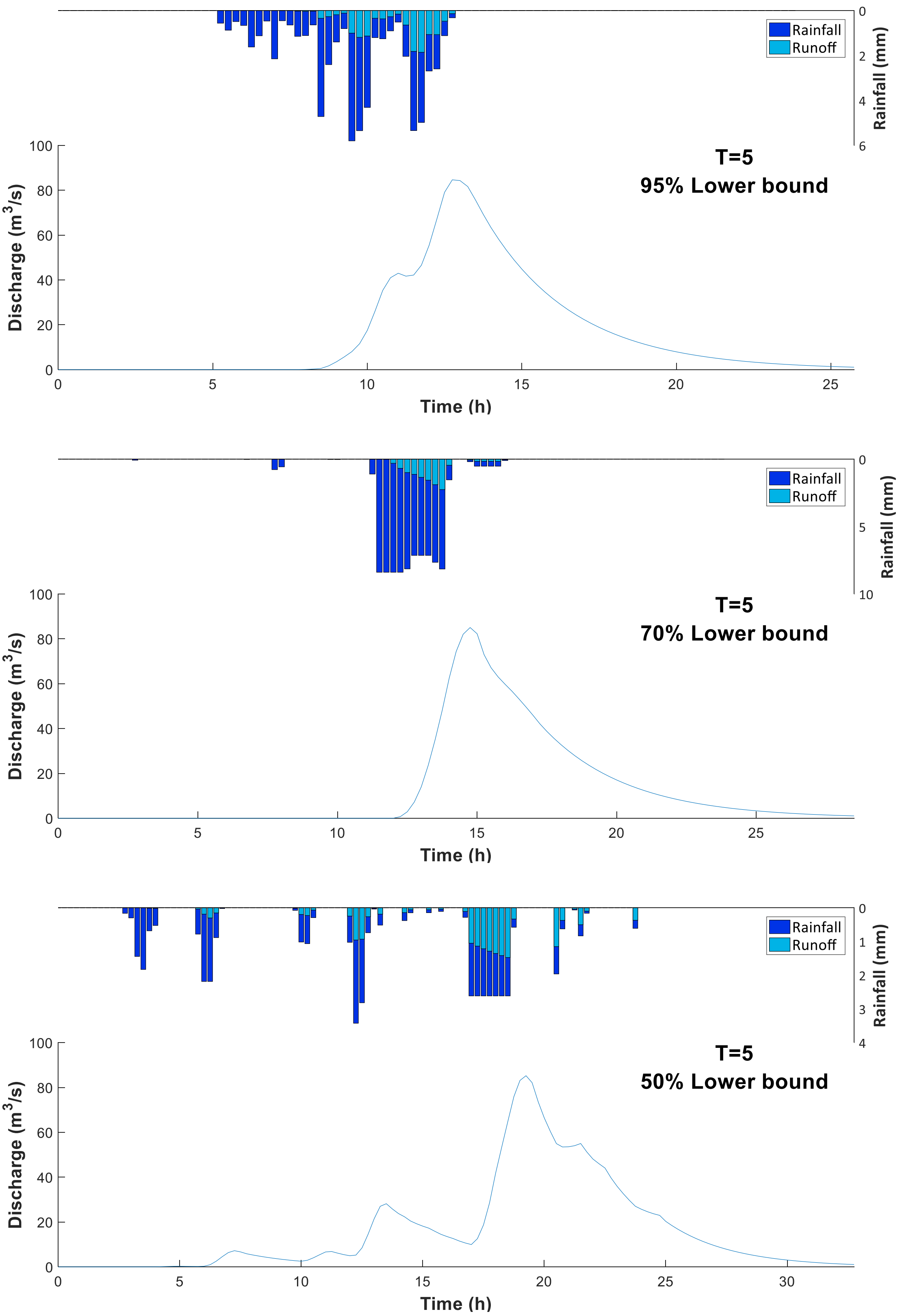

Figure 1 : Lower bound flood hydrographs (T=5 years)

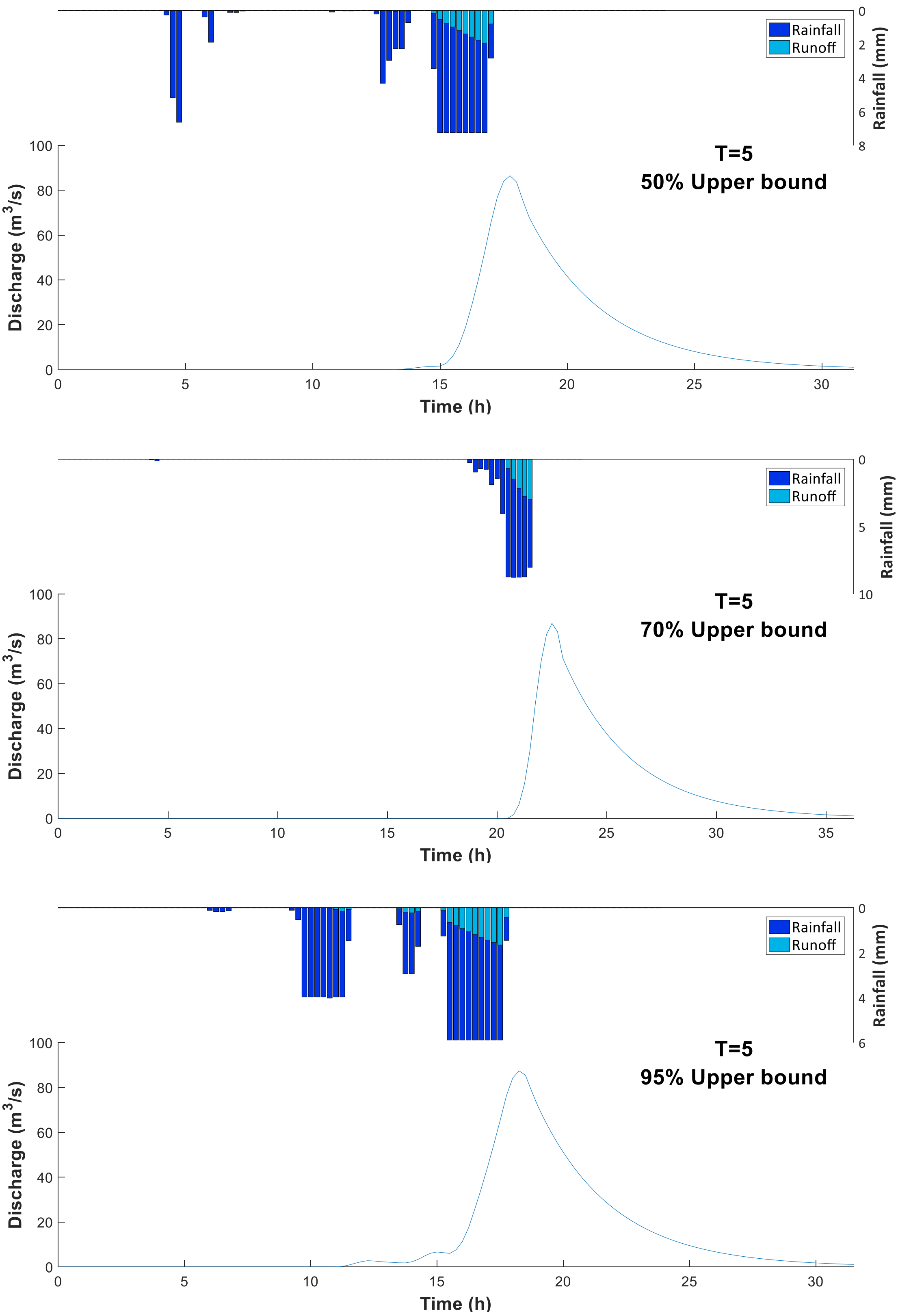

Figure 2 : Upper bound flood hydrographs (T=5 years)

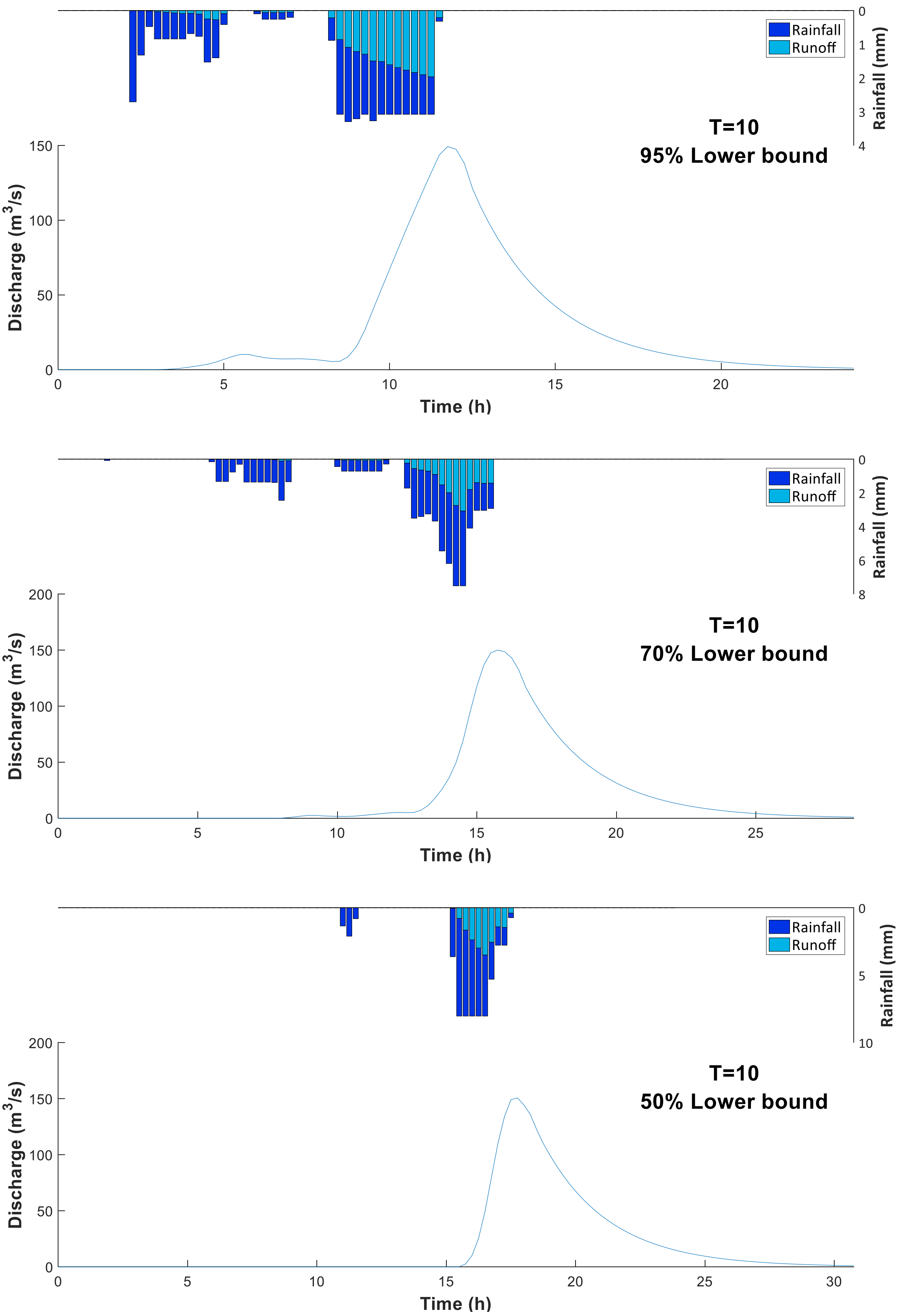

Figure 3 : Lower bound flood hydrographs (T=10 years)

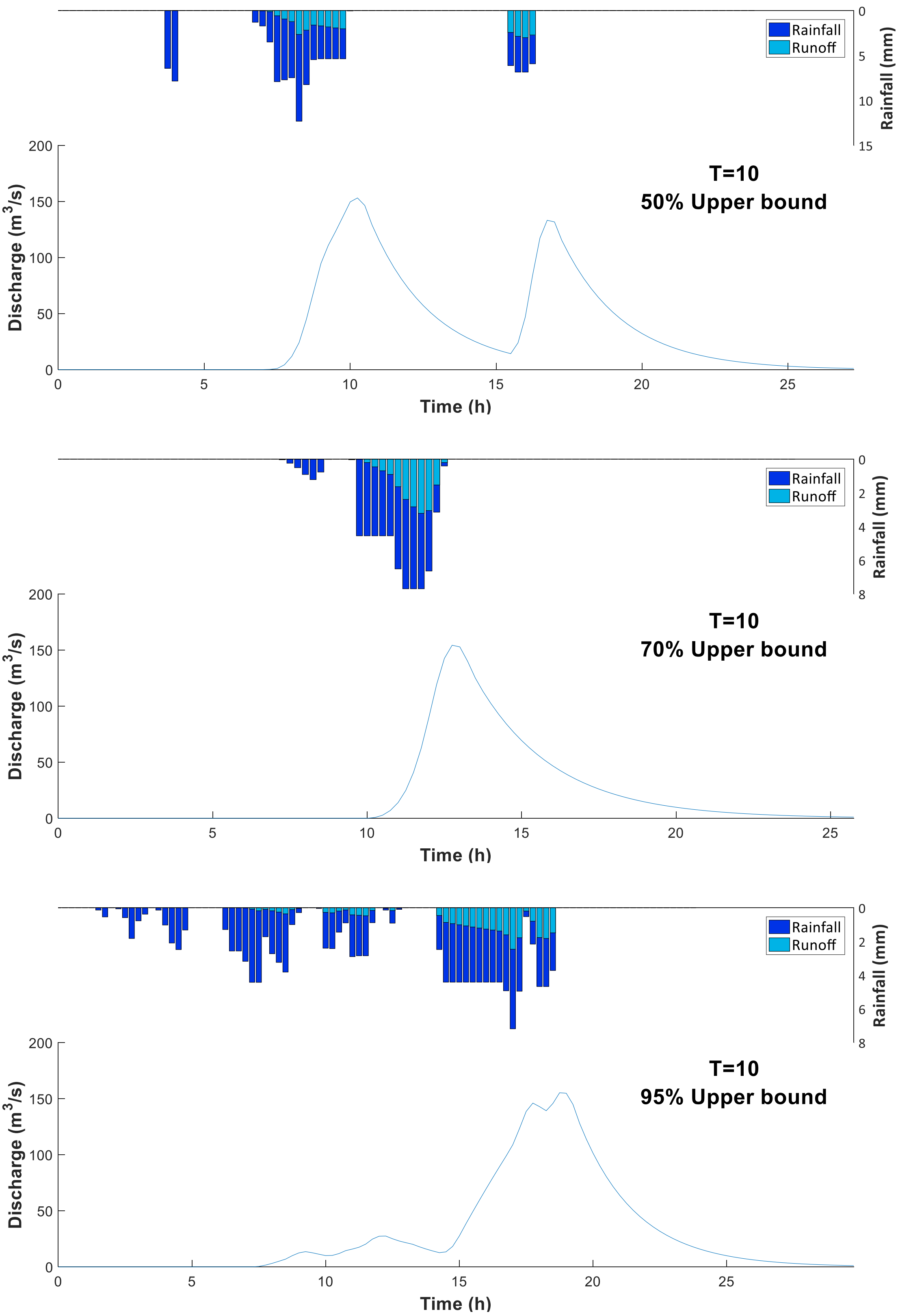

Figure 4 : Upper bound flood hydrographs (T=10 years)

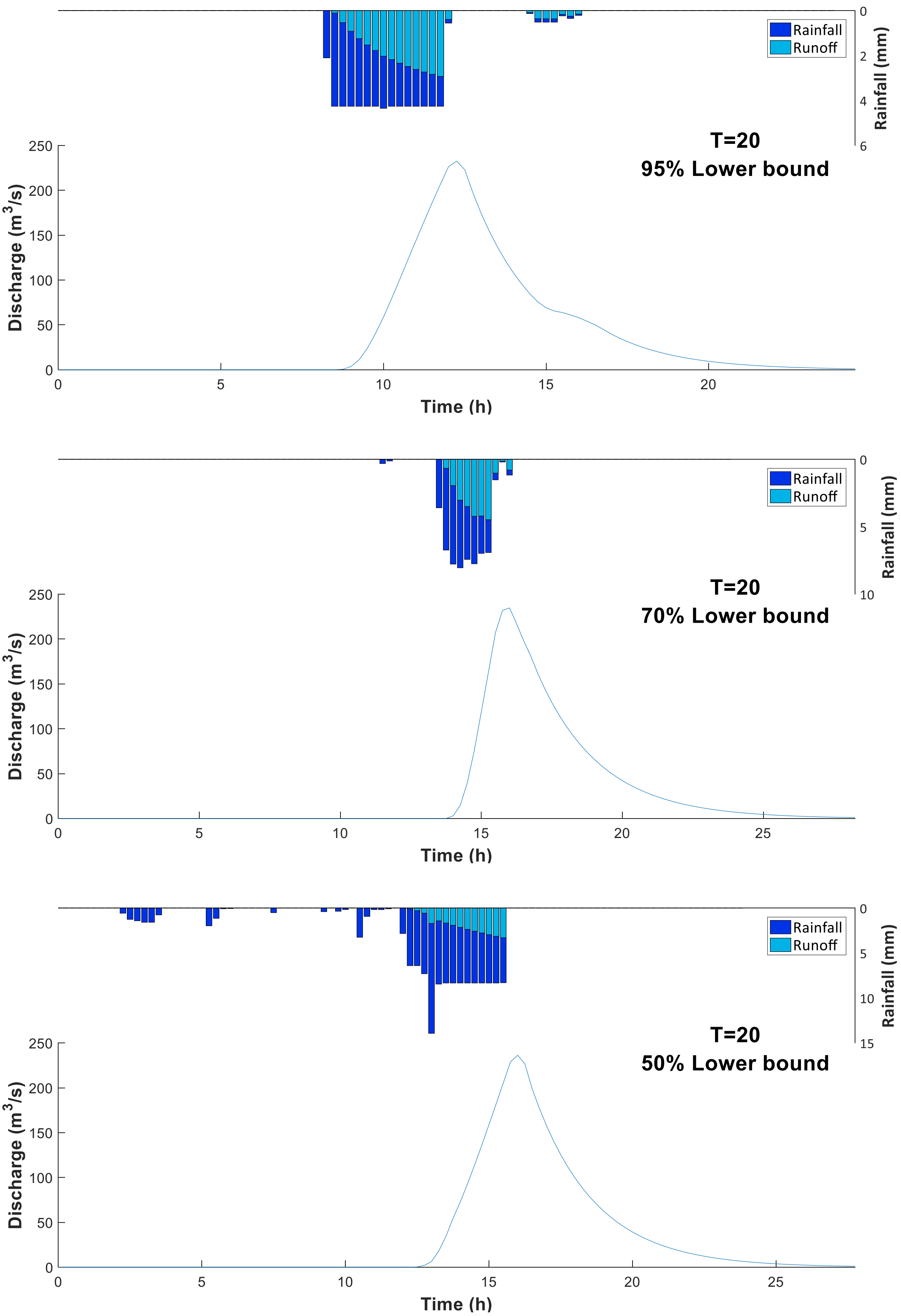

Figure 5 : Lower bound flood hydrographs (T=20 years)

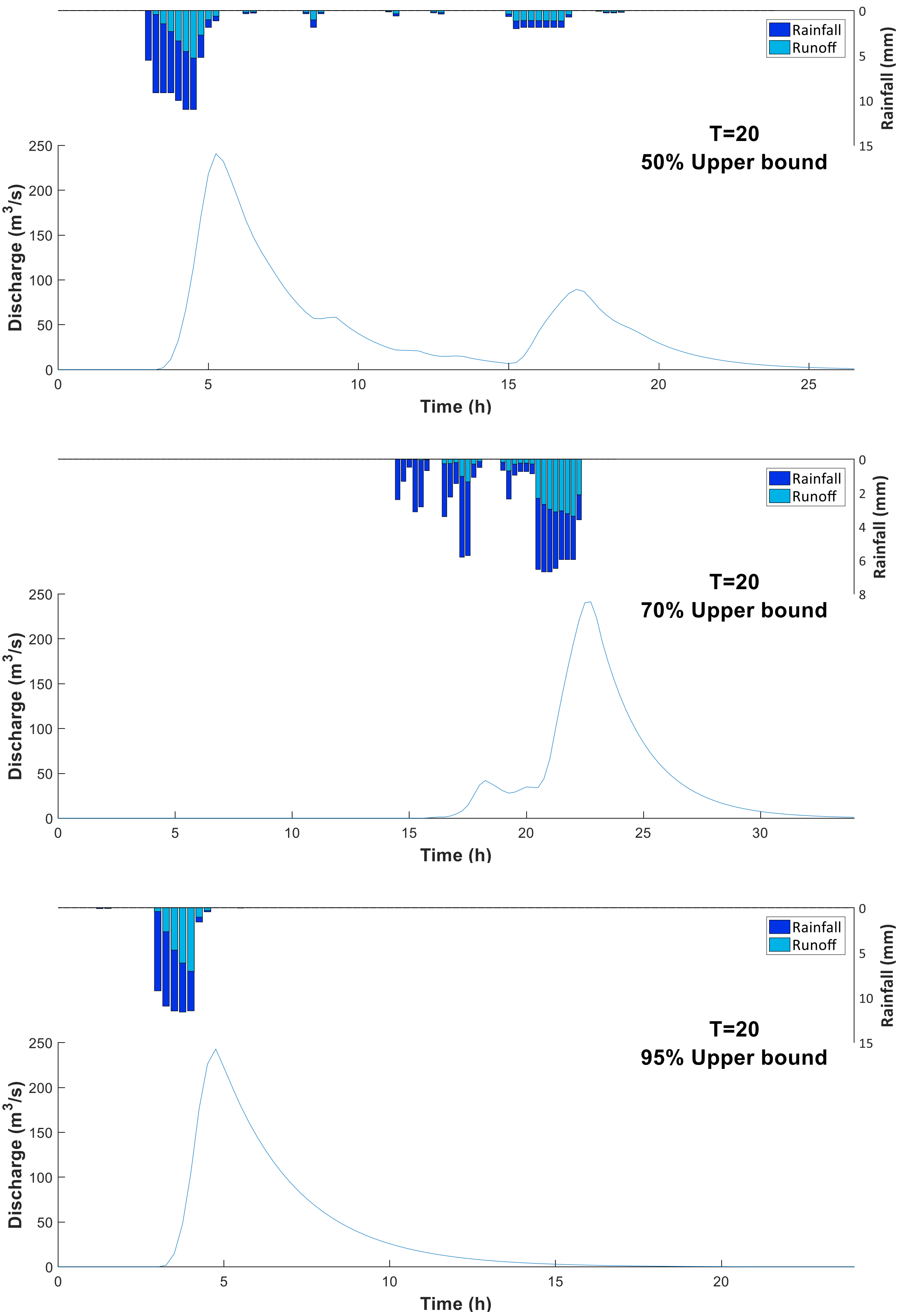

Figure 6 : Upper bound flood hydrographs (T=20 years)

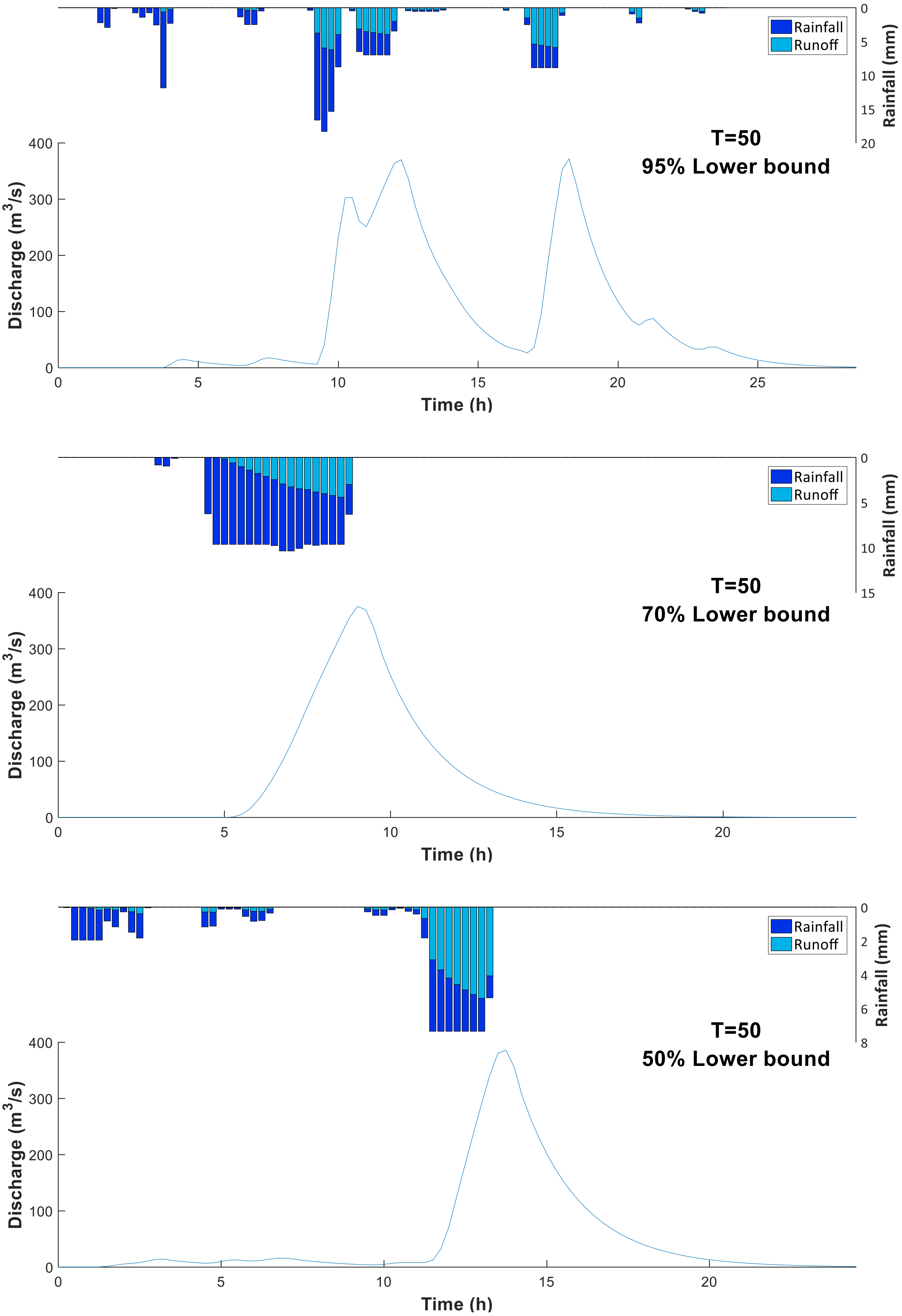

Figure 7 : Lower bound flood hydrographs (T=50 years)

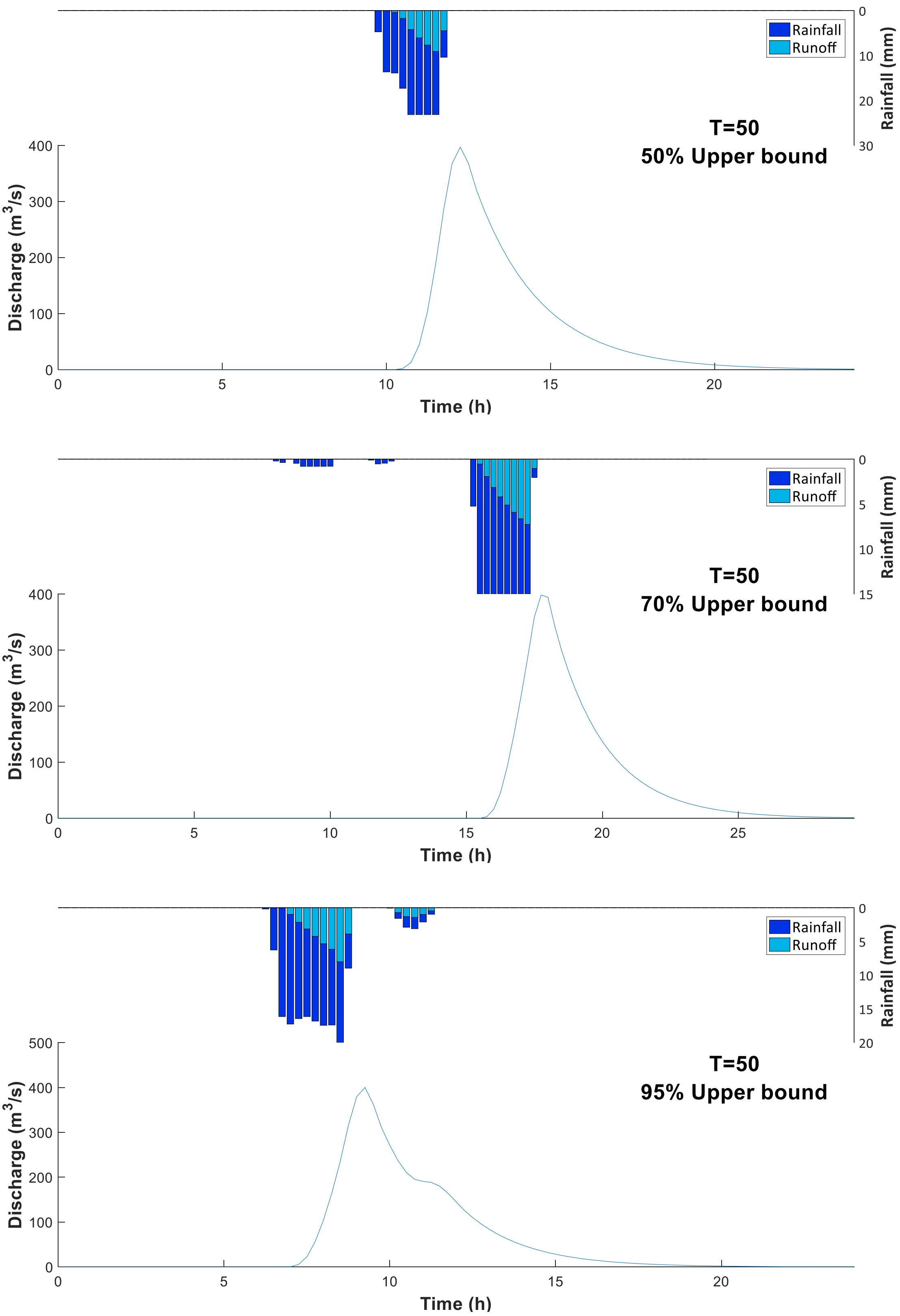

Figure 8 : Upper bound flood hydrographs (T=50 years)

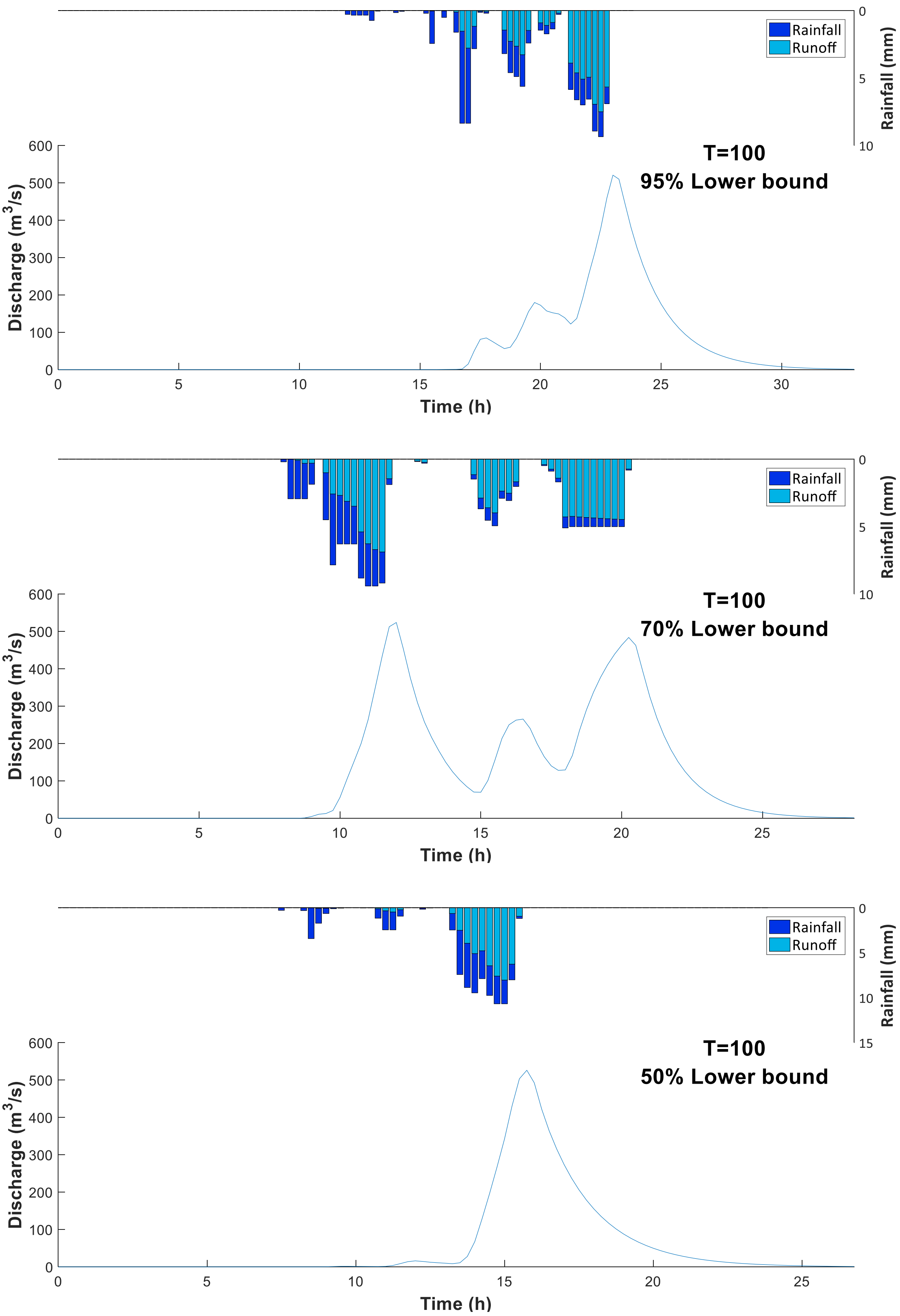

Figure 9 : Lower bound flood hydrographs (T=100 years)

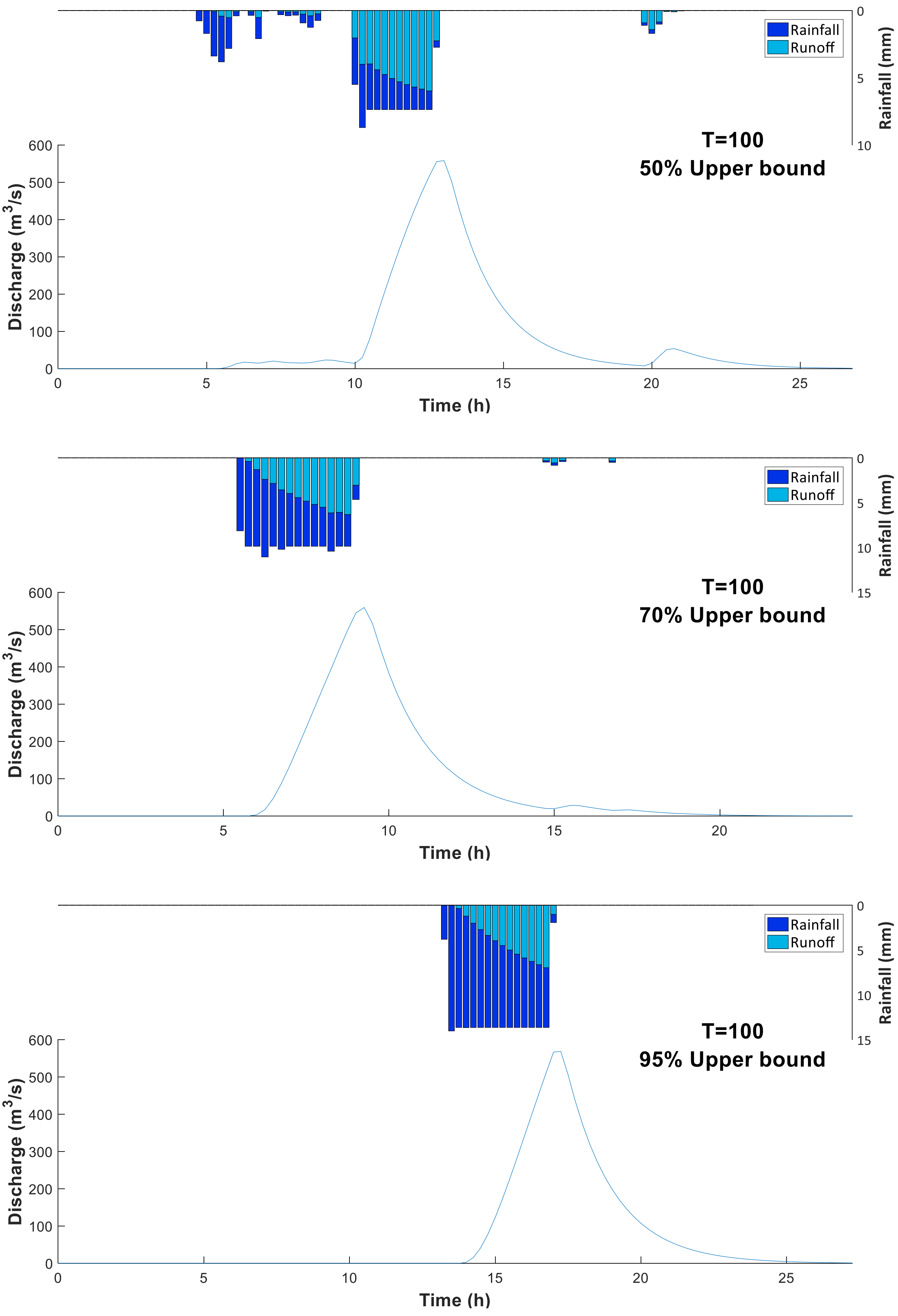

Figure 10 : Upper bound flood hydrographs (T=100 years)

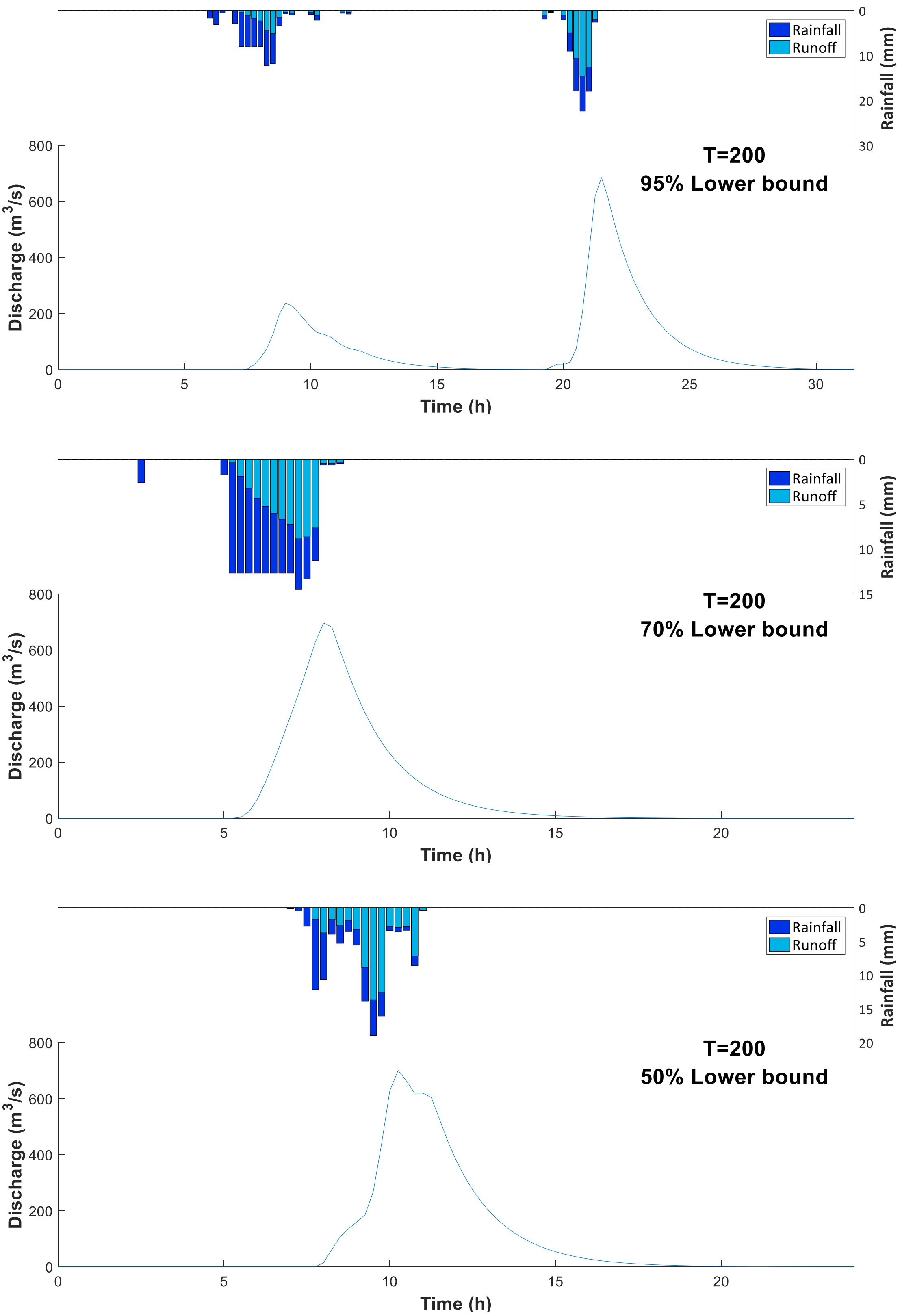

Figure 11 : Lower bound flood hydrographs (T=200 years)

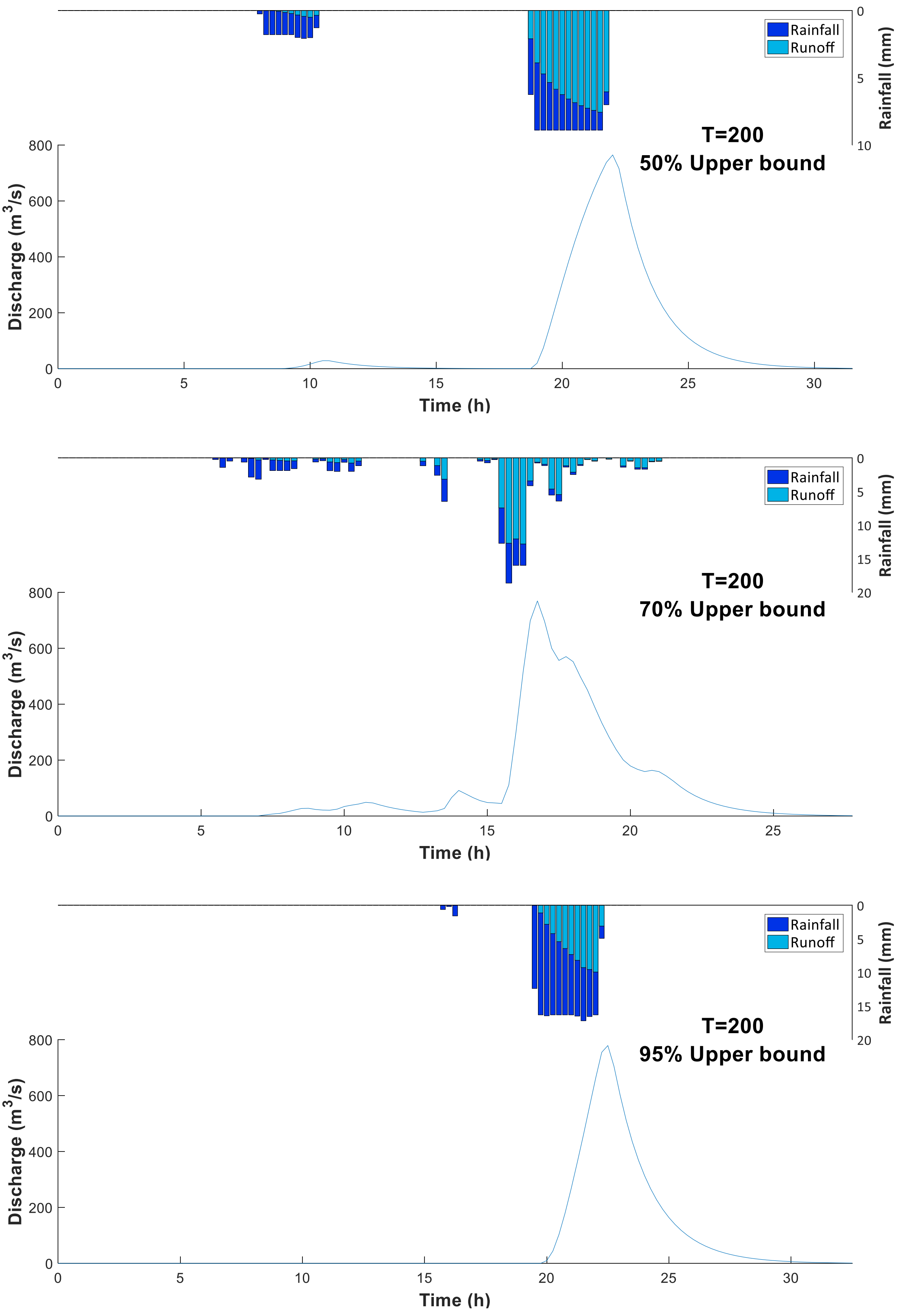

Figure 12 : Upper bound flood hydrographs (T=200 years)

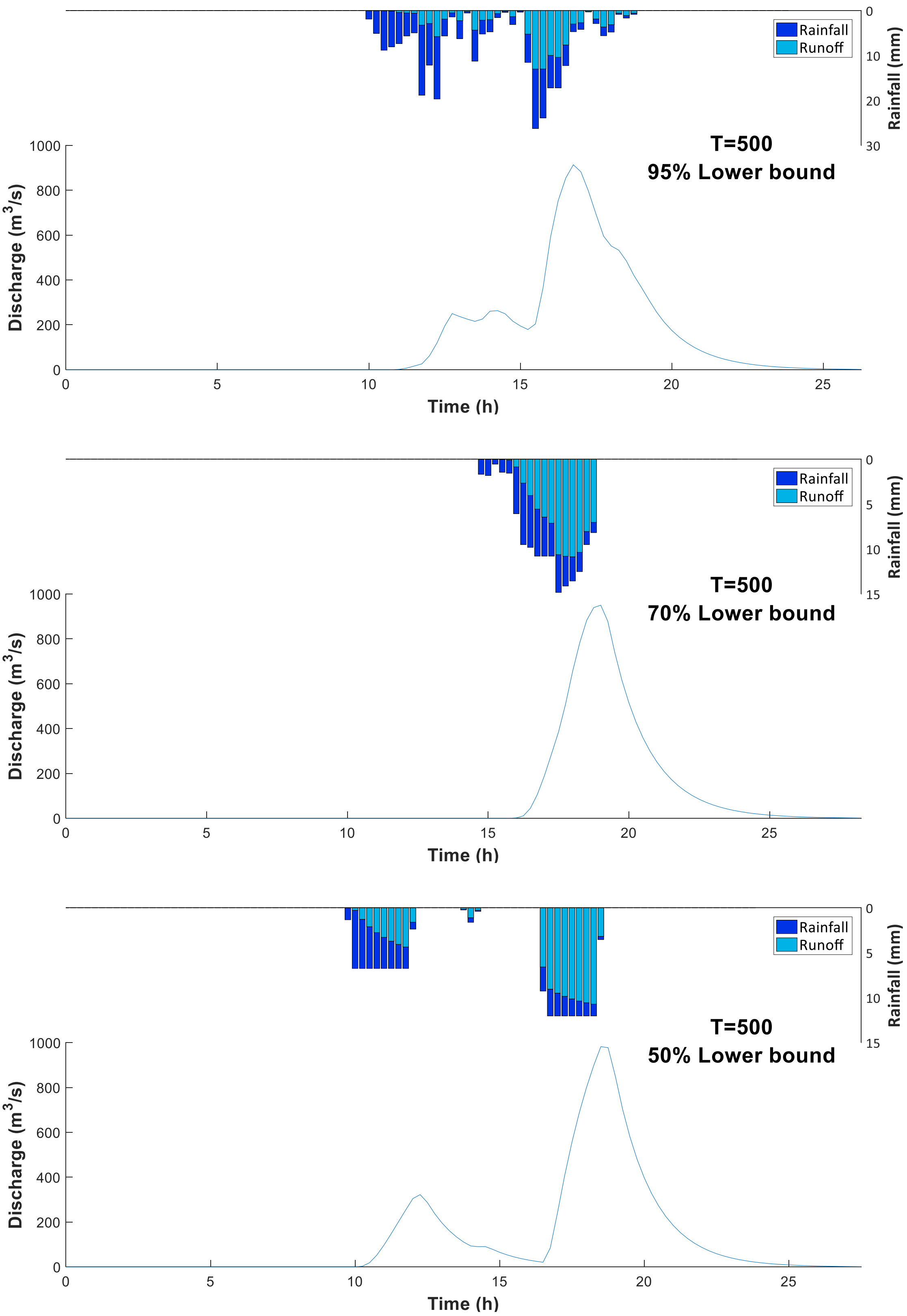

Figure 13 : Lower bound flood hydrographs (T=500 years)

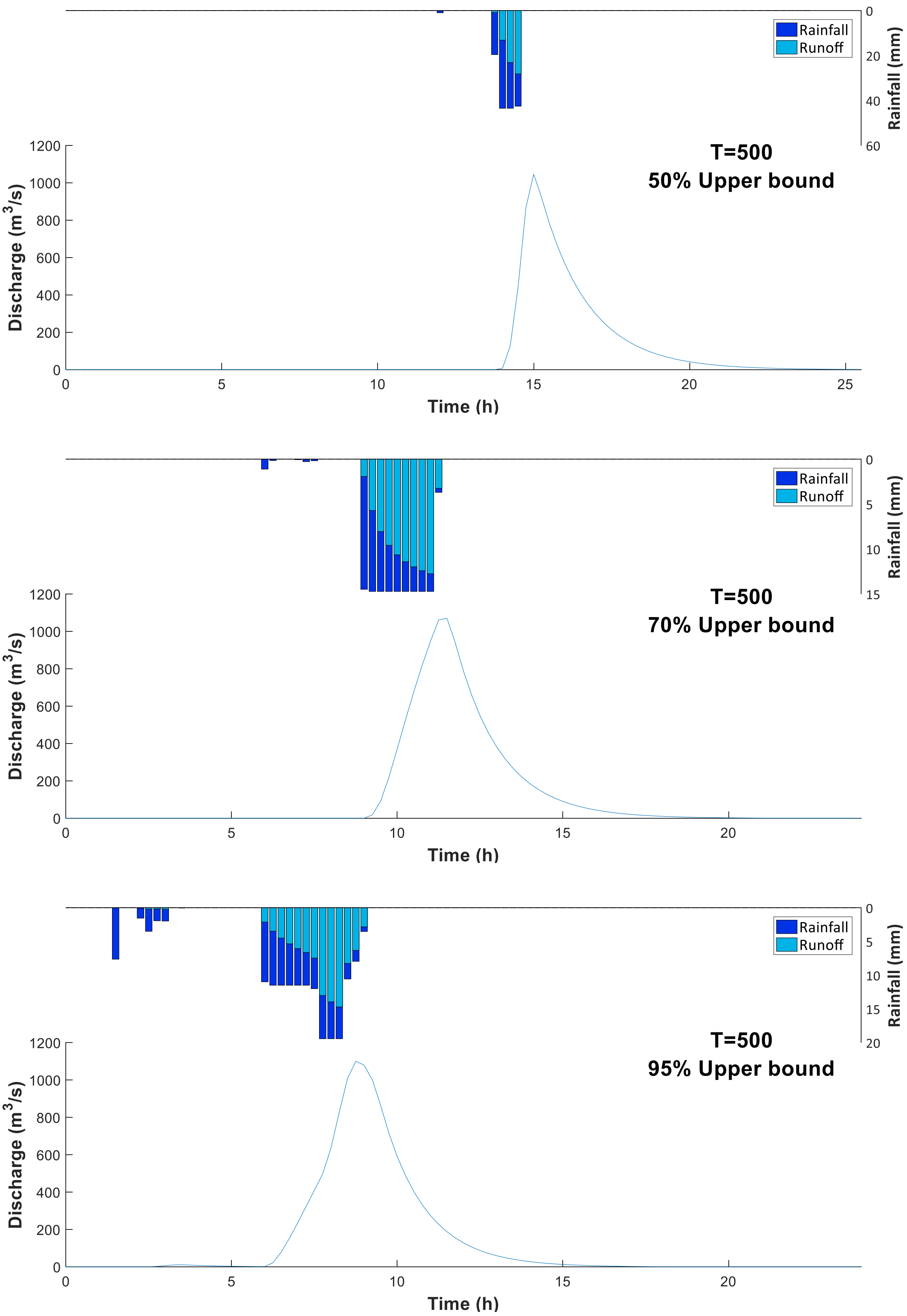

Figure 14 : Upper bound flood hydrographs (T=500 years)

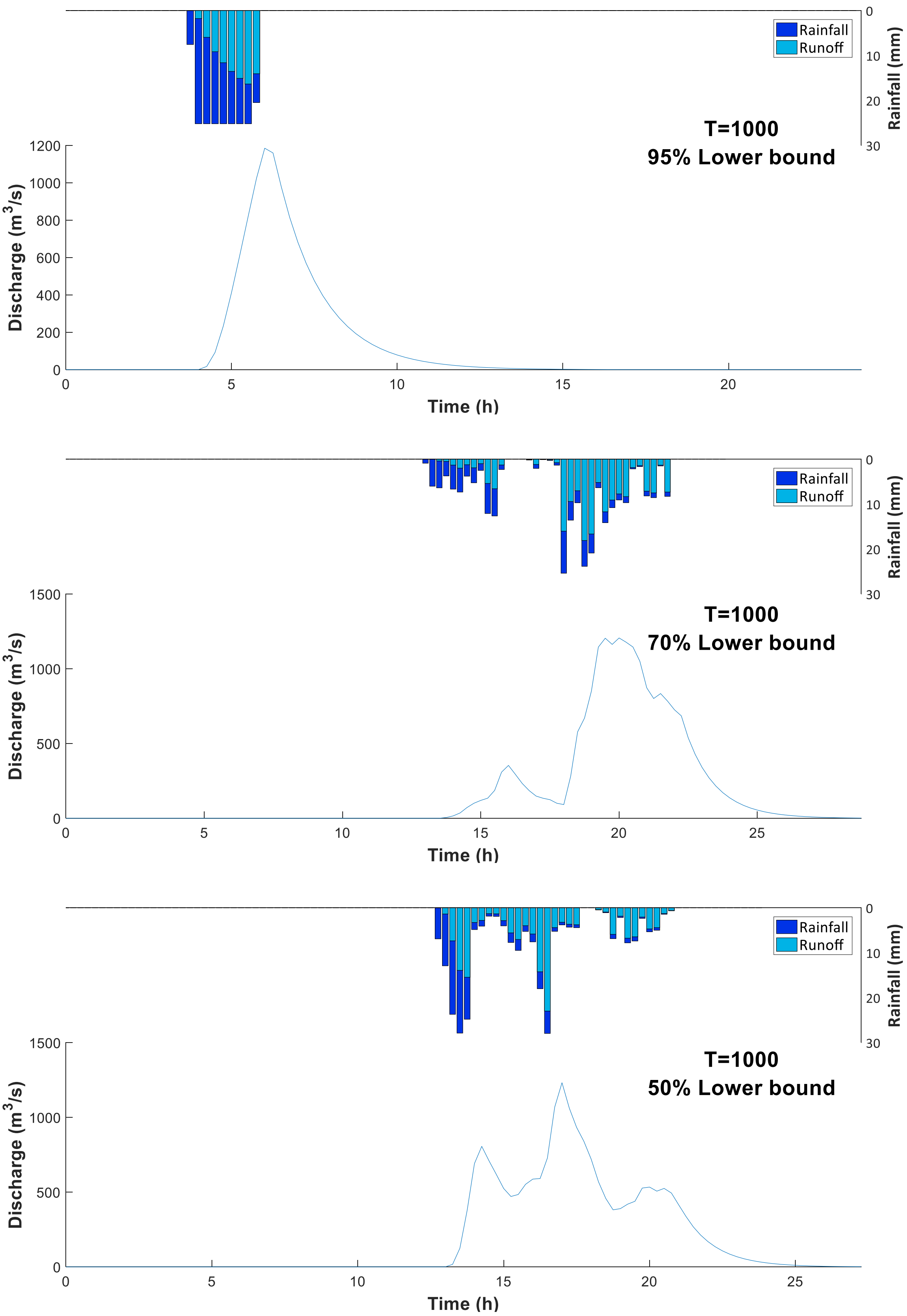

Figure 15 : Lower bound flood hydrographs (T=1000 years)

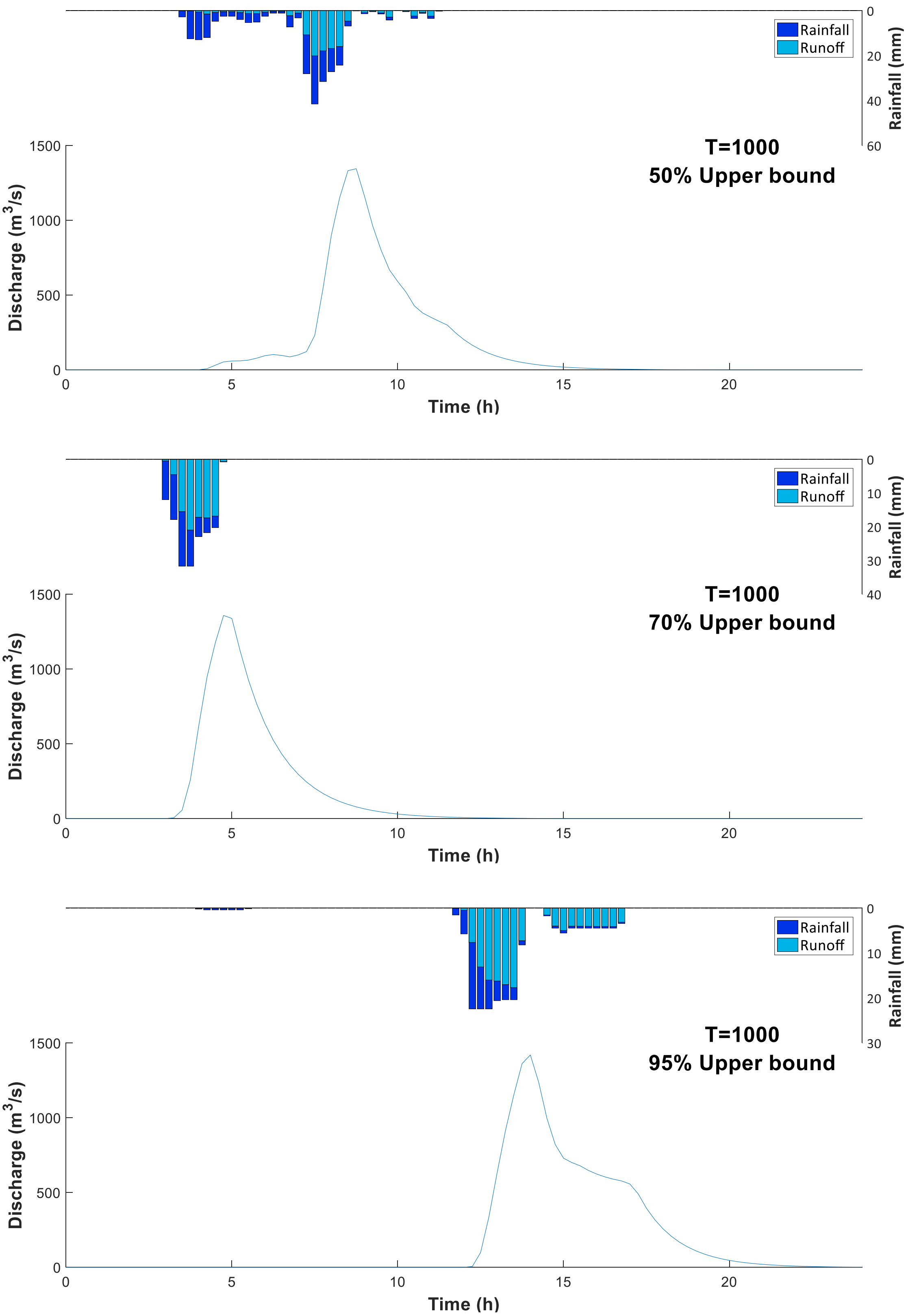

Figure 16 : Upper bound flood hydrographs (T=1000 years)

APPENDIX B: CODE

In the context of this thesis 9 different models were investigated in total. As a result over 70 functions and scripts were created. Of course such a big amount of code cannot be attached in this thesis.

As a result, only the scripts regarding the main proposed pseudo-continuous stochastic simulation framework and the typical deterministic scheme, along with the functions incorporated in them are presented here.

I. Main script of the proposed framework

```
clear
%clc;
tic

%Rainfall timestep and duration of storm
d=1;
vima=15;
vimahour=vima/60;
nosteps=d*24*60/vima;

%Model parameters
CNII=60;
A=123.3;
lamda=0.05;
tca=760.34;
tcb=2.956;
beta=0.3;
gamma=5;

%Read Hyetos files
folder='C:\Users\Giannis
Mous\Documents\MATLAB\thesismoustakis\Hyetos\Tatoi_OBL';
[ Hyetos ] = funReadHyetos(vima,folder);
[rain5,dry,wet]=accurainfive(Hyetos(:,4));
[a,b]=linearCN(CNII,dry,wet);

%Luse tin SCS daily gia na vreis ta CNdaily k.o.k.
[Sdaily,CNdaily,Qdaily,Iadaily]=SCSfun(dry,wet,a,b,Hyetos(:,4),rain5,lamda)
;
tcdaily=funtcdaily(Qdaily,tca,tcb);

%Prosdiorise ta CN,S,Ia,Q tou kathe episoiou diarkeias "d" imeron
[rain,CNepisode,Yearepisode,Qepisode,RowHyetos,TCepisode] =
funScsEpisode(lamda,d,Hyetos(:,4),CNdaily,Hyetos(:,3),tcdaily);

%Select max episodes
[maxrain,Qmaxrain,rainmaxQ,maxQ,CNmaxrain,CNmaxQ,Rowmaxrain,RowmaxQ,tcmaxra
in,tcmaxQ] =
funSelectEpisode(rain,Qepisode,Yearepisode,CNepisode,TCepisode);

%Create matrix with disaggregated episodes
```

```
[ rainstructmaxrain,rainstructmaxQ ] = funChooseEpisodeDisag(
d,Hyetos,Rowmaxrain,RowmaxQ,RowHyetos );
[Dischargemaxrain,accuDischargemaxrain] =
SCSeventfun(rainstructmaxrain,CNmaxrain,lamda,nosteps);
[DischargemaxQ,accuDischargemaxQ] =
SCSeventfun(rainstructmaxQ,CNmaxQ,lamda,nosteps);

%Estimate qp, Tb, Tp for all tc
if d>1
    tcmaxrain=round(tcmaxrain,1);
    tcmaxQ=round(tcmaxQ,1);
end
ho=10;
Vo=A*ho*10^3;
qo=0.001*A;
dt=0.001;
maxtc=max(max(tcmaxrain(:)),max(tcmaxQ(:)));
mintc=min(min(tcmaxrain(:)),min(tcmaxQ(:)));
tc=(round(mintc:0.1:maxtc,1))';
Tp=zeros(length(tc),1);
Tb=zeros(length(tc),1);
par=zeros(length(tc),1);
for i=1:length(tc);
[ par(i),Tp(i),Tb(i)] = funMY(A,tc(i),beta,gamma,vima,Vo,qo,dt);
end
k=-log(qo./par);

%Assign qp,Tb,Tp to each episode
[ TCmaxrain,TBmaxrain,TPmaxrain,Qpmaxrain ] =
funTCtablesdaily(nosteps,accuDischargemaxrain,tc,tcmaxrain,Tb,Tp,par );
[ TCmaxQ,TBmaxQ,TPmaxQ,QpmaxQ ] =
funTCtablesdaily(nosteps,accuDischargemaxQ,tc,tcmaxQ,Tb,Tp,par );

%Estimate floods
[maxQsizemaxrain ] = funQsize(TBmaxrain,vima);
[maxQsizemaxQ ] = funQsize(TBmaxrain,vima);
[ Floodmaxrain,Qpeakmaxrain,Qsizesmaxrain ] =
funFlood(Dischargemaxrain,TBmaxrain,TPmaxrain,maxQsizemaxrain,vima,ho,qo,Qp
maxrain );
[ FloodmaxQ,QpeakmaxQ,QsizesmaxQ ] =
funFlood(DischargemaxQ,TBmaxQ,TPmaxQ,maxQsizemaxQ,vima,ho,qo,QpmaxQ );

Toc
```

II. Main script of the typical deterministic framework

```
clear;
clc;
tic
%Model parameters
A=123.3;
L=29.6;
Dz=225.6;
lamda=0.05;
beta=0.3;
gamma=5;
```

```
CNII=60;

%Uncomment the desired AMC type I or II
%CNII=4.2*CNII/(10-0.058*CNII);
%CNII=23*CNII/(10+0.13*CNII);

%ombrian curve parameters
thetaombrian=0.17;
etaombrian=0.77;
kombrian=0.15;
lamdaombrian=207;
psiombrian=0.61;

%Rainfall timestep
vima=15;
vimahour=vima/60;
nosteps=24*60/vima;

%Return Periods
mikos=10000;
Taf=mikos./(1:mikos);
F=1-1./Taf;
Z=((-log(1-F)).^(-0.15)-1)/0.15;

rainlocal=24*lamdaombrian*(Taf.^kombrian-
psiombrian)/((1+24/thetaombrian)^etaombrian);
[ rain, ARF ] = funARF( rainlocal,A,24 );
[ rainstructmaxQ ] =
funAlterBlocks(rainlocal,thetaombrian,etaombrian,kombrian,lamdaombrian,psio
mbrian,24,vimahour,nosteps,A );
CN=ones(size(rainstructmaxQ,2),1).*CNII;
[DischargemaxQ,accuDischargemaxQ] =
SCSeventfun(rainstructmaxQ,CN,lamda,nosteps);
Q=accuDischargemaxQ(end,:)';

%Concentration time (Giandotti)
tg=round((4*A^0.5+1.5*L)/(0.8*Dz^0.5),1);

%Estimate qp, Tb, Tp for different tc
ho=10;
Vo=A*ho*10^3;
qo=0.001*A;
dt=0.001;
[ Qp,Tp,Tb] = funMY(A,tg,beta,gamma,vima,Vo,qo,dt);

k=-log(qo./Qp);

%Create flood hydrographs
[maxQsize ] = funQsize(Tb,vima);
[ FloodmaxQ,QpeakmaxQ,QsizesmaxQ ] =
funFloodConstant(DischargemaxQ,Tb,Tp,maxQsize,vima,ho,qo,Qp );
```

III. Functions

```
function [ rain,f ] = funARF( rainlocal,A,d )
```

```
%FUNARF Areal reduction factor

f=max(1-(0.048*A^(0.36-0.01*log(A)))/(d^0.35),0.25);
rain=rainlocal.*f;
end


function [ rainstruct ] =
funAlterBlocks(rainlocal,thetaombrian,etaombrian,kombrian,lamdaombrian,psio
mbrian,d,vimahour,nosteps,A )
%FUNALTERBLOCKS Alternative Blocks method
T=((rainlocal.*(1+d/thetaombrian).^etaombrian)./(d*lamdaombrian)+psiombrian
).^(1/kombrian);
D=(vimahour:vimahour:vimahour*nosteps)';
rainstruct=zeros(size(D,1),size(T,1));

for i=1:length(T)

    I=lamdaombrian.*(T(i).^kombrian-
psiombrian)./(1+D./thetaombrian).^etaombrian;
    f=max(1-(0.048.*A.^(0.36-0.01.*log(A)))./(D.^0.35),0.25);
    h=I.*f.*D;

    Dh=zeros(length(D),1);
    Dh(1)=h(1);
    for k=2:length(D);
        Dh(k)=h(k)-h(k-1);
    end
    order=[fliplr(1:2:nosteps-1),2:2:nosteps]';
    sorth=sort(Dh,'descend');

    for j=1:length(order);
    rainstruct(j,i)=sorth(order(j));
    end
end

end


function [Flood,Qpeak,Qsizes] = funFloodConstant(
Discharge,TB,TP,maxQsize,vima,ho,qo,Qp )
%FUNFLOODCONSTANT Create flood hydrographs

Flood=zeros(maxQsize,size(Discharge,2));
arithmossimion=TB*60/vima+1;
vimahour=round(vima/60,2);
Qsizes=zeros(size(Discharge,2),1);

for i=1:size(Discharge,2)

    u=zeros();
j=1;
for k=1:size(Discharge,1)
 u(j:j+arithmossimion-1,k) =Discharge(k,i)/ho.*( funU( qo,Qp,vimahour,TP,TB
))';
j=j+1;
Qsize=size(u,1);
end
Flood((1:Qsize),i)=sum(u,2);
```

```
Qsizes(i)=Qsize;
end
Qpeak=(max(Flood))';

end



function [ Hyetos ] = funReadHyetos(vima,folder)
%FUNREADHYETOS
%   Detailed explanation goes here
Jan=dlmread([folder,'\Jan.txt.Disag.txt']);
Feb=dlmread([folder,'\Feb.txt.Disag.txt']);
Mar=dlmread([folder,'\Mar.txt.Disag.txt']);
Apr=dlmread([folder,'\Apr.txt.Disag.txt']);
May=dlmread([folder,'\May.txt.Disag.txt']);
Jun=dlmread([folder,'\Jun.txt.Disag.txt']);
Jul=dlmread([folder,'\Jul.txt.Disag.txt']);
Aug=dlmread([folder,'\Aug.txt.Disag.txt']);
Sep=dlmread([folder,'\Sep.txt.Disag.txt']);
Oct=dlmread([folder,'\Oct.txt.Disag.txt']);
Nov=dlmread([folder,'\Nov.txt.Disag.txt']);
Dec=dlmread([folder,'\Dec.txt.Disag.txt']);


rowJan=find(Jan(:,1)==1);
rowFeb=find(Feb(:,1)==1);
rowMar=find(Mar(:,1)==1);
rowApr=find(Apr(:,1)==1);
rowMay=find(May(:,1)==1);
rowJun=find(Jun(:,1)==1);
rowJul=find(Jul(:,1)==1);
rowAug=find(Aug(:,1)==1);
rowSep=find(Sep(:,1)==1);
rowOct=find(Oct(:,1)==1);
rowNov=find(Nov(:,1)==1);
rowDec=find(Dec(:,1)==1);

sunathrisi=vima/15;
Hyetosstart=zeros(size([Jan;Feb;Mar;Apr;May;Jun;Jul;Aug;Sep;Oct;Nov;Dec],1)
,size([Jan;Feb;Mar;Apr;May;Jun;Jul;Aug;Sep;Oct;Nov;Dec],2));
Hyetos=zeros(size([Jan;Feb;Mar;Apr;May;Jun;Jul;Aug;Sep;Oct;Nov;Dec],1),(siz
e([Jan;Feb;Mar;Apr;May;Jun;Jul;Aug;Sep;Oct;Nov;Dec],2)-4)/sunathrisi+4);

rowstart=1;
for i=1:length(rowJan)-1

rowfinish=rowJan(i+1)+rowFeb(i+1)+rowMar(i+1)+rowApr(i+1)+rowMay(i+1)+rowJu
n(i+1)+rowJul(i+1)+rowAug(i+1)+rowSep(i+1)+rowOct(i+1)+rowNov(i+1)+rowDec(i
+1)-12;
    Hyetosstart(rowstart:rowfinish,:)=[Jan(rowJan(i):rowJan(i+1)-
1,:);Feb(rowFeb(i):rowFeb(i+1)-1,:);Mar(rowMar(i):rowMar(i+1)-
1,:);Apr(rowApr(i):rowApr(i+1)-1,:);May(rowMay(i):rowMay(i+1)-
1,:);Jun(rowJun(i):rowJun(i+1)-1,:);Jul(rowJul(i):rowJul(i+1)-
1,:);Aug(rowAug(i):rowAug(i+1)-1,:);Sep(rowSep(i):rowSep(i+1)-
1,:);Oct(rowOct(i):rowOct(i+1)-1,:);Nov(rowNov(i):rowNov(i+1)-
1,:);Dec(rowDec(i):rowDec(i+1)-1,:)];
    rowstart=rowfinish+1;
end
```

```
Hyetosstart(rowstart:end,:)=[Jan(rowJan(end):end,:);Feb(rowFeb(end):end,:);
Mar(rowMar(end):end,:);Apr(rowApr(end):end,:);May(rowMay(end):end,:);Jun(ro
wJun(end):end,:);Jul(rowJul(end):end,:);Aug(rowAug(end):end,:);Sep(rowSep(e
nd):end,:);Oct(rowOct(end):end,:);Nov(rowNov(end):end,:);Dec(rowDec(end):en
d,:)];


if sunathrisi>1
    Hyetos(:,5:end)=Hyetosstart(:,5:2:end)+Hyetosstart(:,6:2:end);
    Hyetos(:,1:4)=Hyetosstart(:,1:4);
else
    Hyetos=Hyetosstart;
end


end


function [ rain5, dry, wet ] = accurainfive(rain)
 %Calculate Antecedent Precipitation and estimate dry and wet conditions
rain5=zeros(length(rain),6);
L=length(rain);
numberofdays=5;

for i=numberofdays+1:L
    rain5(i,1)=sum(rain((i-numberofdays):(i-1)));
end

rain5(1,1)=0;

for i=2:numberofdays
    rain5(i,1)=sum(rain(1:(i-1)));
end

rain5(:,2)=sort(rain5(:,1));

rowstart=find(rain5(:,2)>0,1,'first');

for i=rowstart:L
    rain5(i,3)=(i-rowstart+1)/(L-rowstart+1);
end

rain5(:,4)=abs(rain5(:,3)-0.1);
rain5(:,5)=abs(rain5(:,3)-0.9);

dry=rain5(find(rain5(:,4)==min(rain5(:,4)),1,'first'),2);
wet=rain5(find(rain5(:,5)==min(rain5(:,5)),1,'first'),2);
end


function [ a,b ] = linearCN(CNII,dry,wet )
%FUNTCDAILY Performs a linear regression of CN

CN=[4.2*CNII/(10-0.058*CNII);CNII;23*CNII/(10+0.13*CNII)];
P5=[ones(3,1),[dry;0.5*(dry+wet);wet]];

c=P5\CN;
```

```
a=c(2,1);
b=c(1,1);
end


function [ Sevent, CNevent, Q, Iaevent] =
SCSfun(dry,wet,a,b,rain,rain5,lamda)
 %FUNTCDAILY: Estimate CN and generated runoff in a daily basis

CNevent=zeros(length(rain),1);
Q=zeros(length(rain),1);

CNevent(find(rain5(:,1)<=dry))=a*dry+b;
CNevent(find(rain5(:,1)>=wet))=a*wet+b;
CNevent(find(rain5(:,1)>dry & rain5(:,1)<wet))=a.*rain5(find(rain5(:,1)>dry
& rain5(:,1)<wet))+b;
Sevent=25400./CNevent-254;
Iaevent=lamda.*Sevent;

idx=find(rain(:)>Iaevent(:));
Q(idx)=((rain(idx)-Iaevent(idx)).^2)./(rain(idx)+Sevent(idx)-Iaevent(idx));

end


function [ tc ] = funtcdaily(Q,tca,tcb )
%FUNTCDAILY Estimate daily value of tc
tcmax=round((tca/1)^(1/tcb),1);

tc=tcmax*ones(length(Q),1);
tc(find(Q>1))=round((tca./Q(find(Q>1))).^(1/tcb),1);

end


function [Rain,CNepisode,Yearepisode,Qepisode,RowHyetos,TCepisode] =
funScsEpisode(lamda,d,rain,CN,year,tcdaily)
%FUNSCSEPISODE Defining variables corresponding to every episode. If d=1
episodes coincide with daily calculations
Hyetosrows=zeros(size(rain,1)+d-1,d);
Table=zeros(size(rain,1)+d-1,d);
TableYear=zeros(size(rain,1)+d-1,d);
if nargin==6
TableTC=zeros(size(rain,1)+d-1,d);
end

for i=1:d
    Table(i:size(rain,1)+i-1,i)=rain;
    TableYear(i:size(rain,1)+i-1,i)=year;
    Hyetosrows(i:size(rain,1)+i-1,i)=(1:size(rain,1));
end
SumTable=sum(Table,2);
SumTableYear=round(sum(TableYear,2)./d,0);
Yearepisode=SumTableYear(d:end+1-d);
Rain=SumTable(d:end+1-d);
CNepisode=CN(1:end-d+1);
RowHyetos=fliplr(Hyetosrows(d:end+1-d,:));
Sepisode=25400./CNepisode-254;
Iaepisode=lamda.*Sepisode;
```

```
idx=find(Rain>Iaepisode);
Qepisode=zeros(size(CNepisode,1),size(CNepisode,2));
Qepisode(idx)=((Rain(idx)-Iaepisode(idx)).^2)./(Rain(idx)+Sepisode(idx)-
Iaepisode(idx));

if nargin==6
    for i=1:d
        TableTC(i:size(rain,1)+i-1,i)=tcdaily;
    end
    SumTableTC=sum(TableTC,2)./d;
    TCepisode=SumTableTC(d:end+1-d);
end

end


function
[maxrain,Qmaxrain,rainmaxQ,maxQ,CNmaxrain,CNmaxQ,Rowmaxrain,RowmaxQ,tcmaxra
in,tcmaxQ,Qoverflowmaxrain,QoverflowmaxQ,Qscsmaxrain,QscsmaxQ] =
funSelectEpisode(rain,Qepisode,Yearepisode,CNepisode,TCepisode,Qoverflowepi
sode,Qscsepisode)
%FUNSELECTEPISODE Select episodes for annual maxima of runoff and annual
maxima of rainfall
A=unique(Yearepisode);

maxrain=zeros(length(A),1);
Qmaxrain=zeros(length(A),1);
rainmaxQ=zeros(length(A),1);
maxQ=zeros(length(A),1);
B=zeros(length(A),1);
CNmaxrain=zeros(length(A),1);
CNmaxQ=zeros(length(A),1);
Rowmaxrain=zeros(length(A),1);
RowmaxQ=zeros(length(A),1);
if nargin>=5
    tcmaxrain=zeros(length(A),1);
    tcmaxQ=zeros(length(A),1);
end

if nargin<=6
    Qoverflowmaxrain=zeros(length(A),1);
    QoverflowmaxQ=zeros(length(A),1);
    Qscsmaxrain=zeros(length(A),1);
    QscsmaxQ=zeros(length(A),1);
end

for i=1:length(A)

    B(i)=find(Yearepisode==A(i,1),1);
end

for i=1:length(A)-1;

    maxrain(i)=max(rain(B(i):B(i+1)-1));
    maxQ(i)=max(Qepisode(B(i):B(i+1)-1));
end
maxrain(length(A))=max(rain(B(length(A)):length(rain)));
maxQ(length(A))=max(Qepisode(B(length(A)):length(Qepisode)));
```

```
for i=1:length(A)-1
    rowmaxrain=find(rain(B(i):B(i+1)-1)==maxrain(i),1);
    rowmaxQ=find(Qepisode(B(i):B(i+1)-1)==maxQ(i),1);
    Qmaxrain(i)=Qepisode(B(i)-1+rowmaxrain);
    rainmaxQ(i)=rain(B(i)-1+rowmaxQ);
    CNmaxrain(i)=CNepisode(B(i)-1+rowmaxrain);
    CNmaxQ(i)=CNepisode(B(i)-1+rowmaxQ);
     if nargin>=5
        tcmaxrain(i)=TCepisode(B(i)-1+rowmaxrain);
        tcmaxQ(i)=TCepisode(B(i)-1+rowmaxQ);
     end

     if nargin>=6
         Qoverflowmaxrain(i)=Qoverflowepisode(B(i)-1+rowmaxrain);
         QoverflowmaxQ(i)=Qoverflowepisode(B(i)-1+rowmaxQ);
         Qscsmaxrain(i)=Qscsepisode(B(i)-1+rowmaxrain);
         QscsmaxQ(i)=Qepisode(B(i)-1+rowmaxQ);
     end
    Rowmaxrain(i)=B(i)-1+rowmaxrain;
    RowmaxQ(i)=B(i)-1+rowmaxQ;
end

elementmaxrain=find(rain(B(length(A)):length(rain))==maxrain(length(A),1),1
);
elementmaxQ=find(Qepisode(B(length(A)):length(rain))==maxQ(length(A),1),1);
Qmaxrain(length(A))=Qepisode(B(length(A))-1+elementmaxrain);
rainmaxQ(length(A))=rain(B(length(A))-1+elementmaxQ);
CNmaxrain(length(A))=CNepisode(B(length(A))-1+elementmaxrain);
CNmaxQ(length(A))=CNepisode(B(length(A))-1+elementmaxQ);
if nargin>=5
    tcmaxrain(length(A))=TCepisode(B(length(A))-1+elementmaxrain);
    tcmaxQ(length(A))=TCepisode(B(length(A))-1+elementmaxQ);
end

if nargin>=6
    Qoverflowmaxrain(length(A))=Qoverflowepisode(B(length(A))-
1+elementmaxrain);
    QoverflowmaxQ(length(A))=Qoverflowepisode(B(length(A))-1+elementmaxQ);
    Qscsmaxrain(length(A))=Qscsepisode(B(length(A))-1+elementmaxrain);
    QscsmaxQ(length(A))=Qscsepisode(B(length(A))-1+elementmaxQ);
end
Rowmaxrain(length(A))=B(length(A))-1+elementmaxrain;
RowmaxQ(length(A))=B(length(A))-1+elementmaxQ;
end


function [ rainstructmaxrain,rainstructmaxQ ] = funChooseEpisodeDisag(
d,Hyetos,Rowmaxrain,RowmaxQ,RowHyetos )
%FUNCHOOSEEPISODEDISAG Choose rainfall profiles from Hyetos matrix
rainstructmaxrain1=zeros(length(Rowmaxrain)*d,size(Hyetos(:,5:end),2));
rainstructmaxQ1=zeros(length(Rowmaxrain)*d,size(Hyetos(:,5:end),2));
rainstructmaxrain=zeros(length(Rowmaxrain),size(Hyetos(:,5:end),2)*d)';
rainstructmaxQ=zeros(length(Rowmaxrain),size(Hyetos(:,5:end),2)*d)';

start=1;
finish=d;
for i=1:length(Rowmaxrain)

rainstructmaxrain1(start:finish,:)=Hyetos(RowHyetos(Rowmaxrain(i),:),5:end)
;
```

```
    rainstructmaxQ1(start:finish,:)=Hyetos(RowHyetos(RowmaxQ(i),:),5:end);
    start=start+d;
    finish=finish+d;
end
rainstructmaxrain2=rainstructmaxrain1';
rainstructmaxQ2=rainstructmaxQ1';

rainstructmaxrain(:)=rainstructmaxrain2(:);
rainstructmaxQ(:)=rainstructmaxQ2(:);
end


function [finalQ,Qaccu] = SCSeventfun(rainstruct,CN,lamda,nosteps )
 %Scseventfun Calculate runoff evolution during event through NRCS-CN
finalQ=zeros(nosteps,size(rainstruct,2));
Qaccu=zeros(nosteps,size(rainstruct,2));
Ia=zeros(nosteps,size(rainstruct,2));

S=repmat(25400./(CN)'-254,nosteps,1);

Ia=S.*lamda;
cumrain=cumsum(rainstruct);

row=find(cumrain-Ia>0);

Qaccu([row])=(cumrain([row])-Ia([row])).^2./(cumrain([row])+S([row])-
Ia([row]));

for i=2:nosteps
    finalQ(i,:)=Qaccu(i,:)-Qaccu(i-1,:);
end
finalQ(1,:)=Qaccu(1,:);

end


function [ par,Tp,Tb] = funMY(A,tc,beta,gamma,vima,Vo,qo,dt)
%funMY estimate Unit hydrograph
step=vima/60;

tp=step*0.5+beta.*tc;
tb=step+gamma.*tc;
Tp=round(tp/step)*step;
Tb=round(tb/step)*step;

options=optimoptions(@fmincon,'Display','none');
[par]=fmincon(@(qp) funObj( qo,qp,dt,Tp,Tb,Vo
),100,[],[],[],[],0,2000,[],options);

end


function [ SE] = funObj( qo,qp,dt,Tp,Tb,Vo )
V = funV( qo,qp,dt,Tp,Tb);
SE=(Vo-V)^2;
end


function [ V] = funV( qo,qp,dt,Tp,Tb )
```

```
u=funU( qo,qp,dt,Tp,Tb) ;
V=sum(u*dt*60*60);
end


function [ TC,TB,TP,Qp ] =
funTCtablesdaily(nosteps,accuDischarge,tc,tcmax,Tb,Tp,par)
%funTCtablesdaily Assign UH characteristics to every time interval of every
episode

TC=zeros(1,size(accuDischarge,2));
TB=zeros(1,size(accuDischarge,2));
TP=zeros(1,size(accuDischarge,2));
Qp=zeros(1,size(accuDischarge,2));

for i=1:length(tc)
    TC(find(tcmax==tc(i)))=tc(i);
    TB(find(tcmax==tc(i)))=Tb(i);
    TP(find(tcmax==tc(i)))=Tp(i);
    Qp(find(tcmax==tc(i)))=par(i);
end

TC=repmat(TC,nosteps,1);
TB=repmat(TB,nosteps,1);
TP=repmat(TP,nosteps,1);
Qp=repmat(Qp,nosteps,1);

end


 function [ maxQsize ] = funQsize(Tb,vima)
Qsize=zeros(size(Tb,2),1);
 %funQsize determine the size of every flood hydrograph

for k=1:size(Tb,2)

for i=1:size(Tb,1)
    Qsize(k)=max(Tb(i,k)*60/vima+1+i-1);
end
end

maxQsize=max(max(Qsize(:)));
end


function [ Flood,Qpeak,Qsizes ] =
funFlood(Discharge,TB,TP,maxQsize,vima,ho,qo,Qp )
 %funFlood Estimate flood hyhdrograph

Flood=zeros(maxQsize,size(Discharge,2));
arithmossimion=zeros(size(Discharge,1),size(Discharge,2));
vimahour=round(vima/60,2);
Qsizes=zeros(size(Discharge,2),1);

for j=1:size(arithmossimion,2)
    for i=1:size(arithmossimion,1)
        arithmossimion(i,j)=TB(i,j)*60/vima+1;
    end
```

```
end

for i=1:size(arithmossimion,2)

    u=zeros();
j=1;
for k=1:size(TB,1)
 u(j:j+arithmossimion(k,i)-1,k) =Discharge(k,i)/ho.*( funU(
qo,Qp(k,i),vimahour,TP(k,i),TB(k,i) ))';
j=j+1;
Qsize=size(u,1);
end
Flood((1:Qsize),i)=sum(u,2);
Qsizes(i)=Qsize;
end
Qpeak=(max(Flood))';

end
```